**Project No. 10-87-2B** **Final 6/06/14**

# PRECISION ESTIMATES OF AASHTO T 324, "HAMBURG WHEEL-TRACK TESTING OFCOMPACTED HOT MIX ASPHALT (HMA)"

## FINAL REPORT

Prepared for
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University of Texas - El Paso
Utah DOT - Salt Lake City
Utah DOT - Ogden Lab
Vulcan Materials Co.
Wyoming DOT Cheyenne, Wyoming
Washington State DOT, Pullman
University of Texas - Austin
University of Massachusetts – Dartmouth
Texas A&M University

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# CHAPTER 1- INTRODUCTION AND RESEARCH APPROACH

## 1.1 Background

The Hamburg wheel tracking test (HWTT) has been extensively used by the state departments of transportation and industry for identifying mixtures which are prone to rutting or moisture damage. AASHTO T 324, “Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA)” describes the procedure for testing asphalt mixture samples using the HWTT device. The method specifies the testing of submerged, compacted asphalt mixture in a reciprocating rolling-wheel device [1]. The test results provide information about the rate of permanent deformation from a moving, concentrated load. The test accommodates both linearly kneaded slab and gyratory compacted specimens. Alternatively, field cores of 150-mm, 250-mm, or 300-mm in diameter or saw cut slab specimens may be tested.

## 1.2 Problem Statement

The accurate and precise measurement of asphalt mixture properties is an important aspect of designing and selecting appropriate mixtures for various pavement projects. AASHTO T 324 has been extensively used in the recent years for detecting rutting, moisture susceptibility, or both, of asphalt mixtures. However, there is no information on the precision of the test method including the allowable differences between two replicate measurements in one laboratory or measurements in two laboratories. In addition, there are important aspects of the test that are not sufficiently specified in the test method; these include factors such as position of the wheel with respect to specimen, verification of the location of the measurements, specimen preparation and assembly, and analysis and reporting of test data. These factors could have significant effect on the HWTT measurements and performance verification of asphalt mixtures. Therefore, it is important to identify the factors causing variability of measurements and further specify their limits in the test method.

## 1.3 Research Objectives

The objective of this study was to determine precision estimates for AASHTO T 324. To accomplish this objective, the research:

1. Determined the variability of (a) the deformation measurements after specified number of load passes and (b) the creep slope for well-performing mixtures.

2. Determined the variability of (a) the number of passes to threshold deformation, (b) creep slope, (b) stripping slope, and (d) number of passes to the stripping inflection point for poorly-performing mixtures.

3. Compared the mean and variance of the measured properties of gyratory and slab specimens.

4. Compared the mean and variance of properties measured using all measurement locations with those measured using (a) all except the three middle measurement locations and (b) all except two measurement locations at each end.

5. Identified causes of variability of the test results.

6. Proposed modifications to the test method for (a) optimum utilization of the deformation measurements, (b) improvement to the specimen preparation and assembly and (c) necessary adjustments to the machine components.

## 1.4 Scope of Study

The project encompassed the following major steps:

I. Select materials and mixture design for the interlaboratory study (ILS).

II. Design and conduct the ILS:
   a. Prepare instructions for preparation and testing of the ILS specimens.
   b. Identify the laboratories participating in the ILS.
   c. Prepare gyratory and slab asphalt mixture samples.
   d. Provide the compacted samples and instructions to the participating laboratories.

III. Develop precision estimates of AASHTO T 324:
   a. Analyze data received from laboratories to determine variability of the HWTT measurements.
   b. Statistically compare variability of gyratory and slab specimens.
   c. Statistically compare variability of measurements from all measurement locations with those measured using (1) all except three middle measurement locations and (2) all except the two measurement locations at each end.
   d. Determine which variances are not statistically different and therefore can be pooled together.
   e. Prepare a precision statement for AASHTO T 324.

IV. Conduct a research study to identify the causes of variability of the AASHTO T 324 test results.

V. Identify measures for improving accuracy and precision of the test results.

VI. Prepare findings and proposed changes to AASHTO T 324 and the HWTT device based on the research results.

# CHAPTER 2- DESIGN AND CONDUCT OF THE STUDY

The availability of precision estimates for AASHTO T 324 test method is essential for reliable laboratory determination of the rutting and moisture susceptibility of asphalt mixtures. In addition, there are aspects of the test method that are not yet standardized, which could be sources of variability. These sources need to be identified and further specified in the test method. In this respect, an interlaboratory study was designed and conducted in which variability of the test for two different types of mixtures and two methods of compaction was examined. The following sections present the details of the ILS.

## 2.1 Materials Selection

Since determining the level of rutting and moisture susceptibility of HMA is a main aspect of AASHTO T 324, two mixtures with different levels of rutting and moisture susceptibility were selected for the study. The rutting and moisture sensitive (WY) mixture, which was mixed and compacted in laboratory, consisted of 9.5 mm nominal maximum aggregate size (NMAS) gravel stones from Wyoming and PG64-22 asphalt binder. The rutting and moisture resistant (Field) mixture was produced at the Aggregate Industries plant in Maryland and consisted of 19.0 mm NMAS limestone aggregates and PG 64-22 asphalt binder. Table 2-1 provides the aggregate gradation and asphalt content of the two mixtures.

**Table 2-1- volumetric properties of Wyoming laboratory and Maryland field mixtures**

| Sieve Opening (mm) | US Sieve Size | % Passing Maryland (Field) | % Passing Wyoming (WY) |
|---|---|---|---|
| 25 | 1” | 100 | 100 |
| 19 | 3/4" | 98 | 100 |
| 12.5 | 1/2" | 87 | 97 |
| 9.5 | 3/8" | 74 | 87 |
| 4.75 | # 4 | 37 | 51 |
| 2.36 | #8 | 27 | 35 |
| 1.18 | # 16 | 20 | 25 |
| 0.60 | # 30 | 15 | 17 |
| 0.30 | # 50 | 10 | 13 |
| 0.15 | #100 | 7 | 9 |
| 0.075 | #200 | 5.1 | 6.2 |
| Aggregate Water Absorption | | 0.8 | 0.6 |
| $P_b$, % | | 4.5 | 4.4 |
| Gmm | | 2.510 | 2.459 |

## 2.2 Test Samples

Given that AASHTO T 324 allows testing of both slab and gyratory compacted specimens, the effect of specimen type on the test results was also investigated. For this purpose, both 150-mm x 60-mm Superpave gyratory specimens and 265.5- x 331- x 60-mm slab specimens were prepared for the study.

## 2.3 Test Machine

The wheel track testing machines included in the ILS were either one-wheel or two-wheel Hamburg Wheel Track Testers manufactured by Precision Metal Works (PMW). Linear variable displacement transducers (LVDTs) measure deformation at eleven locations referred to as measurement locations along the specimen. The Location 1 is the furthest from the wheel gear and location 11 is the closest to the wheel gear as shown in Figure 2-1. Measurement location 6 is at the mid-point of the test specimen by design. In case of gyratory specimens, measurement location 6 should be at the joint of the two adjoining samples. The wheel makes 52 ± 2 passes across the specimen per minute. The maximum speed of the wheel (0.305 m/s) is reached at the midpoint of the specimen.

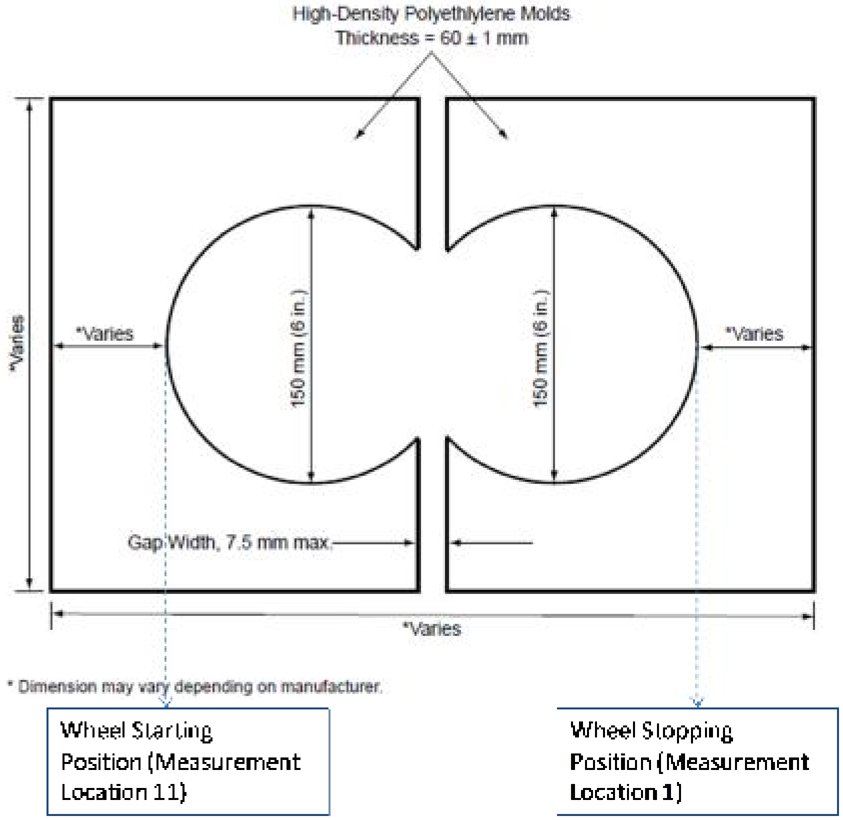


**Figure 2-1- Starting and stopping positions of HWTT wheel and the first and last measurement locations shown on the schematic of the HWTT mounting system from AASHTO T 324 [1]**

## 2.4 Specimen Preparation

Preliminary work was conducted to determine the appropriate weight of the mixtures for compacting gyratory and slab specimens with 7.0% ± 1.0% air voids based on the original job mix formulas. The gyratory samples were prepared using an IPC gyratory compactor (Servopac) following AASHTO T 312 [2]. The slabs were compacted using a PMW linear kneading slab compactor. WY samples were mixed at 165°C and subsequently conditioned at 135°C for four hours according to AASHTO R 30 [3] before compaction. Field samples were reheated to 135°C before compaction. All samples were compacted to the height of 60 mm.

A total of 280 gyratory and 60 slab specimens were compacted for shipment to the participating laboratories. Since the percent water absorption of aggregates of both Field and WY mixtures were less than 1.5%, the maximum specific gravities (Gmm) of the both mixtures were determined according to the weighing in water method (Method A) described in Section 9 of AASHTO T 209 [4]. The Gmm of the Field and WY mixtures are provided in Table 2-1. The bulk specific gravity of the samples was measured according to AASHTO T 166 (SSD) [5] and AASHTO T 331 (Corelok) [6] prior to sending the specimens to the participating laboratories. The average absorption of Field samples was 1.49 % and of WY samples was 1.89%. Since water absorption of the compacted samples was less than 2%, the target air voids of 7.0% ± 1.0% was achieved based on the AASHTO T 166 procedure. The samples were dried using CoreDry® to a constant weight before they were packaged for shipment.

## 2.5 Selection of Laboratories for ILS

State DOT and industry laboratories operating the HWTT device on a regular basis were contacted to participate in the study. All participating laboratories were AASHTO accredited for test methods related to AASHTO T 324. Thirty five laboratories agreed to participate in the ILS from which 28 laboratories returned results on at least one specimen type (gyratory and slab).

## 2.6 Specimen Shipment

Each laboratory received four gyratory and two slab specimens from each of the WY and Field mixtures. Slab specimens were only sent to the 15 laboratories having the capability of testing slabs. The shipment of the two different mixture types was done at a 2-month interval to allow receipt of the results from the first set of materials before the second set of specimens were sent. The reason for sending the compacted samples, rather than raw materials, was to separate the variability in sample preparation from the variability associated with the test configuration and test equipment.

## 2.7 Instructions for Interlaboratory Study

Participants were provided with instructions and data sheets for performing the tests and collecting the data. Since preparation of gyratory and slab specimens is different, different sets of instructions were prepared for the two types of specimens. The preparation of gyratory specimens by the laboratories included cutting across the height of the specimens so that when the two cut specimens were adjoined, there would be a gap of no more than 7.5 mm between the two polyethylene molds holding the specimens in place (Figure 2-1). The laboratories were also asked to measure the air voids of the gyratory specimens before preparing them for the wheel track test. The slab specimens were surrounded by plaster of Paris to form their holder. Air voids measurements were not requested for the slab specimens.

To reduce the size of data files collected during testing, the laboratories were asked to follow these data sampling intervals: every 20th cycle for the first 1000 cycles, every 50th cycle for the second 4000 cycles, and every 100th for the remainder of the test (up to 20,000 cycles).

In addition to the output data file, the laboratories were asked to report back (a) the rut depths at pass counts of 5, 10, 15, and 20 thousands; (b) the creep slope, (c) the stripping slope, (d) the number of cycles to threshold deformation, and (e) the number of passes to stripping inflection point. A copy of each set of instructions for preparing and testing of gyratory and slab specimens and the data sheets for entering measurement results are provided in Appendix A.

# CHAPTER 3- INTERLABORATORY STUDY TEST RESULTS AND ANALYSIS

Prior to determining the precision estimates of the measurements from the results of the ILS, graphical comparisons of the averages and standard deviations of the AASHTO T 324 test properties for different mixture types, specimen types, wheel side, pass number, deformation threshold level, and measurement locations were performed. The test properties, number of data sets, and observed results are explained in the following sections.

## 3.1 Test Properties

The following test properties were computed from the data received from the participating laboratories and compared for the two mixtures and the two specimen types.

- Deformation (rut depth) at 5000, 10,000, 15,000, and 20,000 wheel passes
- Number of wheel passes to 6 mm and 12 mm rut depth
- Creep slope
- Stripping slope
- Pass number and deformation at the Stripping Inflection Point

## 3.2 Number of Data Sets

The following number of laboratories provided completed data sets for the four specimen types (two mixtures x two specimen types):

- Nineteen laboratories sent complete sets of data on the properties of the gyratory compacted Field mixture.
- Seven laboratories sent complete sets of data on the properties of the slab compacted Field mixture.
- Twenty-two laboratories sent complete sets of data on the properties of the gyratory compacted WY mixture.
- Eleven laboratories sent complete set of data on the properties of the slab compacted WY mixture.

Table 3-1 and Figure 3-1 show the number of laboratories that provided results for each combination of material and specimen type. Also shown in Table 3-1, are the number of wheels (two or one) on the Hamburg wheel track tester in each participating laboratory.

**Table 3-1- Mixture/specimen type associated with the results sent and the corresponding number of HWTT wheels for each participating laboratories**

| Laboratories | No. Of Wheels | Field-Gyratory | Field-Slab | WY-Gyratory | WY-Slab |
|---|---|---|---|---|---|
| Alliance Geotechnical Group | 1 | √ | √ | √ | √ |
| AMEC Earth & Environmental | 1 | √ |  | √ |  |
| APAC TX, Inc. | 1 | √ |  | √ |  |
| California DOT, Sacramento, CA | 2 | √ | √ | √ | √ |
| Colorado DOT, Denver, CO | 2 |  |  | √ | √ |
| Florida DOT, Gainesville, FL | 2 | √ |  | √ | √ |
| Iowa DOT Ames, IA | 2 |  | √ |  |  |
| Jones Bros. Dirt & Paving Contractors, Inc. | 1 | √ |  | √ |  |
| Louisiana State University | 2 | √ |  | √ |  |
| Mathy Technology & Engineering Services | 2 | √ |  | √ |  |
| Nactech | 2 |  | √ | √ | √ |
| Oklahoma DOT - Oklahoma City | 2 | √ |  | √ |  |
| Pave Tex | 2 | √ |  | √ |  |
| Road Science LLC | 2 | √ | √ | √ | √ |
| Texas A&M University | 2 |  |  | √ |  |
| Texas DOT - Childress District | 2 |  |  | √ |  |
| Texas DOT – Paris | 1 |  |  | √ |  |
| Texas DOT - San Marcos | 2 | √ |  |  |  |
| Texas DOT - Uvalde Field Lab | 1 | √ |  |  |  |
| Kansas State University – Manhattan | 2 | √ |  | √ |  |
| U. of Massachusetts - Dartmouth | 1 | √ |  | √ |  |
| University of Texas - Austin | 2 | √ |  |  |  |
| University of Texas - El Paso | 2 |  | √ |  |  |
| Vulcan Materials Co. | 1 | √ |  | √ | √ |
| Washington State DOT, Pullman | 2 |  |  | √ | √ |
| Wyoming DOT Cheyenne, Wyoming | 2 | √ |  |  |  |
| Utah DOT – Salt Lake City | 2 |  |  | √ | √ |
| Utah DOT – Ogden Lab | 2 |  |  |  | √ |

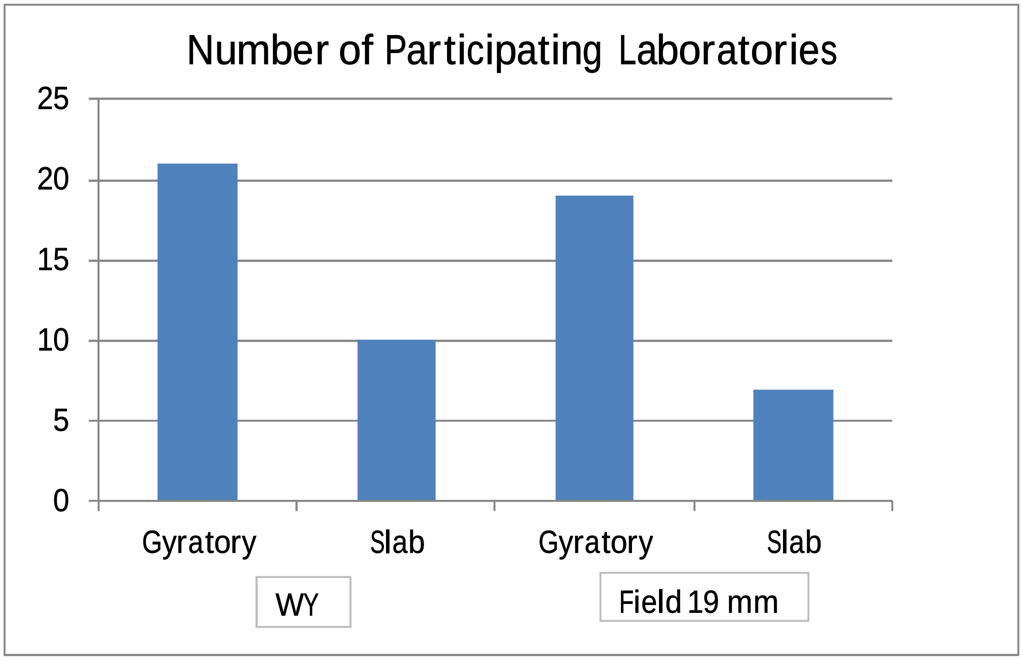


**Figure 3-1- Number of laboratories that provided results**

## 3.3 Results of the ILS

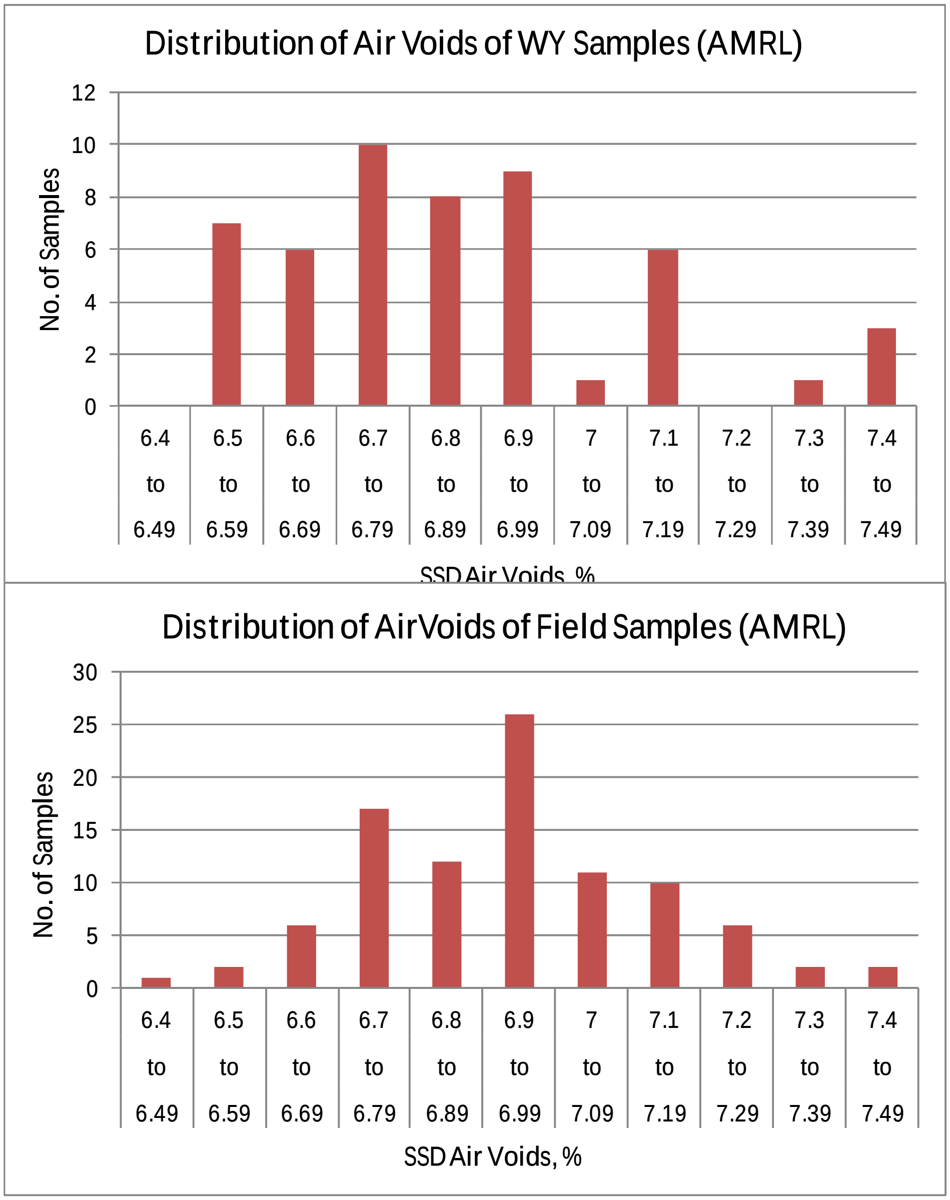
The results received from the participating laboratories include the measurements of the bulk specific gravity of gyratory specimens and HWTT properties of the gyratory and slab samples. These results are discussed in the following sections.

## 3.4 Bulk Specific Gravity Results

The statistics of the air voids measured prior to shipment of samples and the air voids measured by participating laboratories for both WY and Field mixtures using SSD and Corelok are shown in Table 3-2. The average water absorption of the WY and field mixtures were 1.89% and 1.49%, respectively, which were under 2%. Therefore, for both mixtures, the 7% ± 1% air voids specified in AASHTO T 324 for the HWTT samples was achieved based on the SSD air voids. The measurement of air voids by AMRL were made 24 hrs after compaction; for the WY samples, they averaged 6.86% and ranged between 6.51% and 7.49%; for the Field samples, they averaged 6.94% and ranged between 6.48% and 7.52%. The air voids measured by participating laboratories averaged 6.44% for WY samples and ranged from 5.72% to 7.00%. For Field samples, the average air voids was 6.86%, ranging between 6.25% and 7.45%. Despite the difference between average SSD values of AMRL and the participating laboratories for the WY samples, the Corelok values were similar (averaged 7.73% and 7.54% respectively), which indicates that the difference in the SSD values may be due to the subjectivity in SSD determination. The distribution of SSD air voids for both mixtures, measured by AMRL, are shown in Figure 3-2.

**Table 3-2- Air voids of Field and WY samples measured by AMRL and participating laboratories**

| Mixture | Lab | Test | Average | STD | Min | Max | N |
|---|---|---|---|---|---|---|---|
| WY | AMRL | SSD | 6.86 | 0.24 | 6.51 | 7.49 | 51 |
| | | Corelok | 7.73 | 0.17 | 7.42 | 8.15 | 51 |
| | Participating Labs | SSD | 6.44 | 0.32 | 5.72 | 7.00 | 62 |
| | | Corelok | 7.54 | 0.36 | 6.95 | 8.32 | 22 |
| Field | AMRL | SSD | 6.94 | 0.19 | 6.48 | 7.52 | 95 |
| | | Corelok | - | - | - | - | - |
| | Participating Labs | SSD | 6.86 | 0.27 | 6.25 | 7.45 | 63 |
| | | Corelok | 8.05 | 0.37 | 7.60 | 8.70 | 19 |


Distribution of Air Voids of WY Samples (AMRL)

Distribution of AirVoids of Field Samples (AMRL)

**Figure 3-2-Distribution of SSD air voids of WY samples (top) and Field samples (bottom) measured at AMRL**

Evaluation of the difference between the SSD and Corelok values in Table 3-2 might indicate the method that is more reliable for measuring the air voids of HWTT samples. For the WY samples, at 7% SSD air voids, Corelok air voids were 0.8% higher (7.8%) as measured at AMRL. The difference was similar (0.9%) when measured by participating laboratories. The difference between Corelok and SSD air voids for Field samples conducted by participating laboratories was 1.1%. The Corelok air voids of the Field mixture were not measured at AMRL due to the press for time to send the samples within 48 hrs after the compaction. Figure 3-3 shows the Corelok and SSD air voids from measurements made at AMRL (only WY mixture) and Figure 3-4 shows the Corelok and

SSD air voids from measurements made by participating laboratories (both WY and Field mixtures). As indicated from the figures, the SSD and Corelok air voids are distinctly different for both mixtures. Considering the level of absorption of 1.89% and 1.49% of WY and Field mixtures, it is suggested that bulk specific gravity of samples with absorption level of above 1.0 % to be measured using Corelok method.

It is important to note that the data shown in Figure 3-3 includes air voids of samples that were prepared for the study but were either not sent to the participating laboratories or sent but not tested by any laboratories. Examples of these samples are those with SSD air void values between 6.2% and 6.5% in Figure 3-3. On the other hand, Figure 3-4 includes only air voids of samples that have been measured by both SSD and Corelok methods. Not all laboratories measured bulk specific gravity of the samples according to both SSD and Corelok; therefore, less number of data points than the number of sent samples are included in Figure 3-4.

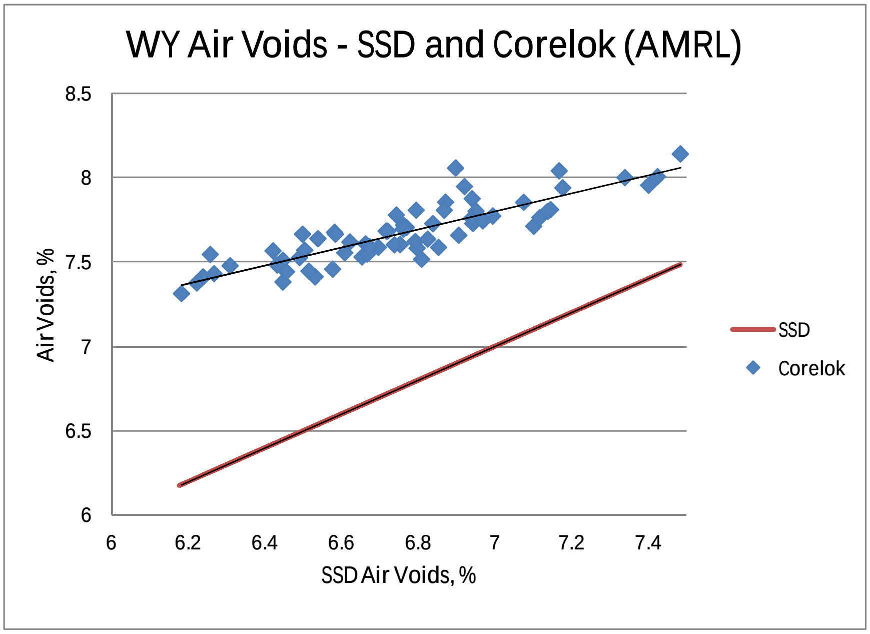


**Figure 3-3-Air voids of WY samples using SSD and Corelok measured at AMRL**

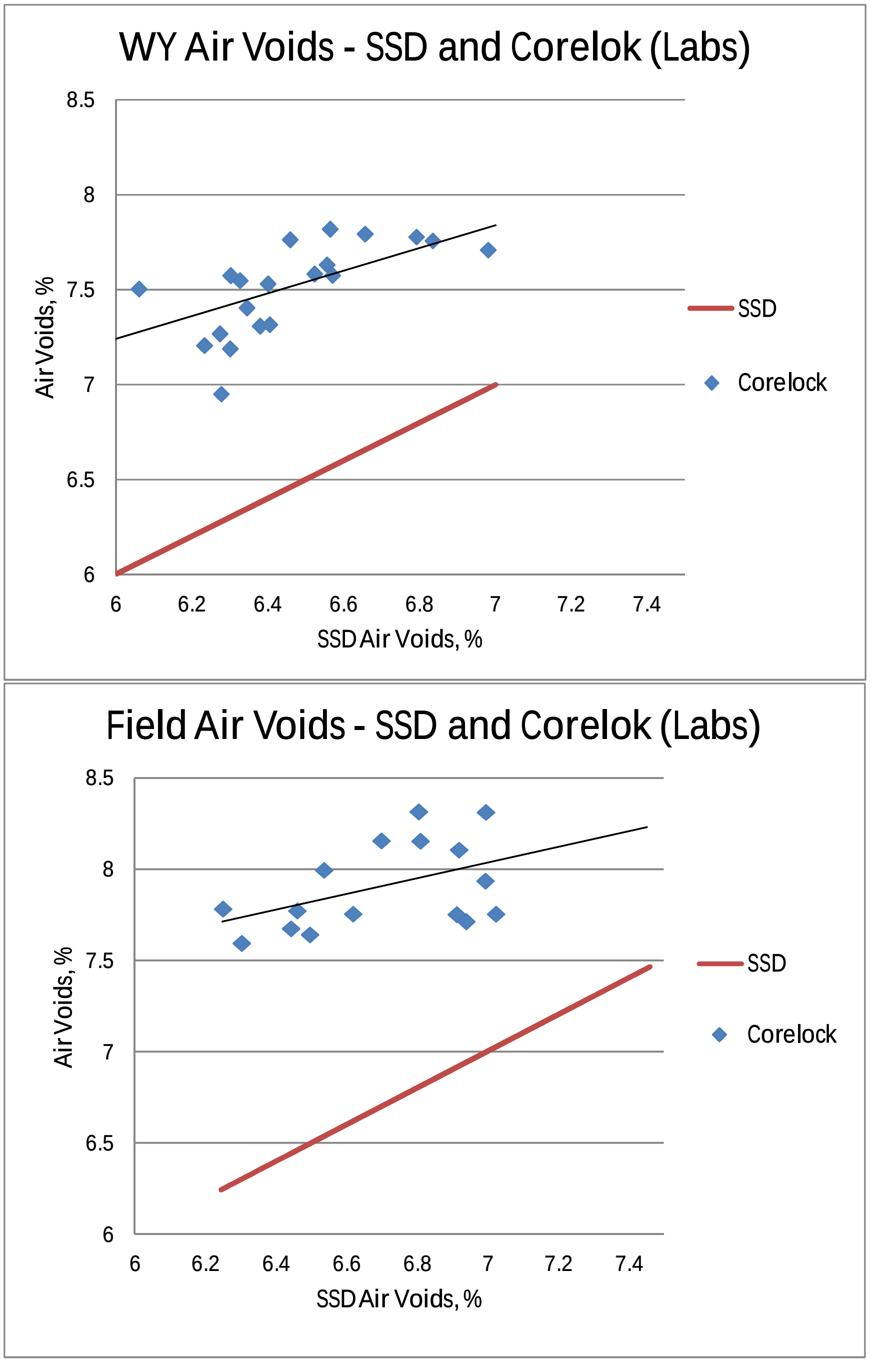


**Figure 3-4-Air voids of WY Samples (top) and Field samples (bottom) using SSD and Corelok measured at participating laboratories**

## 3.5 Deformation versus Number of Passes

Graphs of average deformation versus number of passes for the four material/specimen combinations from all laboratories are provided in Figure 3-5. Graphs of the individual tests are provided in Appendix B. Some general observations can be made from the graphs:

1. The Field mixture has a small deformation versus number of passes (low creep slope).
2. Other than two outlier results, the Field mixture does not exhibit an inflection point. Loosening of the bolts holding specimens in test trays was reported by the laboratories as the reason for the outlier data.
3. The WY mixture clearly shows an stripping inflection point.
4. The inflection point of the WY mixture occurs after a greater number of passes in the slab specimens than in the gyratory specimens.
5. In each mixture, slab and gyratory specimens show similar trends, but the deformation curves of slabs seem less noisy than those of gyratory specimens.
6. For the WY mixture, the stripping slopes (2nd slope) are generally larger in gyratory specimens than in slab specimens.

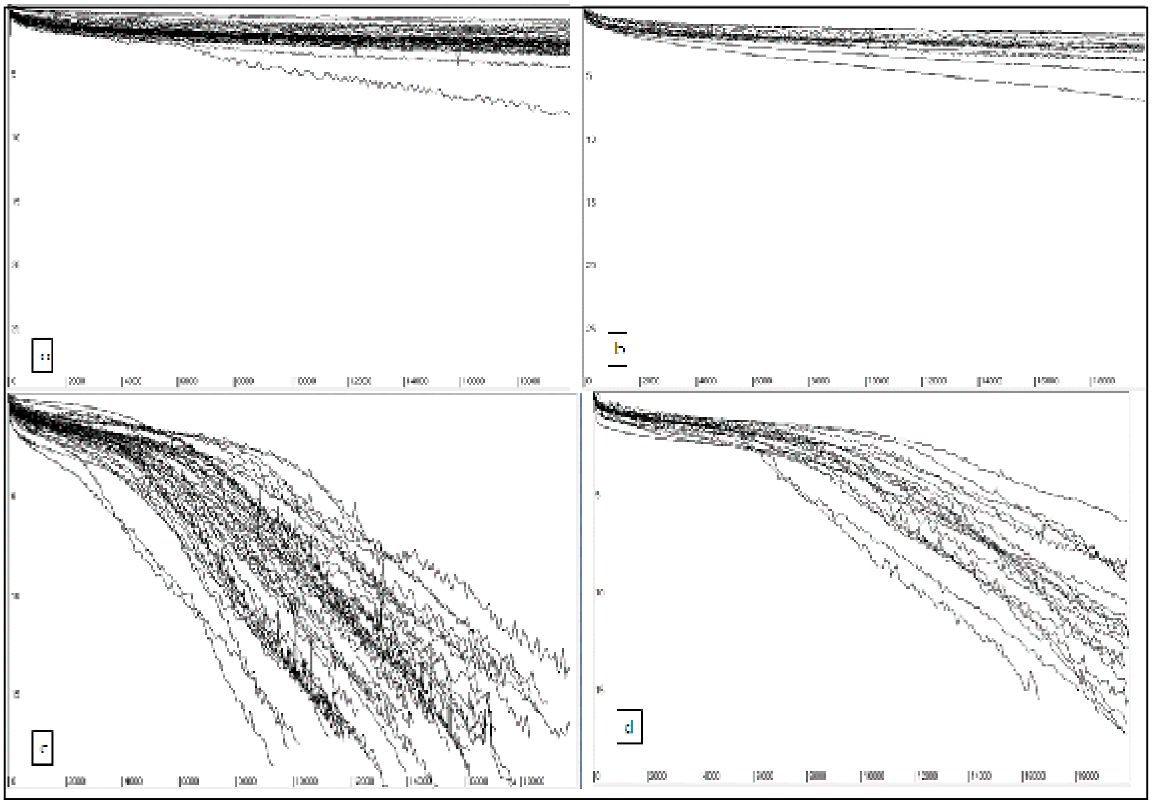


**Figure 3-5- Deformation (mm) versus number of passes for (a) Field gyratory (b) Field slabs (c) WY gyratory (d) WY slabs (c) received from laboratories**

## 3.6 Deformation versus Measurement Location

Figure 3-6 shows the deformation profile from the last wheel pass at the measurement location 11 of the HWTT for the four mixture/specimen combinations. The x-axis shows the measurement locations and the y-axis shows the deformation measurements in mm. The top and bottom graphs for each combination show the measurements from the right and left wheels in a two-wheel machine or replicate measurements in a one-wheel machine. Several observations can be made from the profiles:

1. For the well-performing Field mixture, the deformation profiles of gyratory and slab specimens appear similar.

2. For the poorly-performing WY mixture, as indicated from the deformation profiles, the deformations from different measurement locations are more consistent for the slab specimens than for the gyratory specimens.

3. The maximum deformations for WY gyratory specimens mostly occur at measurement locations 7 and 8, rather than measurement location 6, which is the midpoint.

4. For the WY gyratory specimens, a maximum deformation typically occurs at or around the midpoint of the specimen (Measurement locations 6, 7, or 8). However, for the slabs only a few profiles show a maximum deformation around the center. This might indicate that the midpoint of gyratory specimens, where the two samples join, is the weakest part of the test specimen.

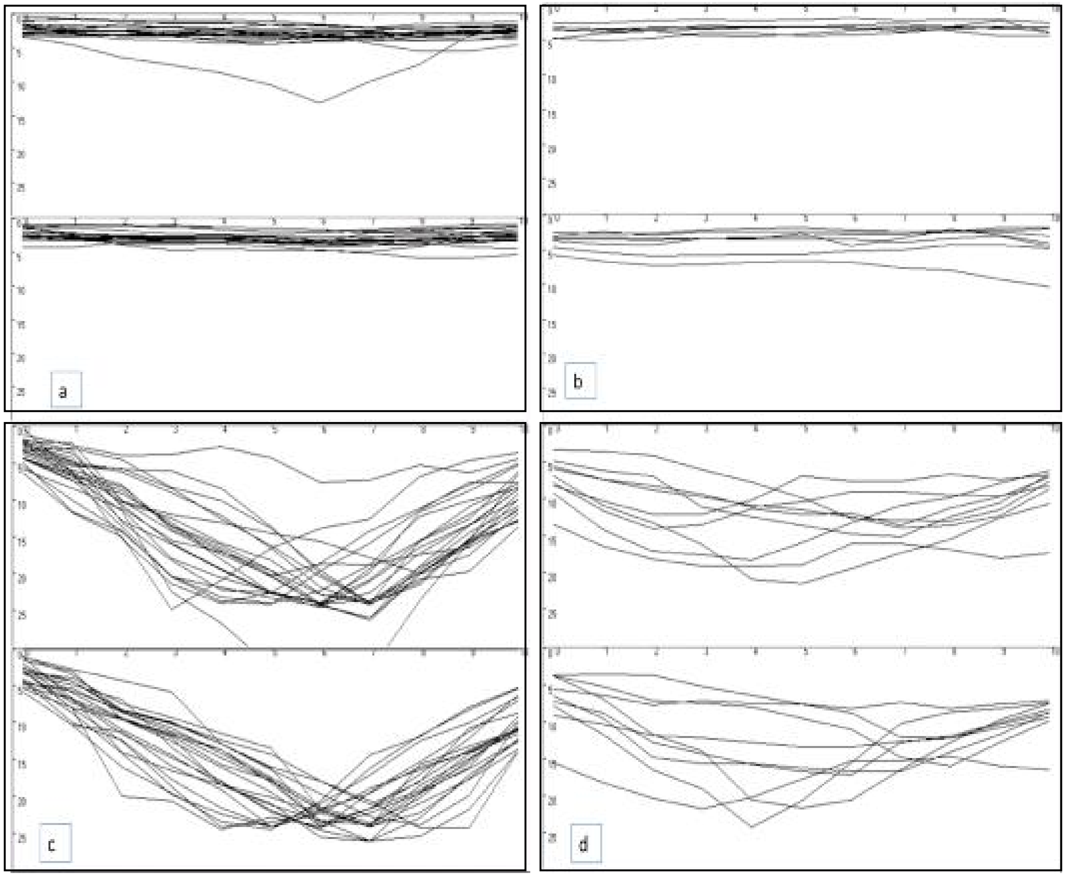


**Figure 3-6-Deformation profiles of (a) Field gyratory (b) Field slabs (c) WY gyratory (d) WY slabs received from laboratories**

## 3.7 Difference in Deformation from Right and Left

The top and bottom of Figure 3-7 show the measurement locations versus deformation (deformation profile) and number of passes versus deformation (deformation history) for the WY gyratory mixture reported by one of the laboratories. As indicated from the deformation profile (top), the magnitudes of the maximum deformations of the left and right wheels are the same; however, the maximum deformation occurred at measurement location 6 for the right wheel and measurement location 9 for the left wheel. This shows that either replicate samples do not always wear similarly or the measurement locations are not the same on the two sides of the machine. The deformation history from measurement location 7, shown at the bottom of the figure, indicates that the deformations from right and left wheels are very different. Similar problems can be observed from deformation profiles and deformation history of the mixtures from individual laboratories in Appendix B.

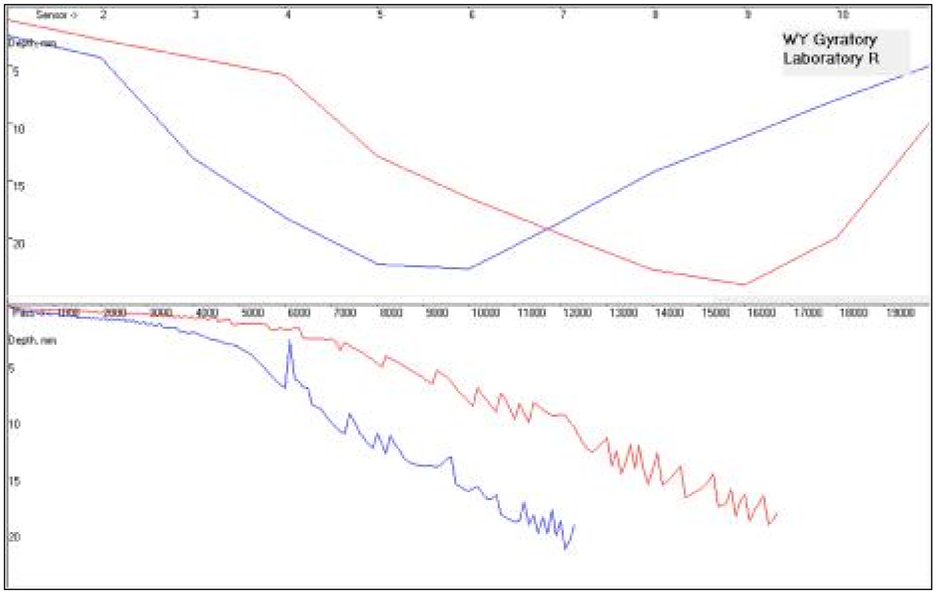


**Figure 3-7-Deformation versus measurement locations and versus number of passes for the gyratory specimens of WY reported by Laboratory R**

## 3.8 Difference in Laboratory Results

**Close examination of the deformation history (deformation versus number of passes) and deformation profiles (deformation versus measurement location) presented in the previous sections found that the results could be grouped into two categories: 1) a group of laboratories with very similar deformation profiles to each other and 2) a group of laboratories with different deformation**

**profiles from each other and from those in the first group.**

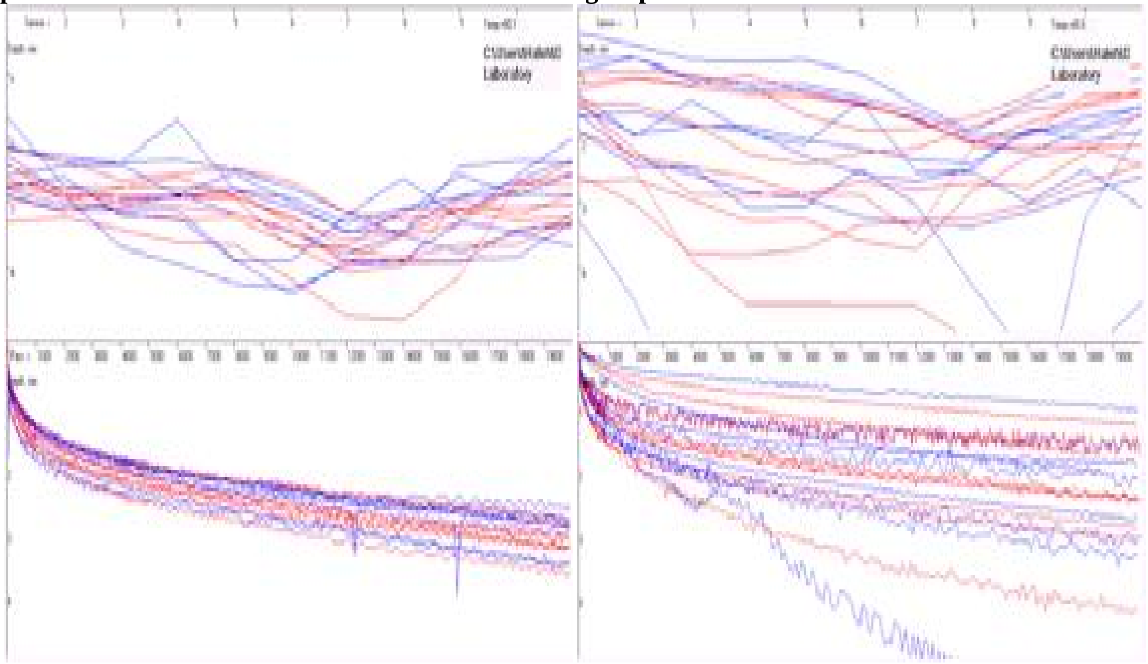


Figure 3-8Figure 3-8 shows the deformation measurements of gyratory specimens of the Field mixture. The left graph shows the deformation measurements from the laboratories with similar results and the right graph shows the deformation measurements from the laboratories with different results from each other and from those in the first group. The large spread in the deformation measurements of the laboratories in the second group suggests that there are problems with either the calibration or alignment of the HWTT device or the specimen-mold assembly in those laboratories. This finding emphasizes the need for regular calibration check of the machines and standardization of the specimen-mold assembly to reduce variability of the data.

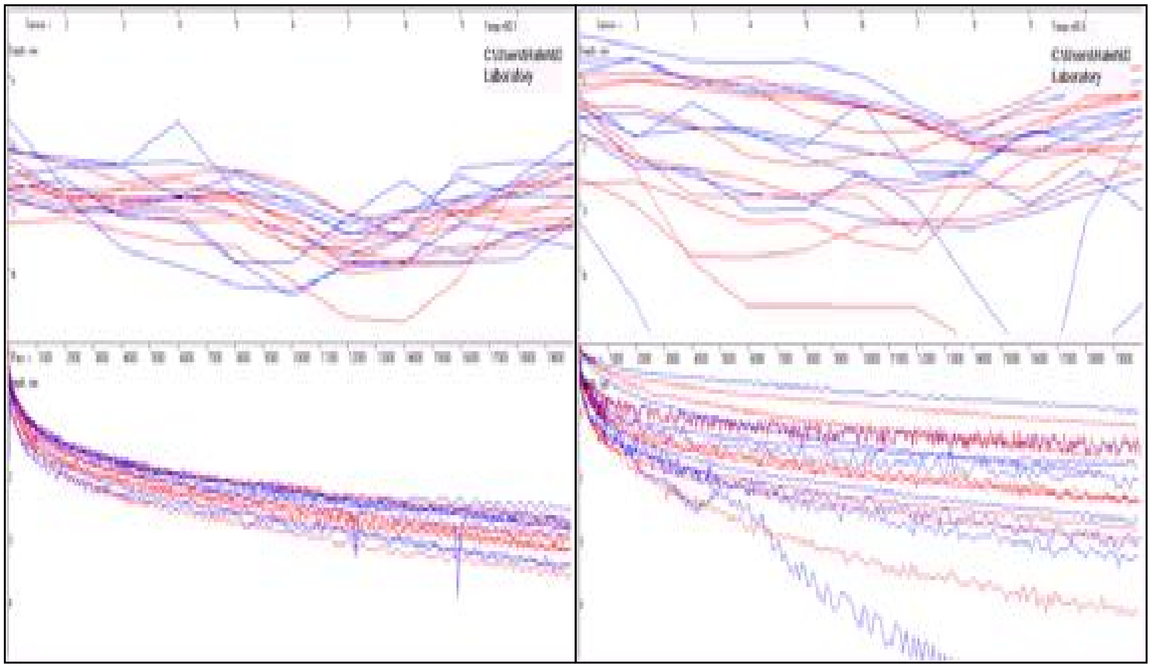


**Figure 3-8-Deformation profile and deformation history of the gyratory specimens of Field mixture; the left graph shows the laboratories with similar results and the right graph shows laboratories with different results from each other and from laboratories in the left graph**

## 3.9 Percent Error in Measurement Location Data

Figure 3-9 shows the % error in deformation signals caused by electrical and mechanical interferences (noise) in HWTT, determined from laboratories' data. The percent error is the same as coefficient of variation, which is standard deviation of signal amplitude divided by the mean signal amplitude, times 100. The Percent error is the reciprocal of Signal to Noise Ratio (SNR), which describes how much noise is in the output of a device, in relation to the signal level.

To evaluate the quality of the HWTT data, a threshold % error needed to be established. From the analysis of the data, it was experienced that when percent error is less than 5%, the least amount of filtering and averaging was required for determining the properties of the test. In addition, several literatures show that a typical SNR threshold for an acceptable signal quality is 20 [7, 8, 9], which is equivalent to 5% signal error (inverse of 20). Therefore, a threshold value of 5% was selected for evaluating the quality of the signal data.

The graphs in Figure 3-9 represent the average percent error from readings of measurement locations 4 through 8 of Passes 5,000 through 10,000 of the four mixture/specimen types. As indicated from the figure, the % error is as small as 1% in one laboratory and as large as 25% in another laboratory. Considering the acceptable percent error of 5%, this threshold has been exceeded in more than 30% of the laboratories, especially for the WY mixture.

The percent error in deformation signals could be a major source of measurement variability. When the noise level is low, the parameter of the test could be easily determined without major manipulation of the signal data. However, if the noise in the data is high, significant smoothing and averaging are required to determine the value of the parameters. This would result in estimated value of the property that is different from the actual value and therefore, causing high variability of the measured properties especially when measured in different laboratories. Reducing the % error in the signal data is another step in reducing variability of the measurements. Figure 3-10 shows the data from laboratory F. While the deformation profiles and history of the right and left wheels are very similar; however, the % error of the deformation signals from the two wheels is very high.

**Figure 3-9- % error in sensor data corresponding to the deformation measurements of the four material/specimen types**

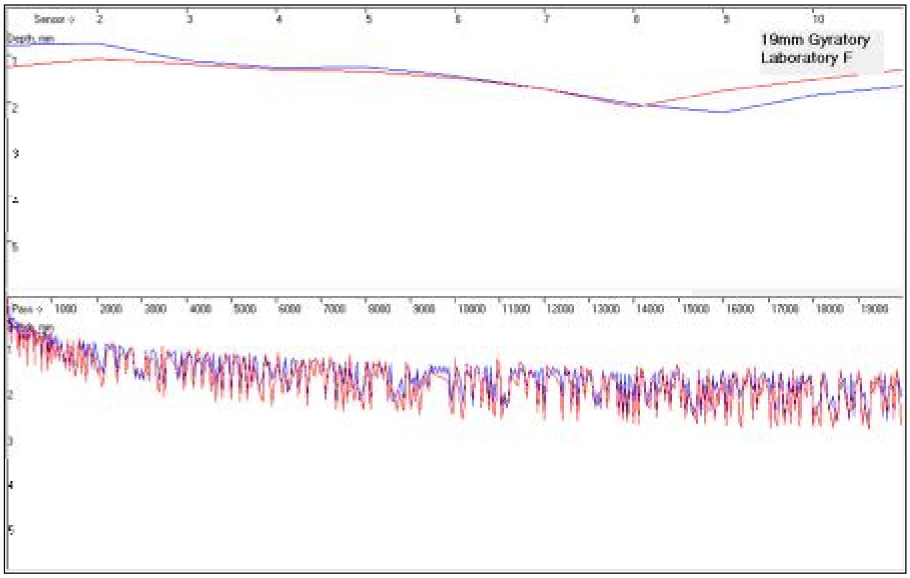


**Figure 3-10- Deformation profiles and deformation history for gyratory specimens of WY, Laboratory F**

## 3.10 Comparison of Properties of Various Mixture/Specimen Types

The deformation curves in Figure 3-6 demonstrate that the preferred HWTT measurement parameters for the well-performing and the poorly-performing mixtures are likely to be different.

For well-performing mixtures, where the test could be continued for specified number of passes, the deformation at those passes is a meaningful test parameter as is the slope of the deformation curve before the end of the test, also known as creep slope.

For the poorly-performing mixtures, where deformation is large and the duration of the test is ultimately limited by the degree of deformation, the number of cycles to a specified threshold deformation is a meaningful test parameter. Additionally, since poorly-performing mixtures have a clear inflection point, the slope of the deformation curve before and after the inflection point (the creep and striping slopes) and the number of cycles to the inflection point are also useful test parameters for poorly-performing mixtures.

It is important to note, however, that the choice of test parameters for a given mixture is not made *a priori*, but is based on the observed performance of the mixture in the HWTT.

### 3.10.1 Comparison of Properties of Gyratory and Slab Specimens of Field Mixture

The properties of the well-performing mixture include creep slope, deformation at specified number of passes, and deformation at the end of the test. The comparison of the properties of the gyratory and slab specimens is explained as follows.

### 3.10.1.1 Creep Slopes of Gyratory and Slab

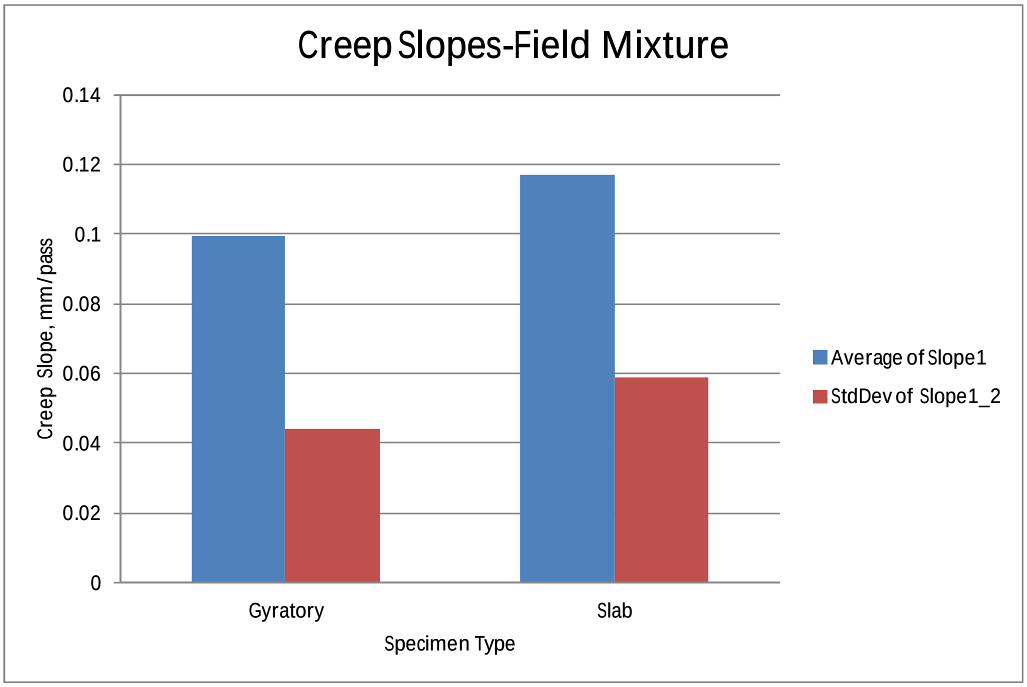


Figure 3-11shows the average and standard deviation of the creep slope for the gyratory and slab specimens of the well-performing Field mixture. For this mixture, the creep slope represents the rate of deformation before the end of the test. As indicated from the figure, the average and standard deviation of creep slope of gyratory specimens is only slightly smaller than those of slab specimens. This suggests that for well-performing mixtures, gyratory specimens may provide a better estimate of rutting performance of the mixture than slab specimens.

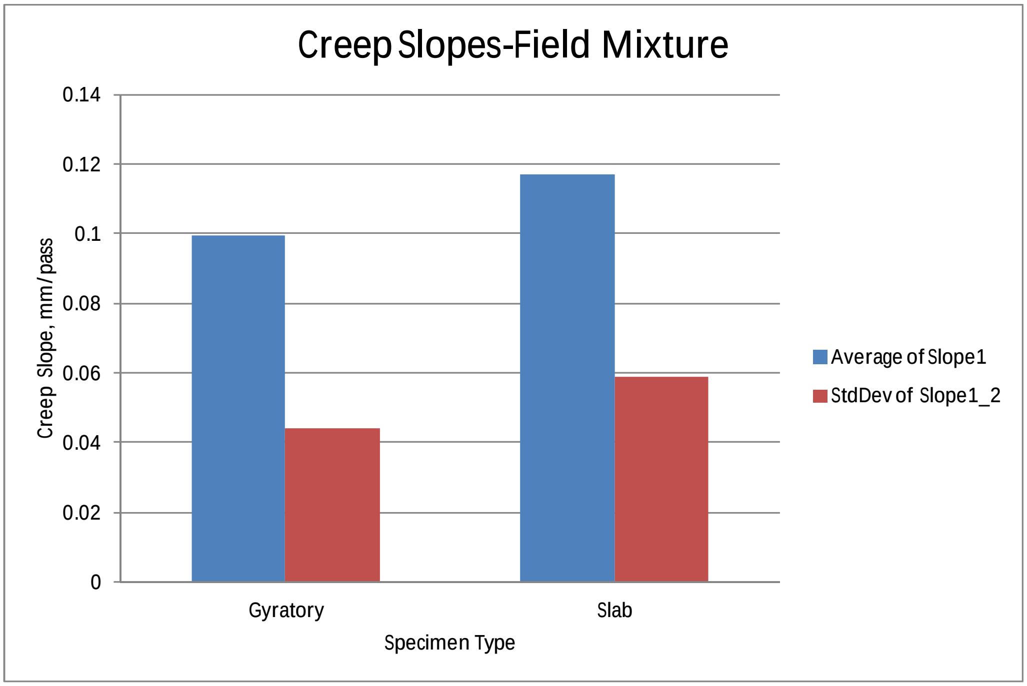


**Figure 3-11- Comparison of average and standard deviation of creep slopes of gyratory and slab specimens of well-performing mixture**

### 3.10.1.2 Deformation of Gyratory and Slab Specimens at End

Figure 3-12 shows the average and standard deviation of deformation of the Field mixture at the end of the test. The criteria for the test termination are either 20,000 passes or 25 mm of deformation, whichever comes first. For the well-performing mixture, which experienced a small deformation, tests were ended after 20,000 passes. As indicated from the figure, the deformation of the gyratory specimens is an average 0.4 mm less than the deformation of slab specimens at the end of the test. This also indicates that gyratory specimens may provide a better estimate of rutting performance of well-performing mixtures than slab specimens.

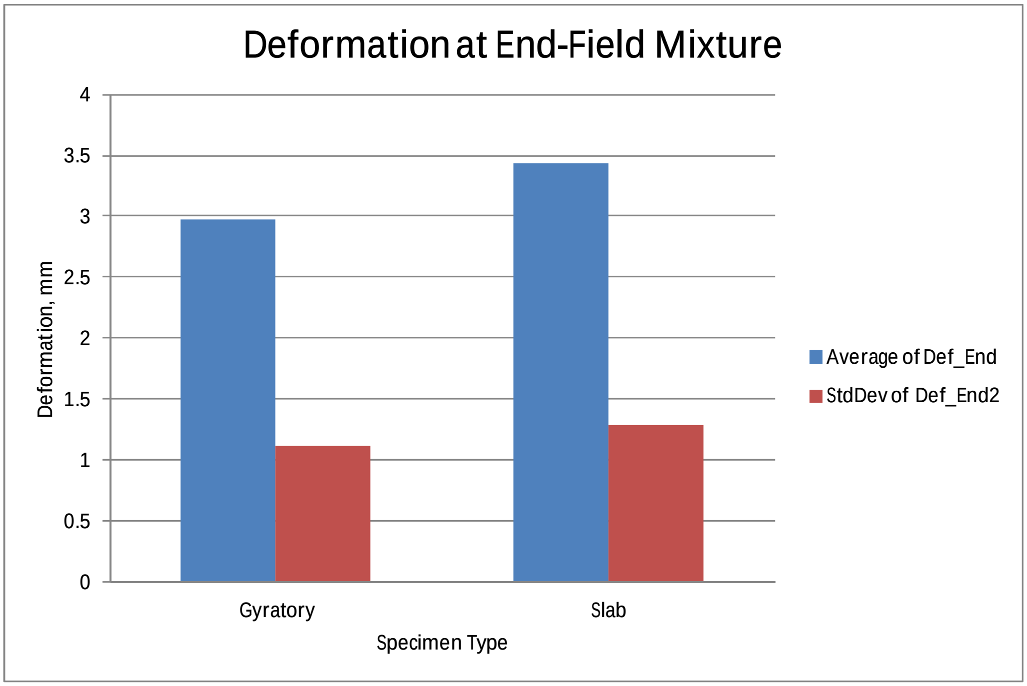


**Figure 3-12- Average deformation of gyratory and slab specimens of the well-performing mixture at the end of the test**

### 3.10.1.3 Deformation of Gyratory and Slab Specimens after Specified Number of Passes

Figure 3-13 and Figure 3-14 show the average and standard deviation of deformation for the gyratory and slab specimens of the well-performing Field mixture after 1000, 2000, 5000, 10,000, and 20,000 passes. It is observed from the graph that after each set of passes, slab specimens have experienced slightly more deformation than the gyratory specimens. The standard deviations of the deformation of the slab specimens are shown to be larger than those of gyratory specimens after 5,000 passes. This indicates that for the well-performing mixtures, gyratory specimens are slightly more resistant to rutting and moisture and provide slightly less variable results than slab specimens.

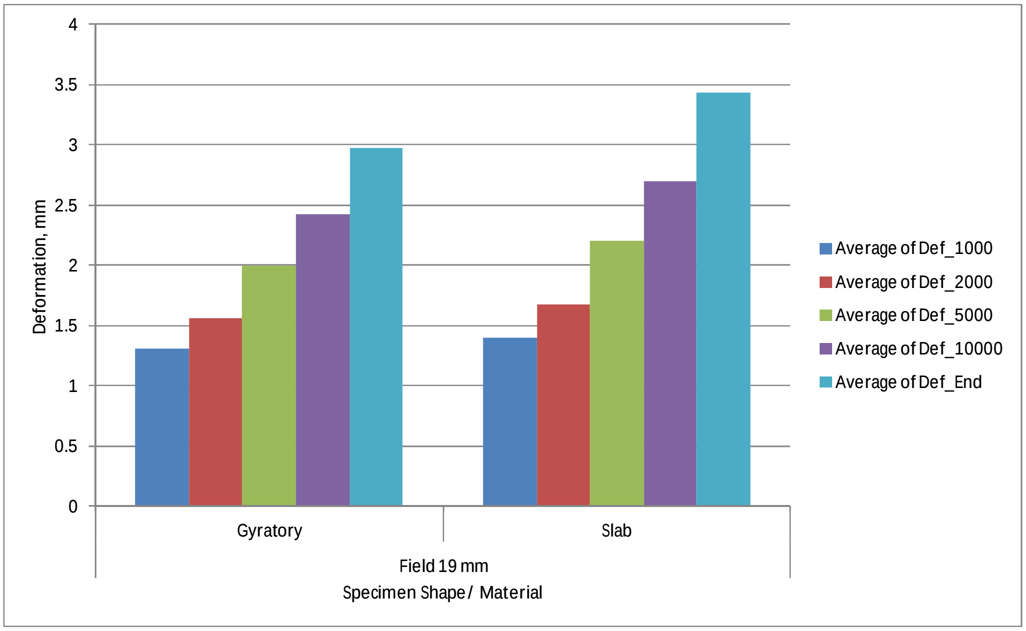


**Figure 3-13- Average deformation of the Field mixture after various number of passes**

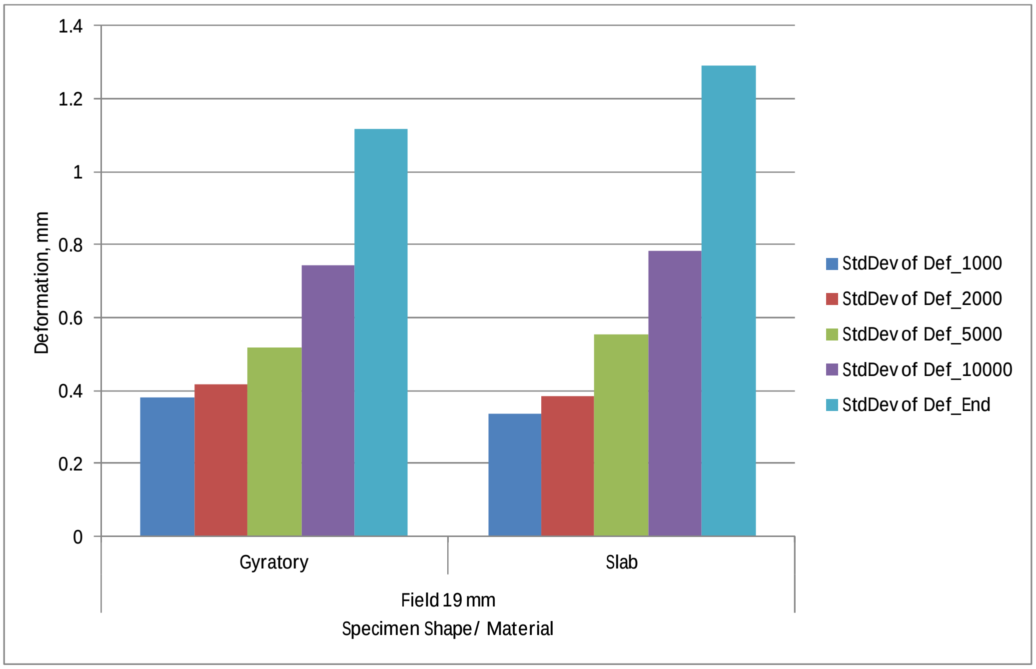


**Figure 3-14- Standard deviation of deformation of Field mixture after various number of passes**

### 3.10.2 Comparison of Properties of Gyratory and Slab Specimens of Wyoming Mixture

Test properties for the poorly-performing WY mixture include number of passes to threshold rut depth, creep and stripping slopes, and inflection point. Different state DOTs specify different rut depth thresholds to define test failure. The more commonly used failure criteria are 6-mm and 12-mm rut depths. Herein, the number of passes to these two failure criteria was compared for the gyratory and slab specimens of WY mixture.

#### 3.10.2.1 Creep Slopes of Gyratory and Slab of Wyoming Mixture

Figure 3-15 shows the average and standard deviation of the creep slope for the gyratory and slab specimens of the WY mixture. The creep slopes represent the rate of deformation before the inflection point. As indicated from the figure, for the WY mixture, the average and standard deviation of the creep slope of gyratory specimens is larger than those of slab specimens. The fact that gyratory specimens are less resistant to rutting and moisture damage might indicate that the rate of deformation of the poorly-performing mixture is underestimated using gyratory specimens.

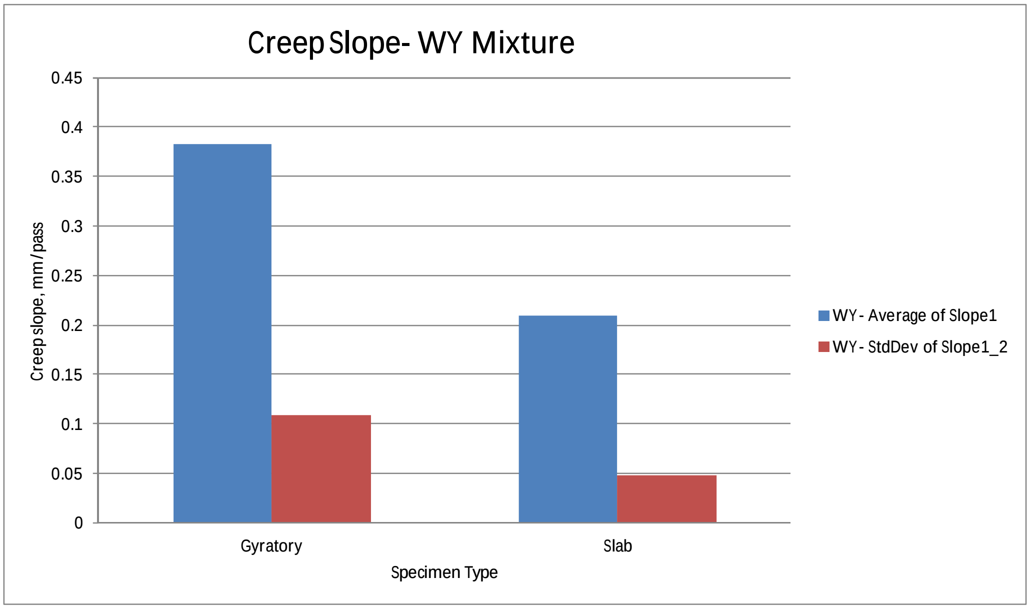


**Figure 3-15- Comparison of average and standard deviation of creep slopes of gyratory and slab specimens of the poorly-performing mixture**

#### 3.10.2.2 Number of Passes to 6-mm Deformation

Figure 3-16 shows the average and standard deviation of the number of passes to 6-mm rut depth for gyratory and slab specimens of WY mixture. As indicated from the figure, a greater number of passes was needed to achieve the same amount of deformation in the slab than in gyratory specimens (12,000 versus 7,000 passes). Although the standard deviation of the number of passes is larger for the slab specimens, considering the larger number of passes, the coefficient of variation for the slab specimens would be smaller. This shows that a poorly-performing mixture is more vulnerable to rutting and moisture damage when tested in the form of gyratory specimens than slab specimens. The weaker performance of gyratory specimens of the poorly-performing mixture is speculated to be caused by the cut cross-sections of the jointed gyratory specimens.

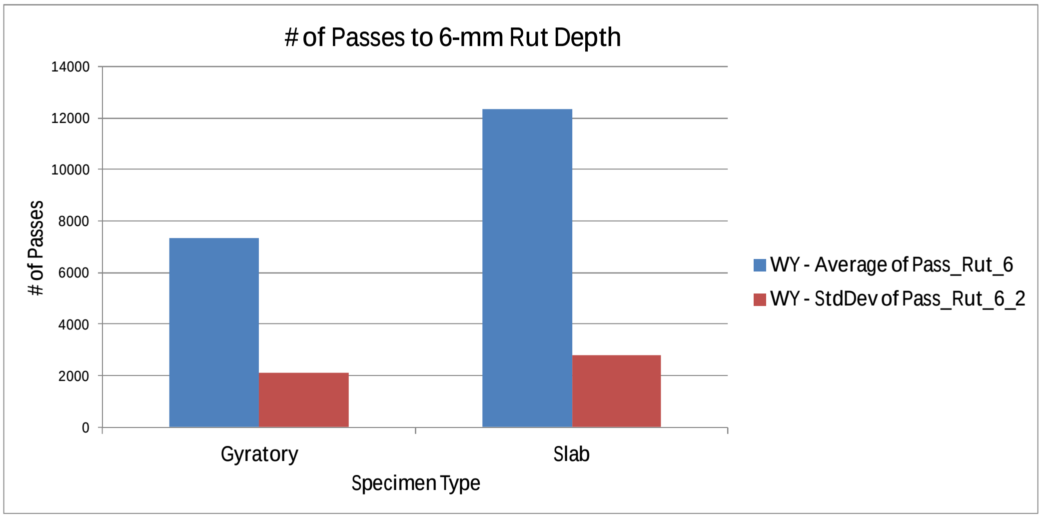


**Figure 3-16- Comparison of the number of passes to 6-mm deformation**

### 3.10.2.3 Number of Passes to 12-mm Deformation

Figure 3-17 shows the average and standard deviation of the number of passes to 12-mm rut depth for the WY specimens. Similar to the observation above, more number of passes were needed to achieve 12-mm rut depth in slabs than in gyratory specimens (17,000 versus 10,000), indicating more vulnerability of gyratory specimens to rutting and moisture damage. The standard deviation and consequently the coefficient of variation of number of passes to 12-mm deformation are smaller for slab specimens than for the gyratory specimens.

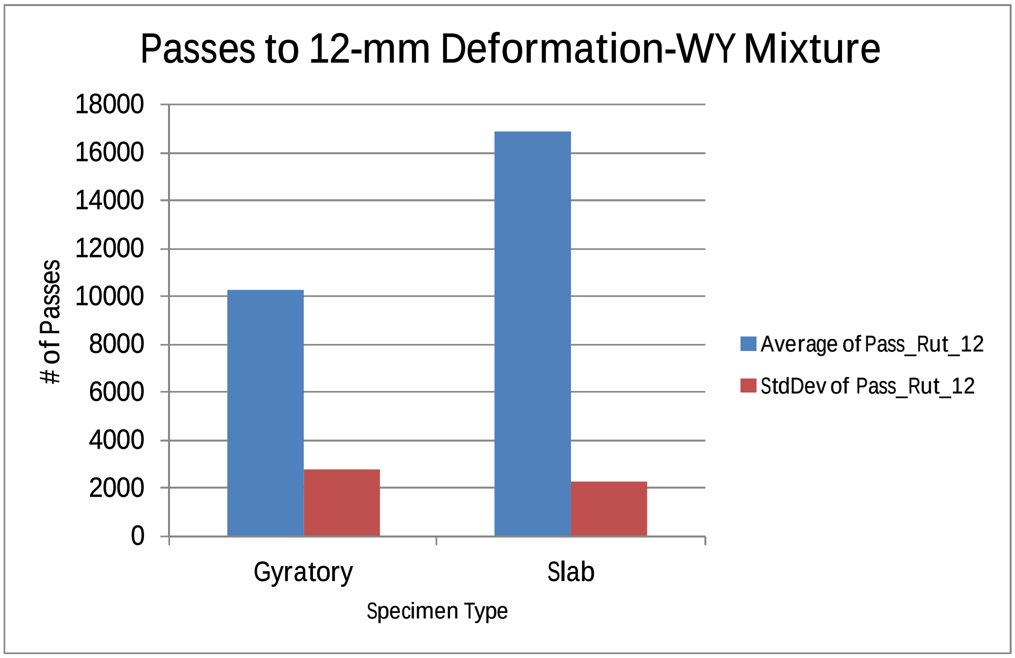


**Figure 3-17- Comparison of Number of passes to 12 mm deformation in WY mixture**

### 3.10.2.4 Number of Passes to Inflection Point

Figure 3-18 shows the average and standard deviation of the number of passes to the inflection point for the gyratory and slab specimens of the WY mixture. The graph indicates that the gyratory specimens exhibit an inflection point around 4000 passes while the slab specimens exhibit an inflection point around 7000 passes. The variability of this parameter for gyratory and slab specimens is comparable considering that the higher number of passes were required to develop the inflection point in the slab specimens. These results also indicate that for poorly-performing mixtures, gyratory specimens are more vulnerable to rutting and moisture damage than the slab specimens, probably due to the cut cross-sections of the jointed samples.

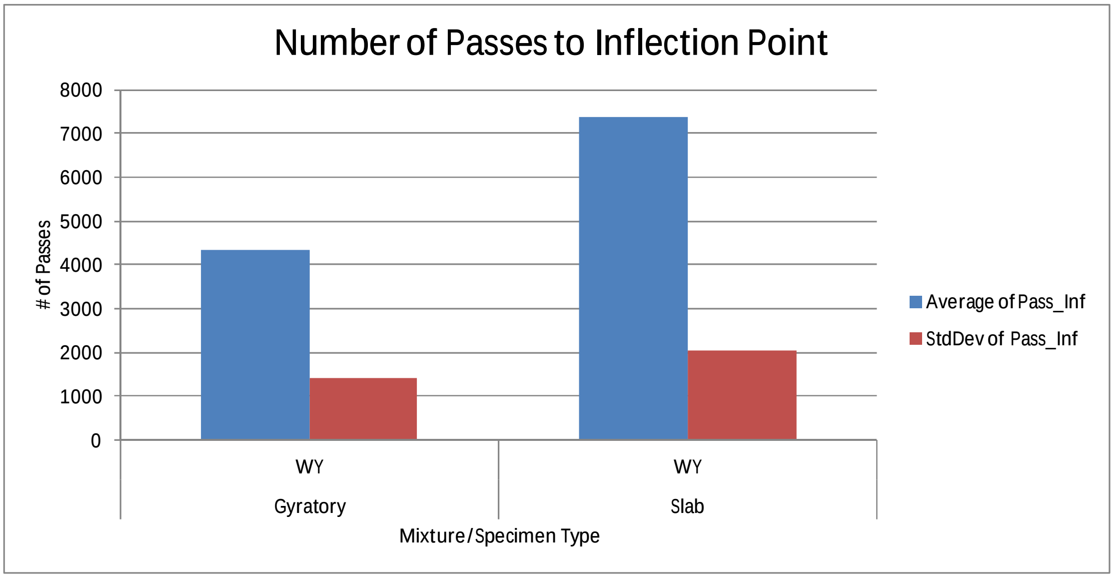


**Figure 3-18- Number of passes to the inflection point for the WY mixture**

### 3.10.2.5 Deformation at Inflection Point

Figure 3-19 provides the average and standard deviation of deformation at the inflection points of the WY specimens. As indicated from the figure, although inflection point occurs after different number of passes for gyratory and slab specimens, as was shown in the previous section, the average deformations at the inflection point are not very different (around 2.5 mm) for the two specimen types. This might indicate that slope of the deformation curve before the inflection point (creep slope) is a better test parameter than deformation and number of passes because creep slope explains how fast mixtures reach the same level of deformation.

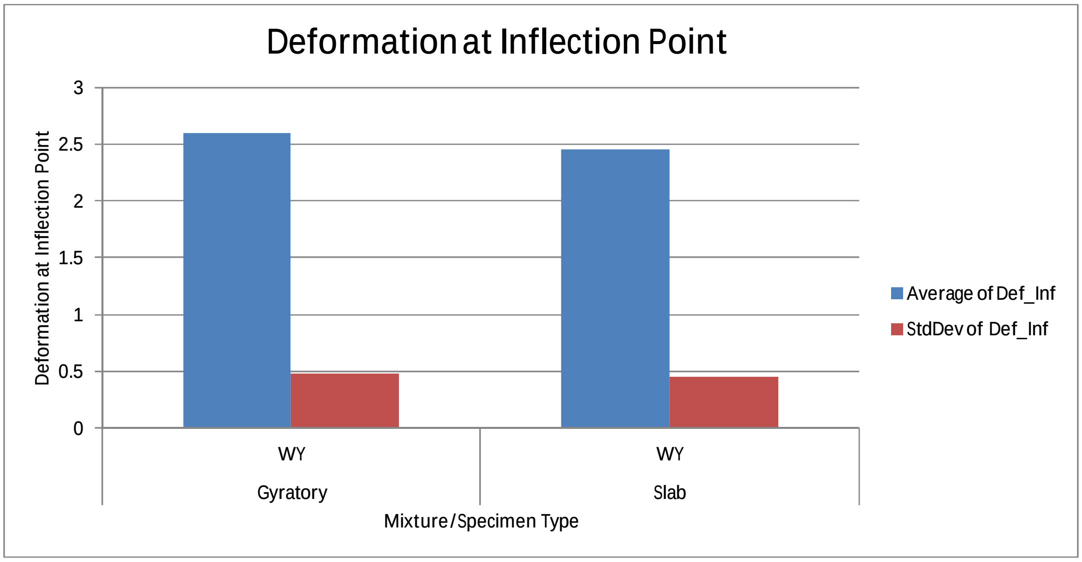


**Figure 3-19- Average deformation at the inflection point**

### 3.10.2.6 Stripping Slopes of Gyratory and Slab of Wyoming Mixture

Figure 3-20 shows the average and standard deviation of the stripping slopes for the gyratory and slab specimens of WY mixture. The stripping slopes represent the rate of deformation after the inflection point. As shown in the figure, the average and standard deviation of the stripping slope of gyratory specimens is larger than that of slab specimens, indicating a faster degradation of the gyratory specimens of the poorly-performing mixture after the inflection point.

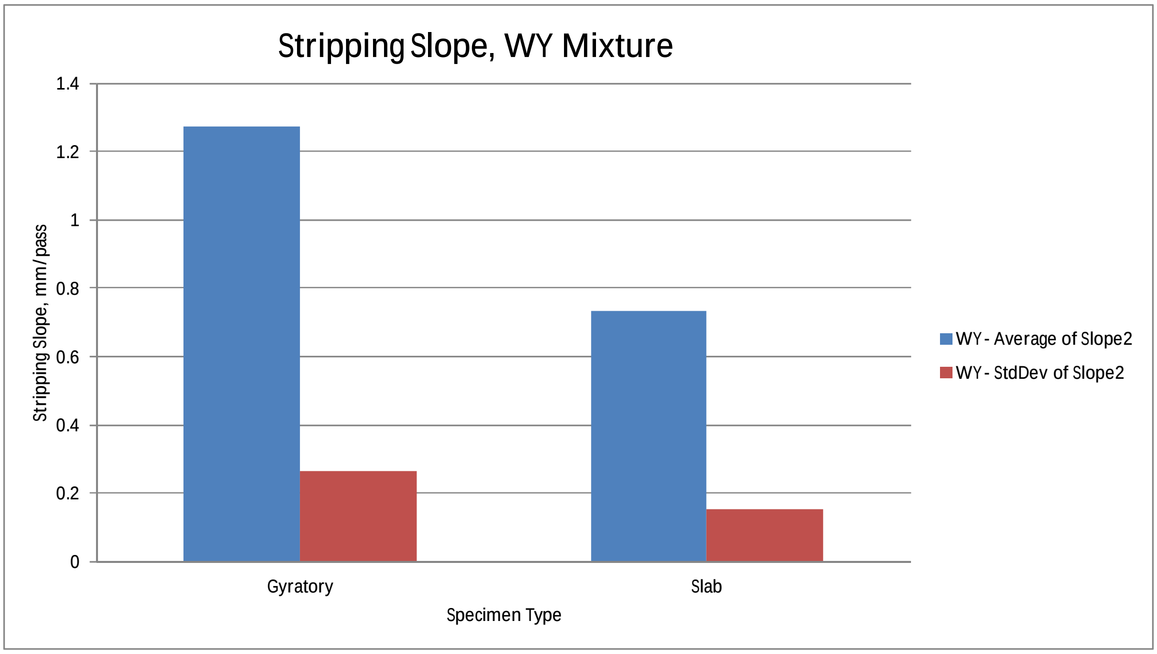


**Figure 3-20- Comparison of average and standard deviation of stripping slopes of the gyratory and slab of poorly-performing mixture**

### 3.10.3 Measurement Locations of Maximum Deformation

Figure 3-21 shows the distribution of the maximum deformation at the measurement locations from all laboratories. As indicated from the figure, for the gyratory specimens, maximum deformation occurs most frequently at measurement locations 7 and 8; while for the slab specimens, frequency of maximum deformation is relatively equal at all measurement locations. This clearly shows that despite the maximum speed of the wheel at the midpoint, maximum deformation for gyratory specimens occur most frequently at or around the midpoint due to the weakness at the joint.

Another observation from Figure 3-21 is that the most frequent readings of maximum deformation occur at measurement locations 7 and 8 and not at measurement locations 6, which is the midpoint. This indicates that there is a possibility that the positions of the measurement locations and therefore the spacing between measurement locations are not consistent among different machines. An in-house investigation into this matter was conducted and the results are discussed in Appendix C.

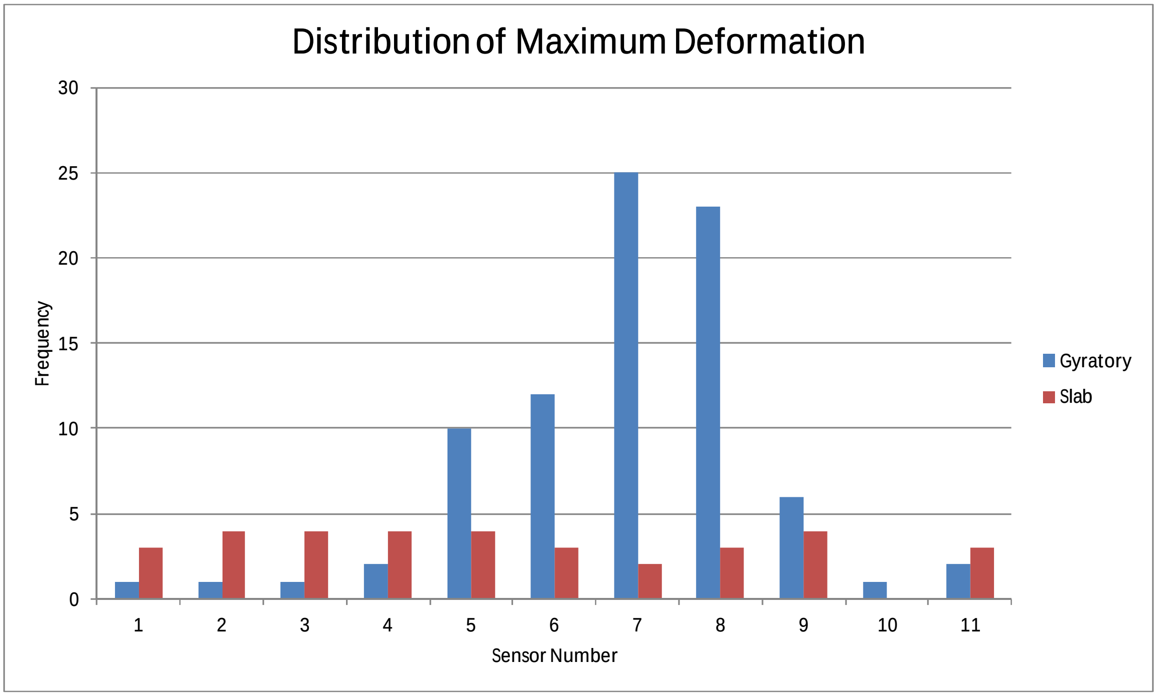


**Figure 3-21- Number of maximum deformation at each measurement location**

### 3.10.4 Effect of Left and Right Wheels on Replicates' Variability

Figure 3-22 and Figure 3-23 show average and standard deviation of rut depth from one-wheel and two-wheel HWTT machines for the WY gyratory specimens. Figure 3-22 shows that the two-wheel HWTT causes about a 10% greater average rut depth than one-wheel HWTT. Figure 3-23 indicates lower variability for two-wheel HWTT below 10,000 cycles and similar variability at 10,000 cycles; however, the two-wheel HWTT's variability at the end of the test is twice as much as that from the one-wheel machine. This may be due to the dynamics of the wheels and the dynamic effect of one wheel on the other as the specimens' rut depth significantly increases. This was usually after 10,000 passes for the WY mixture.

Figure 3-24 shows the standard deviation of the rut depths for Field mixture specimens. Lower standard deviations for two-wheel than for one-wheel machines are seen throughout the test. The dynamic effect is less evidence from the Field mixture since this material does not rut significantly, even after 10,000 cycles.

It may be concluded that the two-wheel system produces more precise replicate measurements for well-performing mixtures with low rut depths; however, the variability between replicates increases significantly with the increased rut depth of the specimens, probably due to the dynamic effect of one wheel on another. If this hypothesis is true, then having separate mechanical systems for each wheel may be warranted.

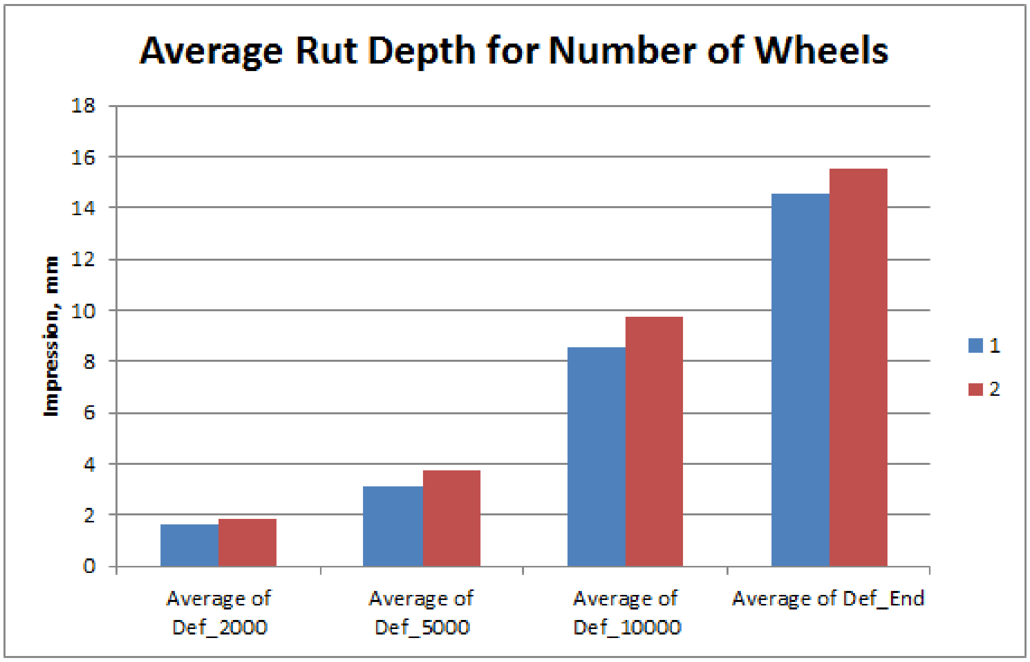


**Figure 3-22- Average Impression of one-wheeler and two-wheeler HWTT for WY gyratory specimens**

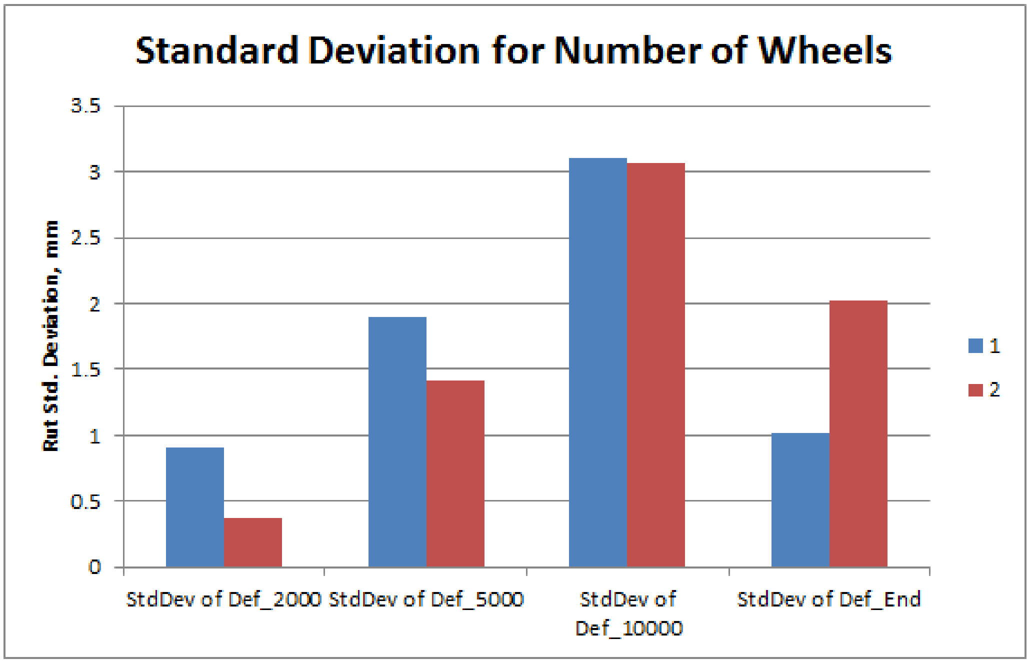


Figure 3-23- Standard Deviation of one-wheel and two-wheel HWTT for WY gyratory specimens

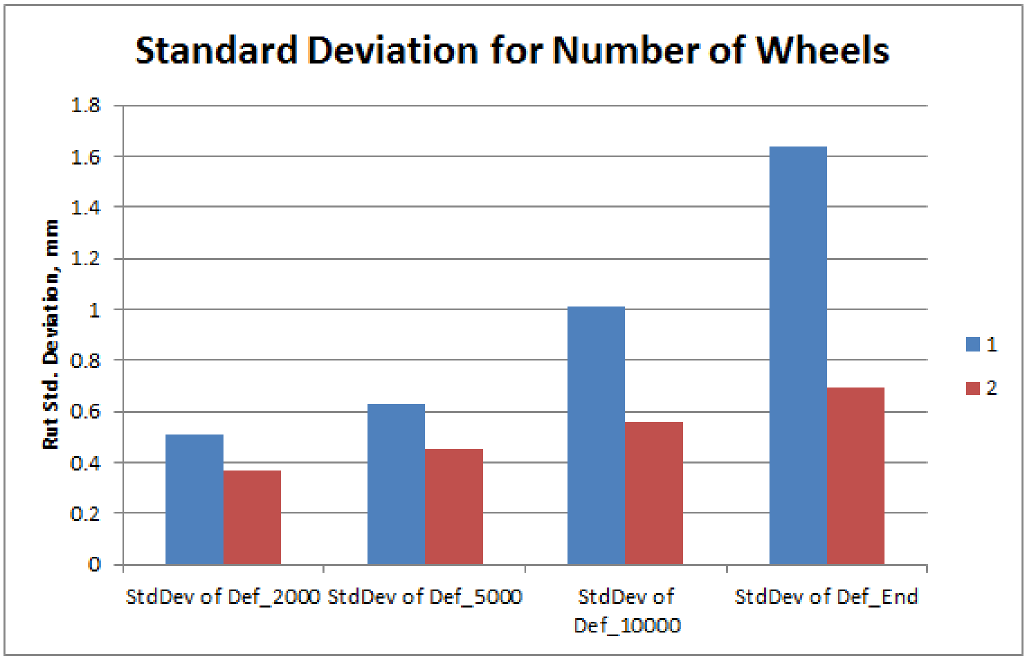


Figure 3-24- Standard Deviation of one-Wheel and Two-Wheel HWTT for Field gyratory specimen

# CHAPTER 4- PRECISION ESTIMATES

## 4.1 Method of Analysis of ILS Test Results

The ILS test results were analyzed for precision in accordance with ASTM E691, “Standard Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method” [10]. Prior to the analysis, partial sets of data were eliminated by following the procedures described in E691 for determining repeatability ($S_r$) and reproducibility ($S_R$) estimates of precision. Data exceeding the critical *h* and *k* statistics, representing the threshold values for the within- and between-laboratory variability, were eliminated from the analysis. The *h* and *k* statistics are provided in Appendices D through H. The measured data and the computed statistics for each mixture and specimen type are also provided in the tables and displayed in the figures of Appendices D through H. The shaded cells in the tables indicate data eliminated from the analysis because they exceeded the critical *h* and *k* statistics. The graphical display of the data received from laboratories and their associated error bars are provided in the appendices. For each replicate data set, the bottom bar represents the minimum value, the top bar represents the maximum value, and middle point represents the median. The spacing between the median and the top and bottom values indicate the degree of dispersion. This is a useful technique for summarizing the data and determining how variable the data are in each laboratory and among various laboratories.

## 4.2 Statistical Comparisons

The measurements according to AASHTO T 324 were collected at 11 measurement locations on two different specimen types, gyratory and slab, of well-performing and poorly-performing asphalt mixtures. The analysis of the measured data is conducted with respect to different sets of measurement locations and specimen types. To prepare precision estimates of the properties, variability corresponding to the various measurement locations, specimen types, number of passes to various threshold rut depth criteria, and the rut depths after various numbers of wheel passes were compared statistically. Those variability values that were not statistically significantly different were pooled together to prepare the precision estimates. Statistical t- and F-tests were used to examine the significance of the following differences:

1. Difference between statistics of gyratory and slab specimens
2. Difference between statistics calculated from all measurement locations, all except the middle three measurement locations, and all except two measurement locations at each end
3. Difference between variability of rut depth after 10,000, 15,000, and 20,000 passes (for well-performing mixture)

4. Difference between variability of number of passes to 6-mm and 12-mm rut depth and to the inflection point (for poorly-performing mixture)

The rejection probability of the computed t- and F- statistics would indicate if the differences from the above comparisons are significantly different. For a 5% level of significance, a rejection probability (p) of less than 0.05 is an indication of significant difference. In the preparation of the precision estimates, those standard deviations that are not significantly different (P> 0.05) would be pooled together.

Since the parameters of the wheel track test are different for the well- and poorly-performing mixtures, separate analyses were conducted for the well-performing Field mixture and the poorly-performing WY mixture. For the well-performing mixture, the parameters of the test are deformation after 10,000, 15,000, and 20,000 passes and the creep slope. For the poorly-performing mixture, the parameters of the test are number of passes to either 6-mm or 12-mm deformation, the creep and stripping slopes, and the number of passes to the inflection point.

## 4.3 Results of Analysis

### 4.3.1 Well-Performing Field Mixture

Table 4-1 provides the statistics of the rut depth after 10,000, 15,000, and 20,000 passes and the statistics of the creep slope for the gyratory and slab specimens of the well-performing Field mixture. The statistics are calculated using data from all measurement locations, all except the three middle measurement locations (#s 5, 6, and 7), and all except the two measurement locations at each end (#s 1 and 2, and 10 and 11). The statistical tests were conducted to compare the averages and variability of the properties measured: 1) from different sets of measurement locations and 2) measured on gyratory and slab specimens.

#### *4.3.1.1 Comparison of Statistics from Various Measurement Locations*

A review of the statistics in Table 4-1 indicates that there are relationships between the averages and standard deviations. Therefore, comparison of variability is based on the coefficient of variation (COV). Figure 4-1 and Figure 4-2 show the averages and COV of the measurements from various measurement locations. Table 4-2 through Table 4-4 provide the results of statistical comparison of the averages and the repeatability/reproducibility COVs of the properties measured using different sets of measurement locations. In the figures and tables, the comparisons corresponding to the gyratory specimens come first followed by the comparisons corresponding to the slab specimens. The observations are as follows:

1. For the gyratory specimens, excluding the readings from the three middle measurement locations resulted in slight, but not statistically significant, decreases in average rut depth and creep slope. This is because the deformations at the locations of the middle measurement locations are larger than those at other

locations. There is no trend of change in repeatability COV; however, there is increase in reproducibility COV of the properties from excluding the readings of the middle three measurement locations. None of the differences are statistically significant.

2. For the gyratory specimens, excluding the readings of the end measurement locations resulted in slight, but not statistically significant, increases in average rut depths and creep slope. This is because the deformations at the location of the end measurements are smaller than the deformations at other measurement locations. There is an increase in repeatability and a decrease in reproducibility COV of the properties from excluding the readings of the end measurement locations; however, none of the differences are statistically significant.

3. For the slab specimens, excluding the readings from the three middle measurement locations resulted in slight, but not statistically significant, increases in average creep slope and average rut depth after 10,000, 15,000, or 20,000 passes. This could be because deformation at and around the midpoint of the slab, where the speed of the wheel is the highest, is the smallest. There is no trend of change in the repeatability and a slight, but not significant, decrease in the reproducibility COV of the properties from excluding the data from the middle three measurement locations of the slab specimens (Figure 4-2).

4. For the slab specimens of the well-performing mixture, excluding the readings of the end measurement locations resulted in slight, but not statistically significant, decreases in average rut depths and average creep slope. This indicates that in the slabs, contrary to gyratory specimens, the deformations at the ends are slightly larger than the deformation at other locations. There is no trend of change in the repeatability; however, there is a slight increase in the reproducibility coefficients of variation. None of the differences are statistically significant.

From the above it can be concluded that all measurement locations are equally important for measurement of properties of either gyratory and slab specimens of well-performing mixtures. Therefore, it is proposed that for well-performing mixtures, the readings from all measurement locations be averaged when analyzing the data from the HWTT.

**Table 4-1- Summary of Statistics of rut depth (mm) and creep slope (mm/pass) of gyratory and slab specimens of Field material from average of all measurement locations, average of all except middle three measurement locations, and average of all except two measurement locations at each end**

| Condition | Property | # of Labs | Average | Repeatability |  | Reproducibility |  | Sx |
|---|---|---|---|---|---|---|---|---|
|  |  |  |  | STD | CV% | STD | CV% |  |
| Field gyratory (all measurement locations) | Rut after 10,000 cycles | 18 | 2.26 | 0.275 | 12.2 | 0.594 | 26.3 | 0.561 |
|  | Rut after 15,000 cycles | 18 | 2.53 | 0.334 | 13.2 | 0.665 | 26.3 | 0.621 |
|  | Rut after 20,000 cycles | 18 | 2.71 | 0.386 | 14.2 | 0.729 | 26.9 | 0.676 |
|  | Creep Slope | 18 | 0.089 | 0.014 | 15.8 | 0.023 | 25.7 | 0.021 |
| Field gyratory (except middle measurement locations) | Rut after 10,000 cycles | 19 | 2.22 | 0.309 | 13.9 | 0.616 | 27.7 | 0.575 |
|  | Rut after 15,000 cycles | 18 | 2.46 | 0.318 | 12.9 | 0.677 | 27.6 | 0.639 |
|  | Rut after 20,000 cycles | 18 | 2.63 | 0.360 | 13.7 | 0.739 | 28.1 | 0.694 |
|  | Creep Slope | 18 | 0.086 | 0.013 | 15.7 | 0.023 | 27.3 | 0.021 |
| Field gyratory (except end measurement locations) | Rut after 10,000 cycles | 18 | 2.36 | 0.328 | 13.9 | 0.601 | 25.5 | 0.554 |
|  | Rut after 15,000 cycles | 18 | 2.65 | 0.392 | 14.8 | 0.669 | 25.3 | 0.609 |
|  | Rut after 20,000 cycles | 18 | 2.85 | 0.459 | 16.1 | 0.744 | 26.1 | 0.669 |
|  | Creep Slope | 18 | 0.095 | 0.017 | 18.0 | 0.024 | 25.5 | 0.021 |
| Field Slab (all measurement locations) | Rut after 10,000 cycles | 6 | 2.60 | 0.333 | 12.8 | 0.606 | 23.3 | 0.558 |
|  | Rut after 15,000 cycles | 6 | 2.99 | 0.443 | 14.8 | 0.762 | 25.5 | 0.694 |
|  | Rut after 20,000 cycles | 6 | 3.27 | 0.532 | 16.3 | 0.889 | 27.2 | 0.805 |
|  | Creep Slope | 6 | 0.112 | 0.029 | 26.4 | 0.039 | 34.8 | 0.033 |
| Field slab (except middle measurement locations) | Rut after 10,000 cycles | 6 | 2.62 | 0.338 | 12.9 | 0.587 | 22.4 | 0.536 |
|  | Rut after 15,000 cycles | 6 | 3.00 | 0.443 | 14.8 | 0.735 | 24.5 | 0.665 |
|  | Rut after 20,000 cycles | 6 | 3.28 | 0.528 | 16.1 | 0.849 | 25.8 | 0.762 |
|  | Creep Slope | 6 | 0.113 | 0.029 | 25.6 | 0.037 | 32.6 | 0.031 |
| Field slab (except end measurement locations) | Rut after 10,000 cycles | 6 | 2.56 | 0.312 | 12.2 | 0.613 | 24.0 | 0.573 |
|  | Rut after 15,000 cycles | 6 | 2.94 | 0.414 | 14.1 | 0.780 | 26.6 | 0.723 |
|  | Rut after 20,000 cycles | 6 | 3.23 | 0.517 | 16.0 | 0.924 | 28.6 | 0.848 |
|  | Creep Slope | 6 | 0.109 | 0.029 | 26.9 | 0.041 | 37.6 | 0.035 |

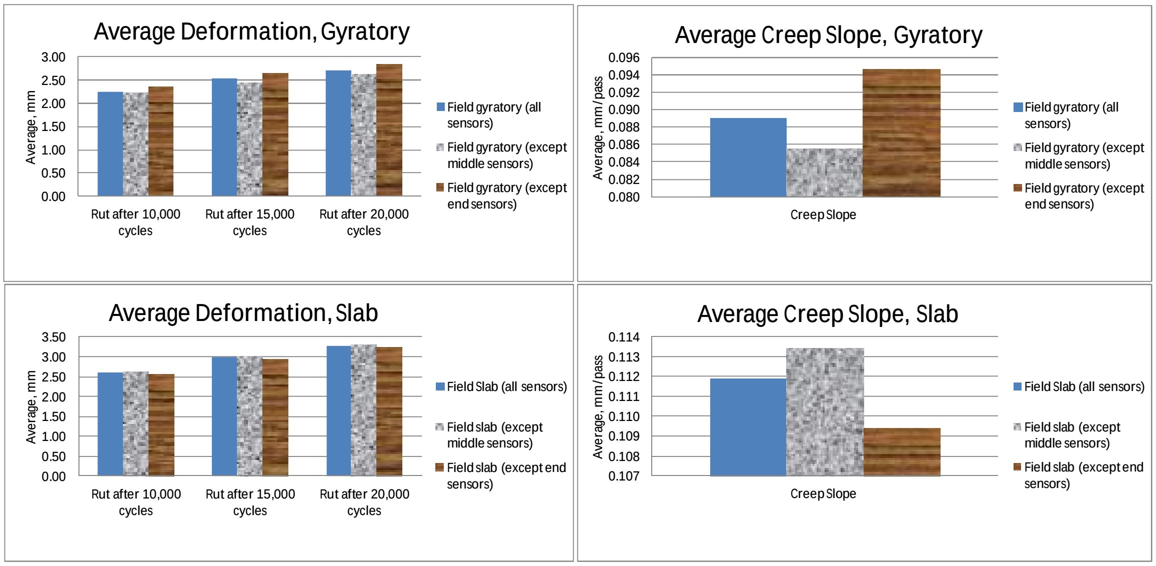


**Figure 4-1-Graphical comparison of average properties of Field mixture measured using data from all measurement locations, all except three middle measurement locations, and all except two measurement locations at each end**

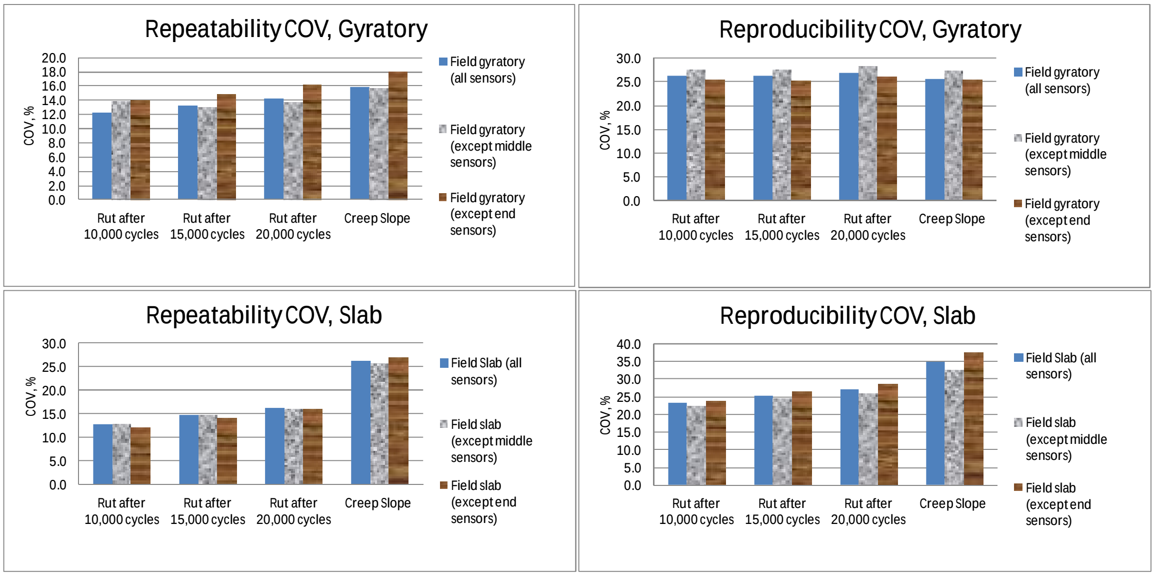


**Figure 4-2-Graphical comparison of coefficients of variation (COV) of properties of Field mixture measured using data from all measurement locations, all except middle 3 measurement locations, and all except two measurement locations at each end**

**Table 4-2- Statistical t-test on the average rut depth (mm) after 10,000, 15,000, and 20,000 cycles and creep slope (mm/pass) of Field mixture for the comparison of measurements from various sets of measurement locations**

| Comparison | Property | Averages | S | T | df | Critical t | P | Decision |
|---|---|---|---|---|---|---|---|---|
| Field gyratory (all measurement locations) Vs. Field gyratory (except middle measurement locations) | Rut after 10,000 cycles | 2.26 vs. 2.22 | 0.568 | 0.17 | 35 | 1.69 | 0.435 | Accept |
| | Rut after 15,000 cycles | 2.53 vs. 2.46 | 0.630 | 0.34 | 34 | 1.69 | 0.367 | Accept |
| | Rut after 20,000 cycles | 2.71 vs. 2.63 | 0.685 | 0.35 | 34 | 1.69 | 0.363 | Accept |
| | Creep Slope | 0.089 vs. 0.086 | 0.021 | 0.50 | 34 | 1.69 | 0.311 | Accept |
| Field gyratory (all measurement locations) Vs. Field gyratory (except end measurement locations) | Rut after 10,000 cycles | 2.26 vs. 2.36 | 0.558 | -0.54 | 34 | 1.69 | 0.297 | Accept |
| | Rut after 15,000 cycles | 2.53 vs. 2.65 | 0.615 | -0.58 | 34 | 1.69 | 0.284 | Accept |
| | Rut after 20,000 cycles | 2.71 vs. 2.85 | 0.672 | -0.62 | 34 | 1.69 | 0.270 | Accept |
| | Creep Slope | 0.089 vs. 0.095 | 0.021 | -0.81 | 34 | 1.69 | 0.211 | Accept |
| Field slabs (all measurement locations) Vs. Field slab (except middle measurement locations) | Rut after 10,000 cycles | 2.6 vs. 2.62 | 0.547 | -0.07 | 10 | 1.81 | 0.473 | Accept |
| | Rut after 15,000 cycles | 2.99 vs. 3 | 0.680 | -0.03 | 10 | 1.81 | 0.490 | Accept |
| | Rut after 20,000 cycles | 3.27 vs. 3.28 | 0.784 | -0.04 | 10 | 1.81 | 0.485 | Accept |
| | Creep Slope | 0.112 vs. 0.113 | 0.032 | -0.08 | 10 | 1.81 | 0.468 | Accept |
| Field slabs (all measurement locations) Vs. Field slab(except end measurement locations) | Rut after 10,000 cycles | 2.6 vs. 2.56 | 0.565 | 0.13 | 10 | 1.81 | 0.451 | Accept |
| | Rut after 15,000 cycles | 2.99 vs. 2.94 | 0.709 | 0.13 | 10 | 1.81 | 0.451 | Accept |
| | Rut after 20,000 cycles | 3.27 vs. 3.23 | 0.827 | 0.07 | 10 | 1.81 | 0.473 | Accept |
| | Creep Slope | 0.112 vs. 0.109 | 0.034 | 0.13 | 10 | 1.81 | 0.451 | Accept |

**Table 4-3- Statistical F-test on repeatability coefficients of variation (COV) of rut depth (mm) after 10,000, 15,000, and 20,000 cycles and of creep slope (mm/pass) of Field mixture for the comparison of measurements from various sets of measurement locations**

| Comparison | Property | COV, % | F | Critical F | df1 | df2 | P | Decision |
|---|---|---|---|---|---|---|---|---|
| Field gyratory (all measurement locations) vs. Field gyratory (except middle measurement locations) | Rut after 10,000 cycles | 12.2 vs. 13.9 | 1.29 | 2.26 | 18 | 17 | 0.300 | Accept |
| | Rut after 15,000 cycles | 13.2 vs. 12.9 | 1.04 | 2.27 | 17 | 17 | 0.467 | Accept |
| | Rut after 20,000 cycles | 14.2 vs. 13.7 | 1.08 | 2.27 | 17 | 17 | 0.440 | Accept |
| | Creep slope | 15.8 vs. 15.7 | 1.02 | 2.27 | 17 | 17 | 0.485 | Accept |
| Field gyratory (all measurement locations) vs. Field gyratory (except end measurement locations) | Rut after 10,000 cycles | 12.2 vs. 13.9 | 1.30 | 2.27 | 17 | 17 | 0.295 | Accept |
| | Rut after 15,000 cycles | 13.2 vs. 14.8 | 1.26 | 2.27 | 17 | 17 | 0.319 | Accept |
| | Rut after 20,000 cycles | 14.2 vs. 16.1 | 1.28 | 2.27 | 17 | 17 | 0.306 | Accept |
| | Creep Slope | 15.8 vs. 18 | 1.29 | 2.27 | 17 | 17 | 0.303 | Accept |
| Field Slab (all measurement locations) vs. Field slab (except middle measurement locations) | Rut after 10,000 cycles | 12.8 vs. 12.9 | 1.01 | 5.05 | 5 | 5 | 0.494 | Accept |
| | Rut after 15,000 cycles | 14.8 vs. 14.8 | 1.01 | 5.05 | 5 | 5 | 0.497 | Accept |
| | Rut after 20,000 cycles | 16.3 vs. 16.1 | 1.03 | 5.05 | 5 | 5 | 0.489 | Accept |
| | Creep Slope | 26.4 vs. 25.6 | 1.06 | 5.05 | 5 | 5 | 0.474 | Accept |
| Field Slab (all measurement locations) vs. Field slab (except end measurement locations) | Rut after 10,000 cycles | 12.8 vs. 12.2 | 1.11 | 5.05 | 5 | 5 | 0.456 | Accept |
| | Rut after 15,000 cycles | 14.8 vs. 14.1 | 1.10 | 5.05 | 5 | 5 | 0.458 | Accept |
| | Rut after 20,000 cycles | 16.3 vs. 16.0 | 1.04 | 5.05 | 5 | 5 | 0.485 | Accept |
| | Creep Slope | 26.4 vs. 26.9 | 1.04 | 5.05 | 5 | 5 | 0.481 | Accept |

**Table 4-4- Statistical F-test on reproducibility coefficients of variation (COV) of rut depth (mm) after 10,000, 15,000, and 20,000 cycles and of creep slope (mm/pass) of Field mixture for the comparison of measurements from various sets of measurement locations**

| Comparison | Property | COV, % | F | Critical F | df1 | df2 | P | Decision |
|---|---|---|---|---|---|---|---|---|
| Field gyratory (all measurement locations) vs. Field gyratory (except middle measurement locations) | Rut after 10,000 cycles | 26.3 vs. 27.7 | 1.10 | 2.26 | 18 | 17 | 0.420 | Accept |
| | Rut after 15,000 cycles | 26.3 vs. 27.6 | 1.10 | 2.27 | 17 | 17 | 0.423 | Accept |
| | Rut after 20,000 cycles | 26.9 vs. 28.1 | 1.09 | 2.27 | 17 | 17 | 0.428 | Accept |
| | Creep Slope | 25.7 vs. 27.3 | 1.12 | 2.27 | 17 | 17 | 0.406 | Accept |
| Field gyratory (all measurement locations) vs. Field gyratory (except end measurement locations) | Rut after 10,000 cycles | 26.3 vs. 25.5 | 1.06 | 2.27 | 17 | 17 | 0.450 | Accept |
| | Rut after 15,000 cycles | 26.3 vs. 25.3 | 1.08 | 2.27 | 17 | 17 | 0.437 | Accept |
| | Rut after 20,000 cycles | 26.9 vs. 26.1 | 1.06 | 2.27 | 17 | 17 | 0.452 | Accept |
| | Creep Slope | 25.7 vs. 25.5 | 1.02 | 2.27 | 17 | 17 | 0.484 | Accept |
| Field Slab (all measurement locations) vs. Field slab (except middle measurement locations) | Rut after 10,000 cycles | 23.3 vs. 22.4 | 1.08 | 5.05 | 5 | 5 | 0.466 | Accept |
| | Rut after 15,000 cycles | 25.5 vs. 24.5 | 1.08 | 5.05 | 5 | 5 | 0.467 | Accept |
| | Rut after 20,000 cycles | 27.2 vs. 25.8 | 1.11 | 5.05 | 5 | 5 | 0.456 | Accept |
| | Creep Slope | 34.8 vs. 32.6 | 1.14 | 5.05 | 5 | 5 | 0.444 | Accept |
| Field Slab (all measurement locations) vs. Field slab (except end measurement locations) | Rut after 10,000 cycles | 23.3 vs. 24 | 1.06 | 5.05 | 5 | 5 | 0.476 | Accept |
| | Rut after 15,000 cycles | 25.5 vs. 26.6 | 1.09 | 5.05 | 5 | 5 | 0.464 | Accept |
| | Rut after 20,000 cycles | 27.2 vs. 28.6 | 1.10 | 5.05 | 5 | 5 | 0.459 | Accept |
| | Creep Slope | 34.8 vs. 37.6 | 1.16 | 5.05 | 5 | 5 | 0.436 | Accept |

#### *4.3.1.2 Comparison of Statistics from Gyratory and Slab Specimens*

Figure 4-3 and Figure 4-4 show the comparison of the averages and the COVs of the measurements from slab and gyratory specimens. Table 4-5 through Table 4-7 provide the results of statistical comparison of the averages and repeatability/reproducibility COVs of deformation and creep slope from gyratory and slab specimens. In the figures and tables, the first comparison corresponds to all measurement locations, the second comparison corresponds to all except the middle three measurement locations, and the third comparison corresponds to all except the two measurement locations at each end. The following are observed from the tables:

1. Regardless of the sets of measurement locations used, the average deformation and creep slope of the slab specimens of the well-performing mixture are always larger than those of the gyratory specimens. This indicates that gyratory

specimens of well-performing mixtures are more resistant to rut and moisture damage than slab specimens.

2. When all measurement locations are used, the average creep slope of slab specimens is significantly larger than that of gyratory specimens (Table 4-5).
3. When the middle three measurement locations are excluded, the average rut depths after 15,000 and 20,000 passes and the average creep slope of slab specimens are statistically larger than those of gyratory specimens. The significant differences are shown as the shaded cells in Table 4-5.
4. When the four end measurement locations are excluded, the differences between rut depth and creep slope of gyratory and slab specimens become smaller. This is because by excluding the end measurement locations, the average deformation of gyratory specimens slightly increases and average deformation of slab specimens slightly decreases resulting in smaller differences between properties of the two specimen types. However, as indicated from Table 4-5, none of the differences are statistically significant.
5. Regardless of the sets of measurement locations used, both the repeatability and reproducibility COV of the creep slope from the slab specimens is larger than that of the gyratory specimens. However, the differences are not statistically significant.
6. There appears to be a relationship among the differences between the COV of rut depths from gyratory and slab specimens, number of passes, and the measurement locations. As indicated from Table 4-6 and Table 4-7, prior to 10,000 passes, slab specimens provide either the same or lower repeatability/reproducibility COVs than gyratory specimens. However, variability of rut depth corresponding to the slab specimens increases as the number of passes increases. On the other hand, the difference between the variability of measurements corresponding to gyratory and slab specimens decreases when the data from the end measurement locations are excluded from the analysis. However, none of the differences between variability of gyratory and slab specimens are statistically significant.

From the above observations it can be concluded that the type of specimens used for the HWTT should be recorded along with the test results, since the average of one or more properties could be significantly different depending on which measurement location data are used in the analysis. However, if the end measurement locations are excluded from the analysis, the estimate of mixture performance from the gyratory and slab specimens would not be different.

Since the differences in variability of measurements using gyratory and slab specimens are not statically significant, the precision estimates for the properties of well-performing mixtures were prepared by pooling together the COV of the properties of gyratory and slab specimens.

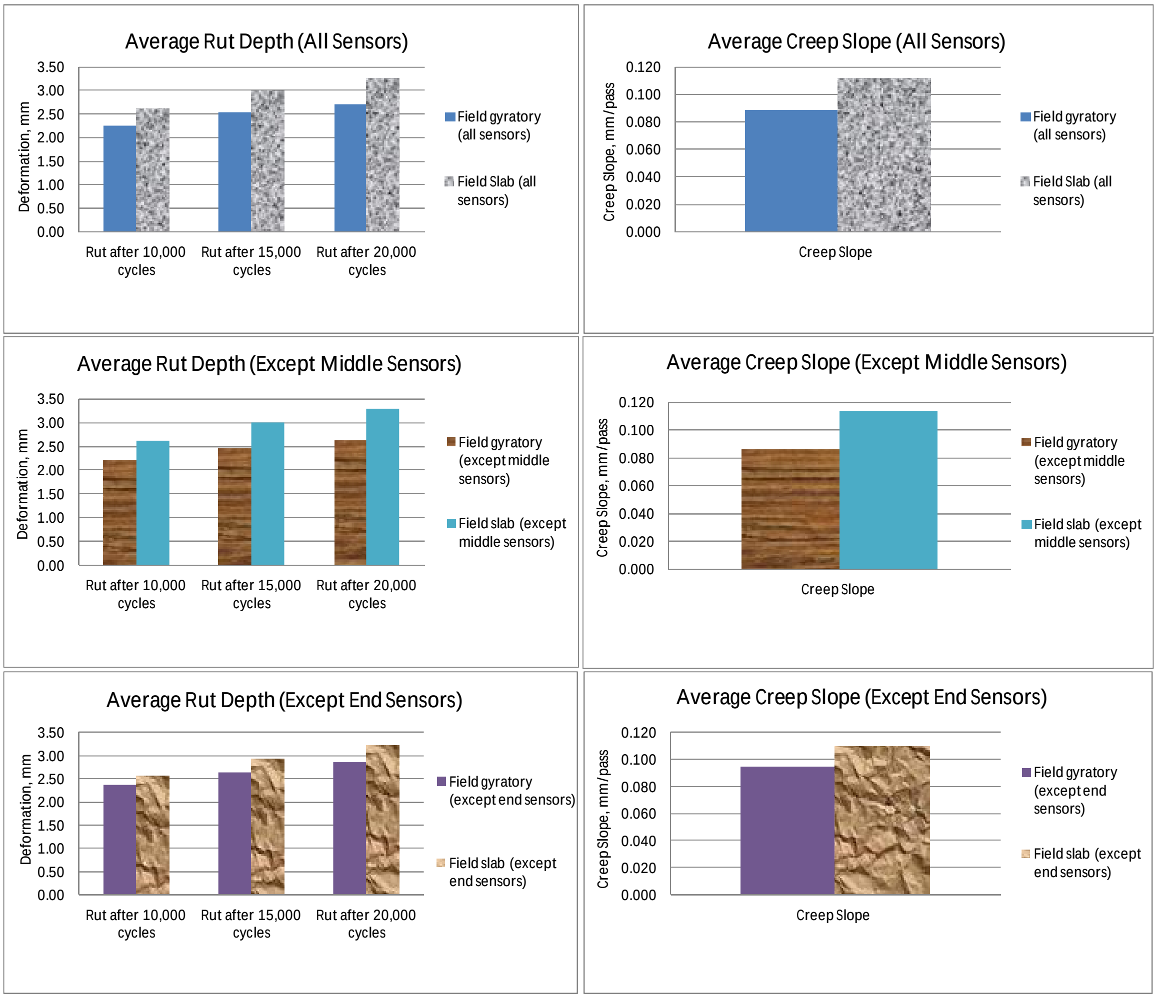


**Figure 4-3- Graphical comparison of average of the properties of gyratory and slab specimens of the Field mixture measured using data from all measurement locations, all except middle 3 measurement locations, and all except 4 end measurement locations**

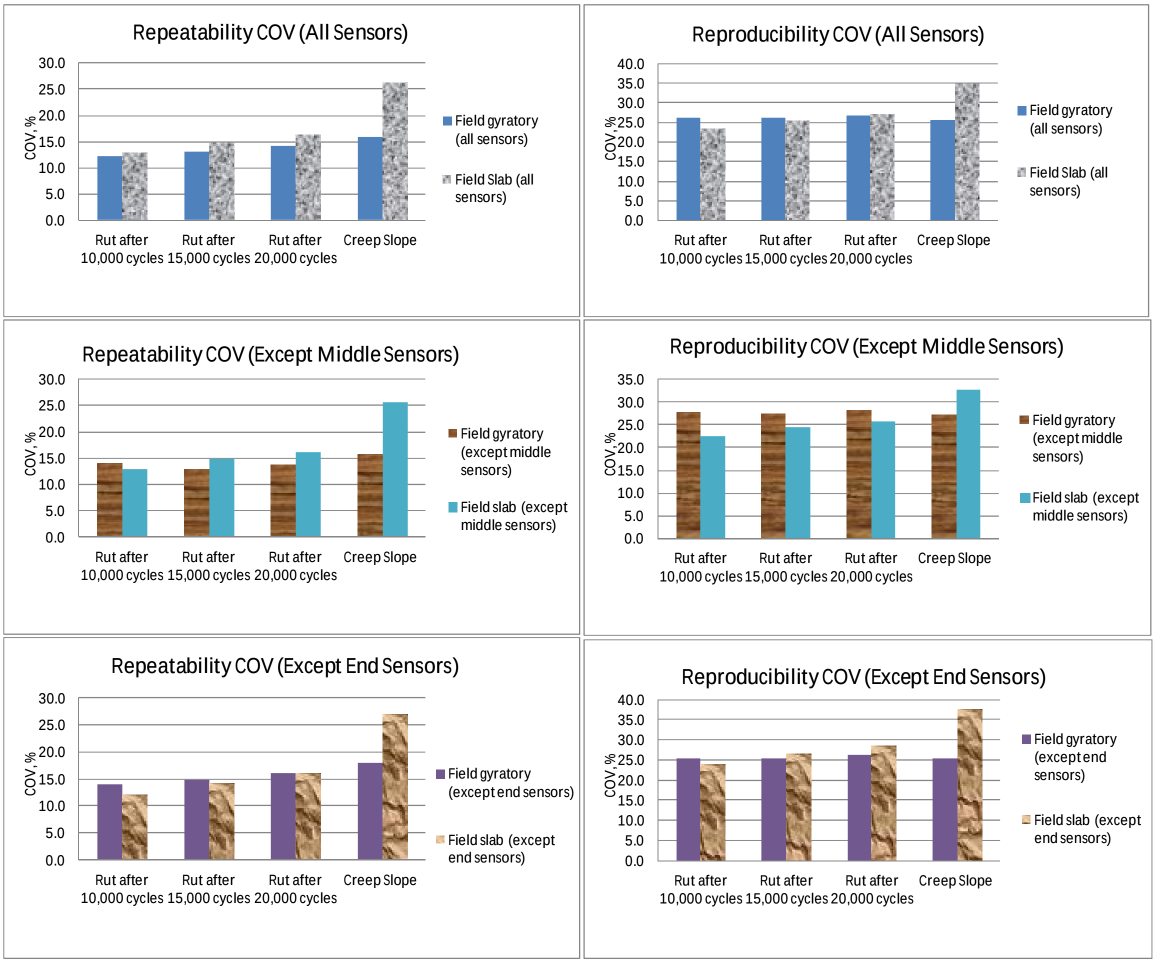


**Figure 4-4- Graphical comparison of coefficients of variation (COV) of the properties of gyratory and slab specimens of the Field mixture measured using data from all measurement locations, all except middle 3 measurement locations, and all except 4 end measurement locations**

**Table 4-5- Statistical t-test on averages of rut depth (mm) after 10,000, 15,000, and 20,000 passes and of creep slope (mm/pass) corresponding to gyratory and slab specimens of Field mixture**

| Comparison | Property | Averages | S | T | df | Critical t | P | Decision |
|---|---|---|---|---|---|---|---|---|
| Field gyratory (all measurement locations) vs. Field slabs (all measurement locations) | Rut after 10,000 cycles | 2.26 vs. 2.6 | 0.56 | -1.30 | 22 | 1.72 | 0.103 | Accept |
| | Rut after 15,000 cycles | 2.53 vs. 2.99 | 0.64 | -1.53 | 22 | 1.72 | 0.070 | Accept |
| | Rut after 20,000 cycles | 2.71 vs. 3.27 | 0.71 | -1.67 | 22 | 1.72 | 0.055 | Accept |
| | Creep Slope | 0.089 vs. 0.112 | 0.02 | -2.02 | 22 | 1.72 | 0.028 | Reject |
| Field gyratory (except middle measurement locations) vs. Field slab (except middle measurement locations) | Rut after 10,000 cycles | 2.22 vs. 2.62 | 0.57 | -1.49 | 23 | 1.71 | 0.074 | Accept |
| | Rut after 15,000 cycles | 2.46 vs. 3 | 0.64 | -1.79 | 22 | 1.72 | 0.043 | Reject |
| | Rut after 20,000 cycles | 2.63 vs. 3.28 | 0.71 | -1.95 | 22 | 1.72 | 0.032 | Reject |
| | Creep Slope | 0.086 vs. 0.113 | 0.02 | -2.49 | 22 | 1.72 | 0.011 | Reject |
| Field gyratory (except end measurement locations) vs. Field slab (except end measurement locations) | Rut after 10,000 cycles | 2.36 vs. 2.56 | 0.56 | -0.77 | 22 | 1.72 | 0.225 | Accept |
| | Rut after 15,000 cycles | 2.65 vs. 2.94 | 0.64 | -0.97 | 22 | 1.72 | 0.171 | Accept |
| | Rut after 20,000 cycles | 2.85 vs. 3.23 | 0.71 | -1.14 | 22 | 1.72 | 0.133 | Accept |
| | Creep Slope | 0.095 vs. 0.109 | 0.02 | -1.25 | 22 | 1.72 | 0.111 | Accept |

**Table 4-6- Statistical F-test for comparison of the repeatability COV of rut depth (mm) after 10,000, 15,000, and 20,000 passes and of creep slope (mm/pass) corresponding to gyratory and slab specimens of the Field mixture**

| Comparison | # of Passes | COV, % | F | Critical F | df 1 | df 2 | P | Decision |
|---|---|---|---|---|---|---|---|---|
| Field gyratory (all measurement locations) vs. Field Slab (all measurement locations) | Rut after 10,000 cycles | 12.2 vs. 12.8 | 1.10 | 2.81 | 5 | 17 | 0.395 | Accept |
| | Rut after 15,000 cycles | 13.2 vs. 14.8 | 1.26 | 2.81 | 5 | 17 | 0.326 | Accept |
| | Rut after 20,000 cycles | 14.2 vs. 16.3 | 1.31 | 2.81 | 5 | 17 | 0.305 | Accept |
| | Creep Slope | 15.8 vs. 26.4 | 2.77 | 2.81 | 5 | 17 | 0.052 | Accept |
| Field gyratory (except middle measurement locations) vs. Field slab (except middle measurement locations) | Rut after 10,000 cycles | 13.9 vs. 12.9 | 1.16 | 4.58 | 18 | 5 | 0.477 | Accept |
| | Rut after 15,000 cycles | 12.9 vs. 14.8 | 1.30 | 2.81 | 5 | 17 | 0.308 | Accept |
| | Rut after 20,000 cycles | 13.7 vs. 16.1 | 1.38 | 2.81 | 5 | 17 | 0.282 | Accept |
| | Creep Slope | 15.7 vs. 25.6 | 2.65 | 2.81 | 5 | 17 | 0.060 | Accept |
| Field gyratory (except end measurement locations) vs. Field slab (except end measurement locations) | Rut after 10,000 cycles | 13.9 vs. 12.2 | 1.31 | 4.59 | 17 | 5 | 0.411 | Accept |
| | Rut after 15,000 cycles | 14.8 vs. 14.1 | 1.10 | 4.59 | 17 | 5 | 0.500 | Accept |
| | Rut after 20,000 cycles | 16.1 vs. 16 | 1.02 | 4.59 | 17 | 5 | 0.545 | Accept |
| | Creep Slope | 18 vs. 26.9 | 2.24 | 2.81 | 5 | 17 | 0.097 | Accept |

**Table 4-7- Statistical F-test on reproducibility COV of rut depth (mm) after 10,000, 15,000, and 20,000 cycles and of creep slope (mm/pass) of gyratory and slab specimens of the Field mixture**

| Comparison | # of Passes | COV, % | F | Critical F | df 1 | df 2 | P | Decision |
|---|---|---|---|---|---|---|---|---|
| Field gyratory (all measurement locations) vs. Field Slab (all measurement locations) | Rut after 10,000 cycles | 26.3 vs. 23.3 | 1.28 | 4.59 | 17 | 5 | 0.425 | Accept |
| | Rut after 15,000 cycles | 26.3 vs. 25.5 | 1.06 | 4.59 | 17 | 5 | 0.519 | Accept |
| | Rut after 20,000 cycles | 26.9 vs. 27.2 | 1.02 | 2.81 | 5 | 17 | 0.434 | Accept |
| | Creep Slope | 25.7 vs. 34.8 | 1.83 | 2.81 | 5 | 17 | 0.160 | Accept |
| Field gyratory (except middle measurement locations) vs. Field slab (except middle measurement locations) | Rut after 10,000 cycles | 27.7 vs. 22.4 | 1.53 | 4.58 | 18 | 5 | 0.338 | Accept |
| | Rut after 15,000 cycles | 27.6 vs. 24.5 | 1.27 | 4.59 | 17 | 5 | 0.428 | Accept |
| | Rut after 20,000 cycles | 28.1 vs. 25.8 | 1.18 | 4.59 | 17 | 5 | 0.463 | Accept |
| | Creep Slope | 27.3 vs. 32.6 | 1.43 | 2.81 | 5 | 17 | 0.265 | Accept |
| Field gyratory (except end measurement locations) vs. Field slab (except end measurement locations) | Rut after 10,000 cycles | 25.5 vs. 24 | 1.13 | 4.59 | 17 | 5 | 0.486 | Accept |
| | Rut after 15,000 cycles | 25.3 vs. 26.6 | 1.10 | 2.81 | 5 | 17 | 0.394 | Accept |
| | Rut after 20,000 cycles | 26.1 vs. 28.6 | 1.20 | 2.81 | 5 | 17 | 0.351 | Accept |
| | Creep Slope | 25.5 vs. 37.6 | 2.17 | 2.81 | 5 | 17 | 0.105 | Accept |

### 4.3.2 Poorly-Performing Wyoming Mixture

Table 4-8 provides statistics of the properties of gyratory and slab specimens of the poorly-performing Wyoming mixture. The properties include number of passes to 6-mm and 12-mm threshold rut depths, creep slope, stripping slope, and the number of cycles to the inflection point. The comparison of statistics from various measurement locations and from gyratory and slab specimens are discussed in the following sections. A review of the data in Table 4-8 indicates that there is a strong relationship between averages and the standard deviations. Therefore, the statistical comparison has been performed on the averages and repeatability/reproducibility coefficients of variation.

**Table 4-8- Summary of Statistics of HWTT properties for gyratory and slab specimens of WY mixture computed from all measurement locations, all except the middle three measurement locations, and all except the end measurement locations**

| Specimens Type/ Measurement locations Set | Property | # of labs | Average | Repeatability | | Reproducibility | | Sx |
|---|---|---|---|---|---|---|---|---|
| | | | | STD | COV, % | STD | COV, % | |
| WY gyratory (all measurement locations) | Cycles to 6 mm | 25 | 7619 | 1180 | 15.5 | 1928 | 25.3 | 1738 |
| | Cycles to 12 mm | 25 | 11879 | 2030 | 17.1 | 2686 | 22.6 | 2270 |
| | Creep Slope | 24 | 0.36 | 0.057 | 16.0 | 0.116 | 32.4 | 0.106 |
| | Stripping Slope | 24 | 1.09 | 0.186 | 17.1 | 0.229 | 21.0 | 0.172 |
| | Cycles to Inflection Point | 24 | 4605 | 1091 | 23.7 | 1510 | 32.8 | 1219 |
| WY gyratory (except middle measurement locations) | Cycles to 6 mm | 25 | 8193 | 1262 | 15.4 | 2022 | 24.7 | 1815 |
| | Cycles to 12 mm | 19 | 12919 | 2225 | 17.2 | 2902 | 22.5 | 2438 |
| | Creep Slope | 24 | 0.32 | 0.063 | 19.6 | 0.100 | 30.9 | 0.089 |
| | Stripping Slope | 24 | 0.91 | 0.151 | 16.5 | 0.177 | 19.4 | 0.141 |
| | Cycles to Inflection Point | 25 | 4756 | 1093 | 23.0 | 1469 | 30.9 | 1250 |
| WY gyratory (except end measurement locations) | Cycles to 6 mm | 25 | 7041 | 1138 | 16.2 | 1843 | 26.2 | 1659 |
| | Cycles to 12 mm | 25 | 10517 | 1883 | 17.9 | 2492 | 23.7 | 2106 |
| | Creep Slope | 24 | 0.38 | 0.054 | 14.1 | 0.106 | 27.8 | 0.099 |
| | Stripping Slope | 24 | 1.36 | 0.250 | 18.4 | 0.274 | 20.2 | 0.210 |
| | Cycles to Inflection Point | 24 | 4290 | 1161 | 27.1 | 1525 | 35.5 | 1285 |
| WY Slab (all measurement locations) | Cycles to 6 mm | 10 | 11870 | 1620 | 13.6 | 2385 | 20.1 | 2092 |
| | Cycles to 12 mm | 5 | 16540 | 858 | 5.2 | 1478 | 8.9 | 1347 |
| | Creep Slope | 10 | 0.21 | 0.031 | 14.7 | 0.048 | 22.4 | 0.040 |
| | Stripping Slope | 10 | 0.69 | 0.120 | 17.4 | 0.163 | 23.7 | 0.131 |
| | Cycles to Inflection Point | 10 | 7540 | 1555 | 20.6 | 2214 | 29.4 | 1814 |
| WY slab (except middle measurement locations) | Cycles to 6 mm | 9 | 11544 | 1414 | 12.3 | 1713 | 14.8 | 1391 |
| | Cycles to 12 mm | 5 | 17460 | 728 | 4.2 | 1793 | 10.3 | 1717 |
| | Creep Slope | 10 | 0.22 | 0.026 | 12.3 | 0.047 | 21.9 | 0.043 |
| | Stripping Slope | 9 | 0.59 | 0.085 | 14.5 | 0.096 | 16.3 | 0.075 |
| | Cycles to Inflection Point | 10 | 7495 | 1478 | 19.7 | 2181 | 29.1 | 1914 |
| WY slab (except end measurement locations) | Cycles to 6 mm | 10 | 11480 | 1795 | 15.6 | 2292 | 20.0 | 1908 |
| | Cycles to 12 mm | 6 | 16017 | 1244 | 7.8 | 1794 | 11.2 | 1563 |
| | Creep Slope | 9 | 0.20 | 0.046 | 23.6 | 0.043 | 21.8 | 0.027 |
| | Stripping Slope | 10 | 0.79 | 0.175 | 22.0 | 0.190 | 23.9 | 0.144 |
| | Cycles to Inflection Point | 10 | 7160 | 1809 | 25.3 | 2506 | 35.0 | 2156 |

#### *4.3.2.1 Comparison of Statistics from Different Measurement Locations*

Figure 4-5 and Figure 4-6 show the averages and COV of the properties from various measurement locations. The results of statistical comparisons are provided in Table 4-9 through Table 4-13. Discussion of the results follows.

STATISTICAL COMPARISON OF AVERAGE VALUES

Figure 4-5 provides graphical comparison of the average values using different measurement locations. Table 4-9 provides the results of statistical comparison of the averages of various properties of gyratory and slab specimens using different measurement locations: all measurement locations, all except three middle measurement locations, and all except two measurement locations at each end. In each table, the first two comparisons correspond to gyratory specimens and the third and fourth comparisons correspond to the slab specimens. The following are observed from Figure 4-5 and Table 4-9.

1. For the gyratory specimens, excluding the data from the three middle measurement locations resulted in an increase in the average number of cycles to both 6-mm and 12-mm rut depth, decreases in the creep and stripping slopes, and an increase in the number of cycles to the inflection point. This is because the deformations at the location of three middle measurement locations are larger than those at other measurement locations and, therefore, excluding them would result in an estimate of greater resistance of the mixture to deformation. The effect of excluding the readings from the three middle measurement locations is statistically significant for the stripping slope (Table 4-9).

2. For the gyratory specimens, excluding the data from the end measurement locations resulted in decreases in the average number of cycles to 6-mm and 12-mm rut depth and the inflection point and an increase in the creep and stripping slopes. This is because the deformations at the ends are smaller than those at other locations and excluding them yields an estimate of less resistance of the mixture to deformation. Among the comparisons, the differences between numbers of passes to 12-mm rut depth and between the stripping slopes are statistically significant.

3. For the slab specimens, excluding the data from the three middle measurement locations or the four end measurement locations does not show any consistent trend of decrease or increase in the average properties. This might be because the deformation of slabs is more uniform among various measurement locations than those of gyratory specimens. The stripping slope is shown to be significantly decreased by excluding the three middle measurement locations. However, the physical significance of this difference is not clear, since an increase in stripping slope is expected when the smaller deformation at the location of the three middle measurement locations are excluded from the analysis.

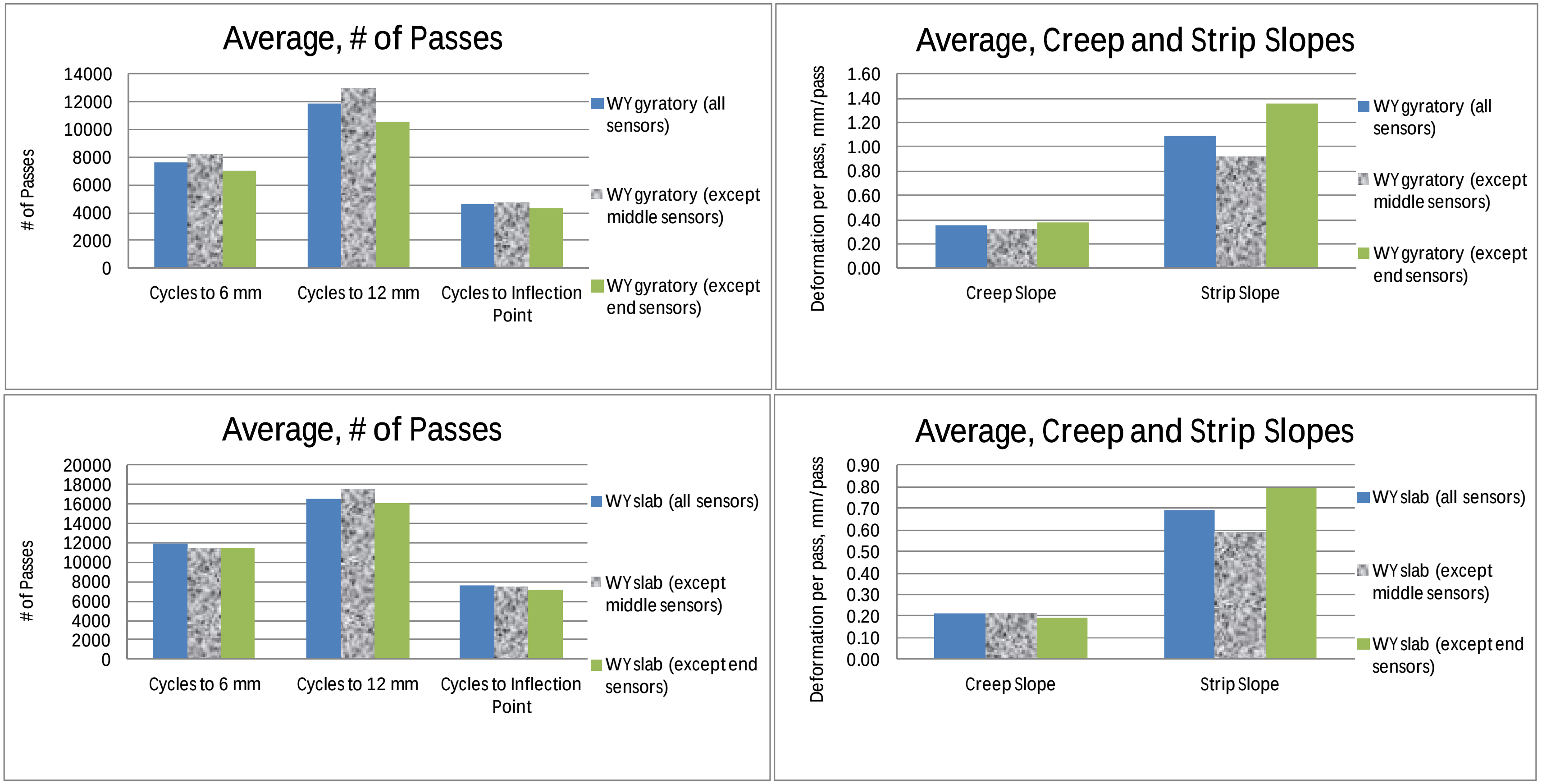


**Figure 4-5-Comparison of the average properties measured using all measurement locations, all except middle three measurement locations, and all except the end measurement locations**

**Table 4-9- Statistical t-test for comparison of the average # of cycles to 6-mm and 12-mm rut depths, creep and stripping slopes, and # of cycles to inflection point of WY gyratory and slab specimens from various measurement location sets**

| Comparison | Property | Averages | S | T | df | Critical t | P | Decision |
|---|---|---|---|---|---|---|---|---|
| WY gyratory (all measurement locations) Vs. WY gyratory (except middle measurement locations) | Cycles to 6 mm | 7619 vs. 8193 | 1777 | -1.14 | 48 | 1.68 | 0.130 | Accept |
| | Cycles to 12 mm | 11879 vs. 12919 | 2344 | -1.46 | 42 | 1.68 | 0.076 | Accept |
| | Creep Slope | 0.36 vs. 0.32 | 0.098 | 1.24 | 46 | 1.68 | 0.111 | Accept |
| | Stripping Slope | 1.09 vs. 0.91 | 0.157 | 3.86 | 46 | 1.68 | 0.000 | Reject |
| | Cycles to Inflection Point | 4605 vs. 4756 | 1235 | -0.43 | 47 | 1.68 | 0.335 | Accept |
| WY gyratory (all measurement locations) Vs. WY gyratory (except end measurement locations ) | Cycles to 6 mm | 7619 vs. 7041 | 1699 | 1.20 | 48 | 1.68 | 0.117 | Accept |
| | Cycles to 12 mm | 11879 vs. 10517 | 2190 | 2.20 | 48 | 1.68 | 0.016 | Reject |
| | Creep Slope | 0.36 vs. 0.38 | 0.102 | -0.72 | 46 | 1.68 | 0.237 | Accept |
| | Stripping Slope | 1.09 vs. 1.36 | 0.192 | -4.84 | 46 | 1.68 | 0.000 | Reject |
| | Cycles to Inflection Point | 4605 vs. 4290 | 1252 | 0.87 | 46 | 1.68 | 0.194 | Accept |
| WY Slab (all measurement locations) Vs. WY slab (except middle measurement locations) | Cycles to 6 mm | 11870 vs. 11544 | 1796 | 0.39 | 17 | 1.74 | 0.349 | Accept |
| | Cycles to 12 mm | 16540 vs. 17460 | 1543 | -0.94 | 8 | 1.86 | 0.187 | Accept |
| | Creep Slope | 0.21 vs. 0.22 | 0.042 | -0.15 | 18 | 1.73 | 0.442 | Accept |
| | Stripping Slope | 0.69 vs. 0.59 | 0.108 | 2.03 | 17 | 1.74 | 0.029 | Reject |
| | Cycles to Inflection Point | 7540 vs. 7495 | 1865 | 0.05 | 18 | 1.73 | 0.479 | Accept |
| WY Slab (all measurement locations) Vs. WY Slab (except end measurement locations) | Cycles to 6 mm | 11870 vs. 11480 | 2002 | 0.44 | 18 | 1.73 | 0.334 | Accept |
| | Cycles to 12 mm | 16540 vs. 16017 | 1471 | 0.59 | 9 | a1.83 | 0.286 | Accept |
| | Creep Slope | 0.21 vs. 0.2 | 0.035 | 1.04 | 17 | 1.74 | 0.157 | Accept |
| | Stripping Slope | 0.69 vs. 0.79 | 0.138 | -1.70 | 18 | 1.73 | 0.053 | Accept |
| | Cycles to Inflection Point | 7540 vs. 7160 | 1992 | 0.43 | 18 | 1.73 | 0.337 | Accept |

### STATISTICAL COMPARISON OF VARIABILITY

Table 4-10 through Table 4-13 provide the results of statistical comparison of the repeatability and reproducibility COV of the number of passes to 6-mm and 12-mm rut depth, creep slope, stripping slope, and number of cycles to inflection point using different measurement locations: all, all except middle three, and all except two at each end. The COV values are shown in Figure 4-6. As indicated by Table 4-10 through Table 4-13, there are no specific trends of decrease or increase in variability by excluding data from any measurement location sets. Moreover, none of the differences between the COVs corresponding to different measurement locations are statistically significant.

In summary, for the gyratory specimens of the poorly-performing mixture, excluding the data from the four end measurement locations provides significantly smaller average number of passes to 12-mm rut depth and larger average stripping slope, which are a more conservative estimate of mixture performance. On the other hand, excluding the data from the three middle measurement locations provided a significantly smaller stripping slope, which is a less conservative estimate of the mixture's performance. In terms of variability, excluding the measurements from the end or the middle measurement locations did not significantly improve the variability of the properties. The variation of the deformation along various measurement locations can be improved by reducing the confinement at the ends and increasing the confinement around the midpoint of gyratory specimens, as discussed in Appendix C.

Thus, it can be concluded that the precision estimates of AASHTO T 324 should be prepared by pooling the statistics from all sets of measurement locations. Considering that at various measurement locations the deformations are interdependent, excluding the deformation from any measurement location is not recommended. An average deformation from all measurement locations would provide a more comprehensive representation of the entire deformation basin.

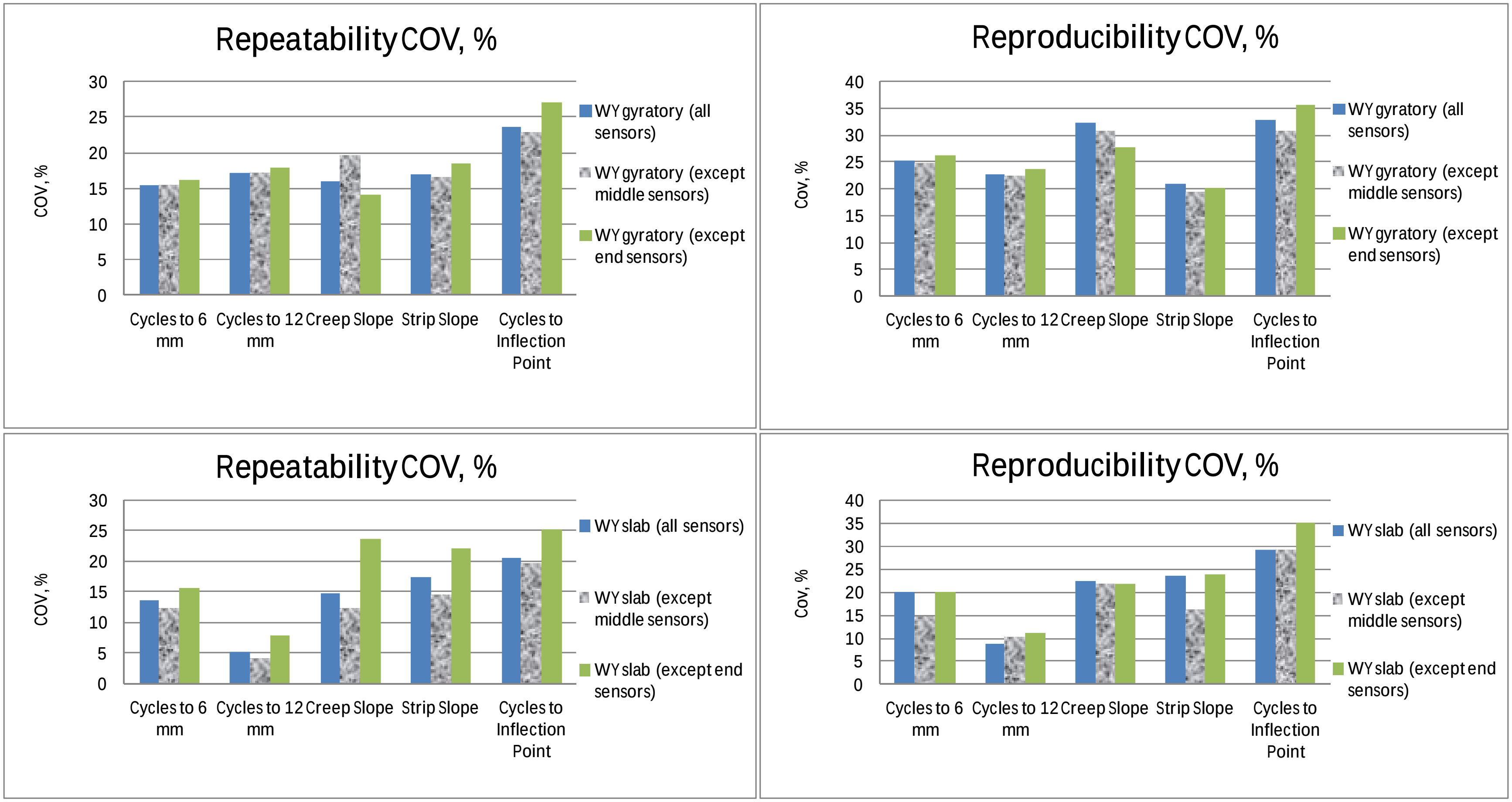


**Figure 4-6- Comparison of the repeatability and reproducibility coefficients of variation of properties of the poorly-performing mixture using all measurement locations, all except middle three measurement locations, and all except the end measurement locations**

**Table 4-10- Statistical F-test on repeatability coefficients of variation of number of cycles to 6-mm and 12-mm rut depth, and number of cycles to inflection point of gyratory and slab specimens of Wyoming mixture measured using different measurement locations sets**

| Comparison | Property | COV,% | F | Critical F | df1 | df2 | P | Decision |
|---|---|---|---|---|---|---|---|---|
| WY gyratory (all measurement locations) Vs. WY gyratory (except middle measurement locations) | Cycles to 6 mm | 15.5 vs. 15.4 | 1.01 | 1.98 | 24 | 24 | 0.490 | Accept |
| | Cycles to 12 mm | 17.1 vs. 17.2 | 1.02 | 2.05 | 18 | 24 | 0.478 | Accept |
| | Cycles to Inflection Point | 23.7 vs. 23 | 1.06 | 1.99 | 23 | 24 | 0.441 | Accept |
| WY gyratory (all measurement locations) Vs. WY gyratory (except end measurement locations) | Cycles to 6 mm | 15.5 vs. 16.2 | 1.09 | 1.98 | 24 | 24 | 0.418 | Accept |
| | Cycles to 12 mm | 17.1 vs. 17.9 | 1.10 | 1.98 | 24 | 24 | 0.411 | Accept |
| | Cycles to Inflection Point | 23.7 vs. 27.1 | 1.31 | 2.01 | 23 | 23 | 0.263 | Accept |
| WY slab (all measurement locations) Vs. WY slab (except middle measurement locations) | Cycles to 6 mm | 13.6 vs. 12.3 | 1.24 | 3.39 | 9 | 8 | 0.386 | Accept |
| | Cycles to 12 mm | 5.2 vs. 4.2 | 1.55 | 6.39 | 4 | 4 | 0.341 | Accept |
| | Cycles to Inflection Point | 20.6 vs. 19.7 | 1.09 | 3.18 | 9 | 9 | 0.449 | Accept |
| WY slab (all measurement locations) Vs. WY slab (except end measurement locations) | Cycles to 6 mm | 13.6 vs. 15.6 | 1.31 | 3.18 | 9 | 9 | 0.346 | Accept |
| | Cycles to 12 mm | 5.2 vs. 7.8 | 2.24 | 6.26 | 5 | 4 | 0.227 | Accept |
| | Cycles to Inflection Point | 20.6 vs. 25.3 | 1.50 | 3.18 | 9 | 9 | 0.278 | Accept |

**Table 4-11- Statistical F-test on repeatability coefficients of variation of creep slope and stripping slope of gyratory and slab specimens of Wyoming mixture measured using different measurement locations sets**

| Comparison | Property | COV, % | F | Critical F | df1 | df2 | P | Decision |
|---|---|---|---|---|---|---|---|---|
| WY gyratory (all measurement locations) Vs. WY gyratory (except middle measurement locations) | Creep Slope | 16 vs. 19.6 | 1.50 | 2.01 | 23 | 23 | 0.170 | Accept |
| | Stripping Slope | 17.1 vs. 16.5 | 1.07 | 2.01 | 23 | 23 | 0.437 | Accept |
| WY gyratory (all measurement locations) Vs. WY gyratory (except end measurement locations) | Creep Slope | 16 vs. 14.1 | 1.28 | 2.01 | 23 | 23 | 0.278 | Accept |
| | Stripping Slope | 17.1 vs. 18.4 | 1.17 | 2.01 | 23 | 23 | 0.357 | Accept |
| WY slab (all measurement locations) Vs. WY slab (except middle measurement locations) | Creep Slope | 14.7 vs. 12.3 | 1.43 | 3.18 | 9 | 9 | 0.303 | Accept |
| | Stripping Slope | 17.4 vs. 14.5 | 1.45 | 3.39 | 9 | 8 | 0.306 | Accept |
| WY slab (all measurement locations) Vs. WY slab (except end measurement locations) | Creep Slope | 14.7 vs. 23.6 | 2.58 | 3.23 | 8 | 9 | 0.090 | Accept |
| | Stripping Slope | 17.4 vs. 22 | 1.60 | 3.18 | 9 | 9 | 0.247 | Accept |

**Table 4-12- Statistical F-test on reproducibility coefficients of variation of number of cycles to 6-mm and 12-mm rut depth and number of cycles to inflection point of gyratory specimens of Wyoming mixture measured using different measurement locations sets**

| Comparison | Property | COV, # of Cycles | F | Critical F | df1 | df2 | P | Decision |
|---|---|---|---|---|---|---|---|---|
| WY gyratory (all measurement locations) Vs. WY gyratory (except middle measurement locations) | Cycles to 6 mm | 25.3 vs. 24.7 | 1.05 | 1.98 | 24 | 24 | 0.452 | Accept |
| | Cycles to 12 mm | 22.6 vs. 22.5 | 1.01 | 2.15 | 24 | 18 | 0.496 | Accept |
| | Cycles to Inflection Point | 32.8 vs. 30.9 | 1.13 | 1.99 | 23 | 24 | 0.387 | Accept |
| WY gyratory (all measurement locations) Vs. WY gyratory (except end measurement locations) | Cycles to 6 mm | 24.7 vs. 26.2 | 1.12 | 1.98 | 24 | 24 | 0.388 | Accept |
| | Cycles to 12 mm | 22.6 vs. 23.7 | 1.10 | 1.98 | 24 | 24 | 0.410 | Accept |
| | Cycles to Inflection Point | 32.8 vs. 35.5 | 1.17 | 2.01 | 23 | 23 | 0.351 | Accept |
| WY Slab (all measurement locations) Vs. WY slab (except middle measurement locations) | Cycles to 6 mm | 20.1 vs. 14.8 | 1.83 | 3.39 | 9 | 8 | 0.203 | Accept |
| | Cycles to 12 mm | 8.9 vs. 10.3 | 1.32 | 6.39 | 4 | 4 | 0.397 | Accept |
| | Cycles to Inflection Point | 29.4 vs. 29.1 | 1.02 | 3.18 | 9 | 9 | 0.490 | Accept |
| WY Slab (all measurement locations) Vs. WY slab (except end measurement locations) | Cycles to 6 mm | 20.1 vs. 20 | 1.01 | 3.18 | 9 | 9 | 0.493 | Accept |
| | Cycles to 12 mm | 8.9 vs. 11.2 | 1.57 | 6.26 | 5 | 4 | 0.341 | Accept |
| | Cycles to Inflection Point | 29.4 vs. 35 | 1.42 | 3.18 | 9 | 9 | 0.304 | Accept |

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**Table 4-13- Statistical F-test on reproducibility coefficients of variation of number of creep slope and stripping slope of gyratory specimens of Wyoming mixture measured using different measurement locations sets**

| Comparison | Property | COV, % | F | Critical F | df1 | df2 | P | Decision |
|---|---|---|---|---|---|---|---|---|
| WY gyratory (all measurement locations) Vs. WY gyratory (except middle measurement locations) | Creep Slope | 32.4 vs. 30.9 | 1.10 | 2.01 | 23 | 23 | 0.410 | Accept |
| | Stripping Slope | 21 vs. 19.4 | 1.18 | 2.01 | 23 | 23 | 0.347 | Accept |
| WY gyratory (all measurement locations) Vs. WY gyratory (except end measurement locations) | Creep Slope | 32.4 vs. 27.8 | 1.36 | 2.01 | 23 | 23 | 0.235 | Accept |
| | Stripping Slope | 21 vs. 20.2 | 1.08 | 2.01 | 23 | 23 | 0.425 | Accept |
| WY Slab (all measurement locations) Vs. WY slab (except middle measurement locations) | Creep Slope | 22.4 vs. 21.9 | 1.04 | 3.18 | 9 | 9 | 0.476 | Accept |
| | Stripping Slope | 23.7 vs. 16.3 | 2.12 | 3.39 | 9 | 8 | 0.152 | Accept |
| WY Slab (all measurement locations) Vs. WY slab (except end measurement locations) | Creep Slope | 22.4 vs. 21.8 | 1.06 | 3.39 | 9 | 8 | 0.475 | Accept |
| | Stripping Slope | 23.7 vs. 23.9 | 1.02 | 3.18 | 9 | 9 | 0.489 | Accept |

#### *4.3.2.2 Comparison of Statistics from Gyratory and Slab Specimens*

Figure 4-7 and Figure 4-8 provide the graphical representations of the averages and repeatability/reproducibility statistics of the properties of the gyratory and slab specimens. Table 4-14 through Table 4-18 provide the results of statistical comparison of the averages and variability of the properties of gyratory and slab specimens. The COV values are the basis of repeatability/reproducibility precision estimates since there are strong relationships between the averages and standard deviations. In each table, the first comparison corresponds to all measurement locations, the second comparison corresponds to all except three middle measurement locations, and the third comparison corresponds to all except two measurement locations at each end. The following are observed from the graphs and tables:

1. The comparison of the average properties of gyratory and slab specimens in Table 4-14 and Figure 4-7 indicates that regardless of the measurement locations used, the slab specimens of the poorly-performing mixture are more resistance to rutting and moisture damage than the gyratory specimens. The difference between average properties of slab and gyratory specimens become statically significant when the three middle measurement locations or the four end measurement locations are excluded from the analysis. This suggests that for the poorly-performing mixtures, unlike well-performing mixture, gyratory specimens are less

resistant to rut and moisture damage. This is because for the well-performing mixture, the mold for gyratory specimens provides confinement higher than the confinement for slabs; so gyratory specimens perform better. However, for the poorly-performing mixture, the high confinement of gyratory specimens causes increased differential deformation between the mid-point and the ends. This is because the material is not allowed to move laterally at the ends but free to move at the center. When deformation increases beyond a certain level, the wheels' dynamic for gyratory specimens intensifies resulting in more deformation and poorer performance of gyratory than slab specimens.

2. The comparison of variability of properties of gyratory and slab specimens in Table 4-15 through Table 4-18 indicate that the COVs of the majority of the properties of slab specimens are significantly smaller than those of gyratory specimens. However, this could be attributed to the significantly smaller degrees of freedom (the number of values in the final calculation of F statistics) of slab specimens than those of gyratory specimens.

In summary, since depending on the measurement locations used, the average of the properties measured using gyratory and slab specimens could be significantly different, the type of specimens used should be recorded along with the wheel track test results of poorly-performing mixtures. The differences between properties of gyratory and slab specimens can be reduced by decreasing the confinement at the ends and increasing the confinement around the midpoint of gyratory specimens.

The significantly smaller COV of the number of passes to 12-mm rut depth for the slab specimens than for the gyratory specimens is most probably due to the significantly smaller number of slab specimens compared to gyratory specimens. Therefore, in preparing the precision estimates of the number of passes to 12-mm rut depth, the COV corresponding to gyratory specimens were used. For other properties, where the COVs associated with the gyratory and slab specimens are not significantly different, they were pooled together.

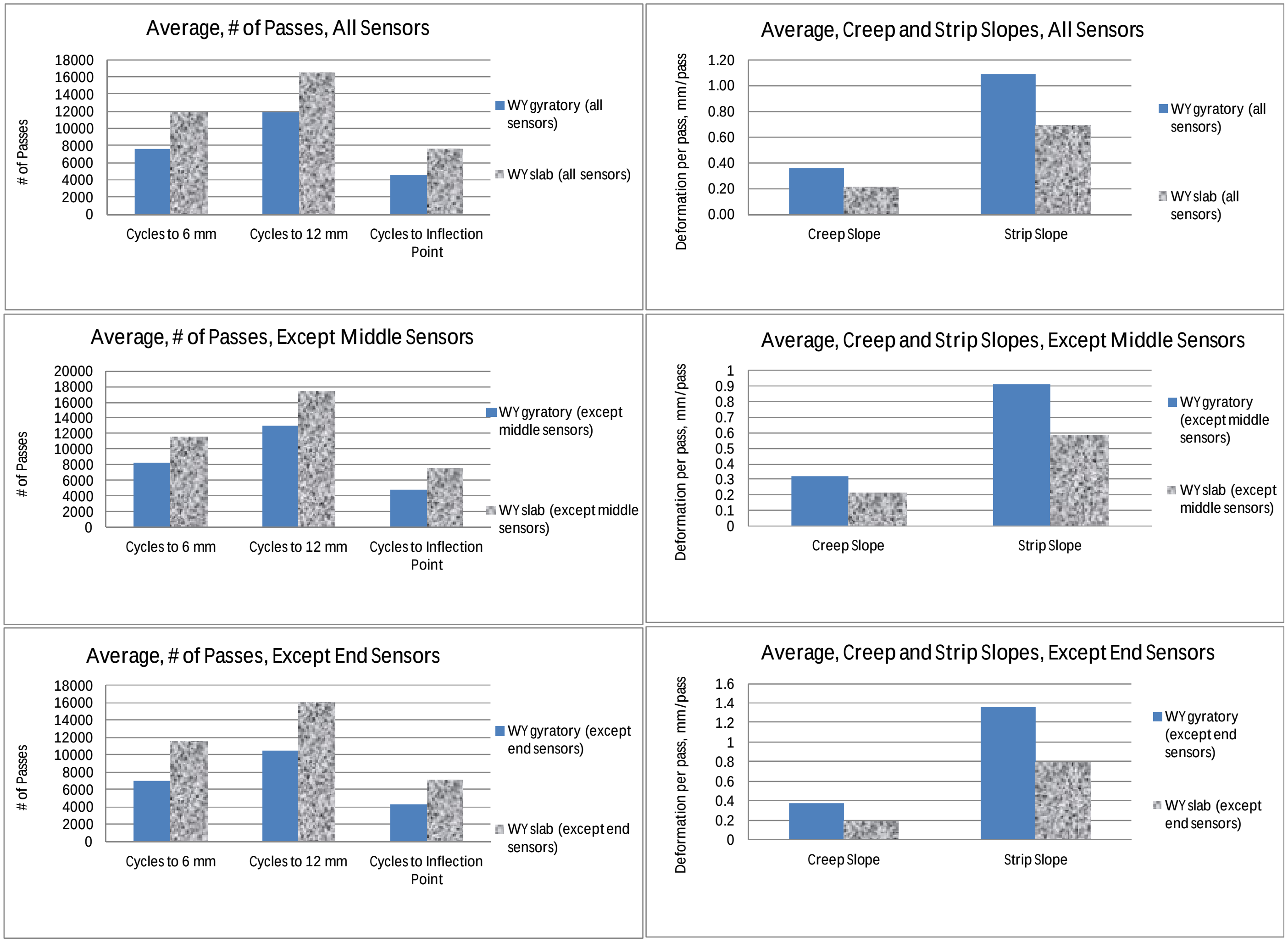

**Figure 4-7- Comparison of average properties of gyratory and slab specimens of WY mixture measured using all measurement locations, all except middle three measurement locations, and all except the end measurement locations**

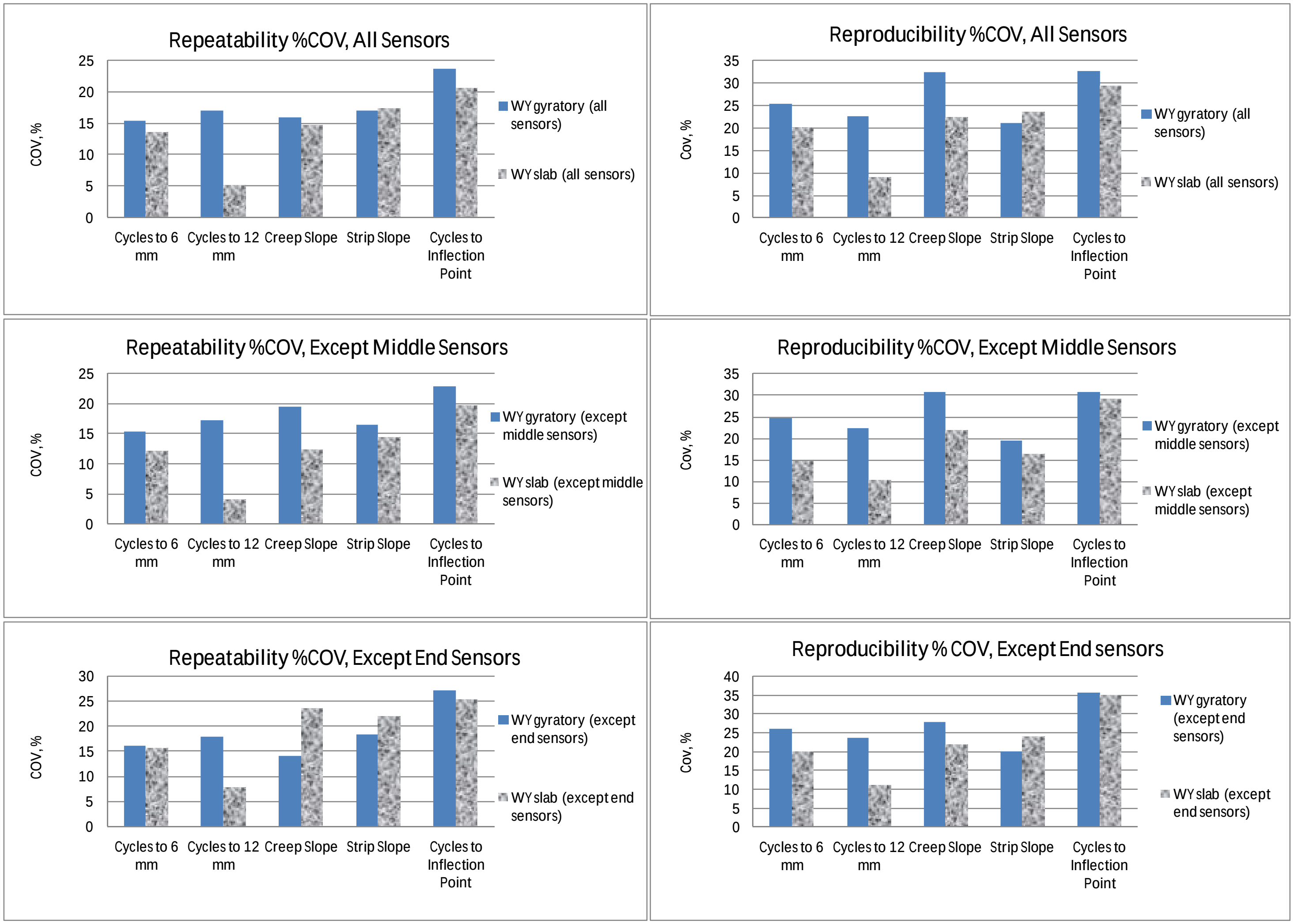

**Figure 4-8- Comparison of coefficients of variation (COV) of properties of gyratory and slab specimens measured using all measurement locations, all except middle three measurement locations, and all except the end measurement locations**

**Table 4-14- Statistical t-test for comparison of average properties of gyratory and slab specimens of WY mixture using various measurement location sets**

| Comparison | Property | Averages | S | T | df | Critical t | P | Decision |
|---|---|---|---|---|---|---|---|---|
| WY gyratory (all measurement locations) Vs. WY Slab (all measurement locations) | Cycles to 6 mm | 7619 vs. 11870 | 1841 | -1.10 | 33 | 1.69 | 0.139 | Accept |
| | Cycles to 12 mm | 11879 vs. 16540 | 2163 | -1.58 | 28 | 1.70 | 0.063 | Accept |
| | Creep Slope | 0.358 vs. 0.213 | 0.093 | 1.31 | 32 | 1.69 | 0.100 | Accept |
| | Stripping Slope | 1.09 vs. 0.69 | 0.161 | 3.77 | 32 | 1.69 | 0.000 | Reject |
| | Cycles to Inflection Point | 4605 vs. 7540 | 1412 | -0.37 | 32 | 1.69 | 0.355 | Accept |
| WY gyratory (except middle measurement locations) Vs. WY slab (except middle measurement locations) | Cycles to 6 mm | 8193 vs. 11544 | 1719 | -5.02 | 32 | 1.69 | 0.000 | Reject |
| | Cycles to 12 mm | 12919 vs. 17460 | 2324 | -3.89 | 22 | 1.72 | 0.000 | Reject |
| | Creep Slope | 0.323 vs. 0.215 | 0.079 | 3.62 | 32 | 1.69 | 0.000 | Reject |
| | Stripping Slope | 0.914 vs. 0.589 | 0.127 | 6.53 | 31 | 1.70 | 0.000 | Reject |
| | Cycles to Inflection Point | 4756 vs. 7495 | 1461 | -5.01 | 33 | 1.69 | 0.000 | Reject |
| WY gyratory (except 2 ends ) Vs. WY Slab (except 2 ends ) | Cycles to 6 mm | 7041 vs. 11480 | 1730 | -6.86 | 33 | 1.69 | 0.000 | Reject |
| | Cycles to 12 mm | 10517 vs. 16017 | 2023 | -5.98 | 29 | 1.70 | 0.000 | Reject |
| | Creep Slope | 0.38 vs. 0.196 | 0.086 | 5.46 | 31 | 1.70 | 0.000 | Reject |
| | Stripping Slope | 1.357 vs. 0.794 | 0.193 | 7.73 | 32 | 1.69 | 0.000 | Reject |
| | Cycles to Inflection Point | 4290 vs. 7160 | 1579 | -4.83 | 32 | 1.69 | 0.000 | Reject |

**Table 4-15- Statistical F-test for comparison of repeatability coefficients of variation (COV) of number of cycles to 6-mm and 12-mm rut depth and to the inflection point for gyratory and slab specimens of WY mixture using various measurement location sets**

| Comparison | Property | COV of # of Cycles | F | Critical F | df 1 | df 2 | P | Decision |
|---|---|---|---|---|---|---|---|---|
| WY gyratory (all measurement locations) Vs. WY Slab (all measurement locations) | Cycles to 6 mm | 15.5 vs. 13.6 | 1.29 | 2.90 | 24 | 9 | 0.361 | Accept |
| | Cycles to 12 mm | 17.1 vs. 5.2 | 10.85 | 5.77 | 24 | 4 | 0.016 | Reject |
| | Cycles to Inflection Point | 23.7 vs. 20.6 | 1.32 | 2.91 | 23 | 9 | 0.345 | Accept |
| WY gyratory (except middle measurement locations) Vs. WY slab (except middle measurement locations) | Cycles to 6 mm | 15.4 vs. 12.3 | 1.58 | 3.12 | 24 | 8 | 0.257 | Accept |
| | Cycles to 12 mm | 17.2 vs. 4.2 | 17.06 | 5.82 | 18 | 4 | 0.007 | Reject |
| | Cycles to Inflection Point | 23 vs. 19.7 | 1.36 | 2.90 | 24 | 9 | 0.328 | Accept |
| WY gyratory (except end measurement locations) Vs. WY slab (except end measurement locations) | Cycles to 6 mm | 16.2 vs. 15.6 | 1.07 | 2.90 | 24 | 9 | 0.487 | Accept |
| | Cycles to 12 mm | 17.9 vs. 7.8 | 5.31 | 4.53 | 24 | 5 | 0.036 | Reject |
| | Cycles to Inflection Point | 27.1 vs. 25.3 | 1.15 | 2.91 | 23 | 9 | 0.436 | Accept |

**Table 4-16- Statistical F-test for comparison of repeatability coefficient of variations of creep and stripping slope of gyratory and slab specimens of WY mixture using various measurement location sets**

| Comparison | Property | COV (%) of Slope | F | Critical F | df 1 | df 2 | P | Decision |
|---|---|---|---|---|---|---|---|---|
| WY gyratory (all measurement locations) Vs. WY Slab (all measurement locations | Creep Slope | 16 vs. 14.7 | 1.19 | 2.91 | 23 | 9 | 0.414 | Accept |
| | Stripping Slope | 17.1 vs. 17.4 | 1.04 | 2.32 | 9 | 23 | 0.439 | Accept |
| WY gyratory (except middle measurement locations) Vs. WY slab (except middle measurement locations) | Creep Slope | 19.6 vs. 12.3 | 2.54 | 2.91 | 23 | 9 | 0.075 | Accept |
| | Stripping Slope | 16.5 vs. 14.5 | 1.30 | 3.12 | 23 | 8 | 0.367 | Accept |
| WY gyratory (except end measurement locations) Vs. WY slab (except end measurement locations) | Creep Slope | 14.1 vs. 23.6 | 2.78 | 2.37 | 8 | 23 | 0.026 | Reject |
| | Stripping Slope | 18.4 vs. 22 | 1.43 | 2.32 | 9 | 23 | 0.234 | Accept |

**Table 4-17- Statistical F-test for comparison of reproducibility coefficients of variation (COV) of number of cycles to 6-mm and 12-mm rut depth and to the inflection point for gyratory and slab specimens of WY mixture using various measurement location sets**

| Comparison | Property | COV of # of Cycles | F | Critical F | df1 | df2 | P | Decision |
|---|---|---|---|---|---|---|---|---|
| WY gyratory (all measurement locations) Vs. WY Slab (all measurement locations) | Cycles to 6 mm | 25.3 vs. 20.1 | 1.59 | 2.90 | 24 | 9 | 0.240 | Accept |
| | Cycles to 12 mm | 22.6 vs. 8.9 | 6.41 | 5.77 | 24 | 4 | 0.042 | Reject |
| | Cycles to Inflection Point | 32.8 vs. 29.4 | 1.25 | 2.91 | 23 | 9 | 0.381 | Accept |
| WY gyratory (except middle measurement locations) Vs. WY slab (except middle measurement locations) | Cycles to 6 mm | 24.7 vs. 14.8 | 2.77 | 3.12 | 24 | 8 | 0.069 | Accept |
| | Cycles to 12 mm | 22.5 vs. 10.3 | 4.78 | 5.82 | 18 | 4 | 0.070 | Accept |
| | Cycles to Inflection Point | 30.9 vs. 29.1 | 1.13 | 2.90 | 24 | 9 | 0.450 | Accept |
| WY gyratory (except end measurement locations) Vs. WY slab (except end measurement locations) | Cycles to 6 mm | 26.2 vs. 20 | 1.72 | 2.90 | 24 | 9 | 0.201 | Accept |
| | Cycles to 12 mm | 23.7 vs. 11.2 | 4.48 | 4.53 | 24 | 5 | 0.051 | Accept |
| | Cycles to Inflection Point | 35.5 vs. 35 | 1.03 | 2.91 | 23 | 9 | 0.511 | Accept |

**Table 4-18- Statistical F-test for comparison of reproducibility coefficient of variations (COV) of creep and stripping slope of gyratory and slab specimens of WY mixture using various measurement location sets**

| Comparison | Property | COV (%) of Slope | F | Critical F | df1 | df2 | P | Decision |
|---|---|---|---|---|---|---|---|---|
| WY gyratory (all measurement locations) Vs. WY Slab (all measurement locations) | Creep Slope | 32.4 vs. 22.4 | 2.09 | 2.91 | 23 | 9 | 0.125 | Accept |
| | Stripping Slope | 21 vs. 23.7 | 1.27 | 2.32 | 9 | 23 | 0.304 | Accept |
| WY gyratory (except middle measurement locations) Vs. WY slab (except middle measurement locations) | Creep Slope | 30.9 vs. 21.9 | 1.98 | 2.91 | 23 | 9 | 0.144 | Accept |
| | Stripping Slope | 19.4 vs. 16.3 | 1.41 | 3.12 | 23 | 8 | 0.319 | Accept |
| WY gyratory (except end measurement locations) Vs. WY slab (except end measurement locations) | Creep Slope | 27.8 vs. 21.8 | 1.63 | 3.12 | 23 | 8 | 0.243 | Accept |
| | Stripping Slope | 20.2 vs. 23.9 | 1.40 | 2.32 | 9 | 23 | 0.244 | Accept |

### 4.3.3 Pooled Statistics

Precision estimates were prepared for the properties of the two types of mixtures. For the well-performing mixture, the precision estimates are prepared for deformation after specific numbers of passes and for creep slope. For the poorly-performing mixture, the precision estimates are prepared for the number of passes to the threshold rut depth, creep slope, stripping slope, and number of passes to the inflection point. Since creep slope is a common property for both well-performing and poorly performing mixtures, statistical analysis will be conducted to determine if the statistics of creep slope from the two mixture types are the same and can be pooled together. Precision estimates of all other properties will be prepared independent of each other. The following sections explain which statistics were pooled in determining the precision estimates of the properties.

#### *4.3.3.1 Well-Performing Mixture*

For the rutting and moisture resistant mixture, the statistical comparisons in Table 4-3 and Table 4-4 indicated that the COV of the properties measured from any sets of measurement locations are not significantly different. Therefore, they are pooled together. Additionally, the COV of the properties of the gyratory and slab specimens, as shown in Table 4-6 and Table 4-7 are not significantly different. For the rut depth after each set of pass numbers, the COVs are pooled from different specimen types as presented in Table 4-19. However, for the creep slope, although the difference between COVs corresponding to gyratory and slab specimens are not statistically significant, the COVs are not pooled. This is because the rejection probability for the comparison of the repeatability COV of creep slope of gyratory and slab specimens is only slightly larger than 0.05% (0.052 % in Table 4-6) and considering the magnitude of the difference between the variability of creep slope of gyratory and slab specimens, this difference is considered significant from practical stand point. Since the number of gyratory specimens is larger than the number of slabs, the COVs measured from gyratory specimens are considered more accurate and therefore, the precision estimates of creep slope is determined using the COVs corresponding to gyratory specimens as presented in Table 4-19.

**Table 4-19- Pooled COV of deformation after 10, 15, and 20 thousand number of passes and of creep slope for well-performing mixture**

| Property | Repeatability COV, % | Reproducibility COV, % |
|---|---|---|
| Rut after 10,000 passes (mm) | 13.0 | 24.9 |
| Rut after 15,000 passes (mm) | 14.1 | 25.9 |
| Rut after 20,000 passes (mm) | 15.4 | 27.1 |
| Creep slope (mm/pass) | 16.5 | 26.2 |

A statistical comparison of the repeatability and reproducibility COVs of the rut depth after various number of passes was conducted to determine if they are the same and can be pooled together. The results are shown in Table 4-20. As shown in the table, the COVs of the rut depths after various number of passes are not significantly different. Therefore, the COVs of rut depth after 10,000, 15,000, and 20,000 are pooled together, resulting in the 1s repeatability COV of 14.2% and 1s reproducibility COV of 26.0%.

**Table 4-20- Statistical comparison of the pooled COV of deformation after 10, 15, and 20 thousands number of passes for well-performing mixture**

| Comparison, Passes | Statistics | F | Critical F | df1 | df2 | P | Decision |
|---|---|---|---|---|---|---|---|
| 10,000 vs. 15,000 | Repeatability | 1.18 | 1.50 | 66 | 67 | 0.25 | Accept |
| | Reproducibility | 1.09 | 1.50 | 66 | 67 | 0.37 | Accept |
| 15,000 vs. 20,000 | Repeatability | 1.19 | 1.50 | 66 | 66 | 0.24 | Accept |
| | Reproducibility | 1.09 | 1.50 | 66 | 66 | 0.36 | Accept |
| 10,000 vs. 20,000 | Repeatability | 1.41 | 1.50 | 66 | 67 | 0.08 | Accept |
| | Reproducibility | 1.19 | 1.50 | 66 | 67 | 0.24 | Accept |

#### *4.3.3.2 Poorly-Performing Mixture*

For the poorly-performing mixture, the statistical comparisons in Table 4-10 through Table 4-13 showed that COV of the properties measured from various measurement location sets are not significantly different. Therefore, they are pooled together as presented in Table 4-21 and Table 4-22.

**Table 4-21- Pooled coefficients of variation (COV) of number of cycles to 6-mm and 12- mm rut depth and to inflection point for gyratory and slab specimens of the poorly-performing mixture**

| Specimen Type | Property | Repeatability STD, # of Cycles | Reproducibility STD, # of Cycles |
|---|---|---|---|
| Gyratory | Passes to 6-mm | 15.7 | 25.4 |
| | Passes to 12-mm | 17.4 | 22.9 |
| | Passes to Inflection Point | 24.6 | 33.1 |
| Slab | Passes to 6-mm | 13.8 | 18.3 |
| | Passes to 12-mm | 5.7 | 10.1 |
| | Passes to Inflection Point | 21.9 | 31.2 |

**Table 4-22- Pooled coefficients of variation (COV) of creep and stripping slopes of gyratory and slab specimens of the poorly-performing mixture**

| Specimen Type | Property | Repeatability COV, % | Reproducibility COV, % |
|---|---|---|---|
| Gyratory | Creep Slope, mm/pass | 16.6 | 30.4 |
| | Stripping Slope, mm/pass | 17.3 | 20.2 |
| Slab | Creep Slope, mm/pass | 16.9 | 22.0 |
| | Stripping Slope, mm/pass | 18.0 | 21.3 |

A statistical comparison of the variability of properties of gyratory and slab specimens in Table 4-21 and Table 4-22 was conducted to determine if the COVs are the same and can be pooled. Table 4-23 and Table 4-24 provide the results. As indicated from the tables, the repeatability/reproducibility COVs for the number of passes to 12-mm rut depth are significantly different and the reproducibility COVs of passes to 6 mm and of creep slope are significantly different. Considering the smaller number of slab specimens compared to gyratory specimens, the COV of the number of passes to 6 mm and 12-mm rut depth and of the creep slope corresponding to gyratory specimens are considered more accurate and therefore used for preparing the precision estimates. For other properties, COVs are not significantly different, and they are pooled together. The pooled COVs are presented in Table 4-25.

**Table 4-23- Results of statistical comparison of repeatability COVs of the properties of gyratory and slab specimens**

| Property | COV | F | Critical F | df1 | df2 | P | Decision |
|---|---|---|---|---|---|---|---|
| Cycles to 6 mm | 16 vs. 14 | 1.28 | 1.79 | 72 | 26 | 0.242 | Accept |
| Cycles to 12 mm | 17 vs. 6 | 9.30 | 2.29 | 66 | 13 | 0.000 | Reject |
| Cycles to Inflection Point | 25 vs. 22 | 1.26 | 1.77 | 70 | 27 | 0.253 | Accept |
| Creep Slope | 17 vs. 17 | 1.03 | 1.66 | 26 | 69 | 0.440 | Accept |
| Stripping Slope | 17 vs. 18 | 1.07 | 1.76 | 18 | 69 | 0.395 | Accept |

**Table 4-24- Results of statistical comparison of reproducibility COVs of the properties of gyratory and slab specimens**

| Property | COV | F | Critical F | df1 | df2 | P | Decision |
|---|---|---|---|---|---|---|---|
| Cycles to 6 mm | 25 vs. 18 | 1.93 | 1.79 | 72 | 26 | 0.032 | Reject |
| Cycles to 12 mm | 23 vs. 10 | 5.12 | 2.29 | 66 | 13 | 0.001 | Reject |
| Cycles to Inflection Point | 33 vs. 31 | 1.13 | 1.77 | 70 | 27 | 0.375 | Accept |
| Creep Slope | 30 vs. 22 | 1.90 | 1.79 | 69 | 26 | 0.035 | Reject |
| Strip Slope | 20 vs. 21 | 1.11 | 1.76 | 18 | 69 | 0.359 | Accept |

**Table 4-25- Pooled coefficients of variation (COV) of properties of poorly-performing mixture**

| Property | Repeatability COV, % | Reproducibility COV, % |
|---|---|---|
| # of Cycles to 6-mm | 15.7 | 25.4 |
| # of Cycles to 12-mm | 17.4 | 22.9 |
| # of Cycles to inflection point | 23.2 | 32.1 |
| Creep Slope, mm/pass | 16.7 | 30.4 |
| Stripping Slope, mm/pass | 17.7 | 20.8 |

A statistical comparison of the repeatability and reproducibility COV of the number of passes to 6-mm and 12-mm rut depth and to the inflection point was conducted to determine if the COVs are the same and can be pooled together. The results are provided in Table 4-26. As indicated from the table, the COV of the number of passes to 6-mm and 12-mm rut depth are the same and, therefore, they can be pooled together. However, the COV of the number of passes to the inflection point is significantly different from those of number of passes to 6-mm and 12-mm rut depth. Therefore, in preparing the precision statement, a separate set of precision estimates is provided for the number of passes to inflection point. The resulted 1s repeatability/reproducibility COVs of the # of passes to threshold rut depth are

**Table 4-26- Statistical comparison of the pooled COV of number of passes to 6-mm and 12-mm deformation and to the inflection point for poorly-performing mixture**

| Comparison | Statistics | COV, % | F | Critical F | df1 | df2 | P | Decision |
|---|---|---|---|---|---|---|---|---|
| 6-mm vs. 12-mm | Repeatability | 15.7 vs. 17.4 | 1.23 | 1.44 | 66 | 98 | 0.173 | Accept |
| | Reproducibility | 25.4 vs. 22.9 | 1.23 | 1.46 | 98 | 66 | 0.188 | Accept |
| 6-mm vs. Inflection Point | Repeatability | 15.7 vs. 23.2 | 2.19 | 1.40 | 97 | 98 | 0.000 | Reject |
| | Reproducibility | 25.4 vs. 32.1 | 1.60 | 1.40 | 97 | 98 | 0.011 | Reject |
| 12-mm vs. Inflection Point | Repeatability | 17.4 vs. 23.2 | 1.78 | 1.46 | 97 | 66 | 0.007 | Reject |
| | Reproducibility | 22.9 vs. 32.1 | 1.96 | 1.46 | 97 | 66 | 0.002 | Reject |

### 4.3.4 Comparison of COV of Creep Slopes of the Two Mixture Types

The COVs of the creep slope corresponding to well-performing and poor-performing mixtures were statistically compared to investigate if they are statistically the same and can be pooled together. The results of the analysis are provided in Table 4-27. As shown in the table the differences between repeatability/reproducibility COVs of creep slope corresponding to the two mixtures are not significantly different and can be pooled together. The resulting 1s repeatability COV of creep slope is 16.6% and 1s reproducibility COV is 28.3%.

**Table 4-27- Statistical comparison of the COVs of creep slope of well-performing and poorly-performing mixtures**

| Statistics | COV, % | F | Critical F | df1 | df2 | P | Decision |
|---|---|---|---|---|---|---|---|
| Repeatability | 16.6 vs. 16.5 | 1.47 | 1.55 | 51 | 69 | 0.069 | Accept |
| Reproducibility | 30.4 vs. 26.2 | 1.35 | 1.55 | 51 | 69 | 0.122 | Accept |

### 4.3.5 Precision Estimates of AASHTO T 324

Table 4-28 provides the precision estimates for AASHTO T 324 developed in this research. The table includes repeatability and reproducibility COVs for various properties of HWTT. A single set of precision estimates were prepared for the properties of both gyratory and slab specimens either by combining the COVs corresponding to the gyratory and slab specimens or by using COVs corresponding to the gyratory specimens since they were larger number of gyratory specimens than slab specimens. The proposed precision statement that includes the developed precision estimates is provided in Appendix I.

It is important to note that the variability computed in this research only reflects the variability from the HWTT and the test specimen assembly since test specimens were fabricated at AMRL. The variability of measurements is attributed to the factors such as the dynamic effect of the wheels, position of the wheel with respect to specimen, the actual measurement locations compared to the design locations, lack of confinement at the joint between gyratory samples, and the effect of the dynamics of the right and left wheels on each other, as discussed in Appendix C. To minimize the variability of the test measurements, factors such as position of the wheel with respect to specimen and position of measurement locations should be regularly verified. Improving the specimen assembly and mold geometry would also assist in reducing the variability of the test.

**Table 4-28- Precision estimates for AASHTO T 324**

| Properties | Single-Operator | | Multilaboratory | |
|---|---|---|---|---|
| | Coefficient of Variation (%) | Acceptable Range of Two Test Results (Percent of Mean)[a] | Coefficient of Variation (%) | Acceptable Range of Two Test Results (Percent of Mean)[a] |
| Deformation (mm) | 14.2 | 40.2 | 26.0 | 73.6 |
| Number of Passes to Threshold Rut Depth | 16.6 | 47.0 | 24.2 | 68.5 |
| Number of Passes to Inflection Point | 23.9 | 67.6 | 32.1 | 90.9 |
| Creep Slope (mm/cycle) | 16.6 | 47.0 | 28.3 | 80.1 |
| Strip Slope, mm/pass | 17.7 | 50.0 | 20.8 | 58.8 |

[a] These values represent the 1s and d2s limits described in ASTM Practice C670

# CHAPTER 5- FINDINGS AND PROPOSED CHANGES TO AASHTO T 324 AND THE HWTT EQUIPMENT

## 5.1 Findings

This report presents the results of an interlaboratory study (ILS) to determine precision estimates for AASHTO T 324, “Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA).” The ILS included preparing and sending four replicates of Superpave gyratory and two replicates of linearly kneaded compacted slab specimens of each of a rutting and moisture resistant (well-performing) and a rutting and moisture susceptible (poorly-performing) mixture to laboratories participating in the ILS to be tested according the AASHTO T 324. Using the results reported back by the laboratories, the precision estimates for properties of the two mixtures were prepared. The precision estimates include the within- and between-laboratory precisions for deformation, the number of passes to threshold rut depths, the creep and strip slopes, and the number of passes to the inflection point.

The effect of measurement locations used in the analysis and the effect of specimen type on the mean and variance of the HWTT properties. The properties of the mixtures measured using all measurement locations were statistically compared with those measured using all except three middle measurement locations and those measured using all except the two measurement locations at each end. Moreover, the statistics of the properties of gyratory and slab specimens were statistically compared. These results along the precision estimates are presented in Chapter 4. The precision statement that includes the developed precision estimates is provided in Appendix I.

In addition to developing precision estimates, the data from the ILS and from an in house research were used to gain insight into the causes of variability of the test results. The effects of various components of the wheel track tester and the effect of specimen assembly on the test measurements were investigated. These results are presented in Chapter 3. The results of the cause and effect study are presented in Appendix C.

## 5.2 Proposed Changes to AASHTO T 324 and the HWTT Equipment

The results of the ILS suggest that the repeatability and reproducibility of measurements from the HWTT may be improved by these proposed changes:

1. The current AASHTO T 324 does not address key factors affecting performance such as starting location of the wheel, alignment of the wheel with respect to specimen, and the measurement locations used in the analysis. These factors, which have significant effect of variability of measurements, need to be standardized.

2. The operation of the equipment should be periodically verified by the manufacturer to identify any machine-related deficiencies.

3. Reducing the confinement at the ends of the two gyratory specimens and increasing the confinement at mid-point around the joints may achieve a more consistent deformation profile. Currently there is high confinement at the ends and little or no confinement at the mid-point causing differential wear in the wheel path, which would result in bias and high variability in measurements.

4. The variability in cutting the gyratory specimens may possibly affect the measured performance of mixtures (especially that of poorly-performing mixtures). The possibility of eliminating the cut should be investigated.

5. The possibility of increasing the specimen length should be explored. This will result in a greater distance between the wheels and the ends of specimens, reduction in the confinement, and more even wear of the sample.

6. A means of confining around the joint of the two adjoined gyratory specimens need to be investigated. A new mold can be designed for this purpose. The use of plaster of Paris is a possible solution for confining the gyratory specimen around the joint using the existing mold configuration. This will also prevent the movement of the molds that might be a cause of loosening of bolts during the test.

7. The expansion of the polyethylene mold due to increase in temperature was discussed as another possible cause of the tray bolts to loosen. Retightening of the tray bolts at the end of 30-min temperature conditioning is recommended.

8. Exploring a material for the mold with smaller coefficient of thermal expansion than polyethylene is suggested.

9. Due to the possible deficiencies in the equipment and test setup that could affect the accuracy and precision of the test results, the results from HWTTs should be occasionally verified against the test results of reference specimens with known properties. Testing reference specimens can identify problems with the machine or test setup and remove any anomalies. It is expected that this reference testing can significantly reduce the variability of the test results between participating laboratories.

10. Considering that the deformations across various measurement locations are inter-dependent, excluding the deformation from any measurement location is not recommended. An average deformation from all measurement locations would provide a more comprehensive representation of the entire deformation basin.

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