# LABORATORY REPEATABILITY OF THE HAMBURG WHEEL-TRACKING DEVICE AND SIMILAR WHEEL-TRACKING DEVICES

**DHT-44**

# DEPARTMENTAL RESEARCH

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*Technical Report Documentation Page*

| 1. Report No. | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| DHT-44 | | |

| 4. Title and Subtitle | 5. Report Date |
|---|---|
| LABORATORY REPEATABILITY OF THE HAMBURG WHEEL-TRACKING DEVICE AND SIMILAR WHEEL-TRACKING DEVICES | |
| | 6. Performing Organization Code |
| 7. Author(s) | 8. Performing Organization Report No. |
| Richard P. Izzo and Maghsoud Tahmoressi | Research Report DHT-44 |
| 9. Performing Organization Name and Address | 10. Work Unit No. (TRAIS) |
| Texas Department of Transportation<br>Bituminous Branch, Materials and Tests Section, Construction Division<br>2311 West Rundberg Lane, Suite 100<br>Austin, Texas 78758 | 11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address | 13. Type of Report and Period Covered |
| Texas Department of Transportation<br>Research and Technology Transfer Section, Construction Division<br>P. O. Box 5080<br>Austin, Texas 78763-5080 | In-house from July 1997 to September 1998 |
| | 14. Sponsoring Agency Code |

15. Supplementary Notes

16. Abstract


The objective of this research was to assess the repeatability of HMAC moisture susceptibility testing using the Hamburg wheel-tracking device and similar equipment. The tests were performed round-robin-style among seven laboratories. The seven participants were the University of Arkansas, the Colorado Department of Transportation (CDOT), the Federal Highway Administration (FHWA), Koch Materials Company, Superfos Construction, Inc., and Utah Department of Transportation (UTDOT).

All the steel-wheeled devices showed very good repeatability during testing of the polymer-modified asphalt gravel mixture; however, the repeatability was poor during testing of the limestone aggregate mixture. There was less variation within the data collected for Helmut Wind manufactured devices compared to the amount of variation from all the wheel-tracking devices.

Cylindrical test specimens fabricated with a Superpave gyratory compactor can be used in place of the rectangular slab test specimens. The use of rubber wheels for wheel-track testing produced different test results compared to the results from steel wheel tracking devices.

No standard test procedure exists for the Hamburg wheel-tracking device, so the amounts of variation caused by operator error and other sources of error are unknown.


| 17. Key Words | 18. Distribution Statement |
|---|---|
| moisture susceptibility, HMAC, Superpave, Hamburg steel wheel-tracking device, Couch Rut Tester, testing, rutting, asphalt mixtures, materials | No restrictions. This document is available to the public through the Texas Department of Transportation Research Library, P.O. Box 5080, Austin, TX, 78763-5080. |

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

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# LABORATORY REPEATABILITY OF THE HAMBURG WHEEL-TRACKING DEVICE AND SIMILAR WHEEL-TRACKING DEVICES

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September 1, 1998

## ACKNOWLEDGMENTS

The authors gratefully acknowledge the participants for their involvement in this study and taking the time and effort to perform testing and reporting their test results.

## INTRODUCTION

The Hamburg wheel-tracking device has been used in Europe and, to a limited extent, in the United States to measure performance related properties of hot mix asphalt (HMA). The Hamburg wheel-tracking device evaluates the moisture susceptibility of HMA. The testing device can be seen in figure 1. Typically, a pair of rectangular slab samples are tested under water simultaneously with two steel wheels moving concurrently connected by a crank to a flywheel. This type of movement produces a constantly varying velocity where the maximum velocity occurs in the center of the specimen. Rut depth measurements are taken at the center of the specimen. Test specimens are compacted to 7±1% air voids and to a height approximately 40 mm. Test parameters determined by the device include the creep slope, stripping slope, and stripping inflection point, which can be seen in figure 2. The creep slope relates to rutting primarily from plastic flow. It is the number of passes required to create a 1-mm rut depth. The stripping inflection point (SIP) is the number of passes at the intersection of the creep slope and stripping slope. It is the number of passes at which stripping starts to dominate performance. The stripping slope is a measure of the accumulation of rutting primarily from moisture damage. It is the number of passes required to create 1-mm rut depth after the stripping inflection point (*1*).

FHWA and the Colorado Department of Transportation (CDOT) have performed extensive amounts of research evaluating HMA with the Hamburg wheel-tracking device. FHWA has utilized the device for testing dense-graded and stone matrix asphalt mixtures ***(2, 3)***, as well as material from the Accelerated Loading Facility at Turner Fairbank Highway Research Center in McLean, Virginia ***(4)***, and from Westrack in Nevada for research purposes ***(5)***. CDOT has also performed research evaluating various mixtures, as well as the influence of testing variables and compaction. Variables investigated included test temperature, air void content, short-term aging, and use of hydrated lime as an antistripping agent ***(6-9)***. CDOT utilized the information gathered from their research efforts to develop a test method that is currently in use by the department to evaluate HMA throughout the state for moisture damage.

Interest in the Hamburg wheel-tracking device or devices similar to it have been shown by other state department of transportation agencies, universities, and private sector companies. Texas Department of Transportation (TxDOT) conducted research investigating the use of Superpave-gyratory-compacted (SGC) specimens with the Hamburg wheel-tracking device. It was found that SGC-molded test specimens could be used for moisture evaluation in the Hamburg wheel-tracking device for comparative evaluation of one material to another. Differences were seen in the test results from the comparison of the SGC-molded specimens and slab-molded specimens. Therefore, test results from SGC-molded specimens could not be directly compared to the slab-molded specimens ***(1)***. Also, TxDOT has ongoing research investigating the effects of the use of antistripping additives and test temperature, as well as evaluating different aggregate sources throughout the state of Texas. The development of a test method is anticipated utilizing the Hamburg wheel-tracking device to evaluate HMA for moisture susceptibility.

Utah Department of Transportation (UTDOT) has been utilizing a wheel-tracking device similar to the Hamburg wheel-tracking device to evaluate their conventional and Superpave HMA. They purchased their wheel-tracking device from Copper Unlimited located in England. However, they have only recently started testing material and have not performed many tests. UTDOT has not developed a specification for the wheel-tracking device. Consequently, CDOT is the only state agency in the United States to develop a test method for laboratory use to evaluate the moisture susceptibility of HMA with the Hamburg wheel-tracking device.

Arkansas and Purdue University utilize laboratory wheel-tracking devices that are similar to the Hamburg wheel-tracking device to measure the moisture susceptibility of HMA. University of Arkansas uses the evaluator of rutting and stripping in asphalt (ERSA) and Purdue University uses the Purdue University wheel test device (PTD). The ERSA and PTD were developed using certain features of the Hamburg wheel-tracking device but have unique features of their own. The PTD is capable of testing larger specimens and uses air cylinders to operate at a constant speed over the longitudinal center of specimens with location and number of rut depth measurements being user specified. The PTD is a flexible test apparatus with numerous user-specified test parameters ***(10)***.

Koch Materials and Superfos Construction are private sector companies that also use laboratory wheel tracking devices to evaluate moisture damage of HMA. Koch Materials uses a Hamburg wheel-tracking device. Superfos Construction manufactured their own wheel tracking device that is similar to the Hamburg wheel-tracking device and named the Couch Rut Tester. However, the device uses a solid, rubber wheel for load application. The Hamburg wheel-tracking device has the capability of using rubber wheels as well. However, there hasn't been any published research conducted with rubber wheels. Both of these companies utilize their wheel-tracking device for research purposes to evaluate moisture susceptibility. In addition, Koch Materials uses the Hamburg wheel-tracking device for quality control of asphalt materials. Superfos Construction also uses its wheel-tracking device to evaluate HMA used in construction.

## EXPERIMENTAL PLAN

The objective of this study is to assess the repeatability of the Hamburg wheel-tracking device and similar devices among different laboratories. It is important to note that a standard test procedure has not been developed or a ruggedness study not performed on this testing device. Several laboratories throughout the United States use a Hamburg wheel-tracking device or a wheel-tracking device that is similar to evaluate HMA for moisture susceptibility, either for research or other agency needs. State highway departments are eager to develop test procedures utilizing a wheel-tracking device to evaluate moisture susceptibility and rutting of HMA. Within the past 20 years, laboratory testing capabilities for prediction of moisture damage have improved. However, there are a limited number of basic tests with many variations of each test. It has been shown that these different tests and test variations do not yield the same results and thus vary in the prediction of moisture susceptibility ***(11)***.

Seven agencies participated in this study and are listed in table 1 along with their location and contact person. Testing material (HMA) and test parameters were defined by TxDOT and the method of compaction was chosen by the participants. All of the participants compacted test specimens with a linear kneading compactor; however, it is more than likely that the compaction devices were manufactured by different producers. Table 2 provides specifications of the wheel-tracking devices used in this round robin study. It is important to note that TxDOT, FHWA, CDOT, and Koch use a Hamburg wheel-tracking device manufactured by Helmut Wind, located in Hamburg, Germany. The other participants have wheel-tracking devices that are similar to the Hamburg wheel-tracking device. The specifications are alike for all the devices with exception to that of Superfos Construction, Inc. The wheel-tracking device used by Superfos Construction, Inc., utilizes a solid, rubber wheel to induce damage, and the passes of the wheel occur at a faster rate as listed in table 2. It is also important to note that the load applied by the rubber wheel is greater than the load applied by the steel wheel.

The testing configuration was the same for all tests where each participant received a letter specifically identifying the testing criteria. The tests were performed at 50°C with two test replicates/specimens fabricated to an air void content of 7±1%.

## Materials Selection and Specimen Fabrication

Two types of HMA mixtures were used to evaluate the performance of the wheel-tracking devices in this study for moisture susceptibility. The mixtures composed of a limestone and a gravel aggregate. Limestone is commonly used throughout central Texas and the aggregate used in the HMA for this study was 100% crushed with a Los Angeles (LA) abrasion of 31 and specific gravity approximately 2.57. The gravel aggregate that was used in the HMA for this study was crushed to a minimum of 85% with a LA abrasion of 26 and specific gravity approximately 2.61. The asphalt used for the limestone and gravel mixtures were an AC-20 and an AC-30P, respectively. AC-30P is a polymer-modified asphalt where an AC-10 is blended with a minimum of 3% styrene-butadiene-styrene (SBS). The limestone and gravel mixture components are listed in tables 3 and 4. The optimum asphalt content and aggregate gradation for each mixture are listed in table 5. The limestone mixture was procured from Industrial Asphalt, Inc., located in Buda, Texas. The gravel mixture was obtained from Texarkana Asphalt, Inc., located in Atlanta, Texas. It is also important to note that 1% of hydrated lime as well as 10% of mineral filler was used in the gravel mixture. No antistripping additives were used in the limestone mixture. These mixtures were not particularly chosen for this study but were readily available at the time the study began.

The materials used in this study were obtained at the HMA plants mentioned above and shipped to all the participants. Each participant received approximately 40 kg of material for each mixture. The participants fabricated tests specimens with a linear kneading compactor, which is typical for the compaction of rectangular slabs. TxDOT also produced specimens with a SGC at the same air void content.

## Superpave Gyratory Compacted Test Specimens

TxDOT modified the test specimen configuration such that one test specimen for the Hamburg wheel-tracking device consists of two SGC specimens. The specimens are secured in the mounting tray with two molds and two spacer plates fabricated with an acrylic material. Figure 3 illustrates a top view of the set up. The spacer plates, which aid in securing the configuration, are placed behind each mold at opposite ends. The molds are shaped as rectangles with semicircles cut out approximately 25 mm from the back edge. However, with the spacer plates the semicircles are approximately 40 mm from the back edge of the mounting tray. The specimens are sawed such that they fit into the molds. The specimens are tightly fastened in the mounting tray by tightening nuts that adjoin a front plate to the mounting tray. Overall, the whole specimen resembles a snowman figure with a contact area among the SGC specimens approximately 51 cm$^2$ and is adequately secured such that movement during testing does not occur other than any degradation or dilation resulting from the test. The sawed portion is approximately 5% of the total volume of a single SGC specimen. Figure 4 is a picture of the test specimen configuration for the Hamburg wheel-tracking device with SGC-compacted specimens. The setup without any specimens can also be seen in figure 1 in the testing device.

# RESULTS AND DISCUSSION

Data analysis included the evaluation of rut depth at 5,000, 10,000, 15,000, and 20,000 cycles (where applicable). The analysis also included the evaluation of the following test parameters: number of passes to failure, $N_f$, creep slope, SIP, and stripping slope (where applicable). In addition to evaluating the variability between laboratories of the wheel-tracking devices, other comparisons were made. The comparison of slab versus SGC specimens and of the steel versus rubber wheels were evaluated.

The test results for the gravel mixture compared well among all the laboratories. Figure 5 illustrates the wheel-tracking data from each participant for the gravel mixture. The test results were similar where the mixture performed well for each agency. This performance is most likely attributable to the use of the antistripping additive, hydrated lime. Figure 6 represents the test results for the limestone mixture. The results for the limestone mixture did not compare as well as the results for the gravel mixture. Four out of the seven participating laboratories obtained similar test results for the limestone mixture. As shown in Figure 6, data from UTDOT and ERSA devices are significantly different from the others. Results from Superfos that utilize the solid, rubber wheels have shown lower rut depths with both mixtures in comparison to all of the other participants as seen in both figures.

Tables 6 and 7 list the data provided by the participants for the gravel and limestone mixtures, respectively. The tables list results for the test parameters mentioned above. Four different analyses were performed and listed in each table. The statistical mean and standard deviation were determined for the data within each group analyzed. The first group, *Steel Wheel Devices — Slab Test Data,* included all the participants with wheel-tracking devices using steel wheels and testing rectangular slab test specimens. The second group, *Steel Wheel Devices — Slab and SGC Test Data,* included all the participants with wheel-tracking devices using steel wheels testing rectangular slab and cylindrical test specimens. The third group, *Steel Wheel Devices — Helmut Wind Manufactured, Slab Test Data,* included the participants that own wheel-tracking devices manufactured by Helmut Wind using rectangular slab test specimens. The fourth group, *Steel Wheel Devices — Helmut Wind Manufactured, Slab and SGC Test,* included the participants that own wheel-tracking devices manufactured by Helmut Wind using rectangular slab and cylindrical test specimens.

## SLAB COMPARISON

### Gravel Mixture

The following discussion is based upon the test results listed in table 6 and illustrated in figure 5.

#### *Steel Wheel Devices — Slab Test Data*

The laboratory repeatability of the steel wheel, wheel-tracking devices testing the gravel mixture has shown to be good. The specimens didn't exhibit any significant amount of rutting or stripping. The SIP was not reached, therefore, only the creep slope was evaluated along with the rut depth measurements. The creep slope values were fairly similar with exception to FHWA, UTDOT, and University of Arkansas. The FHWA and UTDOT have shown results with higher creep slope values, whereas University of Arkansas have shown a lower creep slope value. The standard deviation listed in table 6 for *Steel Wheel Devices — Slab Test Data* indicate small variation among the test results. It is important to note that these testing devices have not been correlated to field performance. Therefore, the significance of the standard deviation in these comparisons is not truly known. A standard deviation of 3,000 passes for the creep slope may or may not be significant in the field.

#### *Steel Wheel Devices — Slab and SGC Test Data*

The test results for the gravel SGC test specimens have shown higher rut depths than all the other participants. However, the differences seen in the data is not significant. The performance of the test specimens was similar to that of the rectangular slab test specimens where the SIP was not reached and no significant amount of rutting or stripping occurred. The standard deviation for the rut depths increased in comparison to the results from the slabs only. However, standard deviation for the creep slope decreased. The differences with these standard deviations are not significant. The importance is that the SGC specimens did not introduce a significant amount of variation to the data and their use can be accepted.

### *Steel Wheel Devices — Helmut Wind Manufactured, Slab Test Data*

TxDOT, FHWA, CDOT, and Koch were the participants in this study that used a Hamburg wheel-tracking device manufactured by Helmut Wind located in Hamburg, Germany. The data from these participants was analyzed and compared to the results from the other wheel-tracking devices. The test results are similar, but more important is that the Helmut Wind manufactured devices show a lower standard deviation. The differences may not all be significant but this lower standard deviation is an indication of better repeatability where less variation occurs among the data. Therefore, differences in manufactured wheel-tracking devices used to test the specimens influenced the test results.

### *Steel Wheel Devices — Helmut Wind Manufactured, Slab and SGC Test Data*

The evaluation of the use of the SGC testing configuration was also examined with the Helmut Wind manufactured wheel-tracking devices. The standard deviation increased for the rut depths and decreased for the creep slope. Once again, the differences seen in the data are not significant. The performance of the SGC test specimens with the Helmut Wind devices was similar to that of the rectangular slab test specimens where the SIP was not reached and no significant amount of rutting or stripping occurred. Again, the importance is that the SGC specimens did not introduce any significant amount of variation to the data and that this modified testing configuration can be used.

Overall, the test results from all the participants have shown the gravel mix to have a high resistance to rutting and stripping. Testing of this mix has shown less than 4 mm of rutting after 20,000 passes. The gravel mixture has shown a high resistance to stripping where the stripping inflection point was not reached. However, it is important to note that this mix was produced with a polymer-modified asphalt and 1 percent of hydrated lime was added. Therefore, the enhanced performance of this gravel mixture in this study can be attributed to the use of the antistripping additive and a polymer-modified asphalt binder.

## Limestone Mixture

The following discussion is based upon the test results listed in table 7 and illustrated in figure 6.

### *Steel Wheel Devices — Slab Test Data*

The laboratory repeatability of the steel wheel, wheel-tracking devices testing the limestone mixture has shown to be moderate. There are two test results that stand out in this group and are from UTDOT and University of Arkansas. The results reported by University of Arkansas have shown the limestone mixture to be less susceptible to rutting than the other agencies, where test specimens did not fail or rutting was shown to be less than 20 mm after 20,000 passes. The results submitted by UTDOT have characterized the mix to be more susceptible to rutting where there were greater rut depths and the test specimens failed before 5,000 passes. These scattered results have a significant affect upon the statistical parameters, which is mentioned later in more detail.

### *Steel Wheel Devices — Slab and SGC Test Data*

The test results for the limestone SGC test specimens do not stand out from that of the other participants where results are either predominately greater or lower. The differences seen in the data is not significant. The performance of the test specimens was similar to the rectangular slab test specimens where the SIP was reached and a significant amount of rutting was recorded prior to 20,000 passes. No statistical parameters are listed in the table for the rut depths in this section because they could not be computed. UTDOT test specimens failed before 5,000 passes, therefore, there was no known value for the rut depth other than that it was greater than 20 (noted as '>20' in the table). The standard deviation decreased for every parameter with exception to the SIP, where it slightly increased for the SGC test specimens. The differences with these standard deviations are not significant. The importance is that the SGC specimens did not introduce any significant amount of variation to the data thus their use can be accepted.

### *Steel Wheel Devices — Helmut Wind Manufactured, Slab Test Data*

The data from the participants using the Hamburg wheel-tracking device manufactured by Helmut Wind was analyzed and compared to the results from the other wheel-tracking devices with the slab test specimens. The test results are similar, but more important is that the data show less variation with lower standard deviation. The differences are significant where they are much less. The data do not include the results from UTDOT and University of Arkansas in this section. The standard deviation for the $N_f$, SIP, and stripping slope are less than 50% and greater for the creep slope. The Helmut Wind devices have shown better repeatability where less variation occurs among the data. Therefore, differences in manufactured wheel-tracking devices used to test the limestone specimens influenced the test results.

### *Steel Wheel Devices — Helmut Wind Manufactured, Slab and SGC Test Data*

The evaluation of the use of the SGC testing configuration was also examined with the Helmut Wind manufactured wheel-tracking devices testing the limestone mixture. The standard deviation increased for the test parameters, with exception of the rut depth at 5,000 passes. The differences of these values are not significant, with exception of the SIP. The SIP standard deviation for the SGC test specimens was approximately 30% greater than that for the slab test specimens. The performance of the SGC test specimens with the Helmut Wind devices was similar to the rectangular slab test specimens where the SIP was reached and failure occurred before 20,000 passes. Again, the importance is that the SGC specimens did not introduce any significant amount of variation to the data and that this modified testing configuration can be used.

The performance of the limestone mixture seen in figure 6 cannot be compared to the performance of the gravel mixture seen in figure 5. Typically, limestone mixtures perform better than gravel mixtures in terms of moisture susceptibility throughout Texas. The gravel aggregate used is round in shape and has a smooth surface, thus more likely prone to stripping. These mixtures cannot be compared because an antistripping additive and polymer-modified asphalt binder were used in the gravel mixture, which were not used in the limestone mixture.

### *Rubber Wheel-Tracking Test Data*

Test results from the rubber wheel-tracking device, Couch Rut Tester of Superfos have been compared to the data from the other participants that utilize steel wheel-tracking devices. Figures 5 and 6 illustrate the test results for all the participants. It can be seen that the test results from the Couch Rut Tester are significantly lower than that of the steel wheel-tracking devices. This result may be expected considering the use of a rubber wheel versus a steel wheel. However, as shown in table 2, the Couch Rut Tester applies the greatest load where there is a difference of at least 115 N (94 lbs) from the other wheel-tracking devices. Also important to note is that the speed of the device is greater than that of the steel wheel-tracking devices. It is expected that a greater load would be required for a rubber wheel-tracking device to simulate conditions produced by a steel wheel-tracking device.

## CONCLUSIONS

The Hamburg wheel-tracking device has gained popularity in the United States since its acknowledgment in 1990. Several laboratories throughout the United States either own a Hamburg wheel-tracking device or a similar wheel-tracking device to assess the moisture susceptibility of hot mix asphalt. The purpose of this study was to evaluate the laboratory repeatability of the Hamburg wheel-tracking device among different laboratories throughout the United States. This evaluation included four Hamburg wheel-tracking devices manufactured by Helmut Wind (TxDOT, FHWA, CDOT, and Koch), two other wheel-tracking devices designed with similar specifications but different manufacturers (UTDOT and University of Arkansas), and one rubber wheel-tracking device (Superfos' Couch Rut Tester). Based upon the test results presented in this paper the following has been concluded:

The steel wheel-tracking devices have shown to be very repeatable in testing the gravel mixture. All of the devices predicted similar performance where the stripping inflection point was not reached, thus no major signs of stripping potential and small amounts of rutting. However, these results are most likely due to mixture characteristics, because this mixture contained 1% hydrated lime and produced with a polymer-modified asphalt binder. It is suspected that the moisture susceptibility of this mixture was drastically improved with these materials.

The steel wheel-tracking devices have shown poor repeatability in testing the limestone mixture. However, test results from UTDOT and University of Arkansas varied significantly from the others. These scattered results had a significant affect upon the statistical parameters. All of the devices predicted similar performance where the stripping inflection point was reached with a significant amount of rutting.

- Averaged data only from the Helmut Wind manufactured wheel-tracking devices were similar to that of the entire group of wheel-tracking devices. More important was that the standard deviation for each parameter improved or decreased. There was less variation within the data collected from the tests performed with the Helmut Wind devices in comparison to the amount of variation from all the wheel-tracking devices. This change in variation is an indication that different types of wheel-tracking devices may not be comparable.
- The testing configuration for the Hamburg wheel-tracking device was modified by TxDOT such that cylindrical test specimens fabricated with a Superpave gyratory compactor (SGC) could be used in lieu of rectangular slab test specimens. The SGC test results with the gravel and limestone mixture have found to be comparable to the slab test results with the gravel and limestone mixtures. No significant differences were seen in the standard deviation for each test parameter. The level of performance for both mixtures can be predicted with either a slab or SGC test specimen relatively accurate. The SGC specimens did not introduce any significant amount of variation to the data, and it is apparent that this modified testing configuration can be used
- The use of rubber wheels for wheel-track testing produced different test results in comparison to the results found with a steel wheel-tracking device. The rutting or damage induced by the rubber wheels was significantly less than that produced by the steel wheels. It is apparent that the use of rubber wheels for wheel-track testing require additional weight or force to simulate the conditions that are produced with steel wheels.
- There is no standard test procedure with the Hamburg wheel-tracking device, therefore, there may be unsuspected error introduced from the procedure itself. Also, variation within the data may be from operator error. Different compactors were used to fabricate the test specimens, however, in most cases all the test specimens met the specified air void content within tolerance. These sources of error are unknown and could not be accounted for in the analysis performed in this study.

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*Table 1  Agencies Participating in the Round Robin*

| PARTICIPANT | LOCATION | CONTACT |
|---|---|---|
| Texas Department of Transportation | Austin, Texas | Richard P. Izzo |
| Federal Highway Administration | McLean, Virginia | Kevin D. Stuart |
| Colorado Department of Transportation | Denver, Colorado | Richard R. Bouska |
| Koch Materials Company | Wichita, Kansas | Charles J. Brady |
| University of Arkansas | Fayetteville, Arkansas | Kevin Hall |
| Utah Department of Transportation | Salt Lake City, Utah | Steve Niederhauser |
| Superfos Construction, Inc. | Dothan, Alabama | Paul Messersmith |

*Table 2  Specifications for Wheel-Tracking Devices Used in the Round Robin Study*

| Agency | Load | | Wheel | | | | | Speed |
|---|---|---|---|---|---|---|---|---|
| | | | Type | Width | | Diameter | | |
| | N | (lbs) | | mm | (in) | mm | (in) | Passes/min |
| TxDOT | 685 | (154) | Steel | 47 | (1.85) | 203 | (8) | 53 |
| FHWA | 685 | (154) | Steel | 47 | (1.85) | 204 | (8) | 53 |
| CDOT | 705 | (158) | Steel | 47 | (1.85) | 204 | (8) | 53 |
| KOCH | 705 | (158) | Steel | 47 | (1.85) | 203 | (8) | 52 |
| Univ. Ark. | 705 | (158) | Steel | 47 | (1.85) | 203 | (8) | 52 |
| UTDOT | 705 | (158) | Steel | 47 | (1.85) | 204 | (8) | 53 |
| Superfos | 810 | (182) | Rubber | 46 | (1.85) | 194 | (7.6) | 84 |

*Table 3 Limestone Mixture Components*

| Aggregate | Percent |
| --- | --- |
| Hunter Pit Type C Rock | 22 |
| Hunter Pit Type D Rock | 21 |
| Hunter Pit Type F Rock | 20 |
| Hunter Pit Screenings | 22 |
| Seguin Field Sand | 15 |

Type C — Aggregate with a maximum nominal size of 12.5 mm.
Type D — Aggregate with a maximum nominal size of 9.5 mm.
Type F — Aggregate with a maximum nominal size 4.75 mm.

*Table 4 Gravel Mixture Components*

| Aggregate | Percent |
| --- | --- |
| GHLR Type C Rock | 17 |
| GHLR Type D Rock | 39 |
| GHLR Screenings | 21 |
| GH Hoot Pit Field Sand | 12 |
| Donnafill | 10 |
| Hydrated Lime | 1 |

GHLR — Gifford Hill Little River

*Table 5 Asphalt Content and Aggregate Gradation in Percent Passing for Limestone and Gravel Mixtures*

| Sieve Size, Mm | | Limestone Mixture | Gravel Mixture |
|---|---|---|---|
| 22.40 | (7/8) | 100.0 | 100.0 |
| 16.00 | (5/8) | 100.0 | 97.1 |
| 9.50 | (3/8) | 73.7 | 81.1 |
| 4.75 | (# 4) | 50.9 | 61.3 |
| 2.00 | (# 10) | 31.1 | 38.2 |
| 0.425 | (# 40) | 15.6 | 20.7 |
| 0.180 | (# 80) | 6.1 | 9.9 |
| 0.075 | (# 200) | 2.0 | 5.0 |
| Asphalt Content | | 5.0 % | 4.8 % |
| Asphalt Binder | | AC-20 | AC-30P |

*Table 6 Rut Depth and Creep Slope Data for the Gravel Test Specimens*

| Agency | Air Voids % | Rut Depth, mm 5 k | 10 k | 15 k | 20 k | Creep Slope |
|---|---|---|---|---|---|---|
| TxDOT* | 6.1 | 1.62 | 2.10 | 2.41 | 2.73 | 16,129 |
| SGC* | 6.8 | 2.92 | 3.52 | 3.87 | 4.12 | 14,700 |
| FHWA* | 6.0 | 1.97 | 2.28 | 2.58 | 2.85 | 19,256 |
| CDOT* | 7.5 | 2.11 | 2.61 | 2.97 | 3.25 | 14,995 |
| Koch* | 7.3 | 1.87 | 2.34 | 2.61 | 2.89 | 14,276 |
| Univ.Ark.+ | 8.4 | 2.10 | 2.75 | 3.22 | 3.48 | 11,415 |
| UTDOT+ | 7.3 | 2.22 | 2.30 | 2.32 | 2.60 | 19,972 |
| Superfos° | 6.6 | 0.84 | 1.10 | 1.37 | 1.51 | 5,882 |
| ***Steel Wheel Devices — Slab Test Data*** | | | | | | |
| Mean | 7.1 | 1.98 | 2.40 | 2.69 | 2.97 | 16,007 |
| Std. Dev. | 0.91 | 0.21 | 0.24 | 0.34 | 0.33 | 3,206 |
| ***Steel Wheel Devices — Slab & SGC Test Data*** | | | | | | |
| Mean | 7.1 | 2.12 | 2.56 | 2.85 | 3.13 | 15,820 |
| Std. Dev. | 0.84 | 0.41 | 0.48 | 0.55 | 0.53 | 2,968 |
| ***Steel Wheel Devices — Helmut Wind Manufactured, Slab Test Data*** | | | | | | |
| Mean | 6.7 | 1.89 | 2.33 | 2.64 | 2.93 | 16,164 |
| Std. Dev. | 0.78 | 0.21 | 0.21 | 0.24 | 0.22 | 2,198 |
| ***Steel Wheel Devices — Helmut Wind Manufactured, Slab & SGC Test Data*** | | | | | | |
| Mean | 6.7 | 2.10 | 2.57 | 2.89 | 3.17 | 15,871 |
| Std. Dev. | 0.68 | 0.49 | 0.56 | 0.59 | 0.57 | 2,013 |

Note: Stripping inflection point (SIP) and stripping slope data not available because test specimens did not reach the SIP.
Number of passes to failure (Nf) is 20,000 passes for all test specimens.

* — Wheel-tracking devices manufactured by Helmut Wind
\+ — Wheel-tracking devices replicating the Helmut Wind model.
° — Wheel-tracking device replicating the Helmut Wind model and also utilizing solid, rubber tires.

*Table 7 Rut Depth Data for the Limestone Test Specimens*

| Agency | Air Voids % | Rut Depth, mm 5k | 10k | 15k | 20k | Nf | Creep Slope | SIP | Stripping Slope |
|---|---|---|---|---|---|---|---|---|---|
| TxDOT* | 6.5 | 6.35 | >20 | >20 | >20 | 9,800 | 1,573 | 544 | 4,486 |
| SGC* | 6.9 | 6.83 | 12.97 | >20 | >20 | 12,800 | 1,459 | 662 | 7,237 |
| FHWA* | 5.6 | 7.74 | >20 | >20 | >20 | 9,300 | 1,442 | 331 | 3,889 |
| CDOT* | 7.2 | 5.63 | 15.20 | >20 | >20 | 12,900 | 1,568 | 330 | 6,140 |
| Koch* | 7.6 | 5.12 | 15.10 | >20 | >20 | 8,800 | 1,653 | 566 | 4,276 |
| Univ.Ark.+ | 8.3 | 3.50 | 6.83 | 11.71 | 18.53 | 20,000 | 3,032 | 962 | 7,928 |
| UTDOT+ | 7.9 | >20 | >20 | >20 | >20 | 4,000 | 386 | 226 | 2,041 |
| Superfos° | 6.2 | 1.34 | 1.95 | 2.56 | 2.93 | 20,000 | 2,039 | NA | NA |
| ***Steel Wheel Devices — Slab Test Data*** | | | | | | | | | |
| Mean | 7.2 | NC | NC | NC | NC | 10,800 | 1,609 | 493 | 4,793 |
| Std. Dev. | 0.99 | NC | NC | NC | NC | 5,339 | 843 | 265 | 2,020 |
| ***Steel Wheel Devices — Slab & SGC Test Data*** | | | | | | | | | |
| Mean | 7.1 | NC | NC | NC | NC | 11,086 | 1,588 | 517 | 5,142 |
| Std. Dev. | 0.91 | NC | NC | NC | NC | 4,932 | 772 | 250 | 2,062 |
| ***Steel Wheel Devices — Helmut Wind Manufactured, Slab Test Data*** | | | | | | | | | |
| Mean | 6.7 | 6.21 | NC | NC | NC | 10,200 | 1,559 | 443 | 4,698 |
| Std. Dev. | 0.88 | 1.14 | NC | NC | NC | 1,846 | 87 | 130 | 993 |
| ***Steel Wheel Devices — Helmut Wind Manufactured, Slab & SGC Test Data*** | | | | | | | | | |
| Mean | 6.8 | 6.33 | NC | NC | NC | 10,720 | 1,539 | 487 | 5,206 |
| Std. Dev. | 0.76 | 1.02 | NC | NC | NC | 1,977 | 88 | 149 | 1,424 |

Note: NA — Not Available, test specimens did not reach stripping inflection point.
NC — Not Computable, specimens failed prior to the designated number of passes; therefore, assigned >20 to indicate failure.

* — Wheel-tracking devices manufactured by Helmut Wind

\+ — Wheel-tracking devices replicating the Helmut Wind model.

o — Wheel-tracking device replicating the Helmut Wind model with solid, rubber wheels.

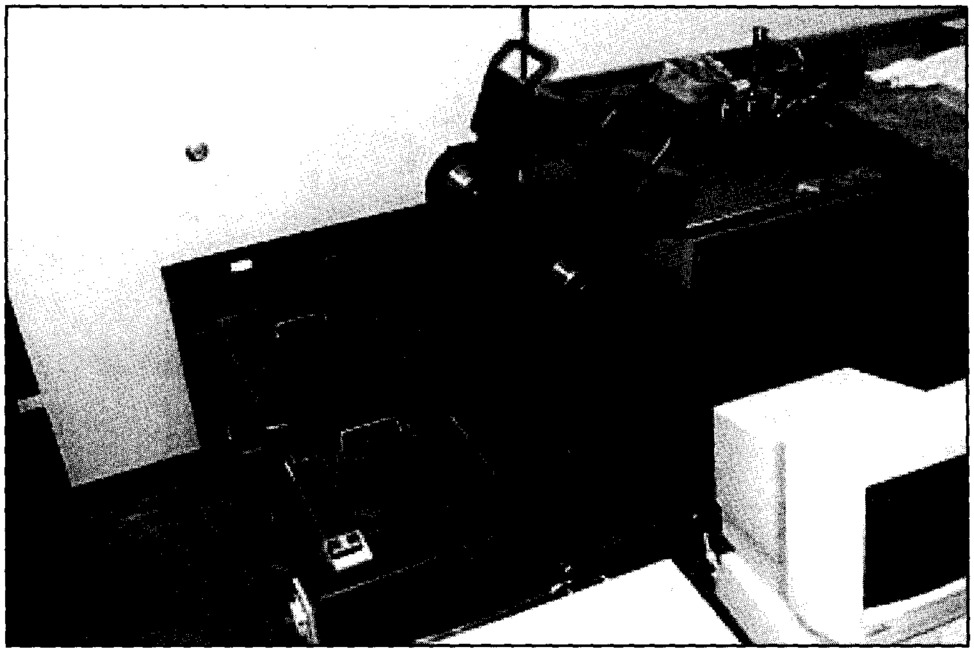


*Figure 1 Helmut Wind Manufactured Hamburg Wheel-Tracking Device*

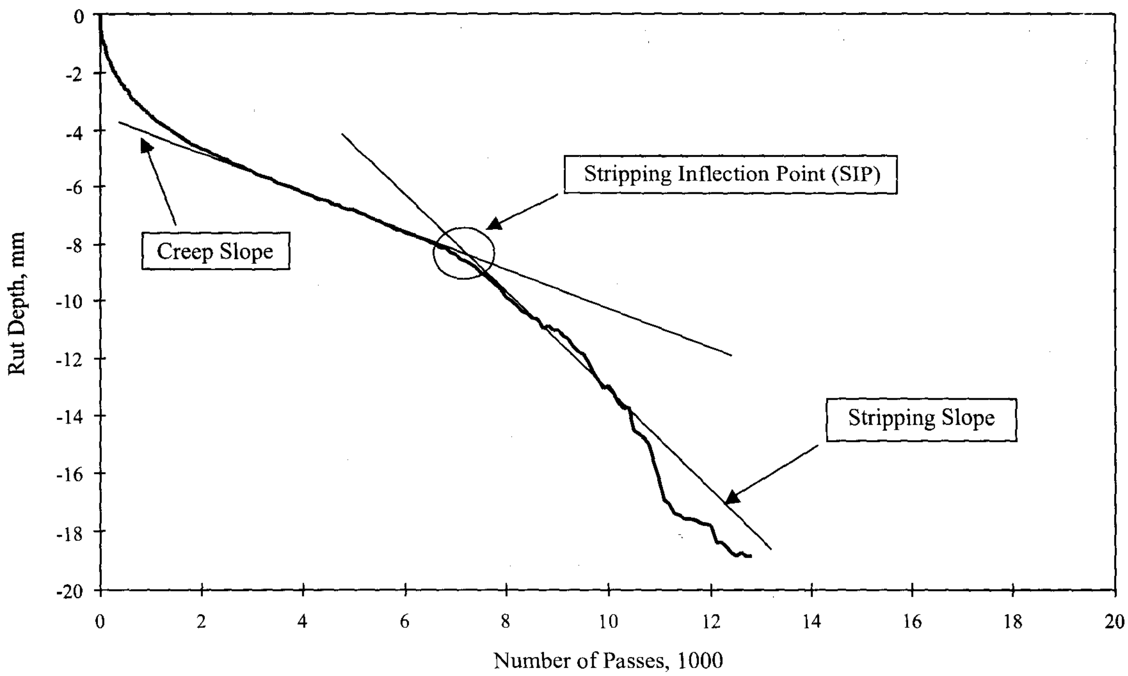
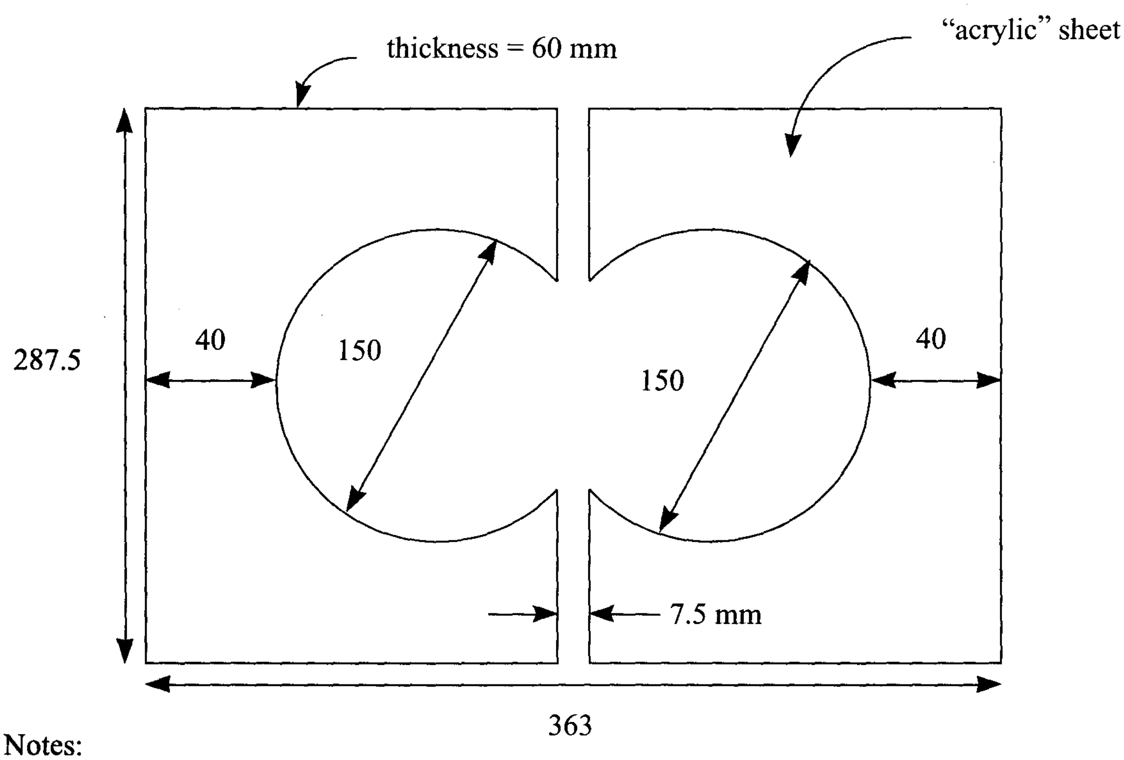



*Figure 2 Illustration of Hamburg Wheel-Tracking Test Parameters*




Notes:

1. not to scale
2. dimensions in millimeters

*Figure 3 Top View of Superpave Gyratory Specimen Configuration for the Hamburg Wheel-Tracking Device*

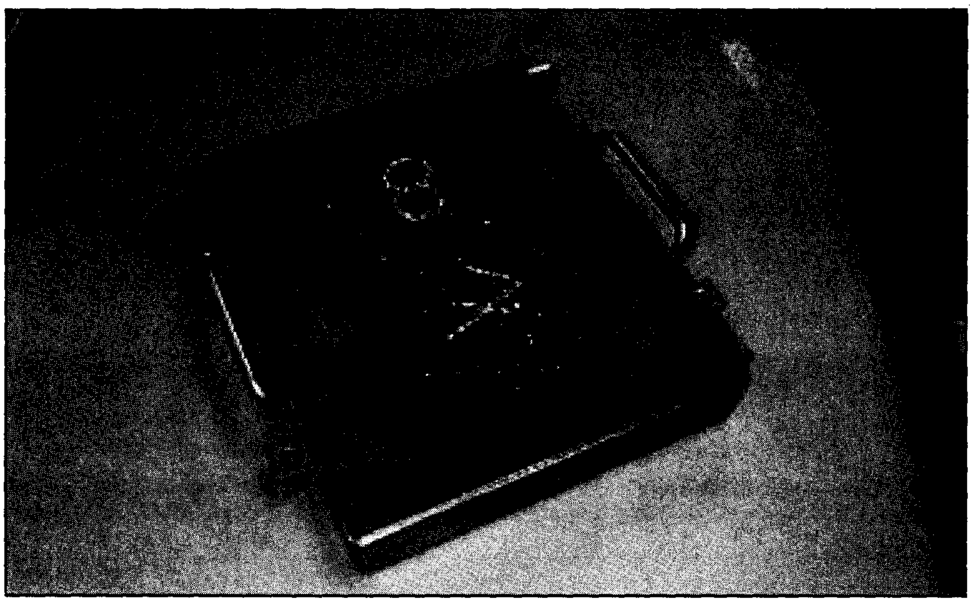


*Figure 4 Test Specimen Configuration for the Hamburg Wheel-Tracking Device with Superpave Gyratory Compacted Specimens*

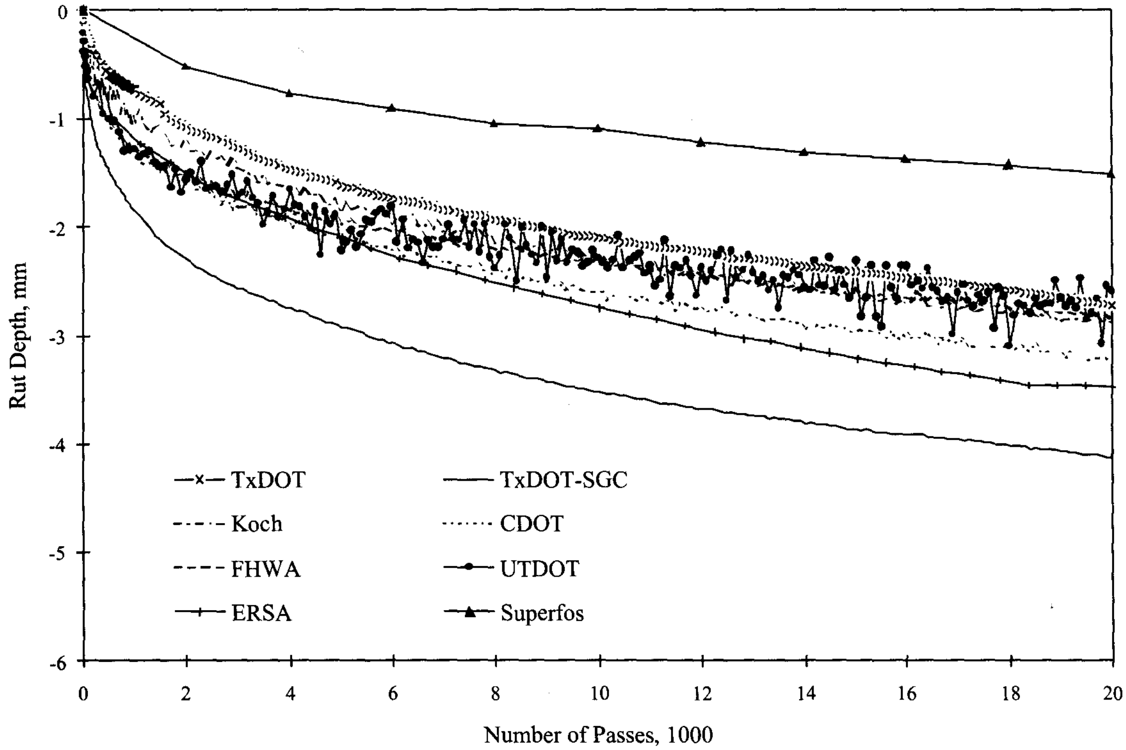



*Figure 5 Rut Depth Data of the Gravel Mixture for all the Participants*

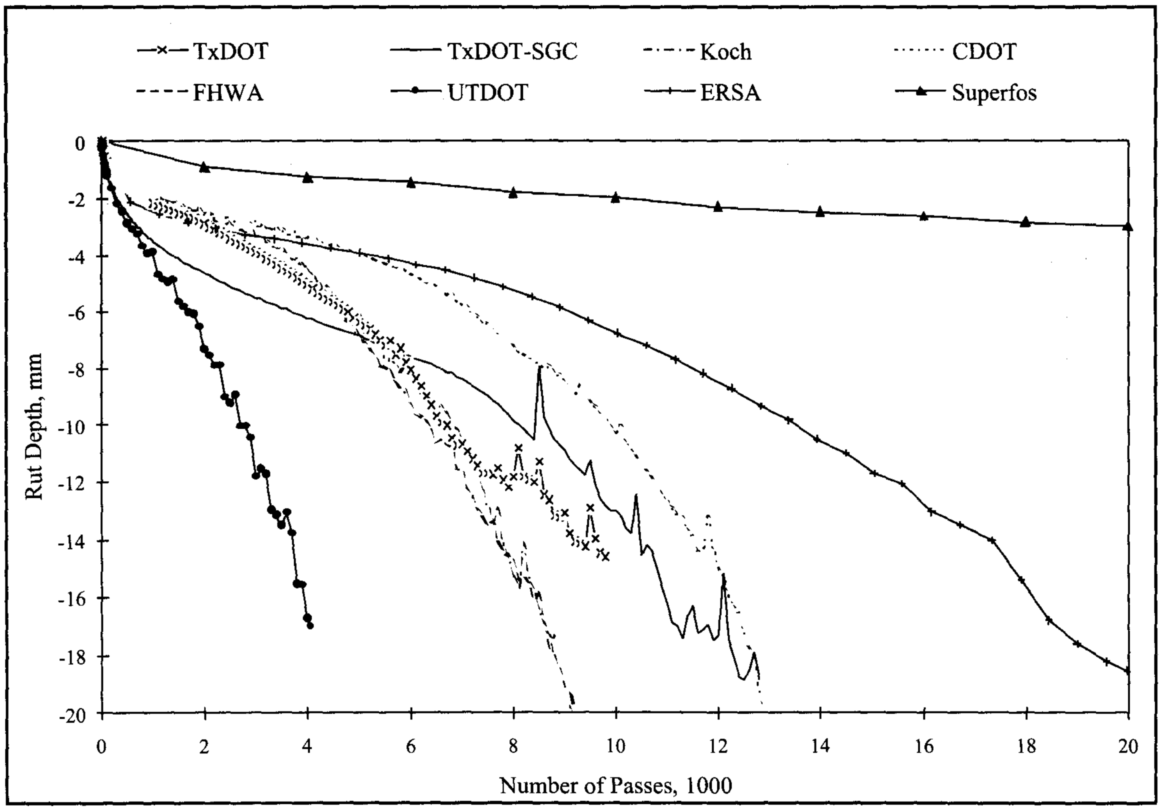



*Figure 6 Rut Depth Data for the Limestone Mixtures for all the Participants*

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