CIVIL ENGINEERING STUDIES
Illinois Center for Transportation Series No. 17-016
UILU-ENG-2017-2016
ISSN: 0197-9191

EVALUATION OF I-FIT RESULTS AND MACHINE VARIABILITY USING MNROAD TEST TRACK MIXTURES

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Research Report No. FHWA-ICT-17-012

A report of the findings of

ICT PROJECT R27-SP31
Evaluation of I-FIT Results and Machine Variability using MnRoad Test Track Mixtures

Illinois Center for Transportation

June 2017

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. FHWA-ICT-17-012	**2. Government Accession No.** N/A	**3. Recipient's Catalog No.** N/A
4. Title and Subtitle Evaluation of I-FIT Results and Machine Variability using MnRoad Test Track Mixtures		**5. Report Date** June 2017
		6. Performing Organization Code N/A
7. Author(s) Hasan Ozer, Imad L. Al-Qadi, Edoardo Barber, Egemen Okte, Zehui Zhu, and Shenghua Wu		**8. Performing Organization Report No.** ICT-17-016 UIUL 2017-2016
9. Performing Organization Name and Address Illinois Center for Transportation Department of Civil and Environmental Engineering University of Illinois at Urbana-Champaign 205 North Mathews Avenue, MC-250 Urbana, IL 61801		**10. Work Unit No.** N/A
		11. Contract or Grant No. R27-SP31
12. Sponsoring Agency Name and Address Illinois Department of Transportation (SPR) Bureau of Material and Physical Research 126 East Ash Street Springfield, IL 62704		**13. Type of Report and Period Covered** Final report: 8/16/16 – 6/30/17
		14. Sponsoring Agency Code FHWA

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

The Illinois Flexibility Index Test (I-FIT) was developed to distinguish between different mixtures in terms of potential cracking. Several machines were manufactured and are currently available to perform the I-FIT. This report presents the results and findings from an experimental program developed to compare various I-FIT configurations. Three different I-FIT devices were compared in collaboration with Illinois Department of Transportation (IDOT). The main focus of the study was the comparison of the two custom designs: an InstroTek screw-driven device with a spring rollers support system and a TestQuip servo-hydraulic system with both spring and bearing rollers support systems. In addition, the Interlaken 100 kN servo-hydraulic universal testing frame equipped with an I-FIT fixture with spring roller support system was also evaluated. In total, eight asphalt concrete (AC) mixtures with varying design characteristics were analyzed by evaluating the difference in the mean values of fracture energy, slope, and overall patterns of load-displacement curves in addition to the statistical analysis. According to the results obtained, the various machines did not significantly affect the flexibility index (FI) calculated for each mixture in this study. In all cases, the results were within approximately one unit of FI for each machine and mixture. Statistical analysis conducted using the ANOVA analysis and t-test also supported the conclusion that the device configurations were found to have no significant effect on the FI results for the AC mixtures evaluated in this study, regardless of the loading system (hydraulic or screw-driven) and the configuration of the support system (spring or bearing rollers).

17. Key Words Asphalt mixture, fracture, machine, Illinois Flexibility Index (I-FIT)		**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 59 pp + appendices	**22. Price** N/A

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

ACKNOWLEDGMENT, DISCLAIMER, MANUFACTURERS' NAMES

This publication is based on the results of **ICT-R27-SP31, Evaluation of I-FIT Results and Machine Variability using MnRoad Test Track Mixtures**. ICT-R27-SP31 was conducted in cooperation with the Illinois Center for Transportation; the Illinois Department of Transportation; and the U.S. Department of Transportation, Federal Highway Administration.

Members of the Technical Review panel were the following:

- Tom Zehr (TRP Chair), Illinois Department of Transportation
- James Trepanier, Illinois Department of Transportation

The authors would like to thank personnel at the MnRoad Research Facility for providing materials and assisting sampling. Thanks also go to the National Center for Asphalt Technology (NCAT) for providing mixture design information.

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EXECUTIVE SUMMARY

The Illinois Flexibility Index Test (I-FIT) was developed to distinguish between different asphalt concrete (AC) mixtures in terms of potential cracking. Several machines were manufactured and are currently available to perform the I-FIT. Even though the equipment can be consistent with the AASHTO TP 124 standards, machine variability due to compliance and precision of the loading and measurement system can cause discrepancies in the test results. Therefore, it is of significant importance to evaluate the effect of machine type and fixture configuration on the I-FIT results.

This report presents the results and findings from an experimental program developed to compare different I-FIT configurations. Three different I-FIT devices were compared in collaboration with IDOT. The loading system and the support fixture are the two factors compared in the current study. In particular, the main focus was the comparison of two custom design systems: the InstroTek screw-driven device with a spring rollers support system and the TestQuip servo-hydraulic system with both spring and bearing rollers support systems. InstroTek and TestQuip machines with the spring fixture were located at the Illinois Center for Transportation, while the TestQuip machine with bearing supports was located at IDOT's facility. Furthermore, two additional machines at ICT were briefly evaluated: the universal Interlaken 100 kN servo-hydraulic testing frame equipped with the I-FIT fixture containing spring roller support system and the TestQuip with bearing supports (same as the device at IDOT's Central Bureau of Materials lab).

In total eight AC mixtures were evaluated. Six of the eight AC mixtures were sampled from the MnRoad track test mixtures that were constructed for the MnRoad Cracking Group Study. These mixtures had similar gradation and volumetric characteristics (VMA and binder content) and the same NMAS (12.5 mm) with varying binder type and asphalt binder replacement (ABR). One lab produced mix with a 4.75 mm nominal maximum aggregate size (NMAS) and plant produced 19.0 mm NMAS mixture were added to the experimental program. All of the AC mixtures were processed and compacted at ICT for consistency. I-FIT specimen fabrication was performed at the ICT and IDOT laboratories. Test results were analyzed to compare differences in the values of flexibility index (FI), fracture energy, slope, and overall patterns of load-displacement curves. In addition, statistical analysis were conducted to assess the differences in test results that may be caused by using different machines or the test having been conducted by a different operator.

According to the results obtained, all of the mixtures had similar FI values from all machines considered in the study. The results were within approximately one unit of FI except for the mixtures C18 and C23 (MnRoad mixtures with moderate ABR but different binder grades). When the tests were repeated for these two mixtures using the InstroTek and TestQuip spring roller devices, similar mean values of FI were also obtained. This indicates that the AC mixture variability governs the random differences in the results. Statistical analysis conducted using the ANOVA analysis and t-test also supported this conclusion that the device configurations were found to have no significant effect on the FI results for the AC mixtures evaluated in this study, regardless of the loading system (hydraulic or screw-driven) and the configuration of the support rollers (spring or bearing rollers).

The coefficient of variation (COV) values of the FI results varied between 10% and 35%. There is no consistent trend between the machines to provide higher or lower COVs. The COV values were governed by the material variability. Based on the sample size analysis, it is recommended to increase the number of replicates to a minimum of six to eight. This allows a better representation of the material variability and improves reproducibility of the test results. When the sample size is four, it was shown that there can be significant random fluctuations in the FI results. Different sample reduction techniques were also investigated. A reduction in the COV can be achieved at the expense of changes in the FI, especially when the number of replicates is four. Therefore, this study does not recommend any of these sample reduction techniques unless the data is proven to be an outlier.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Thermal and load-related fatigue types of cracking are among the most commonly occuring distresses affecting flexible pavement service lifetime (Al-Qadi et al. 2005, EI-Basyouny and Witczak 2005, Flintsch and McGhee 2009). When coupled with other structural and functional distresses, they can greatly influence the performance of the pavement structure, maintenance costs, and serviceability. The factors affecting cracking include asphalt pavement structure, base support, and material properties, as well as external factors such as environmental and traffic loading conditions. Once a pavement structure is designed for a specific design life under given loading conditions, the selection of materials and mixes to be used in each layer will govern whether the design life can be achieved or not. Therefore, it is important to understand the mechanics of crack initiation and propagation of the overall asphalt concrete (AC) materials, and determine which of the material parameters affect cracking potential, so that appropriate mix designs can be selected.

To evaluate cracking behavior and resistance of AC to cracking, various laboratory tests capturing mechanics of fracture were developed. Initially, single-edge notch beam (SEB) (Wagoner et al. 2005) and disk-shaped compact tension tests (DCT) were developed (Wagoner et al. 2005). However, use of the SEB test was discontinued because it required significant testing effort and materials, in addition to inapplicability of the field cores. On the other hand, the DCT was found to be a more practical test to characterize low-temperature cracking; later, the ASTM D7313 standard test method was developed (ASTM D7313). However, the relatively high cost of equipment, time-consuming specimen preparation procedures, and inability to clearly distinguish between AC mixtures through the DCT fracture energy (Al-Qadi et al. 2015) are among the factors impeding implementation by practitioners.

At the same time, another fracture test using semi-circular bending (SCB) geometry was used for AC by Marasteanu et al. 2002. The SCB test was proposed as an alternative because of ease of specimen preparation and a more practical testing setup. The test was first proposed by Chong and Kruppu in 1984, and it acquired popularity because it provided repeatability, applicability to field cores, and easy specimen preparation for rock samples. Later, the SCB test was adapted as a cracking test for AC by Marasteanu et al. (2012), Wu et al. (2005), Al-Qadi et al. (2015) because practical-yet-reliable cracking tests had become a necessity in the asphalt industry. With the increasing use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS), the need for such a cracking test became more crucial to evaluate resistance of AC mixes to cracking. As such, a modified SCB test, named the Illinois Flexibility Index Test (I-FIT), was developed in project ICT R27-128 by Al-Qadi et al. (2015) to examine cracking potential of AC.

The flexibility index (FI) obtained from the I-FIT test considers both fracture energy and the slope of the load-displacement curve after the point where a crack starts to propagate at the inflection point. It was found that FI showed a consistent trend with approximate crack growth rate. It was also found that FI could be correlated to fundamental crack mechanisms around the process zone which describes the region at or near the notch tip that cracks occur and develop during testing. It was shown that FI could be used as a measure of cracking resistance (Ozer et al. 2016a and Ozer et al. 2016b). The I-FIT protocol was recently accepted as an AASHTO provisional standard (AASHTO TP 124).

Flexibility index is expected to be implemented by IDOT as part of a performance-related specification to complement Superpave volumetric criteria as well as Hamburg wheel-tracking test rut depth results. Therefore, the accuracy and repeatability of the FI parameters are important. Currently, there are several machines available to conduct the I-FIT. When the I-FIT is implemented by agencies, one should anticipate the use of different equipment by contractors and independent labs. Even though the equipment is consistent with AASHTO TP 124 standards, machine variability can cause discrepancies in the test results. Machine variability can be related to compliance and precision of the loading and measurement system. Therefore, it is of significant importance to evaluate the effect of machine type on the I-FIT results.

1.2 RESEARCH OBJECTIVES AND SCOPE

The objective of this research is to compare I-FIT results using two machine types with servo-hydraulic and screw-driven machine loading systems using various mixes and samples to ensure the repeatability and accuracy of the I-FIT results. The scope of the study includes an experimental plan to test eight different AC mixes using two different machines and laboratories. The mixes were selected to represent a wide range of mix design characteristics used in Illinois. Statistical analysis were conducted to assess the differences in test results that may be caused by using different machines or the test having been conducted by a different operator.

1.3 REPORT ORGANIZATION

This report consists of five chapters and three appendices, as follows:

- Chapter 1 describes the research background and objectives.
- Chapter 2 presents the experimental plan executed in this study and the materials used.
- Chapter 3 presents the I-FIT test results.
- Chapter 4 discusses the test results based on statistical analysis.
- Chapter 5 summarizes the findings from this study and presents the conclusions.
- Appendices A, B, and C present the job mix formula, volumetrics data, and I-FIT test data for each AC mixture tested in this study, respectively.

CHAPTER 2: EXPERIMENTAL PLAN AND MATERIALS

2.1 METHODOLOGY AND MATERIALS

The purpose of this project is to compare several Illinois Flexibility Index Test (I-FIT) machines to verify whether they can produce the same FI results. The variability of the test parameters was evaluated through statistical analysis. In addition to the final test outcome, the other elements of test outputs, such as fracture energy and post-peak slope of the load-displacement curve, were also evaluated.

Three different machines were compared in this project, and eight AC mixes were included. Six of the eight mixes were constructed for the MnRoad Cracking Group Study and were provided by the MnRoad testing facility in Albertville, Minnesota . The seventh mix was provided by the Illinois Department of Transportation (IDOT). These seven mixes were produced in an asphalt plant. The eighth mix was designed and produced in the laboratory. The Bailey method was used for the design. Gradations and essential mix design parameters of the AC mixes are shown in Table 2.1. The detailed job mix formula (JMF) for each mix design is provided in Appendix A.

Table 2.1 Gradations and Design Parameters of Mixes

% Passing Sieve	MnRoad C16	MnRoad C17	MnRoad C18	MnRoad C19	MnRoad C21	MnRoad C23	IDOT Base	N50 Lab Sand Mix
1" (25.0 mm)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4" (19.0 mm)	100.0	100.0	100.0	100.0	100.0	100.0	98.0	100.0
1/2" (12.5 mm)	93.9	93.1	93.7	93.7	93.7	93.1	80.0	100.0
3/8" (9.5 mm)	83.1	81.1	82.7	82.7	82.7	81.0	71.0	99.5
No. 4 (4.75 mm)	61.0	57.9	60.4	61.6	60.4	56.6	45.0	86.2
No. 8 (2.36 mm)	45.5	42.2	43.5	45.3	43.5	39.8	27.0	64.5
No. 16 (1.18 mm)	32.5	29.9	30.8	31.5	30.8	28.1	18.0	42.8
No. 30 (600 µm)	22.0	20.3	21.0	20.7	21.0	19.3	13.0	28.0
No. 50 (300 µm)	13.3	12.7	12.8	11.8	12.8	12.0	7.0	15.6
No. 100 (150 µm)	8.0	7.8	7.6	6.5	7.6	7.3	5.0	8.1
No. 200 (75 µm)	5.3	5.2	5.0	4.1	5.0	4.9	3.5	6.0
Asphalt Content (%)	5.3	5.4	5.4	5.7	5.4	5.2	5.0	7.5
Binder Grade	64S-22	64S-22	64S-22	64S-22	58H-34	64E-34	64-22	SBS 70-22
Total ABR (%)	39.8 with RAS	27.3 with RAS	22.7	21.6	22.9	17.7	10.2	0.0
VMA (%)	14.5	14.9	14.6	14.8	14.6	14.4	14.1	18.4
NMAS (mm)	12.5	12.5	12.5	12.5	12.5	12.5	19.0	4.75

Note: VMA = void in mineral aggregate; ABR = asphalt binder replacement; NMAS = nominal maximum aggregate size; NA = not available.

2.2 PILOT STUDY OF THE ASPHALT CONCRETE MIXES

Before the actual experimental plan was conducted, a pilot study was performed on the AC mixes. The pilot study aimed to determine the proper amount of material needed in the gyratory compactor to obtain the target air voids (7.0 % ± 0.5 %) on the final I-FIT specimen. The maximum specific gravity

(G_{mm}) of each AC mix was determined in accordance with the IL-modified AASHTO T209 procedure. The bulk specific gravity (G_{mb}) of a compacted specimen was determined in accordance with IL-modified AASHTO T166. Furthermore, the lab-produced mix was designed also considering AASHTO M 323-04 requirements.

Out of the 18 buckets of mix (about 20 kg of material each) provided by MnRoad for each mix, two buckets per mix were blended and split in order to obtain G_{mm} and compacted gyratory samples for the pilot study. The same amount of material was also used for the IDOT mix. Blending and splitting (as shown in Figure 2.1) were performed in accordance with the AASHTO T248 procedure. A minimum of two buckets (or bags) was used for the tests. Blending two buckets ensured that the samples used for the pilot study were representative of the mix. The pilot study was necessary to provide consistency during compaction and avoid waste of material by failing to meet air void requirements.

Figure 2.1 Blending and splitting mix.

2.3 SPECIMEN PREPARATION

Great care and consistency were put in fabrication of the specimens for the I-FIT. All the specimens from a certain mix and used for the comparison were compacted on the same day. Buckets of the same mix were first blended and then split to the sample size (7.8 to 9.0 kg) and poured in pans. During the compaction process, samples of mix were transferred from pans to compaction molds using a chute to avoid any mix segregation. Test specimens were fabricated from 180.0 mm gyratory-compacted cylinders (also called pills), in accordance with IL-modified AASHTO T312.

Two slices of 50 mm were cut from the center of the pill, as shown in Figure 2.2. The slices were then halved to obtain two semi-circular specimens, which were eventually notched.

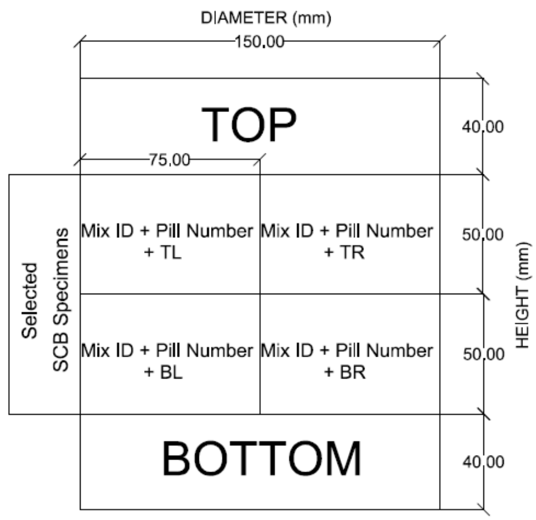
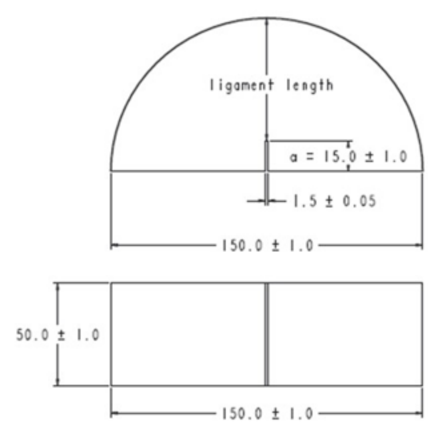


Figure 2.2 Naming criterion adopted for the test specimens.

Air voids during the fabrication process were checked twice. The first control was made on the gyratory-compacted specimen, before performing the cuts. This was made for quality control (QC) purposes only. The specifications target air voids on the slices. The air void was checked again on the unnotched semi-circular specimen. Only specimens in the specified air void range were notched. The air void checking process was applied to provide every device with more consistent specimens so as to ensure better results for the comparison.

Finally, the fabricated specimens were measured to check thickness and notch length. Illinois Test Procedure 405 specification set measurements for both the parameters: 50 + 1 mm for the thickness and 15 + 1 mm for the notch length. Specimens that did not meet these requirements were discarded. Figures 2.3 (a) and (b) show the final specimen and the specimen geometry, respectively.

(a)



(b)

Figure 2.3 I-FIT specimen: (a) prepared specimen; (b) geometry of the specimen.

2.4 DESCRIPTION OF MACHINES

2.4.1 InstroTek

The InstroTek machine has a screw-driven loading application system, as shown in Figure 2.4. In this setup, the loading ram is located under the test fixture. The test specimen is pressed against a fixed loading rod. The loading capacity of this machine is 10 kN. Displacements are recorded through a linear variable displacement transducer (LVDT) fixed with respect to the loading ram. A plate that is part of the loading head provides the contrast for the LVDT. Displacements recorded during the test and used to control the test are the load line displacements. The test fixture is composed of a steel base plate that supports two U-shaped steel blocks that accommodate the two steel roller supports, which have a diameter of 25 mm. Springs and backstops, which establish the initial test span, fix the initial roller position. The support rollers rotate from the backstop during the test, always remaining in contact with the specimen. The initial span between the rollers is 120 mm (from center to center). With this machine, an alignment bar and a centering pin are provided so that the positioning of the sample is made easier.

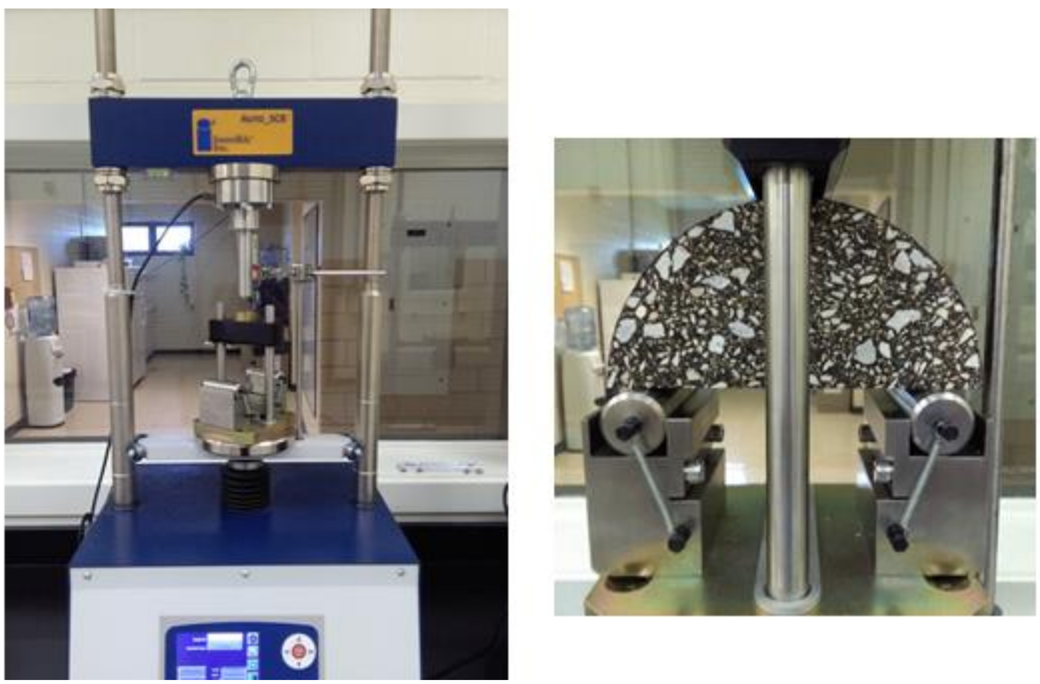


Figure 2.4 InstroTek test machine with spring rollers.

2.4.2 TestQuip

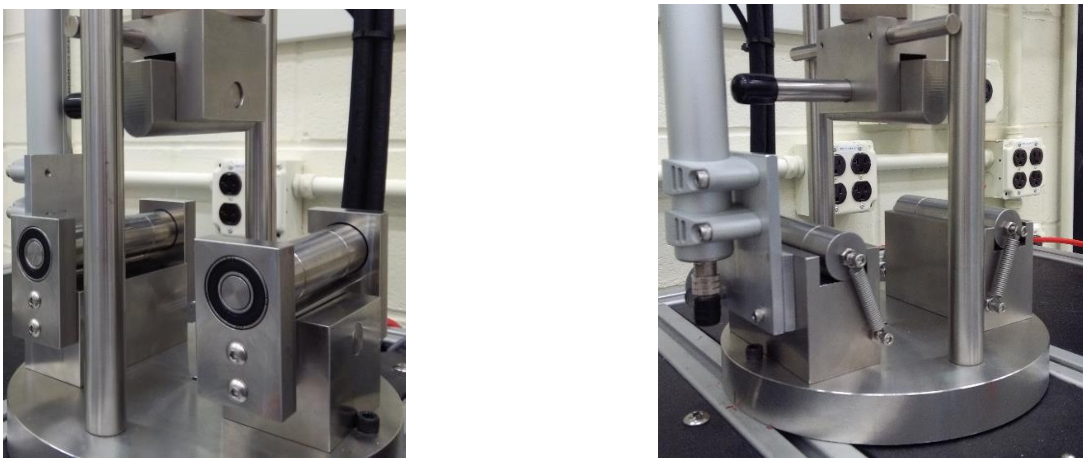
Figure 2.5 is a photograph of the TestQuip test machine. It has a hydraulic loading system with a loading capacity of 20 kN. The load is applied by a loading head mounted at the end of the rod connected to the hydraulic system. The displacements are recorded without a direct contact between the moving part of the fixture and the body part of the transducer. The displacement measuring device is composed of two parts: one is fixed to the loading head (moving part); the other is mounted on a plate fixed to the support roller.

Figure 2.5 TestQuip machine.

Two support fixtures were evaluated for the TestQuip in this study: bearing roller and spring roller. The bearing fixture, as shown in Figure 2.6(a), is made up of a steel base plate on which the rollers are mounted. Roller-bearing pins have a diameter of 25 mm and can freely rotate without any friction. One of the two support rollers can pivot to establish full contact with the bottom face of the test specimen to avoid problems with specimens whose bottom face is not perfectly perpendicular to the horizontal plane. The rollers are able to rotate around their own longitudinal axis. The span between the two rollers is 120 mm. This device is referred to as TestQuip bearing rollers.

The spring roller test fixture is shown in Figure 2.6(b). It uses springs and backstops that fix the initial position of the two 25 mm support rollers like the one used on the InstroTek device. As previously described, the rollers are able to rotate inside the U-shaped roller supports, placed on the above-mentioned steel plate. The initial span between the support rollers is 120 mm. This device is referred to as TestQuip spring rollers.

The fourth device included in the study is another TestQuip device with bearing rollers, located at IDOT's facilities. Unlike the device previously described, this one has two LVDTs, one on each side of the specimen. The displacements as measured by the two LVDTs are averaged to ensure more accurate representation of vertical displacements. This machine is referred to as TestQuip IDOT.



(a) (b)

Figure 2.6 Support fixtures for TestQuip machine: (a) bearing rollers; (b) spring rollers.

2.4.3 Interlaken

The Interlaken hydraulic system is shown in Figure 2.7. The load is applied through a loading head mounted on a rod actuated by the loading system. The testing frame has a loading capacity of 100 kN. The fixture assembled for the I-FIT used a load cell with a measuring capacity of 44 kN. Displacements are recorded with an LVDT. The test fixture is similar to the one described for the InstroTek and TestQuip with spring rollers. In this case, the U-shaped steel blocks are not mounted on a steel plate. Instead, they are held by two vertical plates. Roller diameter and distance are the same as described for the TestQuip with spring rollers. The LVDT is fastened to the loading head; a contrast bar next to the test fixture is used to measure relative displacement. This device is used primarily for research purposes, and it is not owned by any of the contractors or IDOT labs to date.

Figure 2.7 Interlaken machine.

2.5 DESCRIPTION OF I-FIT AND DATA ANALYSIS

I-FIT is a three-point bending test on a semi-circular AC mix sample. The test is carried out in load line displacement control at a rate of 50 mm/min and a test temperature of 25°C in accordance with AASHTO TP 124 and Illinois specification IL-405.

Raw data sheets provided with the machines provide the load in kN and deformation in mm as a function of time in seconds. A load-displacement curve, as shown in Figure 2.8, needs to be plotted to obtain the parameters necessary to compute the final FI. All of the displacements recorded and reported are load line displacements.

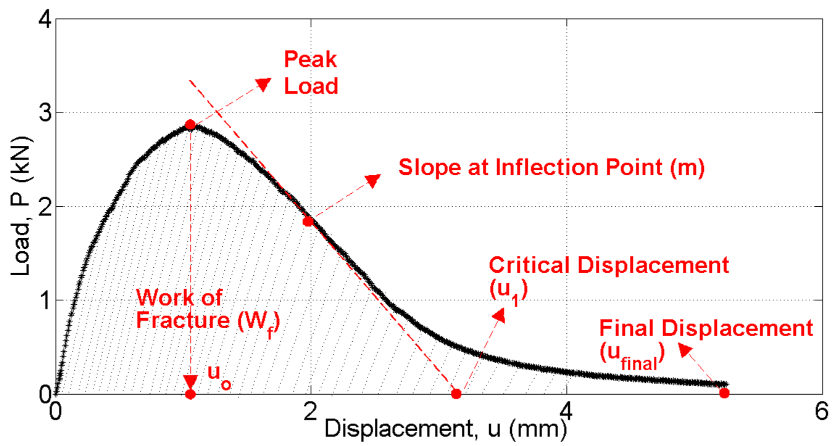


Figure 2.8 Typical load-load line displacement curve obtained from I-FIT and critical parameters.

The FI is determined by the ratio of the fracture energy (G_f) and the absolute value of the slope at the inflection point of the curve (m). Fracture energy is the ratio between the work of fracture, W_f (the area under the load-displacement curve) and the ligament area, A_{lig}, (the product of the ligament length, defined as the difference between the radius of the specimen and the notch length, and the thickness of the specimen). Figure 2.8 shows a typical load-displacement curve with the above-described parameter. Fracture energy and the FI are calculated in Equations 1 and 2, respectively.

$$G_f = \frac{w_f}{A_{lig}} \tag{1}$$

$$FI = A \times \frac{G_f}{|m|} \tag{2}$$

where coefficient A is a conversion factor that can adjust the units and sets the FI in a lower range of values. It was defined as 0.01 for the lab-compacted mixes used in this study.

Statistical analysis was conducted to compare and rank the means of the measured parameters obtained from the tests run on each machine. One-way analysis of variance (ANOVA) and Tukey's comparison were used to compare the different FI averages and rank the parameters, respectively.

ANOVA is a collection of statistical models and their associated procedures that are used to identify the differences within group means. In short, ANOVA can provide a statistical analysis of whether the means of different groups are equal. Tukey’s test, which is also known as Tukey’s range test, can be used based on raw data or with ANOVA to find means among groups that have notably different means. The purpose of the statistical analysis is to determine whether it is statistically possible to find which machine the test was run on and whether the machines investigated lie in the same rank. If the analysis results provide different rankings, the machines will be defined as statistically different, and therefore, the test fixture will be deemed to have impact on the test results.

CHAPTER 3: RESULTS

Chapter 3 presents the test results from the experimental program described in the previous chapter. The chapter is organized in three sections. The first one presents the data related to the quality control of specimens prepared to ensure that all the tests conducted on different machines are in accordance with the I-FIT standards (AASHTO TP 124). The second section presents the results of the tests obtained for the eight AC mixes on the four machines with the main parameters investigated. The third section contains an analysis of the performances of the different AC mixes and the correlatation results of the FI with mix properties such as asphalt binder replacement (ABR), nominal maximum aggregate size (NMAS), and binder type.

3.1 SPECIMEN PREPARATION QUALITY CONTROL

To obtain consistent specimens for the study, a strict protocol for their fabrication was followed. Because the aim of the research was to compare different test devices, other factors affecting variability should be minimized. Although the geometry of the specimens is a parameter easily manageable, ensuring the correct air voids in the specimens is a critical issue. During the pilot study, the correct amount of material was determined so that the semi-circular test specimens would be in the required air void range (7±0.5%).

As a quality control, the maximum specific gravity of all the AC mixes was measured and compared to available plant mix design data, when available. In this way, more reliable values were obtained because most of the AC mixes were plant produced. Table 3.1 presents a summary of the measured G_{mm} compared to the designed G_{mm} from the job mix formula (JMF).

Table 3.1 Summary of Maximum Specific Gravity of Plant Mixes

	MnRoad C16	MnRoad C17	MnRoad C18	MnRoad C19	MnRoad C21	MnRoad C23	IDOT Base
JMF	2.518	2.517	2.511	2.494	2.514	2.519	2.524
Measured	2.517	2.515	2.529	2.505	2.534	2.526	2.534

The measured G_{mm} values were used to determine the corrected gyratory sample weight. In Figure 3.1, a summary of the number of gyrations is presented. The chart refers to all the samples compacted for the study.

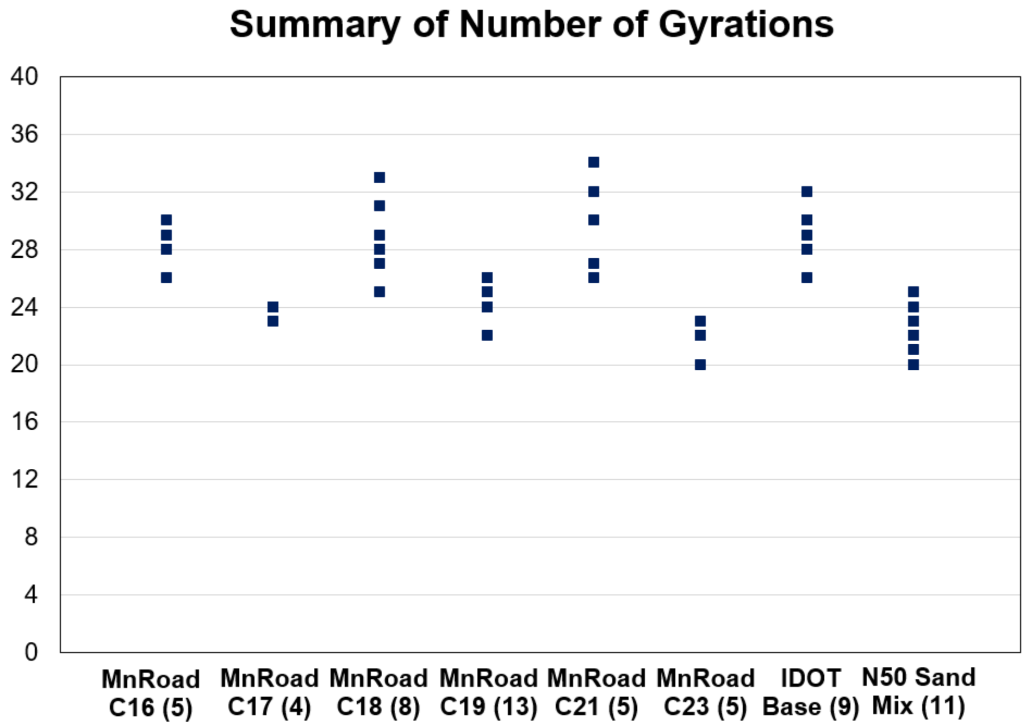


Figure 3.1 Gyrations for the compacted pills (the number of samples compacted are in parentheses after each mix name).

In Figure 3.1 it is possible to observe that the numbers of gyrations are very consistent within the mix. Except for MnRoad C18 and C21, the lowest and highest number of gyrations do not have a difference greater than 5. The good consistency indicated by the number of gyrations in the compaction process does not necessarily indicate good consistency as indicated by air voids for individual I-FIT test specimens. As can be seen in Figure 3.2, specimens fabricated from each compacted pill (one pill yields four test specimens) cover a wide range of air void values. The boundaries of the target air void range for I-FIT is marked. The majority of the specimens are in the target range for most of the mixes because an accurate pilot study was performed. However, some of the samples fabricated were out of range because of the high variability of the mix, which cannot be thoroughly controlled. Therefore, only specimens within the target range of air voids were used in testing.

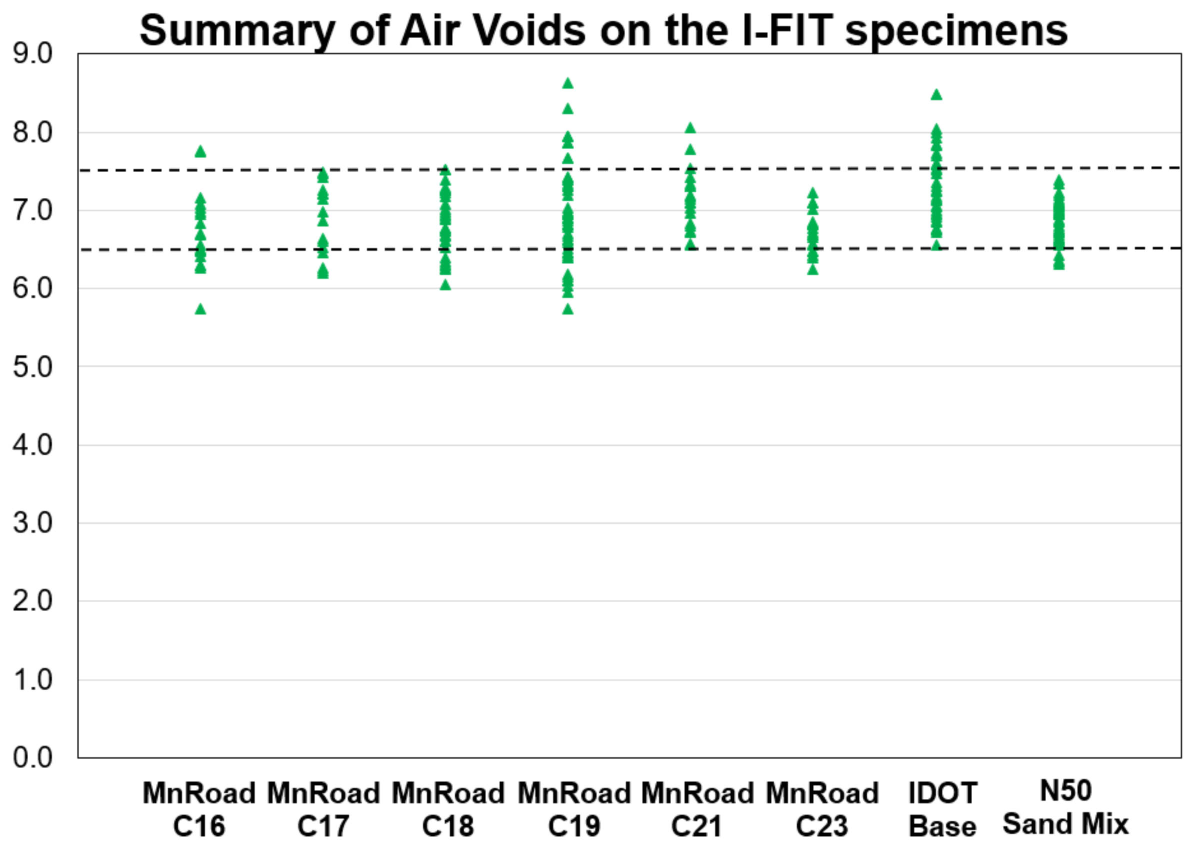


Figure 3.2 Air void distribution for fabricated specimens.

3.2 MACHINE VARIABILITY EFFECTS ON I-FIT PARAMETERS

The effects of potential machine variability will be discussed by presenting various test outcomes and different machine configurations. First, an analysis of the displacement rate applied by each configuration is presented. The FI, fracture energy, and peak load obtained for each mixture is presented to evaluate variability between screw driven and hydraulic loading systems as well as different fixture support configurations.

3.2.1 Displacement Rate Analysis

Asphalt mixtures are sensitive to displacement rate due to viscoelastic nature of asphalt materials resulting in time and temperature dependency. As such, it is critical to examine the machines' ability to apply an approximately constant displacement rate. Displacement rate refers to the speed of applied load line displacement and derived from the load line displacement-time series data. AASHTO TP124 and Illinois Test Procedure 405 require that the I-FIT machine should be capable of applying a constant displacement rate at a precision of 50 ± 1 mm/min. Figure 3.3 presents the average load line displacement rate of tested specimens for each machine in terms of different mixes. The error bar indicates the standard deviation of load line displacement rate. The two red dot lines denote upper and lower limit of displacement rate. As seen, the TestQuip machine regardless of BR, SR, and IDOT is able to maintain the displacement rate at 50 ± 1 mm/min. However, in all cases the average displacement rate for Instrotek is higher than other machines, and in some cases (MnR C16, MnR C18, and IDOT mix) is slightly beyond the limit. Details regarding displacement-time curves and resultant load-time for each mix are discussed in Sections 3.2.1.1 through 3.2.1.8.

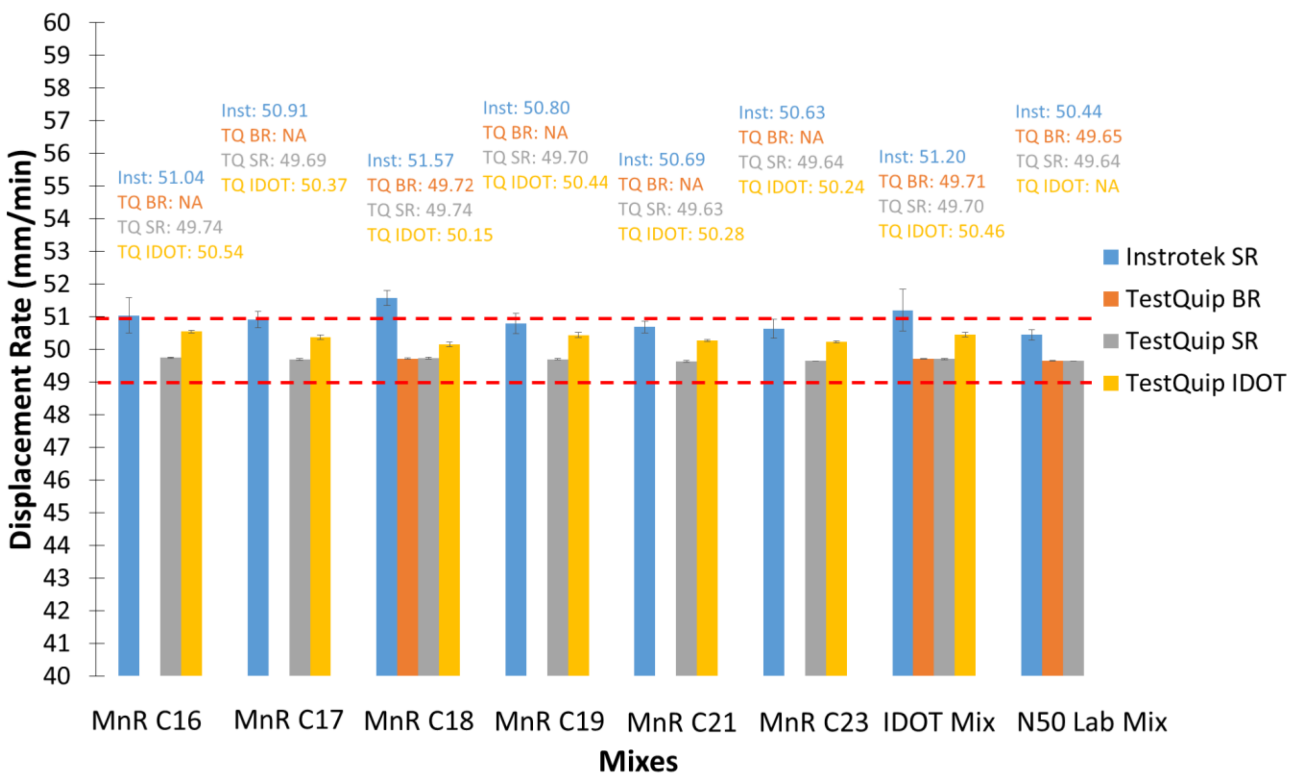


Figure 3.3 Average load line displacement rate for each machine.

3.2.1.1 MnRoad C16 Mix

Figure 3.4 shows the displacement-time curve for MnRoad C16 mix using Instrotek and TestQuip SR. Only two test results are presented for each machine to demonstrate their difference. The displacement rate is the slope in the regression equation, in the unit of mm/s. As seen, Instrotek has a slightly higher displacement rate than TestQuip SR. Figure 3.5 presents the resultant load-time curve. The load-time curve for Instrotek moves to the right slightly as compared to that for TestQuip SR. The bump in the displacement history obtained from the Instrotek machine corresponds to the peak load. As seen with the other test results, such a bump exists in all of the results obtained from the Instrotek machine even though it becomes less apparent for some mixtures with especially smaller peak load. However, the average rate of displacement is within the range of specifications in almost all of the cases.

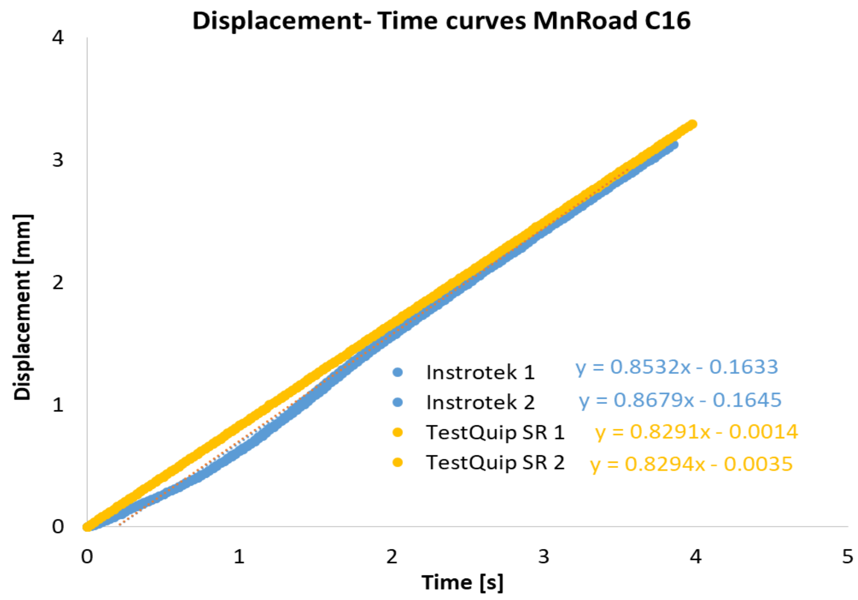


Figure 3.4 Load line displacement-time curve for MnRoad C16 mix.

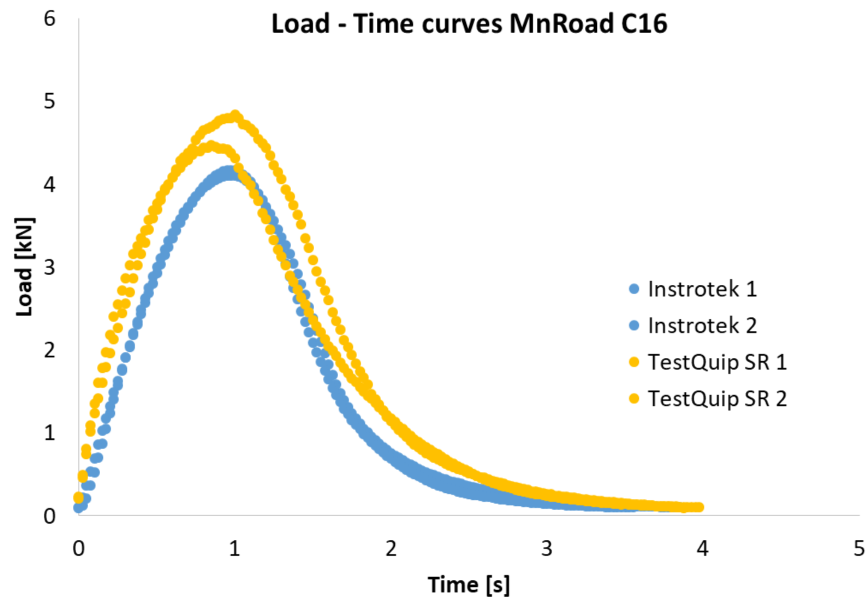


Figure 3.5 Load-time curve for MnRoad C16 mix.

3.2.1.2 MnRoad C17 Mix

Figure 3.6 shows the displacement-time curve for MnRoad C17 mix using Instrotek and TestQuip SR. The Instrotek has a slightly higher displacement rate than TestQuip SR. Figure 3.7 presents the resultant load-time curve. Instrotek presents similar load-time curve as the TestQuip SR before reaching peak load, but shows higher peak load than TestQuip SR.

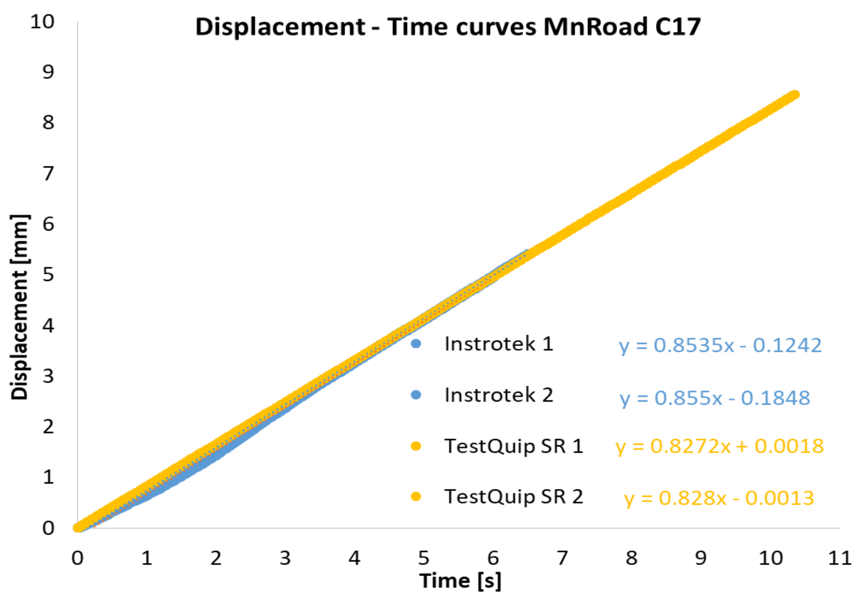


Figure 3.6 Load line displacement-time curve for MnRoad C17 mix.

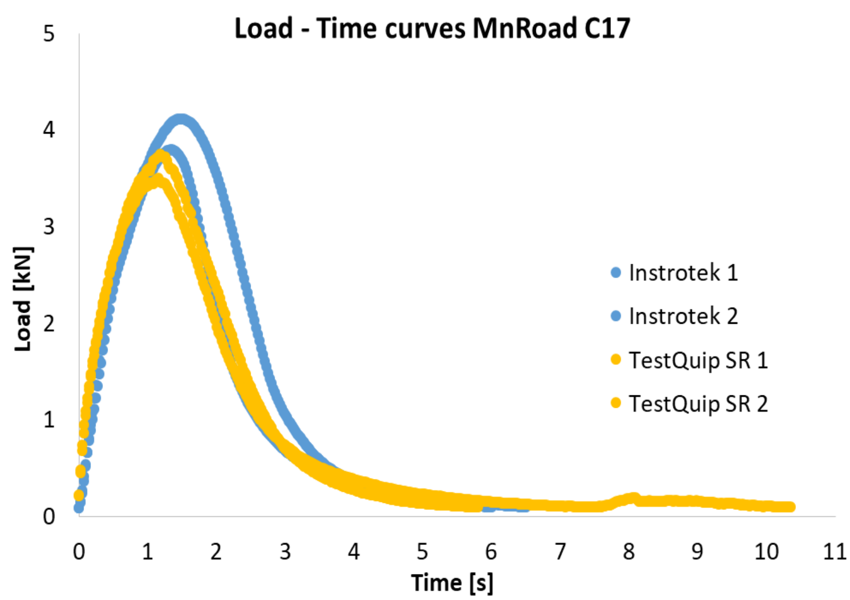


Figure 3.7 Load-time curve for MnRoad C17 mix.

3.2.1.3 MnRoad C18 Mix

Figure 3.8 shows the displacement-time curve for MnRoad C18 mix using Instrotek, TestQuip SR, and Testquip BR. Instrotek has a slightly higher displacement rate than other machine types. Figure 3.9 presents the resultant load-time curve. Again, the load-time curves for Instrotek move to the right slightly before the peak load as compared to other machines' curves.

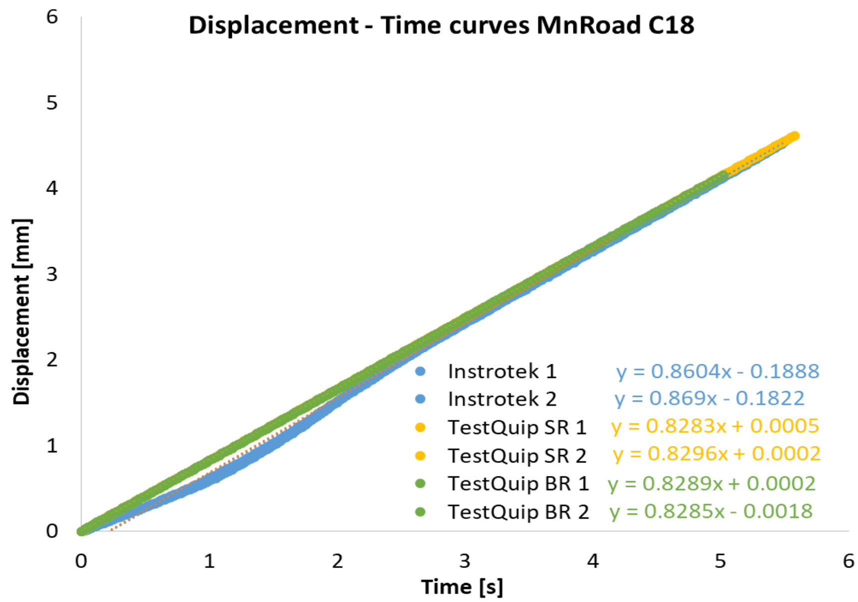


Figure 3.8 Load line displacement-time curve for MnRoad C18 mix.

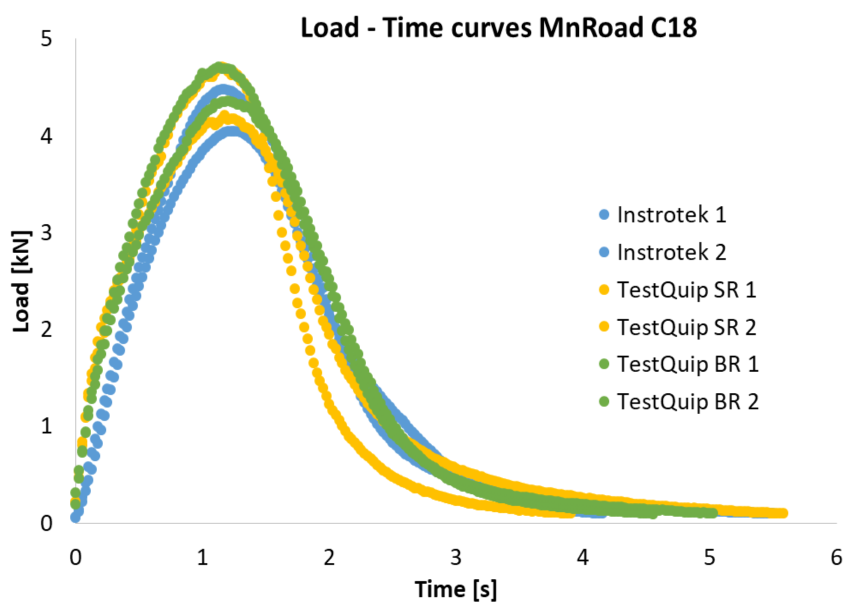


Figure 3.9 Load-time curve for MnRoad C18 mix.

3.2.1.4 MnRoad C19 Mix

Figure 3.10 compares the displacement-time curve for MnRoad C19 mix using Instrotek and TestQuip SR. Instrotek has a slightly higher displacement rate than TestQuip SR. Figure 3.11 shows the resultant load-time curve. As noted, the load-time curve for Instrotek moves to the right compared to that for TestQuip.

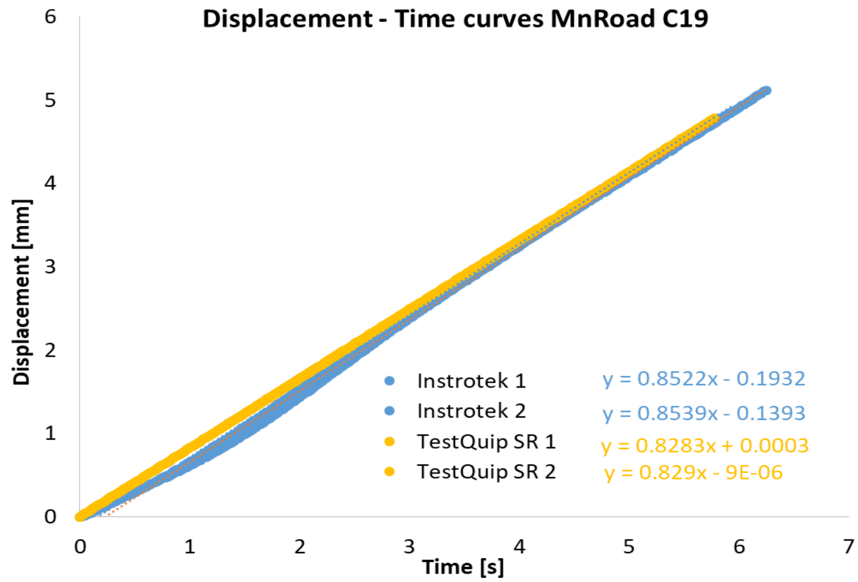


Figure 3.10 Load line displacement-time curve for MnRoad C19 mix.

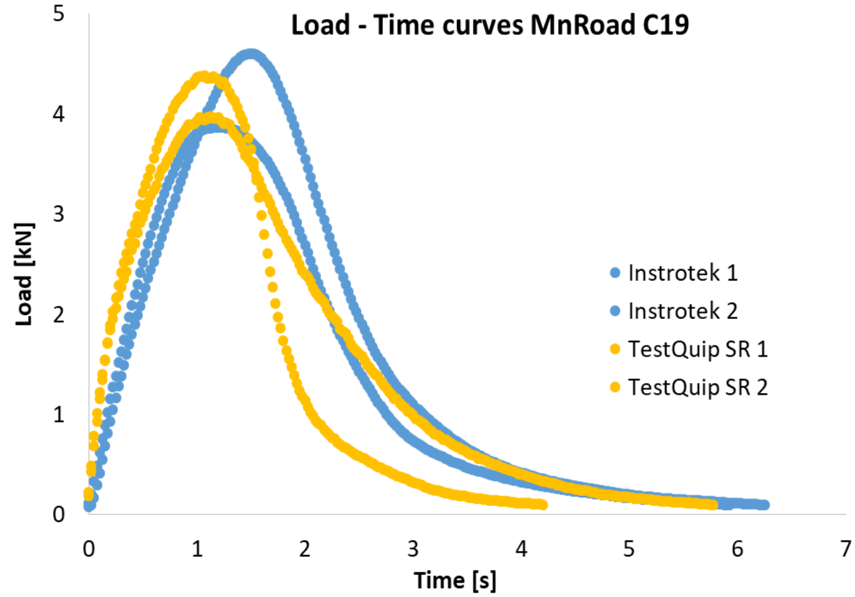


Figure 3.11 Load-time curve for MnRoad C19 mix.

3.2.1.5 MnRoad C21 Mix

Figure 3.12 compares the displacement-time for MnRoad C21 Mix using Instrotek and TestQuip SR. The displacement rate for Instrotek is sightly higher than that for TestQuip SR. The resultant load-time curve before the peak load for Instrotek moves slightly to the right as compared to that for TestQuip SR, as shown in Figure 3.13.

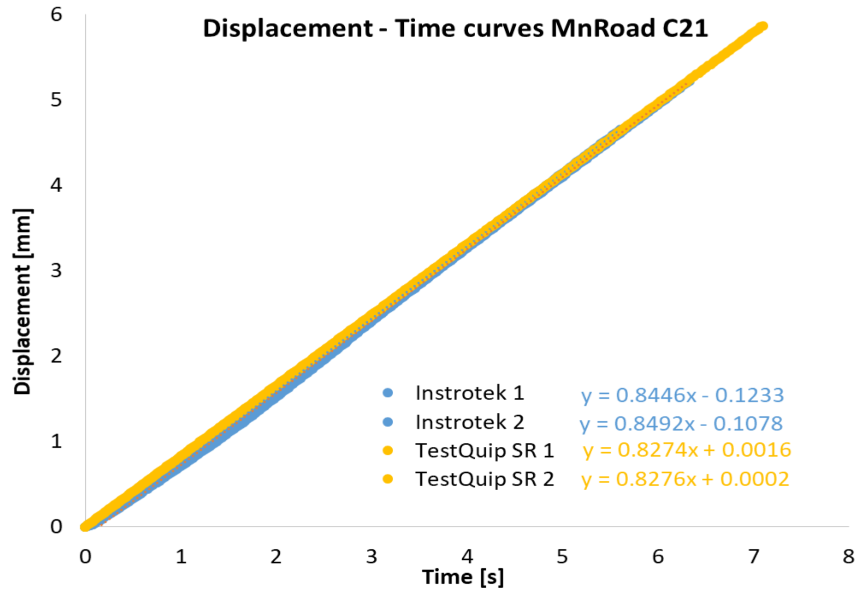


Figure 3.12 Load line displacement-time curve for MnRoad C21 mix.

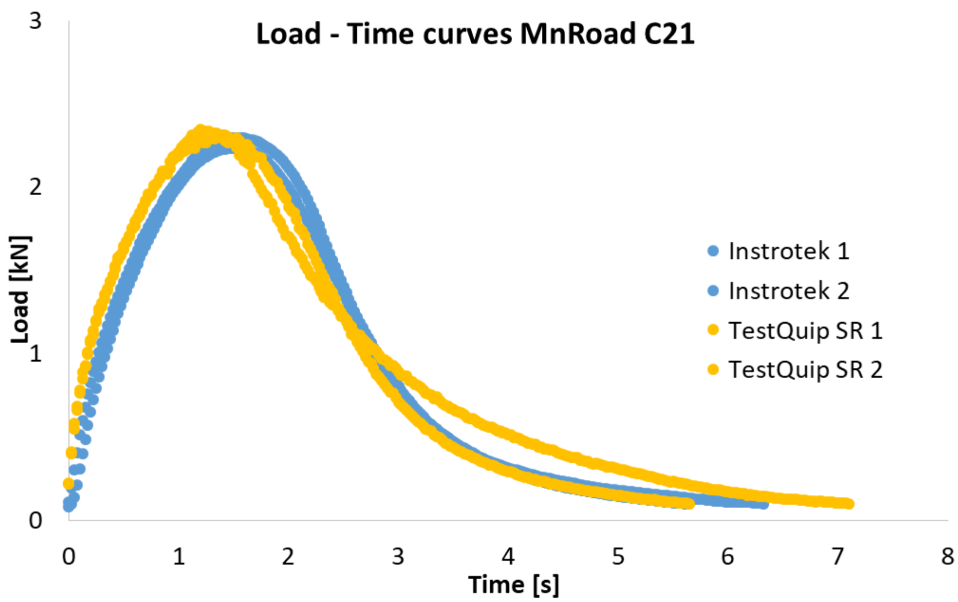


Figure 3.13 Load-time curve for MnRoad C21 mix.

3.2.1.6 MnRoad C23 Mix

Figure 3.14 compares the displacement-time curve for MnRoad C23 mix using Instrotek and TestQuip SR. It is observed that the displacement rate for Instrotek is sightly higher than that for TestQuip SR. Figure 3.15 shows the resultant load-time cure. As seen, the load-time curve after the peak load for Instrotek moves slightly to the right compared to that for TestQuip.

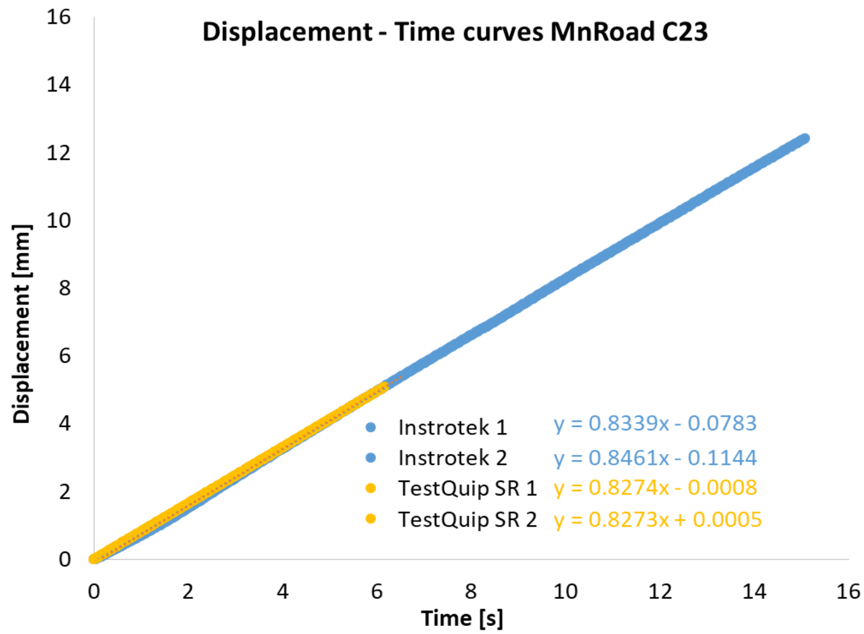


Figure 3.14 Load line displacement-time curve for MnRoad C23 mix.

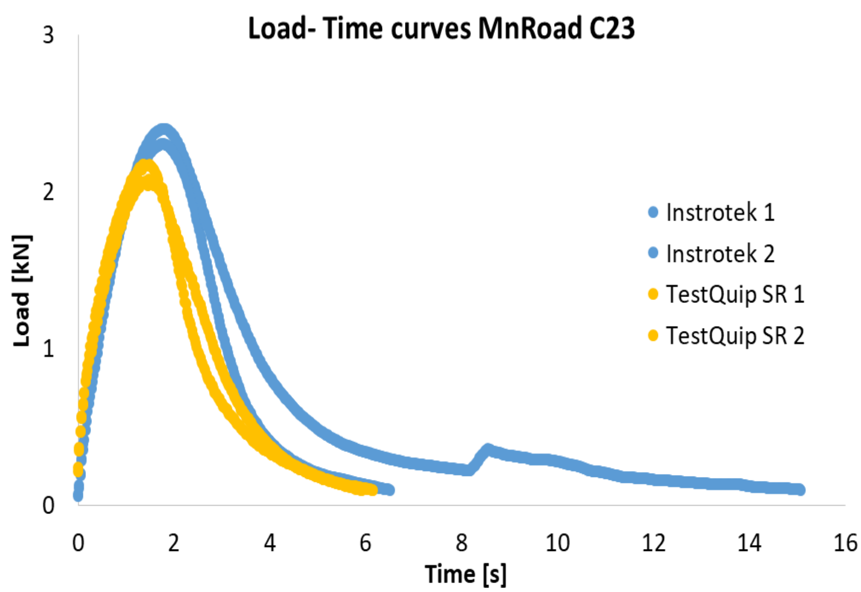


Figure 3.15 Load-time curve for MnRoad C23 mix.

3.2.1.7 IDOT Mix

Figure 3.16 compares the displacement-time curve for IDOT mix using Instrotek, TestQuip SR, and TestQuip BR. The displacement rate for TestQuip SR and BR is similar, and the support fixture does not affect the displacement rate for TestQuip. Again, the displacement rate for Instrotek is higher than that for TestQuip. The resultant load-time curves for each machine type seem to be similar, as shown in Figure 3.17.

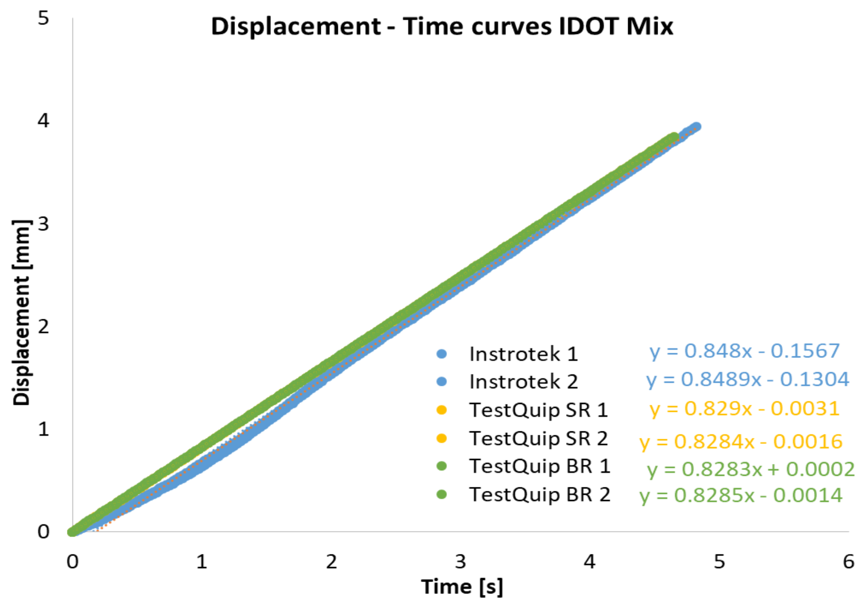


Figure 3.16 Load line displacement-time curve for IDOT mix.

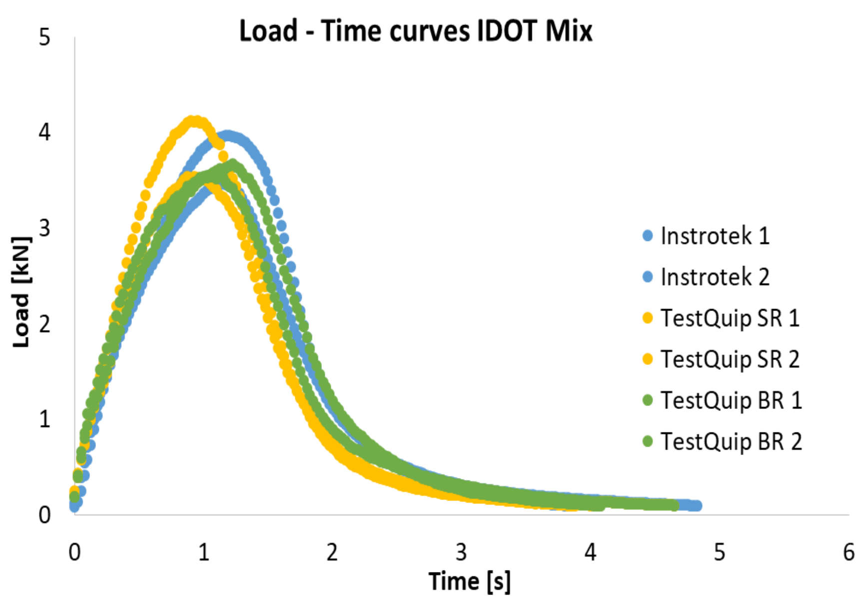


Figure 3.17 Load-time curve for IDOT mix.

3.2.1.8 N50 Sand Mix

Figure 3.18 compares the displacement-time curve for the N50 sand mix using Instrotek, TestQuip SR, and TestQuip BR. The two supports (SR and BR) for TestQuip result in a similar displacement rate. The displacement rate for Instrotek is higher than that for TestQuip. Figure 3.19 presents the resultant load-time curve. The load-time curve for Instrotek moves to the right as compared to that for TestQuip.

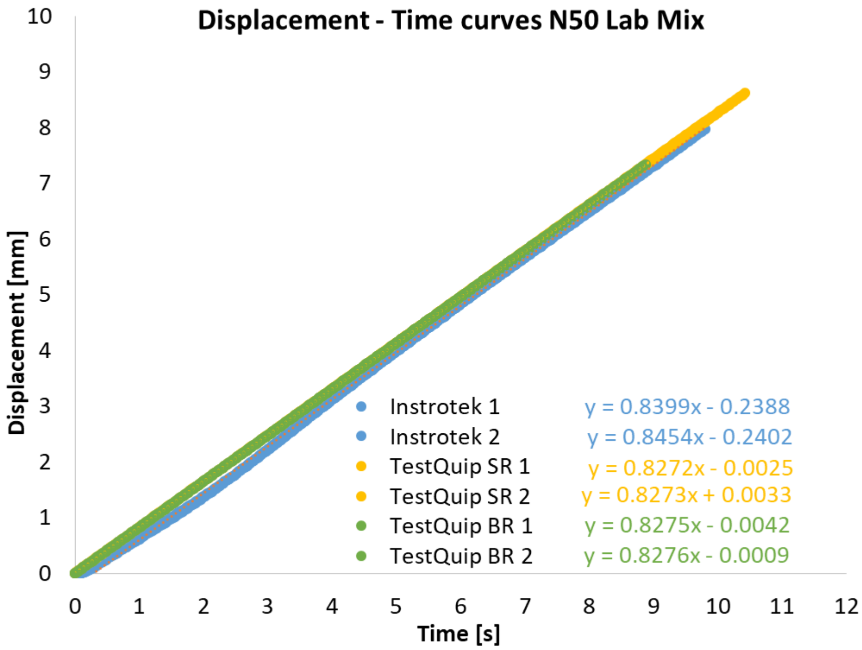


Figure 3.18 Load line displacement-time curve for N50 sand mix.

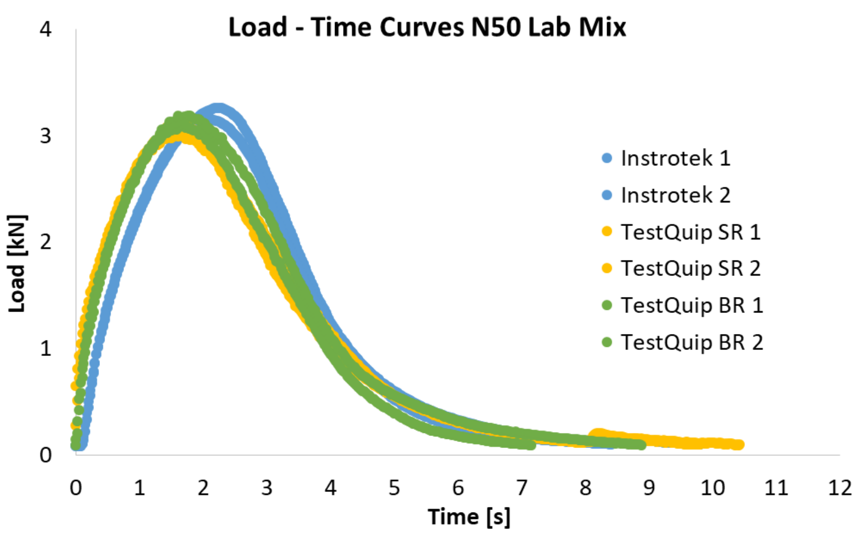


Figure 3.19 Load-time curve for N50 sand mix.

3.2.2 Comparison with Interlaken System

Two of the mixes were tested using all of the machine configurations, including the Interlaken servohydraulic system that was used in the ICT R27-128 study. This allowed a comparison of recently manufactured devices with the existing servohydraulic testing device. Those mixes were the MnRoad C18 and the N50 lab sand mixes.

3.2.2.1 N50 Sand Mix

Figure 3.20 presents test results for the N50 lab sand mix. Due to high asphalt content and low NMAS, this mix exhibits high ductility inferred from high FI values. Average values of fracture energy are very consistent among the four devices. The slope is the key parameter responsible for the variation in FI; in fact, the small variation of the average value of slope can cause a difference of more than one FI unit. According to the tests conducted, the highest average value of FI (23.23) was observed from the Interlaken machine, and the lowest average FI (19.64) was from the InstroTek machine. Figure 3.21 shows the load-displacement curves obtained on the compared devices. Only four tests are represented in the chart. The N50 sand mix is the only one in the study that was not tested at IDOT's laboratory. In Table 3.2, values of the coefficient of variation (COV) for all the analyzed parameters are reported. The COV is generally low for this mix for all of the parameters investigated (less than 15%, except for one machine).

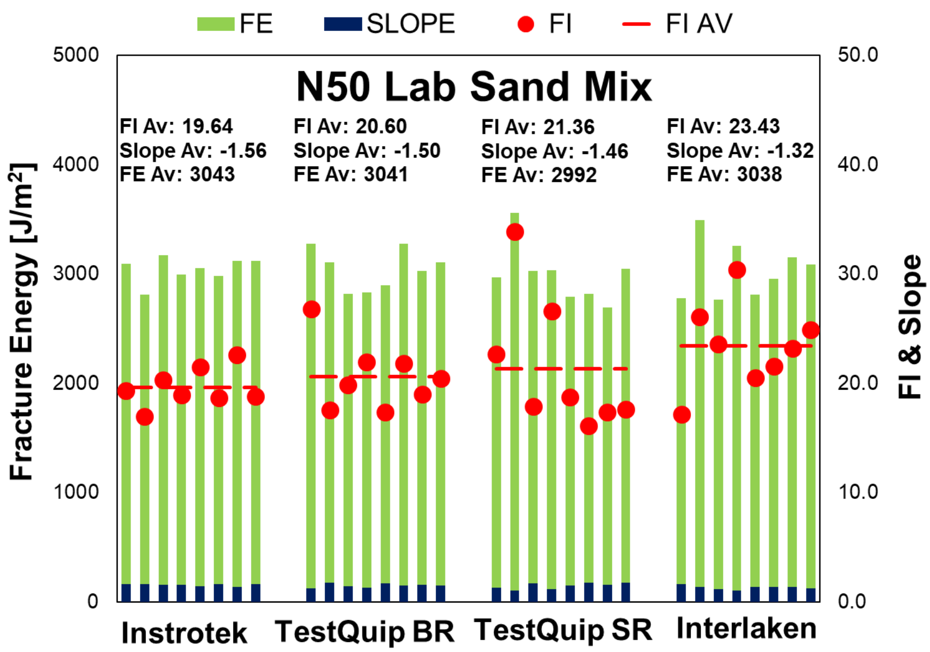
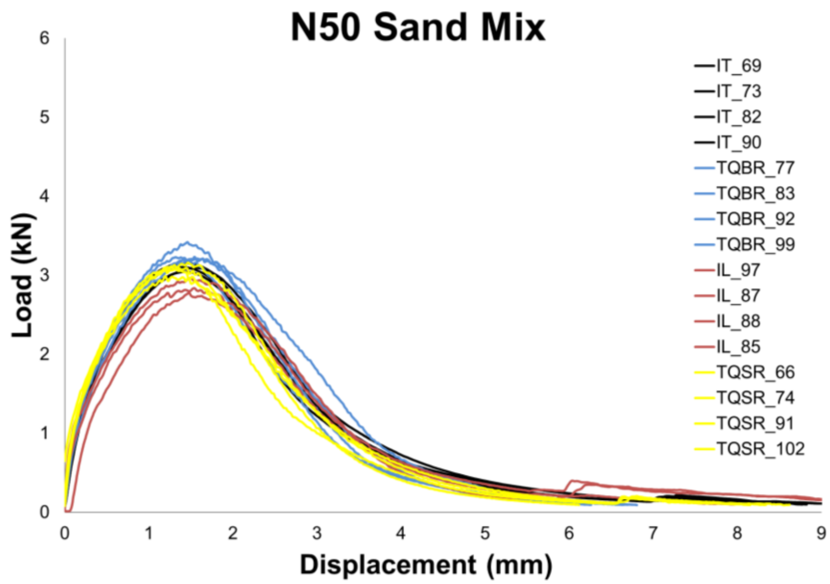


Figure 3.20 Results of tests on N50 lab sand mix.



Note: IT = InstroTek; TQBR = TestQuip bearing rollers; IL = Interlaken; TQSR = TestQuip spring rollers.

Figure 3.21 Load-load line displacement curves for N50 sand mix.

Table 3.2 COV Values Obtained in Percent for Tests on N50 Lab Sand Mix

	InstroTek	TestQuip BR	TestQuip SR	Interlaken
Flexibility Index	8.48	13.86	26.81	15.77
Fracture Energy	3.46	5.62	8.23	7.99
Slope	6.24	11.55	17.28	11.65

3.2.2.2 MnRoad C18 Mix

Figure 3.22 presents the results for the MnRoad C18 mix. In this case, the most brittle mix was selected for the comparison of the machines in the study. The FI values are lower and more variable (within the same machine). In general, all of the machines provide a similar range of values for all of the parameters investigated. Three of the devices compared showed good correlation in the results. In particular, InstroTek, TestQuip BR, and TestQuip IDOT (with the last two having the same roller arrangement) resulted in close average FI values. Results obtained on the TestQuip SR and Interlaken (both with spring rollers and a hydraulic loading system) were relatively lower on average but were still comparable with the other results. A second round of tests was conducted to verify if closer average values of FI could be obtained. Only Instrotek and TestQuip SR were involved. Figure 3.23 reports the results of the second round. In general, higher values of FI were achieved in the second group of tests and a closer gap between the two average values was obtained. As shown in Figure 3.24, load-displacement curves of four tests on each device are plotted. The differences in the slope part of the load-displacement curves are clearly observed, and could be partly due to variability in the AC mix and the machines. Figure 3.25 shows load-displacement curves for the second round of tests. Table 3.3 provides COV values for all parameters. Due to the higher NMAS and the presence of recycled binder, test results within each machine were more variable, with the COV generally in the range of 25% to 35%, except for the Interlaken machine, which had a low COV.

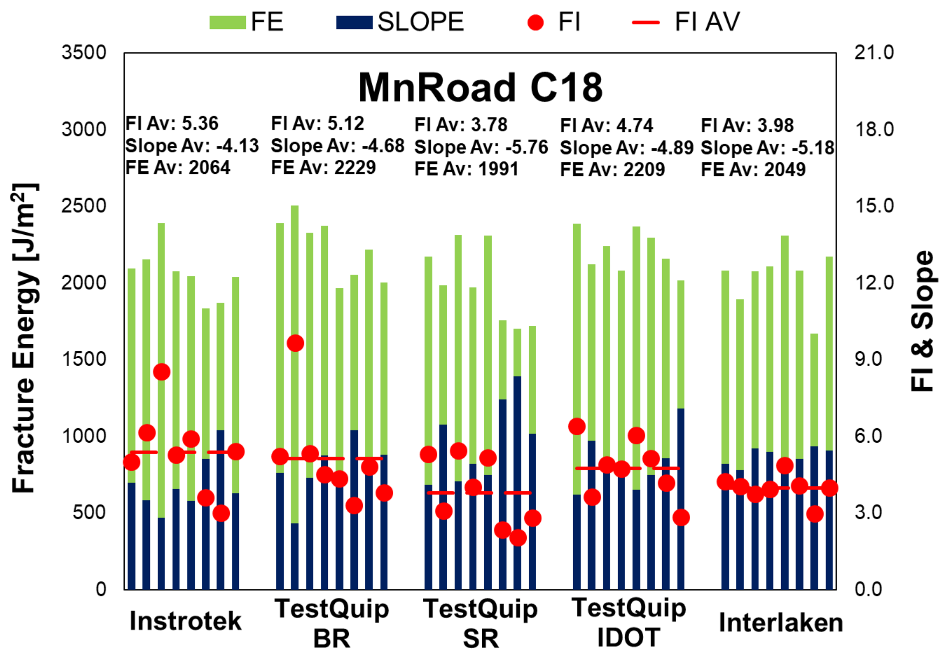


Figure 3.22 Results of tests on MnRoad C18.

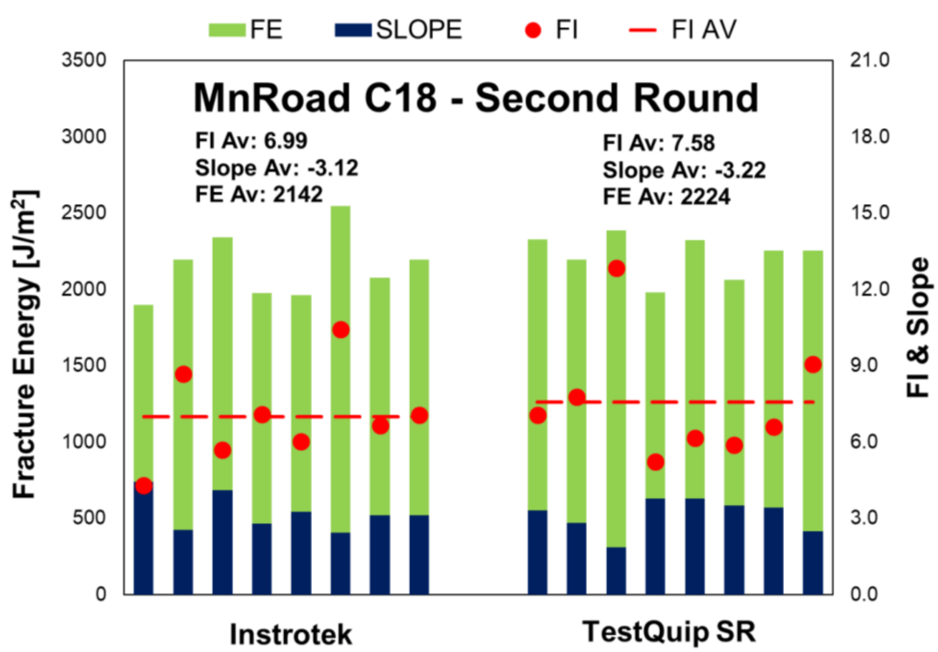
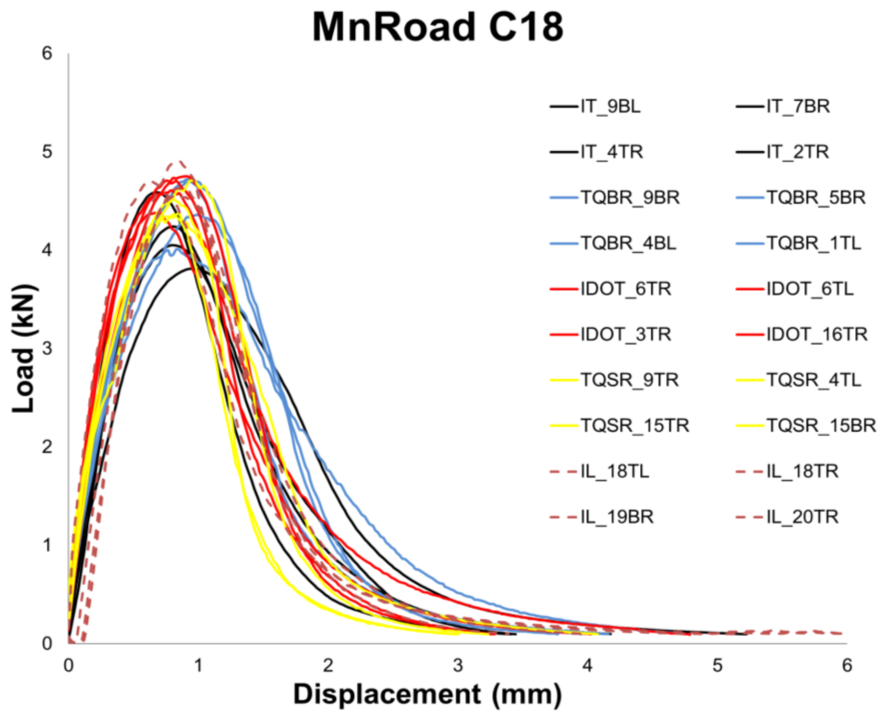
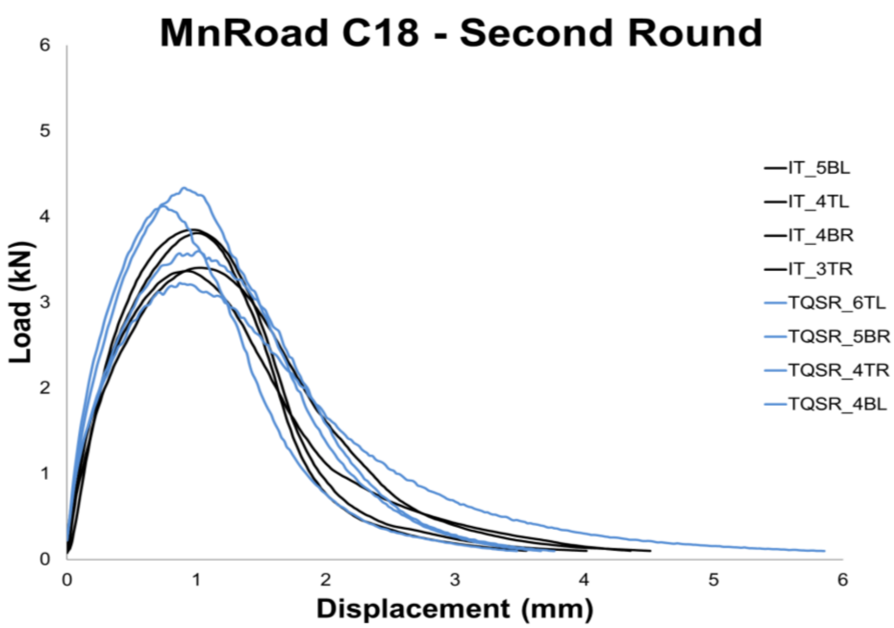


Figure 3.23 Results of tests on MnRoad C18 – Second Round.



Note: IT = InstroTek; TQBR = TestQuip bearing rollers; IDOT = TestQuip IDOT; TQSR = TestQuip spring rollers; IL = Interlaken.
BL: Bottom Left; BR: Bottom Right, TL: Top Left; TR: Top Right (SCB specimens fabricate bottom and top slices)

Figure 3.24 Load-load line displacement curves for MnRoad C18.



Note: IT = InstroTek; TQBR = TestQuip bearing rollers; IDOT = TestQuip IDOT; TQSR = TestQuip spring rollers; IL = Interlaken.
BL: Bottom Left; BR: Bottom Right, TL: Top Left; TR: Top Right (SCB specimens fabricate bottom and top slices)

Figure 3.25 Load-load line displacement curves for MnRoad C18 – Second Round.

Table 3.3 COV Values Obtained in Percentage for MnRoad C18 – In brackets values obtained from the second round

	InstroTek	TestQuip BR	TestQuip SR	TestQuip IDOT	Interlaken
Flexibility Index	29.44 (25.19)	35.75	34.44 (30.08)	23.34	12.33
Fracture Energy	7.81 (9.48)	8.44	11.93 (5.86)	5.69	8.73
Slope	24.55 (20.66)	20.83	25.72 (20.30)	21.22	6.66

Although results on the Interlaken were found to be relatively higher for the N50 sand mix and lower for the MnRoad C18, it can be stated that results obtained from the Interlaken machine are comparable with the ones obtained from the other devices. This statement is supported by the statistical analysis presented in Chapter 4.

3.2.3 Assessment of Roller Configurations in Standalone I-FIT Machines

The section focuses on the FI test results for the comparison of roller configurations. The devices evaluated were the InstroTek, TestQuip BR, TestQuip SR, and TestQuip IDOT. The main purpose of this section is to present an evaluation of the influence of the support system (spring or bearing rollers) on the results.

3.2.3.1 IDOT Base Course Mix

The IDOT base course mix was tested on the aforementioned four machines. Figure 3.26 presents the test results using the 19 mm NMAS AC mix. Average FI values are consistent among the four devices. Despite the high value of NMAS, the IDOT base course mix showed low variability within each one of the machines, achieving low COVs. Figure 3.27 and Table 3.4 show load-displacement curves and COV values obtained from the results, respectively.

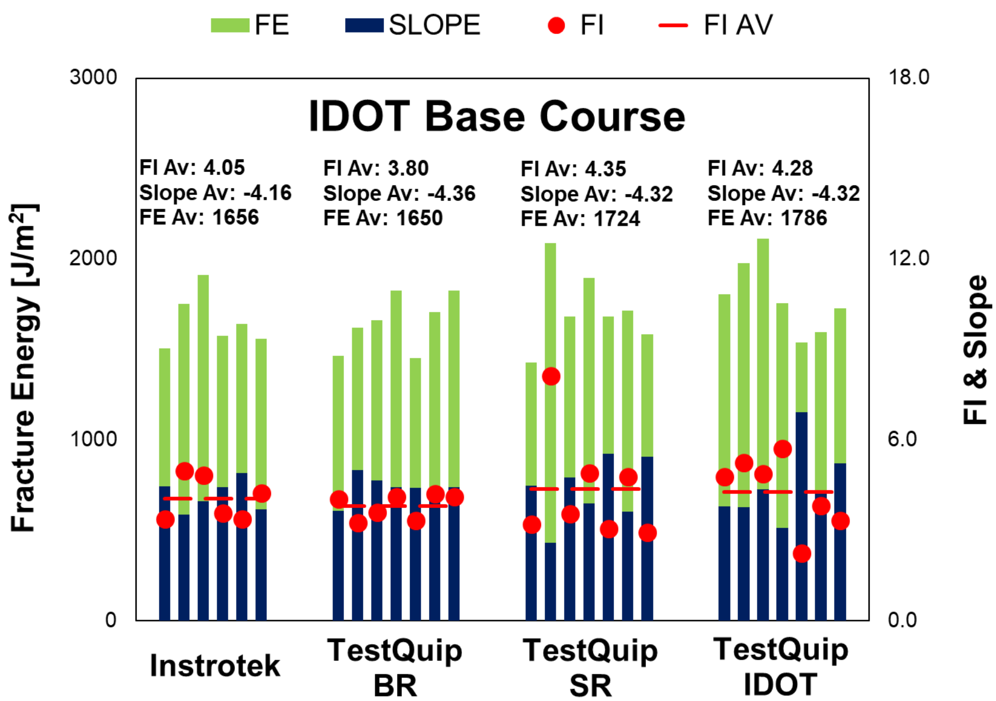
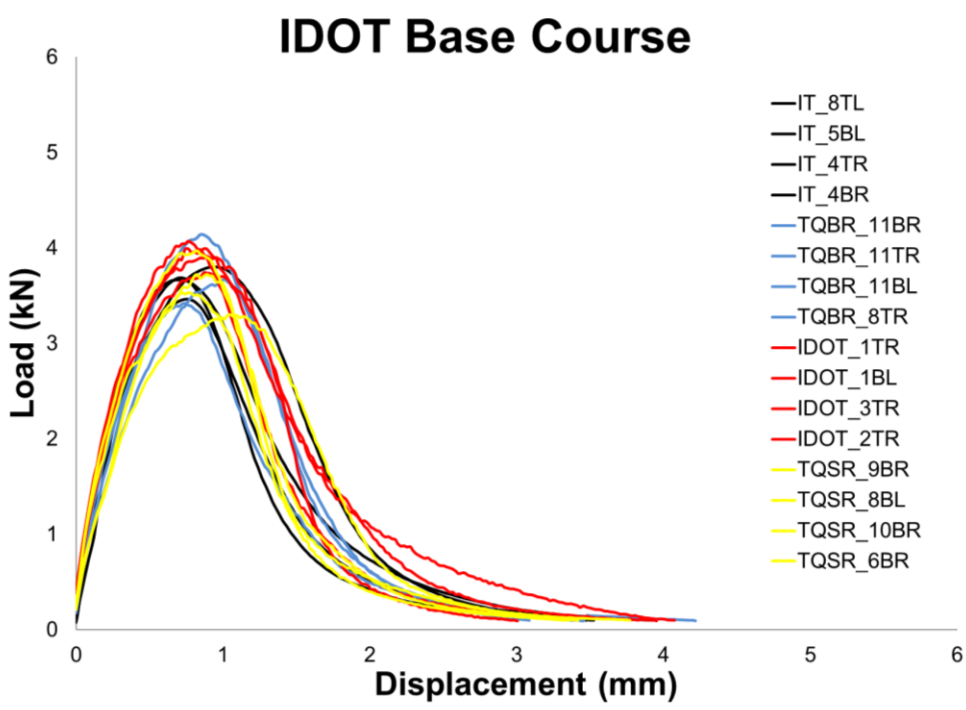


Figure 3.26 Results of tests on IDOT base course mix.



Note: IT = InstroTek; TQBR = TestQuip bearing rollers; IDOT = TestQuip IDOT; TQSR = TestQuip spring rollers; IL = Interlaken.

Figure 3.27 Load-load line displacement curves for IDOT base course mix.

Table 3.4 COV Values in percentages for IDOT Base Course Mix

	InstroTek	TestQuip BR	TestQuip SR	TestQuip IDOT
Flexibility Index	16.47	10.02	39.34	26.41
Fracture Energy	8.29	8.48	11.50	10.50
Slope	11.48	9.09	22.67	26.00

3.2.3.2 MnRoad C19 Mix

Figures 3.28 and 3.29 present the results and load-displacement curves, respectively, for the MnRoad C19 mix. For this mix, 13 tests were conducted on each of the three machines. The number of replicates were increased to evaluate the impact of increasing sample size on the actual FI values (examine if true mean of population is covered) and COV obtained from each machine. Consistent averages for FI values, fracture energy, and slope were obtained among the devices. Even if the number of replicates was increased, COV remained similar to the previous test results obtained using many fewer replicates (Table 3.5) for FI and slope. A comprehensive evaluation of sample size is presented in Chapter 4.

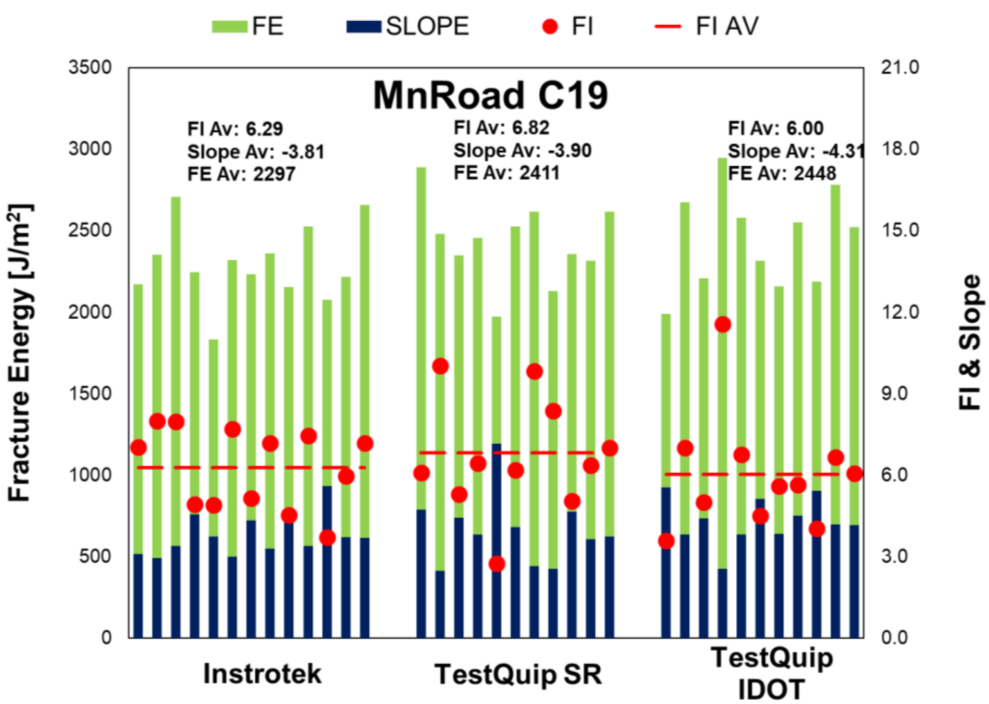
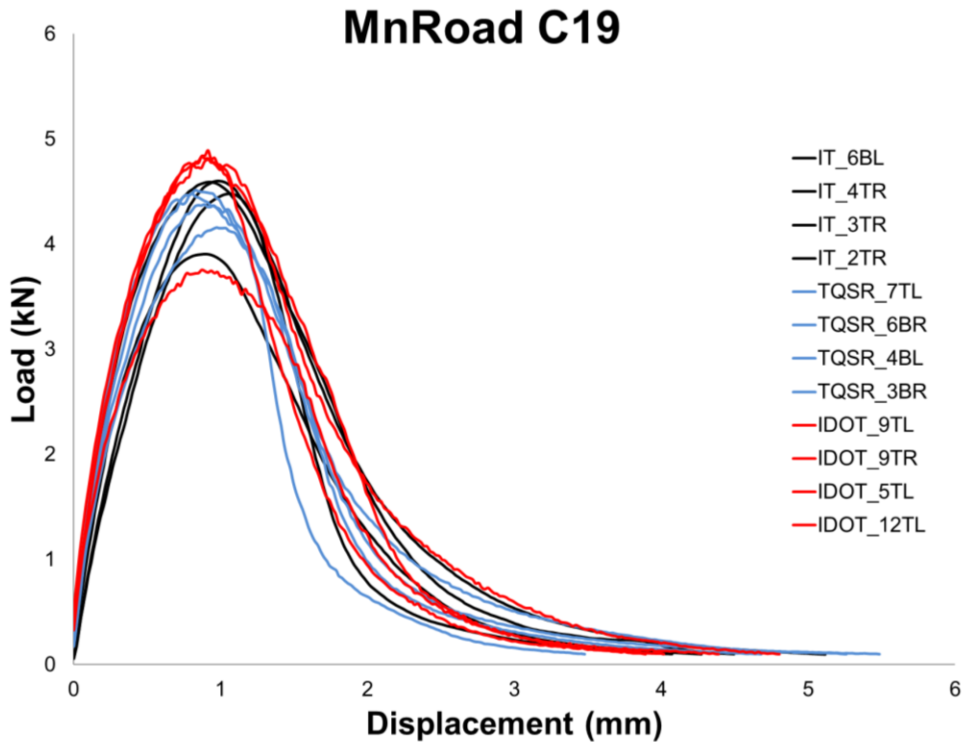


Figure 3.28 Results of tests on MnRoad C19.



Note: IT = InstroTek; TQSR = TestQuip spring rollers; IDOT = TestQuip IDOT.

Figure 3.29 Load-load line displacement curves for MnRoad C19.

Table 3.5 COV Values in percentage for Tests on MnRoad C19

	InstroTek	TestQuip SR	TestQuip IDOT
Flexibility Index	22.55	31.13	33.93
Fracture Energy	9.92	9.22	11.59
Slope	19.86	32.33	18.99

3.2.3.3 MnRoad C16 Mix

The MnRoad C16 mix was tested using only six replicates per machine. The reduced number of specimens was a direct consequence of the high variability of the mixes in terms of air voids. The MnRoad C19 and C16 mixes have similar characteristics in terms of the high contents of recycled material, including RAS. Due to the observations carried out analyzing mix MnRoad C19 in terms of variability, six specimens were considered a reasonable sample size for the study. Figures 3.30 and 3.31 show results and load-displacement curves of tests performed on mix MnRoad C16, respectively. Also for this AC mix, average FI values are consistent among the machines. Because it has the highest content of recycled material among all the AC mixes investigated, MnRoad C16 has the lowest FI values. The COVs for fracture energy, slope, and FI, shown in Table 3.6, were found to be comparable with the other AC mixes that were tested using a larger number of replicates.

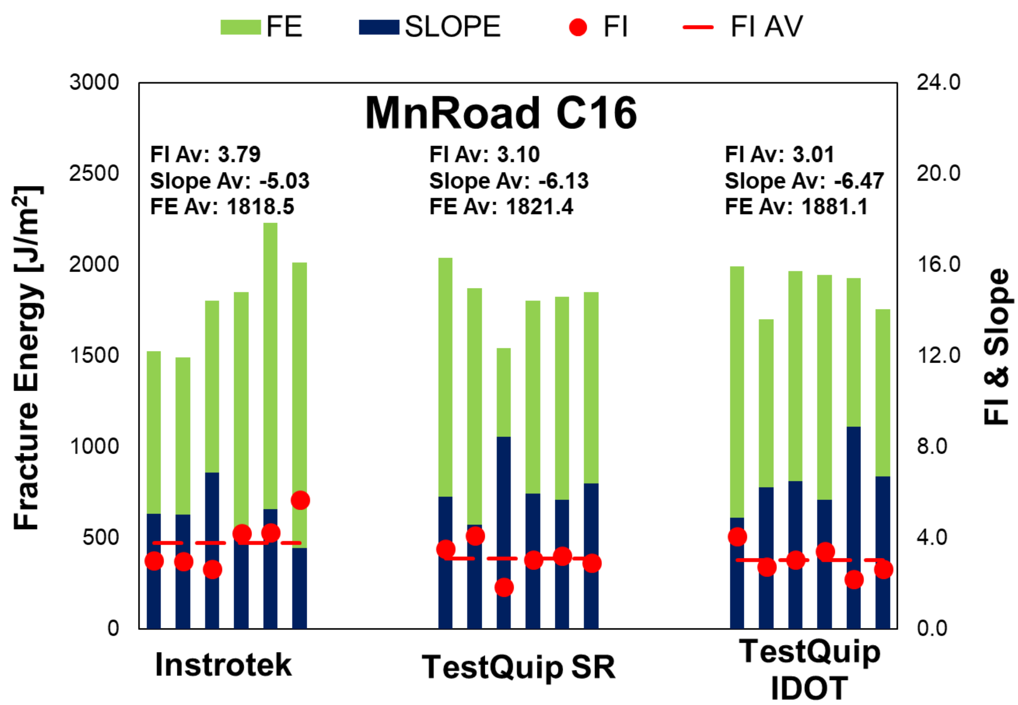
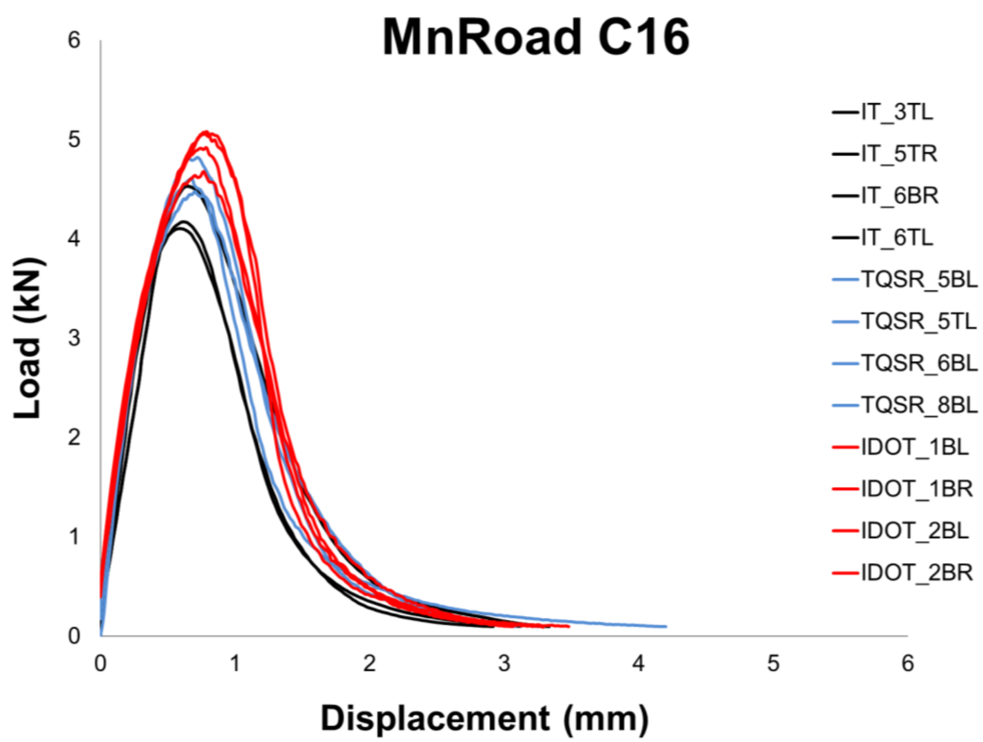


Figure 3.30 Results of tests on MnRoad C16.



Note: IT = InstroTek; TQSR = TestQuip spring rollers; IDOT = TestQuip IDOT.

Figure 3.31 Load-load line displacement curves for MnRoad C16.

Table 3.6 COV Values in percentage for Tests on MnRoad C16

	InstroTek	TestQuip SR	TestQuip IDOT
Flexibility Index	27.60	22.11	20.24
Fracture Energy	14.23	8.04	5.93
Slope	19.89	18.97	18.94

3.2.3.4 MnRoad C17 Mix

Figure 3.32 shows results for mix MnRoad C17. The average values of test results are approximately equal for InstroTek and TestQuip SR. However, the FI values were found to be slightly higher in the tests performed on TestQuip IDOT. The FI among the machines can be considered comparable. Figure 3.33 shows the load-displacement curves of the tests. As observed also for MnRoad C16, the smaller sample size did not produce unusual COV values (Table 3.7).

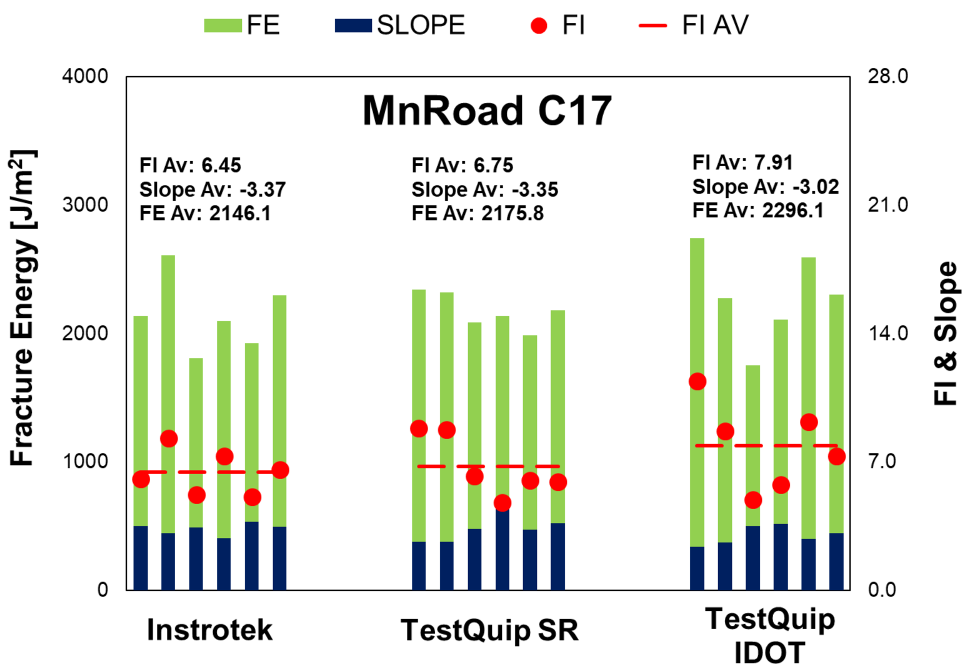
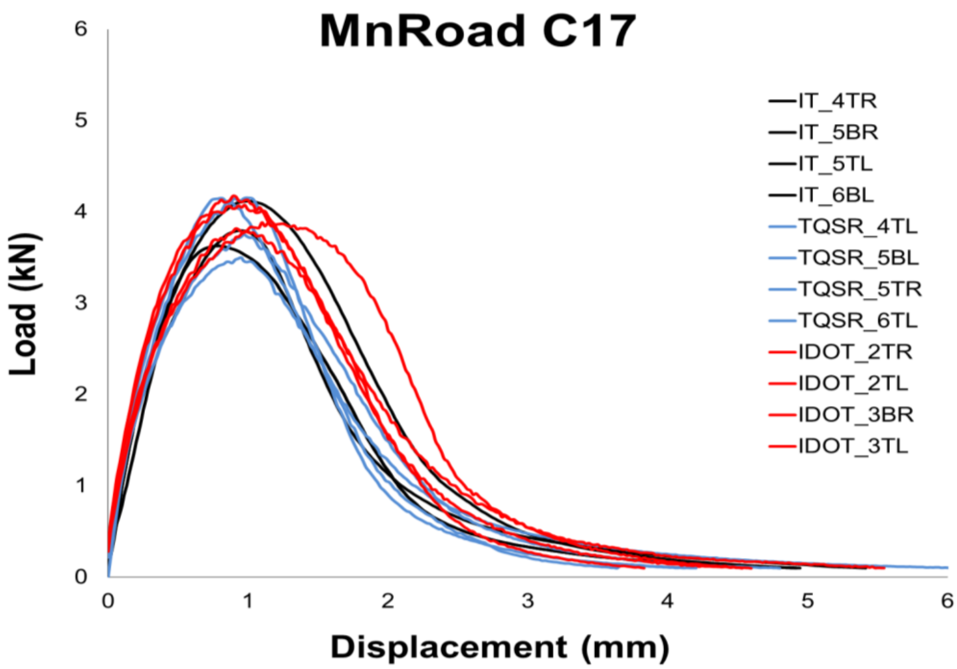


Figure 3.32 Results of tests on MnRoad C17.



Note: IT = InstroTek; TQSR = TestQuip spring rollers; IDOT = TestQuip IDOT.

Figure 3.33 Load-load line displacement curves for MnRoad C17.

Table 3.7 COV Values in percentage for Tests on MnRoad C17

	InstroTek	TestQuip SR	TestQuip IDOT
Flexibility Index	17.46	22.41	27.43
Fracture Energy	12.07	5.71	14.01
Slope	8.57	18.56	15.03

3.2.3.5 MnRoad C21 Mix

Figure 3.34 shows the results of the MnRoad C21 mix. This AC mix has higher FI values (ranging approximately between 10 and 11) and lower fracture energy compared to the other AC mixes presented. Lower fracture energy is primarily due to the relatively low load-carrying capacity shown with peak loads in Figure 3.35. The MnRoad C21 had a lower bearing capacity than all of the AC mixes presented previously, including the N50 lab sand mix. Double grade bumping for low-temperature grade and single grade bumping for high-temperature grade was applied to this mix to reduce the grade from PG 64-22 to PG 58-34, resulting in a more compliant and flexible AC mix. No remarkable differences were observed among the machines in terms of FI and other parameters. Table 3.8 shows the COV values. The COV for FI was kept under 20% for this AC mix.

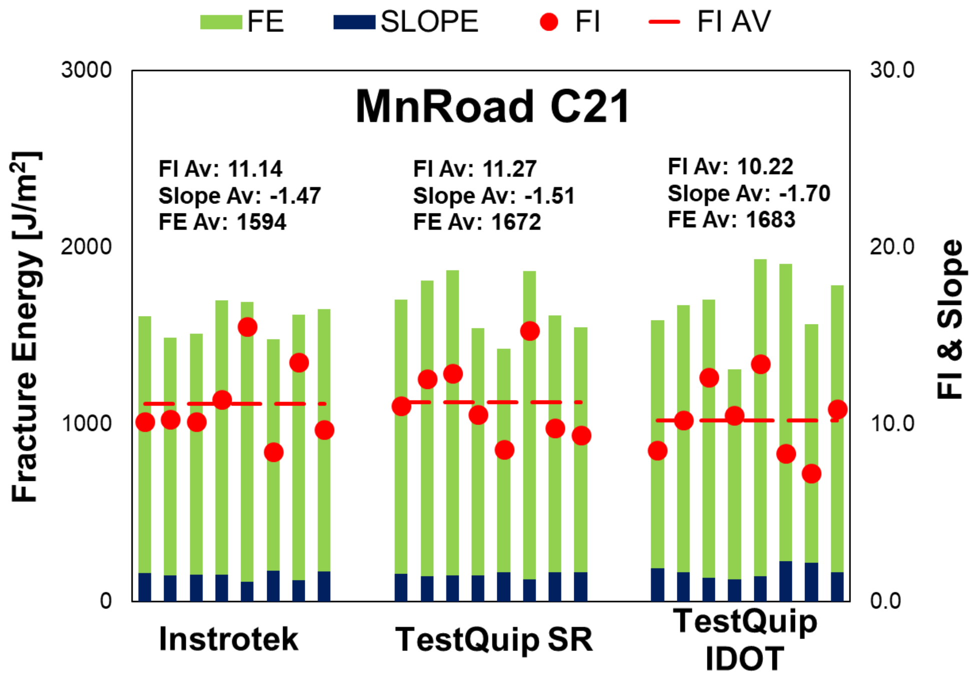
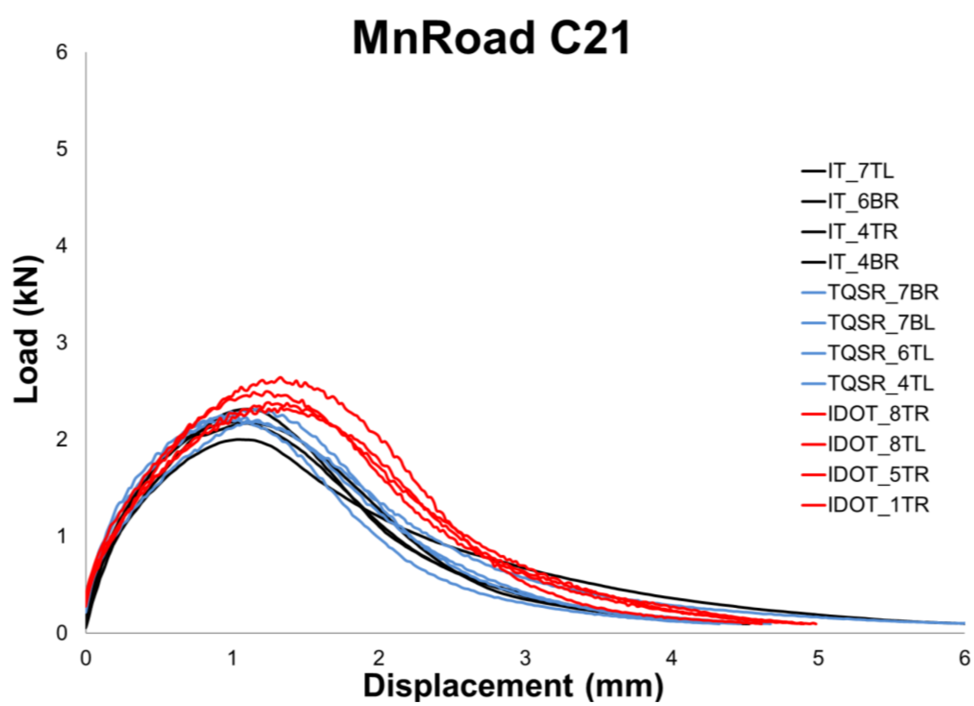


Figure 3.34 Results of tests on MnRoad C21.



Note: IT = InstroTek; TQSR = TestQuip spring rollers; IDOT = TestQuip IDOT.

Figure 3.35 Load-load line displacement curves for MnRoad C21.

Table 3.8 COV Values in Percentage for Tests on MnRoad C21

	InstroTek	TestQuip SR	TestQuip IDOT
Flexibility Index	19.26	18.33	19.52
Fracture Energy	5.22	9.30	11.14
Slope	14.51	9.31	20.60

3.2.3.6 MnRoad C23 Mix

The MnRoad C23 mix produced the highest FI values among the MnRoad AC mixes tested (Figure 3.36). The mix showed good ductility based on the high FI values in the range between 11 and 14. There are similar characteristics to the C21 and C23 AC mixes when I-FIT results and load-displacement curves were compared. One major difference between the two mixes was that PG 64-34 was used in the C23 mix. Two of the three datasets analyzed showed comparable results; the other displayed a lower fracture resistance potential. In particular, InstroTek and TestQuip IDOT were found to deliver close results, while TestQuip SR gave, on average, lower results in terms of FI. Because values of slope were consistent among the three machines, what mainly influenced FI outcomes were the lower values of fracture energy found on TestQuip resulting from lower peak loads. It is also important to note that there are several replicates with InstroTek and TestQuip IDOT machines having very low or high FI values. Because air void values and number of gyrations are in an acceptable range, such differences could be due to random mixture variability. Therefore, this mix was repeated with the InstroTek and TestQuip SR.

Figure 3.37 shows the results from the second round of tests conducted to compare TestQuip SR with InstroTek. The second round of test results showed a better agreement in terms of average values between the two devices indicating the values of FI are considered to be equivalent. Load-displacement curves for tests run on MnRoad C23 AC mix are displayed in Figure 3.38. Figure 3.39 shows load-displacement curves for the second round of tests. Table 3.9 shows the COVs for the main parameters investigated.

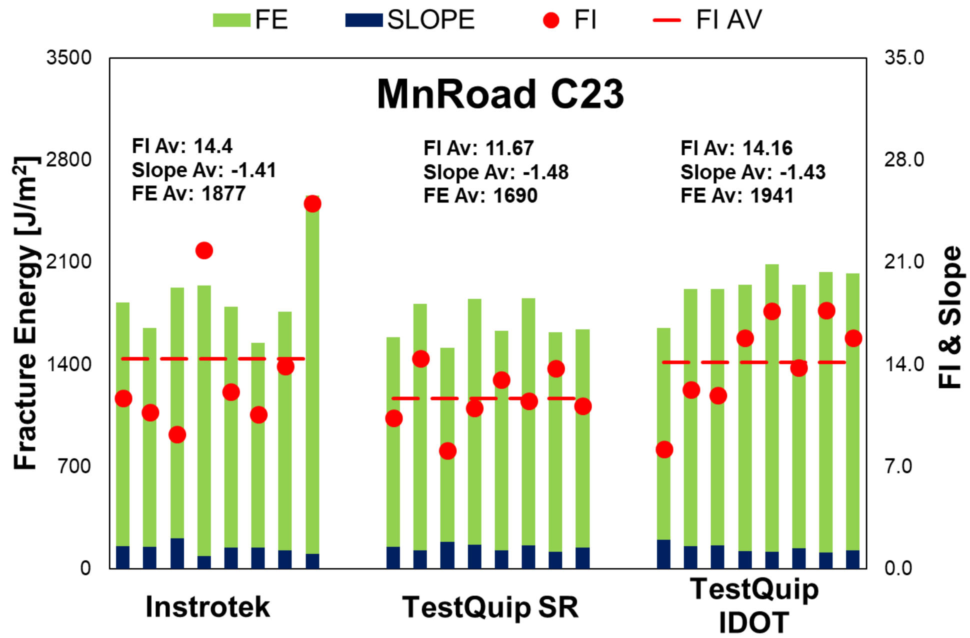


Figure 3.36 Results of tests on MnRoad C23.

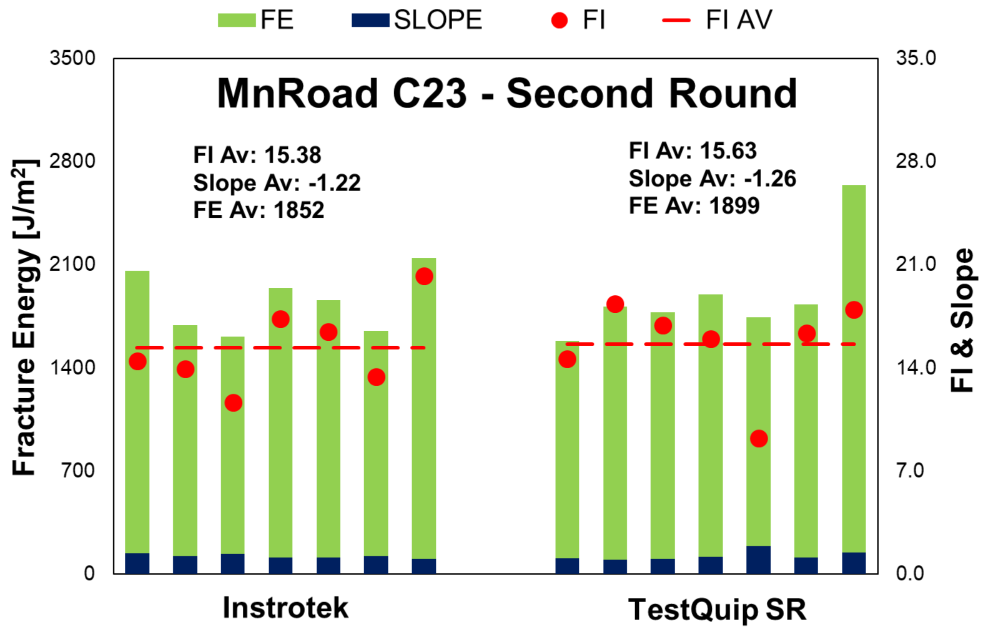
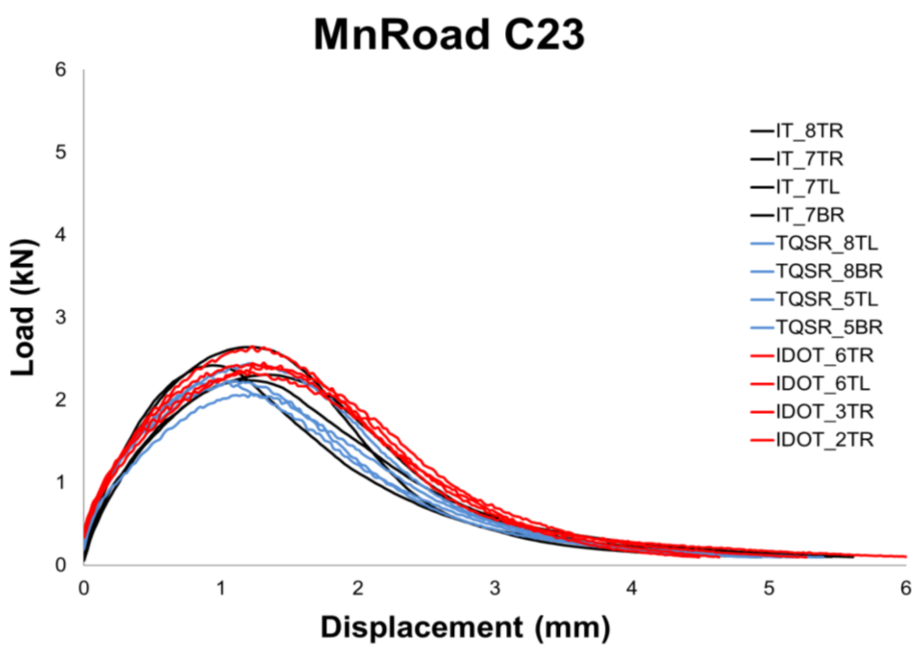


Figure 3.37 Results of tests on MnRoad C23 – Second Round



Note: IT = InstroTek; TQSR = TestQuip spring rollers; IDOT = TestQuip IDOT.

Figure 3.38 Load-load line displacement curves for MnRoad C23.

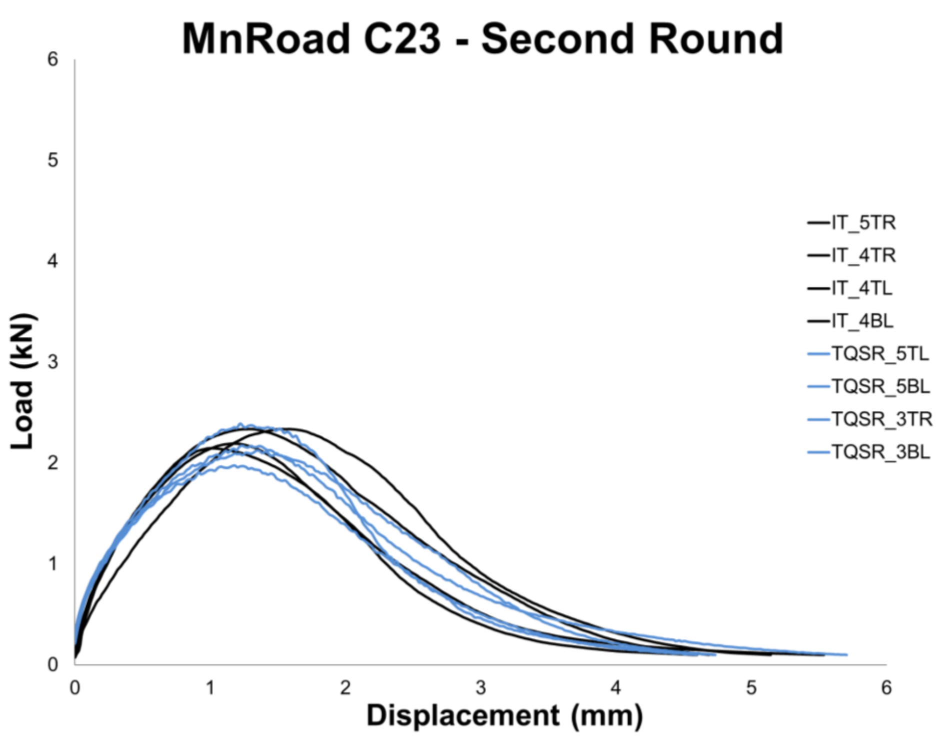


Figure 3.39 Load-load line displacement curves for MnRoad C23 – Second Round.

Table 3.9 COV Values in Percentage for Tests on MnRoad C23 - In brackets values obtained from the second round

	InstroTek	TestQuip SR	TestQuip IDOT
Flexibility Index	37.77 (17.20)	16.14 (18.26)	21.55
Fracture Energy	15.20 (10.43)	7.28 (16.68)	6.37
Slope	24.39 (10.24)	14.92 (23.60)	19.00

3.2.4 Summary of Machine Performance

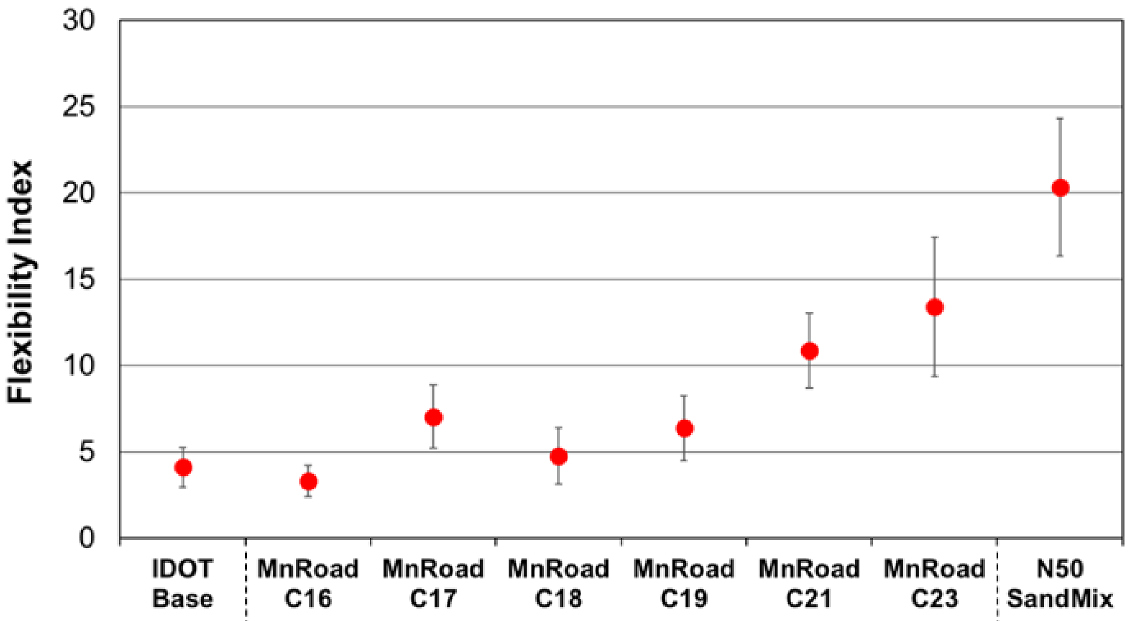
In summary, out of the eight mixes (N50 lab sand mix, IDOT base course mix, and MnRoad C16, C17, C18, C19, C21, C23) considered in this section, MnRoad C23 did not show good correlation of FI among the machines. In general, there is no consistent trend in terms of one machine or fixture consistently yielding higher or lower FI values. The variations between the machines appeared to be random, indicating that there may not be any statistically significant machine-related variability introduced. The COVs for FI were in the range of 10% to 35% for all of the AC mixes. None of the replicates were removed unless it was determined to be an outlier or had air voids outside the acceptable range. It was shown that increasing the number of replicates did result in reducing the COV values. Overall, the fracture energy results yielded COV values lower than 15%.

Based on the comparison of TestQuip (with spring roller) and TestQuip IDOT (with bearing roller) using data from seven mixes, it can be concluded that the support roller arrangement does not influence the I-FIT results. Systems with spring rollers or bearing rollers were found to be equivalent in this study. Furthermore, a comparison of systems with the same support arrangement and different manufacturers was completed using InstroTek and TestQuip SR devices. InstroTek and TestQuip SR have the spring roller supports, but the former is a screw-driven system and the latter is hydraulic. Results of the tests showed no visual difference between the two loading systems in terms of FI. These conclusions were verified using various statistical tests, as discussed in Chapter 4.

3.3 SUMMARY OF MIXTURE PERFORMANCE

Various types of AC mixes were evaluated in the study using different machines. This section compares AC mixture performance related to mix design characteristics such as NMAS, binder type, and ABR. The mixes used for the comparison of the machines covered a wide spectrum of NMAS and binder types. In particular, MnRoad AC mixes had consistent gradations so that the effect of binder grade and asphalt content on the FI could be easily observed.

In Figure 3.40, the average FI values are shown for each mix. Furthermore, the summary of all I-FIT results is shown in Table 3.10. The values are averages of every FI calculated for each test on the same AC mix. The error bars represent standard deviation of all the data points for a given AC mix. So, the variation includes within-the-machine and machine-to-machine variability. Mixes are ordered from the largest to the smallest value of NMAS. The order also considers the performance of the mixes in terms of FI, from worst to best. The main features of the AC mixes are also indicated in the lower part of the figure.



	IDOT Base	MnRoad C16	MnRoad C17	MnRoad C18	MnRoad C19	MnRoad C21	MnRoad C23	N50 SandMix
NMAS	**19.0 mm**	**12.5 mm**						**4.75 mm**
Binder Grade	64-22	64S-22 [RAS]	64S-22 [RAS]	64S-22	64S-22	58H-34	64E-34	70-22 [SBS]
Asphalt Content (%)	5.0	5.3	5.4	5.4	5.7	5.4	5.2	7.5
Total ABR	10.2	39.8	27.3	22.7	21.6	22.9	17.7	0.0
VMA (%)	14.1	14.5	14.9	14.6	14.8	14.6	14.4	18.4

Note: Letters S, H, and E stand for standard, heavy, and extra heavy and are classified according to high-temperature grade requirements determined using the multiple stress creep and recovery (MSCR) test.

Figure 3.40 Summary of AC mix performances.

At the two extremes of the chart are the AC mixes with the largest and smallest value of NMAS (IDOT base and N50 sand mix). The IDOT base mix and the MnRoad mixes with common features (mixes from C16 through C19) resulted in lower FI values, approximately in the range between 4 and 7. These mixes had relatively high ABR (more than 20%), high NMAS (19.0 and 12.5 mm), and standard grade (S-grade) PG 64-22 without any grade bumping. Standard, heavy, and extra-heavy grades determined based on the multiple stress creep and recovery (MSCR) test were used in characterization of binders to indicate which traffic level the mixes can be used for.

Various levels of binder grade bumping was applied to AC mixes C21 and C23. These two mixes were designed with different binder types, PG 58H-34 (heavy traffic grade) and PG 64E-34 (extra-heavy traffic grade). The amount of ABR was around 20% in both AC mixes, while the binder content differed by 0.2% in favor of C21. Both of the AC mixes demonstrated good flexibility, with FI values equal or greater than 11. The reduction in cracking potential of the mixes can be attributed to the use of softer PG binders, superior recovery characteristics (E and H grade) of the binder, and the low amount of ABR used in the two AC mixes.

The N50 sand mix with the highest binder content (7.5%), lowest NMAS (4.75 mm), and polymer modification had the highest FI values. Even though NMAS is only one of the AC mix design variables that makes a mix different from the others, it can be expected that the AC mix with a lower NMAS has a potential to achieve higher values of flexibility due to higher asphalt binder content. However, it is important to note that this study evaluated only one mix having small NMAS (4.75) and large NMAS (19.0 mm).

In summary, it was observed that AC mixes with a higher amount of ABR had greater cracking potential. This was concluded using any of the machine configurations in the study. This suggests the negligible contribution of machine compliance to variability in the testing results.

Table 3.10 Summary of I-FIT Results.

Machine ID	Mix ID	FI	COV [%]	FE [J/m^2]	COV [%]	Slope	COV [%]
Instrotek	MnRoad C16	3.79	27.60	1819	14.23	-5.03	19.89
TestQuip SR		3.10	22.11	1821	8.04	-6.13	18.97
TestQuip IDOT		3.01	20.24	1881	5.93	-6.47	18.94
Instrotek	MnRoad C17	6.45	17.46	2146	12.07	-3.37	8.57
TestQuip SR		6.75	22.41	2176	5.71	-3.35	18.56
TestQuip IDOT		7.91	27.43	2296	14.01	-3.02	15.03
Instrotek	MnRoad C18	5.36	29.44	2064	7.81	-4.13	24.55
TestQuip BR		5.12	35.75	2229	8.44	-4.68	20.83
TestQuip SR		3.78	34.44	1991	11.93	-5.76	25.72
TestQuip IDOT		4.74	23.34	2209	5.69	-4.89	21.22
Interlaken		3.98	12.33	2049	8.73	-5.18	6.66
Instrotek	MnRoad C19	6.29	22.55	2297	9.92	-3.81	19.86
TestQuip SR		6.82	31.13	2411	9.22	-3.90	32.33
TestQuip IDOT		6.04	33.93	2448	11.59	-4.31	18.99
Instrotek	MnRoad C21	11.14	19.26	1594	5.22	-1.47	14.51
TestQuip SR		11.27	18.33	1672	9.30	-1.51	9.31
TestQuip IDOT		10.22	19.52	1683	11.14	-1.70	20.60
Instrotek	MnRoad C23	14.40	37.77	1877	15.20	-1.41	24.39
TestQuip SR		11.67	16.14	1690	7.28	-1.48	14.92
TestQuip IDOT		14.16	21.55	1941	6.37	-1.43	19.00
Instrotek	IDOT Base Course	4.05	16.47	1656	8.29	-4.16	11.48
TestQuip BR		3.80	10.02	1650	8.48	-4.36	9.09
TestQuip SR		4.35	39.34	1724	11.50	-4.32	22.67
TestQuip IDOT		4.28	26.41	1786	10.50	-4.47	26.00
Instrotek	N50 Lab Sand Mix	19.64	8.48	3043	3.46	-1.56	6.24
TestQuip BR		20.60	13.86	3041	5.62	-1.50	11.55
TestQuip SR		21.36	26.81	2992	8.23	-1.46	17.28
Interlaken		23.43	15.77	3038	7.99	-1.32	11.65

CHAPTER 4: STATISTICAL ANALYSIS

This chapter presents the statistical analysis performed on the datasets collected in this study. The statistical analysis was performed first to determine outliers and evaluate the options to reduce data sets. Then, statistical tests were used to support visual observation presented in Chapter 3 to evaluate variability between machines.

4.1 DETERMINING OUTLIERS AND REDUCING THE DATASET

4.1.1 Outlier Determination

One of the most common and simplest ways of determining outliers is the interquartile range (IQR) rule. This method uses five variables to determine an outlier:

1. Lowest value in the dataset
2. The first quartile, Q1, which represents one-quarter of the way through the list of data
3. Median of the dataset
4. The third quartile, Q3, which represents three-quarters of the list of data
5. Maximum value in the dataset

Interquartile range is IQR = Q3 – Q1. Any value that is greater than Q3 + 1.5 * IQR or smaller than Q1 – 1.5 * IQR is a potential outlier (Upton et al 1996). Table 4.1 provides an example (for the MnRoad C17 mix) to determine outliers.

Table 4.1 Example for Determining Outliers for MnRoad C17 from InstroTek Results

Col. B Data (FI)	Outlier?		The Interquartile Range Rule Variables			
6.08	NO			Value		Excel Function
8.31	NO		**Q1**	5.82	**First Quartile**	**"=QUARTILE(B:B,3)"**
5.23	NO		**Q3**	8.60	**Third Quartile**	**"=QUARTILE(B:B,1)"**
7.33	NO		**IQR**	2.77	**Interquartile Range**	**= 8.60 – 5.82**
5.13	NO		**Q3+IQR**	12.76	**Upper Bound for Outliers**	**= 8.60 + 1.5*2.77**
6.59	NO		**Q1-IQR**	1.66	**Lower Bound for Outliers**	**= 5.82 – 1.5*2.77**

This method was applied to all of the other AC mixes. Statistical box plots are used to present the data and their variability in Figures 4.1 through 4.8. Note that the blue lines on each box plot represent the first and third interquartile range, the red line represents the median, the black horizontal bars represent the upper and lower bound for outliers, and the red cross represents any outlier found by the IQR method. Only four outliers were found among all of the mixes analyzed. These are with the C16 mix tested with TestQuip SR, C18 mix tested with TestQuip IDOT, C19 mix tested with TestQuip IDOT, and IDOT base mix tested with TestQuip SR. The outliers were not removed from the dataset because the statistical tests performed requires same-size sample sets for comparative assessment.

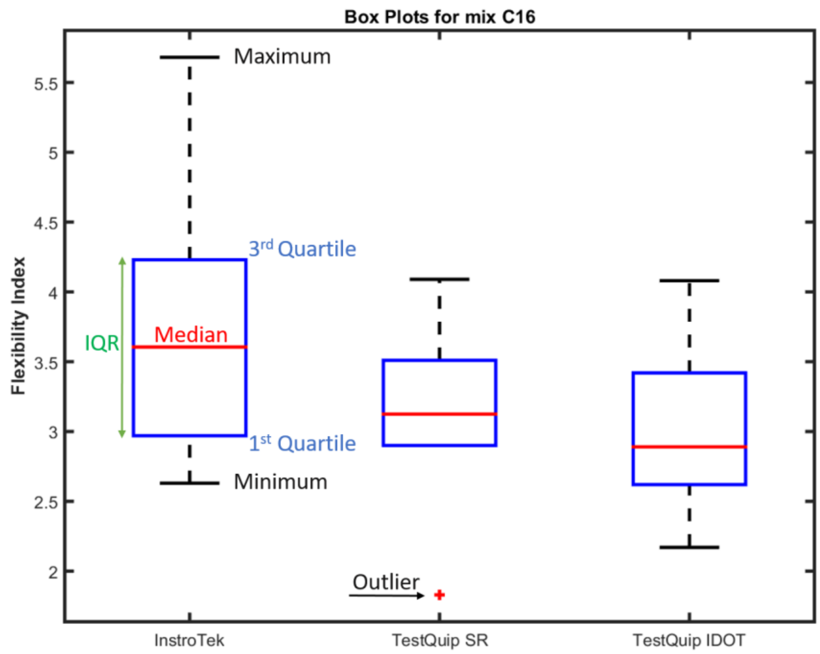


Figure 4.1 Box plot for mix C16.

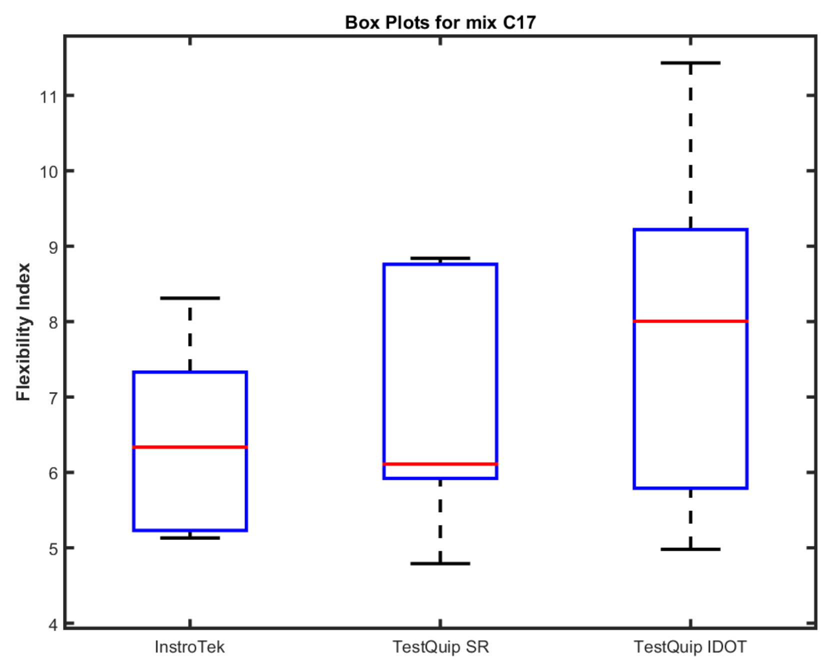


Figure 4.2 Box plot for mix C17.

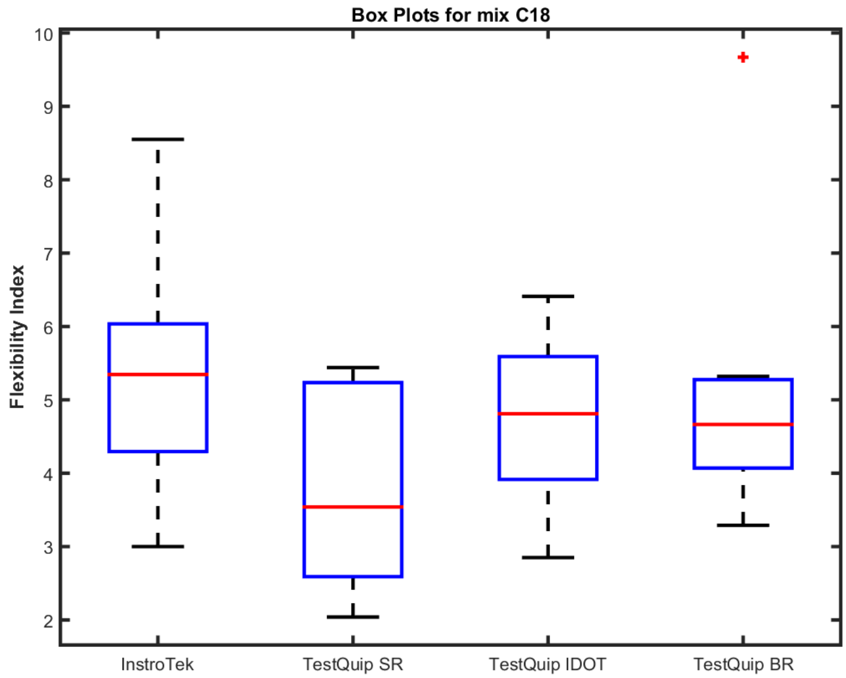


Figure 4.3 Box plot for mix C18.

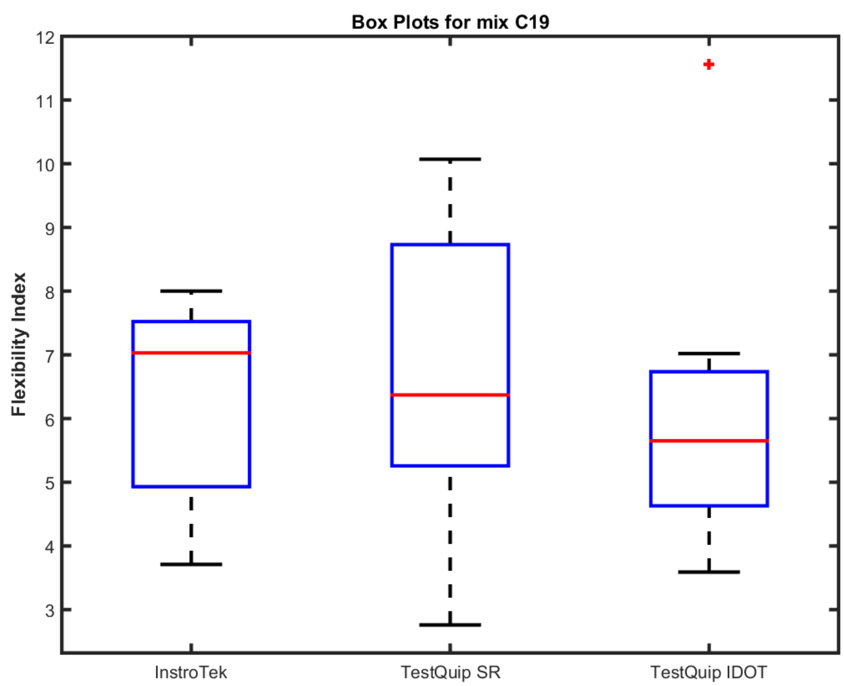


Figure 4.4 Box plot for mix C19.

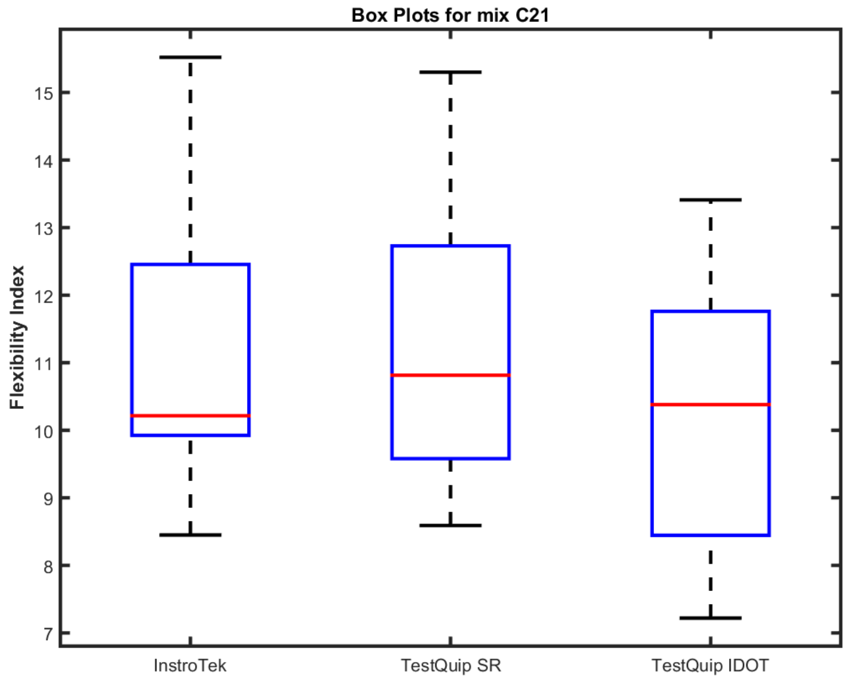


Figure 4.5 Box plot for mix C21.

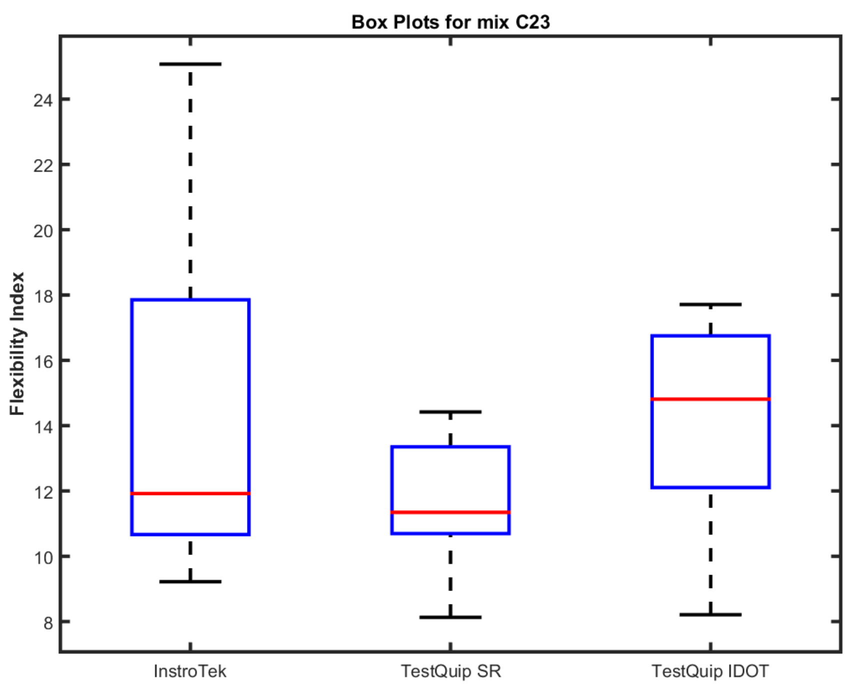


Figure 4.6 Box plot for mix C23.

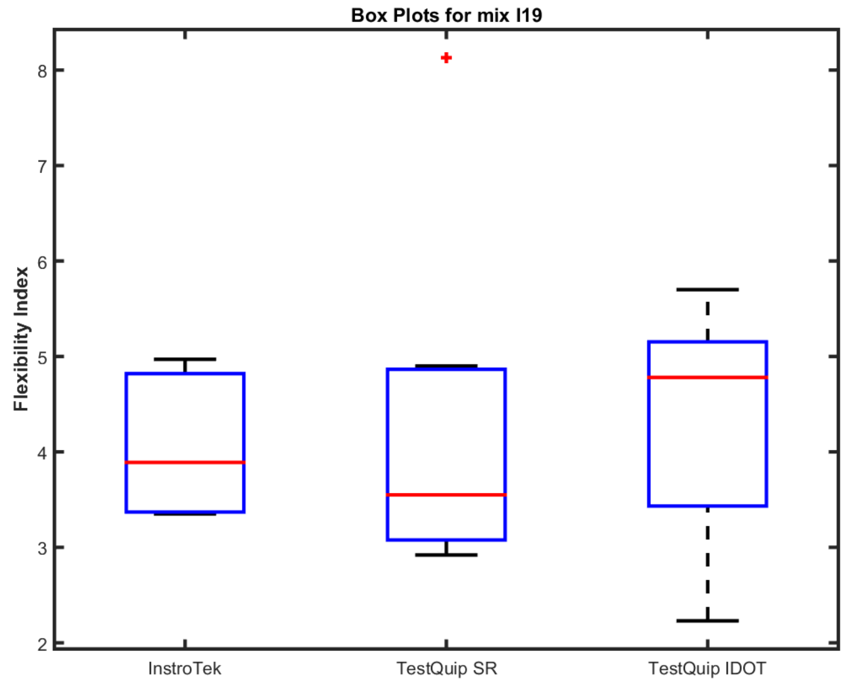


Figure 4.7 Box plot for mix IDOT base mix with 19.0 mm.

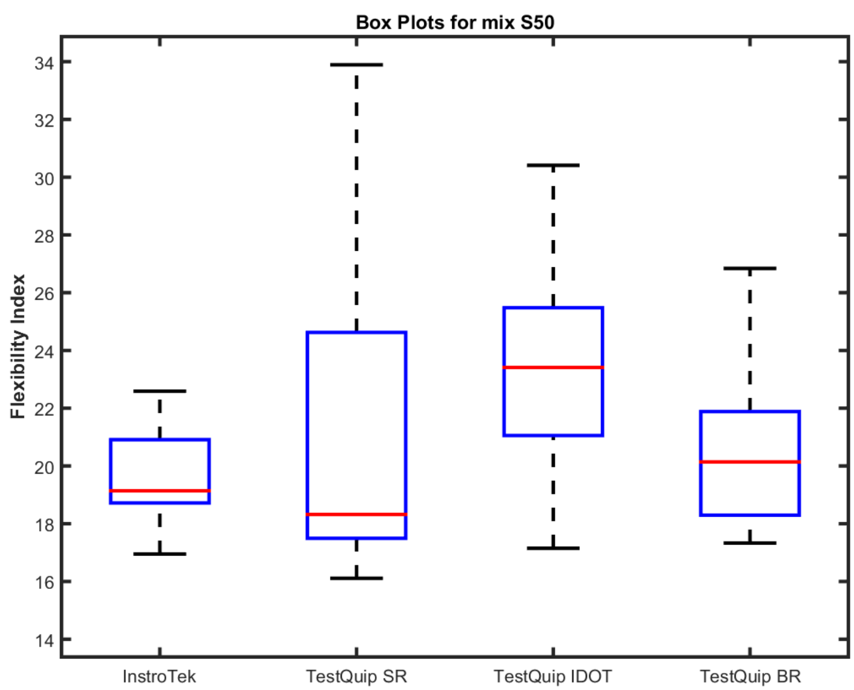


Figure 4.8 Box plot for mix S50.

4.1.2 Determination of Optimum Sample Size

Currently, AASHTO TP124 and Illinois Test Specification 405 recommend using four replicates fabricated from one gyratory-compacted or two field core specimens. The number of replicates used in this study was greater than four because the goal is to evaluate machine variability and minimize or randomize any other variability that might affect the results. Therefore, specimens were prepared from multiple gyratory-compacted specimens and distributed to the machines randomly. The number of replicates ranged from six to thirteen. This also allowed an evaluation of optimum sample size for the I-FIT protocol. The focus of this analysis is not to find a method to reduce COV but to seek a method to identify a minimum number of replicates that can result in repeatable and reproducable I-FIT results.

In this regard, the FI results for mix C19 were analyzed. This mix was tested using 13 replicates. The mean FI resulting from increasing the number of replicates is shown in Figures 4.9 and 4.10 for the two machines. Because data are randomly selected, significant variations are observed when the number of replicates is less than six. As the number of replicates increases, a more stable mean of FI values is observed. This general pattern is identical for both machines. This indicates that when the number of replicates is low, there is a great risk of notable fluctuations in the FI results when the test is repeated or sample size is changed. A convergence behavior to a stable mean was observed with an increasing number of replicates. However, this may be due to a reduction in randomness when the number of replicates constitutes an increasing percentage of the total sample population of 13. Therefore, more replicates are needed to find the true mean of this mix and evaluate mean variation when the number of replicates is high. Nevertheless, this analysis proves the randomness in the results of FI when the number of replicates is kept under six. Because of high variability in the material, it is essential to increase the number of replicates to represent average material behavior. Otherwise, FI results may not be reproducible.

Another note about the randomness of the COV: Sometimes it is possible to get a very low COV when the number of replicates is as low as 2 to 4, but significant fluctuations in the mean values is observed when the test is repeated or sample size is increased (e.g. two and four replicates in Figure 4.9 has the lowest COV or two or three replicates in Figure 4.10 has the lowest COV). One can reach a convergent mean value of FI with a higher number of replicates with relatively high COV. Therefore, COV should not be the criterion for determining the minimum sample size.

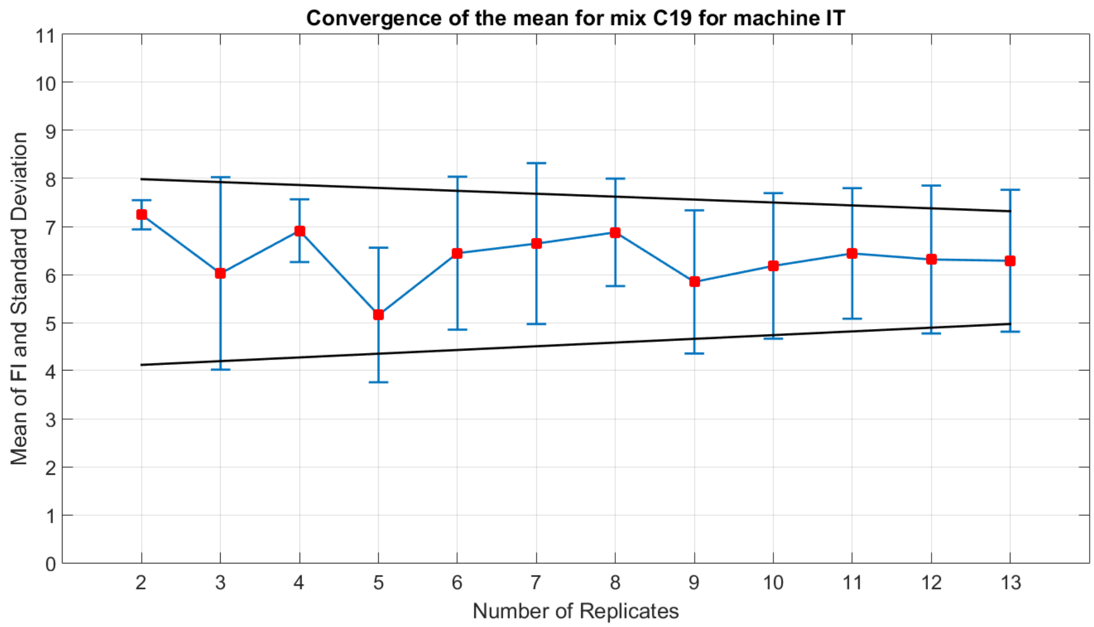


Figure 4.9 Convergence behavior of mix C19 tested on InstroTek spring rollers.

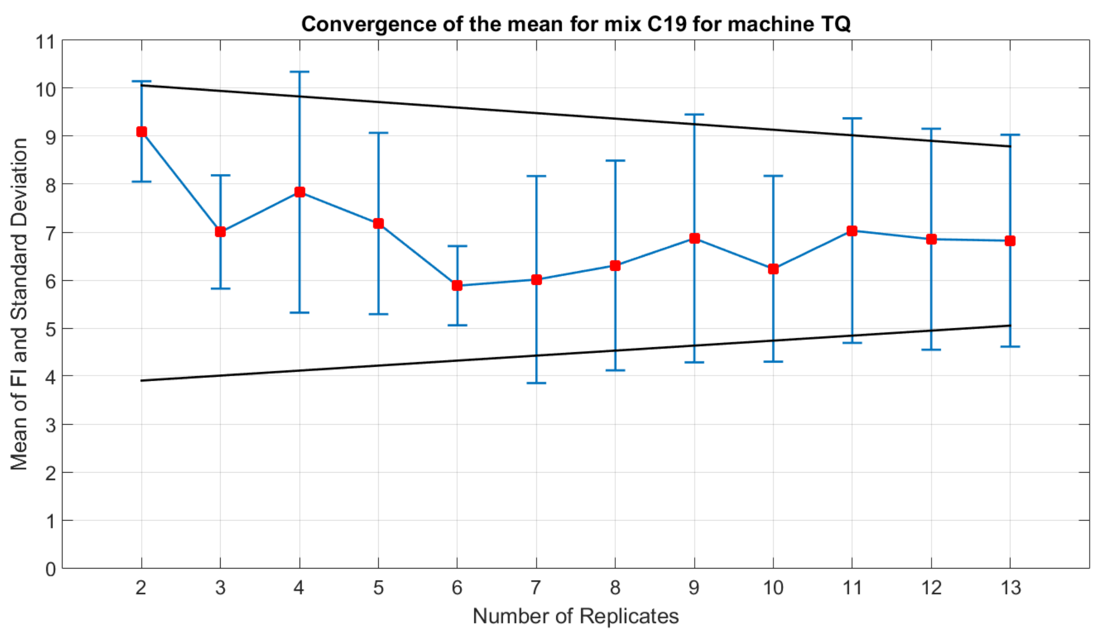


Figure 4.10 Convergence behavior of mix C19 tested on TestQuip spring rollers.

It is common to use different techniques to reduce sample size to improve COV. Different sample reduction techniques were used to demonstrate the feasibility of sample size reduction. The first sample reduction method is to remove the highest and lowest of the dataset with a size of at least six samples per machine. The results are shown in Figures 4.11 and 4.12 using the two machines. In this case, the mean of the FI did not change significantly (maximum change was 6% with C23). However, a significant and consistent reduction was observed in the COV after the reduction of sample size.

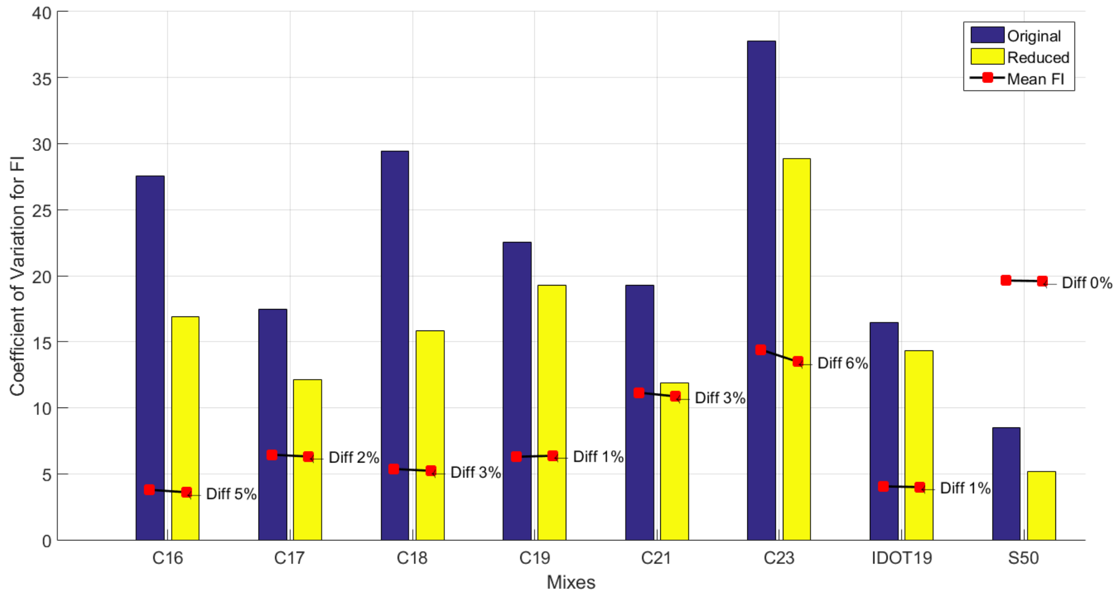


Figure 4.11 Sample reduction method 1 for InstroTek spring rollers.

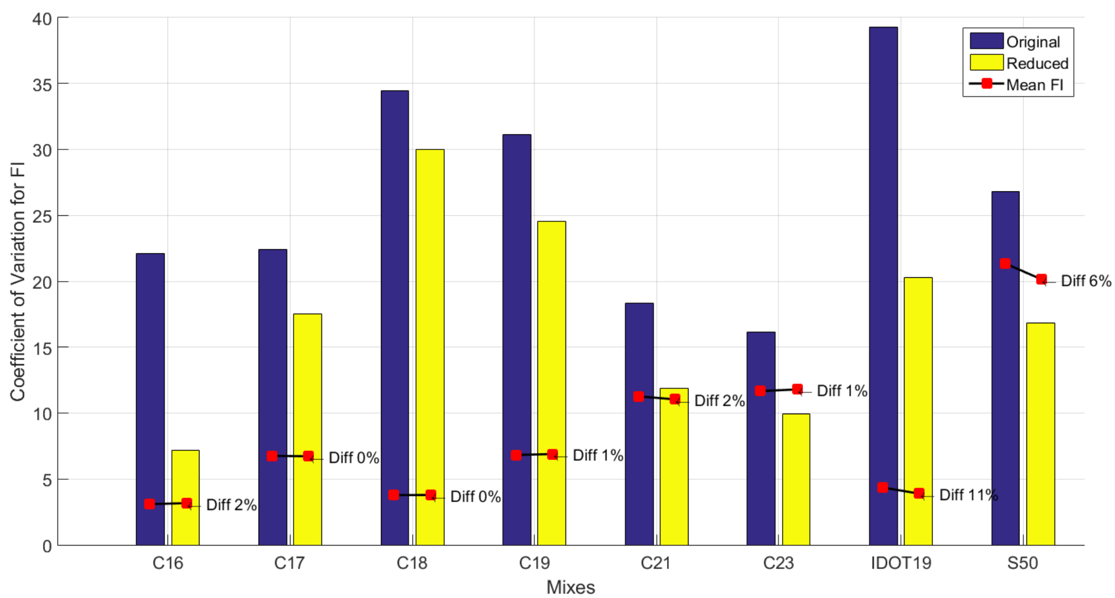


Figure 4.12 Sample reduction method 1 for TestQuip spring rollers.

The second sample reduction method assumed that only four replicates can be consistent with the current AASHTO standards and common practices. Four samples were randomly selected for each machine. Each sample set and the data point farthest away from the mean was removed and compared again to the data set with the original set with four replicates. This is a common practice to remove the point farthest away from the mean, which is considered an outlier. The results for the change in COV and mean FI values are presented in Figures 4.13 and 4.14. This reduction technique resulted in significant changes in the COV as well as the mean value of the FI, which is as high as 16%. This practice of sample reduction can cause significant changes in the mean values of FI when especially sample size is limited to four. These changes can be random and affect reproducibility adversely.

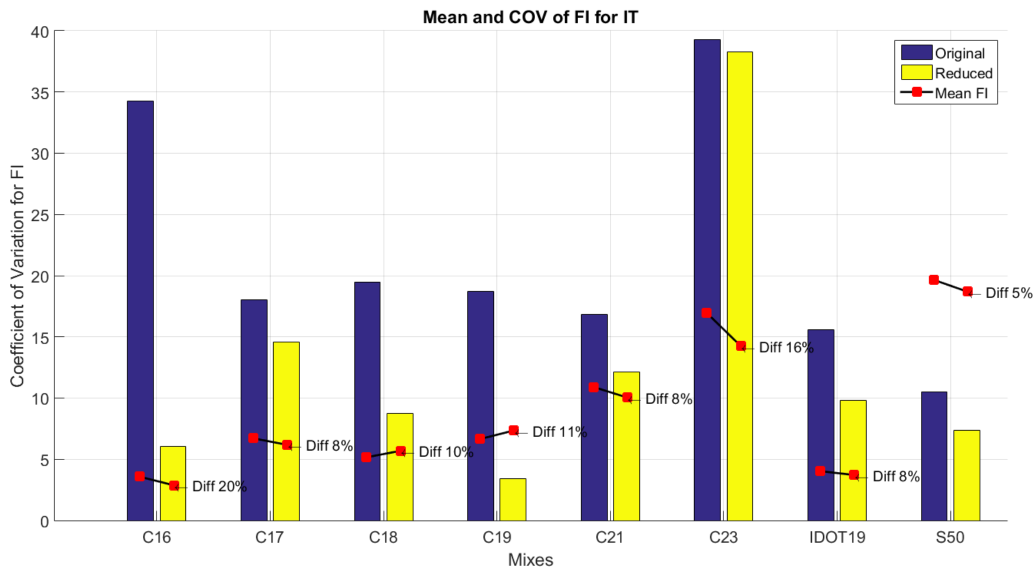


Figure 4.13 Sample reduction method 2 for InstroTek spring rollers.

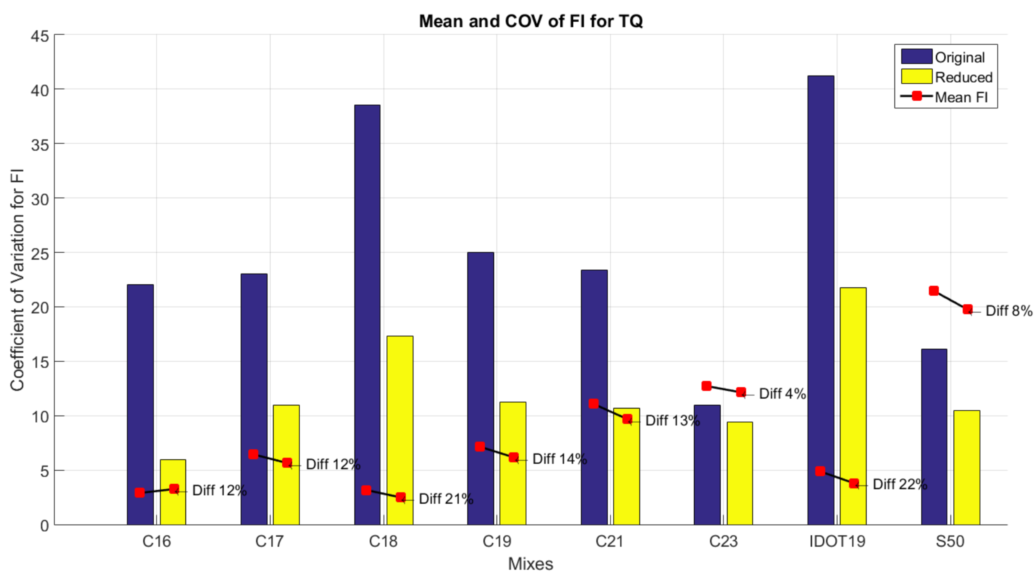


Figure 4.14 Sample reduction method 2 for TestQuip spring rollers.

Based on the sample size analysis, it was concluded that it is essential to increase the number of replicates to a minimum of six to eight. This allows a better representation of the material variability and improves reproducibility of the test results. Outliers can be determined and removed from the dataset, however, that may not change the results (COV and mean FI) significantly. When other sample reduction techniques are used (i.e., removing the lowest and highest values from a dataset of a minimum six or removing the lowest or highest values from a dataset of four), COV can be improved. Removing the lowest and highest data from a larger dataset did not appear to change mean values significantly, but it did improve the COV. By reducing the dataset by four, the COV reduced again, accompanied by significant random changes in the FI. Therefore, this study does not recommend the use of any of the aforementioned sample reduction techniques unless a data point is proven to be an outlier. It is recommended that the number of replicates be increased to a six to achieve a better representation of the material and improve reproducibility. Material variability and its effects on the FI results may need to be evaluated using other AC mixes and sample sizes.

4.2 STATISTICAL EVALUATION OF THE IMPACT OF TESTING DEVICES

4.2.1 ANOVA analysis

An analysis of variance (ANOVA) was performed on the results obtained from the tests. The ANOVA is used to evaluate the means of different datasets and determine whether they are equal. The ANOVA will analyze the means of FI obtained from the different I-FIT devices. The statistical test allows comparing the means considering only one mix at a time. The outcome of the analysis provides information on the statistical difference between the I-FIT machines. The statistical tests were completed using the FI values because they are the primary outcome of the I-FIT.

In order to perform the ANOVA, the values in the datasets must be normally distributed, and the datasets must have homogeneous variances, which means that all the groups have similar variances. The same number of observations in each group is required for the ANOVA. Because some of the datasets had fewer numbers of observations than others, some of the data points were taken out to achieve the same sample size. Data points were randomly removed in a way that the average of the analyzed dataset was not changed. Table 4.2 summarizes the number of observations used for the ANOVA for each mix and device.

Table 4.2 Number of Observations Used for the ANOVA

	MnRoad C16	MnRoad C17	MnRoad C18	MnRoad C19	MnRoad C21	MnRoad C23	IDOT Base	N50 Sand Mix
InstroTek	6 tests	6 tests	8 tests	11 tests	8 tests	8 tests	6 tests	8 tests
TestQuip SR	6 tests	6 tests	8 tests	11 tests	8 tests	8 tests	6 tests	8 tests
TestQuip BR	—	—	8 tests	—	—	—	6 tests	8 tests
TestQuip IDOT	6 tests	6 tests	8 tests	11 tests	8 tests	8 tests	6 tests	—
Interlaken	—	—	8 tests	—	—	—	—	8 tests

Once the groups are equal, the hypotheses of normality and homogeneity must be satisfied in order to conduct the ANOVA analysis. For this purpose, two statistical tests were used: The Shapiro-Wilk for normality and the Levene test for homogeneity of variances. For both the tests, the outcome is a p-value that validates or rejects the null hypothesis of normality (for the Shapiro-Wilk test) or homogeneity (for the Levene test). For the null hypothesis to be true, the p-value delivered by the test must be greater than the significance level (alpha value) selected for the test. The significance level selected for both the tests is 0.05. If the dataset is not normal or a group of datasets is not homogeneous, a transformation should be applied to make the data normal or homogeneous. Table 4.3 presents the p-values for the tests of normality and the transformations that were applied for non-normal groups. All datasets were tested without transformations first. The groups that showed non-normal distributions of the values were transformed and tested again. The results in Table 4.3 refer to datasets already transformed. Eventually, p-values obtained in the Shapiro-Wilk test were all greater than 0.05, which ensured the normality of each dataset.

Table 4.3 Summary of P-Values for the Shapiro-Wilk Test

	MnRoad C16	MnRoad C17	MnRoad C18[1]	MnRoad C19[1]	MnRoad C21	MnRoad C23[1]	IDOT Base	N50 Sand Mix[1]
InstroTek	0.2299	0.674	0.5246	0.0695	0.2025	0.2299	0.1678	0.8445
TestQuip SR	0.4515	0.1562	0.3072	0.1946	0.7017	0.4515	0.0936	0.1733
TestQuip BR	—	—	0.5021	—	—	—	0.2157	0.6373
TestQuip IDOT	0.1091	0.9075	0.588	0.6301	0.7918	0.1091	0.338	—
Interlaken	—	—	0.1436	—	—	—	—	0.9537
Transformation	NO	NO	YES	YES	NO	YES	NO	YES
Transformation type	—	—	$1/\sqrt{Y}$	$\ln Y$	—	$1/\sqrt{Y}$	—	$1/\sqrt{Y}$

[1] Y is the observation from the original data set.

Table 4.4 shows the p-values obtained from the Levene test. In this case, the variances resulting from the different groups are compared; only one p-value is provided for each mix. Since the p-values reported in the table are all greater than 0.05, the null hypothesis of homogeneity of variances is accepted.

Table 4.4 P-Values from the Levene Test

	MnRoad C16	MnRoad C17	MnRoad C18	MnRoad C19	MnRoad C21	MnRoad C23	IDOT Base	N50 Sand Mix
P-Value	0.2989	0.3317	0.0606	0.9956	0.9776	0.5941	0.2528	0.3597

Tables 4.3 and 4.4 showed the results of preliminary statistical tests that the data respect the hypotheses of normality and the datasets are homogeneous. Because the hypotheses of normality and homogeneity are satisfied, the ANOVA can be performed on the results. The ANOVA is based on a null hypothesis of equality of the dataset means. In particular, the null hypothesis assumed is the equality of the average FI values obtained from the different machines. It is important to emphasize that every mix was analyzed separately. The p-value was used to accept or reject the null hypothesis. As before, a p-value greater than 0.05 (the significance level chosen for the analysis) indicates that the null hypothesis is true. Otherwise, the null hypothesis is discarded. Table 4.5 reports the p-values obtained from the ANOVA.

Table 4.5 ANOVA Test Results

	MnRoad C16	MnRoad C17	MnRoad C18	MnRoad C19	MnRoad C21	MnRoad C23	IDOT Base	N50 Sand Mix
P-value	0.227	0.358	0.089	0.743	0.614	0.385	0.508	0.110

From the analysis of variance, the hypothesis of equality of the means was accepted for all the mixes investigated—there is no significant difference in FI results among different machines performing the same AC mix. Because all the means were equal, the Tukey's multi-comparison is not necessary.

4.2.2 T-test to evaluate machine-to-machine variability

In addition to the ANOVA analysis, the t-test was performed to compare betwee pairs of machines for each AC mix tested. The p-vaue results are presented in Tables 4.6 through 4.13. A p-value greater than 0.05 (the significance level chosen for the analysis) indicates that the null hypothesis is true which means that average FI values obtained from the two machines compared are equal. Otherwise, the null hypothesis is discarded. Per the p-values, the average FI results are statistically equal for all combinations of machine-to-machine comparisons for each AC mix.

Table 4.6 Pairwise Comparison of Each Machine for IDOT Base Course

IDOT Base Course	Instrotek	TestQuip SR	TestQuip BR	TestQuip IDOT
Instrotek		0.70	0.48	0.69
TestQuip SR	0.70		0.47	0.93
TestQuip BR	0.48	0.47		0.36
TestQuip IDOT	0.69	0.93	0.36	

Table 4.7 Pairwise Comparison of Each Machine for MnRoad Mix C16

MnRoad C16	Instrotek	TestQuip SR	TestQuip IDOT
Instrotek		0.25	0.19
TestQuip SR	0.25		0.84
TestQuip IDOT	0.19	0.84	

Table 4.8 Pairwise Comparison of Each Machine for MnRoad Mix C17

MnRoad C17	Instrotek	TestQuip SR	TestQuip IDOT
Instrotek		0.72	0.22
TestQuip SR	0.72		0.36
TestQuip IDOT	0.22	0.36	

Table 4.9 Pairwise Comparison of Each Machine for MnRoad Mix C18

MnRoad C18	Instrotek	TestQuip SR	TestQuip BR	TestQuip IDOT	Interlaken
Instrotek		0.06	0.76	0.51	0.08
TestQuip SR	0.06		0.08	0.14	0.39
TestQuip BR	0.76	0.08		0.72	0.11
TestQuip IDOT	0.51	0.14	0.72		0.22
Interlaken	0.08	0.39	0.11	0.22	

Table 4.10 Pairwise Comparison of Each Machine for MnRoad Mix C19

MnRoad C19	Instrotek	TestQuip SR	TestQuip IDOT
Instrotek		0.65	0.61
TestQuip SR	0.65		0.41
TestQuip IDOT	0.61	0.41	

Table 4.11 Pairwise Comparison of Each Machine for MnRoad Mix C21

MnRoad C21	Instrotek	TestQuip SR	TestQuip IDOT
Instrotek		0.91	0.42
TestQuip SR	0.91		0.35
TestQuip IDOT	0.42	0.35	

Table 4.12 Pairwise Comparison of Each Machine for MnRoad Mix C23

MnRoad C23	Instrotek	TestQuip SR	TestQuip IDOT
Instrotek		0.76	0.51
TestQuip SR	0.76		0.28
TestQuip IDOT	0.51	0.28	

Table 4.13 Pairwise Comparison of Each Machine for N50 Sand Mix

N50 Lab Sand Mix	Instrotek	TestQuip SR	TestQuip BR	Interlaken
Instrotek		0.06	0.51	0.76
TestQuip SR	0.06		0.14	0.08
TestQuip BR	0.51	0.14		0.72
Interlaken	0.76	0.08	0.72	

The aforementioned performed statistical analysis support the results and findings discussed in Chapter 3. A holistic comparison of each AC mix tested utilizing the devices evaluated was completed using the ANOVA analysis. The individual device-to-device comparison was completed using the t-test. While the ANOVA considered a broader range of FI values, admitting a less strict comparison between the devices, the t-test provides a method to compare the devices in a more direct way and in a narrower range of values. The two approaches of comparing the machines are considered statistically equivalent. From a statistical point of view, the different loading systems and support roller arrangement did not influence the I-FIT FI results. Thus, it can be concluded that both a screw-driven system and a hydraulic system are suitable for this test. Also, the statistical analysis showed that both the spring roller and the bearing roller arrangements are acceptable for the I-FIT.

CHAPTER 5: SUMMARY OF FINDINGS AND CONCLUSIONS

In this study, the effect of the devices on the determination of the fracture potential of AC mixes through the I-FIT was assessed. An experimental program was established to investigate the influence of the loading system and configurations of support rollers on the results of the I-FIT. Eight different AC mixes were included in the study. The mixes had NMAS ranging from 4.75 mm to 19.0 mm. Six of the mixes were obtained from MnRoad. These mixes had similar gradation and volumetric characteristics (VMA and binder content) and same NMAS (12.5 mm) with varying binder type and ABR. Two additional mixes (N50 sand mix with 4.75 mm NMAS and high FI, and an IDOT base mix with 19.0 mm and low FI) were added to the study to increase the range of AC mixture variables. All of the AC mixes were tested primarily using three machine configurations (InstroTek and TestQuip with spring roller support system at ATREL and TestQuip with bearing roller system at IDOT). The Interlaken machine was also used for two of the mixes. After the AC mixes were tested, a statistical analysis was performed on the data collected. Below is a summary of the experimental findings of this study:

- The AC mixes evaluated followed the expected trend of increasing FI and reduction in fracture potential with decreasing NMAS, increasing binder content, binder modification as well as the reduction in the content of recycled materials.
- In general, the AC mixes had similar FI values from all machines considered in the study. The results were within approximately one unit of FI except for the mixes C18 (values ranging from 3.8 to 5.8) and C23 (values ranging from 11.0 to 14.0). When the tests were repeated for these two mixes using the InstroTek and TestQuip spring roller devices, similar mean values of FI were obtained. The COV values of the FI results varied between 10% and 35%. There is no consistent trend between the machines to provide higher or lower COVs. It is concluded that the COV values were governed by the material variability.
- According to the statistical analysis, there was also no difference among any of the devices, including AC mixes C18 and C23. Based on the mixes presented, FI results were found independent of device configurations, inlcuding loading system (hydraulic or screw-driven) and the configuration of the support rollers (spring or bearing rollers). Hence, the equality of the means of FI between all devices lead to the conclusion that screw-driven systems and hydraulic systems and support systems can be used to conduct the I-FIT.
- The FI values and load-displacement curves appeared to randomly change between the machines for each mix. This indicates that the variability in the material, given its random nature, governs the variability in the results, not the machines considered in this study.
- Two mixes (N50 sand mix and MnRoad C18) were tested using the four I-FIT devices, including the Interlaken hydraulic system used in the development of I-FIT protocol as part of the ICT R27-128 study (Al-Qadi et al. 2015). The results showed that there is no statistically significant effect of machine variability on the FI results.
- Based on the AC mixes analyzed in this study, the two devices with the same test fixture and different loading systems did not show any significant differences in terms of FI.

- For all the mixes tested, the two fixture arrangements were not found to be significantly different based on visual observations and statistical analyses.
- Based on the analysis of sample size, it was concluded that the number of test replicates should be increased to a minimum of six test specimes obtained from multiple gyratory compacted samples. This allows a better representation of the material variability and improves reproducibility of the test results.

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APPENDIX A: JOB MIX FORMULAS

A.1 JOB MIX FORMULA OF MNROAD C16

National Center for Asphalt Technology at AUBURN UNIVERSITY

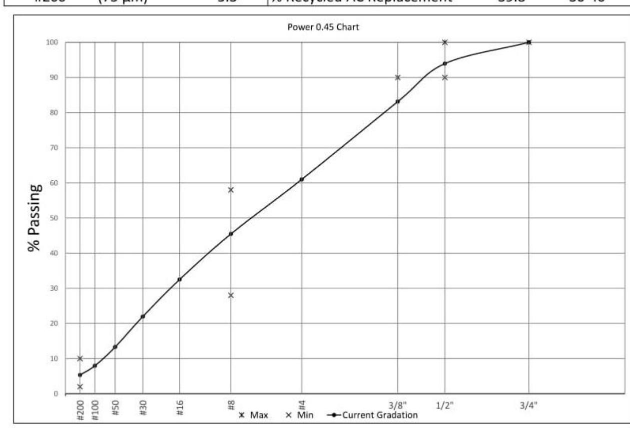
National Center for Asphalt Technology
Job-Mix Formula

NCAT Project ID:	2016 MnROAD	NCAT Mix ID:	30-40% ABR with RAS
Principal Investigator:	Randy West	Mix Design Engineer:	Grant Julian
Producer:	Hardrives, Inc. Plant #501	Design Completion Date:	8/2/2016
Intended Use:	MnROAD CG	Intended Section:	Cell 16
Mix Type:	Dense-Graded Superpave	Virgin Binder Grade:	FHR PG 64S-22
Nom. Max Agg. (NMAS):	12.5mm (1/2")	Virgin Binder Specific Gravity:	1.041
Max Agg. Size (MAS):	19.0mm (3/4")	Anti-Strip:	None
Mixing Temp, °F :	308-316	Anti-Strip Dosage (TOTAL Binder):	NA
Compaction Temp, °F :	286-294	A.S. Dose Rate for Virgin Binder:	NA
		Other Binder Additives:	NA

AASHTO Superpave Volumetric Mix Design

Cold Feed %	Aggregate Description	Pile ID	Source	Gsb	Gsa	% Abs.
28	Martin Marietta Washed Sand	1	Pit #73006	2.687	2.722	0.47
10	Kingsway Pit Man Sand	2	Pit #49114	2.682	2.800	1.56
12	Martin Marietta 1/2" Chips	3	Pit #73006	2.661	2.705	0.61
24	Martin Marietta 3/4" Chips	4	Pit #73006	2.705	2.748	0.58
1	Vonco II Baghouse Fines	5		2.716	2.716	0.00
20	Vonco II Millings	6		2.639	2.720	1.09
5	MWSS	7		2.749	2.749	0.00

Job Mix			Mix Design Information		Criteria
Sieve	Sieve	% Passing			
1 1/2"	(37.5 mm)	100.0	% Total AC Required	5.27	--
1"	(25 mm)	100.0	Max Spec. Gravity Mix (Gmm)	2.518	--
3/4"	(19.0 mm)	100.0	Bulk Spec. Gravity Mix (Gmb)	2.418	--
1/2"	(12.5 mm)	93.9	Design Air Voids (Va)	4.0	4.0
3/8"	(9.5 mm)	83.1	VMA	14.5	>14.0
#4	(4.75 mm)	61.0	VFA	72.7	65-75
#8	(2.36 mm)	45.5	Dust/Asphalt Ratio	1.17	0.6 - 1.2
#16	(1.18 mm)	32.5	Effective AC (Pbe)	4.56	--
#30	(600 µm)	22.0	Absorbed AC (Pba)	0.75	--
#50	(300 µm)	13.3	% AC Contribution from RAP	1.23	--
#100	(150 µm)	8.0	% AC Contribution from RAS	0.87	--
#200	(75 µm)	5.3	% Virgin Binder	3.17	--
			% Recycled AC Replacement	39.8	30-40



Aggregate Information		Criteria
Agg. Bulk Gravity (Gsb)	2.681	--
Agg. Effective Gravity (Gse)	2.734	--
Agg. Apparent Gravity (Gsa)	2.735	--
Agg. Absorption (Abs)	0.72	--
Coarse Agg. Angularity (1)	100 assumed*	95 min
Coarse Agg. Angularity (2+)	100 assumed*	90 min
Fine Agg. Angularity (FAA)	47	45 min
Flat and Elongated 5:1 (F & E)	3	10 max
Sand Equivalency (SE)	91	45 min

Other Information	
Ndes Gyrations	80
Ignition Oven CF	0.09
Design Sample Mass, g	4850
RAP % AC (Ignition)	6.16
Corrected RAS % AC	17.33
Assumed RAS AC Contribution	1.00
Uncorrected RAS % AC (TCE)	17.33
RAP Binder True Grade	86.5-19.8
RAS Binder True Grade	120.7-23.0
TSR	0.85
Uncond. Tensile Strength, psi	163.9
Cond. Tensile Strength, psi	139.6
Cantabro % Loss	7.13

Additional Notes

* Crushed granite - Confirmed by Visual Inspection

PSCI = 6.5

National Center for Asphalt Technology
Job-Mix Formula

NCAT Project ID:	2016 MnROAD	NCAT Mix ID:	30-40% ABR with RAS
Principal Investigator:	Randy West	Mix Design Engineer:	Grant Julian
Producer:	Hardrives, Inc. Plant #501	Design Completion Date:	8/2/2016
Intended Use:	MnROAD CG	Intended Section:	Cell 16

Individual Stockpile Gradations

Sieve Size (mm)	Sieve Size (in)	Stockpile ID (See Page 1)								
		1	2	3	4	5	6	7		
37.5	1.5"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
25	1.0"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
19	3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
12.5	1/2"	100.0	100.0	99.9	78.3	100.0	95.7	100.0		
9.5	3/8"	100.0	100.0	95.0	43.6	100.0	86.6	99.2		
4.75	# 4	99.4	87.5	26.2	7.6	100.0	67.7	98.1		
2.36	# 8	78.0	59.7	4.2	2.0	100.0	54.5	95.2		
1.18	# 16	49.9	43.3	2.0	1.5	100.0	43.0	80.0		
0.6	# 30	29.1	32.4	1.4	1.2	98.9	30.6	60.5		
0.3	# 50	13.5	23.2	1.0	1.0	94.1	18.0	45.8		
0.15	#100	4.8	16.2	0.7	0.8	73.0	11.1	34.9		
0.075	#200	1.9	11.5	0.5	0.6	51.6	7.8	27.0		

Average of Design Values

%AC	Gmm	Gmb	% Air Voids	% VMA	%VFA	Dust/Asphalt
5.0	2.528	2.406	4.8	14.8	67.2	1.24
5.5	2.510	2.430	3.2	14.4	77.7	1.11
6.0	2.491	2.445	1.8	14.3	87.1	1.01

A.2 JOB MIX FORMULA OF MNROAD C17

National Center for Asphalt Technology
Job-Mix Formula

NCAT Project ID:	2016 MnROAD	NCAT Mix ID:	20-30% ABR with RAS
Principal Investigator:	Randy West	Mix Design Engineer:	Grant Julian
Producer:	Hardrives, Inc. Plant #501	Design Completion Date:	7/29/2016
Intended Use:	MnROAD CG	Intended Section:	Cell 17
Mix Type:	Dense-Graded Superpave	Virgin Binder Grade:	FHR PG 64S-22
Nom. Max Agg. (NMAS):	12.5mm (1/2")	Virgin Binder Specific Gravity:	1.041
Max Agg. Size (MAS):	19.0mm (3/4")	Anti-Strip:	None
Mixing Temp, °F :	308-316	Anti-Strip Dosage (TOTAL Binder):	NA
Compaction Temp, °F :	286-294	A.S. Dose Rate for Virgin Binder:	NA
		Other Binder Additives:	NA

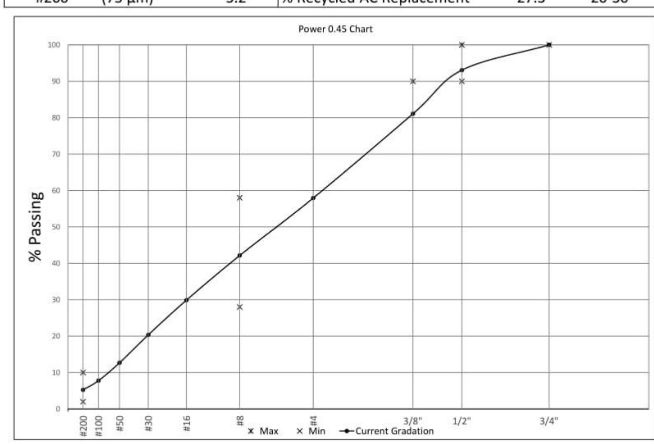
AASHTO Superpave Volumetric Mix Design

Cold Feed %	Aggregate Description	Pile ID	Source	Gsb	Gsa	% Abs.
26	Martin Marietta Washed Sand	1	Pit #73006	2.687	2.722	0.47
16	Kingsway Pit Man Sand	2	Pit #49114	2.682	2.800	1.56
12	Martin Marietta 1/2" Chips	3	Pit #73006	2.661	2.705	0.61
30	Martin Marietta 3/4" Chips	4	Pit #73006	2.705	2.748	0.58
1	Vonco II Baghouse Fines	5		2.716	2.716	0.00
10	Vonco II Millings	6		2.639	2.720	1.09
5	MWSS	7		2.749	2.749	0.00

Job Mix

Sieve	Sieve	% Passing
1 1/2"	(37.5 mm)	100.0
1"	(25 mm)	100.0
3/4"	(19.0 mm)	100.0
1/2"	(12.5 mm)	93.1
3/8"	(9.5 mm)	81.1
#4	(4.75 mm)	57.9
#8	(2.36 mm)	42.2
#16	(1.18 mm)	29.9
#30	(600 µm)	20.3
#50	(300 µm)	12.7
#100	(150 µm)	7.8
#200	(75 µm)	5.2

Mix Design Information		Criteria
% Total AC Required	5.43	--
Max Spec. Gravity Mix (Gmm)	2.517	--
Bulk Spec. Gravity Mix (Gmb)	2.416	--
Design Air Voids (Va)	4.0	4.0
VMA	14.9	>14.0
VFA	73.7	65-75
Dust/Asphalt Ratio	1.10	0.6 - 1.2
Effective AC (Pbe)	4.72	--
Absorbed AC (Pba)	0.74	--
% AC Contribution from RAP	0.62	--
% AC Contribution from RAS	0.87	--
% Virgin Binder	3.94	--
% Recycled AC Replacement	27.3	20-30



Aggregate Information		Criteria
Agg. Bulk Gravity (Gsb)	2.687	--
Agg. Effective Gravity (Gse)	2.739	--
Agg. Apparent Gravity (Gsa)	2.741	--
Agg. Absorption (Abs)	0.73	--
Coarse Agg. Angularity (1)	100 assumed*	95 min
Coarse Agg. Angularity (2+)	100 assumed*	90 min
Fine Agg. Angularity (FAA)	47	45 min
Flat and Elongated 5:1 (F & E)	4	10 max
Sand Equivalency (SE)	87	45 min

Other Information	
Ndes Gyrations	80
Ignition Oven CF	0.03
Design Sample Mass, g	4850
RAP % AC (Ignition)	6.16
Corrected RAS % AC (TCE)	17.33
Assumed RAS AC Contribution	1.00
Uncorrected RAS % AC (TCE)	17.33
RAP Binder True Grade	86.5-19.8
RAS Binder True Grade	120.7-23.0
TSR	0.85
Uncond. Tensile Strength, psi	129.9
Cond. Tensile Strength, psi	110.7
Cantabro % Loss	5.81

Additional Notes

* Crushed granite - Confirmed by Visual Inspection

PSCI = 3.2

National Center for Asphalt Technology
Job-Mix Formula

NCAT Project ID: 2016 MnROAD
Principal Investigator: Randy West
Producer: Hardrives, Inc. Plant #501
Intended Use: MnROAD CG

NCAT Mix ID: 20-30% ABR with RAS
Mix Design Engineer: Grant Julian
Design Completion Date: 7/29/2016
Intended Section: Cell 17

Individual Stockpile Gradations

Sieve Size (mm)	Sieve Size (in)	Stockpile ID (See Page 1)								
		1	2	3	4	5	6	7		
37.5	1.5"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
25	1.0"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
19	3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
12.5	1/2"	100.0	100.0	99.9	78.3	100.0	95.7	100.0		
9.5	3/8"	100.0	100.0	95.0	43.6	100.0	86.6	99.2		
4.75	# 4	99.4	87.5	26.2	7.6	100.0	67.7	98.1		
2.36	# 8	78.0	59.7	4.2	2.0	100.0	54.5	95.2		
1.18	# 16	49.9	43.3	2.0	1.5	100.0	43.0	80.0		
0.6	# 30	29.1	32.4	1.4	1.2	98.9	30.6	60.5		
0.3	# 50	13.5	23.2	1.0	1.0	94.1	18.0	45.8		
0.15	#100	4.8	16.2	0.7	0.8	73.0	11.1	34.9		
0.075	#200	1.9	11.5	0.5	0.6	51.6	7.8	27.0		

Average of Design Values

%AC	Gmm	Gmb	% Air Voids	% VMA	%VFA	Dust/Asphalt
5.0	2.533	2.400	5.3	15.2	65.3	1.22
5.5	2.514	2.419	3.8	14.9	74.8	1.09
6.0	2.495	2.437	2.3	14.8	84.2	0.99

A.3 JOB MIX FORMULA OF MNROAD C18

National Center for Asphalt Technology at AUBURN UNIVERSITY

National Center for Asphalt Technology
Job-Mix Formula

NCAT Project ID:	2016 MnROAD	NCAT Mix ID:	20% ABR
Principal Investigator:	Randy West	Mix Design Engineer:	Adam Taylor
Producer:	Hardrives, Inc. Plant #501	Design Completion Date:	7/21/2016
Intended Use:	MnROAD CG	Intended Section:	Cell 18
Mix Type:	Dense-Graded Superpave	Virgin Binder Grade:	FHR PG 64S-22
Nom. Max Agg. (NMAS):	12.5mm (1/2")	Virgin Binder Specific Gravity:	1.041
Max Agg. Size (MAS):	19.0mm (3/4")	Anti-Strip:	None
Mixing Temp, °F :	308-316	Anti-Strip Dosage (TOTAL Binder):	NA
Compaction Temp, °F :	286-294	A.S. Dose Rate for Virgin Binder:	NA
		Other Binder Additives:	NA

AASHTO Superpave Volumetric Mix Design

Cold Feed %	Aggregate Description	Pile ID	Source	Gsb	Gsa	% Abs.
24	Martin Marietta Washed Sand	1	Pit #73006	2.687	2.722	0.47
20	Kingsway Pit Man Sand	2	Pit #49114	2.682	2.800	1.56
10	Martin Marietta 1/2" Chips	3	Pit #73006	2.661	2.705	0.61
25	Martin Marietta 3/4" Chips	4	Pit #73006	2.705	2.748	0.58
1	Vonco II Baghouse Fines	5		2.716	2.716	0.00
20	Vonco II Millings	6		2.639	2.720	1.09
0	MWSS	7		2.749	2.749	0.00

Job Mix

Sieve	Sieve	% Passing
1 1/2"	(37.5 mm)	100.0
1"	(25 mm)	100.0
3/4"	(19.0 mm)	100.0
1/2"	(12.5 mm)	93.7
3/8"	(9.5 mm)	82.7
#4	(4.75 mm)	60.4
#8	(2.36 mm)	43.5
#16	(1.18 mm)	30.8
#30	(600 µm)	21.0
#50	(300 µm)	12.8
#100	(150 µm)	7.6
#200	(75 µm)	5.0

Mix Design Information		Criteria
% Total AC Required	5.43	--
Max Spec. Gravity Mix (Gmm)	2.511	--
Bulk Spec. Gravity Mix (Gmb)	2.411	--
Design Air Voids (Va)	4.0	4.0
VMA	14.6	>14.0
VFA	73.5	65-75
Dust/Asphalt Ratio	1.09	0.6 - 1.2
Effective AC (Pbe)	4.70	--
Absorbed AC (Pba)	0.77	--
% AC Contribution from RAP	1.232	--
% AC Contribution from RAS	0.00	--
% Virgin Binder	4.20	--
% Recycled AC Replacement	22.7	15-25

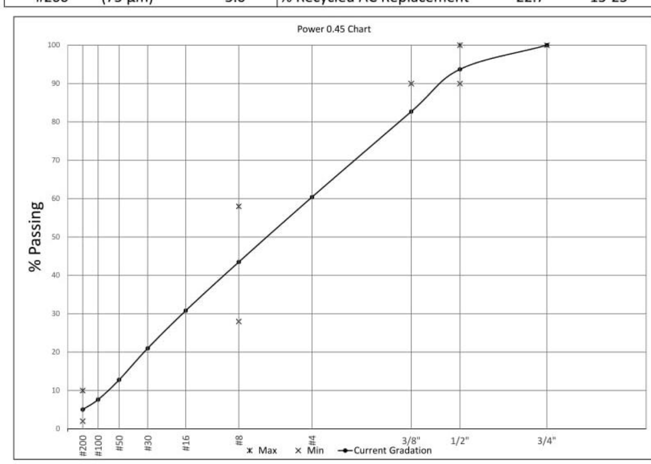
Aggregate Information		Criteria
Agg. Bulk Gravity (Gsb)	2.679	--
Agg. Effective Gravity (Gse)	2.733	--
Agg. Apparent Gravity (Gsa)	2.742	--
Agg. Absorption (Abs)	0.85	--
Coarse Agg. Angularity (1)	100 assumed*	95 min
Coarse Agg. Angularity (2+)	100 assumed*	90 min
Fine Agg. Angularity (FAA)	46	45 min
Flat and Elongated 5:1 (F & E)	3	10 max
Sand Equivalency (SE)	84	45 min

Other Information	
Ndes Gyrations	80
Ignition Oven CF	+0.14
Design Sample Mass, g	4850
RAP % AC (ignition)	6.16
Corrected RAS % AC	NA
Assumed RAS AC Contribution	NA
Uncorrected RAS % AC	NA
RAP Binder True Grade	86.5-19.8
RAS Binder True Grade	NA
TSR	0.859
Uncond. Tensile Strength, psi	137.5
Cond. Tensile Strength, psi	118.1
Cantabro % Loss	5.79

Additional Notes

* Crushed granite - Confirmed by Visual Inspection

PSCI = 4.5



National Center for Asphalt Technology
Job-Mix Formula

NCAT Project ID: 2016 MnROAD
Principal Investigator: Randy West
Producer: Hardrives, Inc. Plant #501
Intended Use: MnROAD CG

NCAT Mix ID: 20% ABR
Mix Design Engineer: Adam Taylor
Design Completion Date: 7/21/2016
Intended Section: Cell 18

Individual Stockpile Gradations

Sieve Size (mm)	Sieve Size (in)	Stockpile ID (See Page 1)								
		1	2	3	4	5	6	7		
37.5	1.5"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
25	1.0"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
19	3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
12.5	1/2"	100.0	100.0	99.9	78.3	100.0	95.7	100.0		
9.5	3/8"	100.0	100.0	95.0	43.6	100.0	86.6	99.2		
4.75	# 4	99.4	87.5	26.2	7.6	100.0	67.7	98.1		
2.36	# 8	78.0	59.7	4.2	2.0	100.0	54.5	95.2		
1.18	# 16	49.9	43.3	2.0	1.5	100.0	43.0	80.0		
0.6	# 30	29.1	32.4	1.4	1.2	98.9	30.6	60.5		
0.3	# 50	13.5	23.2	1.0	1.0	94.1	18.0	45.8		
0.15	#100	4.8	16.2	0.7	0.8	73.0	11.1	34.9		
0.075	#200	1.9	11.5	0.5	0.6	51.6	7.8	27.0		

Average of Design Values

%AC	Gmm	Gmb	% Air Voids	% VMA	%VFA	Dust/Asphalt
4.8	2.535	2.365	6.7	15.9	58.0	1.24
5.3	2.516	2.411	4.2	14.8	71.6	1.10
5.8	2.497	2.430	2.7	14.5	81.6	0.99

A.4 JOB MIX FORMULA OF MNROAD C19

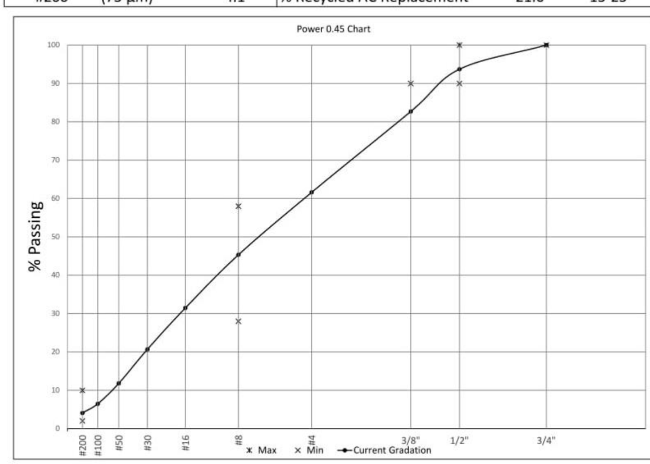
National Center for Asphalt Technology
Job-Mix Formula

NCAT Project ID:	2016 MnROAD	NCAT Mix ID:	20% ABR - 100 gyration - 3.0% Va
Principal Investigator:	Randy West	Mix Design Engineer:	Adam Taylor
Producer:	Hardrives, Inc. Plant #501	Design Completion Date:	7/25/2016
Intended Use:	MnROAD CG	Intended Section:	Cell 19
Mix Type:	Dense-Graded Superpave	Virgin Binder Grade:	FHR PG 64S-22
Nom. Max Agg. (NMAS):	12.5mm (1/2")	Virgin Binder Specific Gravity:	1.041
Max Agg. Size (MAS):	19.0mm (3/4")	Anti-Strip:	None
Mixing Temp, °F :	308-316	Anti-Strip Dosage (TOTAL Binder):	NA
Compaction Temp, °F :	286-294	A.S. Dose Rate for Virgin Binder:	NA
		Other Binder Additives:	NA

AASHTO Superpave Volumetric Mix Design

Cold Feed %	Aggregate Description	Pile ID	Source	Gsb	Gsa	% Abs.
34	Martin Marietta Washed Sand	1	Pit #73006	2.687	2.722	0.47
10	Kingsway Pit Man Sand	2	Pit #49114	2.682	2.800	1.56
10	Martin Marietta 1/2" Chips	3	Pit #73006	2.661	2.705	0.61
25	Martin Marietta 3/4" Chips	4	Pit #73006	2.705	2.748	0.58
1	Vonco II Baghouse Fines	5		2.716	2.716	0.00
20	Vonco II Millings	6		2.639	2.720	1.09
0	MWSS	7		2.749	2.749	0.00

Job Mix			Mix Design Information		Criteria
Sieve	Sieve	% Passing	% Total AC Required	5.70	--
1 1/2"	(37.5 mm)	100.0	Max Spec. Gravity Mix (Gmm)	2.494	--
1"	(25 mm)	100.0	Bulk Spec. Gravity Mix (Gmb)	2.419	--
3/4"	(19.0 mm)	100.0	Design Air Voids (Va)	3.0	3.0
1/2"	(12.5 mm)	93.7	VMA	14.8	>14.0
3/8"	(9.5 mm)	82.7	VFA	79.9	65-75
#4	(4.75 mm)	61.6	Dust/Asphalt Ratio	0.81	0.6 - 1.2
#8	(2.36 mm)	45.3	Effective AC (Pbe)	5.10	--
#16	(1.18 mm)	31.5	Absorbed AC (Pba)	0.64	--
#30	(600 µm)	20.7	% AC Contribution from RAP	1.23	--
#50	(300 µm)	11.8	% AC Contribution from RAS	0.00	--
#100	(150 µm)	6.5	% Virgin Binder	4.46	--
#200	(75 µm)	4.1	% Recycled AC Replacement	21.6	15-25



Aggregate Information		Criteria
Agg. Bulk Gravity (Gsb)	2.679	--
Agg. Effective Gravity (Gse)	2.724	--
Agg. Apparent Gravity (Gsa)	2.734	--
Agg. Absorption (Abs)	0.74	--
Coarse Agg. Angularity (1)	100 assumed*	95 min
Coarse Agg. Angularity (2+)	100 assumed*	90 min
Fine Agg. Angularity (FAA)	47	45 min
Flat and Elongated 5:1 (F & E)	3	10 max
Sand Equivalency (SE)	92	45 min

Other Information	
Ndes Gyrations	100
Ignition Oven CF	
Design Sample Mass, g	4850
RAP % AC (Ignition)	6.16
Corrected RAS % AC	NA
Assumed RAS AC Contribution	NA
Uncorrected RAS % AC	NA
RAP Binder True Grade	86.5-19.8
RAS Binder True Grade	NA
TSR	0
Uncond. Tensile Strength, psi	0
Cond. Tensile Strength, psi	0
Cantabro % Loss	0.00

Additional Notes

* Crushed granite - Confirmed by Visual Inspection
** Volumetrics "Regressed" to 3.0% Air Voids
PSCI = 6.3

National Center for Asphalt Technology
Job-Mix Formula

NCAT Project ID:	2016 MnROAD	NCAT Mix ID:	20% ABR - 100 gyration - 3.0% Va
Principal Investigator:	Randy West	Mix Design Engineer:	Adam Taylor
Producer:	Hardrives, Inc. Plant #501	Design Completion Date:	7/25/2016
Intended Use:	MnROAD CG	Intended Section:	Cell 19

Individual Stockpile Gradations

Sieve Size (mm)	Sieve Size (in)	Stockpile ID (See Page 1)								
		1	2	3	4	5	6	7		
37.5	1.5"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
25	1.0"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
19	3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
12.5	1/2"	100.0	100.0	99.9	78.3	100.0	95.7	100.0		
9.5	3/8"	100.0	100.0	95.0	43.6	100.0	86.6	99.2		
4.75	# 4	99.4	87.5	26.2	7.6	100.0	67.7	98.1		
2.36	# 8	78.0	59.7	4.2	2.0	100.0	54.5	95.2		
1.18	# 16	49.9	43.3	2.0	1.5	100.0	43.0	80.0		
0.6	# 30	29.1	32.4	1.4	1.2	98.9	30.6	60.5		
0.3	# 50	13.5	23.2	1.0	1.0	94.1	18.0	45.8		
0.15	#100	4.8	16.2	0.7	0.8	73.0	11.1	34.9		
0.075	#200	1.9	11.5	0.5	0.6	51.6	7.8	27.0		

Average of Design Values

%AC	Gmm	Gmb	% Air Voids	% VMA	%VFA	Dust/Asphalt
5.0	2.520	2.389	5.2	15.3	66.0	0.9
5.5	2.501	2.411	3.6	15.0	75.9	0.8
6.0	2.483	2.432	2.0	14.7	86.1	0.8

A.5 JOB MIX FORMULA OF MNROAD C21

National Center for Asphalt Technology
Job-Mix Formula

NCAT Project ID:	2016 MnROAD	NCAT Mix ID:	20% ABR with PG 58H-34
Principal Investigator:	Randy West	Mix Design Engineer:	Adam Taylor
Producer:	Hardrives, Inc. Plant #501	Design Completion Date:	7/21/2016
Intended Use:	MnROAD CG	Intended Section:	Cell 21
Mix Type:	Dense-Graded Superpave	Virgin Binder Grade:	FHR PG 58H-34
Nom. Max Agg. (NMAS):	12.5mm (1/2")	Virgin Binder Specific Gravity:	1.030
Max Agg. Size (MAS):	19.0mm (3/4")	Anti-Strip:	None
Mixing Temp, °F :	281-294	Anti-Strip Dosage (TOTAL Binder):	NA
Compaction Temp, °F :	250-254	A.S. Dose Rate for Virgin Binder:	NA
		Other Binder Additives:	NA

AASHTO Superpave Volumetric Mix Design

Cold Feed %	Aggregate Description	Pile ID	Source	Gsb	Gsa	% Abs.
24	Martin Marietta Washed Sand	1	Pit #73006	2.687	2.722	0.47
20	Kingsway Pit Man Sand	2	Pit #49114	2.682	2.800	1.56
10	Martin Marietta 1/2" Chips	3	Pit #73006	2.661	2.705	0.61
25	Martin Marietta 3/4" Chips	4	Pit #73006	2.705	2.748	0.58
1	Vonco II Baghouse Fines	5		2.716	2.716	0.00
20	Vonco II Millings	6		2.639	2.720	1.09
0	MWSS	7		2.749	2.749	0.00

Job Mix Sieve	Sieve	% Passing	Mix Design Information		Criteria
1 1/2"	(37.5 mm)	100.0	% Total AC Required	5.38	--
1"	(25 mm)	100.0	Max Spec. Gravity Mix (Gmm)	2.514	--
3/4"	(19.0 mm)	100.0	Bulk Spec. Gravity Mix (Gmb)	2.413	--
1/2"	(12.5 mm)	93.7	Design Air Voids (Va)	4.0	4.0
3/8"	(9.5 mm)	82.7	VMA	14.6	>14.0
#4	(4.75 mm)	60.4	VFA	73.5	65-75
#8	(2.36 mm)	43.5	Dust/Asphalt Ratio	1.11	0.6 - 1.2
#16	(1.18 mm)	30.8	Effective AC (Pbe)	4.59	--
#30	(600 µm)	21.0	Absorbed AC (Pba)	0.83	--
#50	(300 µm)	12.8	% AC Contribution from RAP	1.23	--
#100	(150 µm)	7.6	% AC Contribution from RAS	0.00	--
#200	(75 µm)	5.0	% Virgin Binder	4.15	--
			% Recycled AC Replacement	22.9	15-25

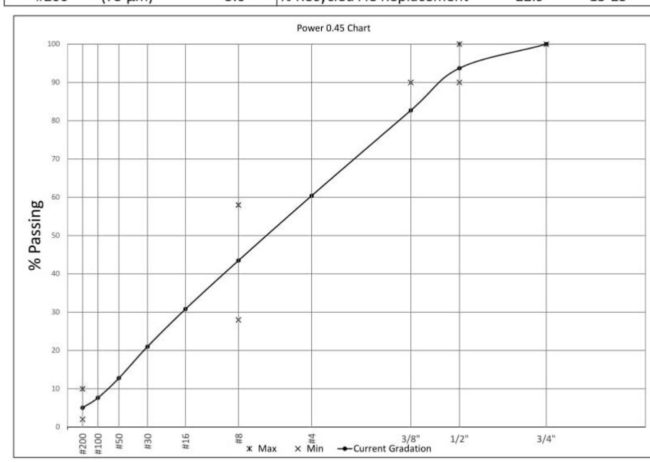
Aggregate Information		Criteria
Agg. Bulk Gravity (Gsb)	2.679	--
Agg. Effective Gravity (Gse)	2.738	--
Agg. Apparent Gravity (Gsa)	2.742	--
Agg. Absorption (Abs)	0.85	--
Coarse Agg. Angularity (1)	100 assumed*	95 min
Coarse Agg. Angularity (2+)	100 assumed*	90 min
Fine Agg. Angularity (FAA)	46	45 min
Flat and Elongated 5:1 (F & E)	3	10 max
Sand Equivalency (SE)	84	45 min

Other Information	
Ndes Gyrations	80
Ignition Oven CF	+0.08
Design Sample Mass, g	4850
RAP % AC (ignition)	6.16
Corrected RAS % AC	NA
Assumed RAS AC Contribution	NA
Uncorrected RAS % AC	NA
RAP Binder True Grade	86.5-19.8
RAS Binder True Grade	NA
TSR	1.023
Uncond. Tensile Strength, psi	98.2
Cond. Tensile Strength, psi	100.4
Cantabro % Loss	2.51

Additional Notes

* Crushed granite - Confirmed by Visual Inspection

PSCI = 4.5



National Center for Asphalt Technology
Job-Mix Formula

NCAT Project ID: 2016 MnROAD
Principal Investigator: Randy West
Producer: Hardrives, Inc. Plant #501
Intended Use: MnROAD CG

NCAT Mix ID: 20% ABR with PG 58H-34
Mix Design Engineer: Adam Taylor
Design Completion Date: 7/21/2016
Intended Section: Cell 21

Individual Stockpile Gradations										
Sieve Size	Sieve Size	Stockpile ID (See Page 1)								
(mm)	(in)	1	2	3	4	5	6	7		
37.5	1.5"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
25	1.0"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
19	3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
12.5	1/2"	100.0	100.0	99.9	78.3	100.0	95.7	100.0		
9.5	3/8"	100.0	100.0	95.0	43.6	100.0	86.6	99.2		
4.75	# 4	99.4	87.5	26.2	7.6	100.0	67.7	98.1		
2.36	# 8	78.0	59.7	4.2	2.0	100.0	54.5	95.2		
1.18	# 16	49.9	43.3	2.0	1.5	100.0	43.0	80.0		
0.6	# 30	29.1	32.4	1.4	1.2	98.9	30.6	60.5		
0.3	# 50	13.5	23.2	1.0	1.0	94.1	18.0	45.8		
0.15	#100	4.8	16.2	0.7	0.8	73.0	11.1	34.9		
0.075	#200	1.9	11.5	0.5	0.6	51.6	7.8	27.0		

Average of Design Values							
%AC	Gmm	Gmb	% Air Voids	% VMA	%VFA	Dust/Asphalt	Cantabro % Loss
5.0	2.528	2.397	5.2	15.0	65.5	1.20	3.20
5.5	2.509	2.424	3.4	14.5	76.5	1.07	2.07
6.0	2.490	2.441	2.0	14.3	86.3	0.97	1.69

A.6 JOB MIX FORMULA OF MNROAD C23

National Center for Asphalt Technology
Job-Mix Formula

NCAT Project ID:	2016 MnROAD	NCAT Mix ID:	20% ABR with PG 64E-34
Principal Investigator:	Randy West	Mix Design Engineer:	Grant Julian
Producer:	Hardrives, Inc. Plant #501	Design Completion Date:	8/16/2016
Intended Use:	MnROAD CG	Intended Section:	Cell 23
Mix Type:	Dense-Graded Superpave	Virgin Binder Grade:	FHR PG 64E-34
Nom. Max Agg. (NMAS):	12.5mm (1/2")	Virgin Binder Specific Gravity:	1.03
Max Agg. Size (MAS):	19.0mm (3/4")	Anti-Strip:	None
Mixing Temp, °F :	300-316	Anti-Strip Dosage (TOTAL Binder):	NA
Compaction Temp, °F :	260-275	A.S. Dose Rate for Virgin Binder:	NA
		Other Binder Additives:	NA

AASHTO Superpave Volumetric Mix Design

Cold Feed %	Aggregate Description	Pile ID	Source	Gsb	Gsa	% Abs.
21	Martin Marietta Washed Sand	1	Pit #73006	2.687	2.722	0.47
22	Kingsway Pit Man Sand	2	Pit #49114	2.682	2.800	1.56
12	Martin Marietta 1/2" Chips	3	Pit #73006	2.661	2.705	0.61
29	Martin Marietta 3/4" Chips	4	Pit #73006	2.705	2.748	0.58
1	Vonco II Baghouse Fines	5		2.716	2.716	0.00
15	Vonco II Millings	6		2.639	2.720	1.09
0	MWSS	7		2.749	2.749	0.00

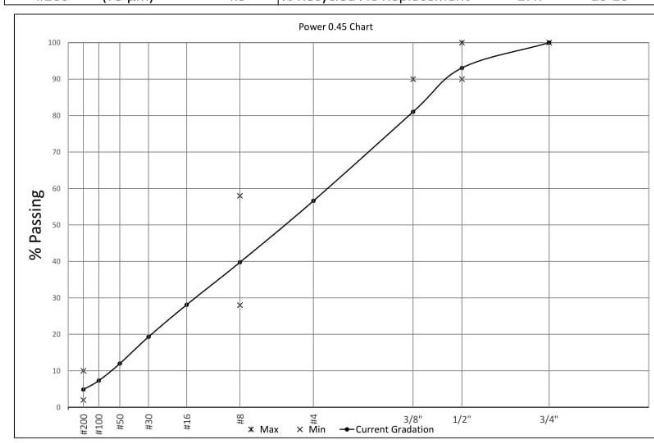
Job Mix			Mix Design Information		Criteria
Sieve	Sieve	% Passing	% Total AC Required	5.23	--
1 1/2"	(37.5 mm)	100.0	Max Spec. Gravity Mix (Gmm)	2.519	--
1"	(25 mm)	100.0	Bulk Spec. Gravity Mix (Gmb)	2.418	--
3/4"	(19.0 mm)	100.0	Design Air Voids (Va)	4.0	4.0
1/2"	(12.5 mm)	93.1	VMA	14.4	>14.0
3/8"	(9.5 mm)	81.0	VFA	72.5	65-75
#4	(4.75 mm)	56.6	Dust/Asphalt Ratio	1.09	0.6 - 1.2
#8	(2.36 mm)	39.8	Effective AC (Pbe)	4.48	--
#16	(1.18 mm)	28.1	Absorbed AC (Pba)	0.79	--
#30	(600 µm)	19.3	% AC Contribution from RAP	0.92	--
#50	(300 µm)	12.0	% AC Contribution from RAS	0.00	--
#100	(150 µm)	7.3	% Virgin Binder	4.31	--
#200	(75 µm)	4.9	% Recycled AC Replacement	17.7	10-20

Aggregate Information		Criteria
Agg. Bulk Gravity (Gsb)	2.681	--
Agg. Effective Gravity (Gse)	2.738	--
Agg. Apparent Gravity (Gsa)	2.744	--
Agg. Absorption (Abs)	0.85	--
Coarse Agg. Angularity (1)	100 assumed*	95 min
Coarse Agg. Angularity (2+)	100 assumed*	90 min
Fine Agg. Angularity (FAA)	47	45 min
Flat and Elongated 5:1 (F & E)	4	10 max
Sand Equivalency (SE)	83	45 min
Other Information		
Ndes Gyrations	80	
Ignition Oven CF	+0.08	
Design Sample Mass, g	4850	
RAP % AC (Ignition)	6.16	
Corrected RAS % AC	NA	
Assumed RAS AC Contribution	NA	
Uncorrected RAS % AC (TCE)	NA	
RAP Binder True Grade	86.5-19.8	
RAS Binder True Grade	NA	
TSR	1.02	
Uncond. Tensile Strength, psi	90.1	
Cond. Tensile Strength, psi	91.9	
Cantabro % Loss	2.9	

Additional Notes

* Crushed granite - Confirmed by Visual Inspection

PSCI = 0.8



National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY

National Center for Asphalt Technology
Job-Mix Formula

NCAT Project ID: 2016 MnROAD
Principal Investigator: Randy West
Producer: Hardrives, Inc. Plant #501
Intended Use: MnROAD CG

NCAT Mix ID: 20% ABR with PG 64E-34
Mix Design Engineer: Grant Julian
Design Completion Date: 8/16/2016
Intended Section: Cell 23

Individual Stockpile Gradations

Sieve Size (mm)	Sieve Size (in)	Stockpile ID (See Page 1) 1	2	3	4	5	6	7		
37.5	1.5"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
25	1.0"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
19	3/4"	100.0	100.0	100.0	100.0	100.0	100.0	100.0		
12.5	1/2"	100.0	100.0	99.9	78.3	100.0	95.7	100.0		
9.5	3/8"	100.0	100.0	95.0	43.6	100.0	86.6	99.2		
4.75	# 4	99.4	87.5	26.2	7.6	100.0	67.7	98.1		
2.36	# 8	78.0	59.7	4.2	2.0	100.0	54.5	95.2		
1.18	# 16	49.9	43.3	2.0	1.5	100.0	43.0	80.0		
0.6	# 30	29.1	32.4	1.4	1.2	98.9	30.6	60.5		
0.3	# 50	13.5	23.2	1.0	1.0	94.1	18.0	45.8		
0.15	#100	4.8	16.2	0.7	0.8	73.0	11.1	34.9		
0.075	#200	1.9	11.5	0.5	0.6	51.6	7.8	27.0		

Average of Design Values

%AC	Gmm	Gmb	% Air Voids	% VMA	%VFA	Dust/Asphalt	Cantabro % Loss
5.0	2.528	2.409	4.7	14.6	67.9	1.15	3.7
5.5	2.509	2.431	3.1	14.3	78.2	1.02	1.8
6.0	2.490	2.438	2.1	14.5	85.6	0.93	0.8

A.7 JOB MIX FORMULA OF N50 SAND MIX

AGGREGATE DETAILS

Agg. Blending %	CM16	FM20	FM02				MF	Target
	17.8	56.0	25.0				1.2	100.0
% Passing Sieve								
1" (25.0 mm)	100.0	100.0	100.0				100.0	100.0
3/4" (19.0 mm)	100.0	100.0	100.0				100.0	100.0
1/2" (12.5 mm)	100.0	100.0	100.0				100.0	100.0
3/8" (9.5 mm)	97.0	100.0	100.0				100.0	99.5
No. 4 (4.75 mm)	32.0	97.0	100.0				100.0	86.2
No. 8 (2.36 mm)	9.0	68.0	94.5				100.0	64.5
No. 16 (1.18 mm)	7.0	40.0	72.0				100.0	42.8
No. 30 (600 μm)	6.0	24.0	49.0				100.0	28.0
No. 50 (300 μm)	6.0	15.0	19.9				100.0	15.6
No. 100 (150 μm)	5.0	9.0	4.1				95.0	8.1
No. 200 (75 μm)	4.6	6.7	1.5				90.0	6.0
Bulk Spec Gravity (Gsb)	2.644	2.691	2.619				2.900	2.667
Apparent Spec Gravity (Gsa)	2.792	2.796	2.719					2.809
Absorption (%)	2.0	1.4	1.4					1.498

BINDER DETAILS

Binder Type	SBS PG 70-22
Specific Gravity, G_b	1.03

MIXING CONDITIONS

Mixing Temperature	165C
Compaction Temperature	153C
G_{mm}	2.451

VOLUMETRICS

Binder%	Gmb @ N50	Ht @N50 (mm)	VTM	VMA	DP	gmm		VFA	Gse	Absorbed Asphalt	Effective Asphalt
7.50%	2.352	118.14	4.0%	18.4%	0.80	2.451		78.1%	2.760	1.30%	6.29%
7.50%	2.352	118.34	4.0%	18.4%	0.80	2.451		78.1%	2.760	1.30%	6.29%

APPENDIX B: SUMMARY OF VOLUMETRICS

Table B.1 Volumetric Information for MnRoad C16

Info	Specimen ID	Dry Weight (g)	Submerged Weight (g)	SSD Weight (g)	G_{mb}	G_{mm}	Air Voids
Pill 3 Number of Gyrations: 29	pill	7248.8	4195.6	7302.6	2.333	2.517	7.3
	TL	996.3	572.9	998.9	2.339	2.517	7.1
	TR	993.4	575.7	996.9	2.358	2.517	6.3
	BL	1015.4	587.7	1018.2	2.359	2.517	6.3
	BR	1004.6	582.1	1007.9	2.359	2.517	6.3
Pill 5 Number of Gyrations: 28	pill	7250.2	4201.4	7307.5	2.334	2.517	7.3
	TL	992.3	572.9	995.4	2.349	2.517	6.7
	TR	982.8	566.7	985.8	2.345	2.517	6.8
	BL	1002.0	579.7	1005.4	2.354	2.517	6.5
	BR	1013.5	588.3	1018.9	2.354	2.517	6.5
Pill 6 Number of Gyrations:28	pill	7251.2	4197.5	7312.0	2.328	2.517	7.5
	TL	1000.8	575.7	1004.0	2.337	2.517	7.2
	TR	992.6	574.0	996.7	2.348	2.517	6.7
	BL	993.8	573.0	997.7	2.340	2.517	7.0
	BR	1016.3	588.4	1020.5	2.352	2.517	6.6
Pill 7 Number of Gyrations: 30	pill	7253.5	4199.4	7308.3	2.333	2.517	7.3
	TL	989.7	566.6	992.9	2.322	2.517	7.8
	TR	1007.2	583.2	1010.8	2.355	2.517	6.4
	BL	991.9	571.9	995.4	2.342	2.517	6.9
	BR	1006.0	586.3	1010.3	2.373	2.517	5.7
Pill 8 Number of Gyrations: 26	pill	7251.1	4194.4	7311.8	2.326	2.517	7.6
	TL	1023.2	592.0	1026.8	2.353	2.517	6.5
	TR	1008.3	583.5	1011.8	2.354	2.517	6.5
	BL	993.7	572.8	997.2	2.341	2.517	7.0
	BR	1005.8	576.1	1009.3	2.322	2.517	7.8

Table B.2 Volumetric Information for MnRoad C17

Info	Specimen ID	Dry Weight (g)	Submerged Weight (g)	SSD Weight (g)	G_{mb}	G_{mm}	Air Voids
Pill 4 Number of Gyrations: 24	pill	7224.3	4176.7	7269.1	2.336	2.515	7.1
	TL	986.6	565.1	988.8	2.329	2.515	7.4
	TR	1010.7	582.6	1012.9	2.349	2.515	6.6
	BL	991.1	573.1	993.2	2.359	2.515	6.2
	BR	1012.0	584.8	1014.1	2.357	2.515	6.3
Pill 5 Number of Gyrations: 24	pill	7225.9	4166.6	7282.8	2.319	2.515	7.8
	TL	1005.8	576.3	1008.6	2.327	2.515	7.5
	TR	998.2	576.1	1000.7	2.351	2.515	6.5
	BL	990.7	568.5	993.0	2.334	2.515	7.2
	BR	1008.3	578.6	1010.7	2.333	2.515	7.2
Pill 6 Number of Gyrations: 23	pill	7222.5	4182.8	7283.3	2.329	2.515	7.4
	TL	993.1	570.2	996.0	2.332	2.515	7.3
	TR	1016.1	584.7	1018.5	2.342	2.515	6.9
	BL	992.9	569.1	994.3	2.335	2.515	7.2
	BR	1018.7	587.8	1019.8	2.358	2.515	6.2
Pill 7 Number of Gyrations: 24	pill	7224.7	4182.9	7283.6	2.330	2.515	7.4
	TL	994.5	573.2	995.9	2.353	2.515	6.5
	TR	991.8	567.0	993.2	2.327	2.515	7.5
	BL	996.9	573.6	998.2	2.348	2.515	6.6
	BR	1005.4	577.3	1007.1	2.339	2.515	7.0

Table B.3 Volumetric Information for MnRoad C18

Info	Specimen ID	Dry Weight (g)	Submerged Weight (g)	SSD Weight (g)	G_{mb}	G_{mm}	Air Voids
Pill 4 Number of Gyrations: 27	pill	7278.2	4206.4	7326.7	2.333	2.529	7.8
	TL	1010.6	580.6	1012.7	2.339	2.529	7.5
	TR	1004.9	580.0	1006.8	2.354	2.529	6.9
	BL	1021.0	587.4	1022.8	2.345	2.529	7.3
	BR	1024.0	593.9	1026.0	2.370	2.529	6.3
Pill 5 Number of Gyrations: 28	pill	7277.8	4213.2	7322.3	2.341	2.529	7.4
	TL	1015.1	588.2	1016.6	2.370	2.529	6.3
	TR	989.3	568.8	991.2	2.342	2.529	7.4
	BL	1008.2	586.5	1010.8	2.376	2.529	6.0
	BR	992.7	571.4	994.5	2.346	2.529	7.2
Pill 7 Number of Gyrations: 25	pill	7275.5	4218.2	7326.3	2.341	2.529	7.4
	TL	1008.6	583.2	1010.6	2.360	2.529	6.7
	TR	1003.7	581.3	1005.3	2.367	2.529	6.4
	BL	1013.2	583.3	1014.9	2.348	2.529	7.2
	BR	1016.9	588.1	1018.3	2.364	2.529	6.5
Pill 9 Number of Gyrations: 31	pill	7275.0	4225.1	7324.6	2.347	2.529	7.2
	TL	1014.8	589.0	1017.0	2.371	2.529	6.2
	TR	1000.6	578.8	1002.7	2.360	2.529	6.7
	BL	1016.5	588.6	1019.0	2.362	2.529	6.6
	BR	1007.3	581.1	1009.1	2.354	2.529	6.9
Pill 11 Number of Gyrations: 33	pill	7276.8	4213.5	7321.7	2.341	2.529	7.4
	TL	1007.2	581.8	1009.0	2.358	2.529	6.8
	TR	992.1	570.7	993.7	2.345	2.529	7.3
	BL	1012.0	585.0	1014.1	2.358	2.529	6.7
	BR	998.8	576.6	1000.7	2.355	2.529	6.9
Pill 13 Number of Gyrations: 33	pill	7275.4	4210.8	7321.8	2.339	2.529	7.5
	TL	1010.6	584.6	1012.5	2.362	2.529	6.6
	TR	988.3	568.4	989.9	2.345	2.529	7.3
	BL	1002.7	581.2	1004.2	2.370	2.529	6.3
	BR	1011.4	585.0	1013.8	2.359	2.529	6.7
Pill 14 Number of Gyrations: 28	pill	7277.1	4221.5	7333.1	2.339	2.529	7.5
	TL	1008.4	581.4	1010.2	2.352	2.529	7.0
	TR	1006.2	582.9	1007.7	2.369	2.529	6.3
	BL	1015.6	584.7	1017.7	2.345	2.529	7.3
	BR	1015.6	585.2	1017.4	2.350	2.529	7.1
Pill 15 Number of Gyrations: 29	pill	7276.5	4217.4	7328.8	2.339	2.529	7.5
	TL	998.6	576.0	1000.5	2.352	2.529	7.0
	TR	985.3	568.8	987.5	2.353	2.529	6.9
	BL	1019.0	588.9	1021.1	2.358	2.529	6.8
	BR	1004.3	576.7	1006.1	2.339	2.529	7.5

Table B.4 Volumetric Information for MnRoad C19

Info	Specimen ID	Dry Weight (g)	Submerged Weight (g)	SSD Weight (g)	G_{mb}	G_{mm}	Air Voids
Pill 1 Number of Gyrations: 24	pill	7213.0	4145.2	7259.6	2.316	2.505	7.5
	TL	1015.3	583.0	1017.4	2.337	2.505	6.7
	TR	988.5	562.3	991.0	2.306	2.505	7.9
	BL	1000.6	575.0	1002.8	2.339	2.505	6.6
	BR	1002.9	573.5	1005.2	2.323	2.505	7.3
Pill 2 Number of Gyrations: 25	pill	7214.1	4142.0	7259.1	2.314	2.505	7.6
	TL	992.2	564.3	994.5	2.306	2.505	7.9
	TR	1011.8	580.7	1014.3	2.333	2.505	6.9
	BL	995.3	571.5	998.0	2.334	2.505	6.8
	BR	999.1	572.9	1001.6	2.331	2.505	6.9
Pill 3 Number of Gyrations: 25	Pill 3	7212.9	4140.8	7259.0	2.313	2.505	7.7
	TL	992.2	564.5	993.4	2.313	2.505	7.7
	TR	1015.6	582.9	1017.9	2.335	2.505	6.8
	BL	990.5	564.4	992.7	2.313	2.505	7.7
	BR	1014.8	582.1	1016.9	2.334	2.505	6.8
Pill 4 Number of Gyrations: 22	pill	7213.0	4147.5	7270.6	2.310	2.505	7.8
	TL	1000.3	567.1	1002.6	2.297	2.505	8.3
	TR	1007.0	577.0	1009.2	2.330	2.505	7.0
	BL	1001.5	574.3	1003.9	2.331	2.505	6.9
	BR	1020.6	588.5	1022.6	2.351	2.505	6.1
Pill 6 Number of Gyrations: 25	pill	7215.0	4148.8	7261.5	2.318	2.505	7.5
	TL	996.4	569.9	998.4	2.325	2.505	7.2
	TR	1029.5	595.4	1031.4	2.361	2.505	5.7
	BL	995.0	568.4	997.2	2.320	2.505	7.4
	BR	1007.1	578.9	1009.7	2.338	2.505	6.7
Pill 7 Number of Gyrations: 24	pill	7213.0	4148.2	7262.0	2.316	2.505	7.5
	TL	1006.1	578.6	1008.6	2.340	2.505	6.6
	TR	1011.6	581.9	1014.4	2.339	2.505	6.6
	BL	C19 7 BL and BR were not tested because of an error during the fabrication process					
	BR						
Pill 8 Number of Gyrations: 24	pill	7213.4	4143.8	7264.3	2.312	2.505	7.7
	TL	1019.2	586.7	1020.1	2.352	2.505	6.1
	TR	1001.4	576.4	1003.5	2.345	2.505	6.4
	BL	1001.4	576.9	1003.9	2.345	2.505	6.4
	BR	1001.3	568.5	1002.8	2.306	2.505	7.9
Pill 10 Number of Gyrations: 24		7213.1	4140.6	7257.9	2.314	2.505	7.6
	TL	1006.2	578.0	1009.5	2.332	2.505	6.9
	TR	1021.1	586.0	1023.8	2.332	2.505	6.9
	BL	1004.3	575.9	1007.0	2.330	2.505	7.0
	BR	1029.6	590.9	1032.1	2.334	2.505	6.8
Pill 11 Number of Gyrations: 26	pill	7213.9	4138.7	7258.2	2.313	2.505	7.7
	TL	1003.9	576.5	1005.0	2.343	2.505	6.5
	TR	1020.1	581.9	1021.2	2.322	2.505	7.3
	BL	993.7	568.6	994.8	2.332	2.505	6.9
	BR	1012.4	574.9	1013.6	2.308	2.505	7.9

(Table continues next page)

Info	Specimen ID	Dry Weight (g)	Submerged Weight (g)	SSD Weight (g)	G_{mb}	G_{mm}	Air Voids
Pill 13 Number of Gyrations: 25	pill	7215.0	4136.5	7259.6	2.310	2.505	7.8
	TL	1020.3	580.6	1022.7	2.308	2.505	7.9
	TR	1014.9	586.5	1017.2	2.356	2.505	5.9
	BL	996.3	564.1	999.4	2.289	2.505	8.6
	BR	1042.8	599.9	1044.9	2.343	2.505	6.5
Pill 14 Number of Gyrations: 25	pill	7213.6	4149.6	7257.0	2.321	2.505	7.3
	TL	989.2	565.2	991.7	2.319	2.505	7.4
	TR	1020.3	582.8	1022.8	2.319	2.505	7.4
	BL	998.0	572.1	1000.7	2.329	2.505	7.0
	BR	1008.7	580.6	1011.0	2.344	2.505	6.4
Pill 15 Number of Gyrations: 26	pill	7213.6	4147.7	7262.6	2.316	2.505	7.5
	TL	1022.3	583.0	1023.4	2.321	2.505	7.3
	TR	1014.3	580.1	1015.2	2.331	2.505	6.9
	BL	1008.3	576.2	1004.9	2.352	2.505	6.1
	BR	1033.0	595.0	1034.6	2.350	2.505	6.2
Pill 16 Number of Gyrations: 25	pill	7211.2	4151.6	7258.8	2.321	2.505	7.3
	TL	989.4	566.9	993.0	2.322	2.505	7.3
	TR	1025.3	593.0	1028.6	2.354	2.505	6.0
	BL	1013.4	579.7	1016.5	2.320	2.505	7.4
	BR	993.9	570.9	995.2	2.342	2.505	6.5

Table B.5 Volumetric Information for C21

Info	Specimen ID	Dry Weight (g)	Submerged Weight (g)	SSD Weight (g)	G_{mb}	G_{mm}	Air Voids
Pill 2 Number of Gyrations: 32	pill	7255.2	4213.0	7316.0	2.338	2.534	7.7
	TL	1008.7	583.3	1010.6	2.361	2.534	6.8
	TR	993.0	568.7	994.9	2.330	2.534	8.1
	BL	1019.0	589.5	1020.7	2.363	2.534	6.7
	BR	1012.4	584.0	1014.4	2.352	2.534	7.2
Pill 7 Number of Gyrations: 26	pill	7258.5	4220.6	7331.4	2.333	2.534	7.9
	TL	989.6	570.5	991.8	2.349	2.534	7.3
	TR	992.7	570.4	995.2	2.337	2.534	7.8
	BL	1021.6	592.5	1024.0	2.368	2.534	6.6
	BR	1007.2	580.5	1009.3	2.349	2.534	7.3
Pill 6 Number of Gyrations: 27	pill	7257.0	4217.2	7329.5	2.332	2.534	8.0
	TL	1003.1	578.5	1006.1	2.346	2.534	7.4
	TR	987.1	570.7	990.2	2.353	2.534	7.1
	BL	1016.4	588.9	1018.9	2.364	2.534	6.7
	BR	1020.7	590.3	1023.9	2.354	2.534	7.1
Pill 4 Number of Gyrations: 34	pill	7256.6	4220.0	7314.7	2.345	2.534	7.5
	TL	983.3	566.7	985.5	2.348	2.534	7.3
	TR	991.2	571.7	993.2	2.352	2.534	7.2
	BL	1011.4	583.8	1013.4	2.354	2.534	7.1
	BR	1013.5	588.2	1016.2	2.368	2.534	6.6
Pill 3 Number of Gyrations: 30	pill	7255.3	4217.6	7323.3	2.336	2.534	7.8
	TL	1004.9	582.9	1008.4	2.362	2.534	6.8
	TR	1011.1	585.0	1014.2	2.356	2.534	7.0
	BL	1002.5	577.3	1005.2	2.343	2.534	7.5
	BR	1014.7	588.1	1018.5	2.358	2.534	7.0

Table B.6 Volumetric Information for MnRoad C23

Info	Specimen ID	Dry Weight (g)	Submerged Weight (g)	SSD Weight (g)	G_{mb}	G_{mm}	Air Voids
Pill 7 Number of Gyrations: 22	pill	7230.6	4196.0	7291.2	2.336	2.526	7.5
	TL	994.0	574.2	996.3	2.355	2.526	6.8
	TR	999.3	578.8	1002.6	2.358	2.526	6.7
	BL	997.6	575.6	1000.7	2.347	2.526	7.1
	BR	1008.5	584.3	1011.2	2.362	2.526	6.5
Pill 1 Number of Gyrations: 23	pill	7229.6	4204.3	7284.2	2.347	2.526	7.1
	TL	988.9	571.6	991.9	2.353	2.526	6.9
	TR	997.1	576.1	999.7	2.354	2.526	6.8
	BL	1013.3	587.6	1015.5	2.368	2.526	6.3
	BR	1020.6	591.2	1023.0	2.364	2.526	6.4
Pill 4 Number of Gyrations: 22	pill	7231.3	4201.4	7293.5	2.339	2.526	7.4
	TL	993.1	574.6	995.9	2.357	2.526	6.7
	TR	999.5	578.9	1002.4	2.360	2.526	6.6
	BL	1003.1	579.9	1005.6	2.356	2.526	6.7
	BR	1000.6	579.6	1003.5	2.360	2.526	6.6
Pill 8 Number of Gyrations: 22	pill	7235.2	4196.6	7294.0	2.336	2.526	7.5
	TL	999.4	578.8	1002.8	2.357	2.526	6.7
	TR	988.9	570.9	991.9	2.349	2.526	7.0
	BL	1018.3	590.7	1021.4	2.364	2.526	6.4
	BR	996.9	574.7	1000.1	2.343	2.526	7.2
Pill 5 Number of Gyrations: 20	pill	7231.5	4201.9	7301.9	2.333	2.526	7.65
	TL	997.5	576.8	1000.6	2.354	2.526	6.8
	TR	979.1	565.3	982.5	2.347	2.526	7.1
	BL	1015.2	586.4	1017.8	2.353	2.526	6.8
	BR	998.4	579.7	1002.3	2.363	2.526	6.5

Table B.7 Volumetric Information for IDOT Base Course Mix

Info	Specimen ID	Dry Weight (g)	Submerged Weight (g)	SSD Weight (g)	G_{mb}	G_{mm}	Air Voids
Pill 4 Number of Gyrations: 30	pill	Data on air voids for the pill are not available for this mix					
	TL	1010.7	583.9	1016.2	2.338	2.534	7.7
	TR	1002.3	578.5	1005.0	2.350	2.534	7.3
	BL	1027.9	595.5	1031.3	2.359	2.534	6.9
	BR	1005.1	582.0	1007.4	2.363	2.534	6.8
Pill 5 Number of Gyrations: 29	pill	Data on air voids for the pill are not available for this mix					
	TL	975.0	563.4	979.5	2.343	2.534	7.5
	TR	993.6	574.7	998.5	2.345	2.534	7.5
	BL	1020.6	589.1	1023.3	2.351	2.534	7.2
	BR	997.3	574.6	1001.0	2.339	2.534	7.7
Pill 6 Number of Gyrations: 32	pill	Data on air voids for the pill are not available for this mix					
	TL	990.2	570.7	992.3	2.349	2.534	7.3
	TR	1012.1	582.4	1014.3	2.343	2.534	7.5
	BL	997.3	576.8	999.8	2.358	2.534	7.0
	BR	1033.8	598.9	1035.5	2.368	2.534	6.6
Pill 7 Number of Gyrations: 26	pill	Data on air voids for the pill are not available for this mix					
	TL	975.2	557.4	977.9	2.319	2.534	8.5
	TR	982.1	569.3	985.0	2.363	2.534	6.8
	BL	1029.2	597.4	1033.0	2.363	2.534	6.8
	BR	996.1	571.6	998.2	2.335	2.534	7.9
Pill 8 Number of Gyrations: 28	pill	Data on air voids for the pill are not available for this mix					
	TL	993.6	575.1	997.4	2.353	2.534	7.1
	TR	979.1	564.3	981.4	2.347	2.534	7.4
	BL	1000.8	578.7	1004.0	2.353	2.534	7.1
	BR	1017.7	588.3	1019.5	2.360	2.534	6.9
Pill 9 Number of Gyrations: 28	pill	Data on air voids for the pill are not available for this mix					
	TL	969.2	557.9	973.3	2.333	2.534	7.9
	TR	999.6	574.2	1003.2	2.330	2.534	8.0
	BL	992.6	571.7	995.6	2.342	2.534	7.6
	BR	1027.0	592.8	1028.8	2.356	2.534	7.0
Pill 10 Number of Gyrations: 30	pill	Data on air voids for the pill are not available for this mix					
	TL	1004.4	583.2	1010.1	2.353	2.534	7.2
	TR	986.7	571.0	989.7	2.357	2.534	7.0
	BL	994.8	571.1	997.0	2.336	2.534	7.8
	BR	1008.9	583.0	1011.9	2.352	2.534	7.2
Pill 11 Number of Gyrations: 28	pill	Data on air voids for the pill are not available for this mix					
	TL	1005.8	580.8	1010.4	2.341	2.534	7.6
	TR	987.9	570.6	990.1	2.355	2.534	7.1
	BL	1006.1	582.7	1009.4	2.358	2.534	7.0
	BR	1029.1	596.7	1032.1	2.364	2.534	6.7
Pill 12 Number of Gyrations: 30	pill	Data on air voids for the pill are not available for this mix					
	TL	986.0	566.9	989.8	2.332	2.534	8.0
	TR	999.9	572.8	1004.0	2.319	2.534	8.5
	BL	982.8	566.3	986.0	2.342	2.534	7.6
	BR	1025.2	594.9	1029.2	2.361	2.534	6.8

Table B.8 Volumetric Information for N50 Lab Sand Mix

Info	Specimen ID	Dry Weight (g)	Submerged Weight (g)	SSD Weight (g)	G_{mb}	G_{mm}	Air Voids
Pill 1 Number of Gyrations: 20	pill	7109.3	3999.7	7132.1	2.270	2.451	7.4
	TL	984.1	554.2	985.3	2.283	2.451	6.9
	TR	971.8	546.6	972.9	2.280	2.451	7.0
	BL	987.7	555.8	988.9	2.281	2.451	7.0
	BR	982.5	554.0	983.6	2.287	2.451	6.7
Pill 2 Number of Gyrations: 20	pill	7105.8	3999.9	7130.3	2.270	2.451	7.4
	TL	979.3	552.1	980.5	2.286	2.451	6.7
	TR	972.0	547.7	973.1	2.285	2.451	6.8
	BL	996.9	562.7	998.2	2.289	2.451	6.6
	BR	982.0	551.9	983.1	2.277	2.451	7.1
Pill 3 Number of Gyrations: 21	Pill 3	7110.2	4001.2	7129.6	2.273	2.451	7.3
	TL	988.1	556.9	989.1	2.286	2.451	6.7
	TR	969.2	543.3	970.3	2.270	2.451	7.4
	BL	993.1	561.5	994.0	2.296	2.451	6.3
	BR	973.2	546.9	974.3	2.277	2.451	7.1
Pill 4 Number of Gyrations: 20	pill	7111.7	4002.0	7133.4	2.271	2.451	7.3
	TL	976.9	549.0	978.1	2.277	2.451	7.1
	TR	965.5	542.8	966.5	2.279	2.451	7.0
	BL	981.8	553.4	983.0	2.285	2.451	6.8
	BR	974.3	549.9	975.3	2.290	2.451	6.6
Pill 5 Number of Gyrations: 22	pill	7109.6	3997.7	7133.8	2.267	2.451	7.5
	TL	981.6	550.9	982.6	2.274	2.451	7.2
	TR	973.4	545.8	974.4	2.271	2.451	7.3
	BL	984.8	554.0	985.9	2.280	2.451	7.0
	BR	980.2	553.2	981.3	2.290	2.451	6.6
Pill 6 Number of Gyrations: 24	pill	7107.0	4000.6	7124.2	2.275	2.451	7.2
	TL	991.5	560.7	992.7	2.295	2.451	6.4
	TR	975.8	551.8	976.9	2.295	2.451	6.3
	BL	984.0	553.8	985.3	2.280	2.451	7.0
	BR	960.9	540.5	961.9	2.280	2.451	7.0
Pill 7 Number of Gyrations: 25	pill	7108.2	4004.6	7126.1	2.277	2.451	7.1
	TL	982.9	553.2	983.9	2.282	2.451	6.9
	TR	975.7	549.8	976.9	2.284	2.451	6.8
	BL	990.1	558.5	991.1	2.289	2.451	6.6
	BR	968.0	544.9	969.3	2.281	2.451	6.9
Pill 8 Number of Gyrations: 23		7111.5	4006.4	7132.5	2.275	2.451	7.2
	TL	989.6	558.3	990.8	2.288	2.451	6.6
	TR	974.5	549.7	975.6	2.288	2.451	6.6
	BL	981.4	551.3	982.2	2.278	2.451	7.1
	BR	967.1	544.1	967.1	2.286	2.451	6.7
Pill 9 Number of Gyrations: 22	pill	7109.2	3997.8	7127.5	2.272	2.451	7.3
	TL	981.5	551.7	982.6	2.278	2.451	7.1
	TR	970.6	545.3	971.6	2.277	2.451	7.1
	BL	981.1	551.7	982.1	2.280	2.451	7.0
	BR	962.4	540.5	963.4	2.276	2.451	7.2

(Table continues next page)

Info	Specimen ID	Dry Weight (g)	Submerged Weight (g)	SSD Weight (g)	G_{mb}	G_{mm}	Air Voids
Pill 10 Number of Gyrations: 23	pill	7108.3	4000.9	7129.1	2.272	2.451	7.3
	TL	983.7	553.8	984.7	2.283	2.451	6.9
	TR	977.3	552.0	978.1	2.294	2.451	6.4
	BL	987.9	555.3	989.1	2.277	2.451	7.1
	BR	969.0	545.1	970.2	2.279	2.451	7.0
Pill 11 Number of Gyrations: 23	pill	7110.3	4000.3	7128.8	2.273	2.451	7.3
	TL	985.6	555.9	986.7	2.288	2.451	6.7
	TR	965.1	542.7	966.3	2.278	2.451	7.0
	BL	979.5	551.0	980.6	2.280	2.451	7.0
	BR	958.7	538.4	959.9	2.274	2.451	7.2

APPENDIX C: I-FIT TEST RESULTS

Table C.1 Results for MnRoad C16

MnRoad C16													
Machine Type	Replicate ID	Energy LLD (J/m2)	AVERAGE	STD DEV	COV	Slope	AVERAGE	STD DEV	COV	FI	AVERAGE	STD DEV	COV
INSTROTEK SPRINGS	3TL	1526	1819	259	14.2	-5.06	-5.03	1.00	-19.9	3.02	3.79	1.04	27.6
	5TR	1491				-5.02				2.97			
	6BR	1802				-6.86				2.63			
	6TL	1850				-4.42				4.19			
	6TR	2231				-5.27				4.23			
	7BL	2011				-3.54				5.68			
TESTQUIP SPRING ROLLERS	5TL	2038	1821	146	8.0	-5.80	-6.13	1.16	-19.0	3.51	3.10	0.68	22.1
	5BL	1871				-4.58				4.09			
	5BR	1542				-8.43				1.83			
	6BL	1803				-5.93				3.04			
	8BL	1823				-5.67				3.21			
	8TR	1852				-6.38				2.90			
TESTQUIP BEARING ROLLERS-IDOT	1TR	1993	1881	111	5.9	-4.89	-6.47	1.23	-18.9	4.08	3.01	0.61	20.2
	2TL	1701				-6.20				2.74			
	2TR	1967				-6.48				3.04			
	2BL	1944				-5.68				3.42			
	4BL	1928				-8.87				2.17			
	4BR	1754				-6.70				2.62			

Table C.2 Test Results for MnRoad C17

MnRoad C17													
Machine Type	**Replicate ID**	**Energy LLD (J/m2)**	**AVERAGE**	**STD DEV**	**COV**	**Slope**	**AVERAGE**	**STD DEV**	**COV**	**FI**	**AVERAGE**	**STD DEV**	**COV**
INSTROTEK SPRINGS	4TR	2136	2146	259	12.1	-3.51	-3.37	0.29	-8.6	6.08	6.45	1.13	17.5
	5BR	2610				-3.14				8.31			
	5TL	1810				-3.46				5.23			
	6BL	2096				-2.86				7.33			
	6TR	1925				-3.75				5.13			
	7BL	2299				-3.49				6.59			
TESTQUIP SPRING ROLLERS	4TL	2342	2176	124	5.7	-2.65	-3.35	0.62	-18.6	8.84	6.75	1.51	22.4
	5BL	2321				-2.65				8.76			
	5TR	2086				-3.35				6.23			
	6TL	2137				-4.46				4.79			
	7BR	1990				-3.32				5.99			
	7TR	2180				-3.68				5.92			
TESTQUIP BEARING ROLLERS-IDOT	1TL	2744	2296	322	14.0	-2.40	-3.02	0.45	-15.0	11.43	7.91	2.17	27.4
	1TR	2278				-2.62				8.69			
	1BL	1751				-3.52				4.98			
	1BR	2108				-3.64				5.79			
	2TL	2591				-2.81				9.22			
	2TR	2304				-3.15				7.32			

Table C.3 Test Results for MnRoad C18

MnRoad C18														
Machine Type	**Replicate ID**	**Energy LLD (J/m2)**	**AVERAGE**	**STD DEV**	**COV**	**Slope**	**AVERAGE**	**STD DEV**	**COV**	**FI**	**AVERAGE**	**STD DEV**	**COV**
INSTROTEK SPRINGS	1BL	2094	2064	161	7.8	-4.19	-4.13	1.01	-24.5	5.00	5.36	1.58	29.4
	14TL	2155				-3.50				6.16			
	2TR	2393				-2.80				8.55			
	4TR	2077				-3.94				5.27			
	7BL	2045				-3.46				5.91			
	9BL	1836				-5.11				3.59			
	13TL	1872				-6.24				3.00			
	14BR	2037				-3.76				5.42			
TESTQUIP BEARING ROLLERS	1TL	2392	2229	188	8.4	-4.57	-4.68	0.97	-20.8	5.23	5.12	1.83	35.8
	4BL	2503				-2.59				9.67			
	5BR	2326				-4.37				5.32			
	9BR	2375				-5.25				4.52			
	11BR	1968				-4.52				4.35			
	11TL	2052				-6.23				3.29			
	11TR	2216				-4.61				4.81			
	15TL	2003				-5.28				3.79			
TESTQUIP SPRING ROLLERS	4TL	2172	1991	238	11.9	-4.10	-5.76	1.48	-25.7	5.30	3.78	1.30	34.4
	9TR	1986				-6.46				3.07			
	13BR	2311				-4.25				5.44			
	13TR	1973				-4.92				4.01			
	14BL	2311				-4.47				5.17			
	15BL	1757				-7.45				2.36			
	15BR	1701				-8.35				2.04			
	15TR	1718				-6.10				2.82			
TESTQUIP BEARING ROLLERS-IDOT	3TL	2385	2209	126	5.7	-3.72	-4.89	1.04	-21.2	6.41	4.74	1.11	23.3
	3TR	2123				-5.83				3.64			
	3BL	2240				-4.57				4.90			
	6TR	2081				-4.41				4.72			
	6BL	2367				-3.91				6.05			
	6BR	2294				-4.47				5.13			
	16TL	2160				-5.15				4.19			
	16TR	2019				-7.09				2.85			
INTERLAKEN	18TL	2079	2049	179	8.7	-4.91	-5.18	0.34	-6.7	4.23	3.98	0.49	12.3
	18TR	1893				-4.67				4.05			
	19TL	2077				-5.53				3.76			
	19BR	2110				-5.38				3.92			
	20TL	2310				-4.74				4.87			
	20TR	2080				-5.12				4.06			
	21TR	1671				-5.61				2.98			
	21BR	2170				-5.45				3.98			

Table C.4 Test Results for MnRoad C19

MnRoad C19													
Machine Type	**Replicate ID**	**Energy LLD (J/m2)**	**AVERAGE**	**STD DEV**	**COV**	**Slope**	**AVERAGE**	**STD DEV**	**COV**	**FI**	**AVERAGE**	**STD DEV**	**COV**
INSTROTEK SPRINGS	4TR	2173	2297	228	9.9	-3.09	-3.81	0.76	-19.9	7.03	6.29	1.42	22.6
	13BR	2352				-2.94				8.00			
	6BL	2710				-3.40				7.97			
	14TL	2247				-4.55				4.94			
	10TR	1834				-3.74				4.90			
	1BL	2320				-3.01				7.71			
	10BR	2234				-4.34				5.15			
	11TR	2360				-3.29				7.17			
	16BR	2154				-4.75				4.53			
	1BR	2529				-3.39				7.46			
	3TR	2076				-5.59				3.71			
	2BL	2217				-3.71				5.97			
	2TR	2661				-3.70				7.19			
TESTQUIP SPRING ROLLERS	1TL	2891	2411	222	9.2	-4.74	-3.90	1.26	-32.3	6.10	6.82	2.12	31.1
	2BR	2481				-2.47				10.05			
	3BR	2349				-4.43				5.30			
	4BL	2457				-3.81				6.45			
	6BR	1973				-7.16				2.76			
	7TL	2528				-4.08				6.20			
	10BL	2619				-2.66				9.84			
	10TL	2133				-2.55				8.36			
	14BL	2359				-4.67				5.05			
	14TR	2317				-3.64				6.37			
	15TL	2619				-3.74				7.00			
	16BL	2307				-2.29				10.07			
	16TL	2314				-4.51				5.13			
TESTQUIP BEARING ROLLERS-IDOT	5BL	1990	2448	284	11.6	-5.55	-4.31	0.82	-19.0	3.59	6.04	2.05	33.9
	5TL	2674				-3.81				7.02			
	5TR	2207				-4.42				4.99			
	9BL	2949				-2.55				11.56			
	9BR	2581				-3.82				6.76			
	9TL	2318				-5.14				4.51			
	9TR	2158				-3.85				5.60			
	12BL	2554				-4.52				5.65			
	12BR	2189				-5.43				4.03			
	12TL	2784				-4.18				6.66			
	12TR	2525				-4.16				6.07			

Table C.5 Test Results for MnRoad C21

MnRoad C21													
Machine Type	**Replicate ID**	**Energy LLD (J/m2)**	**AVERAGE**	**STD DEV**	**COV**	**Slope**	**AVERAGE**	**STD DEV**	**COV**	**FI**	**AVERAGE**	**STD DEV**	**COV**
INSTROTEK SPRINGS	3BR	1613	1594	83	5.2	-1.59	-1.47	0.21	-14.5	10.14	11.14	2.15	19.3
	4TR	1489				-1.45				10.27			
	4BR	1513				-1.49				10.16			
	4BL	1698				-1.49				11.40			
	7TL	1691				-1.09				15.52			
	6BR	1479				-1.75				8.45			
	2BR	1621				-1.20				13.51			
	2BL	1650				-1.70				9.71			
TESTQUIP SPRING ROLLERS	2TL	1704	1672	156	9.3	-1.54	-1.51	0.14	-9.3	11.07	11.27	2.06	18.3
	3TL	1811				-1.44				12.58			
	3TR	1868				-1.45				12.88			
	4TL	1542				-1.46				10.56			
	6TL	1425				-1.66				8.59			
	7BL	1867				-1.22				15.30			
	7BR	1613				-1.65				9.78			
	6BL	1548				-1.65				9.38			
TESTQUIP BEARING ROLLERS-IDOT	ITL	1588	1683	188	11.1	-1.86	-1.70	0.35	-20.6	8.54	10.22	2.00	19.5
	1BL	1672				-1.63				10.26			
	1BR	1706				-1.35				12.64			
	5TL	1312				-1.25				10.50			
	5TR	1931				-1.44				13.41			
	5BL	1904				-2.28				8.35			
	5BR	1567				-2.17				7.22			
	8TL	1785				-1.64				10.88			

Table C.6 Test Results for MnRoad C23

MnRoad C23													
Machine Type	**Replicate ID**	**Energy LLD (J/m2)**	**AVERAGE**	**STD DEV**	**COV**	**Slope**	**AVERAGE**	**STD DEV**	**COV**	**FI**	**AVERAGE**	**STD DEV**	**COV**
INSTROTEK SPRINGS	7TL	1824	1877	285	15.2	-1.56	-1.41	0.34	-24.4	11.69	14.40	5.44	37.8
	7TR	1651				-1.54				10.72			
	7BR	1927				-2.09				9.22			
	1TL	1943				-0.89				21.83			
	4BL	1798				-1.48				12.15			
	7BL	1549				-1.46				10.61			
	8TR	1762				-1.27				13.88			
	4TR	2558				-1.02				25.07			
TESTQUIP SPRING ROLLERS	1TR	1587	1690	123	7.3	-1.53	-1.48	0.22	-14.9	10.37	11.67	1.88	16.1
	4BR	1817				-1.26				14.42			
	4TL	1513				-1.86				8.13			
	5BL	1851				-1.68				11.02			
	5BR	1631				-1.26				12.95			
	5TL	1854				-1.61				11.51			
	8BR	1623				-1.18				13.75			
	8BL	1644				-1.47				11.18			
TESTQUIP BEARING ROLLERS-IDOT	2TL	1651	1941	124	6.4	-2.01	-1.43	0.27	-19.0	8.21	14.16	3.05	21.6
	2TR	1919				-1.56				12.30			
	2BL	1917				-1.61				11.91			
	2BR	1946				-1.23				15.82			
	3TL	2087				-1.18				17.68			
	3TR	1948				-1.41				13.81			
	3BL	2037				-1.15				17.71			
	3BR	2024				-1.28				15.81			

Table C.7 Test Results for IDOT Base Course Mix

IDOT Base Course													
Machine Type	**Replicate ID**	**Energy LLD (J/m2)**	**AVERAGE**	**STD DEV**	**COV**	**Slope**	**AVERAGE**	**STD DEV**	**COV**	**FI**	**AVERAGE**	**STD DEV**	**COV**
INSTROTEK SPRINGS	8BR		1656	137	8.3		-4.16	0.48	-11.5		4.05	0.67	16.5
	8TL	1503				-4.46				3.37			
	4BR	1750				-3.52				4.97			
	4TR	1910				-3.96				4.82			
	10TR	1576				-4.43				3.56			
	4BL	1640				-4.89				3.35			
	5BL	1559				-3.69				4.22			
TESTQUIP BEARING ROLLERS	8TR	1465	1650	140	8.5	-3.63	-4.36	0.40	-9.1	4.04	3.80	0.38	10.0
	6TL	1618				-4.98				3.25			
	11TR	1662				-4.64				3.58			
	11BL	1823				-4.43				4.11			
	5TR	1453				-4.39				3.31			
	7BL	1706				-4.05				4.21			
	11BR	1823				-4.43				4.11			
TESTQUIP SPRING ROLLERS	8BL	1425	1724	198	11.5	-4.47	-4.32	0.98	-22.7	3.19	4.35	1.71	39.3
	6TR	2089				-2.57				8.13			
	6BR	1681				-4.74				3.55			
	5TL	1894				-3.87				4.90			
	10BR	1682				-5.54				3.04			
	9BR	1714				-3.60				4.76			
	6BL	1584				-5.43				2.92			
TESTQUIP BEARING ROLLERS-IDOT	1TL	1805	1786	188	10.5	-3.78	-4.47	1.16	-26.0	4.78	4.28	1.13	26.4
	1TR	1978				-3.77				5.25			
	1BL	2110				-4.34				4.86			
	1BR	1756				-3.08				5.70			
	2TL	1536				-6.90				2.23			
	2BL	1594				-4.19				3.80			
	2BR	1725				-5.21				3.31			

NOTE: Results for specimen 8BR were removed because of issues during the data analysis.

Table C.8 Test Results for N50 Sand Mix

N50 Lab Sand Mix														
Machine Type	**Replicate ID**	**Energy LLD (J/m2)**	**AVERAGE**	**STD DEV**	**COV**	**Slope**	**AVERAGE**	**STD DEV**	**COV**	**FI**	**AVERAGE**	**STD DEV**	**COV**
INSTROTEK SPRINGS	2TL	3094	3043	105	3.5	-1.60	-1.56	0.10	-6.2	19.34	19.64	1.67	8.5
	2BR	2813				-1.66				16.95			
	3TR	3169				-1.56				20.32			
	3BR	2993				-1.58				18.94			
	5BL	3054				-1.42				21.50			
	6BL	2985				-1.60				18.65			
	8TL	3118				-1.38				22.59			
	9BL	3119				-1.66				18.79			
TESTQUIP BEARING ROLLERS	4TR	3274	3041	171	5.6	-1.22	-1.50	0.17	-11.5	26.84	20.60	2.85	13.9
	5TR	3108				-1.77				17.56			
	5BR	2817				-1.42				19.84			
	7BR	2830				-1.29				21.94			
	8BL	2894				-1.67				17.33			
	9TL	3274				-1.50				21.83			
	10BL	3026				-1.59				19.03			
	11BL	3107				-1.52				20.44			
TESTQUIP SPRING ROLLERS	1TR	2966	2992	246	8.2	-1.31	-1.46	0.25	-17.3	22.64	21.36	5.73	26.8
	1BR	3558				-1.05				33.89			
	3TR	3028				-1.69				17.91			
	5TL	3034				-1.14				26.61			
	8TR	2791				-1.49				18.73			
	9TR	2820				-1.75				16.11			
	11TR	2695				-1.55				17.39			
	11BR	3045				-1.73				17.60			
INTERLAKEN	1TL	2778	3038	243	8.0	-1.62	-1.32	0.15	-11.6	17.15	23.43	3.70	15.8
	4TL	3494				-1.34				26.07			
	4BR	2763				-1.17				23.62			
	6BR	3254				-1.07				30.41			
	7TR	2814				-1.37				20.54			
	7BL	2956				-1.37				21.57			
	9BR	3155				-1.36				23.20			
	11TL	3087				-1.24				24.89			

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