Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-04/5-4977-01-1		

4. Title and Subtitle	5. Report Date
VARIABILITY OF HAMBURG WHEEL TRACKING DEVICES	April 2004
	6. Performing Organization Code
7. Author(s) Arif Chowdhury, Joe W. Button, and John P. Wikander	8. Performing Organization Report No. Report 5-4977-01-1
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Project No. 5-4977-01
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Implementation: November 2002-February 2004 14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.
Research Project Title: Implementation of the Hamburg Wheel-Track Device for Design of Hot Mix Asphalt

16. Abstract

The objective of this implementation project was to prepare procurement specifications and purchase three Hamburg Wheel-Track Devices (HWTDs), install them in two different Texas Department of Transportation (TxDOT) laboratories, and provide training to assist the technicians in proper procedures for testing and data analysis. The implementation process included conducting a limited proficiency study of all five of the HWTDs belonging to TxDOT as well as two HWTDs belonging to the Texas Transportation Institute (TTI) and PaveTex. The proficiency study determined the accuracy and precision of the seven HWTD devices.

A statistical analysis of the results revealed no significant differences among the seven HWTDs. However, the ability of the statistical models to detect differences between the machines was restricted because of the low number of replications of the experiment. Observations indicate that it may be possible to improve the current TxDOT HWTD data collection technique to improve statistical validity of the measurements.

17. Key Words	18. Distribution Statement
Hamburg, Precision, Variablity, Rut Depth	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	60	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

VARIABILITY OF HAMBURG WHEEL TRACKING DEVICES

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Report 5-4977-01-01
Project Number 5-4977-01
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Sponsored by the
Texas Department of Transportation
In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

April 2004

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ACKNOWLEDGMENTS

This project was conducted in cooperation with the Texas Department of Transportation and the Federal Highway Administration. The researchers gratefully acknowledge the support and guidance of Mr. Greg Cleveland, director of this project. The researchers are also thankful to Mr. Maghsoud Tahmoressi of PaveTex and the TxDOT technicians at the Austin and Chico laboratories for carefully conducting the tests.

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CHAPTER 1: INTRODUCTION

BRIEF HISTORY

The Hamburg Wheel-Tracking Device (HWTD) is a torture test that indicates susceptibility to premature failure of hot mix asphalt (HMA) paving mixtures that may be attributed to such factors as:

- a weak aggregate structure,
- inadequate binder stiffness,
- moisture damage, and
- inadequate binder to aggregate adhesion.

Several agencies in the U.S. and Europe use the HWTD to evaluate the rutting potential and moisture susceptibility of HMA paving mixtures (*1*). The Texas Department of Transportation (TxDOT) developed test method Tex-242-F, "Hamburg Wheel-Tracking Test," for evaluating HMA specimens (*2*). Test methods Tex-205-F, "Laboratory Method of Mixing Bituminous Mixtures," and Tex-241-F, "Superpave Gyratory Compacting of Test Specimens of Bituminous Mixtures," are typically used to fabricate HWTD test specimens; pavement cores may also be tested. Rut depth measurements are recorded along with the corresponding number of passes of each steel wheel on the HWTD.

According to the new specifications the HWTD will be used for laboratory mixture design verification, trial batch evaluation, and production testing. Both dense-graded and heavy-duty mixture types will require a certain minimum number of passes before reaching a rut depth of 0.5 inch (13 mm) when tested at 122 °F (50 °C). Acceptable rut depth in the specification is a function of the high-temperature portion of the performance grade (PG) of the binder used in the HMA mixture. Therefore, HWTD has become a very important tool for TxDOT to evaluate HMA paving mixtures.

Initially, TxDOT purchased a HWTD from Germany and discovered that testing of laboratory-prepared HMA mixtures and pavement cores related reasonably well to observed performance in the field. Therefore, they adapted the HWTD test to accommodate typical Texas conditions and materials and adopted the test as part of their HMA specifications.

Subsequently, TxDOT decided to purchase additional HWTD devices and place them at strategic locations within the state.

After TxDOT adopted the HWTD as a specification test, the Texas Transportation Institute (TTI) and PaveTex Engineering and Testing purchased HWTD devices primarily to support TxDOT-related research and HMA testing.

OBJECTIVE

The objective of this implementation project was to prepare procurement specifications and purchase three HWTD devices, install them in two different locations (Austin and Chico), and provide training to assist the technicians in proper procedures for testing and data analysis. The implementation process included conducting a proficiency study of all five of the HWTDs belonging to TxDOT as well as the two belonging to TTI and PaveTex. The proficiency study determined the accuracy and precision of the seven HWTD devices.

SCOPE

All project objectives were accomplished as planned. This report will focus on the proficiency tests conducted using the seven HWTDs manufactured by Precision Metal Works, Inc. (PMW) and owned by TxDOT, TTI, and PaveTex.

CHAPTER 2: EXPERIMENTAL DESIGN

GENERAL

The HWTD test has become a standard tool for accepting HMA mixtures used on TxDOT pavement construction projects. Table 1 describes the HMA requirements for HWTD testing at 122 °F (50 °C).

Table 1. HMA Requirement for HWTD Testing at 122 °F (50 °C).

High-Temperature Binder Grade	Minimum Number of Passes @ 0.5 inch Rut Depth
PG 64	10,000
PG 70	15,000
PG 76 or Higher	20,000

This implementation project had three major tasks: procure and install equipment, train technicians, and conduct a laboratory-scale proficiency study.

PROCUREMENT OF EQUIPMENT

The project team developed procurement specifications, acquired three new HWTD devices, and installed two of them in Austin and one in Chico. Procurement and installation was accomplished through PMW of Salina, Kansas.

TRAIN TECHNICIANS

Using materials supplied by the manufacturer (Precision Metal Works, Inc.), the project team developed a training program containing several PowerPoint® files. The project team developed an informal training program and administered the training to technicians as requested by the TxDOT Project Director (PD). The objective of this task was to familiarize the technicians with the general operations of the HWTD, HMA specimen preparation, data acquisition, data reduction, and routine maintenance of the HWTD.

TTI personnel trained TxDOT technicians at their field laboratory located near Chico, Texas. According to the PD, the technicians operating the HWTDs at the TxDOT laboratory at Cedar Park were already well trained and proficient and thus did not need further training. The training materials developed as PowerPoint presentations were delivered to TxDOT separately on a CD-ROM for future use as instructional materials. These files may be used for training on operation, maintenance, sample preparation, and data collection processes for inexperienced technicians and engineers and as refresher courses for more experienced personnel.

PROFICIENCY STUDY

One task of this project was to conduct a small-scale proficiency study to examine the relative precision and accuracy of the three new HWTDs and compare data from them with precision and accuracy of TxDOT's other two HWTDs as well as the HWTDs owned by TTI and PaveTex. Therefore, a total of seven HWTDs were included in the proficiency study. The project team, which includes a statistician, developed the proficiency experiment design and performed the analyses.

Materials Tested

The project team used two different HMA mixtures designed to exhibit considerable rut depth before the tests were terminated at 20,000 cycles. Significant rut depth was desirable because very small deformations would not have provided the data needed to identify any potential differences in the HWTD devices. The project team selected two types of mixtures: a Type D limestone mixture and 9.5 mm river gravel mixture. These relatively fine mixtures were chosen to minimize variability between specimens and aggregate segregation. These mixtures are briefly described below.

Type D Limestone Mixture

The Type D limestone mixture design was obtained from the Fort Worth District. Table 2 and Figure 1 show the gradation used in this mixture design. This Type D mixture used 28 percent Type D aggregate from Tehuacana pit, 27 percent Type D aggregate from Kelly pit, 35 percent manufactured sand from Kelly pit, and 10 percent field sand from TXI, Inc. The asphalt content for this mixture was 5.3 percent using PG 76-22 from Eagle Asphalt.

Table 2. Type D Limestone Mixture Gradation.

Sieve Size	Specification		Percent Passing
	Upper	Lower	
5/8	100	98	100.0
3/8	100	85	98.9
#4	70	50	64.2
#10	42	32	35.8
#40	26	11	18.7
#80	14	4	8.1
#200	6	1	3.0

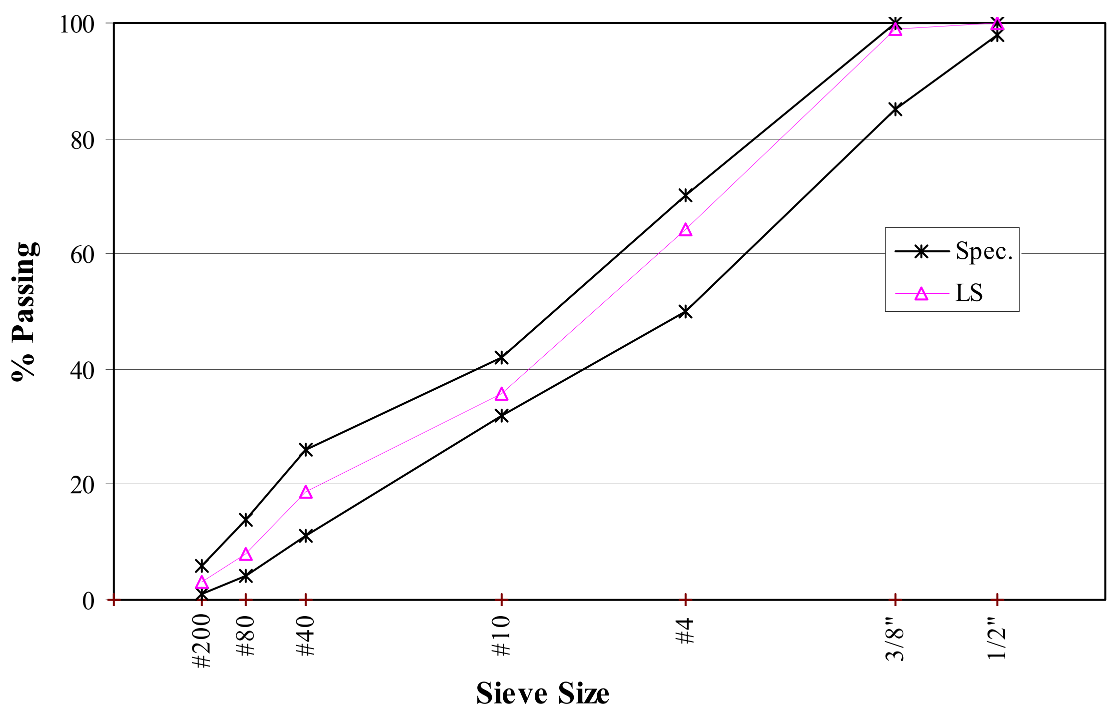

Figure 1. Type D Limestone Gradation.

River Gravel Superpave Mixture

This Superpave mixture design was obtained from the Pharr District. The mixture design used 25 percent Fordyce Grade 4 aggregate, 36 percent Fordyce Grade 6 aggregate, 24 percent Fordyce screenings, 14 percent Upper Valley Materials dry screenings, and 1 percent hydrated lime. This mixture was originally designed with 5.0 percent PG 76-22 asphalt. During the specimen preparation, the project supervisor raised the asphalt content to 5.5 percent in order to decrease rutting resistance and eliminate significant stripping during the 20,000 load cycles. Table 3 and Figure 2 depict the aggregate gradation used for this mixture design.

Table 3. Gradation of 9.5 mm River Gravel Mixture.

Sieve Size	TxDOT Specification		Percent Passing
	Upper	Lower	
12.50	100	--	99.6
9.50	100	90	93.0
4.75			63.1
2.36	67	32	38.3
1.18			25.5
0.60			19.3
0.30			14.0
0.15			7.2
0.075	10	2	5.0

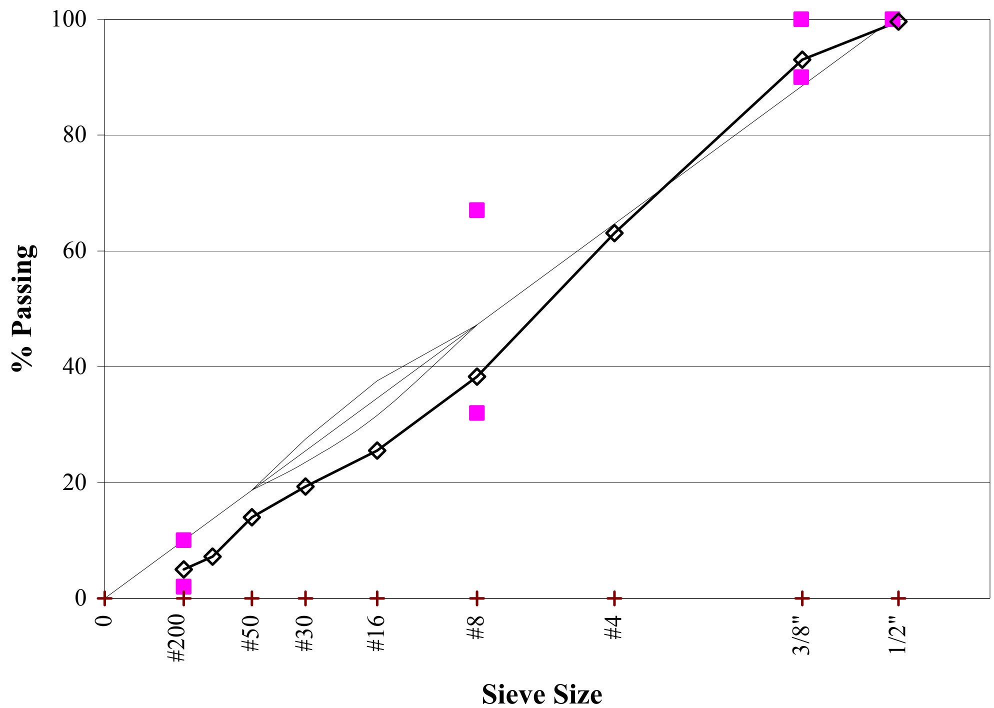

Figure 2. Gradation of 9.5 mm Superpave River Gravel.

Specimen Preparation and Distribution

To minimize specimen variability, a single operator compacted all specimens using a single Superpave gyratory compactor (SGC). A total of 112 specimens (56 specimens for each of the two mixtures) were fabricated. During the compaction process, the target air void level was 7 percent. All specimens were 6 inches in diameter and approximately 2.5 inches in height with 7 ± 0.5 percent final air voids. TxDOT specification Tex-242-F requires an air void level of 7 ± 1 percent for the compacted specimens.

Eight randomly selected specimens of each mixture type were assigned to each of the seven machines included in this project. Each of the seven machines was assigned 16 specimens (eight specimens × two mixture types) to perform the test. That is, each machine tested two sets (four specimens in each set) of each of the two mixture types and therefore each machine yielded four complete replicate tests (two specimens together considered as one replicate) for each mixture type.

Test Instructions

The project team sent clear written instructions for testing to each participating laboratory. The objective was to minimize variation between the laboratories. The laboratories were instructed to follow the procedures provided in Tex-242-F, Hamburg Wheel-Tracking Test. To maximize uniformity of testing, the following instructions were given:

1. Conduct the Test according to Tex-242-F, Hamburg Wheel-Tracking Test.
2. Trim the side of each specimen to properly fit into the sample holder.
3. Conduct the test at a temperature of 122°F (50°C).
4. Set the wheel load at 158 lb.
5. Set the wheel speed at 52 passes/minute.
6. Start the test 30 minutes after the water reaches 122°F (50°C).
7. Collect data at each 20 cycles for the first 5000 cycles and at each 50 cycles thereafter.
8. Terminate the test at 20,000 passes or 0.5 inch (13 mm) rut depth (both wheel paths), whichever comes first.
9. Finish (preferably) all four sets of tests for each machine within two weeks of receiving the specimens.

All the specimens were sent to the different locations at about the same time, and all the specimens were tested within short range of time (three weeks).

MACHINE DESCRIPTION

TxDOT, TTI, or PaveTex owned the seven HWTDs studied in this project. Precision Metal Works, Inc., located at Salina, Kansas, manufactured all machines evaluated. The four HWTDs located at the TxDOT laboratory in Cedar Park were designated based on their procurement history. A description of the machines is included in Table 4. Machine 1 (M1) is the oldest and Machine 4 (M4) is the most recent procurement from Precision Metal Works, Inc.

Table 4. HWTD Machine Description.

Machine Designation	Owner	Location	Manufacturer	Procurement Date
TxDOT-Chico	TxDOT	TxDOT Laboratory, Chico	PMW	May 2003
TxDOT Machine 1 (M1)	TxDOT	TxDOT Laboratory, Cedar Park	PMW	January 2001
TxDOT Machine 2 (M2)	TxDOT	TxDOT Laboratory, Cedar Park	PMW	January 2002
TxDOT Machine 3 (M3)	TxDOT	TxDOT Laboratory, Cedar Park	PMW	June 2003
TxDOT Machine 4 (M4)	TxDOT	TxDOT Laboratory, Cedar Park	PMW	July 2003
TTI	TTI	McNew Laboratory, TTI	PMW	August 2001
PaveTex	PaveTex	PaveTex Laboratory, Austin	PMW	May 2001

CHAPTER 3: PROFICIENCY TEST RESULTS AND STATISTICAL ANALYSES

GENERAL

The four different laboratories completed all testing using the seven different HWTDs within a three-week period. All tests were conducted similarly, following identical instructions distributed before the test. The machines were set such that when one wheel path reached maximum rut depth, the wheel was lifted, and the other wheel kept oscillating until it reached the maximum rut depth. In most cases, the tests were terminated due to attainment of the maximum rut depth (0.5 inch; 13 mm). In some cases, the test completed 20,000 cycles. In only one case, the technician had to stop the test prematurely due to a machine malfunction before reaching the target rut depth or number of cycles. Each laboratory sent the test data to TTI in a Microsoft Excel® spreadsheet for analysis.

The investigators analyzed the data using the Hamburg macro program developed by TxDOT. The most current software used for the HWTDs (PMW version 4.0, developed by PMW) collects 11 data points or rut depths at specific locations along the wheel path by measuring the height of the wheel. As indicated in the previous chapter, rut depths were recorded at fewer intervals during the early stage of testing and at longer intervals during the later stage. The macro developed by TxDOT identifies the largest rut depth for a given load cycle and compares this rut depth with the largest rut depth measured during a previous measurement. In some instances, a rut depth measurement was smaller than the previous one. When this happened the second data point was ignored during the analysis, i.e. the previous measurement was recorded for that given cycle otherwise the actual rut depth measured at that cycle was recorded. As a result, a stepped curve was obtained for each wheel path instead of a saw tooth-shaped curve.

DATA ANALYSIS

The Appendix contains individual test results: Table A1 shows all the specimens tested by each laboratory. Tables A2 and A3 contain all the test results, and Figures A1 through A28 depict the graphs obtained from all replicate tests at the different laboratories. The last columns of Table A2 and A3 describe how the two replicates for a given test (under left and right wheels) varied with each other. The stripping information was recorded from the nature of the graphs.

Since all the machines were not stopped at same rut depth or same load cycle, the investigators normalized the test data by identifying the number of load cycles (or wheel passes) to produce a 0.47-inch (12 mm) rut depth. Some replicates did not yield a 0.47-inch (12 mm) rut depth even after a full 20,000 load cycles. Tables 5 and 6 show the normalized data for the number of load cycles required to cause 0.47 inches (12 mm) of rut depth for the limestone and river gravel mixtures, respectively.

Table 5. Number of Load Cycles to Cause 0.47-inch (12 mm) Rut Depth for Limestone Mixture.

Laboratory Name	Test Sequence	Rut Depth LWP (mm)	No. of Load Cycles, LWP	Rut Depth RWP (mm)	No. of Load Cycles, RWP
TTI	1	12.00	14,551	12.00	12,301
	2	12.00	15,900	12.00	17,450
PaveTex	1	12.00	15,350	12.00	14,875
	2	12.00	16,651	12.00	11,225
TxDOT Chico	1	12.00	19,285	12.00	12,625
	2	12.00	13,001	12.00	16,685
TxDOT Austin, M1	1	12.00	19,200	12.00	18,801
	2	12.00	14,201	8.32*	20,000
TxDOT Austin, M2	1	12.00	18,800	12.00	18,101
	2	12.00	15,650	12.00	15,201
TxDOT Austin, M3	1	11.62	14,100	11.84	16,600
	2	11.96	16,001	12.00	18,301
TxDOT Austin, M4	1	8.46*	19,801	12.00	18,001
	2	12.00	14,540	8.94*	20,000

LWP – Left Wheel Path, RWP – Right Wheel Path. * Rut depth did not reach 12 mm.

Table 6. Number of Load Cycles to Cause 0.47-inch (12 mm) Rut Depth for River Gravel Mixture.

Laboratory Name	Test Sequence	Rut Depth LWP (mm)	No. of Load Cycles, LWP	Rut Depth RWP (mm)	No. of Load Cycles, RWP
TTI	1	12.00	13,951	4.85*	20,001
	2	12.00	13,450	12.00	18,800
PaveTex	1	12.00	11,185	12.00	16,190
	2	12.00	15,590	12.00	11,525
TxDOT Chico	1	12.00	10,800	12.00	15,060
	2	9.10†	14,451	10.48†	14,500
TxDOT Austin, M1	1	12.00	17,301	12.00	10,785
	2	12.00	15,440	12.00	9,480
TxDOT Austin, M2	1	12.00	12,301	12.00	13,150
	2	12.00	11,840	12.00	6,840
TxDOT Austin, M3	1	7.41*	20,000	12.00	14,001
	2	11.99	15,601	11.73	10,301
TxDOT Austin, M4	1	12.00	12,350	11.97	15,901
	2	12.00	15,850	12.00	19,601

LWP – Left Wheel Path, RWP – Right Wheel Path. † Machine malfunction * Rut depth did not reach 12 mm.

The data was analyzed to determine the rut depths at 5,000 and 10,000 cycles. The detailed results are mentioned in Tables A4 through A7, which show that the variability both within a machine and between machines increases with the increasing number of load cycles.

STATISTICAL ANALYSIS

The data for the following analysis are composed of maximum rut depth measurements at various numbers of cycles in the HWTD. For this experiment, 28 sets each of the two HMA mixtures (limestone and river gravel) were randomly assigned to seven HWTDs. Thus, each HWTD evaluated four sample sets of each of the two HMA mixtures, for a total of eight specimen sets per machine.

The following analysis concerns two particular properties of the pavement materials tested. The first measurement of interest is the maximum rut depth achieved at 10,000 cycles of the HWTD, and while the second measurement of interest is the number of cycles necessary to reach the failure point of the materials being tested, which is fixed at a maximum rut depth of 0.47 inches (12 mm). The purposes of the experiment are to determine if any systematic differences or biases exist among the seven machines and to construct interval estimates for the two different mixtures.

Exploratory Analysis

The exploratory portion of the analysis provides a preliminary overview of the data and ascertains whether certain assumptions for the subsequent statistical model are satisfied by the data. Given the design of this experiment (two materials, seven HWTDs, four sample sets per material/machine combination), a two-way analysis of variance (ANOVA) model seems appropriate for comparison purposes. Generally, such a model operates by comparing the variation observed between each treatment combination (mixture/machine) to the variation observed within each treatment combination (*3*).

The ANOVA model assumes the following:

1. Observations are independent of one another.
2. Observations follow a normal (bell-shaped) distribution.
3. Observations have the same variance.

Given sufficient numbers of observations (20–30) per treatment combination, assumptions (2) and (3) can be easily verified; whereas assumption (1) is usually satisfied by the randomization of the experimental design. ANOVA models are fairly robust against violations of the normality assumption, less robust against violations of the equal variance assumption, and vulnerable to violations of the independence assumption. In the case of unequal variances, ANOVA models are less sensitive to differences among means, whereas correlated observations can potentially increase or decrease the significance probabilities of any ANOVA F-tests.

For the data at hand, the low number of observations per treatment combination causes difficulties in ascertaining the normality and equal variance assumptions. Variance-type estimators such as standard deviation are weakly consistent, in that more data are needed for a reliable estimate than would be the case for a sample mean, for example. Most tests for normality have low sensitivity for small numbers of observations as well. Thus, any exploratory analysis of the data will be qualitative in nature, highlighting possible anomalies as opposed to conclusively determining violations of ANOVA model assumptions.

Type D Limestone Mixture

Preliminary data analysis for the limestone mixture indicated disparities among the estimated variances of maximum rut depth for each HWTD. Descriptive statistics for maximum rut depth at 10,000 cycles and the number of cycles to achieve a 0.47-inch (12 mm) rut depth are shown in Tables 7 and 8, respectively. Note that the standard deviations for maximum rut depth, in some cases, differ by nearly one order of magnitude, although these differences may not be significant because each estimate is based on only four observations. In other words, the differences in standard deviations may be a statistical artifact arising from the variability inherent in the pavement material, along with the small sample size used for each machine/material combination. The standard deviations observed for the number of cycles to reach a 0.47-inch (12 mm) rut depth, in contrast, appear roughly similar for the different machines.

Table 7. Rut Depth at 10,000 Cycles (Limestone).

Machine	Mean Rut Depth (mm)	Std. Dev. (mm)
TTI	5.62	1.47
PaveTex	6.40	2.15
TxDOT – Chico	6.59	2.12
TxDOT – M1	5.09	1.66
TxDOT – M2	4.94	0.37
TxDOT – M3	5.12	0.92
TxDOT – M4	4.36	1.46

Two possible outliers were identified for maximum rut depth, the TxDOT - Chico machine (0.35 inch; 8.98 mm) and the PaveTex machine (0.37 inch; 9.45 mm) (see Table A6). Note that these two observations are largely responsible for the larger variability in rut depth observed for these two test machines (see Table 7).

While observations of the number of cycles to reach 0.47-inch (12 mm) rut depth exhibit no obvious outliers, there are three censored observations. In all three observations, the sample being tested was able to withstand the maximum 20,000 cycles without reaching 0.47-inch (12 mm) rut depth. Two of these censored observations occur for the TxDOT M4 machine and the remaining one for the TxDOT M1 machine. These censored data could cause any differences between the two machines (M1 and M4) and other machines to be mildly understated.

Table 8. Number of Cycles to Reach 0.47-inch (12 mm) Rut Depth (Limestone).

Machine	Mean No. of Cycles	Std. Dev.
TTI	15,050	2,182
PaveTex	14,525	2,325
TxDOT – Chico	15,399	3,173
TxDOT – M1	18,050	2,614
TxDOT – M2	16,938	1,779
TxDOT – M3	16,250	1,733
TxDOT – M4	18,135	2,575

Superpave River Gravel

Data for maximum rut depth at 10,000 cycles indicate possible differences in the variability of observations for each machine. These differences are not apparent when examining the data for the number of cycles to reach 0.47-inch (12 mm) rut depth. Tables 9 and 10 show the basic descriptive statistics for both types of measurements.

Table 9. Rut Depth at 10,000 Cycles (River Gravel).

Machine	Mean Depth (mm)	Standard Deviation (mm)
TTI	6.00	1.87
PaveTex	8.05	1.09
TxDOT – Chico	7.72	1.91
TxDOT – M1	8.98	2.88
TxDOT – M2	9.16	2.17
TxDOT – M3	8.30	2.34
TxDOT – M4	6.54	0.37

Table 10. Number of Cycles to Reach 0.47-inch (12 mm) Rut Depth (River Gravel).

Machine	Mean Number of Cycles	Standard Deviation
TTI	16,550	3,333
PaveTex	13,622	2,633
TxDOT – Chico	16,465	4,437
TxDOT – M1	13,251	3,719
TxDOT – M2	11,033	2,847
TxDOT – M3	14,976	4,018
TxDOT – M4	15,926	2,961

For river gravel, two possible outliers were observed, corresponding to the TxDOT M1 machine (0.51 inch; 12.98 mm) and the TxDOT M2 machine (0.49 inch; 12.33 mm) (see Table A7). As was the case for limestone, these possibly outlying observations increased variability; TxDOT M1 had the largest at 0.11 inch (2.81 mm).

There are four censored observations in the data for the number of cycles to reach 0.47 inches (12 mm). Two of these occur for the TxDOT – Chico machine, with the TTI and TxDOT M3 machines each having one censored observation.

Analysis of Variance Results

In the following portion of the analysis, various ANOVA models are fitted to the data. Initial models were developed primarily to test the hypothesis of interaction between the factors of machine and pavement material. In the presence of interaction, differences observed between machines could be disproportionately larger or smaller than those expected under the case of independent factors. Alternatively, the interaction may be thought of as a multiplicative combination as opposed to a purely additive one. Thus, under interaction, it would not be possible to estimate separate effects for machine and HMA mixtures.

Further ANOVA models would examine the significance of separate effects for machine and HMA mixtures; any non-significant effects would be omitted from subsequent model specifications.

Maximum Rut Depth

A two-way ANOVA was conducted to determine whether significant differences existed between the average maximum rut depth recorded for each machine and whether such differences were reduced or amplified by the type of mixture under test. Weighted least squares (WLS) were used here, where weighting was proportional to the observed standard deviation of each machine/mixture combination. Results for the WLS ANOVA model indicated no interaction between HMA mixtures and testing machines ($p = 0.1836$), so the model was refitted excluding interaction terms. Under this revised model, differences between testing machines were insignificant ($p = 0.1235$), whereas HMA mixture type did exhibit significant differences ($p < 0.0001$).

Table 11 shows the means and 95 percent confidence intervals for mean maximum rut depth by machine for the limestone mixture Table 12 lists the corresponding statistics for the river gravel mixture. As shown in each of these tables, the confidence intervals for the mean maximum rut depths for each machine overlap in accordance with the non-significant machine effect of the ANOVA *F*-tests.

Table 11. Confidence Intervals for Limestone Rut Depth at 10,000 Cycles.

Machine	Mean Rut Depth (mm)	95% Confidence Interval (mm)	
		Lower	Upper
TTI	5.62	4.00	7.25
PaveTex	6.40	4.78	8.03
TxDOT – Chico	6.59	4.96	8.21
TxDOT – M1	5.09	3.46	6.71
TxDOT – M2	4.94	3.31	6.57
TxDOT – M3	5.12	3.49	6.75
TxDOT – M4	4.36	2.73	5.99

Table 12. Confidence Intervals for River Gravel Rut Depth at 10,000 Cycles.

Machine	Mean Rut Depth (mm)	95% Confidence Interval (mm)	
		Lower	Upper
TTI	6.00	3.96	8.04
PaveTex	8.05	6.01	10.09
TxDOT – Chico	7.72	5.68	9.77
TxDOT – M1	8.98	6.94	11.02
TxDOT – M2	9.16	7.11	11.20
TxDOT – M3	8.30	6.26	10.34
TxDOT – M4	6.54	4.50	8.59

In the absence of significant differences in mean maximum rut depth across different machines, a final ANOVA model was fitted, in which the only factor was the type of mixture; the overall mean term was excluded in this case. Here the ANOVA model is equivalent to a two-sample *t*-test comparing the mean maximum rut depth observed for each type of pavement material. As expected, the difference in rut depth between the two mixtures is highly significant ($p < 0.0001$). Estimates for rut depth and the associated 95 percent confidence intervals are summarized later.

Since each of the two groups in the final model contain 28 observations, formal tests for normality could be performed for each pavement material. For the limestone mixture, the Shapiro-Wilk test for normality concluded that the data in this case was not normally distributed ($p = 0.0066$). Data for the river gravel pavement material did not exhibit any significant deviation from normality ($p = 0.1326$).

Number of Cycles to Reach 0.47-inch (12 mm) Rut Depth

A two-way ANOVA was conducted to determine whether significant differences existed between the number of cycles needed to achieve 0.47-inch (12 mm) rut depth recorded for each machine and whether such differences were reduced or amplified by the type of mixtures under test. Ordinary least squares (OLS) method was used here, as the sample variances for number of cycles did not differ substantially between machines. Results for the ANOVA model indicated no interaction between pavement materials and testing machines ($p = 0.1372$), so the model was refitted excluding the interaction terms. Under this revised model, differences between testing machines were insignificant ($p = 0.4648$), whereas pavement materials were only marginally significant ($p = 0.0367$).

Tables 13 and 14 clearly show that the mean number of cycles to reach 0.47-inch (12 mm) rut depth does not differ significantly across machines, since the 95 percent confidence intervals for these means all overlap.

Table 13. Confidence Intervals for No. of Cycles to Reach 0.47-mm (12 mm) Rut Depth (Limestone).

Machine	Mean No. of Cycles to 12 mm Rut	95% Confidence Interval	
		Lower	Upper
TTI	15,051	12,569	17,532
PaveTex	14,525	12,044	17,007
TxDOT – Chico	15,399	12,917	17,881
TxDOT – M1	18,051	15,569	20,532
TxDOT – M2	16,938	14,456	19,420
TxDOT – M3	16,251	13,769	18,732
TxDOT – M4	18,135	15,654	20,617

Table 14. Confidence Intervals for No. of Cycles to Reach 0.47-inch (12 mm) Rut Depth (River Gravel).

Machine	Mean No. of Cycles to 12 mm Rut	95% Confidence Interval	
		Lower	Upper
TTI	16,550	12,936	20,165
PaveTex	13,623	10,008	17,237
TxDOT – Chico	16,465	12,851	20,079
TxDOT – M1	13,252	9,637	16,866
TxDOT – M2	11,033	7,418	14,647
TxDOT – M3	14,976	11,361	18,590
TxDOT – M4	15,926	12,311	19,540

In the absence of significant differences between the mean numbers of cycles to achieve 0.47-inch (12 mm) rut depth, a final ANOVA model was fitted, in which the only factor was the type of mixture (the overall mean term was excluded). The ANOVA model, in this case, is equivalent to a two-sample *t*-test comparing the mean number of cycles to reach 0.47-inch (12 mm) rut depth observed for each type of mixture. As was the case for the limestone mixture data, the difference in the number of cycles between the two pavement materials is highly significant ($p < 0.0001$). Estimates for the number of cycles to achieve 0.47-inch (12 mm) rut depth and the associated 95 percent confidence intervals are summarized in Table 15.

Since the two groups in the final model each contain 28 observations, formal tests for normality could be performed for each pavement material. For both types of pavement materials, the Shapiro-Wilk test for normality concluded that the data were normally distributed, with $p = 0.3842$ and $p = 0.2520$ for limestone and river gravel, respectively.

Table 15 summarizes the estimates obtained for rut depth at 10,000 passes and the number of cycles to reach 0.47-inch (12 mm) rut depth for each type of pavement material. These intervals were obtained from

$$\overline{X} \pm t_{1-\alpha/2,n-1}\ s\,,$$

where, $\overline{X}$ and s are the sample mean and sample standard deviation, and $t_{1-\alpha/2,n-1}$ is the upper $\left(1-\alpha/2\right)^{\text{th}}$ percentile of a t distribution having $n-1$ degrees of freedom. For 95% confidence intervals for means based on $n = 28$ observations become

$$\overline{X} \pm (2.052)(s)$$

Table 15. Multiple Machine/Operator Estimates for Observed Data.

Mixture Type	Specification	Mean	Std. Dev.	Number of Replicates	95% Confidence Limits	
					Lower	Upper
Type D Limestone	Rut depth at 10,000 passes (mm)	5.45	1.58	28	4.83	6.06
	Number of cycles to reach 12 mm depth	16,336	2,502	28	15,365	17,306
9.5 mm Superpave River Gravel	Rut depth at 10,000 passes (mm)	7.82	2.06	28	7.02	8.62
	Number of cycles to Reach 12 mm depth	14,546	3,613	28	13,145	15,947

Power of the ANOVA *F*-test

While no significant differences between machines were found in the analysis, this may have been more a function of limited power. That is, the ability of the ANOVA model to detect differences between machines was restricted due to the low number of replications of the experiment. Figure 3 shows the probability of detecting a specified difference in mean maximum rut depth between any two machines for two values of the overall standard deviation of observations. The values of the standard deviation s in the figure correspond to those observed for the limestone mixture (s = 1.58) and for river gravel mixture (s = 2.06) at 10,000 cycles. These probabilities are based on a one-way ANOVA model with seven treatments (machines) and four test sets per machine. Note that a probability of detection of 0.5 compares to a coin toss, in that there are even odds that the experiment will generate a significant result. A good rule of thumb for power or sensitivity is to detect the minimum difference of interest at least 80 percent of the time. Under this criterion, the ANOVA model will only be able to detect a difference of at least 0.18 inch (4.38 mm) (in the case of limestone) or 0.24 inch (6.12 mm) (in the case of river gravel) with 80 percent reliability. It is therefore unlikely that any significant result could have been obtained from the experiment.

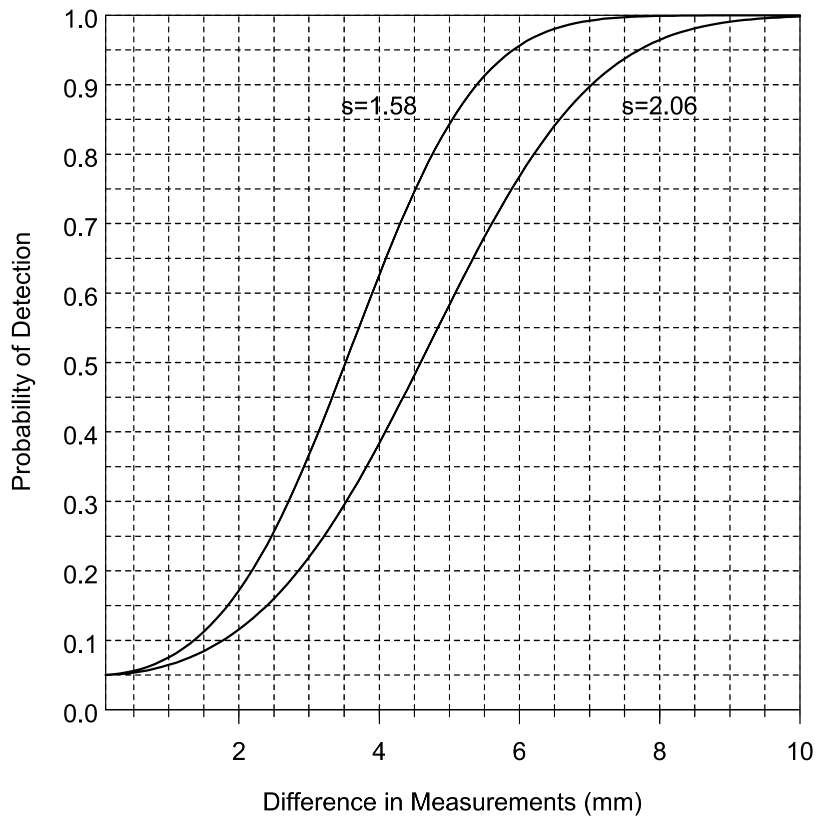

Figure 3. Power of the ANOVA *F*-test under Observed Std. Deviations in Two Mixtures.

Relative Accuracy of Machines

In the absence of widely accepted standard values for pavement test results, statements qualifying the accuracy of the estimates obtained in this experiment must be restricted to the accuracy of the estimation method employed. Generally, an estimator or an estimation process is considered accurate or unbiased if the mean of the statistical distribution of the estimator equals that which would be obtained given an arbitrarily large set of data. In other words, in repeated experiments where a certain estimator is used, the average of all the estimates from each experiment will eventually converge to that of a theoretical experiment encompassing all possible samples. Under the ANOVA assumptions outlined previously, the estimation method employed in this experiment is unbiased or accurate in this regard.

In this report, the researcher attempted to determine the relative accuracy of each machine based on the difference between the average of each machine and the mean of all the machines. Table 16 and 17 depict the relative accuracy of each machines for rut depth measured at 10,000 load cycles for limestone mixture and river gravel mixture, respectively.

Table 16. Relative Accuracy of Macines for Limestone Mixture at 10,000 Cycles.

Machine	Average Rut Depth @ 10,000 Cycles (mm)	Mean Rut Depth @ 10,000 Cycles for all Machines (mm)	Accuracy
TTI	5.62	5.45	0.17
PaveTex	6.40		0.95
TxDOT – Chico	6.59		1.14
TxDOT – M1	5.09		0.36
TxDOT – M2	4.94		0.51
TxDOT – M3	5.12		0.33
TxDOT – M4	4.36		1.09

Table 17. Relative Accuracy of Macines for River Gravel Mixture at 10,000 Cycles.

Machine	Average Rut Depth (mm) @ 10,000 Cycles	Mean Rut Depth @ 10,000 Cycles for all Machines (mm)	Accuracy
TTI	6.00	7.82	1.82
PaveTex	8.05		0.23
TxDOT – Chico	7.72		0.10
TxDOT – M1	8.98		1.16
TxDOT – M2	9.16		1.34
TxDOT – M3	8.30		0.48
TxDOT – M4	6.54		1.28

The observed differences are attributed to the machines alone. It is equally plausible for these differences to arise solely from slight differences in material composition between the samples used in each machine. In conducting the analysis of variance, the researchers assume that the sample sets are homogeneous, but this does not imply that each sample is identical. Homogeneity between samples only means that the statistical behavior of each sample is the same; i.e., the mean and variance of the populations from which the each group of four sample sets is drawn is the same. Thus, one may not conclude that any residual differences must be due only to variations between machines.

CHAPTER 4:
CONCLUSIONS AND RECOMMENDATIONS

Three new HWTDs were purchased for TxDOT and installed in their laboratories. A small experiment was conducted to verify that all of the HWTDs owned by TxDOT and two laboratories that conduct testing for TxDOT will yield essentially the same result on a given material. A statistical analysis of the results yielded the following.

CONCLUSIONS

- Generally, no significant differences between the seven HWTDs were identified. However, the ability of the ANOVA model to detect differences between machines was restricted due to the low number of replications of the experiment.
- For the study proposed and conducted, the low number of observations per treatment combination caused difficulties in ascertaining the normality and equal variance assumptions which were necessary to provide valid statistical analyses.
- Statistical analyses showed that both the variability within a machine and between machines increases with the increasing number of load cycles.
- It may be possible to improve the current TxDOT HWTD data collection technique and thereby improve statistical validity of the measurements.
- Relative accuracy of machines for limestone mixture is better than that of river gravel mixture. Each machine differs slightly from the overall average, and these differences cannot be considered statistically significant.

RECOMMENDATIONS

- Modify the HWTD data collection and/or data analysis procedure; eliminate the rut depth measurement at the midpoint (i.e., at the sawn joint between the two cylindrical specimens). Use the average of the highest five measurements or the remaining ten measurements to produce a rut-depth measurement.
- Develop or identify a non-bituminous homogeneous material for calibrating the HWTD devices. The ideal material is envisioned to be a plastic material (e.g., a polyolefin or polyvinyl acetate) available in a 6-inch diameter cylinder. Specimens could be readily

sawed from the cylinder and used for testing. Desired rut depth for a given number of passes could be controlled by the test temperature.

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1. Izzo, R. P., and M. Tahmoressi. Testing Repeatability of the Hamburg Wheel-Tracking Device and Replicating Wheel Tracking Devices among Different Laboratories. *Journal of the Association of Asphalt Paving Technologists,* Vol. 68, AAPT, 1998.
2. Tex-242-F, Hamburg Wheel-Tracking Test, http://manuals.dot.state.tx.us/dynaweb/colmates/mtp/@Generic__BookView;cs=default;ts=default Accessed April 1, 2004.
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APPENDIX:
INTERLABORATORY TEST RESULTS

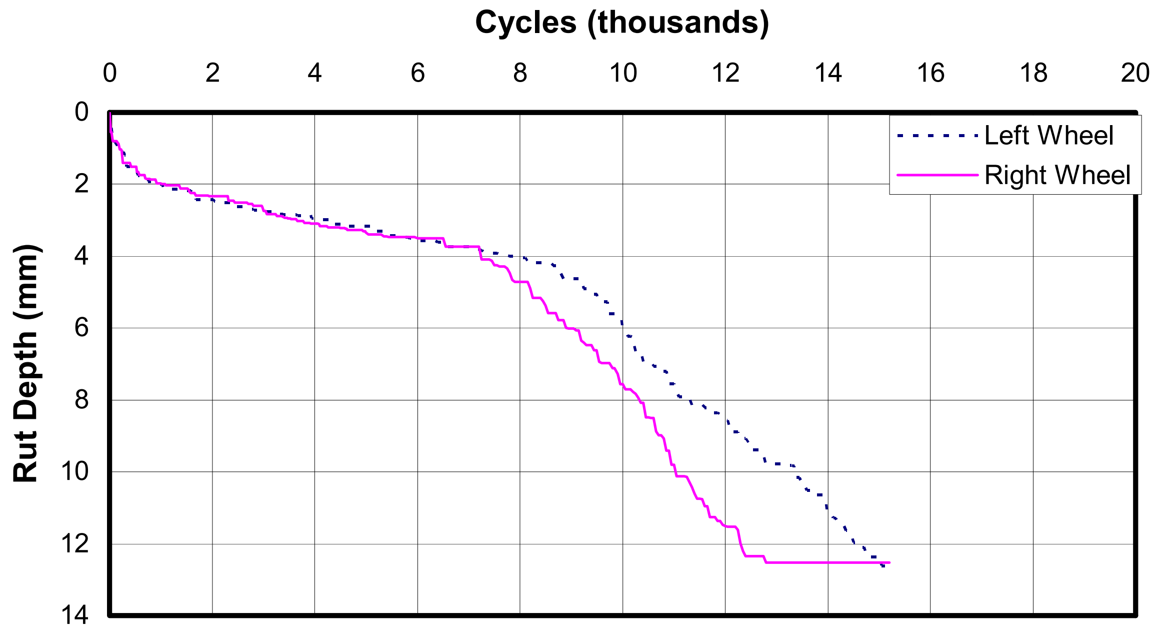

Figure A1. Test 1 – Limestone Mixture at TTI Laboratory.

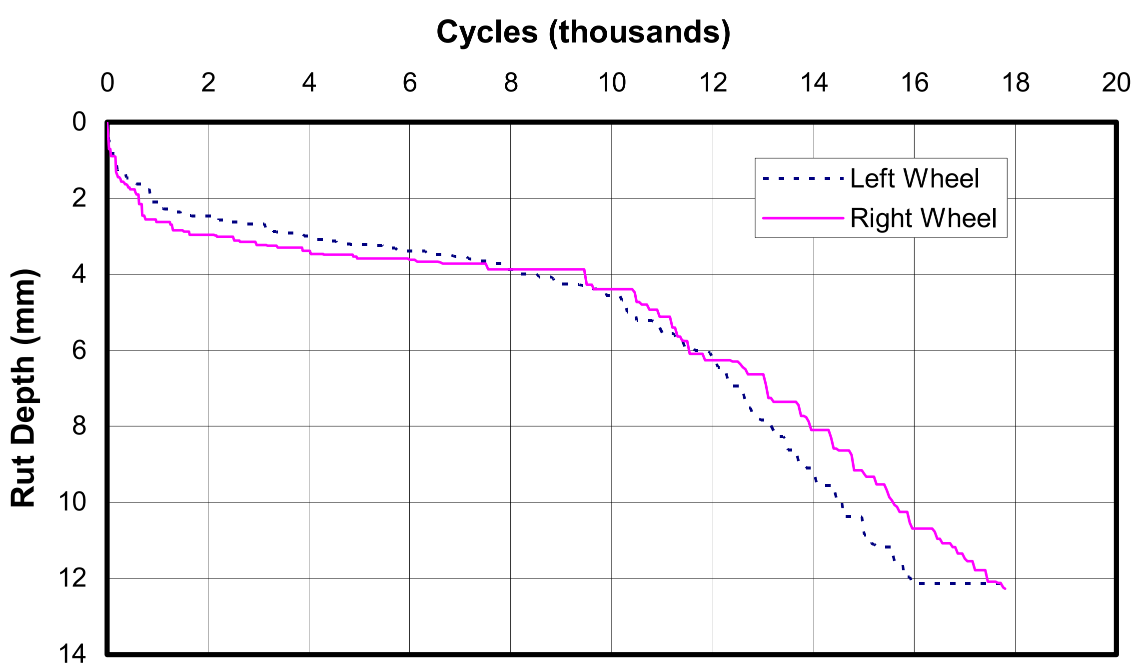

Figure A2. Test 2 – Limestone Mixture at TTI Laboratory.

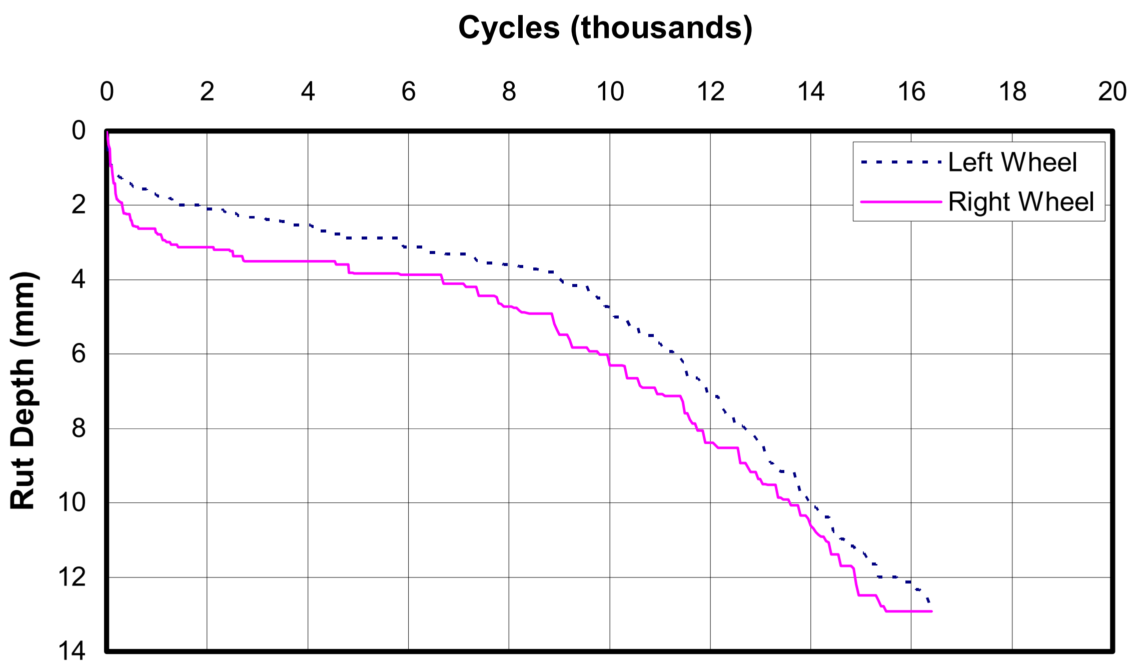

Figure A3. Test 1 – Limestone Mixture at PaveTex Laboratory.

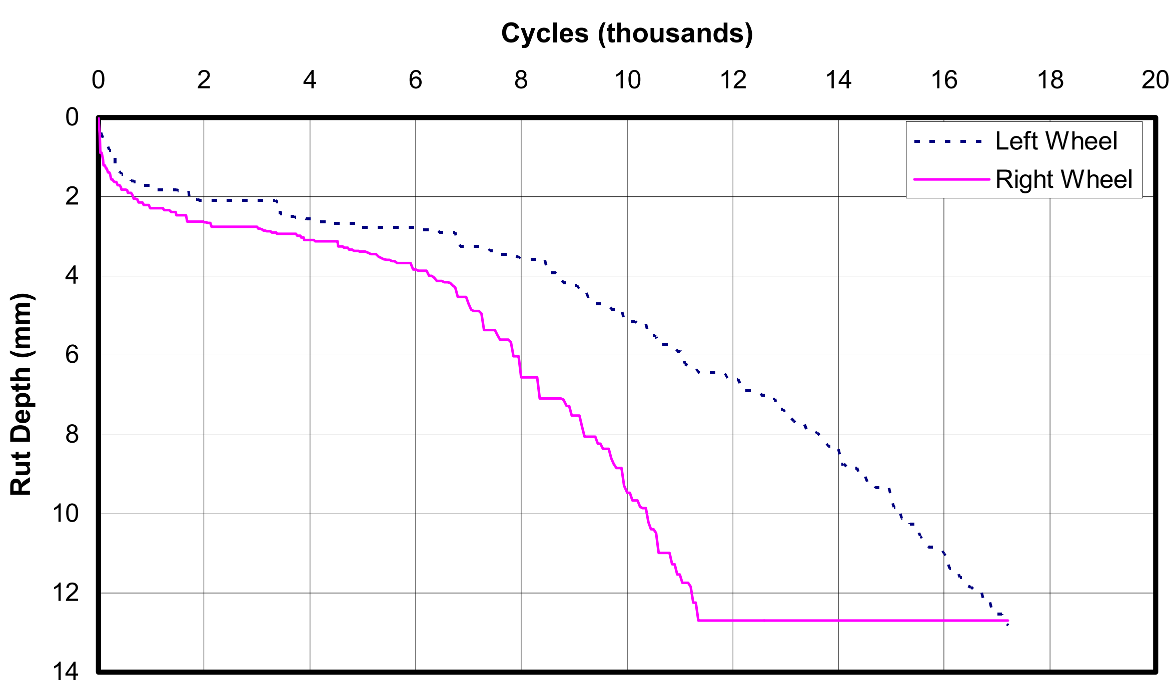

Figure A4. Test 2 – Limestone Mixture at PaveTex Laboratory.

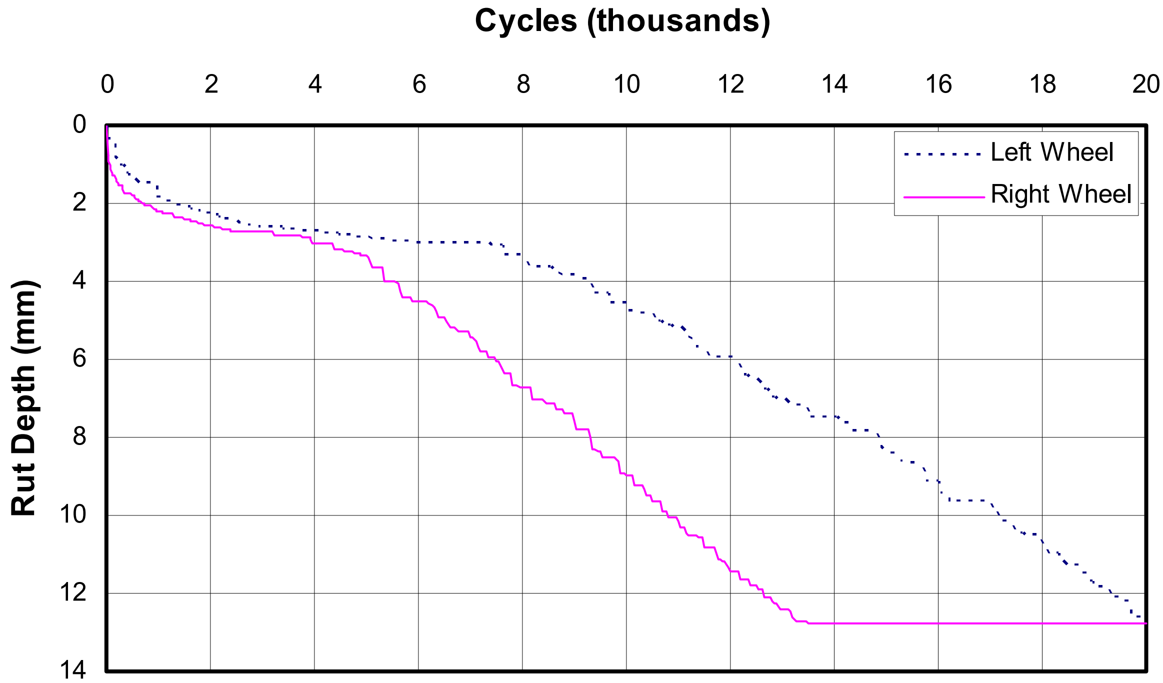

Figure A5. Test 1 – Limestone Mixture at TxDOT Chico Laboratory.

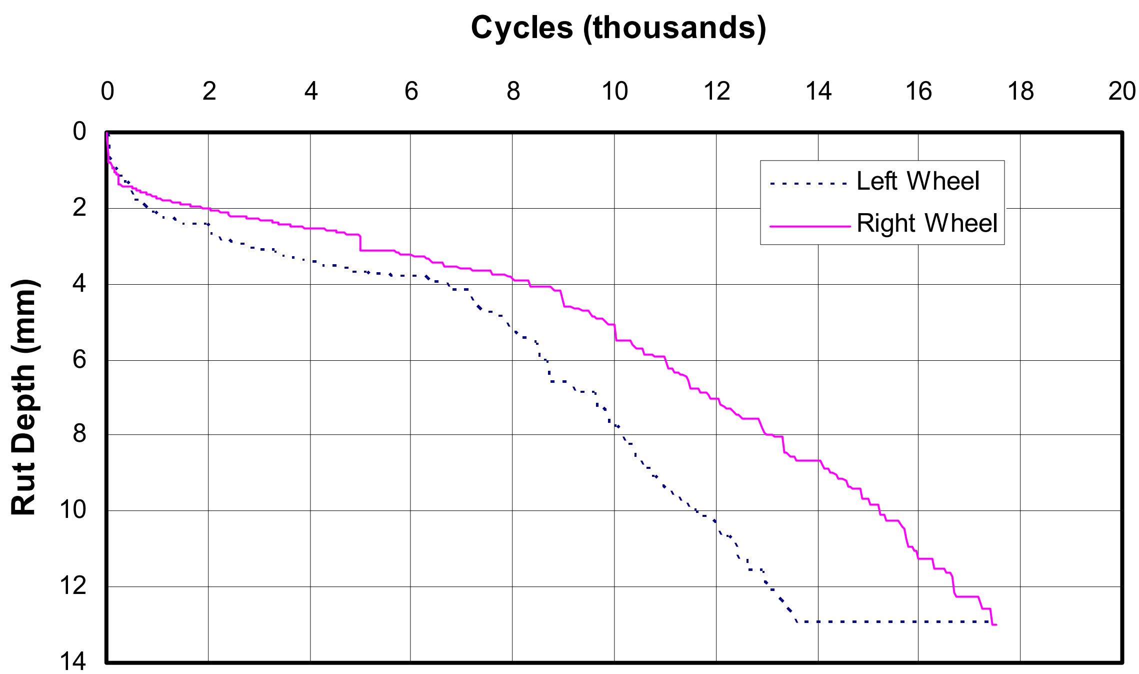

Figure A6. Test 2 – Limestone Mixture at TxDOT Chico Laboratory.

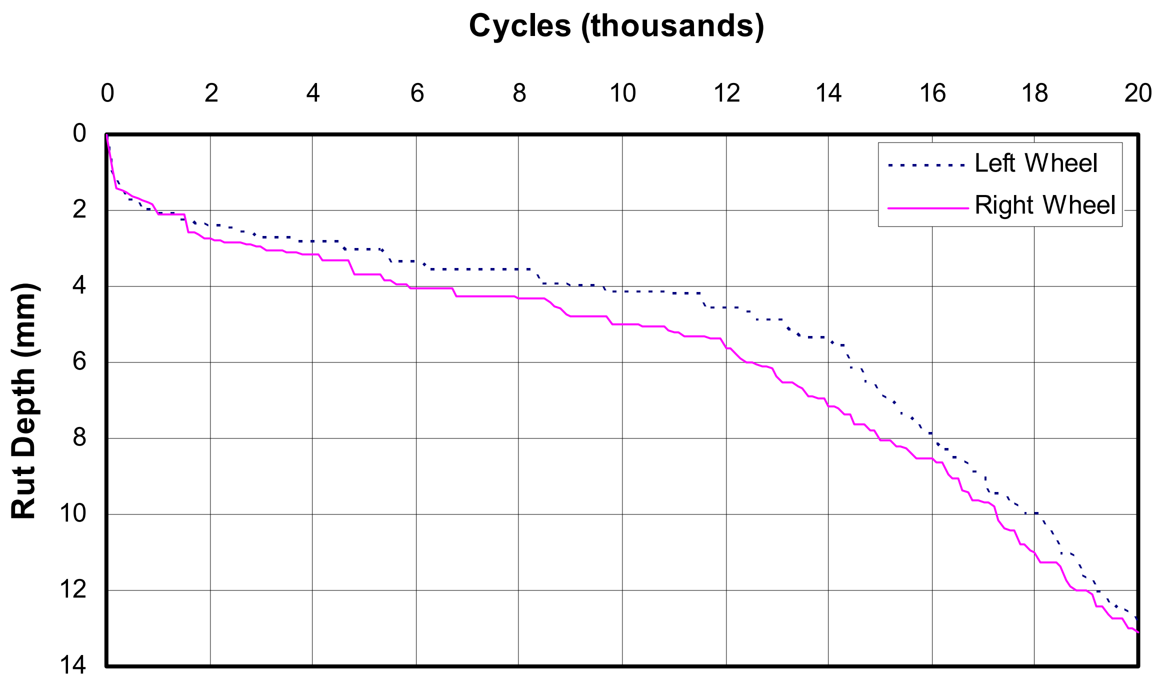

Figure A7. Test 1 – Limestone Mixture at TxDOT Austin Laboratory with Machine 1.

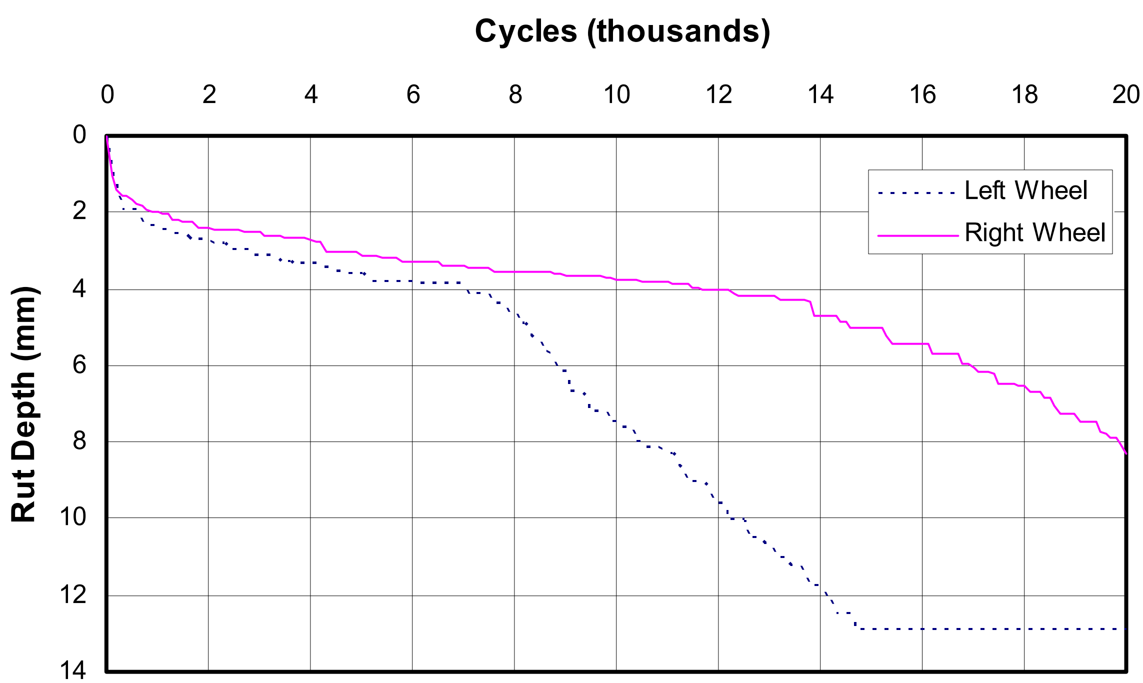

Figure A8. Test 2 – Limestone Mixture at TxDOT Austin Laboratory with Machine 1.

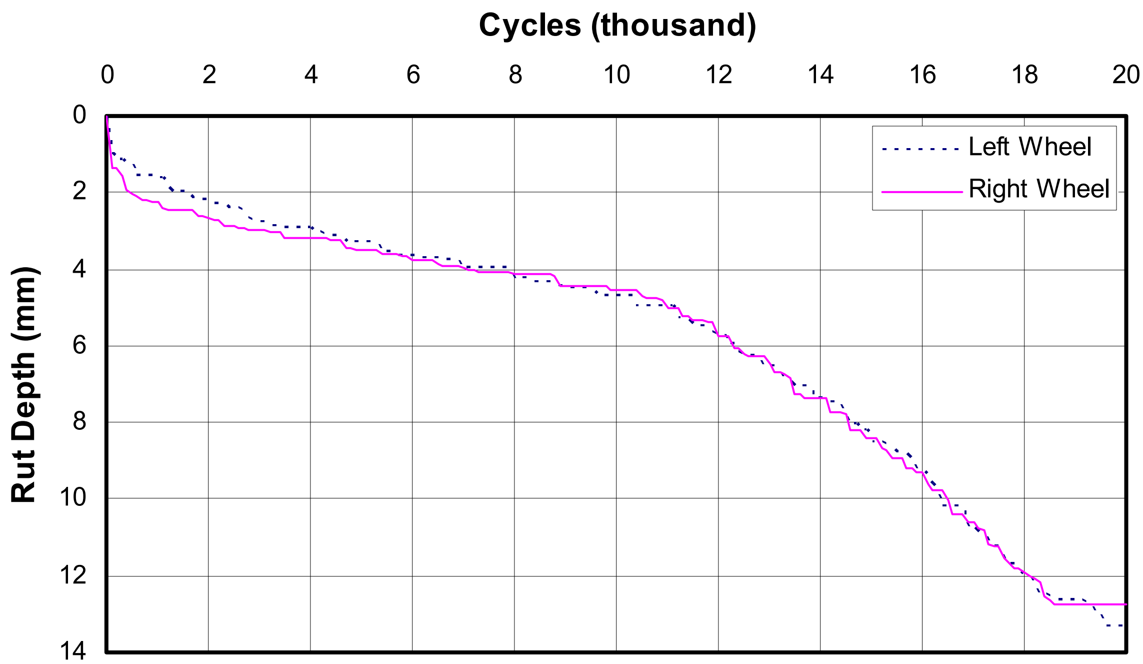

Figure A9. Test 1 – Limestone Mixture at TxDOT Austin Laboratory with Machine 2.

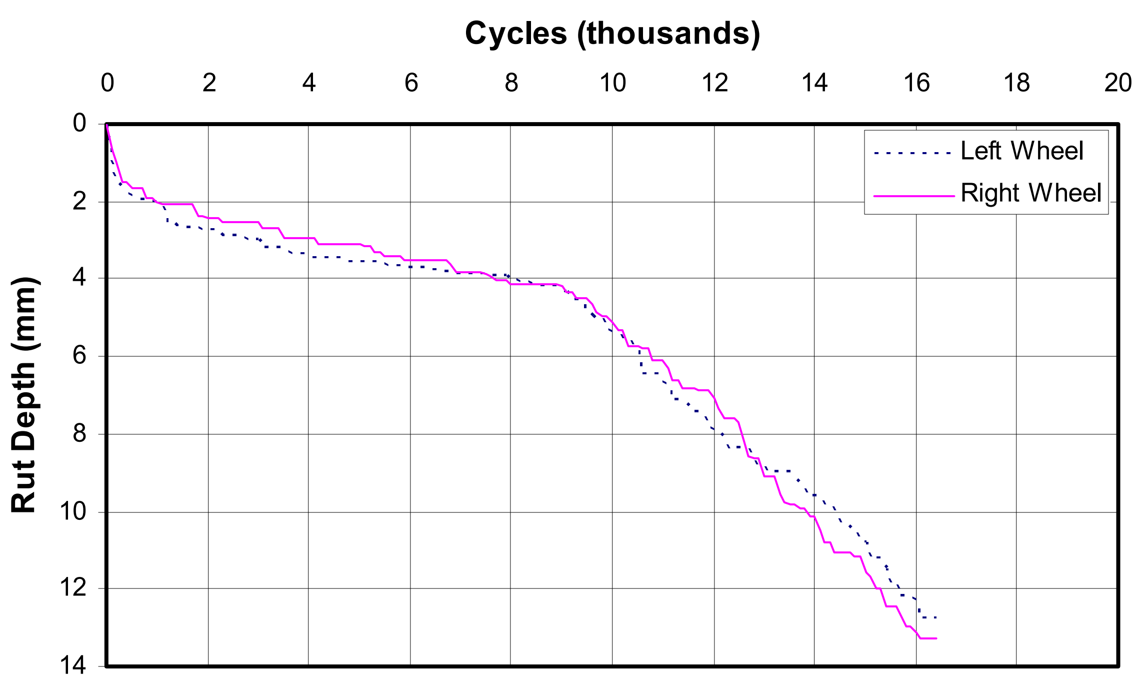

Figure A10. Test 2 – Limestone Mixture at TxDOT Austin Laboratory with Machine 2.

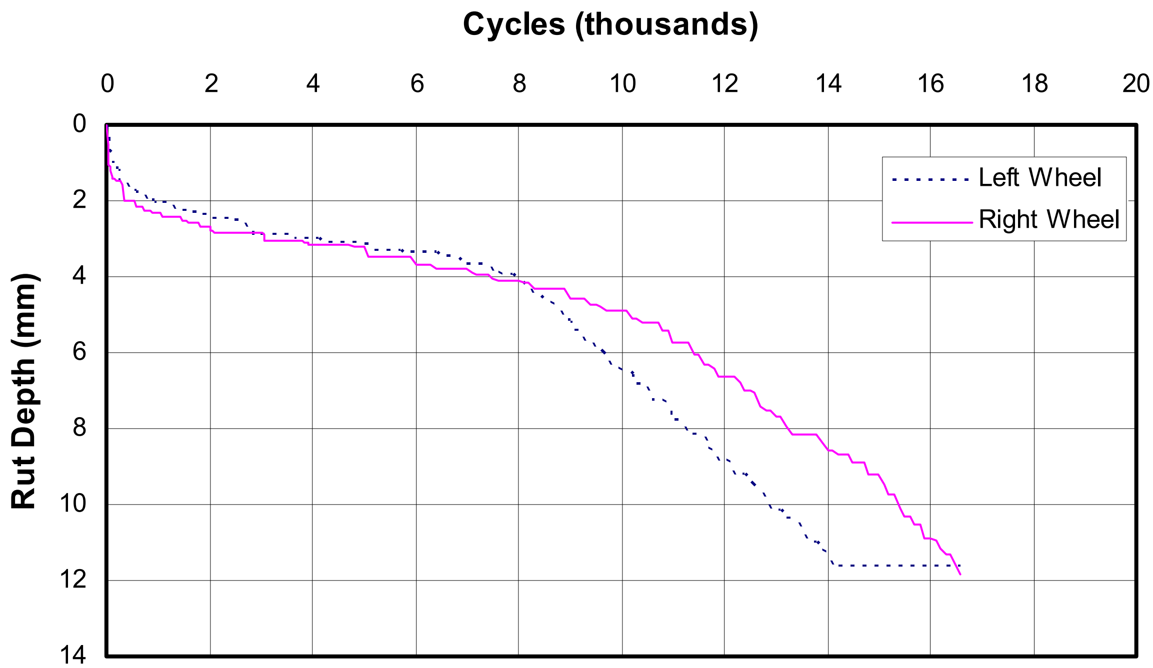

Figure A11. Test 1 – Limestone Mixture at TxDOT Austin Laboratory with Machine 3.

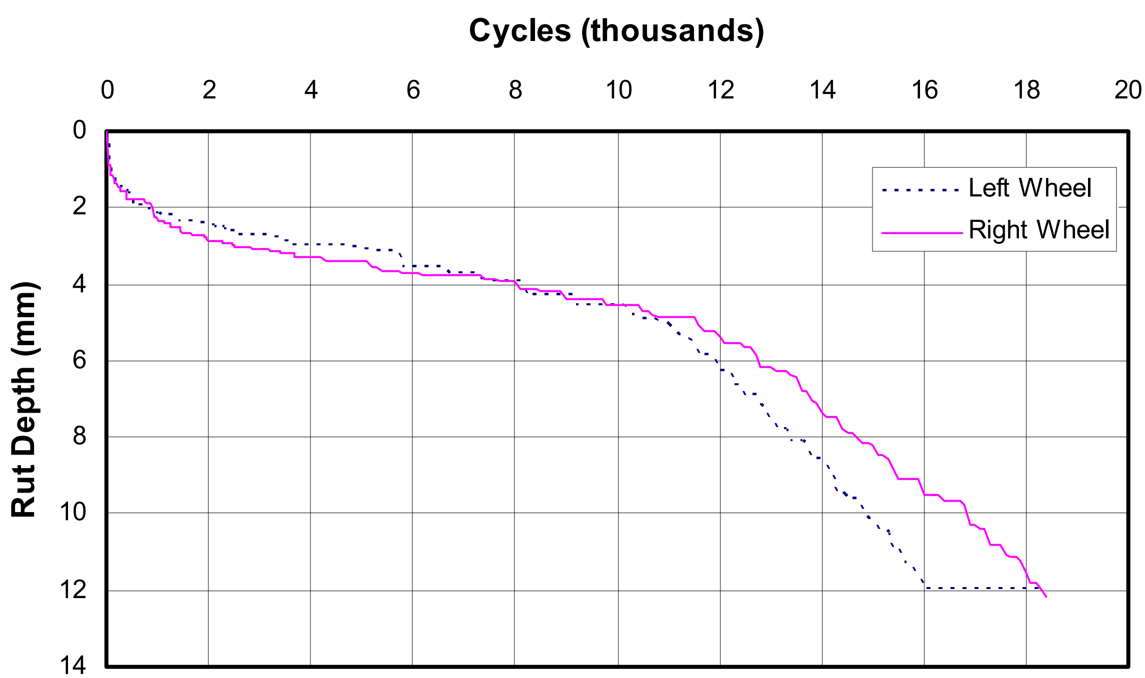

Figure A12. Test 2 – Limestone Mixture at TxDOT Austin Laboratory with Machine 3.

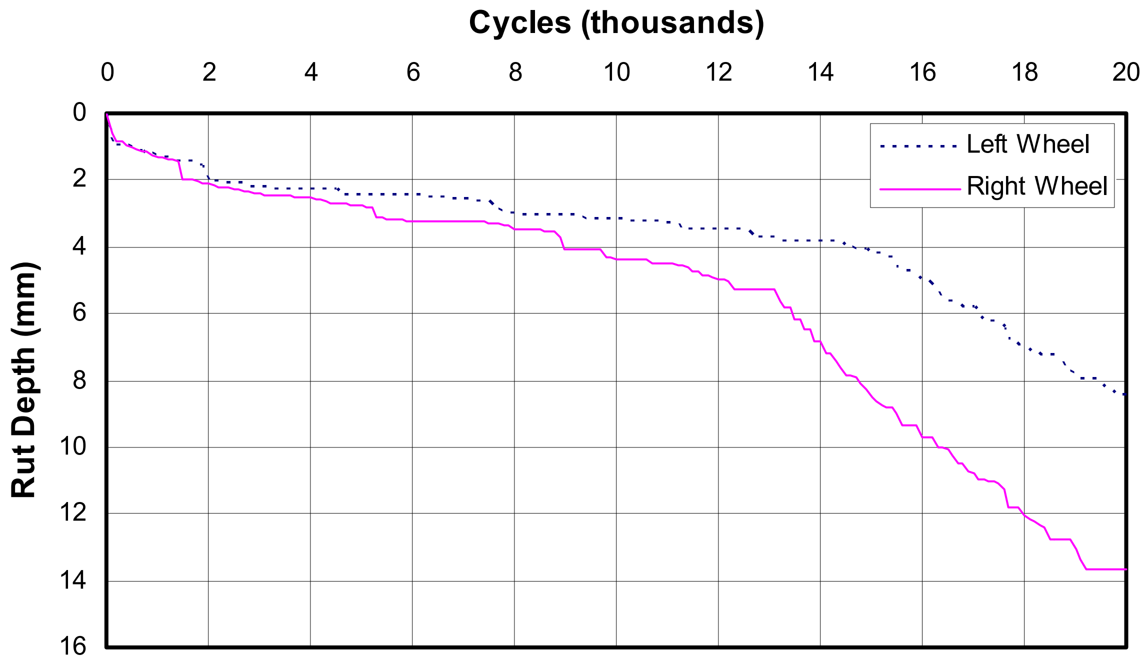

Figure A13.Test 1 – Limestone Mixture at TxDOT Austin Laboratory with Machine 4.

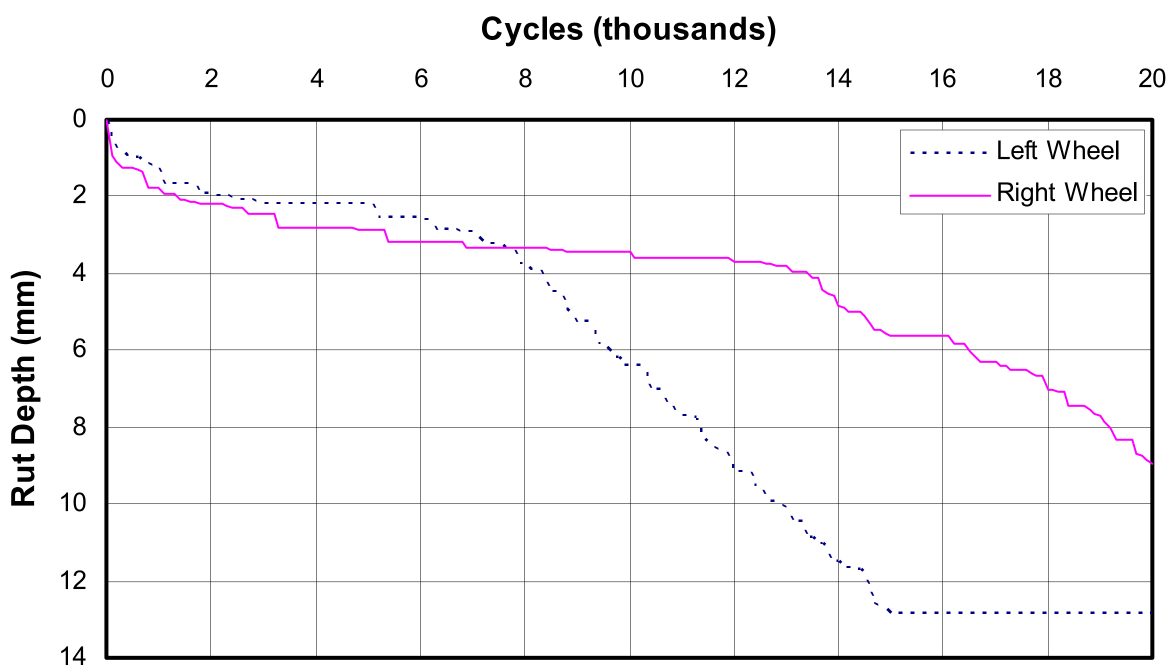

Figure A14. Test 2 – Limestone Mixture at TxDOT Austin Laboratory with Machine 4.

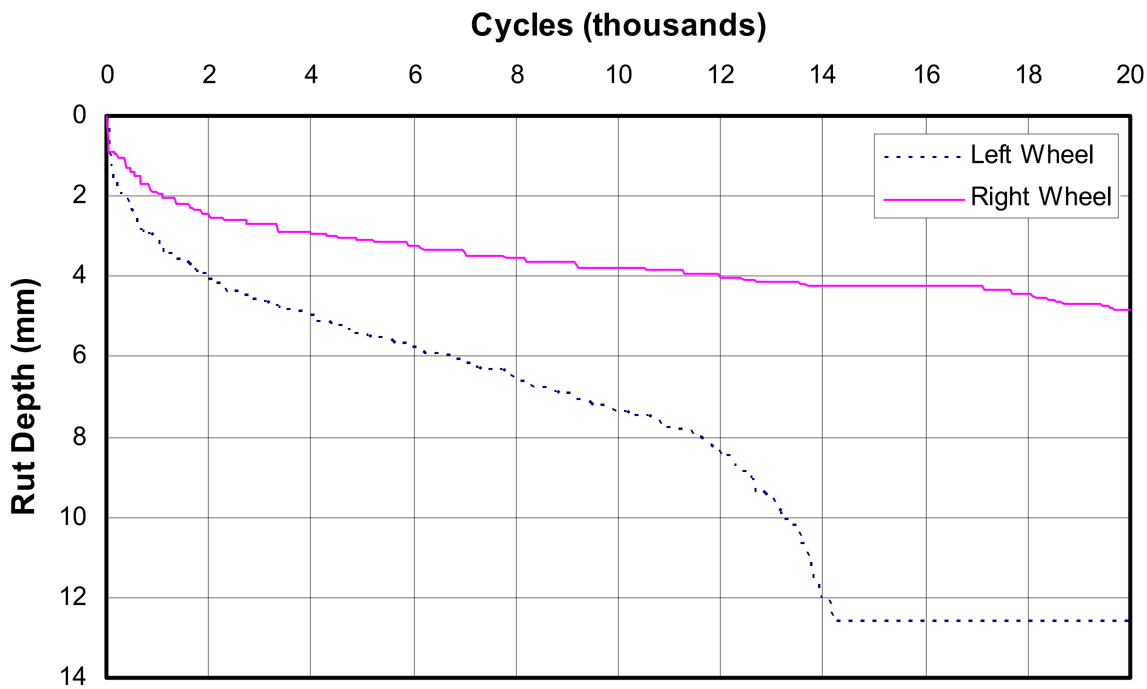

Figure A15. Test 3 – River Gravel Mixture at TTI Laboratory.

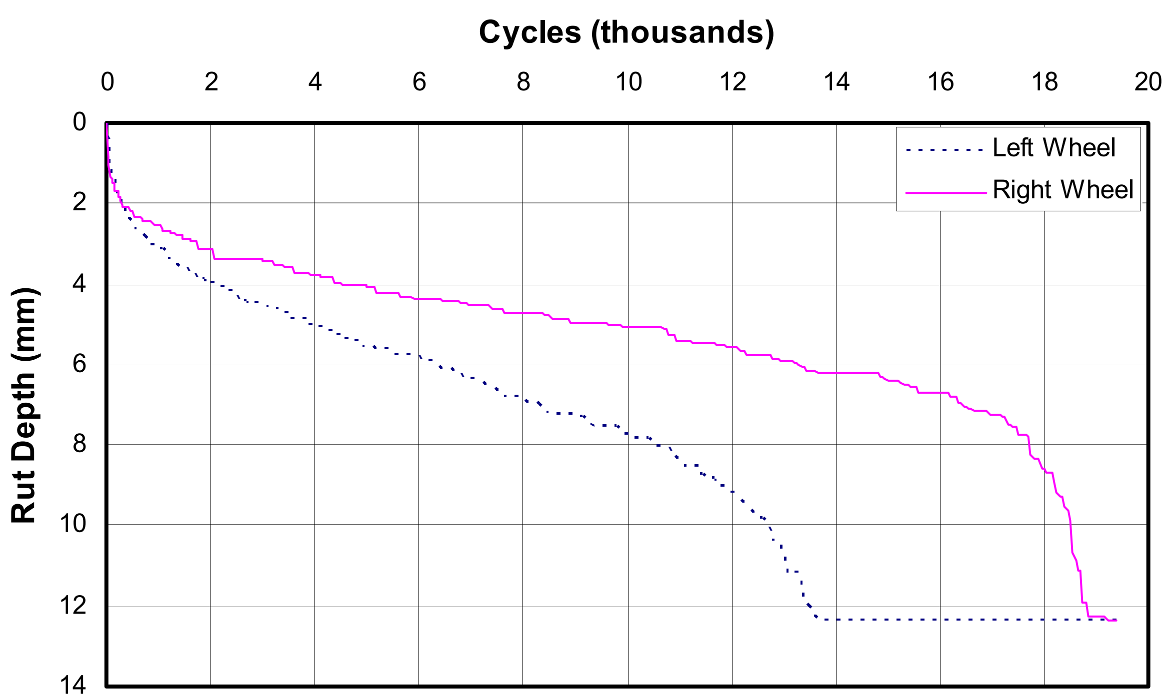

Figure A16. Test 4 – River Gravel Mixture at TTI Laboratory.

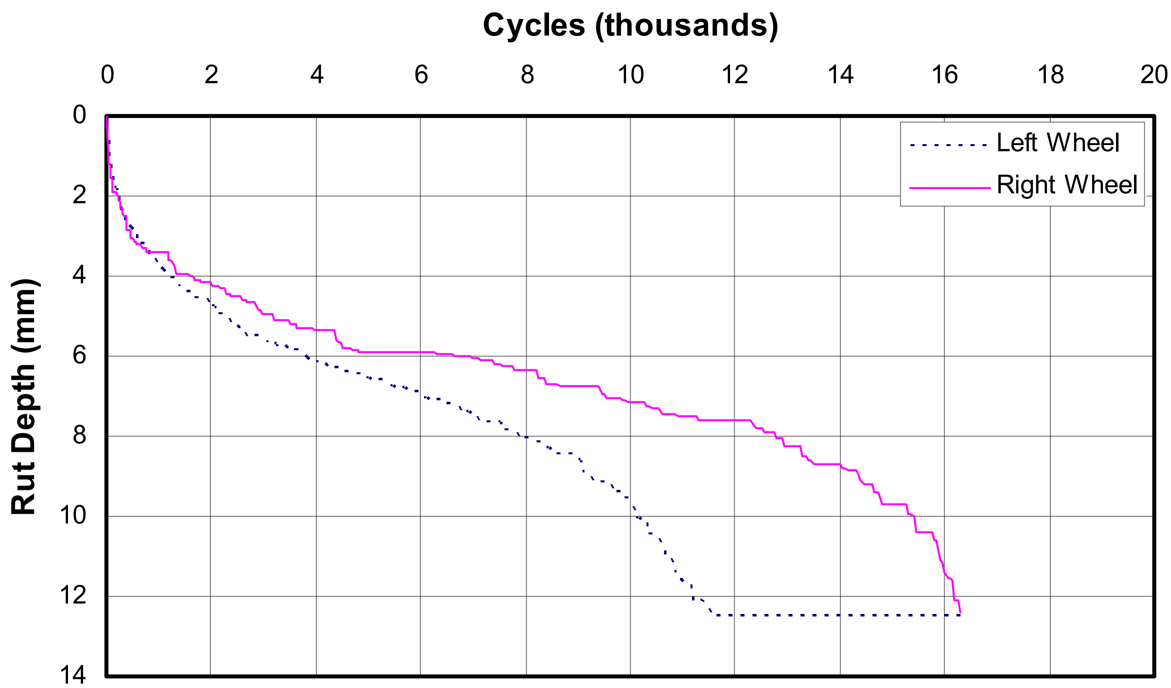

Figure A17. Test 3 – River Gravel Mixture at PaveTex Laboratory.

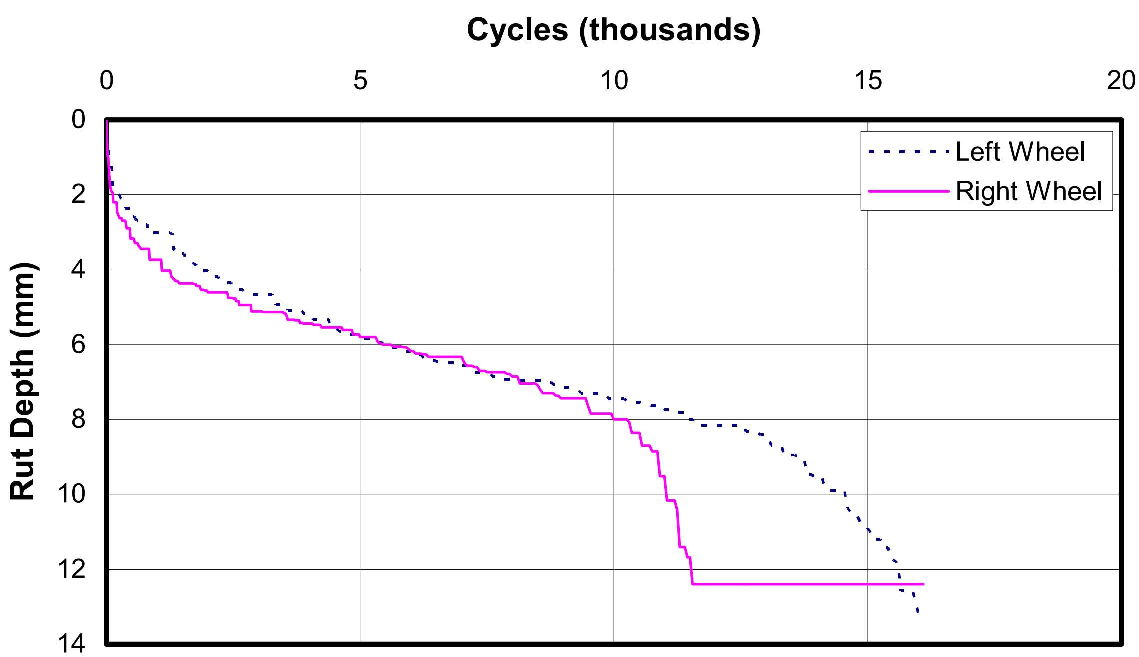

Figure A18. Test 4 – River Gravel Mixture at PaveTex Laboratory.

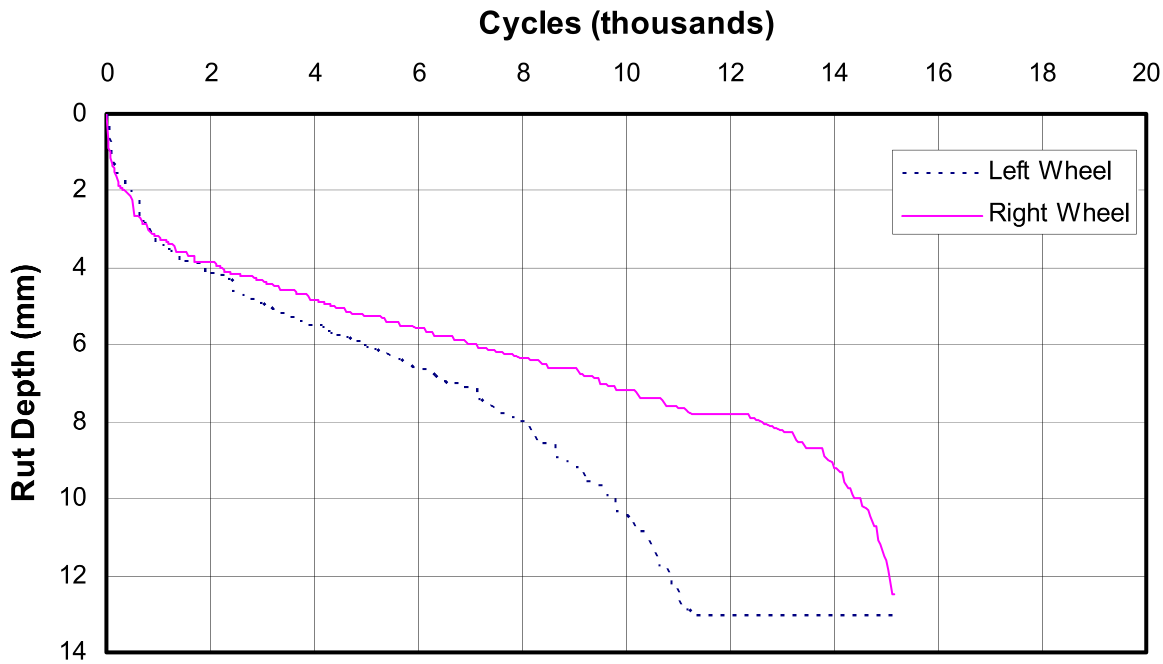

Figure A19. Test 3 – River Gravel Mixture at TxDOT Chico Laboratory.

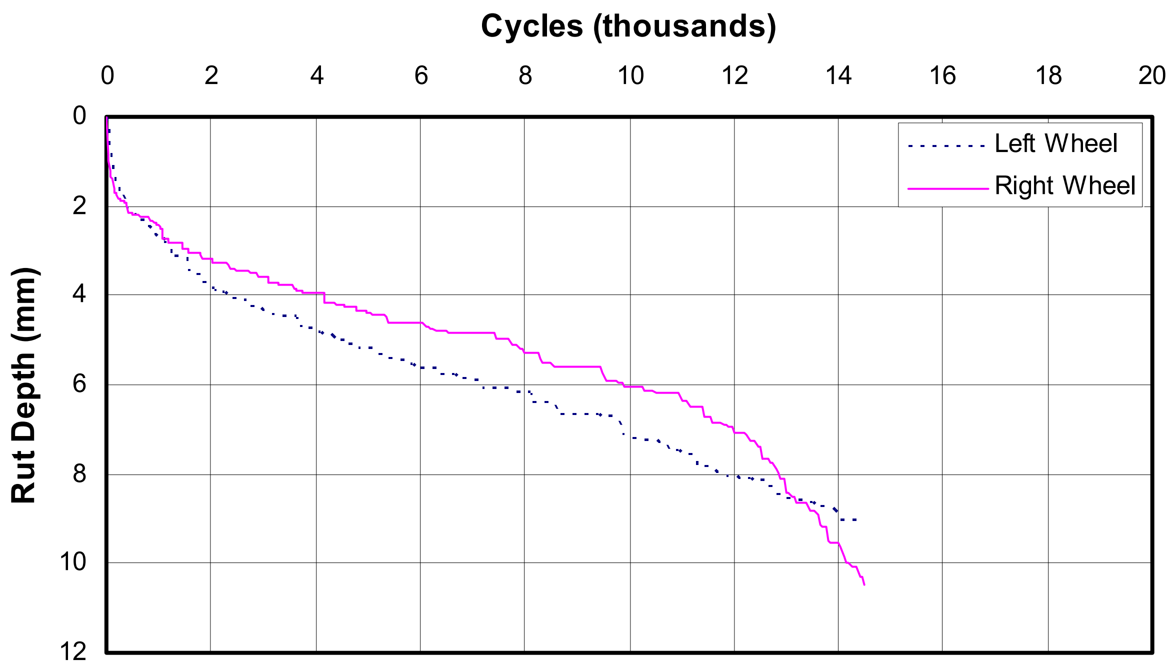

Figure A20. Test 4 – River Gravel Mixture at TxDOT Chico Laboratory.

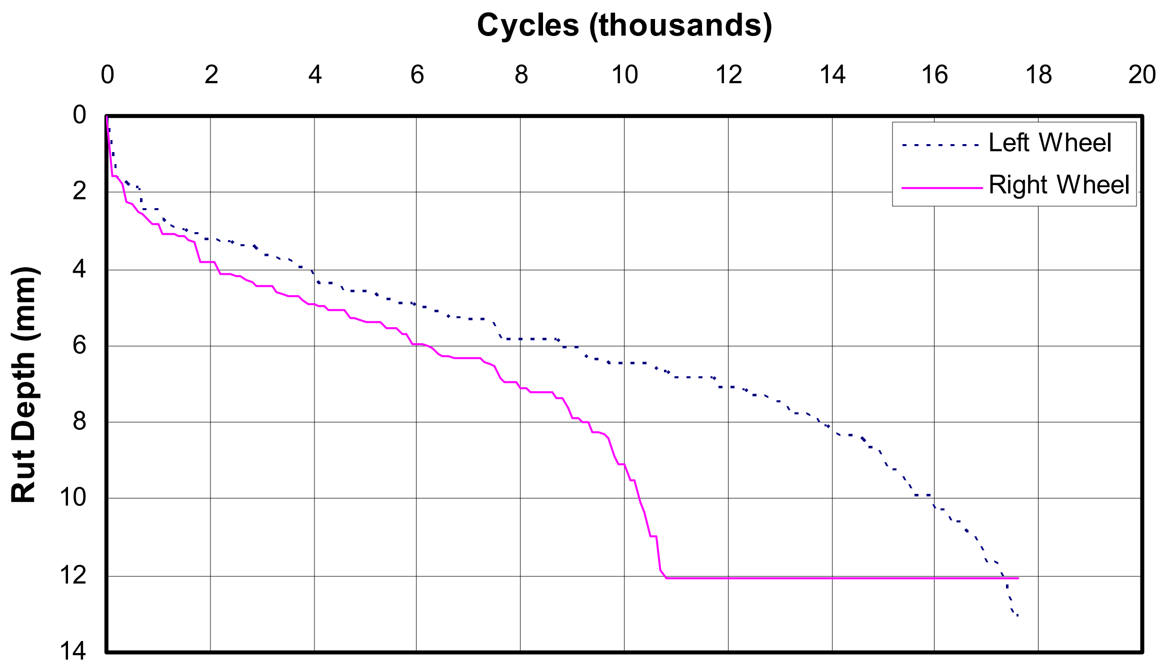

Figure A21. Test 3 – River Gravel Mixture at TxDOT Austin Laboratory with Machine 1.

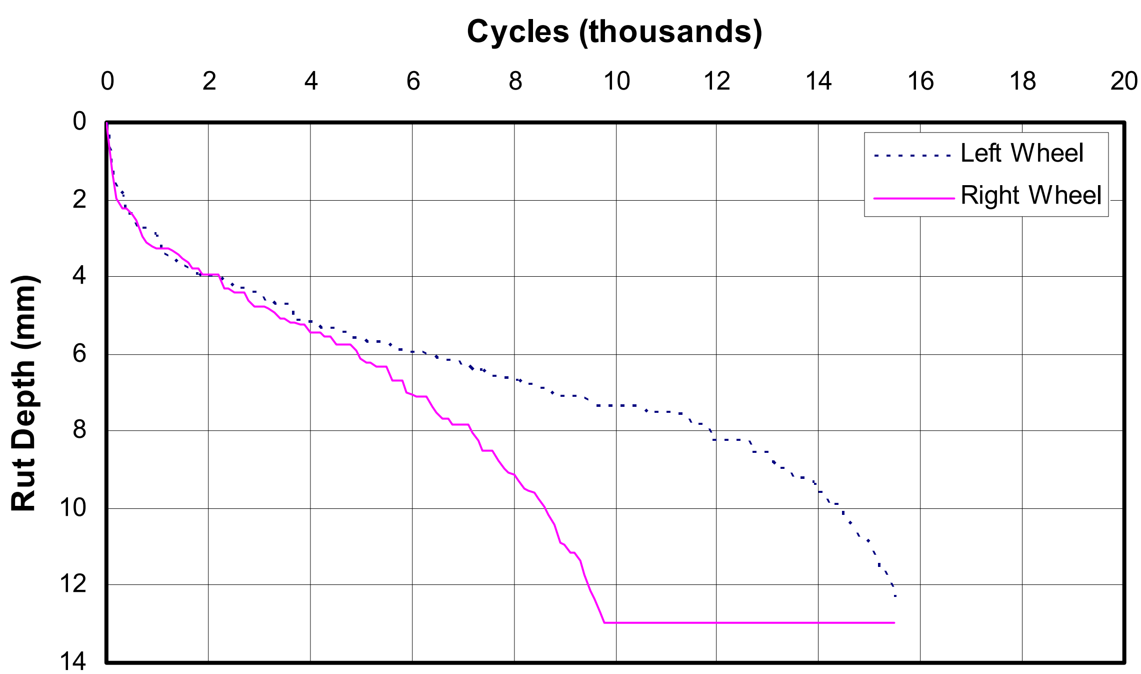

Figure A22. Test 4 – River Gravel Mixture at TxDOT Austin Laboratory with Machine 1.

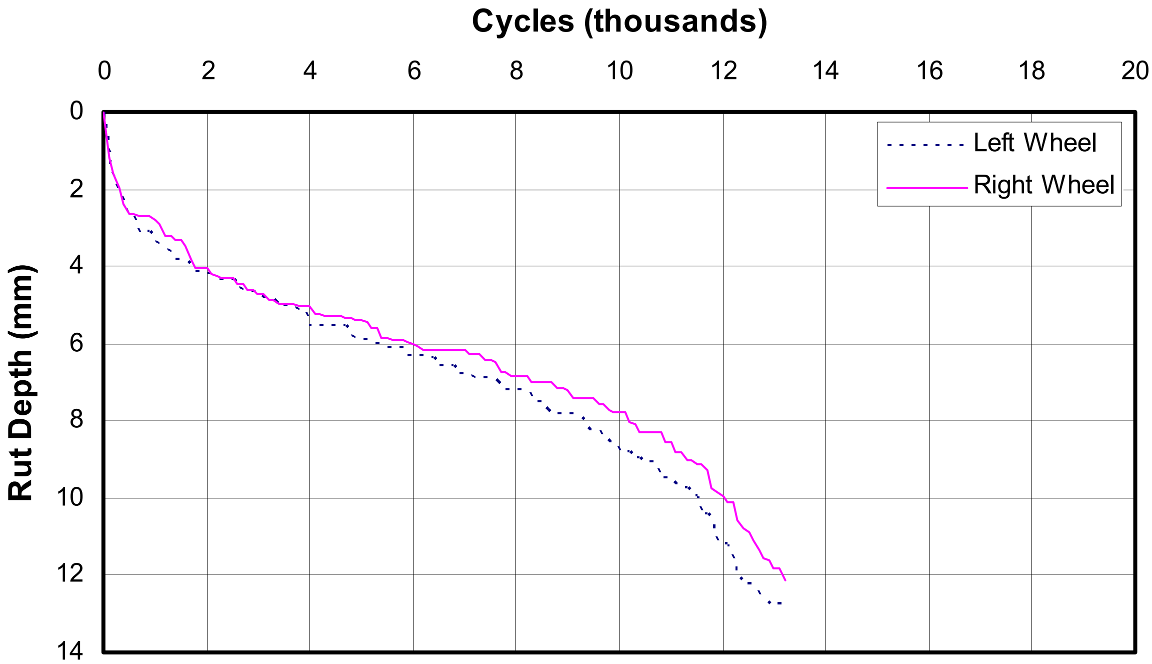

Figure A23. Test 3 – River Gravel Mixture at TxDOT Austin Laboratory with Machine 2.

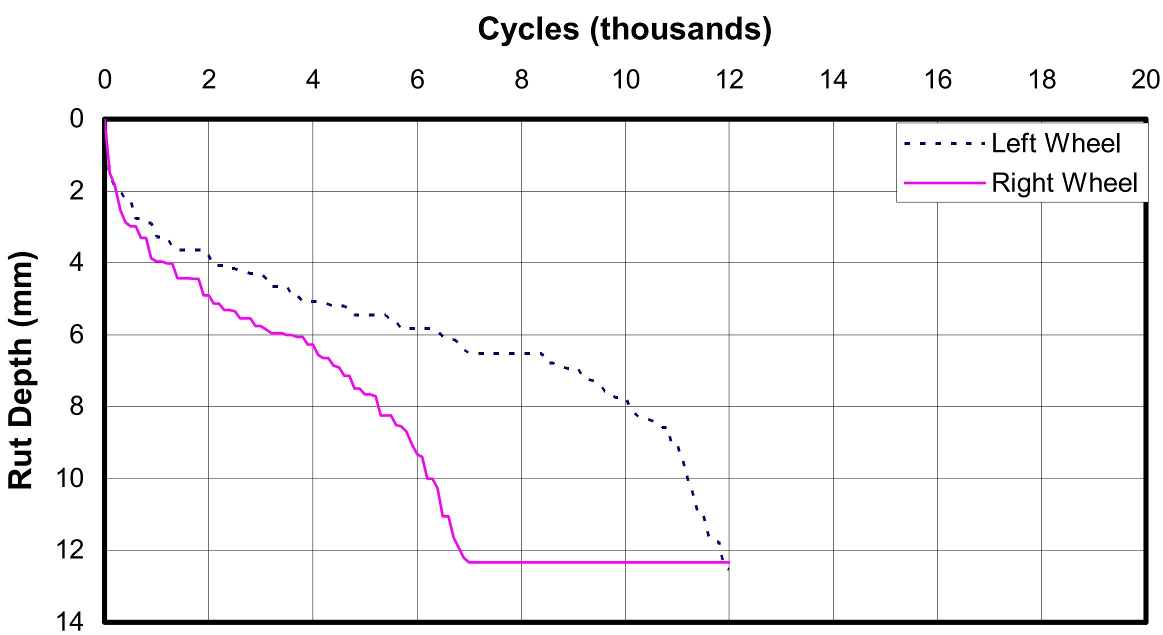

Figure A24. Test 4 – River Gravel Mixture at TxDOT Austin Laboratory with Machine 2.

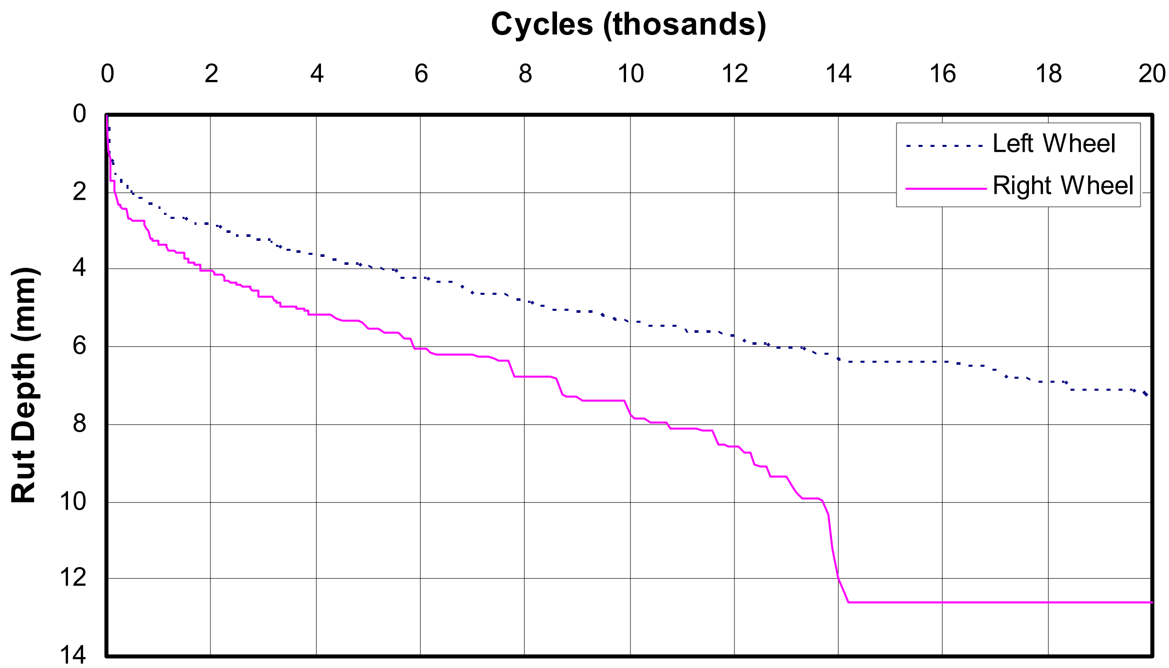

Figure A25. Test 3 – River Gravel Mixture at TxDOT Austin Laboratory with Machine 3.

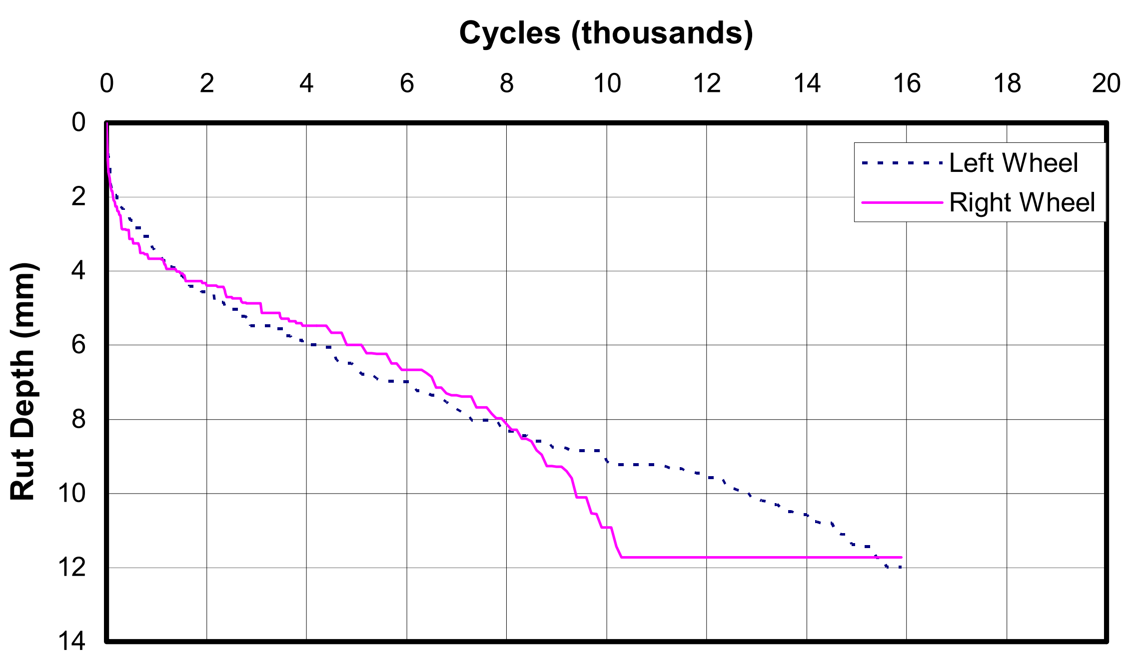

Figure A26. Test 4 – River Gravel Mixture at TxDOT Austin Laboratory with Machine 3.

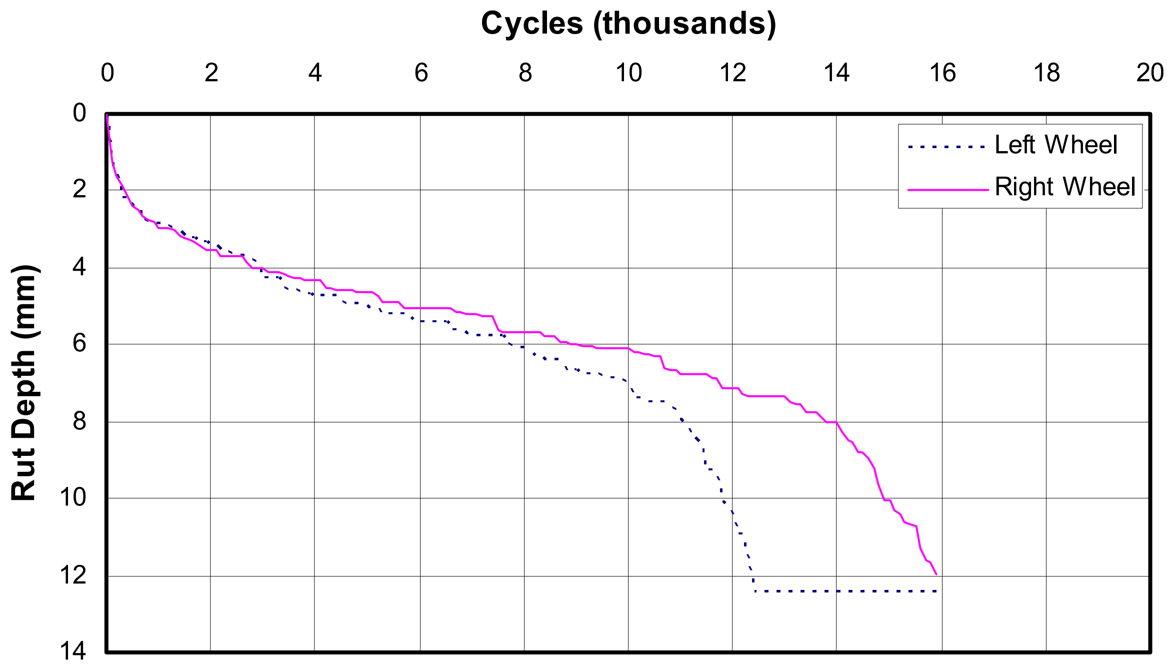

Figure A27. Test 3 – River Gravel Mixture at TxDOT Austin Laboratory with Machine 4.

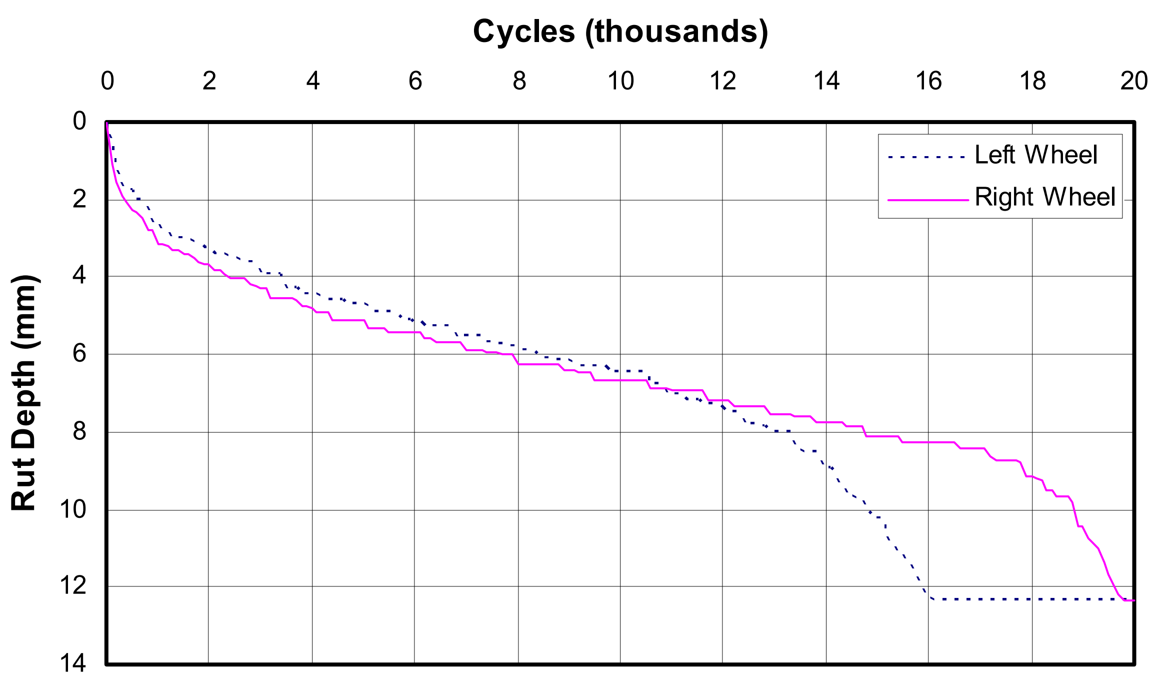

Figure A28. Test 4 – River Gravel Mixture at TxDOT Austin Laboratory with Machine 4.

Table A1. Specimen Identification for Each Laboratory.

Test Sequence	Group 1 TxDOT, Austin Machine 1	Group 2 TxDOT, Austin Machine 2	Group 3 TxDOT, Austin Machine 3	Group 4 TxDOT, Austin Machine 4	Group 5 PaveTex	Group 6 TxDOT, Chico	Group 7 TTI
1	LS 5	LS 18	LS 48	LS 52	LS 41	LS 22	LS 38
	LS 14	LS 39	LS 36	LS 21	LS 47	LS 2	LS 32
	LS 20	LS 44	LS 30	LS 35	LS 12	LS 10	LS 13
	LS 37	LS 40	LS 9	LS 51	LS 55	LS 6	LS 25
2	LS 8	LS 11	LS 43	LS 15	LS 27	LS 31	LS 29
	LS 53	LS 46	LS 4	LS 7	LS 19	LS 49	LS 57
	LS 59	LS 54	LS 23	LS 45	LS 28	LS 58	LS 47
	LS 24	LS 33	LS 34	LS 1	LS 26	LS 16	LS 50
3	RG 5	RG 18	RG 75	RG 52	RG 41	RG 22	RG 38
	RG 14	RG 67	RG 36	RG 65	RG 42	RG 2	RG 32
	RG 20	RG 44	RG 30	RG 69	RG 78	RG 10	RG 80
	RG 66	RG 40	RG 9	RG 76	RG 77	RG 6	RG 25
4	RG 70	RG 11	RG 43	RG 15	RG 27	RG 71	RG 29
	RG 53	RG 46	RG 4	RG 82	RG 83	RG 49	RG 81
	RG 3	RG 54	RG 23	RG 45	RG 28	RG 58	RG 84
	RG 24	RG 59	RG 34	RG 74	RG 26	RG 16	RG 50

LS – limestone, RG – river gravel.

Table A2. Test Results Using Type D Limestone Mixture.

Laboratory Name	Test Seq-uence	Rut Depth LWP (mm)	No. Load Cycles, LWP	Air void @ LWP (%)	Rut Depth RWP (mm)	No. Load Cycles, RWP	Air void @ RWP (%)	Stripping	Comment
TTI	1	12.62	15,050	7.50	12.53	12,801	7.40	Yes	Both wheel paths are close until stripping @ 7500 cycles
	2	12.14	15,951	7.40	12.12	17,651	7.45	Yes	Both wheel paths close all the way
PaveTex	1	12.53	16,300	7.45	12.92	15,500	7.30	Yes	Both wheel paths close all the way
	2	12.82	17,201	7.50	12.61	11,351	7.45	Not obvious	Both wheel apart from beginning
TxDOT Chico	1	12.72	19,950	7.20	12.78	13,501	7.00	Yes	Both wheel apart from beginning
	2	12.93	13,701	7.40	12.97	17,451	7.50	Yes	Both wheel close
TxDOT Austin, M1	1	12.93	20,000	7.00	13.01	19,801	7.50	Yes	Both wheel very close all way
	2	12.89	14,801	7.35	8.32	20,000	7.50	Not Obvious	Both wheel close until 7,700 cycles then way apart
TxDOT Austin, M2	1	12.96	19,500	7.45	12.70	18,601	7.50	Yes	Both wheel very close all the way
	2	12.78	16,101	7.45	12.95	15,801	7.50	Yes	Both wheel very close all the way
TxDOT Austin, M3	1	11.62	14,100	7.50	11.84	16,600	7.50	Yes	Both wheel close until 8,200 cycles
	2	11.96	16,001	7.00	12.19	18,401	7.40	Yes	Both wheel close all the way
TxDOT Austin, M4	1	8.46	19,801	7.40	13.04	19,001	7.40	Yes	Both wheel close until 13,000 cycles
	2	12.87	15,001	7.00	8.94	20,000	7.40	Left wheel only	Both Wheel close until 8,500 cycles

LWP – Left Wheel Path, RWP – Right Wheel Path.

Table A3. Test Results Using 9.5 mm Superpave River Gravel Mixture.

Laboratory Name	Test Seq-uence	Rut Depth LWP[1] (mm)	No. Load Cycles, LWP	Air void @ LWP (%)	Rut Depth RWP (mm)	No. Load Cycles, RWP	Air void @ RWP (%)	Stripping	Comment
TTI	1	12.59	14,351	7.20	4.85	20,001	6.80	Left wheel only	Both wheel deviate as early as 3,000 cycles and way apart at the end
	2	12.37	13,701	6.90	12.34	19,201	7.00	Yes	Both wheel apart from beginning
PaveTex	1	12.48	11,551	7.50	12.42	16,301	6.50	Yes	Both wheel close until 7000 cycles
	2	13.00	15,951	6.85	12.40	11,550	6.80	Yes	Both wheel close until 1000 cycles
TxDOT Chico	1	12.89	11,201	6.75	12.75	15,100	6.90	Right Wheel Only	Both wheel close at beginning
	2	9.10	14,451	7.45	10.48	14,500	6.50	Not obvious	Both wheel close all the way
TxDOT Austin, M1	1	13.06	17,500	6.60	12.06	10,800	7.30	Yes	Both wheel close until 9000 cycles
	2	12.30	15,500	7.40	12.98	9,801	7.15	Yes	Both wheel very close until striping
TxDOT Austin, M2	1	12.75	12,901	7.15	12.14	13,201	7.50	Not Obvious	Both wheel very close all the way
	2	12.53	12,000	7.05	12.33	7,100	7.45	Yes	Somewhat apart from beginning
TxDOT Austin, M3	1	7.41	20,000	7.00	12.58	14,201	7.10	Right Wheel Only	Apart from beginning.
	2	11.99	15,601	7.00	11.73	10,301	7.45	Right Wheel Only	Both wheel close until stripping at 9000 cycles
TxDOT Austin, M4	1	12.45	12,401	7.25	11.97	15,901	7.00	Yes	Both wheel close until 11,000 cycles
	2	12.37	16,101	6.75	12.37	19,801	7.00	Yes	Both wheel close until 13,000 cycles

LWP – Left Wheel Path, RWP – Right Wheel Path.

Table A4. Rut Depth at 5000 Cycles for Limestone Mixture.

Laboratory Name	Test Sequence	Rut Depth LWP (mm)	No. of Load Cycles, LWP	Rut Depth RWP (mm)	No. of Load Cycles, RWP
TTI	1	3.16	5000	3.35	5000
	2	3.21	5000	3.58	5000
PaveTex	1	2.88	5000	3.83	5000
	2	2.77	5000	3.38	5000
TxDOT Chico	1	2.88	5000	3.34	5000
	2	3.71	5000	3.10	5000
TxDOT Austin, M1	1	3.04	5000	3.69	5000
	2	3.62	5000	3.12	5000
TxDOT Austin, M2	1	3.27	5000	3.49	5000
	2	3.55	5000	3.12	5000
TxDOT Austin, M3	1	3.14	5000	3.23	5000
	2	3.07	5000	3.37	5000
TxDOT Austin, M4	1	2.47	5000	2.77	5000
	2	2.16	5000	2.86	5000

LWP – Left Wheel Path, RWP – Right Wheel Path.

Table A5. Rut Depth at 5000 Cycles for River Gravel Mixture.

Laboratory Name	Test Sequence	Rut Depth LWP (mm)	No. of Load Cycles, LWP	Rut Depth RWP (mm)	No. of Load Cycles, RWP
TTI	1	5.43	5000	3.09	5000
	2	5.58	5000	4.05	5000
PaveTex	1	6.56	5000	5.91	5000
	2	5.84	5000	5.80	5000
TxDOT Chico	1	6.09	5000	5.27	5000
	2	5.18	5000	4.41	5000
TxDOT Austin, M1	1	4.62	5000	5.36	5000
	2	5.59	5000	6.14	5000
TxDOT Austin, M2	1	5.91	5000	5.38	5000
	2	5.45	5000	7.66	5000
TxDOT Austin, M3	1	3.95	5000	5.53	5000
	2	6.65	5000	6.00	5000
TxDOT Austin, M4	1	5.03	5000	4.62	5000
	2	4.69	5000	5.14	5000

LWP – Left Wheel Path, RWP – Right Wheel Path.

Table A6. Rut Depth at 10,000 Cycles for Limestone Mixture.

Laboratory Name	Test Sequence	Rut Depth LWP (mm)	No. of Load Cycles, LWP	Rut Depth RWP (mm)	No. of Load Cycles, RWP
TTI	1	5.98	10,000	7.56	10,000
	2	4.56	10,000	4.40	10,000
PaveTex	1	4.74	10,000	6.30	10,000
	2	5.10	10,000	9.47	10,000
TxDOT Chico	1	4.57	10,000	8.98	10,000
	2	7.74	10,000	5.06	10,000
TxDOT Austin, M1	1	4.17	10,000	4.98	10,000
	2	7.46	10,000	3.74	10,000
TxDOT Austin, M2	1	4.72	10,000	4.55	10,000
	2	5.35	10,000	5.14	10,000
TxDOT Austin, M3	1	6.47	10,000	4.91	10,000
	2	4.57	10,000	4.53	10,000
TxDOT Austin, M4	1	3.20	10,000	4.38	10,000
	2	6.41	10,000	3.46	10,000

LWP – Left Wheel Path, RWP – Right Wheel Path.

Table A7. Rut Depth at 10,000 Cycles for River Gravel Mixture.

Laboratory Name	Test Sequence	Rut Depth LWP (mm)	No. of Load Cycles, LWP	Rut Depth RWP (mm)	No. of Load Cycles, RWP
TTI	1	7.35	10,000	3.81	10,000
	2	7.75	10,000	5.08	10,000
PaveTex	1	9.61	10,000	7.16	10,000
	2	7.45	10,000	7.99	10,000
TxDOT Chico	1	10.48	10,000	7.16	10,000
	2	7.20	10,000	6.06	10,000
TxDOT Austin, M1	1	6.49	10,000	9.10	10,000
	2	7.36	10,000	12.98	10,000
TxDOT Austin, M2	1	8.75	10,000	7.80	10,000
	2	7.74	10,000	12.33	10,000
TxDOT Austin, M3	1	5.37	10,000	7.76	10,000
	2	9.14	10,000	10.92	10,000
TxDOT Austin, M4	1	6.99	10,000	6.11	10,000
	2	6.44	10,000	6.64	10,000

LWP – Left Wheel Path, RWP – Right Wheel Path.