Technical Report Documentation Page

1. Report No. FHWA-NH-RD-13733F	**2. Gov. Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle APPLICATION OF THE BAILEY METHOD TO NEW HAMPSHIRE ASPHALT MIXTURES		**5. Report Date** December 2009
		6. Performing Organization Code
7. Author(s) Jo Sias Daniel, Ph.D., P.E. and Felix Rivera		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Department of Civil Engineering, University of New Hampshire, W183 Kingsbury Hall, Durham, NH 03824		**10. Work Unit No. (TRAIS)**
		11. Contract or Grant No. 13733F, X-A000(151)
12. Sponsoring Agency Name and Address New Hampshire Department of Transportation, 7 Hazen Drive, PO Box 483, Concord, NH 03302-0483		**13. Type of Report and Period Covered** FINAL REPORT
		14. Sponsoring Agency Code

15. Supplementary Notes
In cooperation with the U. S. Department of Transportation, Federal Highway Administration

16. Abstract

The Superpave mix design system provides guidance in selecting the appropriate component materials for asphalt concrete mixtures. However, the selection of the design aggregate structure is left to the experience of the mix designer. This necessarily results in a trial and error process for selecting an aggregate gradation to meet specified volumetric parameters. Also, the mix designer has no means to evaluate how the mix will work in the field during placement or how it will perform. It is important to understand the influence of the aggregate structure on the volumetric properties, construction, and performance of the asphalt mixture to achieve the desired properties and performance.

The Bailey Method was originally developed by Robert D. Bailey, an Illinois DOT engineer, as a means to prevent rutting while maintaining durability of mixtures and was based on his experience in the design of asphalt mixtures. Mr. Bailey’s methods have been refined by several researchers to provide a systematic approach to blending aggregates to meet the volumetric criteria for any method of mix design, including Superpave, Marshall, and Hveem. The Bailey Method is based on the concepts of aggregate interlock and aggregate packing. In addition, the Bailey Method provides tools for evaluating the effect of aggregate structure on mixture properties, constructability, and performance.

The primary objective of this project was to determine if the Bailey Method can be a useful tool to design mixtures with improved performance using New Hampshire aggregate. The mode of improvement given attention in this project is resistance to rutting under loading by the Third Scale Model Mobile Load Simulator (MMLS3) in hot, dry conditions. A secondary objective was to evaluate the use of the MMLS3 as a tool to evaluate rutting.

Six mix designs commonly used throughout New Hampshire were chosen for evaluation. Half of the designs used gravel stone with rounded, smooth faces, and the other half used fractured rock with rough, angular faces. Two mixtures also contained 15% RAP. NMSA values of 19 mm and 12.5 mm were chosen as representative of most mixtures placed in the state. The MMLS3 laboratory testing resulted in expected trends in relative performance of the various mixtures. Three of the mixtures were then chosen for redesign with the Bailey Method. The Bailey parameters for the original mixtures were calculated and the gradations were redesigned to fall within the recommended ranges. The predictions of VMA changes based on the Bailey parameters were reasonable for the angular aggregate, but not for the smooth aggregate evaluated in this study. The redesigned Bailey mixtures did show an increase in rutting performance.

Overall, this research project showed that the Bailey Method can be a useful tool in the evaluation and design of New Hampshire mixtures. The Bailey Method should not be used exclusively, but can be used in combination with knowledge of the aggregate angularity, roughness, and engineering judgment to provide guidance during the mix design procedure and improve mixture performance. The study also showed that the MMLS3 is an appropriate method for evaluating the relative rutting performance of different mixtures in the laboratory.

17. Key Words Bailey Method, asphalt, HMA, mixtures, aggregate, Superpave, New Hampshire, mix design, volumetric, rutting, MMLS3, fractured, rounded, angular, gradation, packing, interlock			**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia, 22161
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 185	**22. Price**

DISCLAIMER

Application of the Bailey Method to NH Asphalt Mixtures

Final Research Report
Submitted to:

New Hampshire Department of Transportation
SPR Project No. 13733-F

By:

Jo Sias Daniel, Ph.D., P.E.
Associate Professor of Civil Engineering
University of New Hampshire
Principal Investigator
Ph: (603) 862-3277
Fax: (603) 862-2364
Email: jo.daniel@unh.edu

Felix Rivera
Former Graduate Research Assistant
Department of Civil Engineering
University of New Hampshire

December 2009

Executive Summary

The Superpave mix design system provides guidance in selecting the appropriate component materials for asphalt concrete mixtures. However, the selection of the design aggregate structure is left to the experience of the mix designer. This necessarily results in a trial and error process for selecting an aggregate gradation to meet specified volumetric parameters. Also, the mix designer has no means to evaluate how the mix will work in the field during placement or how it will perform. It is important to understand the influence of the aggregate structure on the volumetric properties, construction, and performance of the asphalt mixture to achieve the desired properties and performance.

The Bailey Method was originally developed by Robert D. Bailey, an Illinois DOT engineer, as a means to prevent rutting while maintaining durability of mixtures and was based on his experience in the design of asphalt mixtures. Mr. Bailey's methods have been refined by several researchers to provide a systematic approach to blending aggregates to meet the volumetric criteria for any method of mix design, including Superpave, Marshall, and Hveem. The Bailey Method is based on the concepts of aggregate interlock and aggregate packing. In addition, the Bailey Method provides tools for evaluating the effect of aggregate structure on mixture properties, constructability, and performance.

The primary objective of this project was to determine if the Bailey Method can be a useful tool to design mixtures with improved performance using New Hampshire aggregate. The mode of improvement given attention in this project is resistance to rutting under loading by the Third Scale Model Mobile Load Simulator (MMLS3) in hot, dry conditions. A secondary objective was to evaluate the use of the MMLS3 as a tool to evaluate rutting.

Six mix designs commonly used throughout New Hampshire were chosen for evaluation. Half of the designs used gravel stone with rounded, smooth faces, and the other half used fractured rock with rough, angular faces. Two mixtures also contained 15% RAP. NMSA values of 19 mm and 12.5 mm were chosen as representative of most mixtures placed in the state. The MMLS3 laboratory testing resulted in expected trends in relative performance of the various mixtures. Three of the mixtures were then chosen for redesign with the Bailey Method. The Bailey parameters for the original mixtures were calculated and the gradations were redesigned to fall within the recommended ranges. The predictions of VMA changes based on the Bailey parameters were reasonable for the angular aggregate, but not for the smooth aggregate evaluated in this study. The redesigned Bailey mixtures did show an increase in rutting performance.

Overall, this research project showed that the Bailey Method can be a useful tool in the evaluation and design of New Hampshire mixtures. The Bailey Method should not be used exclusively, but can be used in combination with knowledge of the aggregate angularity, roughness, and engineering judgment to provide guidance during the mix design procedure and improve mixture performance. The study also showed that the MMLS3 is an appropriate method for evaluating the relative rutting performance of different mixtures in the laboratory.

Table of Contents

1.0 Introduction

1.1 BACKGROUND

Currently, the New Hampshire Department of Transportation (NHDOT) uses the Superpave Method to design and evaluate the paving mixtures used in the state. While Superpave has a detailed procedure to determine the asphalt content of a mix, there is very little instruction given on how to design the aggregate blend. What Superpave does have is a list of criteria for the aggregate blend in the form of control points (upper and lower limits of percent passing for certain standard sieve sizes), and a restricted zone (a range of values of percent passing to avoid for several fine sieve sizes). In addition to the aggregate blend criteria, Superpave lists requirements for the final asphalt mix, which include the air voids (AV), the voids in the mineral aggregate (VMA), and other volumetric measurements. However, Superpave does not give any direction on how to alter the aggregate gradation of a mix if the criteria are not met. The text only tells the engineer to go through the process of trial and error, as stated below:

> *What could be done at this point if none of the blends were acceptable? Additional combinations of the current aggregates could be tested, or additional materials from different sources could be obtained and included in the trial blend analysis.*
>
> (Superpave, SP-2, 2001, p. 82)

Traditionally, engineers have relied on experience to design the aggregate blend of a mix. However, an additional analytical tool designed for dealing with aggregate blends can be useful, especially when combined with experiential knowledge. The Bailey Method is a tool that offers a simplified explanation of the mechanics of aggregate structure, a procedure for aggregate blend evaluation, and a procedure for aggregate blend design. It was initially developed by Mr. Robert Bailey, now retired, who worked with the Illinois Department of Transportation (Vavrik, et al. 2002). The Bailey Method presents a model of an aggregate matrix based on particle compaction as influenced by particle size distribution. The procedures it describes are simple and straight forward and require no fabrication of samples because it requires only aggregate data and gradings. The evaluation portion of the method makes general predictions about the relative VMA and compactability. However, since the Bailey Method only looks at particle size and includes very little about other aggregate properties that significantly affect the behavior of a blend, such as texture and shape, exact results cannot be expected. Although the Bailey Method doesn't require it, the designer would probably benefit from fabricating samples for verification tests. Still, the Bailey Method along with experience can guide the direction of the mix designs, helping to quickly reach a final design that performs well under actual road conditions.

Among the range of tests that can be done to evaluate a mix design, accelerated pavement testing (APT) is a very useful kind of test that applies scaled traffic loading to directly evaluate the performance of the asphalt mix. One such APT device is the Third Scale Mobile Model Load Simulator (MMLS3) that simulates truck traffic at one third the actual size. It is versatile with the ability to test asphalt bricks or slabs in a laboratory and road pavement in the field. It has several pieces of accompanying equipment that allow it to modify and maintain the testing environment to emphasize a desired pavement failure, such as rutting, stripping, or fatigue cracking. Due to its larger scale, it is closer to simulating actual truck traffic than some other APT devices like the Asphalt Pavement Analyzer and the Hamburg Wheel Tester. However, it can also be used simply as a comparative tool to quickly distinguish between good and bad performing mixtures.

1.2 Problem Statement

The Bailey Method was developed to help engineers design better performing mixtures. However, it has not been as useful as expected in some states, because the predictions it makes regarding VMA do not always coincide with the verification tests. The goal of this project is to determine if the Bailey Method can be a useful tool to design mixtures with improved performance using New Hampshire aggregate. The mode of improvement given attention in this project is resistance to rutting under loading by the MMLS3 in hot, dry conditions.

1.3 Objectives

The main objective of this research project was to evaluate the applicability of the Bailey Method to New Hampshire materials. A secondary objective was to evaluate the use of the MMLS3 as a tool to evaluate rutting. The steps taken to meet the main objectives were as follows:

1. Obtain a number of mix designs currently used by the NHDOT that represent a broad spectrum of mixture types employed in road pavement.
2. Evaluate the New Hampshire mix designs according to Bailey Method procedures.
3. Test the New Hampshire mix designs using the MMLS3 and compare their rutting resistances.
4. Redesign the aggregate blends of three mixtures according to the Bailey Method design procedures. The Bailey design calculations and fabricated samples will use the same aggregates as the corresponding original mix designs.
5. Design the asphalt content according to the Superpave Method.
6. Use Superpave criteria and Bailey Method procedures to evaluate the new mix designs.
7. Test the new mixes using the MMLS3 and compare their rutting resistance to those of the corresponding original mixes.
8. Make recommendations, if possible, regarding the usefulness of the Bailey Method in designing better performing asphalt mixes.

1.4 Literature Review

1.4.1 The Bailey Method

Transportation Research E-Circular, No. E-C044, Bailey Method for Gradation selection in HMA Mixture Design (Vavrik, et al. 2002), is the main document used for this project. This was a joint effort by W.R. Vavrik and Mr. Bailey along with several others. As stated above, the Bailey Method looks at particle packing based on particle size. The goal is to design a blend that uses the aggregate particles efficiently, meaning that there is a balance of coarse particles and fine particles. Such a balance allows the coarse aggregate to interlock, meaning each (relatively) large stone is transferring its load to as many other large stones as possible, and allows the fine aggregate to fully support the coarse aggregate by filling the void spaces fully without over filling them, which would push the coarse particles apart. A balanced blend should be strong against rutting and still be easy to compact (Vavrik, et al. 2002).

The procedures in the Bailey Method make use of four parameters. These include the chosen unit weight (CUW) of the coarse aggregate, the coarse aggregate weight ratio (CA), the coarse part of the fine aggregate weight ratio (FAc), and the fine part of the fine aggregate weight ratio (FAf). The Bailey Method predicts certain changes in the VMA and compactability of a mix based on changes in these parameters. However, in a study in Oklahoma, the predictions made by the Bailey Method about the VMA were very different from the actual changes that took place when test samples were fabricated and measured (Gierhart 2007). The reason for this discrepancy might have been the influence of other aggregate properties. If the aggregate is weak, then it will break into smaller pieces, effectively making a blend finer. If the aggregate is particularly rough, then the VMAs of the test samples may be larger than expected because the particles resisted compaction more than usual. Conversely, if there are a number of rounded or smooth particles, more compaction may happen.

A study in Oregon (Thompson 2006) noted that the Bailey Method only uses certain sieves to calculate the weight ratios from which its predictions are made. However, the other sieves that are ignored may have a stronger influence on changes in the VMAs of the fabricated specimens. The Bailey Method's model of particle compaction starts with aggregate particles approximated as circles, then spheres. Coarse particles are defined as those that carry the bulk of the load and have spaces between them. Fine particles are those that perfectly fill the voids between the coarse ones and the ratio of diameters, large to small, can be calculated (Vavrik, et al. 2002). Since real aggregate is not spherical, an average diameter ratio is used. With some aggregate, such as the Oregon aggregate, the average value does not work very well, at least with the initial separation of coarse and fine particles. This is where further testing and experience guide the results of the Bailey Method so that an acceptable blend is found using a combination of all these tools.

The type of mix designed can also make a difference in the reliability of the Bailey Method. Its general procedure deals with coarse graded blends, but there are additional guidelines that adapt both the evaluation and design for fine, dense graded blends, and for stone matrix asphalt (SMA) blends. One study found the Bailey Method to be very good at predicting VMA results based on the CA ratio in SMA mix designs (Qiu 2006). This study did not look at the FAc or the FAf ratios because fine aggregate generally does not influence an SMA mix significantly. On the other hand, the mixes that were studied in Oklahoma were fine graded as defined by the Bailey Method because they had a CUW well below 90% (Gierhart 2007). Although the fine aggregate played a dominant role in influencing VMA in those mix designs, other factors like the coarse aggregate or ignored sieves could have been affecting the VMA enough to throw off the results. One study ignored the predictions made by the Bailey Method and simply calculated a mathematical model of the influence of the weight ratios on VMA based on measurements from a number of samples (Khosla 2005). This model showed that the FAc and FAf ratios had the greatest influence on VMA, which is the same prediction the Bailey Method makes.

Although the Bailey Method only discusses the changes in VMA and expected problems with compaction, other attributes of the asphalt pavement can be predicted based on changes in the parameters. The Oregon study looked at the correlation of changes in the weight ratios to rutting performance under testing by their APT device (Thompson 2006). This study found that the same weight ratios from the unused sieve sizes that most strongly influenced the voids were also the main influence on rut resistance. This shows that the Bailey Method, or a slightly modified version of it, can be used to predict the performance of an aggregate blend. Data from another study showed a correlation between permeability and the CA ratio (Khosla 2005). This can be related to the VMA and gives some indication about the durability against weathering of the asphalt mix.

1.4.2 MMLS3

The MMLS3 is a very useful tool in assessing the performance of asphalt pavement. However, because it is only a simulation, there are several aspects that differ from true traffic loading. These differences are part of the nature of the test and must be accounted for through transformation coefficients and mathematical modeling. One difference is the fact that the tires are pulled over the surface of the pavement as opposed to driven, which means that the horizontal force will be in the same direction as wheel travel instead of the opposite direction as with actual truck loads (personal communication with Fred Hugo, 2006). Another difference is the fact that the MMLS3 is only one third scale and cannot develop very large stresses in layers deep below the surface, which makes it difficult to predict the behavior of multi layered asphalt pavements (Smit, et al 1999).

There have been various studies done at places like Jacksboro (Smit, et al 1999), WesTrack (Epps, et al 2001), and the National Center for Asphalt Technology (NCAT) test track (Smit, et al 2003). In these studies, the results from loading by the MMLS3 are compared to results from the Texas Model Load Simulator (TxMLS) and to actual truck loading. The goal in these projects was to develop a model to predict the performance of a pavement based on preliminary test results. This would allow engineers to try out various mix designs at a fraction of the cost of actually paving stretches of highway with them.

There are established procedures for using the MMLS3 and in reporting the results. A consistency in results publications can help researchers across the country and across the world compare one pavement to another (Kruger 2004). The studies in which the MMLS3 has been run for 1,000,000 loading cycles or more show that rut development after the first 100,000 cycles is comparatively very slow (Smit, et al 1999). Therefore this project followed most of the conventions for MMLS3 testing including maximum number of cycles run, target test temperature, and frequency of profile measurements (Kruger 2004).

2.0 The Bailey Method

2.1 BASIC THEORY

The Bailey Method was initially developed by Robert Bailey, now retired, who worked with the Illinois Department of Transportation. The goal was to design a tool to help engineers better understand the mechanics of aggregate packing and its contribution to the compressive strength of asphalt pavement. The basic principle of the Bailey Method is that maximum compressive strength of an asphalt mix is best achieved when there is stone to stone contact of as many aggregate particles as possible. This allows a spreading of the load from the vehicle tire to the sub layers beneath the pavement through as many particles as possible, leaving no particle under utilized or unsupported. The proper stone to stone contact is achieved when the aggregate blend has a balance of coarse and fine particles. This means that the coarse particles are all touching with the voids between them neither under nor over filled with fine particles (Vavrik, et al. 2002).

The theory of maximum particle compaction in the Bailey Method starts by looking at a two dimensional space in which all the particles are the same size and perfectly circular. It can be mathematically proven that the configuration for maximum density is achieved when all particles are touching six other particles at 60^{o} intervals, as shown in Figure 2.1. The spaces between these particles can be filled with circular particles with diameters 0.15 times the diameter of the large particles. Figure 2.2 illustrates this.

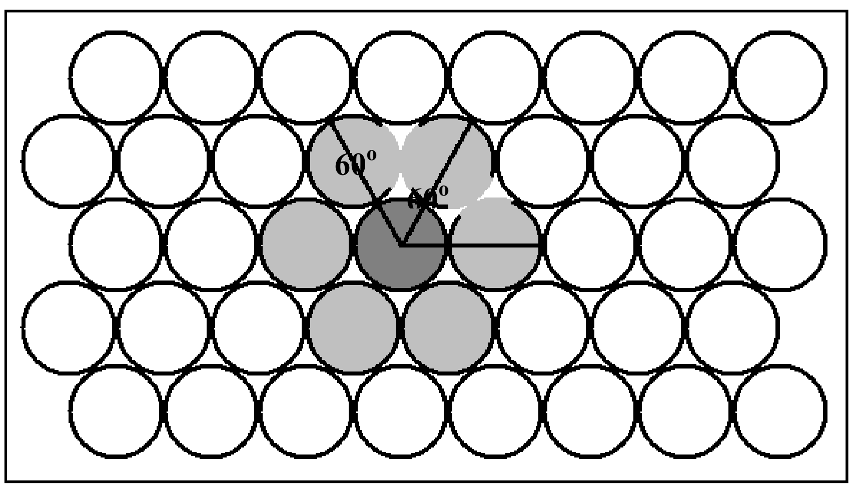


Figure 2.1: Maximum Density Configuration of Uniformly Sized, Circular Particles

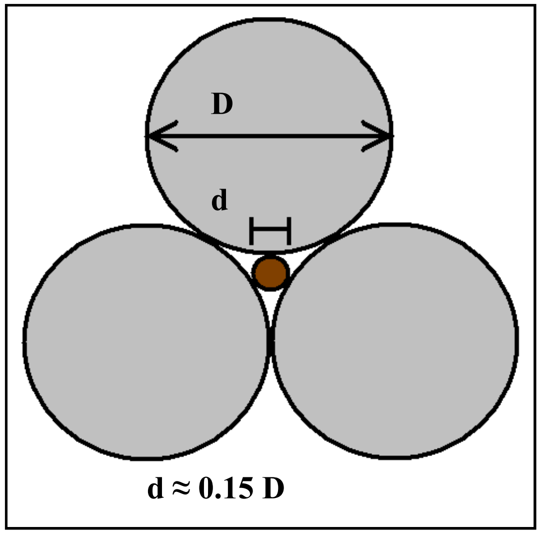


Figure 2.2: A Fine Particle Filling the Gap Between Coarse Particles

The Bailey Method accounts for the irregularity in particle shape by assuming that some of the faces touching the smaller particle are flat. As more of the large particles have flat faces, the gap between them grows, allowing a larger small particle inside it. Figure 2.3 illustrates the increasing size of the small particle with an increasing number of flat faces along with the corresponding ratio of diameters of small to large particles.

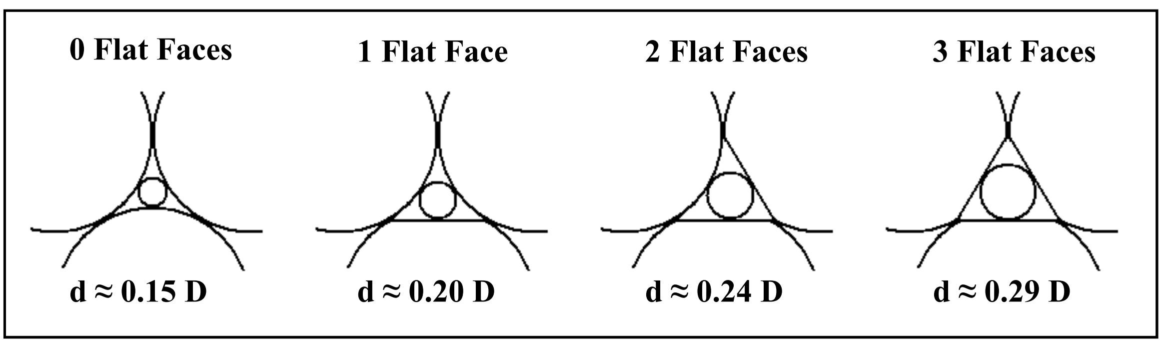


Figure 2.3: Particles Inside Gaps with Varying Number of Flat Faces

Since the gap between any random three large particles contains an unknown number of round and flat faces, the Bailey Method uses an average of the four ratios: 0.22. Although real aggregate is three dimensional, the method assumes that a particle diameter ratio of 0.22 is appropriate for normal aggregate particles, for the purposes of practicality.

The Bailey Method uses this ratio of small to large particles to establish three sieves that separate the aggregate blend into coarse and fine sections. The Nominal Maximum Size Aggregate (NMSA) is the sieve size that is one higher than the first sieve to retain more than 10% of the aggregate blend. The Primary Control Sieve (PCS) is defined as the sieve closest to 0.22 times the NMSA. The Secondary Control Sieve (SCS) is defined as the sieve closest to 0.22 times the PCS, and the Tertiary Control Sieve (TCS) is defined as the sieve closest to 0.22 times the SCS. The Half Sieve is defined as the sieve closest to 0.5 times the NMSA. The Half Sieve is used for calculating aggregate weight ratios, which will be discussed later. Table 2.1

shows the breakdown of control sieves for various NMSA sizes with all values in millimeters. For an NMSA of 12.5 mm, the Bailey Method allows using a calculated value for a fictitious Half Sieve of 6.25 mm instead of the closest normally used sieve, which is the #4 (4.75 mm) sieve. The percent passing the 6.25 mm sieve is calculated by linear interpolation.

Table 2.1: Control Sieves for Various NMSAs

NMSA	25.0		19.0		12.5		9.5	
	Calc.	Chosen	Calc.	Chosen	Calc.	Chosen	Calc.	Chosen
Half	12.5	12.5 (1/2")	9.5	9.5 (3/8")	6.25	6.25	4.75	4.75 (#4)
PCS	5.50	4.75 (#4)	4.18	4.75 (#4)	2.75	2.36 (#8)	2.09	2.36 (#8)
SCS	1.05	1.18 (#16)	1.05	1.18 (#16)	0.52	0.60 (#30)	0.52	0.60 (#30)
TCS	0.26	0.30 (#50)	0.26	0.30 (#50)	0.13	0.15 (#100)	0.13	0.15 (#100)

These control sieves first separate the aggregate into coarse and fine parts, and then separates the fine portions further. Everything larger than the PCS in the blend is considered "coarse", and everything smaller is considered "fine". Within the fine portion, aggregate larger than the SCS is considered the coarse part of the fine aggregate, and smaller aggregate is the fine part of the fine aggregate. The TCS separates the fine part of the fine aggregate similarly. The aggregate smaller than the Half Sieve and larger than the PCS is the fine part of the coarse aggregate. The Bailey Method refers to these particles as "interceptors". Figure 2.4 is a graphical representation of this separation.

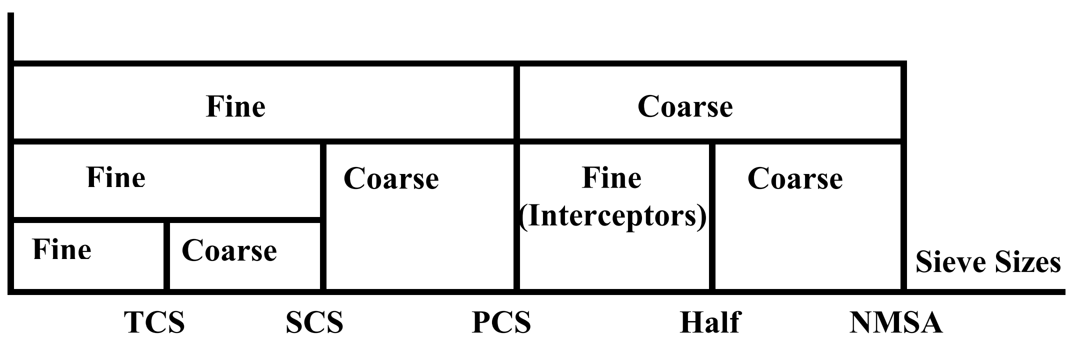


Figure 2.4: Separation of Aggregate Blend into Find and Coarse Parts

To achieve a balanced blend in a practical way, with enough coarse aggregate to form a complete skeleton and enough fine aggregate to fill in the gaps without over filling, it is necessary to know the density of the coarse aggregate. The Chosen Unit Weight (CUW) is a percentage of the measured Loose Unit Weight of the coarse aggregate. It indicates how much void space must be filled by the fine aggregate, which influences the distribution of the amount of aggregate in each section between the control sieves. The Bailey Method uses these weights to calculate three weight ratios that help the engineer better understand and predict how the aggregate blend will behave. These are the Coarse Aggregate (CA) Ratio, the Fine Aggregate - Coarse (FA_c) Ratio, and the Fine Aggregate - Fine (FA_f) Ratio. Table 2.2 shows the four Bailey parameters including the chosen unit weight, the three ratios, their equations, and their recommended limits.

Table 2.2: The Four Bailey Parameters

Parameter	Calculation*	Recomended Limits
CUW	None	95% - 105% (for coarse graded mix)
CA Ratio	=(Half - PCS)/(100 - Half)	0.50 - 0.65 (for NMSA of 12.5mm) 0.60 - 0.75 (for NMSA of 19mm)
FA_c Ratio	=(SCS)/(PCS)	0.35 - 0.50
FA_f Ratio	=(TCS)/(SCS)	0.35 - 0.50

* Each calculation uses the percent passing the control sieves

The CUW can affect the properties of the final asphalt mix by affecting the whole aggregate blend. Since the Loose Unit Weight represents the coarse aggregate under no compactive force, there are lots of spaces for fine aggregate to exist, meaning there will be more aggregate passing the PCS than in a denser configuration. Generally, a higher CUW means greater stone on stone contact for the coarse aggregate because it has been compacted to some degree. This means the blend will be stronger in compression and better at resisting ruts. However, it also means that the asphalt mix will be more difficult to compact. These effects combine to produce, in general, larger voids in the mineral aggregate (VMA). A lower CUW has the opposite effect: greater void space for fine aggregate, greater compactability, less compressive strength, and generally lower VMA. However, the final VMA of a mix will be determined by a combination of all the parameters. The influence of each can be numerically added together for a total predicted influence on VMA. Table 2.3 summarizes the influence of each of the parameters.

Table 2.3: Predicted Effect of Bailey Parameters on VMA

Parameter	Change in parameter	Predicted effect on VMA
CUW	+ 0.5%	+ 0.5% to + 1.0%
CA	+ 0.2	+ 0.5% to + 1.0%
FAc	+ 0.05	− 0.5% to − 1.0%
FAf	+ 0.05	− 0.5% to − 1.0%

In the Bailey Method the coarse aggregate has a strong influence over the strength and workability of the final blend; therefore, it is important to understand the role of the interceptors. A configuration of coarse particles with maximum stone on stone contact would look like a three dimensional version of Figure 2.1. However the actual aggregate particles are neither perfectly spherical nor uniform in size, which leaves irregularly sized gaps throughout. Additionally, there are often not enough particles in the coarse portion of the coarse aggregate to make up a complete skeleton for the whole volume of the pavement. The interceptors can fill in the larger gaps and fill out the rest of the coarse aggregate skeleton. The CA Ratio compares these interceptors, the fine part of the coarse aggregate, to the coarse part of the coarse aggregate to indicate the behavior of the final asphalt mix. Generally, as the CA Ratio increases, the VMA also increases. However, problems can occur if the CA Ratio is too high or too low.

If there are not enough interceptors, the CA Ratio drops below the prescribed limits and the Bailey Method predicts that the compacted asphalt mix may segregate. The Method does not give any mathematical support for this prediction, so it is assumed that it is made on empirical evidence. A pavement that has segregated has patches that are predominantly fine or coarse aggregate (Roberts, et al. 1996). Sections of mainly fine aggregate will have a higher tendency to rut, while the sections of coarse aggregate may be too porous or start to ravel and wear away. The interceptors are needed to fill in any large gaps to complete the coarse aggregate framework, keeping the density generally uniform throughout the pavement so there are no segregated sections.

Another problem may arise when there are too many interceptors. If the CA Ratio is above the limits, then the interceptors push apart the large stones. The large particles from the coarse part of the coarse aggregate still contribute to the strength of the pavement, but their effectiveness is reduced because they are not touching each other. While the interceptors are still coarse aggregate, they are generally only half the size of the very coarse particles. The extreme case is where the interceptors become the new "coarse aggregate" with voids that are too small for the particles passing the PCS. In this scenario, the fine aggregate pushes apart the interceptor frame, thus reducing the strength and promoting rutting. The very coarse particles are not very useful because they have relatively little support.

The FAc Ratio compares the fine part of the fine aggregate to the coarse part of the fine aggregate, and the FAf Ratio in turn compares the coarse and fine portions of the fine part of the fine aggregate. As the fine aggregate fills in the gaps of the larger aggregate, it adds to the strength of the mix by providing support to the coarse aggregate and it brings down the Air Void (AV) ratio to an acceptable level. In addition, the finer portions of the fine aggregate act as a dry lubricant to the larger particles allowing easier compaction. These combined effects mean that as the FAc and FAf Ratios increase, the VMA of the final mix tends to decrease. The problems that can occur when either of these ratios is too high or too low are similar.

If either the FAc or the FAf ratio is allowed to get too high, above 0.5, then the fine particles push their way between the larger ones, overfilling the gaps in the coarse aggregate. The result is a mix that can be too tender and easily deformable as the large particles slide around on their coating of tiny particles. Additionally, the AV and VMA may decrease to below their own limits. When the FAc or FAf ratios drop too low, then the small gaps are under filled. This causes the VMA to rise, but also deprives the mix of the lubricating effect of the fine particles, which may make it difficult to compact the mix to the proper level. Improperly compacted pavement can have too many voids for water and air to invade, which can cause the asphalt binder to be stripped from the aggregate or allow excessive frost heaves in the winter.

2.2 Designing Aggregate Blends with the Bailey Method

The calculations given in the Bailey Method determine the volume of the voids in the coarse aggregate and put in just enough fine aggregate to fill those voids. Then the contributions of the coarse and fine aggregate are adjusted to account for any fine or coarse parts in each respective aggregate. Finally mineral filler is added as needed and final adjustments are made. Several pieces of information about the aggregate stockpiles are required: the Bulk Specific Gravity (Gsb), the Loose Unit Weight, the Rodded Unit Weight, and the grading. For any mineral filler in the mix, such as Bag House Fines, only the grading is required. The full calculations can be found in the Appendix A.

There are several input values that the engineer must chose and include in the calculations. These include the CUW, the contributions of each stockpile, and the desired dust content. For a coarse graded mix, the designer should select a CUW between 95% and 105%. This produces a blend in which the coarse aggregate dominates, yet is still loose enough for reasonable workability. A CUW less than 90% leads to a mix where the coarse aggregate is separated, leaving the fine aggregate to dominate. Altered limits are given for the weight ratios if the designer wants a fine graded mix in this way. According to the Bailey Method, a CUW between 95% and 90% produces a mix where coarse aggregate is not dense enough to adequately dominate, yet doesn't provide enough space for the fine aggregate to adequately dominate. A CUW greater than 110% leads to a very dense configuration of coarse aggregate most commonly associated with a Stone Matrix Asphalt (SMA). Just as with a fine graded mix, alternate limits on the weight ratios are given for designers who want an SMA mix.

Next, the designer chooses the initial contributions of the coarse and fine aggregate stockpiles. Since the amount of fine aggregate needed is not known until the approximate volume of the voids in the coarse aggregate is known, the initial contributions of all the stockpiles are not given as percentages of the whole blend. The contributions of the coarse stockpiles are inputted as percentages of the whole coarse aggregate and the fine stockpiles are inputted as percentages of the whole fine aggregate. Therefore all the coarse contributions add up to 100%, as do all of the fine aggregate contributions. The designer can expect the final blend contributions to closely match the input values.

The final choice for the designer is the amount of dust material that is desired, as defined by particles smaller than 0.075 mm. This is limited to 3.5% to 6% for the entire blend. If the amount of dust provided by the coarse and fine aggregate stockpiles does not satisfy the requirement, then a mineral filler stockpile is added. The final contributions of the fine aggregate are adjusted to account for the added mineral filler. Filler is too fine to affect the final calculations for the coarse aggregate.

Once the calculations have been run, the engineer is left with a final aggregate blend that can be tested against the control points as prescribed by Superpave. The Bailey aggregate ratios can also be directly calculated and compared to the recommended limits. These calculations do not require the fabrication of any samples and can be iterated by a computer as many times as needed to find an acceptable blend. Additionally, when redesigning a blend, the Bailey weight ratios and CUWs of the old and new blends can be compared to have an idea of the expected change in VMA and behavior of the new mix design, as long as the old and new blends are both "coarse" or "fine" as defined by the Bailey parameters.

To evaluate an existing mix design using the Bailey Method, the engineer must first ascertain the aggregate stockpile data including grading, bulk specific gravity, and loose and rodded unit weights. The calculations described above are performed with these data. The engineer varies the input parameters until the calculated aggregate blend matches the original mix design. The purpose is to find the chosen unit weight for this mix. If the chosen unit weight falls between 95% and 105%, then the mix is considered a coarse graded mix. If the chosen unit weight is found to be less than 95% then the mix is considered fine graded, and if it is more than 105% then it is considered an SMA mix.

The next part of the evaluation is to look at the three weight ratios, CA, FAc, and FAf, for the original mix design. The weight ratios are calculated directly from the original mix grading, not the calculated mix grading, and are compared to recommended limits. If the mix is coarse graded, then the calculations and limits stated in Table 2.2 can be used. If the CUW is low enough to put the mix in the fine graded range, there are different calculations for the Bailey weight ratios. Basically, the grading above the coarse graded PCS, which is 0.22 times the NMSA, is ignored and the coarse PCS is considered the new NMSA. The control sieves are recalculated based on this fine NMSA and the weight ratios are calculated from the fine control sieves. The limits on the FAc and FAf ratios are the same; however, the limit for the CA ratio is changed to 0.6 to 1.0 regardless of the original NMSA.

2.3 LIMITATIONS OF THE BAILEY METHOD

The Bailey Method is mainly suited to design well graded asphalt mixes based on particle size distribution. It includes modifications to the ratio limits to accommodate fine graded mixes and SMA mix designs as well. However, the Bailey Method has a couple of limitations. These include accounting for aggregate properties other than size and how to include Recycled Asphalt Pavement (RAP). The Bailey Method also does not provide a method for comparing coarse graded mixtures with fine graded mixtures for the purposes of predicting VMA changes.

The Bailey Method mentions several different aggregate properties that affect performance including size, angularity, texture, and material strength. The calculations and procedures mainly use particle size to design the mix. There are various points where it cautions the engineer not to forget the other properties because they can affect the VMA despite the predictions of the Bailey Method. However, there are no calculations or procedures that describe how to account for these properties. The only time aggregate properties other than size play a practical role in the Bailey Method is by using the loose and rodded unit weights. This is because the configuration of the aggregate particles by rodding or pouring is easily affected by shape and texture. Engineers that use the Bailey Method should compare the results of the calculations to their own experience and make a proper judgement call.

Finally, the Bailey Method does not give very detailed provisions for working with RAP. The main reason RAP cannot be included as simply another aggregate stockpile is because there is often no bulk specific gravity or loose or rodded unit weight data for it. Although bulk specific gravity could be measured, it often isn't and might vary widely throughout the stockpile. Taking measurements on the rodded unit weight might be difficult since there is binder present in the aggregate. Additionally, the RAP may or may not fully blend with the virgin aggregate and binder making the grading approximate at best. Because of this, the Bailey Method states that the engineer should use only virgin aggregates in the calculations. The method directs the designer to add in the RAP at the end, using the RAP grading measured after binder extraction. The engineer should then adjust the virgin contributions so that the total combined grading has the same, or as close to the same, percent passing the PCS as calculated with the virgin aggregate alone. However, there is no mention as to how the virgin contributions should be changed and the preservation of the fine weight ratios is ignored. Additionally, when evaluating an existing mix designed with RAP, the calculations should be done on the virgin aggregate only and then adjusted to account for the RAP. Again, the method of adjustment is left to the engineer.

3.0 Materials and Methods

3.1 MATERIALS

For this project, six mix designs commonly used throughout New Hampshire were chosen for evaluation. Half of these designs used gravel stone and half used fractured rock. The gravel stone has rounded, smooth faces with few flat and elongated particles even when crushed. The fractured rock aggregate is angular and often rough with more flat and elongated particles. One gravel stone and one fractured rock mixture also contained 7/16" processed RAP. Two NMSA levels were chosen as representative of most mixtures placed in the state. Table 3.1 summarizes the six original mix designs. Tables 3.2-3.5 summarize the aggregate information from each location.

Aggregates were sampled from each of the locations in accordance with AASHTO T-291 and stored in 50 gallon drums. The binder was taken directly from the holding tanks connected to the plant mixers and stored indoors in lidded steel buckets.

Field cores containing the Ossipee mixtures were obtained from Route 25, between Effingham and Freedom. The Oss 12.5 mixture was used for the surface layer and the Oss 19 mixture was used for the base course. Nine 150 mm diameter cores were taken by the NHDOT and delivered to UNH for testing. The layers were separated in the lab for individual testing.

Table 3.1: Summary of Original Mix Designs

Mix Name	Aggregate	NMSA	Binder	AC	RAP	Company, Location
Oss 12.5	Gravel Stone	12.5 mm	PG 64-28	5.6	0	Pike, Ossipee
Oss 19	Gravel Stone	19 mm	PG 64-28	5.0	0	Pike, Ossipee
Cont 12.5	Fractured Rock	12.5 mm	PG 64-28	5.5	0	Continental, Londonderry
Cont 19	Fractured Rock	19 mm	PG 64-28	5.0	0	Continental, Londonderry
Farm	Gravel Stone	12.5 mm	PG 64-28	5.5	15%	Pike, Farmington
Hook	Fractured Rock	12.5 mm	PG 64-28	5.6	15%	Pike, Hooksett

Table 3.2: Ossipee Aggregates

Sieve Size	**3/4"**	**1/2"**	**3/8"**	**Grits**	**Dust**	**Scr. Sand**	**BHF**
25.0	100	100	100	100	100	100	100
19.0	97	100	100	100	100	100	100
12.5	24	95	100	100	100	100	100
9.5	7	48	99	100	100	100	100
4.75	3	5	27	96	100	97	100
2.36	2	3	9	83	85	91	100
1.18	2	2	6	61	67	75	100
0.600	2	2	3	33	51	45	100
0.300	1	1	2	14	36	17	99
0.150	1	1	1	7	23	6	95
0.075	1	0.9	1	3.1	13	2.2	80
Gsb	2.629	2.619	2.588	2.556	2.607	2.543	2.607
Gsa	2.694	2.686	2.666	2.618	2.651	2.62	2.651
% Abs	0.92	0.95	1.13	0.93	0.64	1.15	
LUW		1501.6	1510.6	1573.6	1502.6	1541.5	
RUW		1625.8	1616.5	1713.6	1772.6	1691.3	
Source	OssAgg	OssAgg	OssAgg	OssAgg	#618	Madison	Baghouse
% agg for 19 mm mix	24.0	11.0	30.0	14.00	14.00	5.98	1.02
% agg for 12.5 mm	0	19.0	34.9	16.14	19.36	9.60	1.00

Table 3.3: Continental Aggregates

Sieve Size	**3/4"**	**1/2"**	**3/8"**	**WMS**	**DSS**	**BHF**
25.0	100.0	100.0	100.0	100.0	100.0	100.0
19.0	95.4	100.0	100.0	100.0	100.0	100.0
12.5	33.6	98.0	100.0	100.0	100.0	100.0
9.5	9.6	42.7	96.7	100.0	100.0	100.0
4.75	1.1	1.4	34.0	98.0	97.9	100.0
2.36	0.8	0.9	7.0	68.1	93.2	100.0
1.18	0.8	0.8	2.8	38.0	80.3	100.0
0.600	0.8	0.7	1.4	20.9	55.7	100.0
0.300	0.7	0.7	1.1	11.0	24.5	99.8
0.150	0.7	0.6	0.8	6.6	7.6	96.7
0.075	0.6	0.5	0.7	4.9	2.3	87.1
Gsb	2.691	2.722	2.707	2.71	2.687	2.763
Gsa	2.749	2.768	2.756	2.825	2.707	2.763
% Abs	0.8	0.5	0.7	1.2	0.8	
LUW	1492.5	1518.9	1556.7	1567.4	1548.2	
RUW	1636.3	1638.5	1667.1	1740.4	1696.4	
Source	West Road	West Road	West Road	West Road	BOW	Baghouse
% agg for 19 mm mix	16.0	20.0	22.0	22.0	18.0	2.0
% agg for 12.5 mm	0	20.0	28.0	16.0	33.0	3.0

Table 3.4: Farmington Aggregates

	1/2"	3/8"	Wa. Sand	Dust	Scr. Sand	BHF	RAP
Sieve Size							
25.0	100	100	100	100	100	100	100
19.0	100	100	100	100	100	100	100
12.5	96	100	100	100	100	100	100
9.5	43	99	100	100	100	100	100
4.75	4	32	100	100	94	100	81
2.36	3	5	91	85	86	100	63
1.18	2	3	72	67	71	100	50
0.600	2	3	49	51	50	100	35
0.300	2	2	21	36	29	99	23
0.150	2	2	5.0	23.0	12.0	95.0	14
0.075	0.7	0.9	2.0	12.0	5.1	80.0	9.3
Gsb	2.645	2.616	2.565	2.598	2.566	2.607	2.607
Gsa	2.617	2.703	2.625	2.680	2.642	2.651	2.651
% Abs	0.98	1.24	0.89	1.17	1.11		
LUW	1580.4	1615.8	1544.4	1609.9	1604.5		
RUW	1689.0	1691.3	1686.9	1809.0	1797.7		
Source	#618	#618	#618	#618	#618	Baghouse	Farmington
% agg	18.2	31.2	18.82	9.05	7.35	0.98	14.4

Table 3.5: Hooksett Aggregates

	1/2"	3/8"	WMS	Dust	Wa. Sand	BHF	RAP
Sieve Size							
25.0	100	100	100	100	100	100	100
19.0	100	100	100	100	100	100	100
12.5	100	100	100	100	100	100	100
9.5	97	100	100	100	100	100	100
4.75	55	100	100	100	100	100	100
2.36	5	36	100	99	99	100	80
1.18	4	8	77	76	86	100	62
0.600	3	6	47	53	67	100	49
0.300	3	5	29	40	46	99	35
0.150	2	4	16	30	24	99	23
0.075	2	3	8	20.6	7.5	95	13
Source	#607	#607	#607	#607	Michie	#803	Marcou
% agg	25	23	13.14	1.88	21.4	1.13	14.5

3.2 THIRD SCALE MODEL MOBILE LOAD SIMULATOR (MMLS3)

The MMLS3 is an accelerated pavement testing (APT) device designed to test pavement materials in the laboratory and in the field. In this project, the MMLS was used to compare the rutting performance of mixtures in the laboratory. Figure 3.1 shows a picture of the MMLS3 on its test bed in the laboratory at UNH.

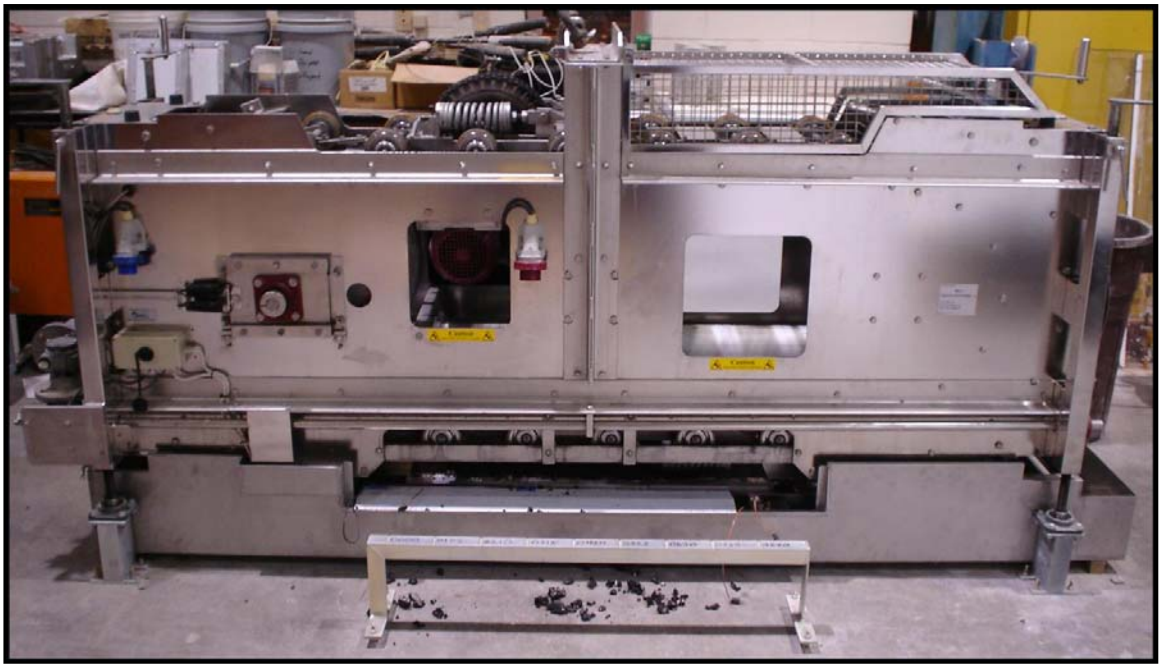


Figure 3.1: The MMLS3

The basic structure of the MMLS3 is shown in Figure 3.2. Four inflated tires are part of a looped wheel train that is made up of eight bogies. The train is driven by a motor at one end that turns a large drive drum. Small guide wheels on each bogie are pinched between the drive drum and a guiding arc. As the drive drum turns, it forces the guide wheels to roll, thus moving the whole train along.

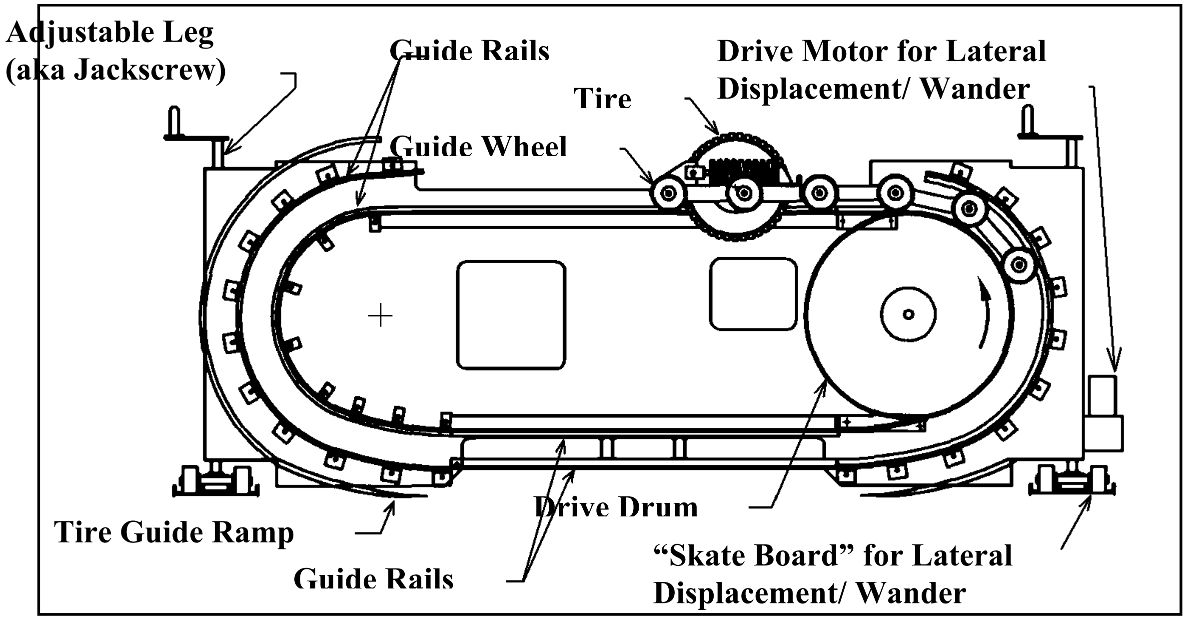


Figure 3.2: Basic Structure of MMLS3 (MMLS3 Operators Manual, p. 5)

A picture of a bogie with a tire and a schematic drawing are shown in Figures 3.3 and 3.4 respectively. The tire is approximately 290 mm in diameter and approximately 80 mm wide. The tires are inflated to 700 kPa.

Figure 3.3: Close Up of Bogie with Tire

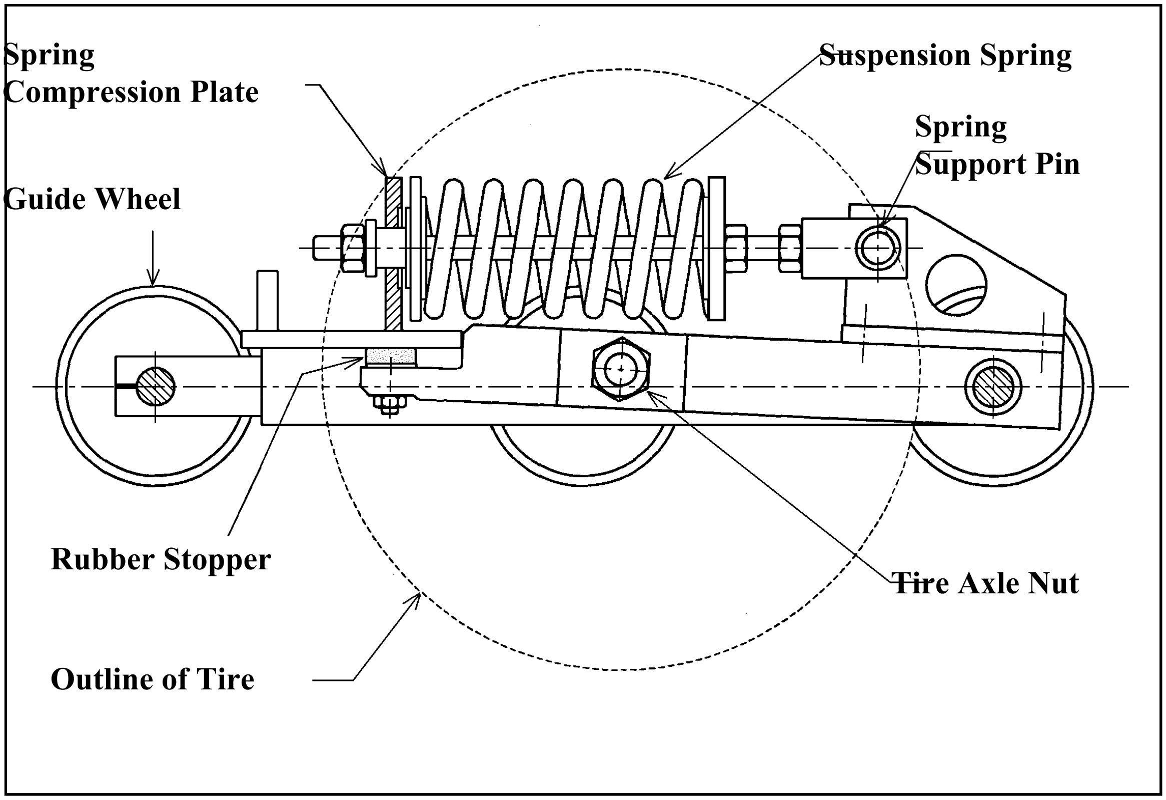


Figure 3.4: Schematic of Bogie with Tire and Suspension (MMLS3 Operators Manual, p. 10)

The guide track along the bottom of the machine keeps the tires running over the same locations at the same height throughout the test. As the test specimens rut, the surface will slowly move away from the tires over the course of the test. The suspension system for the tires was designed to minimize the change in vertical force as the asphalt surface changes. This is achieved by converting large deflections in the tire to small deflections in the horizontal spring. The deflection is reduced by using a large lever arm to hold the tire axle and a small lever arm to connect to the spring, as illustrated in Figure 3.4. The force that the tires apply is adjusted to 2.7 kN by lengthening or shortening the springs and using a detachable load cell to monitor the force, shown in Figure 3.5. Note the deflection of the tire as indicated by the 10 mm gap between the rubber stopper and the metal frame of the bogie.

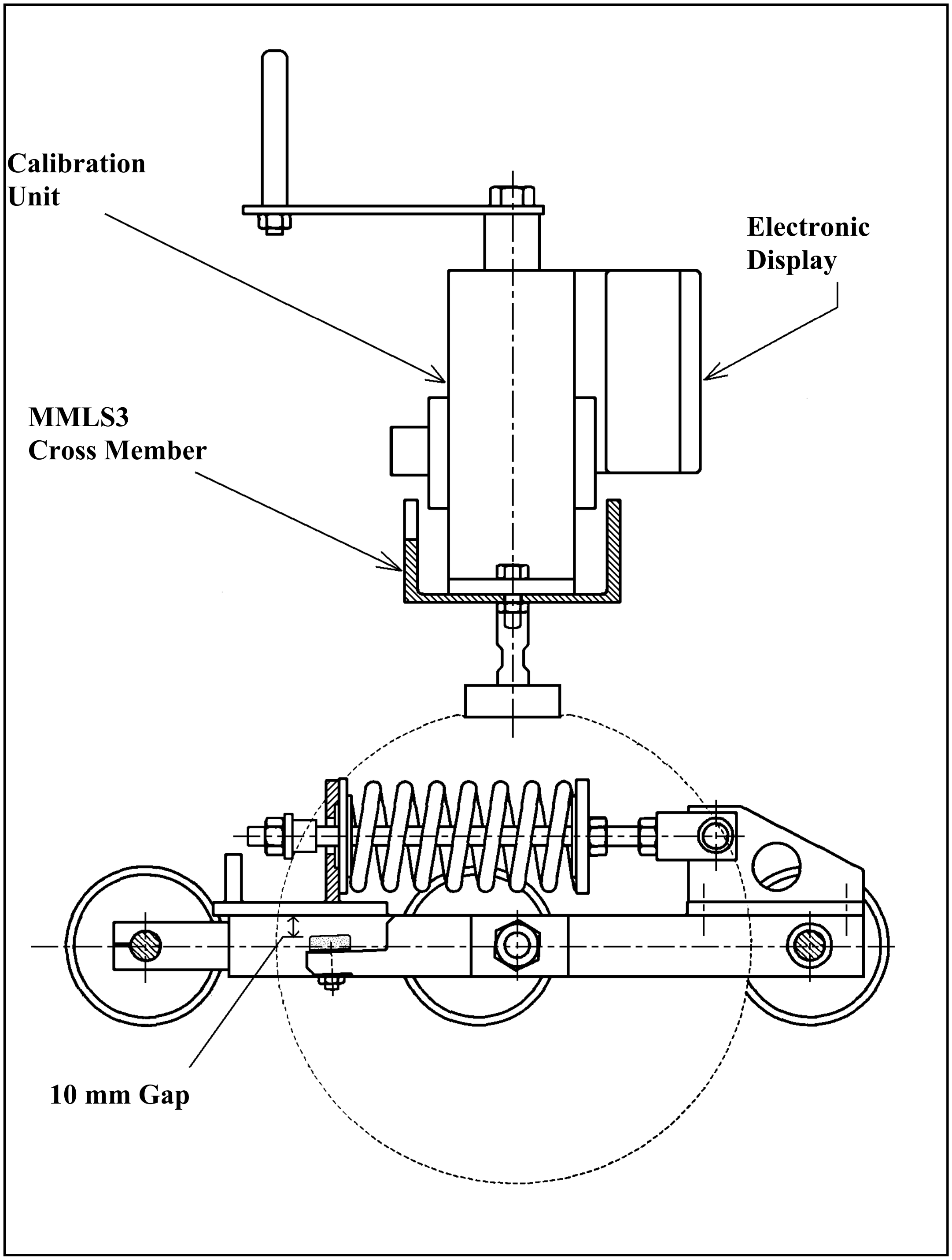


Figure 3.5: Load Calibration Unit (MMLS3 Operators Manual, p. 11)

The MMLS3 control unit supplies power to the machine and records its usage by means of a counter that shows how many tens of wheel loads have been run since it first began. A dial can adjust the speed of the machine from full stop up to two wheel loads per second. Figure 3.6 shows the control unit for the MMLS3.

Figure 3.6: Control Unit for the MMLS3

A dry air heating/ cooling unit was used to control the temperature of the tests in this project. This unit blows air over the surface of the asphalt through two large vents that sit on each side of the environmental chamber. One vent is at positive pressure and one is at negative so that the hot, or cold, air is recycled, reducing strain on the heating/ cooling unit. The chamber walls are made of thin sheets of metal with approximately 40 mm of insulating foam between them. The dry air heater/ cooler is shown in Figure 3.7 and Figure 3.8 shows the environmental chamber erected around the MMLS3.

.

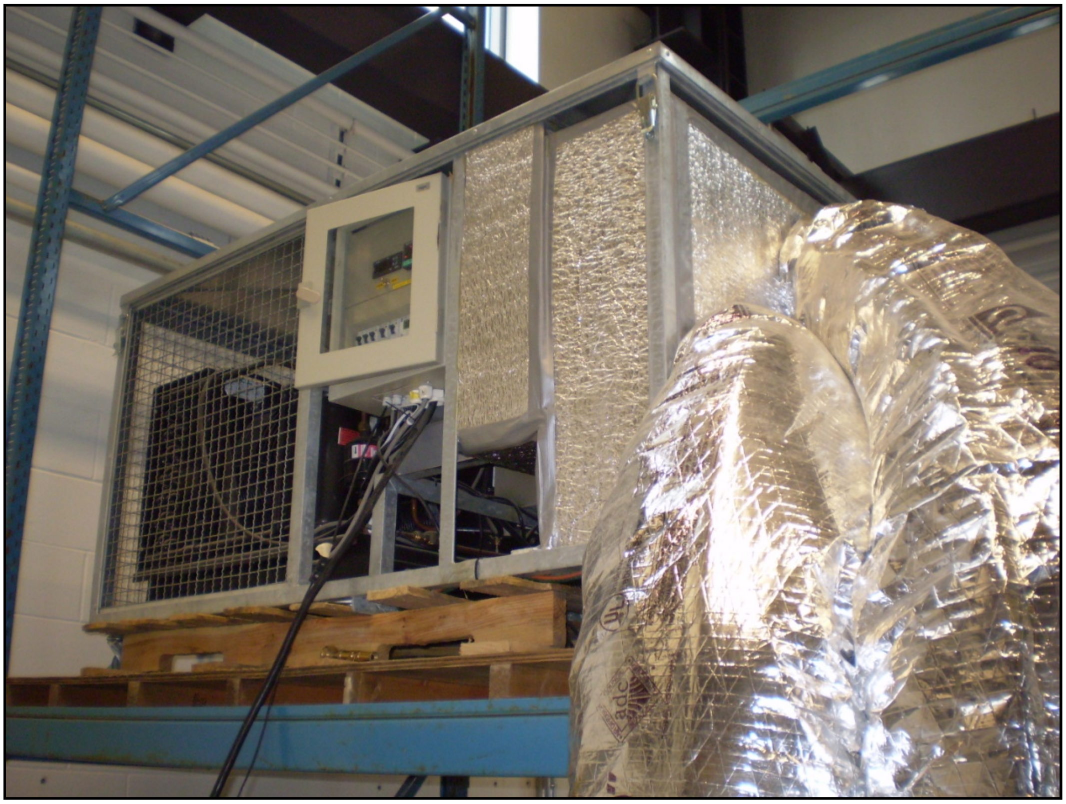


Figure 3.7: Dry Air Heating/ Cooling Unit

Figure 3.8: The Environmental Chamber

The MMLS3 test bed can hold nine bricks, each approximately 150 mm long, round face to round face, and 105 mm wide, cut face to cut face. Figure 3.9 shows a fabricated brick ready for testing. The test bed is 100 mm deep, so aluminum plates are used to raise the bricks to the top. On the bottom are the rectangular plates, 100 mm by 310 mm, that take up most of the height. On top of these are plates the same shape as the brick, but of varying thicknesses. These can be mixed and matched to bring the surfaces of all the bricks to the same level. The top plate is also the same shape as the sample brick and is 10 mm thick with a textured surface to keep the brick from slipping during the test. Figure 3.10 shows the test bed with the various plates and the asphalt bricks.

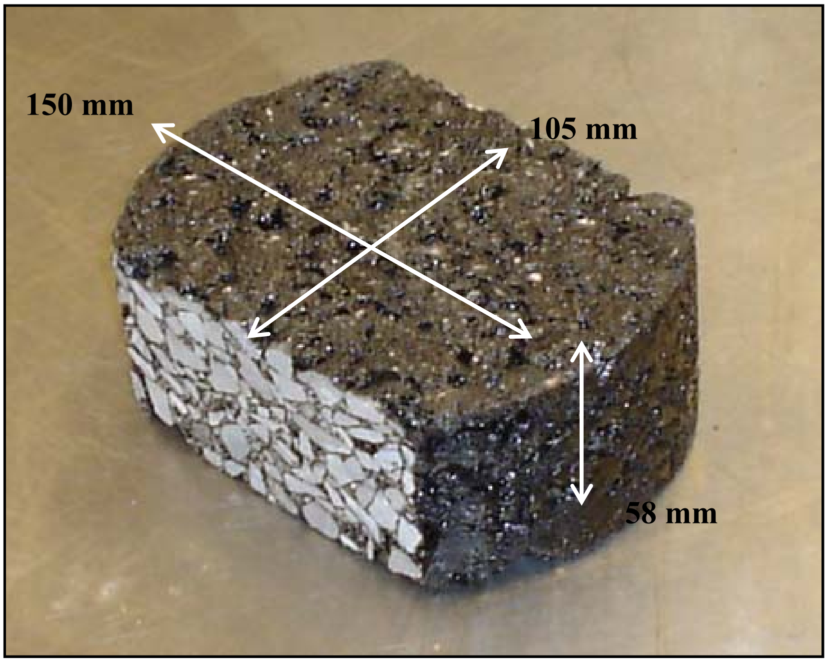


Figure 3.9: Sample Brick

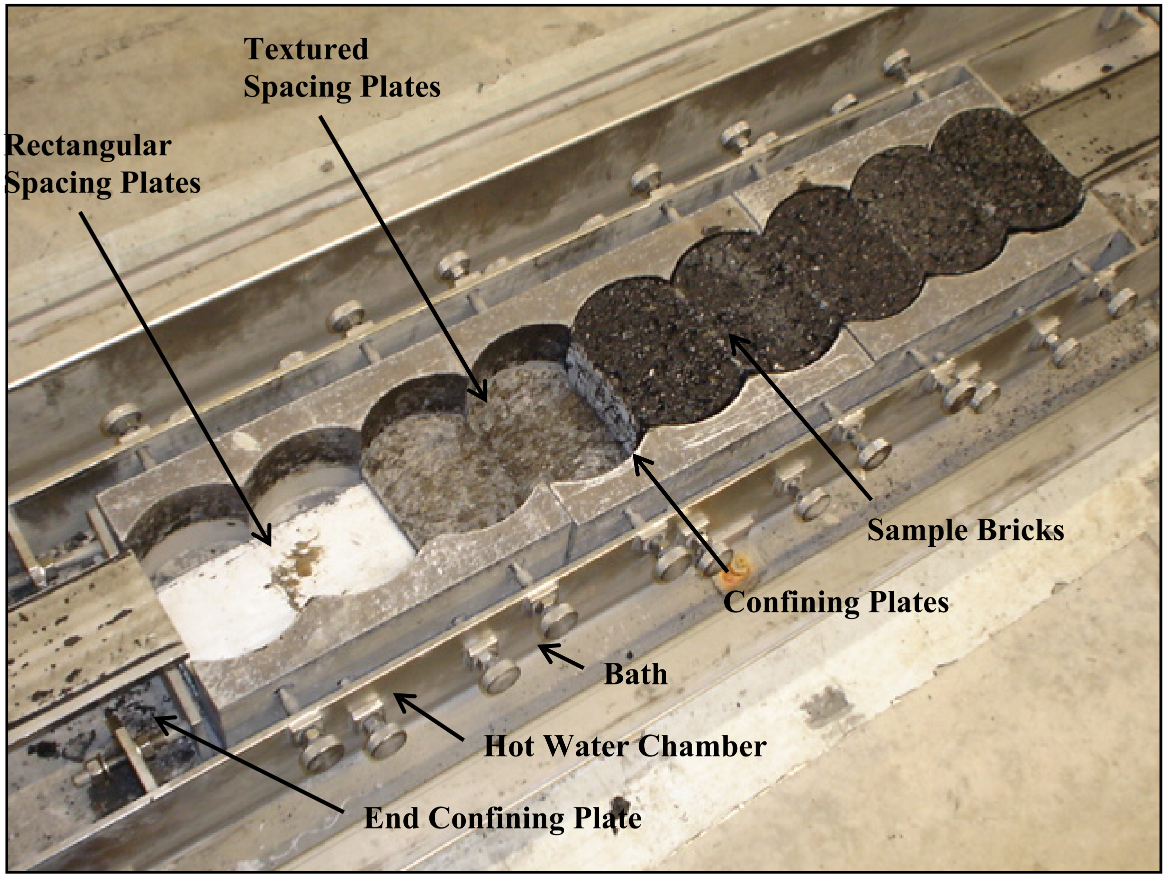


Figure 3.10: The Test Bed

The profile of the specimen surface is measured with a tool called a profilometer. It is approximately one meter long and can measure ruts down to 40 mm from its set height with a sensitivity of 0.001 mm. The profilometer rests on two support rails that are permanently set in place during the course of a test. These support rails have grooves and dimples in them to ensure that the profiles are taken in the same places every time during testing. The height from which each profile is measured is kept constant by screws with locking wing nuts on the ends of the profilometer. The profilometer is connected, through its power supply unit, to a computer. A simple program on the computer allows the user to designate the file the data goes into and the measurement size and increments. The profilometer drags a small metal wheel on a lever arm over the asphalt surface to measure the profile. Changes in the angle of the lever arm are converted to vertical displacement of the wheel. Figure 3.11 shows a diagram of the profilometer in place over rutted pavement. Figure 3.12 shows a close-up of the small wheel as a profile is being measured.

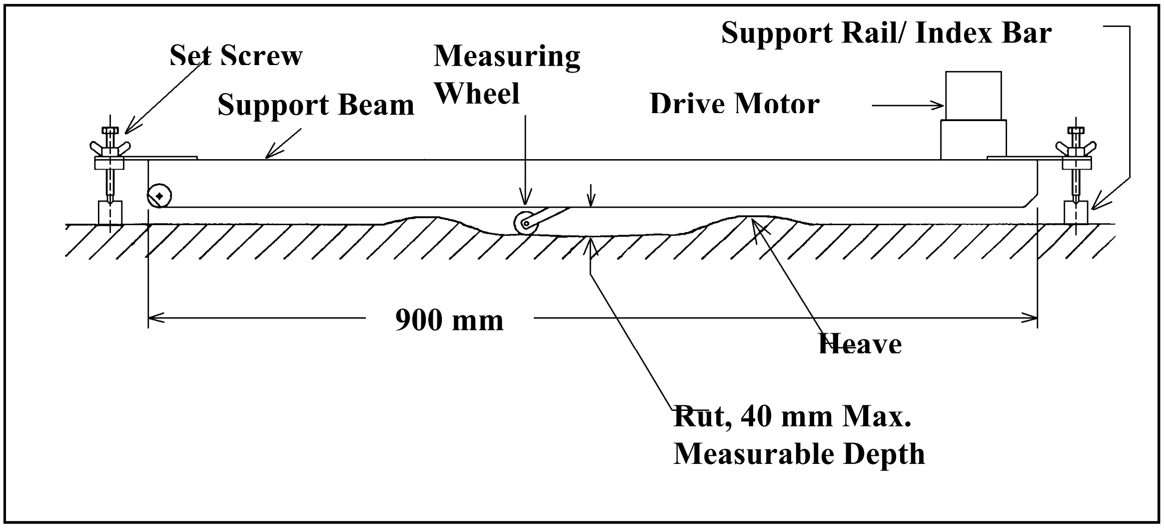


Figure 3.11: The Profilometer (P900 Profilometer Operators Manual, p. 20)

Figure 3.12: A Profile Being Measured

3.3 Methods

3.3.1 Mix Design and Specimen Fabrication

Mixture designs in this project were done using the Superpave mix design system. A superpave gyratory compactor (SGC) manufactured by IPC was used for compaction. RAP was heated for two hours at the mixing temperature prior to combination with virgin asphalt and aggregate at mixing temperature. Short term oven aging of loose mixture was done for two hours at the compaction temperature. Bulk specific gravity of the compacted specimens was measured using the SSD method (AASHTO T-166-05). The maximum theoretical specific gravity for each mixture was measured using a CoreLok vacuum sealing device and protocol.

3.3.2 MMLS3 Testing

The asphalt sample bricks for the MMLS3 were compacted to cylinders 150 mm in diameter. Once the cylinders were ready, the sides were cut off using one of the spacing plates as a guide. The final result is shown in the Figure 3.13.

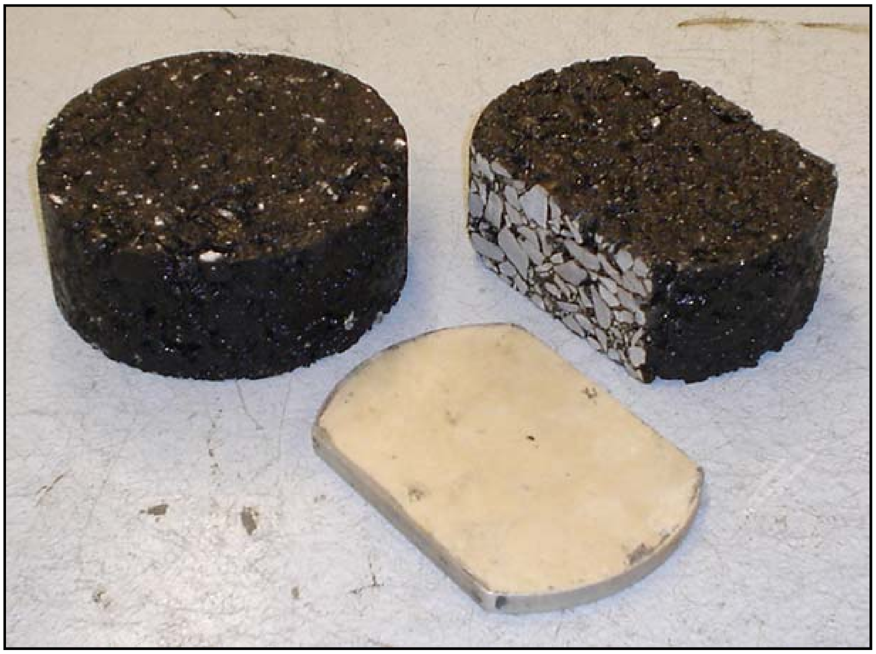


Figure 3.13: A Compacted Sample, a Brick, and the Cutting Template

In preparation for the tests, the MMLS3 was checked and calibrated. The belts were checked and bearings greased periodically. For load calibration, the tires were inflated fully to 700 kPa and locked in place under the calibration unit. The piston connected to the load cell was cranked down to push on the tire, deflecting it enough to make a 10 mm gap between its rubber stopper and metal frame as shown in Figure 3.5. If the force applied at this level of deflection was not 2.7 kN, the tire was released and the suspension springs were compressed more or less as needed to adjust the load. This load calibration was only done a couple of times a year, typically after replacing a tire, since the springs held their stiffness and moved little. After calibrating the load on all the wheel bogies, the MMLS3 was leveled to a proper height above the samples to ensure that 2.7 kN of force was applied evenly to all samples. This was done by lowering or raising the machine on its four adjustable legs until the measured gap between the rubber and steel was roughly 10 mm when the tire was at the ends and middle of the test bed. Stop nuts were placed on the bottoms of the legs to indicate the proper height of the MMLS3 each time it was lowered. Before each test, the tires were inflated to less than 700 kPa. The amount of inflation depended on the air temperature before the test and the target temperature during the test. The formula for tire inflation from the MMLS3 manual is shown in Equation 3.1.

$$P = 700\left(\frac{273 + T_a}{273 + T_t}\right) \tag{3.1}$$

Where:

P is tire pressure in kPa

T_a is the air temperature before the test in Celsius

T_t is the testing temperature in Celsius.

Seven specimens were tested in each run. Dummy specimens were placed in the two end spaces because of uneven loading that occurs where the wheel comes down and lifts off the test bed. The top surfaces of the bricks were brought to a relatively even level with the tops of the confining plates on either side of the samples to within 3 mm over the length of the test bed.

The asphalt temperature was monitored with thermocouples connected to Hobo Type J data loggers that were imbedded in the dummy bricks and placed between the test bricks. Figure 3.14 shows an illustration of the samples in the test bed with the locations of the thermocouples. The dry heating unit had its own thermocouple to monitor and adjust the heating that was placed near the middle of the test bed. For the tests on the original six mixes, the heater's thermocouple and an additional thermocouple connected to a data logger were left in the air next to the sample bricks. The temperature for MMLS3 tests should not vary by more than 2^{o}C above or below the target temperature (Kruger 2004). Therefore, during the tests for the redesigned mixes, the heater's thermocouple was put between the bricks in the middle of the test bed to reduce temperature variation over the course of the test. While this did reduce some of the temperature variation, it did not reduce it to the suggested level.

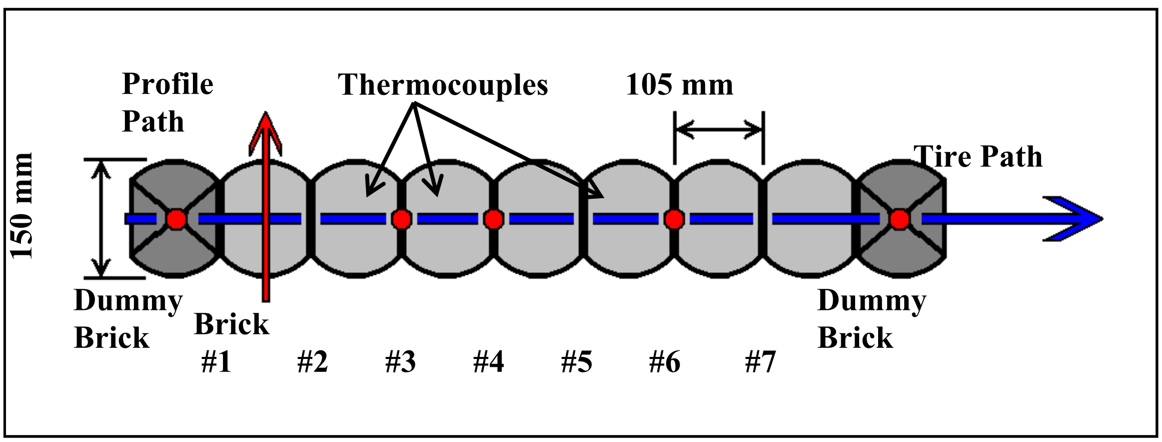


Figure 3.14: Test Bed Configuration

Once the samples were put into the test bed with the thermocouples installed, the confining screws were tightened. The confining screws on the sides were hand tightened only and set in place with locking nuts. The confining plate on the end was tightened by wrench and set in place with locking nuts. At this point, the samples were ready for initial profile measurements to be taken.

The profiles were measured close to the middle of each sample, parallel to the brick's long axis, which was perpendicular to the path of the loading wheels as shown in Figure 3.14. The profiles were measured over 200 mm at 5 mm increments. This took in the entire 150 mm length of each brick with 25 mm extra on each side to account for any heave and/ or over flow that might occur. The first profile was measured before any wheels were driven over the samples.

For all mixtures except the Oss 19, a seating load was applied to the bricks after the initial profile and before starting the first 1000 wheel loads. The loading tires were slowly driven over the bricks between 10 and 20 times to fully seat them in place. While the samples may or may not have been heated at this point, no noticeable deformation occurred during this seating load but the bricks were pushed down and leveled out by a few millimeters. Profiles of the samples in their fully seated condition were used to normalize the rest of the profile data.

The asphalt bricks were heated to the test temperature with the MMLS raised off the test bed so that no loading would be applied to the specimens. Once test temperature was reached, the MMLS3 was first lowered onto the samples and started up. The loading tires were driven over the samples at a rate of 2 tire passes per second. Profiles were taken at 1000, 2000, 4000, 8000, 16000, 30000, 50000, 75000, and 100,000 wheel loads. Table 3.6 summarizes the test parameters for the MMLS3 tests.

Table 3.6: MMLS3 Test Parameters

Parameter	Value
Target Temperature	60^{o}C
Vertical Force	~2.7 kN
Loading Rate	2 Hz
Total Applied Load	100,000 wheels
Profile Measurements (wheels applied upto each measurement)	0, 20, 1,000, 2,000, 4,000, 8,000, 16,000, 30,000, 50,000, 75,000, 100,000

3.3.3 Bailey Method Design and Evaluation

Three mixes were redesigned according to the Bailey Method. The steps involved in this process are:

1. collecting all of the relevant data for the aggregates used, including measuring the unit weights.
2. perform Bailey design calculations to find a suitable aggregate blend.
3. determine the asphalt content according to the Superpave method

Each step is described in more detail below.

The Bailey Method requires the gradings for the aggregate stockpiles, the aggregate bulk specific gravities (Gsb), the loose and rodded unit weights of the coarse aggregate, and the rodded unit weights of the fine aggregate. The gradings and Gsb's were provided by the asphalt plants. The loose and rodded unit weights were measured by following the procedure in the AASHTO test T-19. The only deviation from T-19 was in preparing the samples for measurement. Instead of using a splitter, as called for in test T-248, which is referenced in section 6 of test T-19, the samples were simply batched to a size approximately 125% of what was needed to fill the measuring containers.

As described in Chapter 2, there are several input values for the Bailey calculations that must be chosen by the designer. These include the chosen unit weight (CUW) of the coarse aggregate, which is a percentage of the loose unit weights, the desired dust, and the relative proportions of the coarse and fine aggregate stockpiles. All three mixes were meant to be designed as coarse, well graded mixes, so the CUW was kept between 95% and 105%. A Matlab program was written to automate the process. In each case, the input values were altered until the best design was found. The best designs had gradings within their respective control points, out of their respective restricted zones, and were as close as possible to the target values for the Bailey weight ratios: CA, FAc, and FAf. The target values were the average of the upper and lower limits for each ratio, which were dictated by the NMSA of the mix design.

The Farm-Bailey mix was designed by choosing a set percentage of RAP, 15%, and running the Bailey calculations on the virgin aggregate only. The resulting contributions of the virgin aggregate were reduced by 15% to allow room for the RAP. The final combined grading was then tested against the control points, restricted zone, and target weight ratios. This process was slightly different from the one described in the Bailey Method, because the design program did not aim to keep the percent passing the PCS close to the same value both before and after adding RAP.

4.0 Results for the Original Mixtures

4.1 Mixture Properties

The gradations for the original six mix designs are shown in Figures 4.1 and 4.2. The bricks for the Oss 12.5, Oss 19, and Cont 12.5 mix designs came from large specimens that were cut in half. The T or B in the brick identification indicates whether it came from the top or bottom of the originally compacted specimen. For all the other mix designs, only one brick was fabricated from each compacted specimen to decrease variability in air void content. Appendix B lists the Gmm, Gmb, the percent air voids (V_a), the voids in the mineral aggregate (VMA), and the thickness of each of the seven sample bricks tested in the MMLS3 for each mix design.

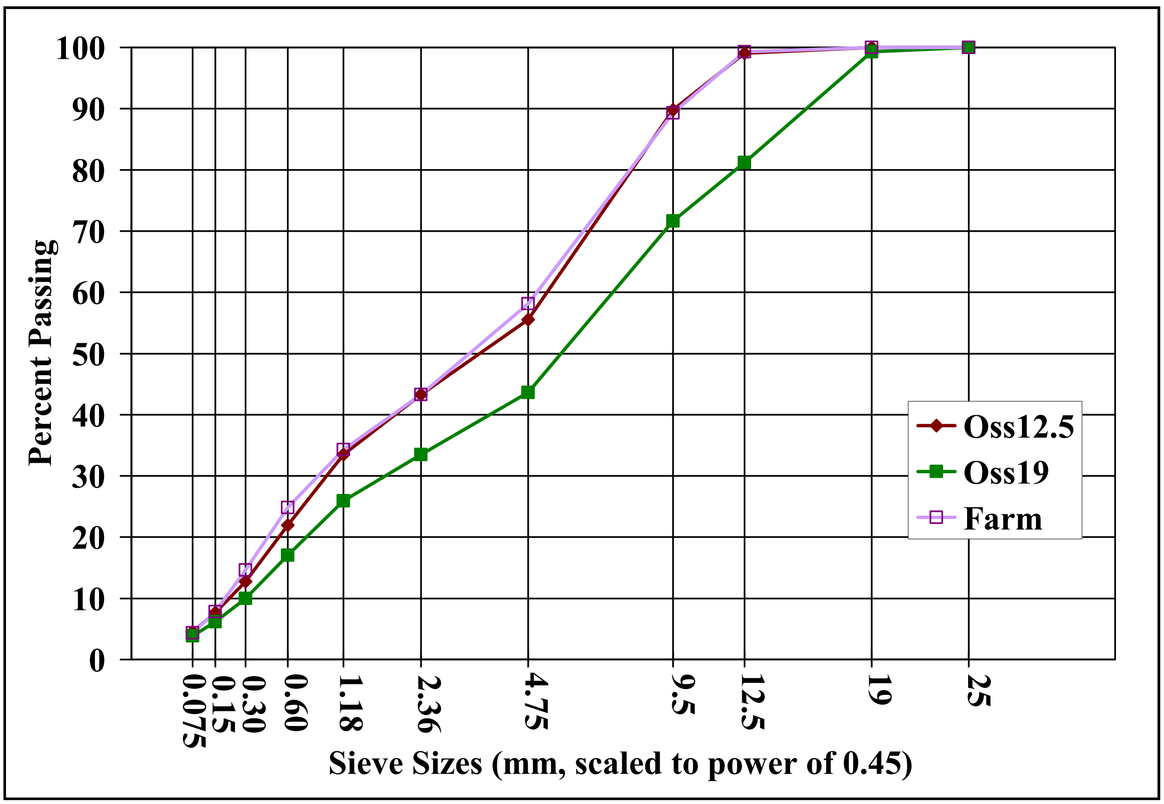


Figure 4.1: Gradations for Mixtures with Gravel Stone

Figure 4.2: Gradations for Mixtures with Fractured Rock

4.2 MMLS3 Test Results

4.2.1 Measuring Rut Depths

The seven sample bricks for each mix were put in a line in the test bed under the MMLS3. Profiles were measured near the middle of each brick, perpendicular to the wheel path, as shown in Figure 3.14. The range of each profile was 200 mm, which covered the full 150 mm width of the brick plus 25 mm on each side to account for any heave or over flow during the test. A typical set of profile measurements is shown in Figure 4.3; both the rutting (negative displacement) and heave (positive displacement) increase over the course of the test. The combination of wear and deformation result in the coarse aggregate being more and more exposed as the test continues, creating the jagged profiles. Appendix C has the data and graphs for all the profile measurements for all the bricks in all the tests.

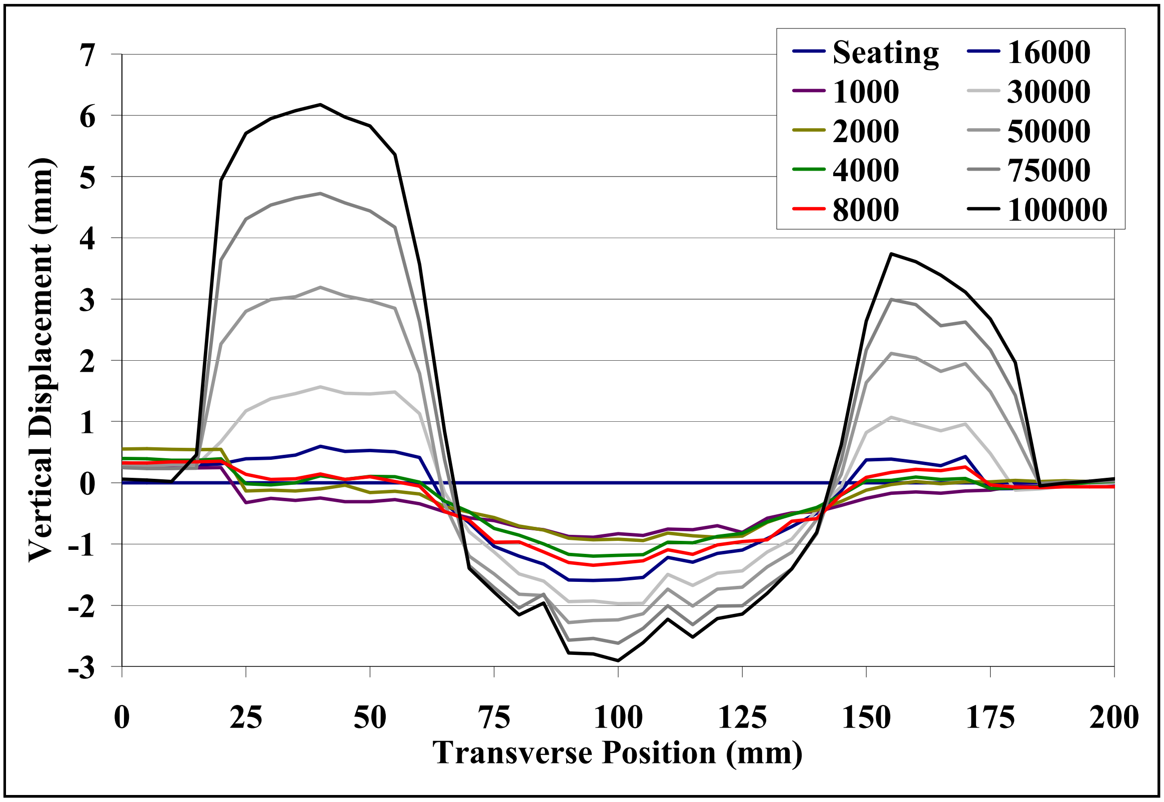


Figure 4.3: Surface Profile Measurements for O12.5M-8B

The three ways to measure rut depth from these profiles are illustrated in Figure 4.4 and described below:

- **Maximum Rut Depth:** Measurement made from normalized base line to the lowest point. Individual aggregate particles can significantly influence this measurement.
- **Max Heave to Max Rut:** Measurement made from the highest point to the lowest point. This method is highly variable depending on the heave and how the heave happens during testing. Individual aggregates or clumps of material can greatly affect this measurement.
- **Average Rut Depth:** Profile measurements within a pre-defined area of the wheelpath are averaged together. Measurement is made from the normalized base line. This method averages out the affect of the individual aggregate particles.

In this project, the average rut depth method is used for comparing the performance of the different mixtures. A 50 mm width from 80 mm to 130 mm lateral position was chosen through visual analysis of all the profile graphs. In some cases, large heaves interfered with the profilometer measurements, resulting in skewed curves. For these profiles, a modified range was chosen for the average rut depth; an example is shown in Figure 4.5.

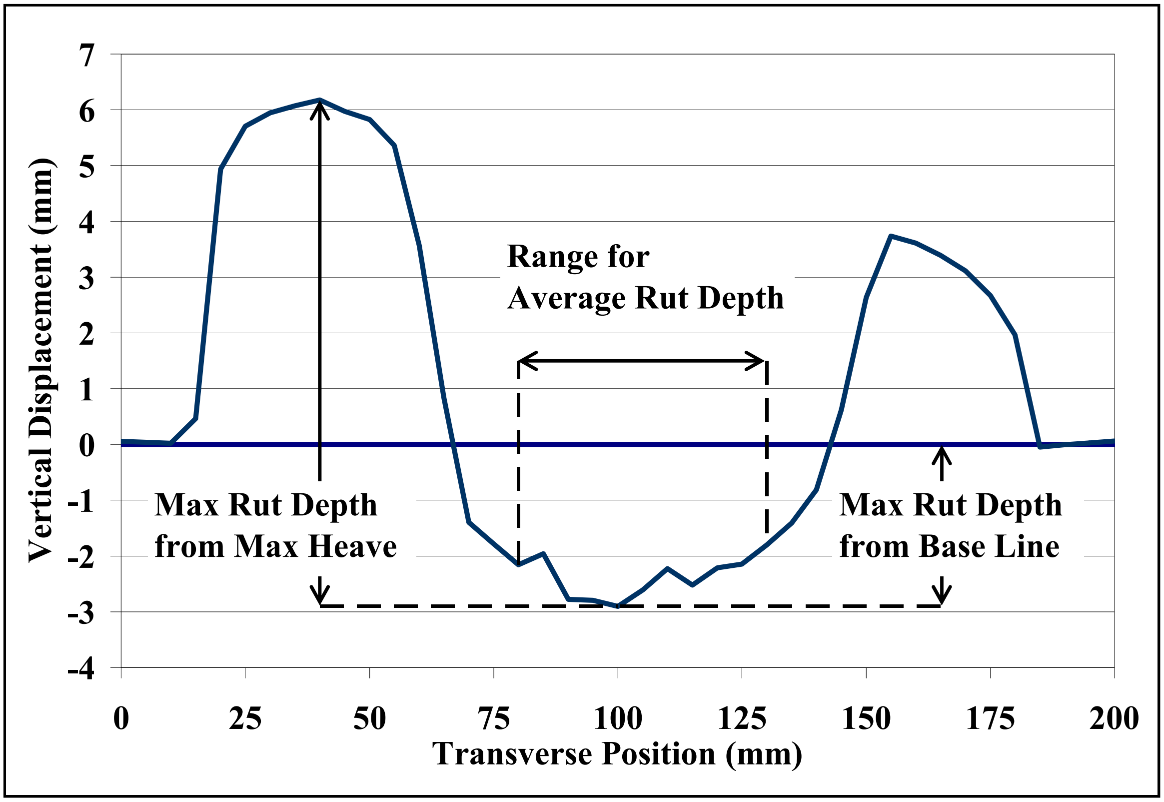


Figure 4.4: Three Methods of Condensing Rut Data from Profile

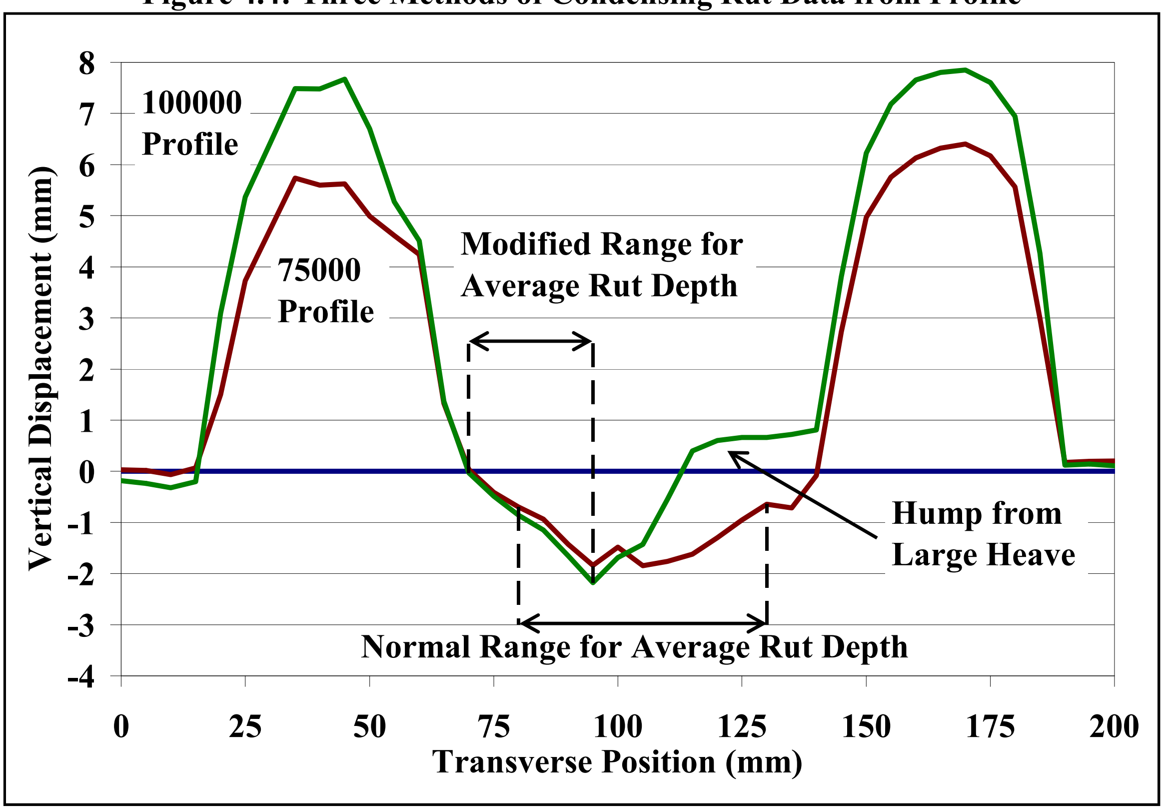


Figure 4.5: Modified Range for Average Rut Depth

The rut depth measurements from each transverse profile can be combined into a longitudinal profile showing rut depths for the individual specimens along the length of the test bed. The data and graphs for all the MMLS3 tests, using all three methods, are in Appendix C. Figure 4.6 shows a typical graph for the longitudinal profile. Typically, the first few specimens show higher rutting than those in the middle of the test bed. This is likely due to the transition of the wheel onto the test bed and has been reported by other researchers as well.

The rut depth measurements for all samples can then be averaged together to show rutting as a function of loading cycles. Figure 4.7 shows a typical graph using all three rut depth measurement techniques.

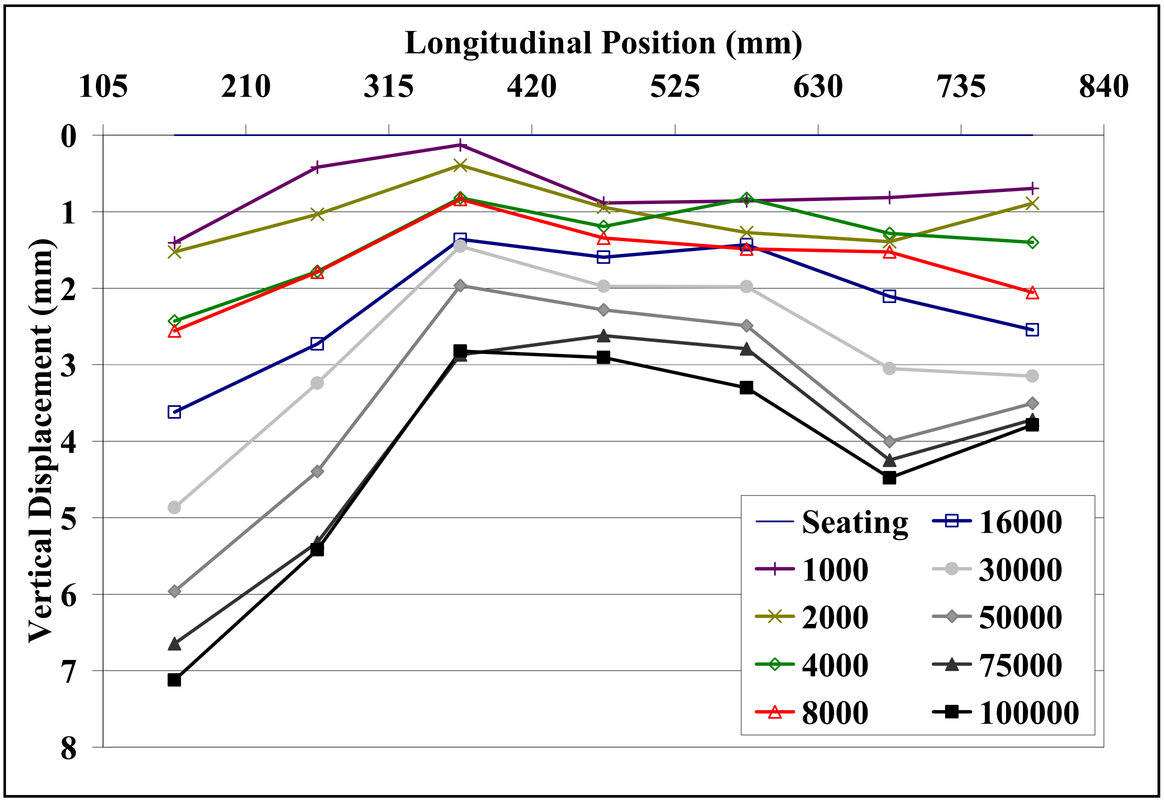


Figure 4.6: Longitudinal Profile of Oss 12.5 Bricks, Max Rut Depth

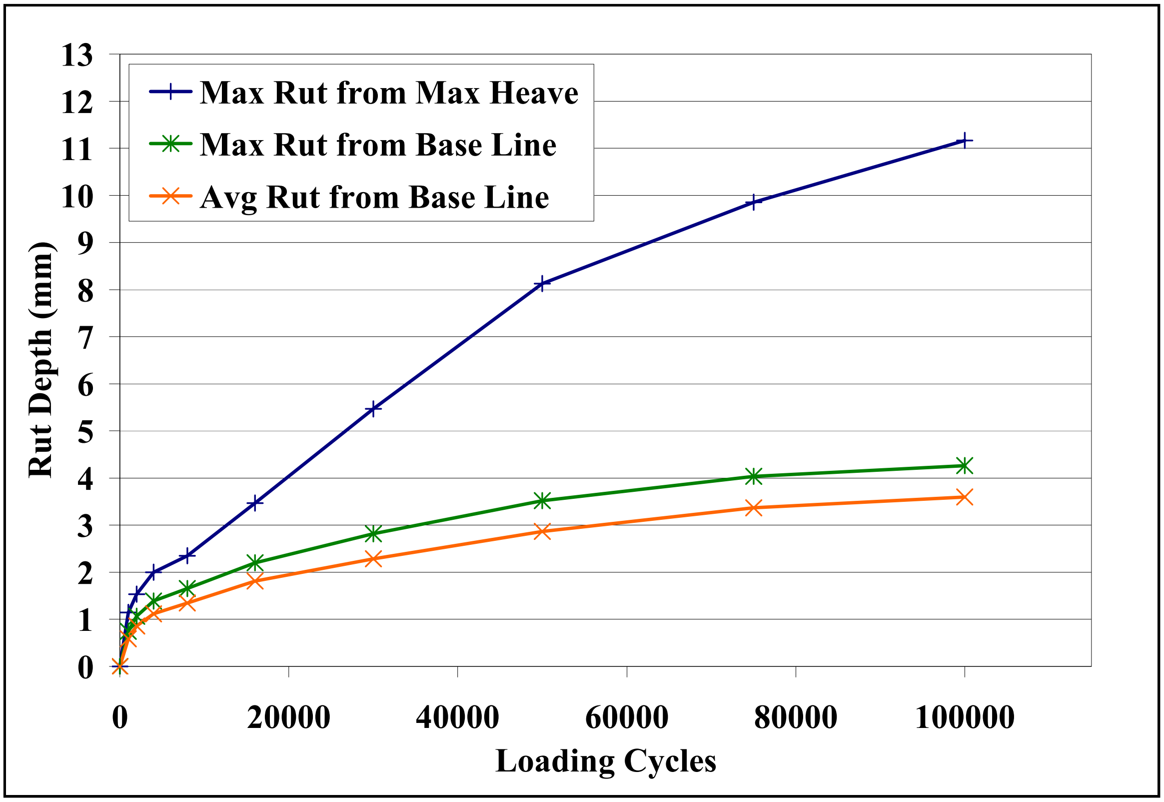


Figure 4.7: Rut Depth vs. Loading Cycles for Oss 12.5

4.2.2 Temperature Adjustment

The target temperature for each of these tests was 60°C. However, it was difficult to maintain a consistent temperature throughout each test. A typical temperature profile during the course a test is shown in Figure 4.8. The dark lines are the temperature readings from the thermocouples imbedded in, or between specimens. The light line is the air temperature measured by the thermocouple in the heater. Temperature drops are observed when the machine is stopped for profile measurements. The temperature profiles for each test were slightly different, so a method of normalizing the rut measurements with respect to temperature was developed; 50°C was chosen as the base temperature. This method uses a factor based on the modulus of the asphalt at the average specimen temperature when the profiles were measured and the modulus of the asphalt at 50°C. Details of the method are presented in Appendix D. Figure 4.9 shows the comparison of original and temperature adjusted profiles. It is important to note that the relative performance of all of the mixtures did not change with the temperature adjustments.

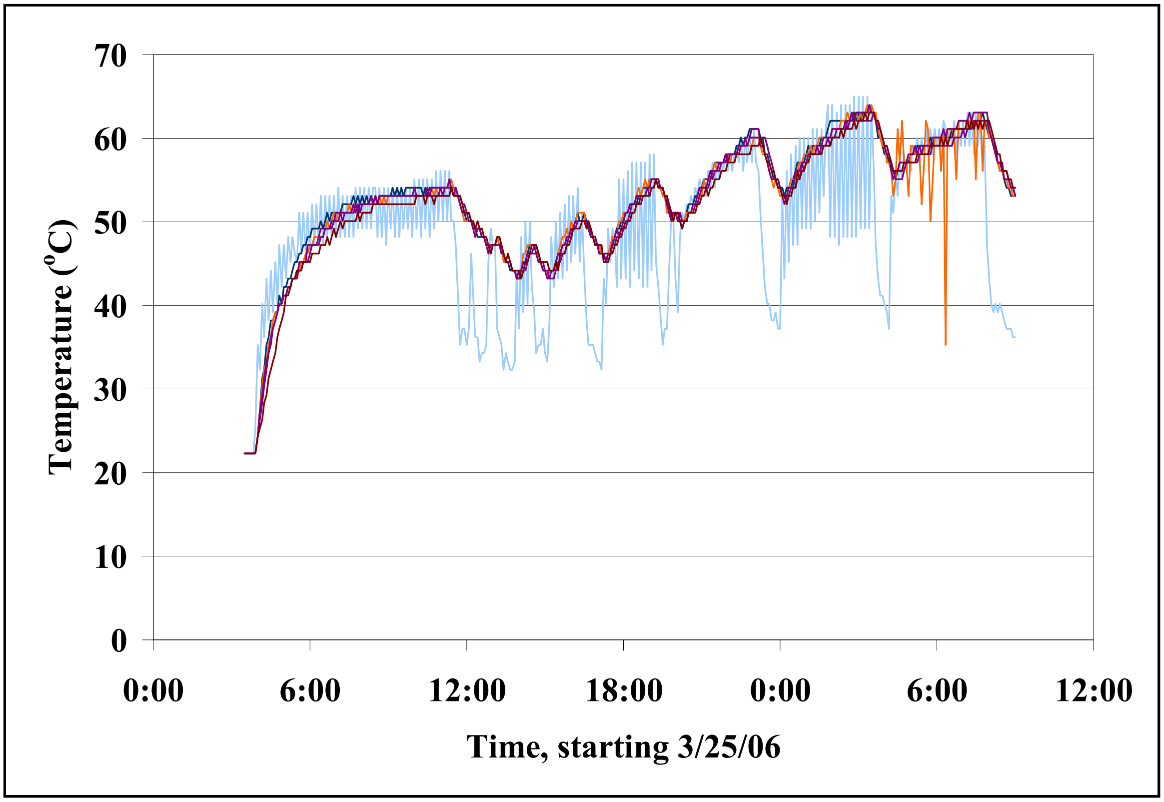


Figure 4.8: Temperature over the Course of the Cont 19 MMLS3 Test

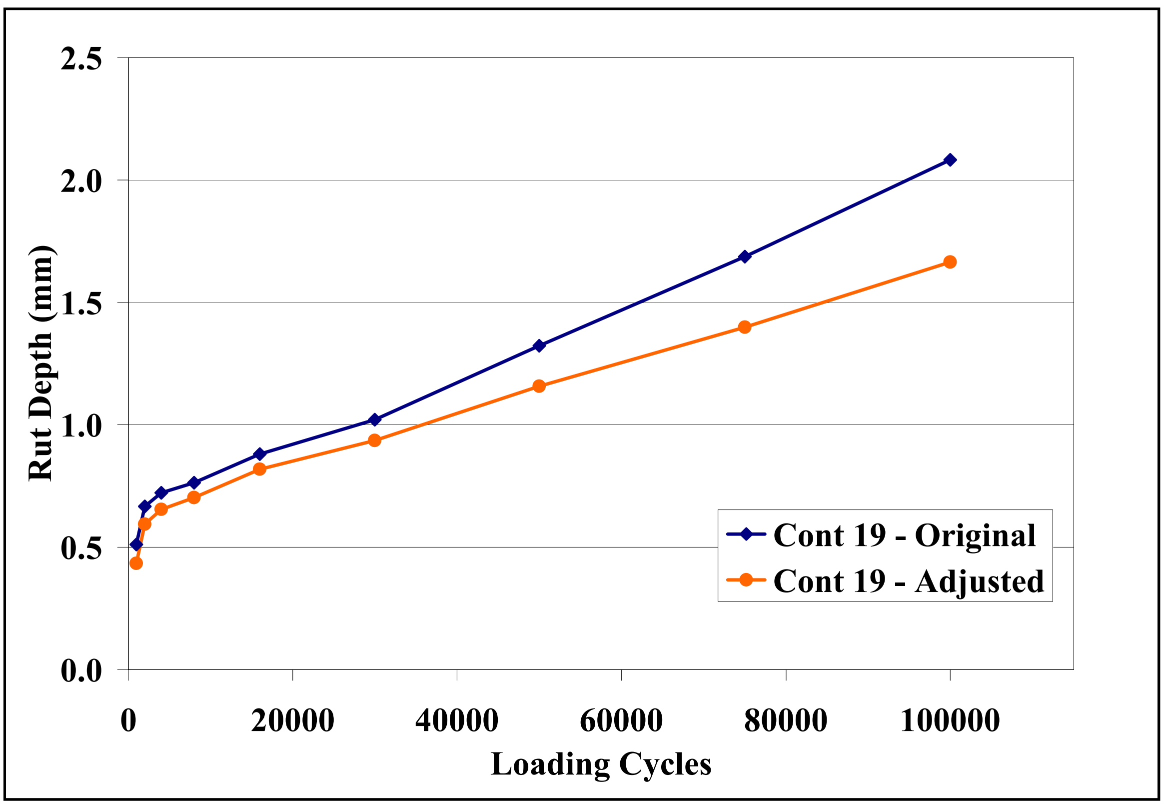


Figure 4.9: Performance of Cont 19 Adjusted to a Constant Temperature of 50°C

4.2.3 Rutting Performance Comparisons for Laboratory Specimens

In this section, the performance of the original mixtures is presented. Statistical analysis was done using the Mann-Whitney/Wilcoxon Rank Sum Test at each profile measurement. The rut depth values for both sets of data are arranged in order, from highest to lowest, in a single list. Each value is then given a rank, 1 for the highest and 14 for the lowest. The rut values, with their ranks, are separated again into their original two data sets. The ranks for each data set are numerically summed. The p-value is the probability that one would get two sums of ranks as widely spaced as the real ones were by random chance.

The statistical test was run using both the maximum rut depth and average rut depth measurements at each profile measurement. Only the statistical comparisons using the average rut depths are shown in this section. The comparisons using the maximum rut depths yielded nearly identical results. A complete explanation of the statistical tests and the full results are in Appendix E.

Figures 4.10 through 4.18 show graphs of the rut depths over the course of the tests for each pair of mixtures that were compared. The seven individual specimens are plotted as points and the solid lines represent the average of all specimens for a particular mixture. Tables 4.7 through 4.13 show p-values for the comparisons at each number of cycles of loading during the tests. The limit of significant difference was set at 5%, so a p-value of 0.05 or less means that the two sample sets are significantly different from a statistical standpoint. Values that are close to the limit must be examined in context to the rest of the values.

4.2.3.1 <u>Effect of NMSA</u>

This section compares the performance of the 19mm and 12.5mm mixtures. Figure 4.10 shows the rutting versus number of wheel loads for the two Ossipee mixtures. There are several things to note about these data; first, the value for the third specimen in the Oss 12.5 sample set, O12.5M-6T, developed a very large heave, so a modified range for the average value was used in the rut depth calculation. Secondly, the last profiles during the Oss 19 MMLS3 test were taken after 111,740 wheel loads, instead of right at 100,000. The rate of rutting is low and linear after 50,000 loading cycles, so these values were used as is in the statistical testing. Also, it is important to note that the 12.5 mm mixtures have an asphalt content about 0.5% higher than the 19 mm mixtures, which will also affect the performance. It is impossible to decouple the effects of the NMSA and asphalt content in the analysis.

The Oss 19 mix shows more rutting during the course of this testing than the Oss 12.5 mix. In general, it is expected that coarse mixtures will perform better than fine mixtures with respect to rutting. More than half of the total average rutting in the Oss 19 specimens took place within the first 1,000 loading cycles. A possible reason for this is the lack of a seating load for the Oss 19 test. To account for this in the analysis, the rut measurements at 1,000 loading cycles are subtracted from each data set and shown in Figure 4.11. When the data is normalized to 1,000 cycles, the Oss 19 mixture shows better performance, as would be expected.

Tables 4.7 and 4.8 show the statistical analysis for the original and normalized Ossipee data, respectively. The original data shows a significant difference between the two mixtures at low cycles of loading, but not at high cycles of loading. The p-value for 30,000 load cycles is very close to the 0.05 limit; considering the data points on either side (16,000 and 50,000) do not show a significant difference, the likelihood is that the data at 30,000 cycles is not significantly different either. The normalized data shows that there is not a significant difference between the two at low cycles of loading, but there is at the end of the test.

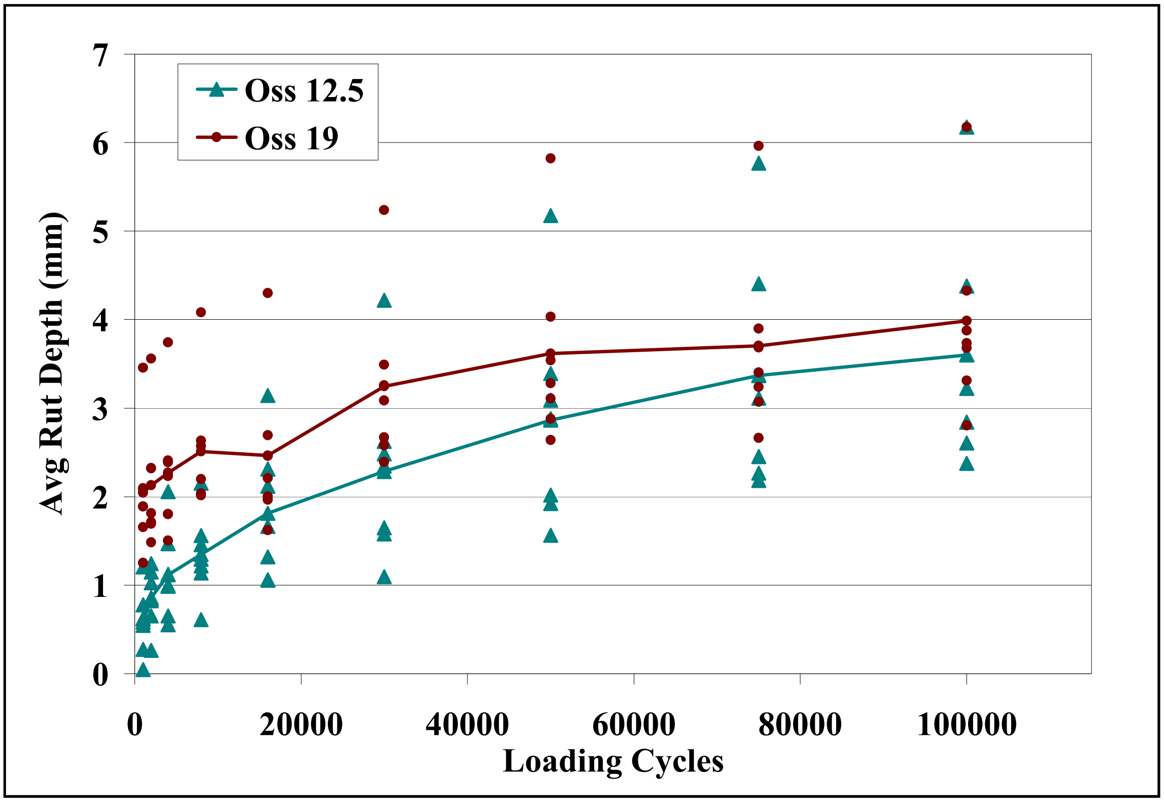


Figure 4.10: Rut Depths for Oss 12.5 and Oss 19

Table 4.7: Comparison of Rut Depths for Oss 12.5 and Oss 19

	Thousands of Loading Cycles								
	1	2	4	8	16	30	50	75	100
P-Value	0.001	0.001	0.004	0.004	0.209	0.053	0.209	0.383	0.337
Significant Difference	Yes	Yes	Yes	Yes	No	No	No	No	No

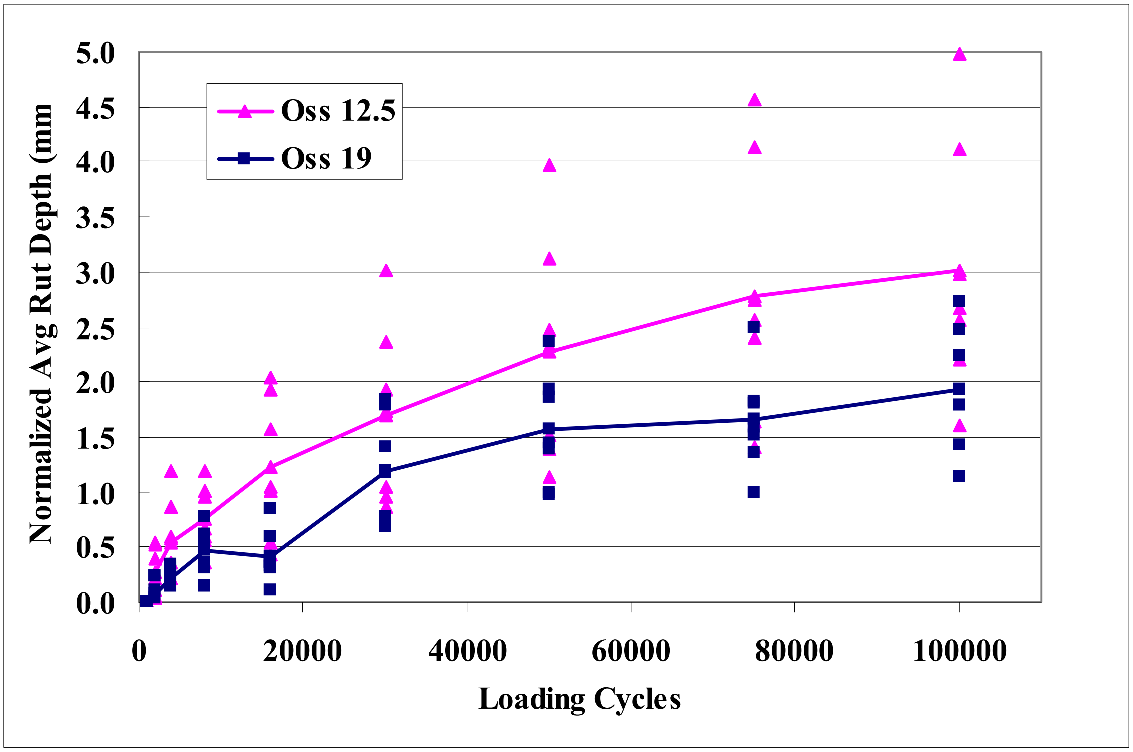


Figure 4.11: Oss 12.5 and Oss 19 Normalized to the Rut Depth at 1000 Cycles

Table 4.8: Comparison of Rut Depths for Oss 12.5 and Oss 19 Normalized to 1000 cycles

	Thousands of Loading Cycles								
	1	2	4	8	16	30	50	75	100
P-Value	N/A	0.199	0.085	0.055	0.009	0.180	0.159	0.048	0.064
Significant Difference		No	No	No	Yes	No	No	Yes	Yes

The comparison between the Cont 12.5 and Cont 19 specimens is shown in Figure 4.12 and Table 4.9. The 19 mm mixture clearly shows better performance than the 12.5 mm mixture, as is expected. Statistically, the two data sets are significantly different at all loading cycles except for the first and the last.

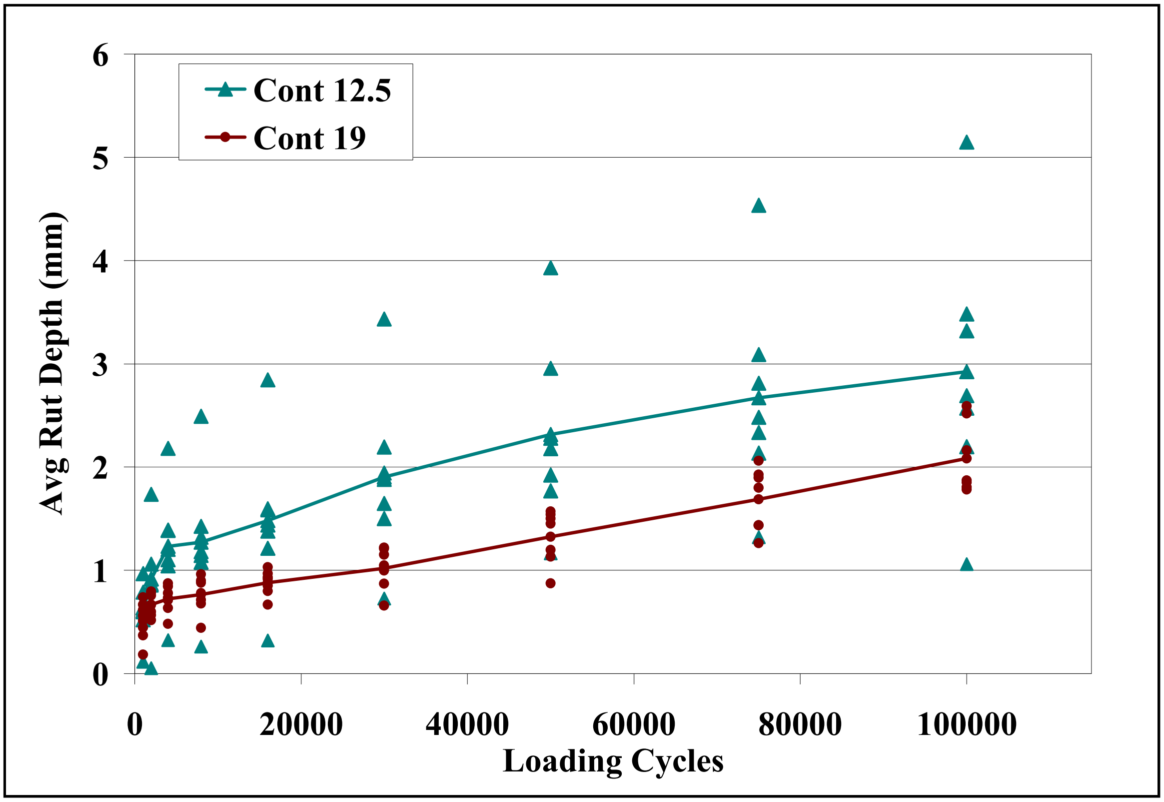


Figure 4.12: Rut Depths for Cont 12.5 and Cont 19

Table 4.9: Comparison of Rut Depths of Cont 12.5 and Cont 19

	Thousands of Loading Cycles								
	1	2	4	8	16	30	50	75	100
P-Value	0.456	0.026	0.026	0.026	0.026	0.018	0.011	0.021	0.073
Significant Difference	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No

4.2.3.2 Effect of Aggregate Type

The performances of the mixtures made with gravel stone verses fractured rock are compared in this section. Figures 4.13 and 4.14 show the rut depth comparisons for the 12.5 mm and 19 mm mixtures, respectively. The average performance of the Cont mixtures, made with fractured rock, is better than the average performance of the Oss mixtures, made with gravel stone, in both cases. Note that the asphalt contents of the 12.5 mm mixtures are within 0.1% and the asphalt content of the two 19 mm mixtures are the same, so the effect of asphalt content is not significant in these comparisons. Normalization of the 19 mm mixtures to 1,000 load cycles reduces the difference between the two mixtures, but the trend remains the same, as shown in Figure 4.15. The statistical analysis of the 12.5 mm mixtures presented in Table 4.10 indicates that there is no significant difference between the fractured rock and gravel stone mixtures at any number of loadings. Tables 4.11 and 4.12 present the analysis for the original and normalized 19 mm data, respectively. The original data indicates a significant difference and the normalized data show significant difference in the middle load cycles, but not at the beginning or end of the test.

Figure 4.16 compares the performance of the two RAP mixtures and Table 4.13 presents the statistical analysis. The Farm mix, with gravel stone has, on average, slightly better performance than the Hook mix made with fractured rock. However, there is no statistical difference between the two mixtures and it is also important to note that the two mixtures used different RAP sources. Possible differences in the stiffness of the RAP could easily account for the observed trends.

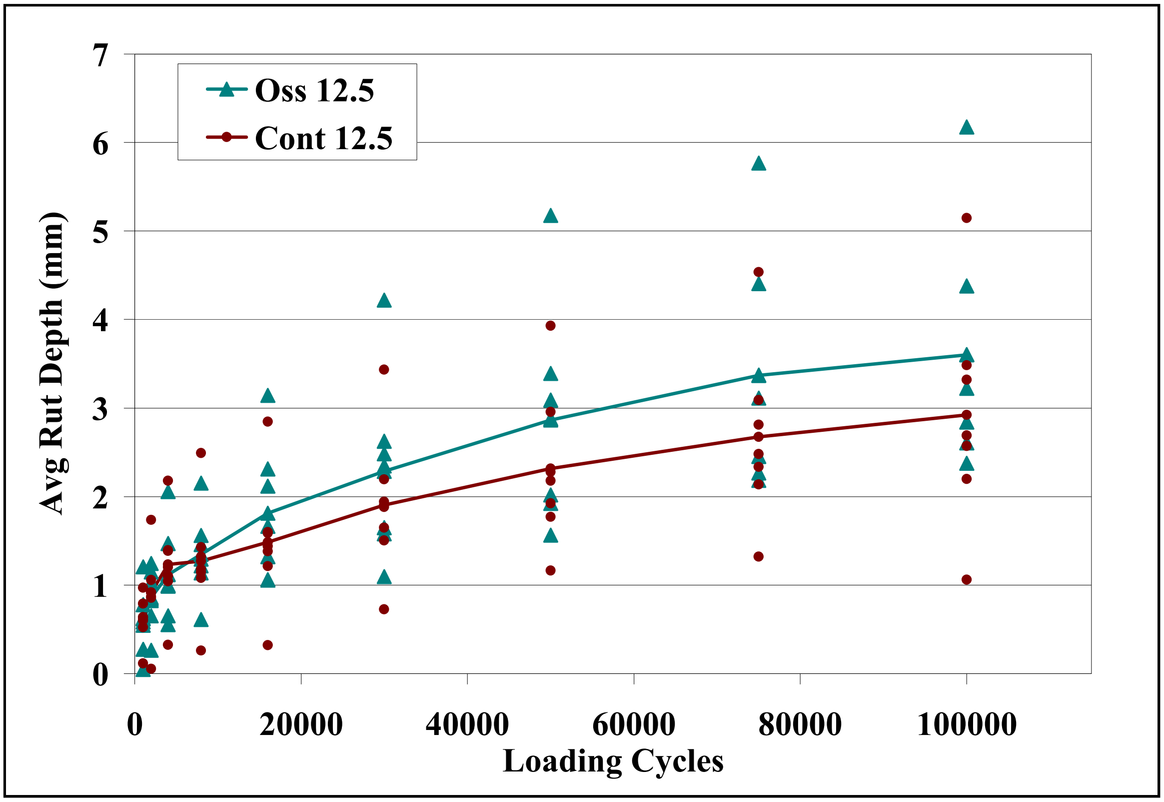


Figure 4.13: Rut Depths for Oss 12.5 and Cont 12.5

Table 4.10: Comparison of Rut Depths of Oss 12.5 and Cont 12.5

	Thousands of Loading Cycles								
	1	2	4	8	16	30	50	75	100
P-Value	0.710	0.710	0.535	0.620	0.620	0.456	0.482	0.383	0.383
Significant Difference	No	No	No	No	No	No	No	No	No

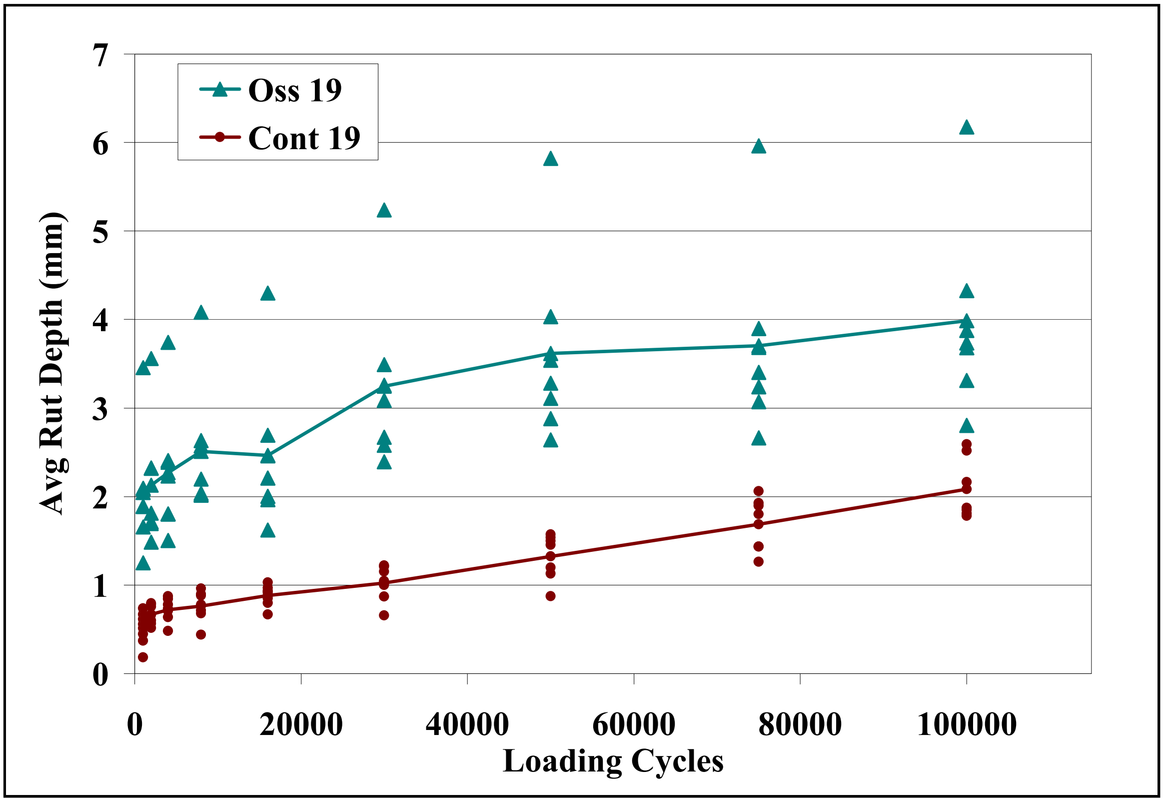


Figure 4.14: Rut Depths for Oss 19 and Cont 19

Table 4.11: Comparison of Rut Depths of Oss 19 and Cont 19

	Thousands of Loading Cycles								
	1	2	4	8	16	30	50	75	100
P-Value	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001
Significant Difference	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

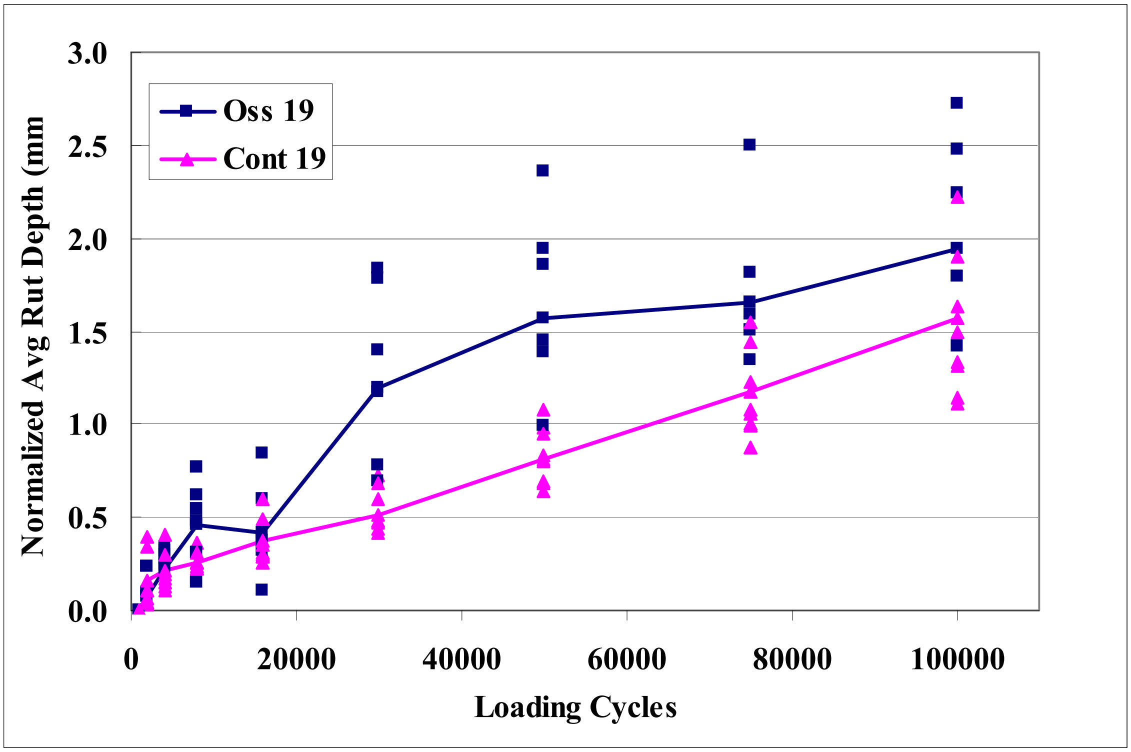


Figure 4.15: Oss 19 and Cont 19 Normalized to the Rut Depth at 1000 Cycles

Table 4.12: Comparison of Rut Depths of Oss 19 and Cont 19 Normalized to 1,000 Load Cycles

	Thousands of Loading Cycles								
	1	2	4	8	16	30	50	75	100
P-Value	N/A	0.403	0.481	0.029	0.370	0.002	0.004	0.035	0.179
Significant Difference		No	No	Yes	No	Yes	Yes	Yes	No

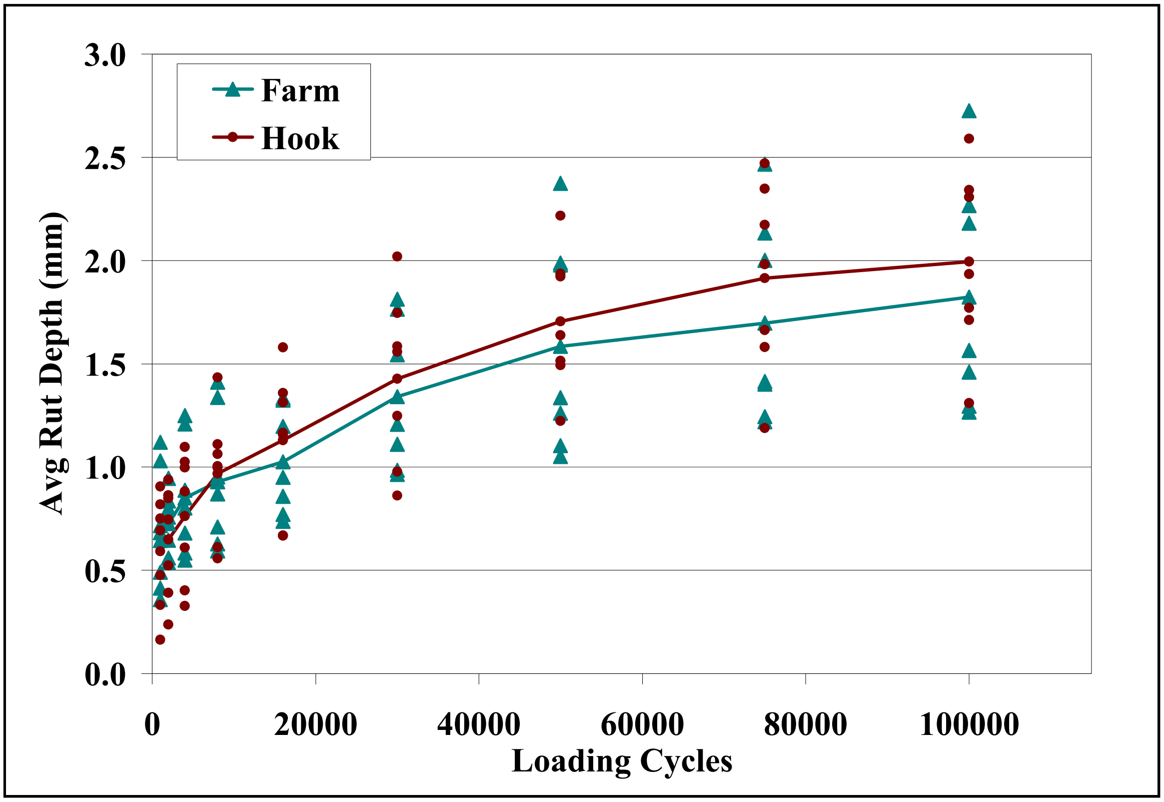


Figure 4.16: Rut Depths for Farm and Hook

Table 4.13: Comparison of Rut Depths of Farm and Hook

	Thousands of Loading Cycles								
	1	2	4	8	16	30	50	75	100
P-Value	0.710	0.710	0.710	0.710	0.805	0.805	0.710	0.456	0.383
Significant Difference	No	No	No	No	No	No	No	No	No

4.2.3.3 Effect of RAP

Mixture performance with and without RAP is presented in this section. Figure 4.17 shows the comparison for the two gravel stone mixtures and Figure 4.18 shows the comparison for the two fractured rock mixtures. Asphalt contents for all mixtures are similar. Tables 4.14 and 4.15 present the statistical results. In both cases, the average performance of the mixture containing RAP is better than the virgin mixture. Statistically, the gravel stone mixtures show a significant difference at the higher loading cycles, but there is no significant difference between the fractured rock mixtures.

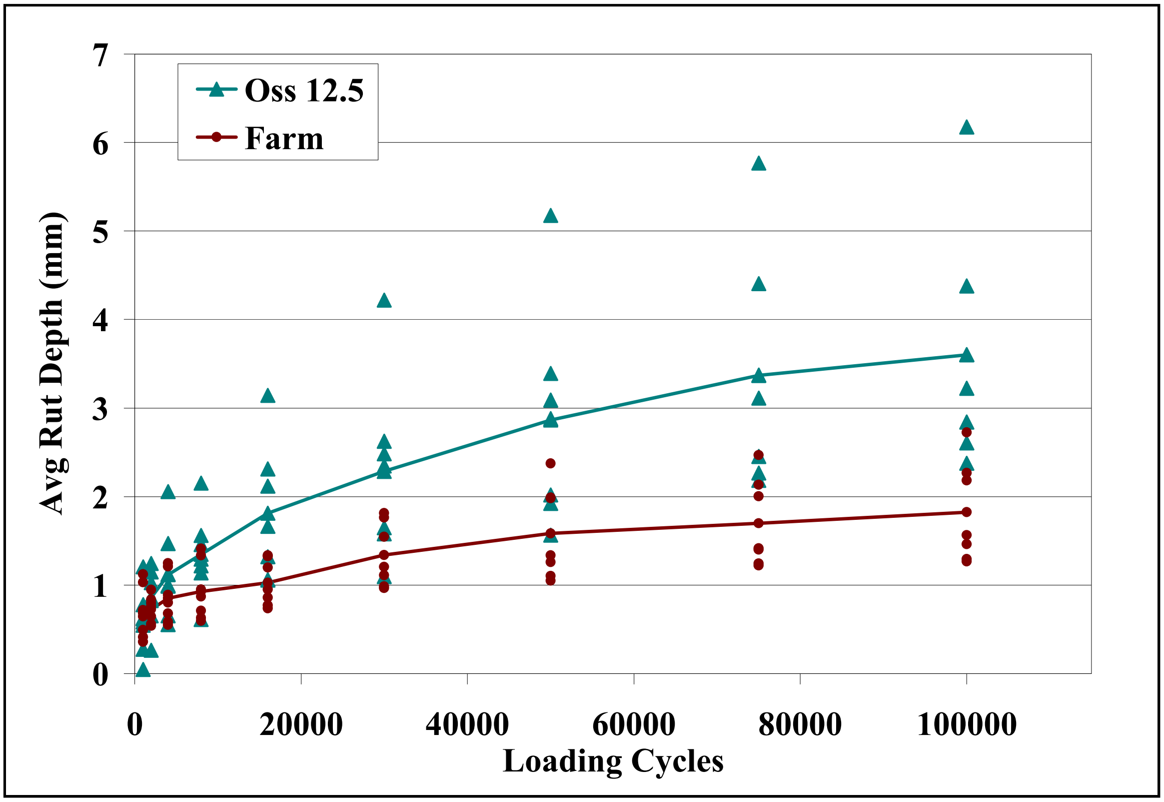


Figure 4.17: Rut Depths for Oss 12.5 and Farm

Table 4.14: Comparison of Rut Depths of Oss 12.5 and Farm

	Thousands of Loading Cycles								
	1	2	4	8	16	30	50	75	100
P-Value	0.710	0.209	0.383	0.128	0.038	0.053	0.026	0.004	0.002
Significant Difference	No	No	No	No	Yes	No	Yes	Yes	Yes

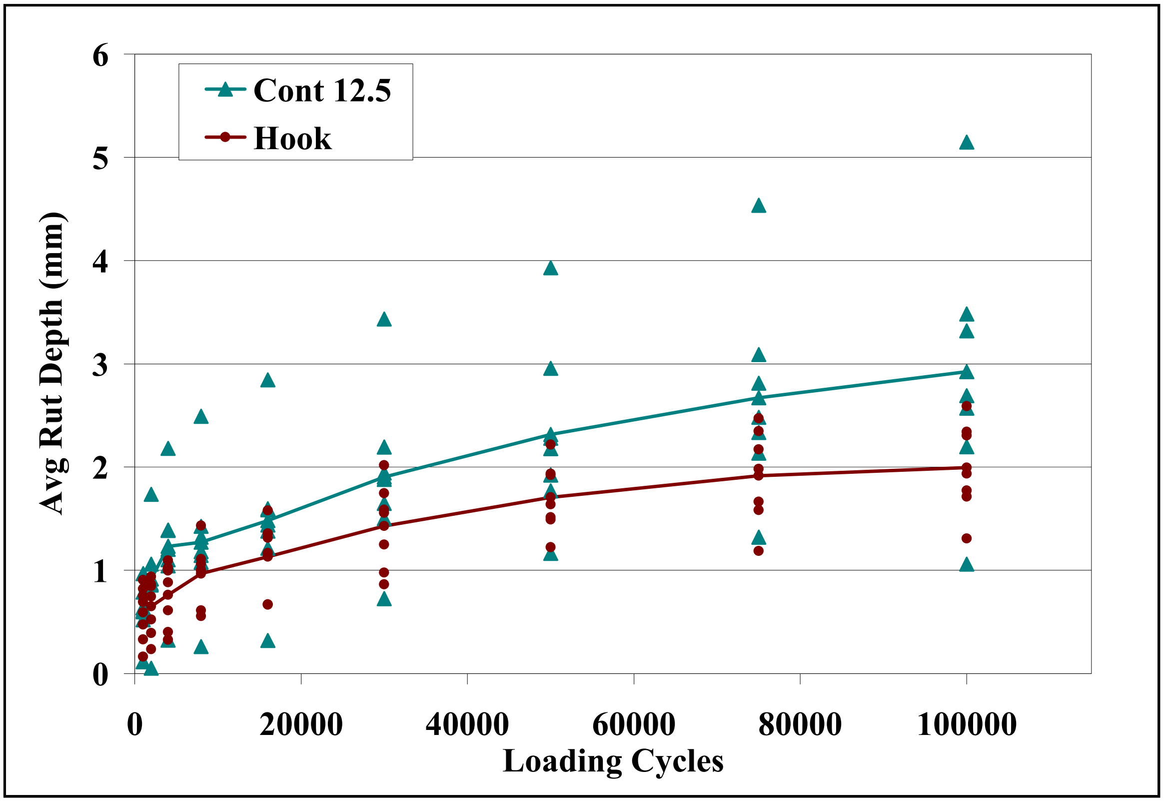


Figure 4.18: Rut Depths for Cont 12.5 and Hook

Table 4.15: Comparison of Rut Depths of Cont 12.5 and Hook

	Thousands of Loading Cycles								
	1	2	4	8	16	30	50	75	100
P-Value	1.000	0.128	0.038	0.165	0.128	0.259	0.179	0.097	0.097
Significant Difference	No	No	Yes	No	No	No	No	No	No

4.2.3.4 Summary

Table 4.16 presents a summary of all comparisons including the average performance and the presence of significant difference overall. For those comparisons that had different p-values at the beginning and end of the tests, only the p-values for the later part of the tests are considered important because that data indicates long term performance of the mix design.

Table 4.16: Summary of Statistical Comparisons

Compared Parameter	Mix Pair	Significant Difference	Better Performer
NMSA	Oss 12.5 vs. Oss 19	No	Oss 12.5
	Oss 12.5 vs. Oss 19, 1k Normalized	Yes	Oss 19
	Cont 12.5 vs. Cont 19	Yes	Cont 19
Aggregate Type	Oss 12.5 vs. Cont 12.5	No	Cont 12.5
	Oss 19 vs. Cont 19	Yes	Cont 19
	Oss 19 vs. Cont 19, 1k Normalized	No	Cont 19
	Farm vs. Hook	No	Farm
RAP	Oss 12.5 vs. Farm	Yes	Farm
	Cont 12.5 vs. Hook	No	Hook

4.2.4 Rutting Performance of Field Cores

The volumetric data for the eight specimens obtained from field cores for the Oss 12.5 and Oss 19 mixtures are shown in Tables 4.17 and 4.18, respectively. The surface (12.5 mm) layer had significantly higher air voids than the base (19 mm) layer, which has an impact on the rutting performance of the mixtures. It should also be noted that the field cores are thinner than the laboratory generated specimens, which may also influence the performance in the MMLS3. The field cores were tested with the same MMLS3 setup as for the laboratory specimens, except that no seating loads were applied for the field cores. For this reason, all of the MMLS data in this section is normalized to 1,000 load cycles. The field cores developed excessively large ruts and heaves, so the tests were terminated after 30,000 loading cycles.

Figure 4.19 shows a comparison between the surface and base field cores. The 19 mm base cores exhibit less rutting than the 12.5 mm surface cores. There are three factors that contribute to this difference in performance: higher air void content for the surface cores, finer aggregate gradation for the surface cores, and thinner surface cores. Statistically, the two sets of field cores are significantly different at the end of the loading cycles, as shown in Table 4.19. Figures 4.20 and 4.21 show the lab specimen versus field core rut depth comparisons for the 12.5 mm and 19 mm mixtures, respectively. Tables 4.20 and 4.21 show the statistical comparisons of the lab versus field cores, respectively. In both cases, the lab specimens show better performance and a statistical difference at the later loading cycles. The higher air void content of the field cores for the 12.5 mm mixture is a major factor in this difference. The difference in specimen thickness, along with the difference in compaction method (field versus lab) also contributes to the differences in performance for both the 12.5mm and the 19 mm mixtures.

Table 4.17: Volumetrics for Field Core Surface Layer

Brick ID	Gmm	Gmb	AV	VMA	Thickness (mm)
EF12.5-1	2.429	2.234	8.0	18.5	39.02
EF12.5-2	2.429	2.274	6.4	17.0	38.68
EF12.5-6	2.429	2.262	6.9	17.5	38.84
EF12.5-8	2.429	2.256	7.1	17.7	37.17
EF12.5-3	2.429	2.281	6.1	16.8	35.28
EF12.5-4	2.429	2.271	6.5	17.2	35.24
EF12.5-5	2.429	2.253	7.3	17.8	30.71
EF12.5-7	2.429	2.248	7.4	18.0	28.83
Average	2.429	2.260	7.0	17.6	35.47

Table 4.18: Volumetrics for Field Core Base Layer

Brick ID	Gmm	Gmb	AV	VMA	Thickness (mm)
EF19-5	2.455	2.321	5.5	15.1	48.29
EF19-4	2.455	2.375	3.3	13.1	45.41
EF19-6	2.455	2.340	4.7	14.4	42.49
EF19-7	2.455	2.324	5.3	15.0	42.97
EF19-2	2.455	2.343	4.5	14.3	41.03
EF19-3	2.455	2.319	5.6	15.2	42.10
EF19-1	2.455	2.323	5.4	15.0	40.18
EF19-8	2.455	2.332	5.0	14.7	40.49
Average	2.455	2.335	4.9	14.6	42.87

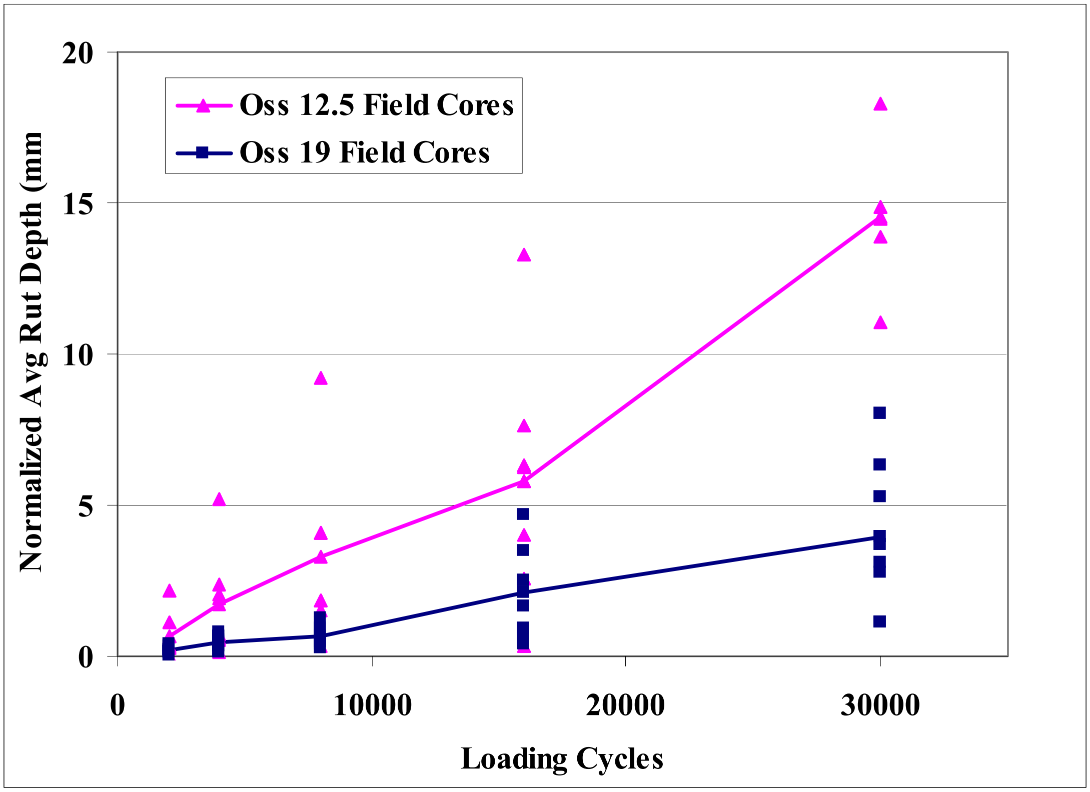


Fig 4.19: Oss 12.5 and Oss 19 Field Cores Normalized to Rut Depth at 1000 Cycles

Table 4.19: Comparison of Rut Depths of Oss 12.5 and Oss 19 Field Cores Normalized to 1000 Cycles

	Loading Cycles				
	2000	4000	8000	16000	30000
P-Value	0.172	0.052	0.015	0.049	0.003
Significant Difference	No	No	Yes	Yes	Yes

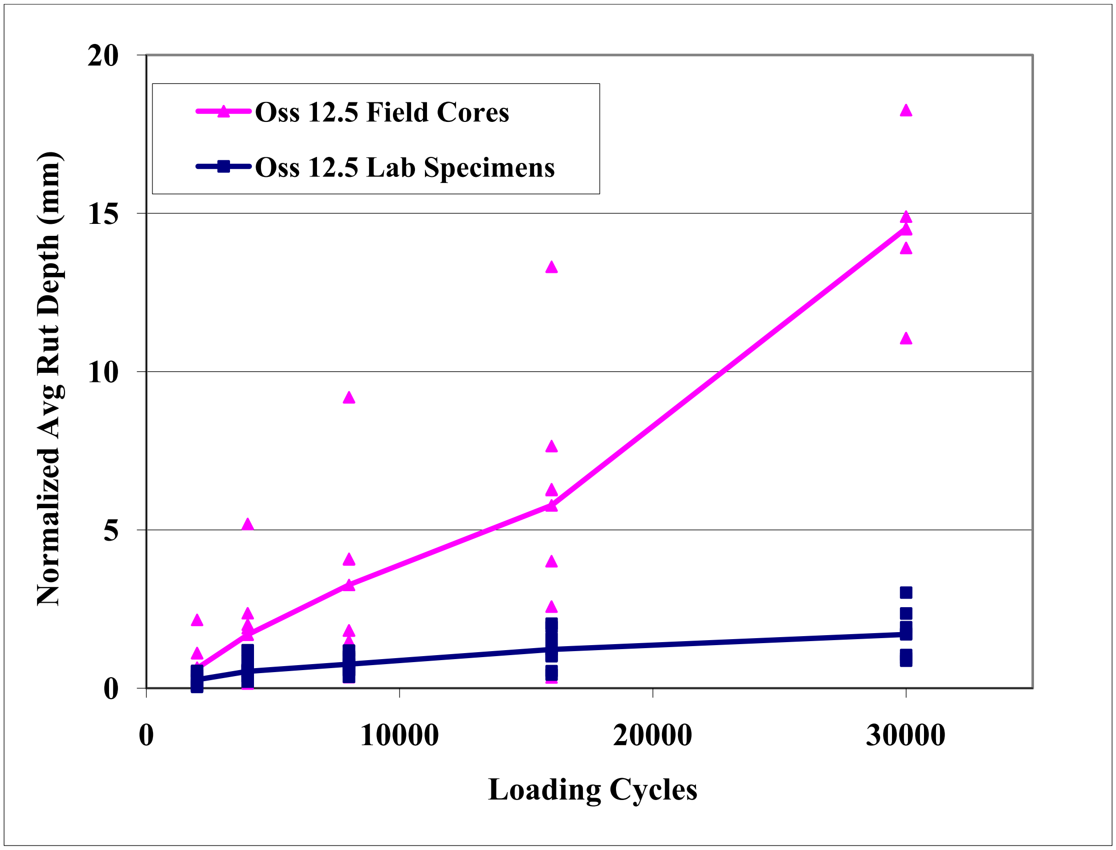


Figure 4.20: Oss 12.5 Lab Samples and Field Cores Normalized to Rut Depth at 1000 Cycles

Table 4.20: Comparison of Rut Depths of Oss 12.5 Field Cores and Lab Samples Normalized to 1000 Cycles

	Loading Cycles				
	2000	4000	8000	16000	30000
P-Value	0.354	0.133	0.025	0.025	0.005
Significant Difference	No	No	Yes	Yes	Yes

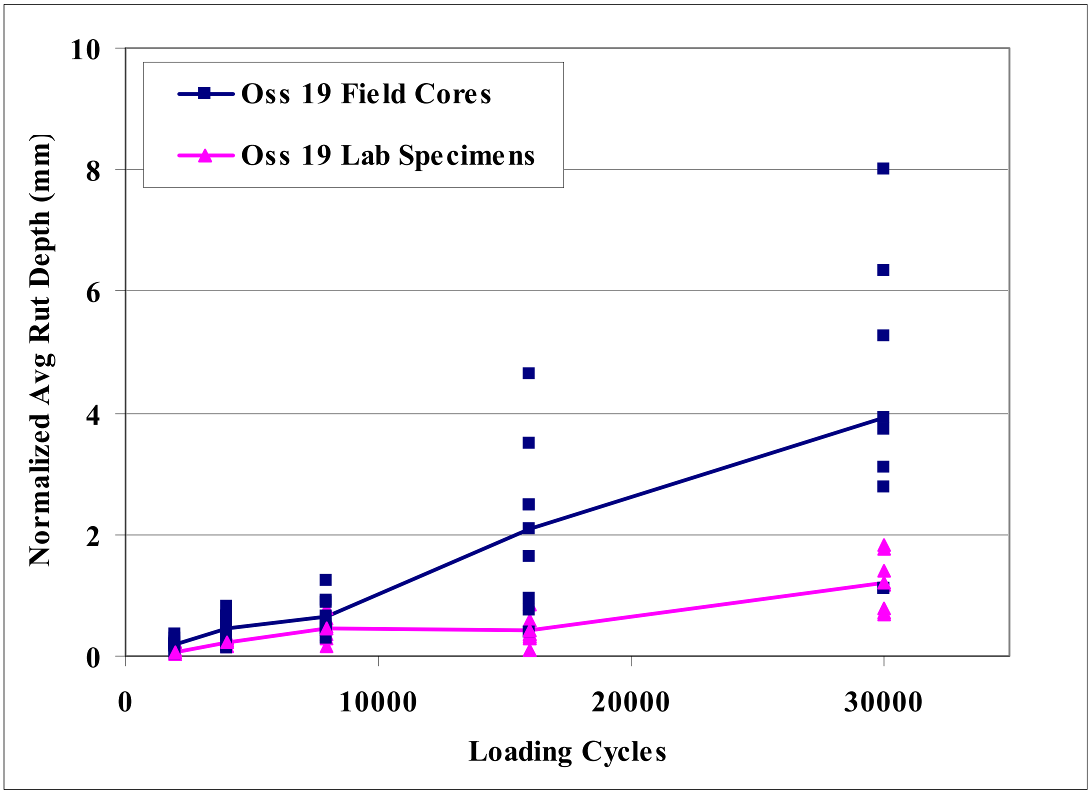


Figure 4.21: Oss 19 Lab Samples and Field Cores Normalized to Rut Depth at 1000 Cycles

Table 4.21: Comparison of Rut Depths of Oss 19 Field Cores and Lab Samples Normalized to 1000 Cycles

	Loading Cycles				
	2000	4000	8000	16000	30000
P-Value	0.323	0.072	0.418	0.004	0.021
Significant Difference	No	No	No	Yes	Yes

5.0 Application of Bailey Method & Results

5.1 Redesigned Mixtures

Three mixtures were chosen for redesign with the Bailey Method; they are Oss 12.5, Cont 19, and Farm. These three mixtures were selected to include the two NMSAs, two aggregate types, and a RAP mixture. For clarity, the original Oss 12.5, Cont 19, and Farm mix designs will be called Oss 12.5-Original, Cont 19-Original, and Farm-Original in this chapter and the Bailey redesigns will be called Oss 12.5-Bailey, Cont 19-Bailey, and Farm-Bailey.

The Bailey parameters for the original and redesigned mixtures are shown in Table 5.1. The CUW for the original mixtures is back calculated, while for the redesigned mixtures it is a chosen value. For all three mixtures, the original CUW value classifies the mixture as a “fine” mixture (CUW <90%) within the Bailey system. The mixtures were redesigned to be “coarse” mixtures according to the Bailey Method, meaning the CUW was chosen to be in the 95%-105% range. The target values for each of the Bailey weight ratios, CA, FAc, and FAf were set to the middle of the recommended limits. The optimum gradation for each mixture was then found such that the Bailey ratios were as close as possible to the target values and the gradation met the superpave gradation control points and did not pass through the restricted zone.

Both the Oss 12.5-Bailey and Cont 19-Bailey mix designs had weight ratios close to their target values. The Farm-Bailey mix had a very high FAc ratio. Several attempts were made to bring this ratio within limits without letting the grading out of the Superpave control points or into the restricted zone. No combination of input values achieved an acceptable FAc ratio without moving the other ratios out of range.

Table 5.1: Bailey Parameters for Redesigned Mixtures

Mix	Bailey Parameter	Bailey Limits (fine mix)	Original Value	Bailey Redesign Value	Redesign Target Value	Bailey Limits (coarse mix)
Oss 12.5	CUW	<85%	80	103		95% - 105%
	CA Ratio	0.60 – 1.0	0.68	0.57	0.58	0.50 – 0.65
	FAc Ratio	0.35 – 0.50	0.51	0.47	0.43	0.35 – 0.50
	FAf Ratio	0.35 – 0.50	0.35	0.42	0.43	0.35 – 0.50
Cont 19	CUW	<85%	74	101		95% - 105%
	CA Ratio	0.60 – 1.0	0.91	0.68	0.68	0.60 – 0.75
	FAc Ratio	0.35 – 0.50	0.52	0.46	0.43	0.35 – 0.50
	FAf Ratio	0.35 – 0.50	0.36	0.42	0.43	0.35 – 0.50
Farm	CUW	<85%	81	101		95% - 105%
	CA Ratio	0.60 – 1.0	0.77	0.58	0.58	0.50 – 0.65
	FAc Ratio	0.35 – 0.50	0.57	0.58	0.43	0.35 – 0.50
	FAf Ratio	0.35 – 0.50	0.32	0.43	0.43	0.35 – 0.50

Figures 5.1 through 5.3 show the gradations for the three redesigned mixes and the original mixes. The mix design details are shown in Appendix F.

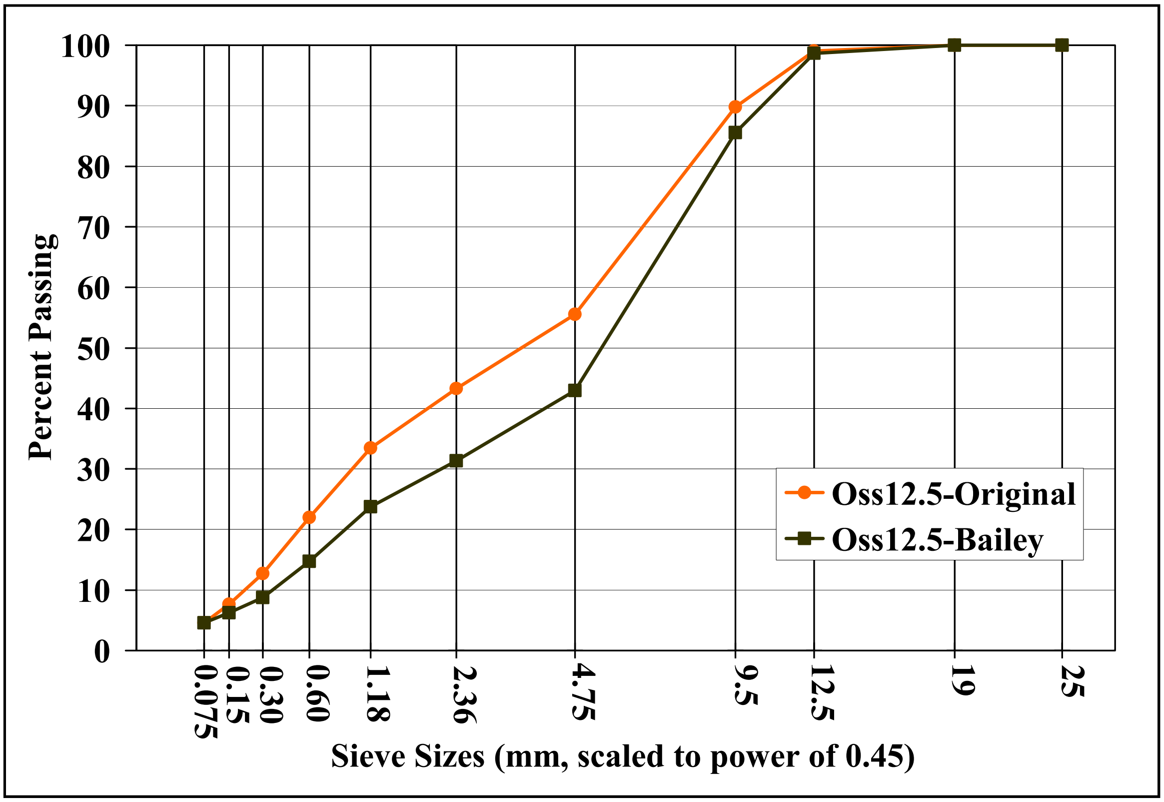


Figure 5.1: Oss 12.5-Original and Oss 12.5-Bailey Mix Design Gradations

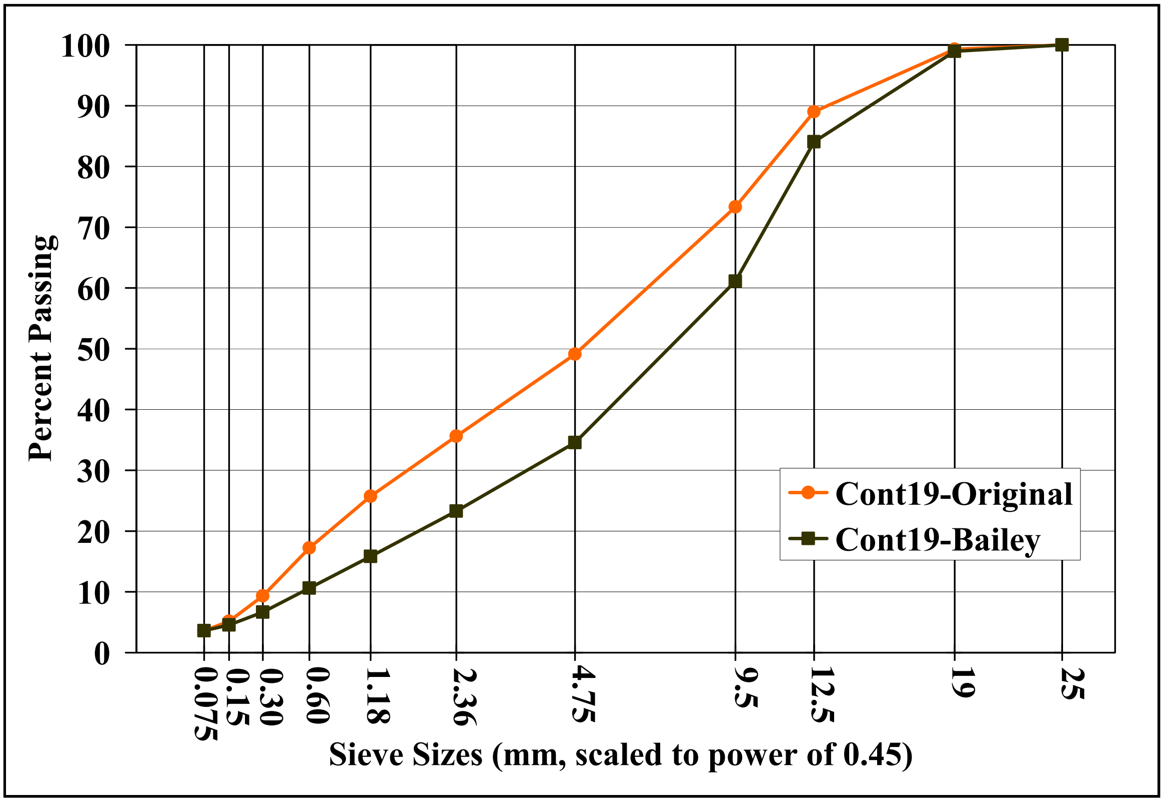


Figure 5.2: Cont 19-Original and Cont 19-Bailey Mix Design Gradations

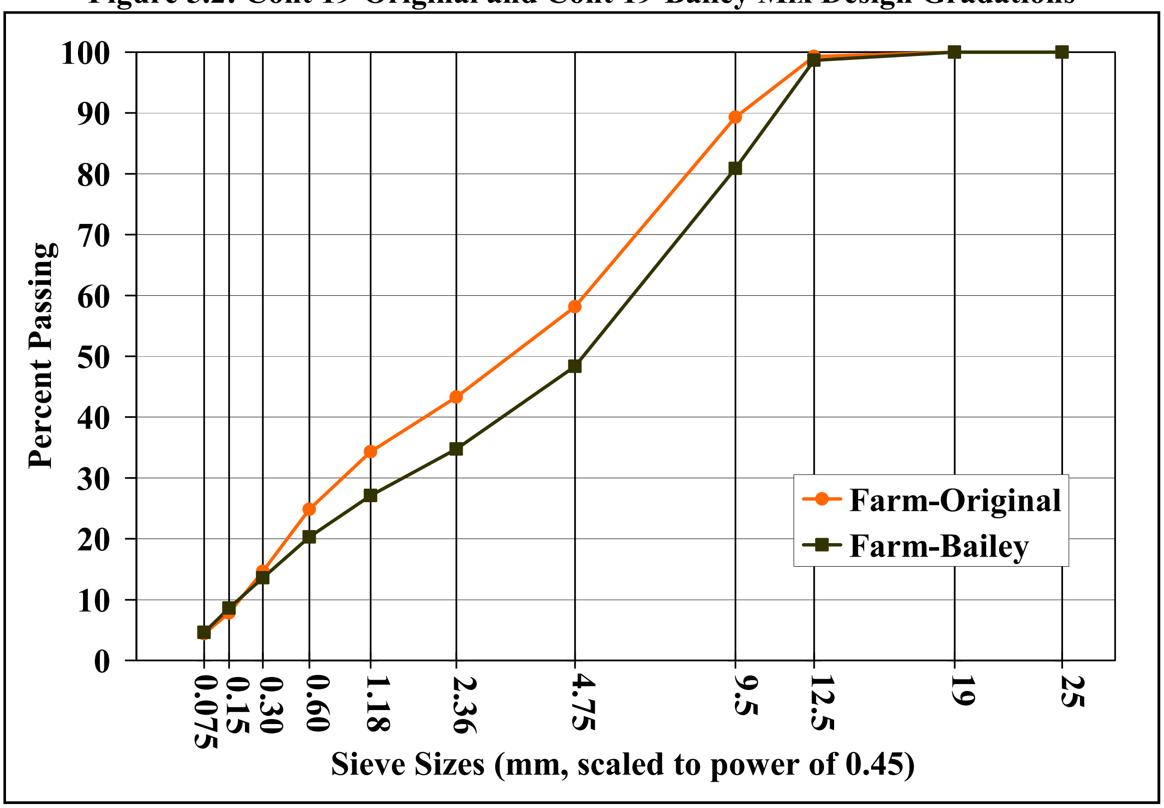


Figure 5.3: Farm-Original and Farm-Bailey Mix Design Gradations

5.2 Bailey Parameters and Volumetric Measurements

One of the strengths of using the Bailey method for evaluating aggregate gradations is that expected changes in VMA of the mix can be predicted from changes in the various Bailey parameters. The change in CUW along with the changes in the CA, FAc, and FAf weight ratios influence the expected change in VMA (see Table 2.3 in Chapter 2). The Bailey Method does not allow for the comparison of a fine graded mix to a coarse graded mix as is the case for the mixtures studied in this project; however some comparisons can be made by calculating the weight ratios twice: once as if both the original and Bailey mixes were coarse graded, and once as if they were fine graded. Tables 5.2, 5.3 and 5.5 display the four Bailey parameters, calculated according to both the coarse and fine graded cases, for the original and redesigned mixes. Additionally, the gradation of the Cont19 mixture is such that it should be defined as a 12.5 mm NMSA mixture according to a refined definition of NMSA in the Bailey Method (Bill pine personal comm.) The Bailey defninition of NMSA is one size larger than the first sieve that retains more than 15%. This was adjusted as experts found many 19 mm mixtures that fall into this category really behave more like 12.5 mm mixtures. The original Cont19 mixture should be redefined as a 12.5 mm mixture, having 89% passing the 12.5mm sieve and the Cont19 Bailey is right on the border, with 84% passing the 12.5 mm sieve. For this reason, the Bailey parameters for the Cont mixture were also calculated as if it were a 12.5mm gradation and these results are shown in Table 5.4.

Table 5.2: Expected Change in VMA from Oss 12.5-Original

	CUW	CA	FAc	FAf	Total
Coarse Graded					
Oss 12.5 Original	80	0.68	0.51	0.35	
Oss 12.5 Bailey	103	0.57	0.47	0.42	
Change	23	-0.11	-0.04	0.08	
Predicted Effect on VMA	3.5	-0.4	0.5	-1.1	2.4
Fine Graded					
Oss 12.5 Original	80	1.18	0.35	NA	
Oss 12.5 Bailey	103	1.18	0.42	NA	
Change	23	0.01	0.08	0.00	
Predicted Effect on VMA	3.5	0.0	-1.1	0.0	2.3

Table 5.3: Expected Change in VMA from Cont 19-Original

	CUW	CA	FAc	FAf	Total
Coarse Graded					
Cont 19 Original	74	0.91	0.52	0.36	
Cont 19 Bailey	101	0.68	0.46	0.42	
Change	27	-0.23	-0.07	0.06	
Predicted Effect on VMA	4.1	-0.9	1.0	-0.9	3.3
Fine Graded					
Cont 19 Original	74	0.73	0.36	0.38	
Cont 19 Bailey	101	0.66	0.42	0.54	
Change	27	-0.07	0.06	0.16	
Predicted Effect on VMA	4.1	-0.3	-0.9	-2.3	0.6

Table 5.4: Expected Change in VMA from Cont 19-Original Evaluated as a 12.5 mm Mixture

	CUW	CA	FAc	FAf	Total
Coarse Graded					
Cont 19/12.5 Original	74	0.49	0.48	0.3	
Cont 19/12.5 Bailey	101	0.34	0.45	0.43	
Change	27	-0.15	-0.03	0.13	
Predicted Effect on VMA	4.1	-0.6	0.5	-2.0	2.0
Fine Graded					
Cont 19/12.5 Original	74	0.86	0.3	NA	
Cont 19/12.5 Bailey	101	0.69	0.43	NA	
Change	27	-0.17	0.13	0	
Predicted Effect on VMA	4.1	-0.6	-2.0	0.00	1.5

Table 5.5: Expected Change in VMA from Farm-Original

	CUW	CA	FAc	FAf	Total
Coarse Graded					
Farm Original	81	0.77	0.57	0.32	
Farm Bailey	101	0.58	0.58	0.43	
Change	20	-0.20	0.01	0.11	
Predicted Effect on VMA	3.0	-0.7	-0.1	-1.6	0.5
Fine Graded					
Farm Original	81	1.06	0.32		
Farm Bailey	101	0.90	0.43		
Change	20	-0.16	0.11	0.00	
Predicted Effect on VMA	3.0	-0.6	-1.6	0.0	0.8

The Bailey Method gives a high and low expected change in VMA, 0.5% and 1.0%, for a given change in each parameter. Tables 5.2 through 5.5 use the average expected change, 0.75%. The fine graded analysis redesignates the original primary control sieve (PCS) as the fine NMSA from which the new, fine control sieves are calculated. For an original NMSA of 12.5mm, the fine tertiary control sieve (TCS) would need openings 0.033 mm in diameter. Since the smallest sieve used for asphalt engineering is the #200 with 0.075 mm openings, the TCS and the FAf ratio were ignored in the fine graded analysis for the 12.5 mm calculations.

The actual changes in VMAs are calculated from the mix design specimens and the samples fabricated for the MMLS3 tests. Figure 5.4 compares the predicted changes in VMA to the actual changes in VMA. The bar chart indicates the average values, with the high and low predicted values designated by the error bars.

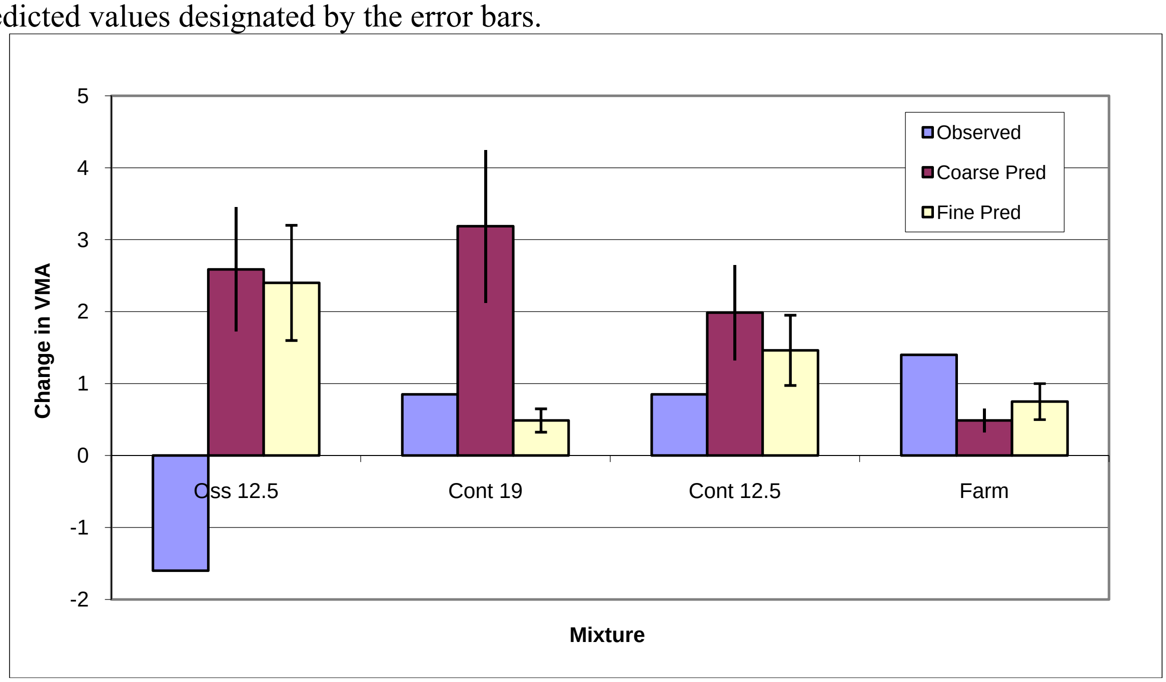


Figure 5.4: Comparison of Observed and Predicted VMA Changes

The prediction for the Ossippe mixture, regardless of whether the fine or coarse analysis is used, is in the opposite direction of the observed change in VMA. The Ossippee aggregate is rounded, so the shape may control the behavior of the mix. The fine graded prediction is closer to the observed changes for the Continental and Farmington mixtures, although the Bailey predictions do not completely account for the observed changes. Also, the 12.5 mm analysis of the Continental mixture appears to be more representative of the actual behavior than the 19 mm analysis.

5.3 MMLS3 Test Results

The MMLS3 testing and analysis for the Bailey mixtures followed the same procedures as the original mixtures. Figures 5.5 and 5.6 show the average rut depths for the Oss 12.5 and Cont 19 mixtures, respectively. The Mann-Whitney statistical analyses for the mixtures are shown in Tables 5.6 and 5.7.

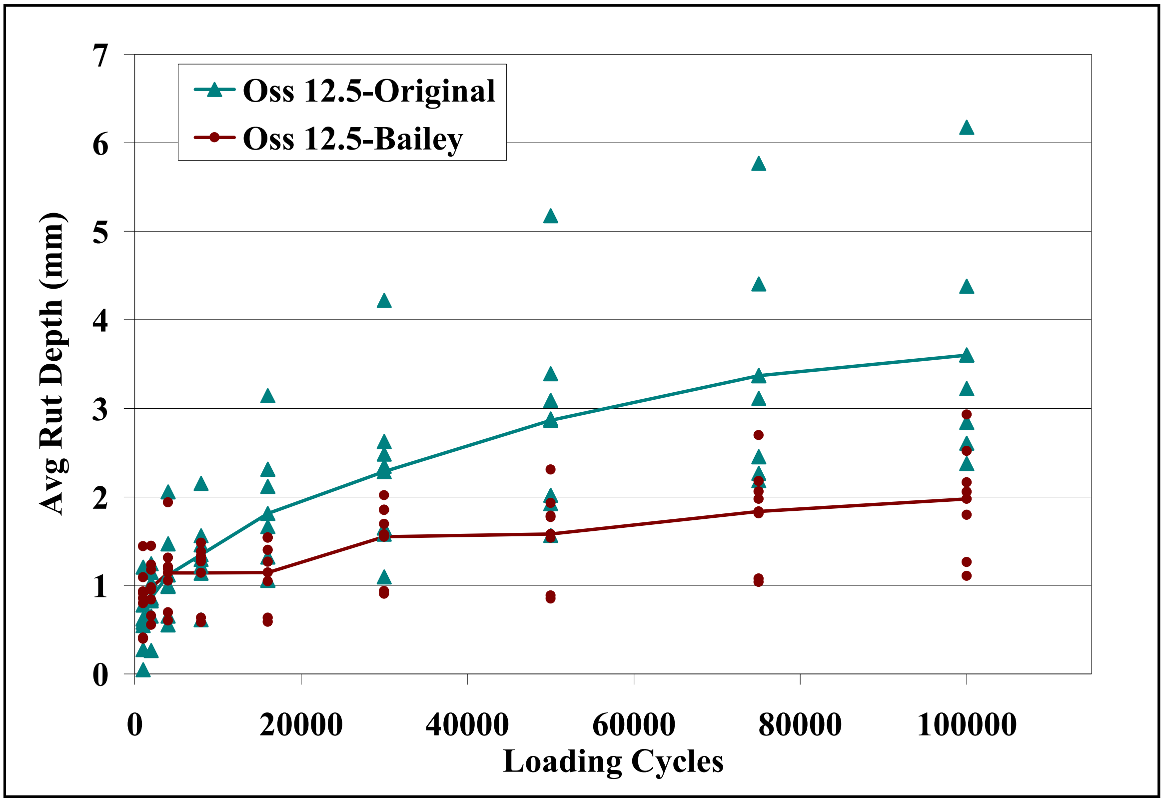


Figure 5.5: Comparison Graph of Oss 12.5-Original and Oss 12.5-Bailey

Table 5.6: Comparison of Rut Depths of Oss 12.5-Original and Oss 12.5-Bailey

	Thousands of Loading Cycles								
	1	2	4	8	16	30	50	75	100
P-Value	0.209	0.620	0.710	0.710	0.097	0.165	0.026	0.004	0.007
Significant Difference	No	No	No	No	No	No	Yes	Yes	Yes

Although the test results only become significantly different after 30,000 loading cycles, Figure 5.5 shows that the Oss 12.5-Bailey mix out performs the Oss 12.5-Original mix. There are several factors that contribute to the improved resistance to rutting. While both mixes have the same NMSA, the Bailey mix is coarser as shown in Figure 5.1. Additionally, the Bailey mix has less VMA, which means there is less room for the aggregate to compact under heavy loads. The value for voids filled with asphalt (VFA) is the percent difference between the air voids and the VMA. Since the VMA is smaller and the air voids were maintained at approximately 4%, the VFA is smaller as well meaning there is less asphalt binder in the mix to lubricate the aggregate. This gives it more resistance to rutting.

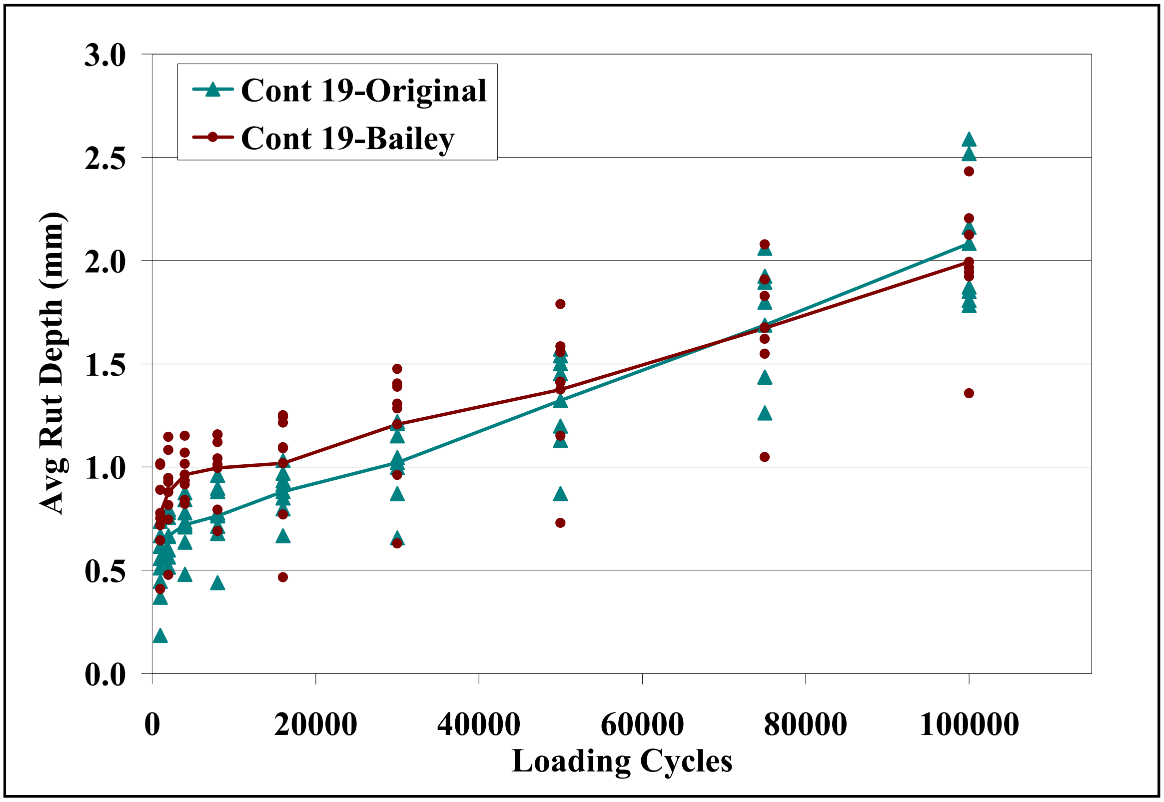


Figure 5.6: Comparison Graph of Cont 19-Original and Cont 19-Bailey

Table 5.7: Comparison of Rut Depths of Cont 19-Original and Cont 19-Bailey

	Thousands of Loading Cycles								
	1	2	4	8	16	30	50	75	100
P-Value	0.038	0.073	0.007	0.038	0.165	0.128	0.710	1.000	0.902
Significant Difference	Yes	No	Yes	Yes	No	No	No	No	No

The Cont 19-Bailey mix did not perform significantly better than the Cont 19-Original mix. Although the Bailey mix was coarser, as is shown in Figure 5.2, it also had greater VMA and, consequently, greater VFA. The greater VMA was predicted by the Bailey Method because a coarser mix tends to resist compaction more than a finer one. Additionally, the rough and angular fractured rock aggregate probably helped the mix resist compaction even more than usual. While the coarse mix and rough aggregate would also help resist rutting, a greater amount of asphalt binder promotes rutting because it allows the aggregate particles to slide around more easily (Qiu 2006). These two factors seem to have off set each other making the net rutting resistance of the Bailey mix about the same as the original one.

The Bailey Method predictions on compactability state that higher CUW and CA ratio values mean greater resistance to compaction. If the values stay within the recommended range, then the increased resistance should be too small to hinder paving operations. Additionally, similar effects occur with lowered FAc ratio and FAf ratio values. Figure 5.7 shows the average compaction for both the Cont 19-Original and Cont 19-Bailey samples. The Bailey samples require approximately 3 times the number of gyrations as the original ones to reach the same height. Figure 5.8 shows the average density of both sets of samples over the course of compaction. The Bailey samples required about 2 times the number of gyrations to reach the same density as the original ones. As it is, the Cont 19-Bailey mix would be difficult to compact in the field.

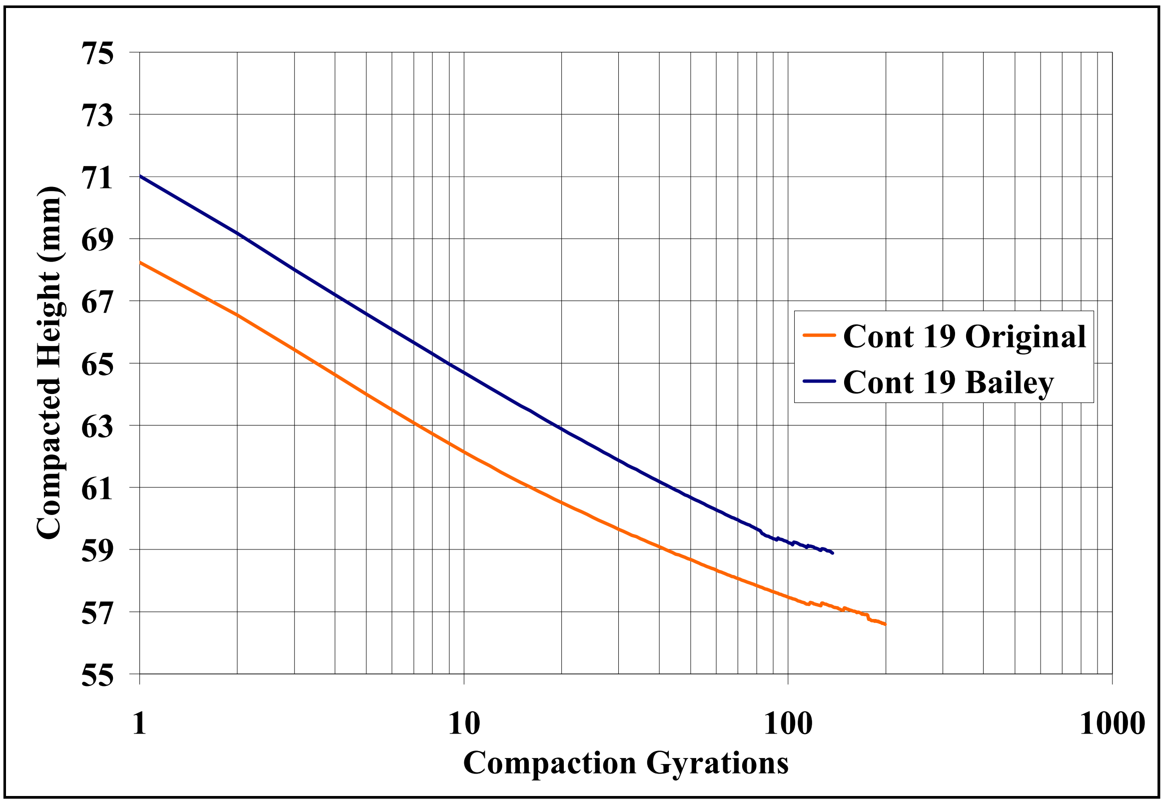


Figure 5.7: Compaction of Cont 19 Mixes

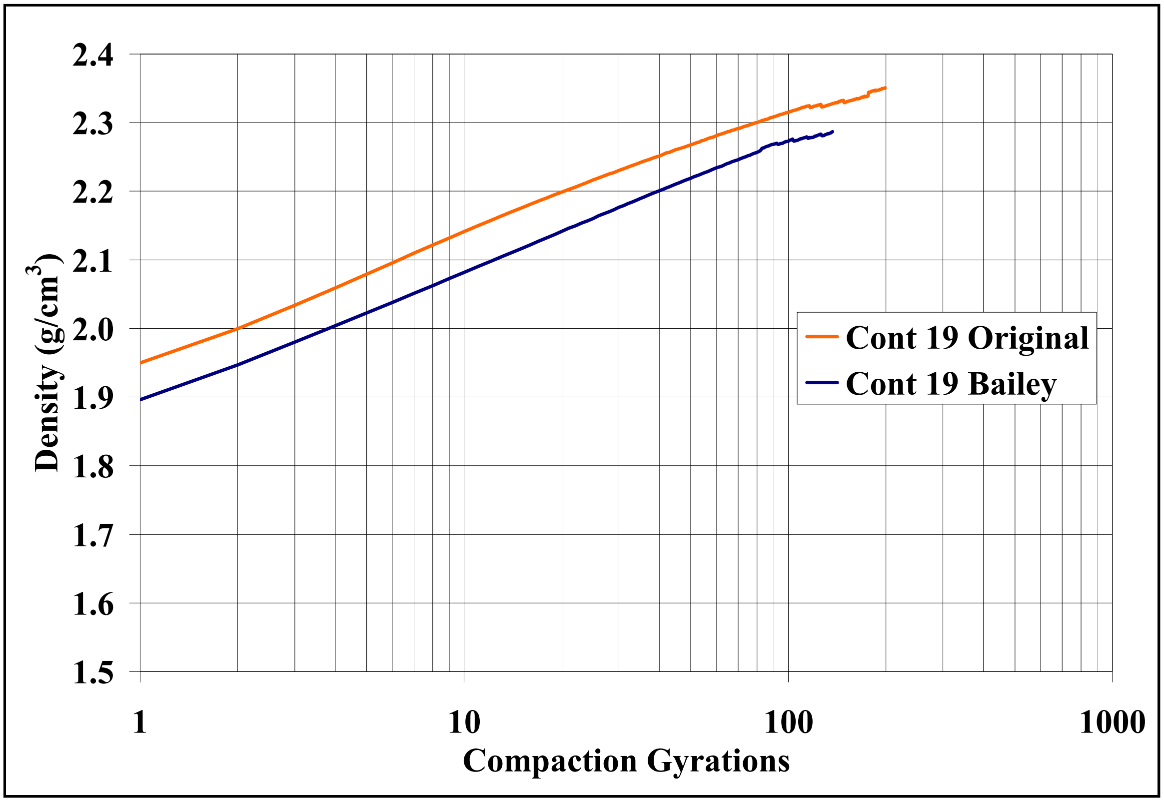


Figure 5.8: Density over Course of Compaction of Cont 19 Mixes

The Oss 12.5-Bailey mix was expected to have a greater VMA than the Oss 12.5-Original mix because the Bailey Method predicts that the greater density in coarse aggregate will resist compaction causing an increase in VMA. While the rough, angular fractured rock in the Cont 19-Bailey mix most likely supported this resistance to compaction, the smooth, rounded gravel stone in the Oss 12.5-Bailey mix may have countered the resistance to compaction. The Bailey Method assumes there will be enough compaction so its model of particle packing applies. However, if there was extra compaction, then voids between the coarse aggregate were smaller than expected and most of the space was taken up by fine aggregate instead of air or binder, thus resulting in a lower VMA. The lower VMA, lower asphalt content, and a coarser blend seem to be the greatest factors that improved the rut resistance over the original design.

The increased CUW for the Oss 12.5-Bailey mix also meant that this mix would have greater resistance to compaction than the original mix. Although the samples for the original mix design were batched to 4500g and the samples for the Bailey design were batched to 2250g, the densities can be compared. Figure 5.9 shows the comparison of the average densities of the two mixes over the course of compaction. The Oss 12.5-Bailey samples require approximately 3 times the number of gyrations to reach the same density as the original samples. This confirms the Bailey Method prediction. The compaction data do not indicate whether the aggregate shape and texture had any effect on the mixture's resistance to compaction.

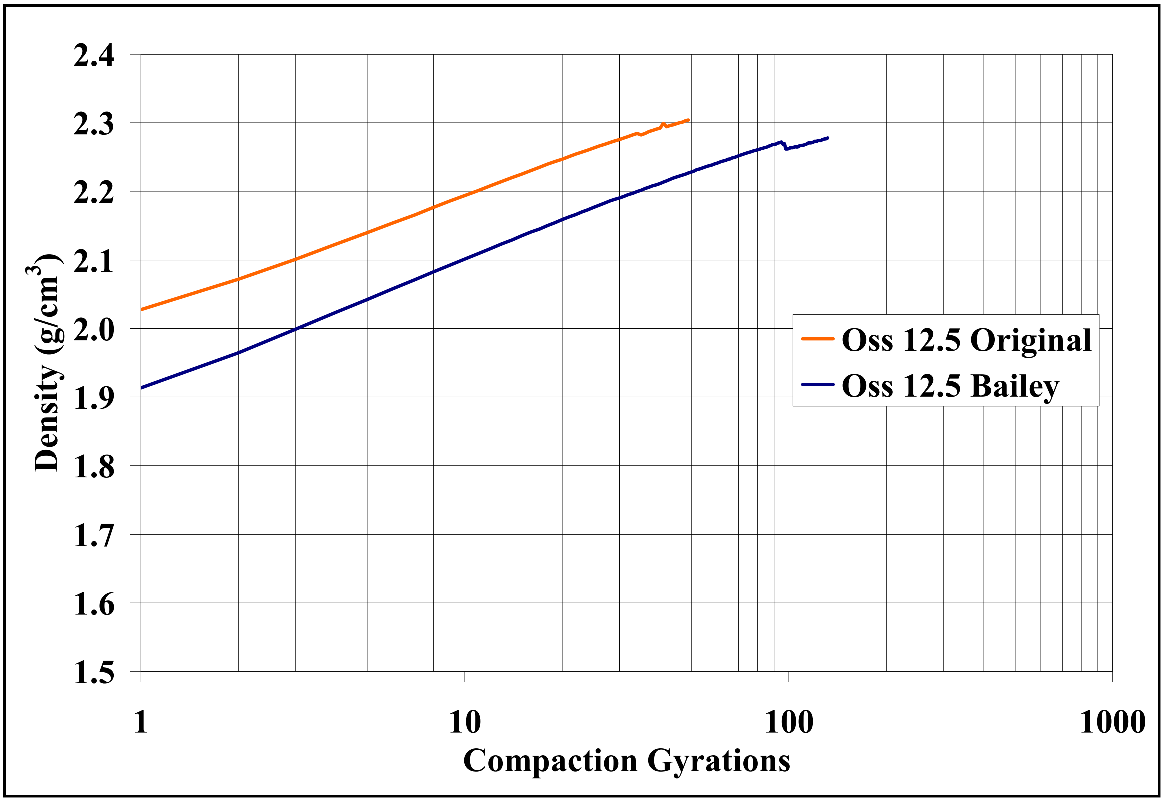


Figure 5.9: Density over Course of Compaction of Oss 12.5 Mixes

6.0 Summary and Conclusions

The objective of this research project was to evaluate the applicability of the Bailey Method to typical New Hampshire materials. Six mix designs commonly used throughout New Hampshire were chosen for evaluation. Half of the designs used gravel stone with rounded, smooth faces, and the other half used fractured rock with rough, angular faces. Two mixtures also contained 15% RAP. NMSA values of 19 mm and 12.5 mm were chosen as representative of most mixtures placed in the state.

Specimens of each mixture were fabricated in the laboratory and tested using the MMLS3 under dry conditions at a target test temperature of 60^{o}C. Transverse rut profiles of each specimen were taken at various load intervals to develop rut depth profiles as a function of time. Average rut depths were calculated and comparisons among the various mixtures were done. Additionally, field cores of two of the mixtures were taken and tested under the MMLS3 loading. Statistical analysis of the rut data was performed using the Mann-Whitney/Wilcoxon Rank Sum Test.

The MMLS3 laboratory testing resulted in expected trends in relative performance of the various mixtures:

- The 19 mm mixtures showed statistically better performance than the 12.5 mm mixtures
- The rough, angular aggregates showed better average performance than the smooth, rounded aggregates. The difference was statistically significant for some cases, but not for all.
- The mixtures containing RAP showed better average performance than those without RAP. The difference was statistically significant for the rounded aggregate, but not for the angular aggregate.
- Laboratory specimens performed significantly better than the field cores

Three of the mixtures were chosen for redesign with the Bailey Method. The Bailey parameters for the original mixtures were calculated and the gradations were redesigned to fall within the recommended ranges. All of the original mixtures are classified as “fine graded” under the Bailey definitions and all were redesigned to be “coarse graded”. Superpave mix designs were done to determine the asphalt content and then specimens were fabricated for testing under the MMLS3. The one RAP mixture could not be redesigned to meet the Superpave criteria and was not tested under the MMLS3.

The Bailey method provides predictions for the change in VMA that correspond to changes in the various Bailey ratios. Although direct comparisons between fine graded and coarse graded mixtures can not be made using this technique, some general trends were observed for the mixtures evaluated in this project. The Bailey method was able to predict the increase in VMA that occurred for the angular aggregate and RAP mixture, but predicted a decrease in VMA for the rounded aggregate and an increase was measured. It is important to note that the Bailey method only takes into consideration aggregate gradation, and other factors that affect compaction and the resulting volumetrics, such as angularity and roughness, are not accounted for. The performance of the redesigned mixtures with respect to compaction and rutting performance was evaluated:

- The 12.5 mm redesigned mixture showed significantly better performance than the original mixture
- The performance of the original and redesigned 19mm mixture was not significantly different.
- The redesigned mixtures required approximately three times the number of gyrations to reach the same density as the original mixtures, confirming the Bailey predictions.

Overall, this research project showed that the Bailey Method would be a useful tool in the evaluation and design of New Hampshire mixtures. The Bailey Method should not be used exclusively, but can be used in combination with knowledge of the aggregate angularity, roughness, and engineering judgment to provide guidance during the mix design procedure and improve mixture performance. The study also showed that the MMLS3 is an appropriate method for evaluating the relative rutting performance of different mixtures in the laboratory.

7.0 References

AASHTO T-2-91 (2000), "Sampling of Aggregates." Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part 2A: Tests, 25th Edition, American Association of State Highway and Transportation Officials, 2005

AASHTO T-19M/ T-19-00 (2004), "Bulk Density (Unit Weight) and Voids in Aggregate." Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part 2A: Tests, 25th Edition, American Association of State Highway and Transportation Officials, 2005

AASHTO T-166-05, "Bulk Specific Gravity of Compacted Hot-Mix Asphalt Using Saturated Surface-Dry Specimens." Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part 2A: Tests, 25th Edition, American Association of State Highway and Transportation Officials, 2005

AASHTO T-209-05, "Theoretical Maximum Specific Gravity and Density of Hot-Mix Asphalt Paving Mixtures." Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part 2A: Tests, 25th Edition, American Association of State Highway and Transportation Officials, 2005

AASHTO T-248-02, "Reducing Samples of Aggregate to Testing Size." Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part 2B: Tests, 25th Edition, American Association of State Highway and Transportation Officials, 2005

Donald W. Christensen, Jr., Terhi Pellinen and Ramon F. Bonaquist (2003). "Hirsch Model for Estimating the Modulus of Asphalt Concrete." *Journal of the Association of Asphalt Paving Technologists*, Vol 72.

Epps, A. L.; T. Ahmed; D. C. Little; F. Hugo. "Performance Prediction with the MMLS3 at Westrack." Texas Department of Transportation, Research Report FHWA/TX-01/2134-1, May 2001

Gierhart, D. "Analysis of Oklahoma Mix Designs for the National Center for Asphalt Technology Test Track Using the Bailey Method." *Practical Approaches to Hot-Mix Asphalt Mix Design and Production Quality Control Testing,* Transportation Research E-Circular No. E-C124, December 2007

Khosla, N.P.; S. Sadasivam. "Determination of Optimum Gradation for Resistance to Permeability, Rutting and Fatigue Cracking." North Carolina Department of Transportation, Final Report FHWA/NC/2004-12, February 2005

Mohammad, L.N.; K. Al Shamsi. "A Look at the Bailey Method and Locking Point Concept in Superpave Mixture Design." *Practical Approaches to Hot-Mix Asphalt Mix Design and Production Quality Control Testing,* Transportation Research E-Circular No. E-C124, December 2007

Qiu, Y.F.; K.M. Lum. "Design and Performance of Stone Mastic Asphalt." *Journal of Transportation Engineering*. December 2006

Roberts, F.L.; P.W. Kandhal; E.R. Brown; D. Lee; T.W. Kennedy. "Hot Mix Asphalt Materials, Mixture Design, and Construction." 2nd Edition. National Asphalt Pavement Association Research and Education Foundation, Lanham MD, 1996

Smit, A. F.; F. Hugo; D. Rand; B. Powell. "MMLS3 Testing at the NCAT Test Track." TRB Annual Meeting, Transportation Research Board, Washington D. C., January 2003

Smit, A.F.; F. Hugo, A. Epps. "Report on the First Jacksboro MMLS Tests." Texas Department of Transportation, Research Report FHWA/TX-00/0-1814-2, December 1999

Superpave Mix Design, Superpave Series No. 2 (SP-2), 3rd Edition, Asphalt Institute, 2001 Printing

Thompson, G. "Investigation of the Bailey Method for the Design and Analysis of Dense-Graded HMAC Using Oregon Aggregates." Oregon Department of Transporation, Federal Highway Administration, Final Report FHWA-OR-DF-07-02, September 2006

Vavrik, W. R.; G. Huber, W. J. Pine, S. H. Carpenter, R. Bailey. "Bailey Method for Gradation Selection in Hot-Mix Asphalt Mixture Design." Transportation Research E-Circular No. E-C044. Transportation Research Board, Washington D.C., October 2002

8.0 Appendices

APPENDIX A: BAILEY CALCULATIONS
APPENDIX B: SPECIMEN VOLUMETRICS
APPENDIX C: MMLS3 TEST RESULTS
APPENDIX D: TEMPERATURE ADJUSTMENT METHOD
APPENDIX E: STATISTICAL COMPARISONS
APPENDIX F: BAILEY SUPERPAVE MIX DESIGNS

APPENDIX A: BAILEY CALCULATIONS

Design Calculations

The calculations shown here use the Oss 12.5 mix design as an example. These calculations were used for both design and evaluation. For design, the input values were varied until the weight ratios were as close to their target values as possible. For evaluation, the input values were varied until the calculated blend matched the original blend as closely as possible. At each step in the calculations, the general equation is shown followed by the calculations using the numerical values for Oss 12.5.

Abbreviations:

CA_1: Coarse Aggregate 1
FA_1: Fine Aggregate 1
MF: Mineral Filler Aggregate
PCS: Percent Passing the Primary Control Sieve
#200: Percent Passing the #200 Sieve
Gsb_i: Bulk Specific Gravity of Aggregate i
LUW_i: Loose Unit Weight of Aggregate i (kg/m^3)
RUW_i: Rodded Unit Weight of Aggregate i (kg/m^3)
CUW: Chosen Unit Weight
Dust: Desired Amount Passing the #200 Sieve for the Final Gradation
CA_iW_c: Contributed Weight for Coarse Aggregate i
FA_iW_c: Contributed Weight for Fine Aggregate i
VCA: Voids in the Coarse Aggregate
TUW: Total Unit Weight
CA_iB_{in}: Initial Contribution of Coarse Aggregate i as a Percentage of the Total Blend
CA_iB_f: Final Contribution of Coarse Aggregate i as a Percentage of the Total Blend
FA_iB_{in}: Initial Contribution of Fine Aggregate i as a Percentage of the Total Blend
FA_iB_{adj}: Adjusted Contribution of Fine Aggregate i as a Percentage of the Total Blend
FA_iB_f: Final Contribution of Fine Aggregate i as a Percentage of the Total Blend
MFB_f: Final Contribution of Mineral Filler as a Percentage of the Total Blend
$FAinCA_i$: Percent of Fine Aggregate in Coarse Aggregate i
$CAinFA_i$: Percent of Coarse Aggregate in Fine Aggregate i
$MFinCA_i$: Percent of Mineral Filler in Coarse Aggregate i
$MFinFA_i$: Percent of Mineral Filler in Fine Aggregate i

Table A1: Aggregate Data

Aggregate	Name	PCS	#200	Gsb	LUW	RUW
CA_1	1/2" Gravel	3	0.9	2.619	1501.6	1625.8
CA_2	3/8" Gravel	9	1.0	2.588	1510.6	1616.5
FA_1	Grits	83	3.1	2.556	1573.6	1713.6
FA_2	Dust	85	13.0	2.607	1502.6	1772.6
FA_3	Scr. Sand	91	2.2	2.543	1541.5	1691.3
MF	BHF	100	80.0			

Table A2: Input Values

Input	Value	Limits
CUW	103	95 – 105
Dust	4.7	3.5 – 6.0
Coarse Agg. Contributions		
CA1	41	
CA2	59	
Fine Agg. Contributions		
FA1	100	
FA2	0	
FA3	0	

Calculations:

Step 1

$CUW_i = LUW_i \times CUW / 100$

$CUW_1 = 1501.6 \times 103 / 100 = 1546.6$

$CUW_2 = 1510.6 \times 103 / 100 = 1555.9$

Step 2

$CA_iW_c = CUW_i \times CA_i$ Contribution / 100

$CA_1W_c = 1546.6 \times 41 / 100 = 634.1$

$CA_2W_c = 1555.6 \times 59 / 100 = 918.0$

Step 3

$VCA_i = CA_i$ Contribution $\times (1 - (CUW_i / (1000 \times Gsb_i)))$

$VCA_1 = 41 \times (1 - (1546.6 / (1000 \times 2.619))) = 16.8$

$VCA_2 = 59 \times (1 - (1555.6 / (1000 \times 2.588))) = 23.5$

Step 4

$VCA_T = \sum VCA_i$

$VCA_T = 16.8 + 23.5 = 40.3$

Step 5

$FA_iW_c = RUW_i \times (FA_i$ Contribution $/ 100) \times (VCA_T / 100)$

$FA_1W_c = 1713.6 \times (100 / 100) \times (40.3 / 100) = 690.9$

$FA_2W_c = 1772.6 \times (0 / 100) \times (40.3 / 100) = 0$

$FA_3W_c = 1691.3 \times (0 / 100) \times (40.3 / 100) = 0$

Step 6

$TUW = \sum CA_iW_c + \sum FA_iW_c$

$TUW = 634.1 + 918.0 + 690.9 = 2243.0$

Step 7

$CA_iB_{in} = 100 \times CA_iW_c / TUW$

$CA_1B_{in} = 100 \times 634.1 / 2243.0 = 28.3$

$CA_2B_{in} = 100 \times 918.0 / 2243.0 = 40.9$

Step 8

$CA_TB_{in} = \sum CA_iB_{in}$
$CA_TB_{in} = 28.3 + 40.9 = 69.2$

Step 9
$FA_iB_{in} = 100 \times FA_iW_c / TUW$
$FA_1B_{in} = 100 \times 690.9 / 2243.0 = 30.8$
$FA_2B_{in} = 100 \times 0 / 2243.0 = 0$
$FA_3B_{in} = 100 \times 0 / 2243.0 = 0$

Step 10
$FA_TB_{in} = \sum FA_iB_{in}$
$FA_TB_{in} = 30.8 + 0 + 0 = 30.8$

Step 11
$FAinCA_i = CA_iB_{in} \times PCS_i / 100$
$FAinCA_1 = 28.3 \times 3 / 100 = 0.8$
$FAinCA_2 = 40.9 \times 9 / 100 = 3.7$

Step 12
$FAinCA_T = \sum FAinCA_i$
$FAinCA_T = 0.8 + 3.7 = 4.5$

Step 13
$CAinFA_i = FA_iB_{in} \times (100 – PCS_i) / 100$
$CAinFA_1 = 30.8 \times (100 – 83) / 100 = 5.2$
$CAinFA_2 = 0 \times (100 – 85) / 100 = 0$
$CAinFA_3 = 0 \times (100 – 91) / 100 = 0$

Step 14
$CAinFA_T = \sum CAinFA_i$
$CAinFA_T = 5.2 + 0 + 0 = 5.2$

Step 15
$CA_iB_f = CA_iB_{in} + FAinCA_i – (CA_iB_{in} \times CAinFA_T / CA_TB_{in})$
$CA_1B_f = 28.3 + 0.8 – (28.3 \times 5.2 / 69.2) = 27.0$
$CA_2B_f = 40.9 + 3.7 – (40.9 \times 5.2 / 69.2) = 41.5$

Step 16
$FA_iB_{adj} = FA_iB_{in} + CAinFA_i – (FA_iB_{in} \times FAinCA_T / FA_TB_{in})$
$FA_1B_{adj} = 30.8 + 5.2 – (30.8 \times 4.5 / 30.8) = 31.5$
$FA_2B_{adj} = 0 + 0 – (0 \times 4.5 / 30.8) = 0$
$FA_3B_{adj} = 0 + 0 – (0 \times 4.5 / 30.8) = 0$

Step 17
$MFinCA_i = CA_iB_f \times \#200 / 100$
$MFinCA_1 = 27.0 \times 0.9 / 100 = 0.2$
$MFinCA_2 = 41.5 \times 1.0 / 100 = 0.4$

Step 18

$MFinFA_i = FA_iB_{adj}$ x #200 / 100

$MFinFA_1$= 31.5 x 3.1 / 100 = 1.0

$MFinFA_2$= 0 x 13.0 / 100 = 0

$MFinFA_3$= 0 x 2.2 / 100 = 0

Step 19

$MF_T = \sum MFinCA_i + \sum MFinFA_i$

MF_T = 0.2 + 0.4 + 1.0 + 0 + 0 = 1.6

Step 20

$MFB_f = (Dust – MF_T) / (\#200_{MF} / 100)$

MFB_f = (4.7 – 1.6) / (80.0 / 100) = 3.8

Step 21

$FA_iB_f = FA_iB_{adj} – (FA_iB_{adj} \text{ x } MFB_f / \sum FA_iB_{adj})$

FA_1B_f = 31.5 – (31.5 x 3.8 / 31.5) = 27.7

FA_2B_f = 0 – (0 x 3.8 / 31.5) = 0

FA_3B_f = 0 – (0 x 3.8 / 31.5) = 0

Table A3: Output Values

Aggregate	% Blend
1/2” Gravel	27.0
3/8” Gravel	41.5
Grits	27.67
Dust	0
Scr. Sand	0
BHF	3.83

Weight Ratio Calculations

The formulas for the weight ratios are the same for both the coarse graded analysis and the fine graded analysis. Only the gradations and the size of the control sieves change from one analysis to the next. The gradations are listed for each mix design along with labels telling which sieves are the control sieves.

Abbreviations:

NMSA: Nominal Maximum Size Aggregate, one sieve higher than the first sieve to retain 10% or more

Half: Percent passing the Half Sieve, the closest sieve to 0.5 times the NMSA

PCS: Percent passing the Primary Control Sieve, the closest sieve to 0.22 times the NMSA

SCS: Percent passing the Secondary Control Sieve, the closest sieve to 0.22 times the PCS

TCS: Percent passing the Tertiary Control Sieve, the closest sieve to 0.22 times

	the SCS
CA:	Coarse Aggregate weight ratio
FAc:	Coarse part of the Fine Aggregate weight ratio
FAf:	Fine part of the Fine Aggregate weight ratio
$Diff_T$:	Total difference between calculated gradation and original blend

Calculations:

CA = (Half – PCS) / (100 – Half)
FAc = SCS / PCS
FAf = TCS / SCS
Half = %Pass 3/8 – (%Pass 3/8 – %Pass #4) x (9.5 – 6.25) / (9.5 – 4.75);
for NMSA of 12.5
$Diff_T = \sum|Blend_{i,original} - Blend_{i,calculated}|$

<u>Oss 12.5 Original</u>

Table A4: Oss 12.5 Original Gradation

	Coarse Graded Analysis		Fine Graded Analysis	
Sieve (mm)	**% Pass**	**Control Sieves**	**% Pass**	**Control Sieves**
25.0	100.0		100.0	
19.0	100.0		100.0	
12.5	99.1	NMSA	100.0	
9.5	89.8		100.0	
6.25	66.3	Half	100.0	
4.75	55.5		100.0	
2.36	43.3	PCS	100.0	NMSA
1.18	33.5		77.3	Half
0.600	21.9	SCS	50.7	PCS
0.300	12.7		29.4	
0.150	7.6	TCS	17.7	SCS
0.075	4.5		10.5	

Table A5: Input Values for Oss 12.5 Original Evaluation

Input	**Value**	**Limits**
CUW	80	95 – 105
Dust	4.6	3.5 – 6.0
Coarse Agg. Contributions		
CA1	37	
CA2	63	
Fine Agg. Contributions		
FA1	35	
FA2	42	
FA3	23	

Table A6: Output Values for Oss 12.5 Original Evaluation

	Coarse Graded Analysis		Fine Graded Analysis	
Parameter	**Value**	**Limits**	**Value**	**Limits**
CUW	80	95 - 105	80	<90
CA	0.68	0.50 - 0.65	1.18	0.60 - 1.00
FAc	0.51	0.35 - 0.50	0.35	0.35 - 0.50
FAf	0.35	0.35 - 0.50	NA	0.35 - 0.50
$Diff_T$	0.60		0.60	

Oss 12.5 Bailey

Table A7: Oss 12.5 Bailey Gradation

	Coarse Graded Analysis		Fine Graded Analysis	
Sieve (mm)	**% Pass**	**Control Sieves**	**% Pass**	**Control Sieves**
25.0	100.0		100.0	
19.0	100.0		100.0	
12.5	98.7	NMSA	100.0	
9.5	85.6		100.0	
6.25	56.4	Half	100.0	
4.75	43.0		100.0	
2.36	31.3	PCS	100.0	NMSA
1.18	23.7		75.7	Half
0.600	14.7	SCS	47.1	PCS
0.300	8.8		28.0	
0.150	6.3	TCS	20.0	SCS
0.075	4.6		14.6	

Table A8: Input Values for Oss 12.5 Bailey Design

Input	Value	Limits
CUW	103	95 – 105
Dust	4.7	3.5 – 6.0
Coarse Agg. Contributions		
CA1	41	
CA2	59	
Fine Agg. Contributions		
FA1	100	
FA2	0	
FA3	0	

Table A9: Output Values for Oss 12.5 Bailey Design

	Coarse Graded Analysis		Fine Graded Analysis	
Parameter	**Value**	**Limits**	**Value**	**Limits**
CUW	103	95 - 105	103	<90
CA	0.57	0.50 - 0.65	1.18	0.60 - 1.00
FAc	0.47	0.35 - 0.50	0.42	0.35 - 0.50
FAf	0.42	0.35 - 0.50	NA	0.35 - 0.50

Cont 19 Original

Table A10: Cont 19 Original Gradation

	Coarse Graded Analysis		Fine Graded Analysis	
Sieve (mm)	% Pass	Control Sieves	% Pass	Control Sieves
25.0	100.0		100.0	
19.0	99.3	NMSA	100.0	
12.5	89.0		100.0	
9.5	73.4	Half	100.0	
4.75	49.1	PCS	100.0	NMSA
2.36	35.6		72.5	Half
1.18	25.7	SCS	52.4	PCS
0.600	17.2		35.0	
0.300	9.3	TCS	19.0	SCS
0.150	5.2		10.5	
0.075	3.6		7.3	TCS

Table A11: Input Values for Cont 19 Original Evaluation

Input	Value	Limits
CUW	74	95 – 105
Dust	3.6	3.5 – 6.0
Coarse Agg. Contributions		
CA1	31	
CA2	38	
CA3	31	
Fine Agg. Contributions		
FA1	55	
FA2	45	

Table A12: Output Values for Cont 19 Original Evaluation

	Coarse Graded Analysis		Fine Graded Analysis	
Parameter	Value	Limits	Value	Limits
CUW	74	95 - 105	74	<90
CA	0.91	0.60 - 0.75	0.73	0.60 - 1.00
FAc	0.52	0.35 - 0.50	0.36	0.35 - 0.50
FAf	0.36	0.35 - 0.50	0.38	0.35 - 0.50
$Diff_T$	0.28		0.28	

Cont 19 Bailey

Table A13: Cont 19 Bailey Gradation

	Coarse Graded Analysis		Fine Graded Analysis	
Sieve (mm)	**% Pass**	**Control Sieves**	**% Pass**	**Control Sieves**
25.0	100.0		100.0	
19.0	98.9	NMSA	100.0	
12.5	84.0		100.0	
9.5	61.1	Half	100.0	
4.75	34.6	PCS	100.0	NMSA
2.36	23.3		67.4	Half
1.18	15.8	SCS	45.7	PCS
0.600	10.6		30.8	
0.300	6.7	TCS	19.2	SCS
0.150	4.6		13.2	
0.075	3.6		10.4	TCS

Table A14: Input Values for Cont 19 Bailey Design

Input	Value	Limits
CUW	101	95 – 105
Dust	3.7	3.5 – 6.0
Coarse Agg. Contributions		
CA1	35	
CA2	45	
CA3	20	
Fine Agg. Contributions		
FA1	75	
FA2	25	

Table A15: Output Values for Cont 19 Bailey Design

	Coarse Graded Analysis		Fine Graded Analysis	
Parameter	**Value**	**Limits**	**Value**	**Limits**
CUW	101	95 - 105	101	<90
CA	0.68	0.60 - 0.75	0.66	0.60 - 1.00
FAc	0.46	0.35 - 0.50	0.42	0.35 - 0.50
FAf	0.42	0.35 - 0.50	0.54	0.35 - 0.50

Farm Original

Table A16: Farm Original Gradation

	Coarse Graded Analysis		Fine Graded Analysis	
Sieve (mm)	**% Pass**	**Control Sieves**	**% Pass**	**Control Sieves**
25.0	100.0		100.0	
19.0	100.0		100.0	
12.5	99.3	NMSA	100.0	
9.5	89.3		100.0	
6.25	68.0	Half	100.0	
4.75	58.1		100.0	
2.36	43.3	PCS	100.0	NMSA
1.18	34.3		79.2	Half
0.600	24.8	SCS	57.4	PCS
0.300	14.6		33.7	
0.150	7.8	TCS	18.1	SCS
0.075	4.4		10.1	

Table A17: Input Values for Farm Original Evaluation

Input	Value	Limits
CUW	81	95 – 105
Dust	3.6	3.5 – 6.0
Coarse Agg. Contributions		
CA1	38	
CA2	62	
Fine Agg. Contributions		
FA1	56	
FA2	24	
FA3	20	
RAP	14.4	

Table A18: Output Values for Farm Original Evaluation

	Coarse Graded Analysis		Fine Graded Analysis	
Parameter	**Value**	**Limits**	**Value**	**Limits**
CUW	81	95 - 105	81	<90
CA	0.77	0.50 - 0.65	1.06	0.60 - 1.00
FAc	0.57	0.35 - 0.50	0.32	0.35 - 0.50
FAf	0.32	0.35 - 0.50	NA	0.35 - 0.50
$Diff_T$	0.55		0.55	

Farm Bailey

Table A19: Farm Bailey Gradation

	Coarse Graded Analysis		Fine Graded Analysis	
Sieve (mm)	**% Pass**	**Control Sieves**	**% Pass**	**Control Sieves**
25.0	100.0		100.0	
19.0	100.0		100.0	
12.5	98.7	NMSA	100.0	
9.5	80.9		100.0	
6.25	58.6	Half	100.0	
4.75	48.3		100.0	
2.36	34.8	PCS	100.0	NMSA
1.18	27.1		78.0	Half
0.600	20.3	SCS	58.3	PCS
0.300	13.6		39.1	
0.150	8.6	TCS	24.8	SCS
0.075	4.6		13.3	

Table A20: Input Values for Farm Bailey Design

Input	Value	Limits
CUW	101	95 – 105
Dust	3.8	3.5 – 6.0
Coarse Agg. Contributions		
CA1	58	
CA2	42	
Fine Agg. Contributions		
FA1	19	
FA2	81	
FA3	0	
RAP	15.0	

Table A21: Output Values for Farm Bailey Design

	Coarse Graded Analysis		Fine Graded Analysis	
Parameter	**Value**	**Limits**	**Value**	**Limits**
CUW	101	95 - 105	101	<90
CA	0.58	0.50 - 0.65	0.90	0.60 - 1.00
FAc	0.58	0.35 - 0.50	0.43	0.35 - 0.50
FAf	0.43	0.35 - 0.50	NA	0.35 - 0.50

Matlab Programs

These Matlab programs iterate through all possible combinations of input values to find the best aggregate blend, whether that means a blend with optimum weight ratios or one that matches a target blend. Baileydesign.m is the main program for designing new aggregate blends. It is set up to work with the Oss 12.5 and Farm mixes because Cont 19 was done manually before hand. The program calls Bailey.m and Baileylimits.m. The first one contains the full Bailey calculations and the second outputs a list of limiting values for both the Bailey Method and Superpave. Baileyevaluation.m is the main program for evaluation and finds the input values to match a target blend.

BAILEYDESIGN.M

```
function inputs=baileydesign(Agg,NMSA,RAP);

% This matlab function determines the input values to acheive the
% optimum bailey parameters given a set of aggregate, a PCS, and a
% desired amount of RAP.  "Optimum" is defined as the minimum sum of
% the deviations from the target values
% INPUT
%    Agg = aggregate info in matrix format (see osspiee.m for example)
%    NMSA = Nominal Maximum Size Aggegate, enter as mm
%    RAP = percentage of aggregate blend that is RAP
% OUTPUT
%    input = a matrix of seven sets of input values, one in each row

% Define variables for comparison and set targets
currentinput=zeros(1,9);
prevTotal=100;
lim=baileylimits(NMSA);
CAtarget=(lim(5)+lim(6))/2;
FActarget=(lim(7)+lim(8))/2;
FAftarget=(lim(9)+lim(10))/2;

% Iterate through all possible inputs
n=0;
for cuw=95:105
   for dd=3.5:0.1:6.0
      for ca2=0:100
         for fa1=0:100
            for fa2=0:100-fa1
               currentinput(1)=cuw;
               currentinput(2)=dd;
               currentinput(3)=0;
               currentinput(4)=ca2;
               currentinput(5)=100-ca2;
               currentinput(6)=fa1;
               currentinput(7)=fa2;
               currentinput(8)=100-fa1-fa2;
               currentinput(9)=RAP;
               [blend,grad,ratios,tests]=bailey(Agg,NMSA,currentinput);
               blendOK=1;
               for stockpile=1:8
                  if blend(stockpile)<0;
                     blendOK=0;
```

```
                  end
               end
               if (tests(1)==1)&&(blendOK==1)
                  n=n+1;
                  CAdiff=abs(ratios(1)-CAtarget);
                  FAcdiff=abs(ratios(2)-FActarget);
                  FAfdiff=abs(ratios(3)-FAftarget);
                  Totaldiff=CAdiff+FAcdiff+FAfdiff;
                  if (Totaldiff<=prevTotal)
                     inputbest=currentinput;
                     prevTotal=Totaldiff;
                  end
               end
            end
         end
      end
   end
end

% Output results.  If n=0 at the end, something went wrong
if (n==0)
    inputs=3.14159;
else
    inputs=zeros(1,9);
    inputs=inputbest;
end

disp('cool beans');

return
```

BAILEY.M

```
function [blend,gradation,ratios,tests]=bailey(Agg,NMSA,Input)

% This matlab function calculates the aggregate blend of an asphalt mix
% using the Bailey Method given a set of aggregate, a PCS, and a set of
% input values.
% INPUT
%    Agg = aggregate info in matrix format (see osspiee.m for example)
%    NMSA = Nominal Maximum Size Aggegate, enter as mm
%    Input = the input values to perform the calculations
% OUTPUT
%    blend = the percentages required from each stockpile
%    gradation = the final gradation of the aggregate blend
%    ratios = the calculated bailey parameters for this blend
%    tests = the results of testing if the blend meets requirements

% blend=0;
% gradation=0;
% ratios=0;
% tests=0;

% DETERMINING LIMITS FOR GIVEN NMSA
lim=baileylimits(NMSA);

% CALCULATING AGGREGATE BLEND
```

```
CUW=Input(1);
DD=Input(2);
CA1=Input(3);
CA2=Input(4);
CA3=Input(5);
FA1=Input(6);
FA2=Input(7);
FA3=Input(8);
RAP=Input(9);

% chosen unit weight
cauw1=Agg(12,1)*CUW/100;
cauw2=Agg(12,2)*CUW/100;
cauw3=Agg(12,3)*CUW/100;

% ca contrubution weight
cacw1=cauw1*CA1/100;
cacw2=cauw2*CA2/100;
cacw3=cauw3*CA3/100;

% voids in ca
cav1=(1-(cauw1/(Agg(11,1)*1000)))*CA1;
cav2=(1-(cauw2/(Agg(11,2)*1000)))*CA2;
cav3=(1-(cauw3/(Agg(11,3)*1000)))*CA3;

% total voids
vt=cav1+cav2+cav3;

% fa contribution weight
facw1=Agg(13,4)*(FA1/100)*(vt/100);
facw2=Agg(13,5)*(FA2/100)*(vt/100);
facw3=Agg(13,6)*(FA3/100)*(vt/100);

% total unit weight
tuw=cacw1+cacw2+cacw3+facw1+facw2+facw3;

% initial blend percentage, ca and fa
caib1=100*cacw1/tuw;
caib2=100*cacw2/tuw;
caib3=100*cacw3/tuw;
faib1=100*facw1/tuw;
faib2=100*facw2/tuw;
faib3=100*facw3/tuw;

% ca percent pass pcs
PCS=lim(2);
cappcs1=Agg(PCS,1);
cappcs2=Agg(PCS,2);
cappcs3=Agg(PCS,3);

% fa percent retain pcs
farpcs1=100-Agg(PCS,4);
farpcs2=100-Agg(PCS,5);
farpcs3=100-Agg(PCS,6);

% percent fa in ca
fainca1=caib1*(cappcs1/100);
```

```
fainca2=caib2*(cappcs2/100);
fainca3=caib3*(cappcs3/100);

% total fa in ca
tfainca=fainca1+fainca2+fainca3;

% percent ca in fa
cainfa1=faib1*(farpcs1/100);
cainfa2=faib2*(farpcs2/100);
cainfa3=faib3*(farpcs3/100);

% total ca in fa
tcainfa=cainfa1+cainfa2+cainfa3;

% adjusted blens for ca and fa
caab1=caib1+fainca1-(caib1*tcainfa/(caib1+caib2+caib3));
caab2=caib2+fainca2-(caib2*tcainfa/(caib1+caib2+caib3));
caab3=caib3+fainca3-(caib3*tcainfa/(caib1+caib2+caib3));
faab1=faib1+cainfa1-(faib1*tfainca/(faib1+faib2+faib3));
faab2=faib2+cainfa2-(faib2*tfainca/(faib1+faib2+faib3));
faab3=faib3+cainfa3-(faib3*tfainca/(faib1+faib2+faib3));

% percent dust (passing #200) in ca and fa
dinca1=caab1*(Agg(10,1)/100);
dinca2=caab2*(Agg(10,2)/100);
dinca3=caab3*(Agg(10,3)/100);
dinfa1=faab1*(Agg(10,4)/100);
dinfa2=faab2*(Agg(10,5)/100);
dinfa3=faab3*(Agg(10,6)/100);

% total dust
td=dinca1+dinca2+dinca3+dinfa1+dinfa2+dinfa3;

% mf blend
mfb=(DD-td)/(Agg(10,7)/100);

% final blend for ca and fa
cafb1=caab1*((100-RAP)/100);
cafb2=caab2*((100-RAP)/100);
cafb3=caab3*((100-RAP)/100);
fafb1=(faab1-(faab1*mfb/(faab1+faab2+faab3)))*((100-RAP)/100);
fafb2=(faab2-(faab2*mfb/(faab1+faab2+faab3)))*((100-RAP)/100);
fafb3=(faab3-(faab3*mfb/(faab1+faab2+faab3)))*((100-RAP)/100);
mffb=mfb*((100-RAP)/100);

% final total blend
blend=[cafb1,cafb2,cafb3,fafb1,fafb2,fafb3,mffb,RAP];

% CALCULATING GRADATION OF AGGREGATE BLEND
gradation=zeros(1,10);
for seive=1:10
    for stockpile=1:8
        gradation(seive)=gradation(seive)+...
        (Agg(seive,stockpile)*blend(stockpile)/100);
    end
end
```

```
% CALCULATING BAILEY AGGREGATE RATIOS
half=lim(1);
SCS=lim(3);
TCS=lim(4);
if (half==6.25)
    halfseive=gradation(3)-(gradation(3)-gradation(4))*...
    (9.5-6.25)/(9.5-4.75);
else
    halfseive=gradation(half);
end
CA=(halfseive-gradation(PCS))/(100-halfseive);
FAc=gradation(SCS)/gradation(PCS);
FAf=gradation(TCS)/gradation(SCS);
ratios=[CA,FAc,FAf];

% TESTING FOR COMPLIANCE TO REQUIREMENTS
% control points
cpOK=1;
if (gradation(1)<lim(11))||(gradation(1)>lim(12))
    %disp('outside of control points at 3/4" seive');
    cpOK=0;
end
if (gradation(2)<lim(13))||(gradation(2)>lim(14))
    %disp('outside of control points at 1/2" seive');
    cpOK=0;
end
if (gradation(3)<lim(15))||(gradation(3)>lim(16))
    %disp('outside of control points at 3/8" seive');
    cpOK=0;
end
if (gradation(4)<lim(17))||(gradation(4)>lim(18))
    %disp('outside of control points at #4 seive');
    cpOK=0;
end
if (gradation(5)<lim(19))||(gradation(5)>lim(20))
    %disp('outside of control points at #8 seive');
    cpOK=0;
end
if (gradation(10)<lim(21))||(gradation(10)>lim(22))
    %disp('outside of control points at #200 seive');
    cpOK=0;
end
%disp('within control points');

% restricted zone
rz16OK=1;
rz30OK=1;
if (gradation(6)>lim(25))&&(gradation(6)<lim(26))
    %disp('in restricted zone at #16 seive');
    rz16OK=0;
end
if (gradation(7)>lim(27))&&(gradation(7)<lim(28))
    %disp('in restricted zone at #30 seive');
    rz30OK=0;
end

% bailey ratios
```

```
CAOK=1;
FAcOK=1;
FAfOK=1;
if (CA<lim(5))||(CA>lim(6))
    %disp('CA outside of recomended range');
    CAOK=0;
end
if (FAc<lim(7))||(FAc>lim(8))
    %disp('FAc outside of recomended range');
    FAcOK=0;
end
if (FAf<lim(9))||(FAf>lim(10))
    %disp('FAf outside of recomended range');
    FAfOK=0;
end

tests=[cpOK,rz16OK,rz30OK,CAOK,FAcOK,FAfOK];

return
```

BAILEYLIMITS.M

```
function limits=baileylimits(NMSA)

% This matlab function returns a list of the limits for the weight
% ratios for the Bailey Method, the gradation control points for
% Superpave, and the restricted zone points for Superpave

FAc_lower=0.35;
FAc_upper=0.50;
FAf_lower=0.35;
FAf_upper=0.50;

if (NMSA==19)
    CA_lower=.6;
    CA_upper=.75;
    Half=3;
    PCS=4;
    SCS=6;
    TCS=8;
    CP19_lower=90;
    CP19_upper=100;
    CP12p5_lower=0;
    CP12p5_upper=90;
    CP9p5_lower=0;
    CP9p5_upper=100;
    CP4_lower=0;
    CP4_upper=100;
    CP8_lower=23;
    CP8_upper=49;
    CP200_lower=2;
    CP200_upper=8;
    RZ8_lower=34.6;
    RZ8_upper=34.6;
    RZ16_lower=22.3;
    RZ16_upper=28.3;
    RZ30_lower=16.7;
```

```
    RZ30_upper=20.7;
    RZ50_lower=13.7;
    RZ50_upper=13.7;
end
if (NMSA==12.5)
    CA_lower=.5;
    CA_upper=.65;
    Half=6.25;
    PCS=5;
    SCS=7;
    TCS=9;
    CP19_lower=100;
    CP19_upper=100;
    CP12p5_lower=90;
    CP12p5_upper=100;
    CP9p5_lower=0;
    CP9p5_upper=90;
    CP4_lower=0;
    CP4_upper=100;
    CP8_lower=28;
    CP8_upper=58;
    CP200_lower=2;
    CP200_upper=10;
    RZ8_lower=39.1;
    RZ8_upper=39.1;
    RZ16_lower=25.6;
    RZ16_upper=31.6;
    RZ30_lower=19.1;
    RZ30_upper=23.1;
    RZ50_lower=15.5;
    RZ50_upper=15.5;
end
if (NMSA==9.5)
    CA_lower=.4;
    CA_upper=.55;
    Half=4;
    PCS=5;
    SCS=7;
    TCS=9;
    CP19_lower=0;
    CP19_upper=100;
    CP12p5_lower=100;
    CP12p5_upper=100;
    CP9p5_lower=90;
    CP9p5_upper=100;
    CP4_lower=0;
    CP4_upper=90;
    CP8_lower=32;
    CP8_upper=67;
    CP200_lower=2;
    CP200_upper=10;
    RZ8_lower=47.2;
    RZ8_upper=47.2;
    RZ16_lower=31.6;
    RZ16_upper=37.6;
    RZ30_lower=23.5;
    RZ30_upper=27.5;
```

```
    RZ50_lower=18.7;
    RZ50_upper=18.7;
end

control_seives=[Half,PCS,SCS,TCS];
ratio_limits=[CA_lower,CA_upper,FAc_lower,FAc_upper,...
    FAf_lower,FAf_upper];
control_points=[CP19_lower,CP19_upper,CP12p5_lower,CP12p5_upper,...
    CP9p5_lower,CP9p5_upper,CP4_lower,CP4_upper,CP8_lower,CP8_upper,...
    CP200_lower,CP200_upper];
restricted_zone=[RZ8_lower,RZ8_upper,RZ16_lower,RZ16_upper,...
    RZ30_lower,RZ30_upper,RZ50_lower,RZ50_upper];
limits=[control_seives,ratio_limits,control_points,restricted_zone];

return
```

OSSIPEE.M

```
function M=ossipee(x)

% This matlab function makes a 13 row by 8 column matrix of aggregate
% info.
% Aggregate origin: Pike Industries in Ossipee, NH
% Each line makes a column for one stockpile with percent passing in
% rows 1-10, Gsb in row 11, loose unit weight in 12, and rodded unit
% wt. in 13
% INPUTS
%    x = anything; without some input, I could not get this to work
% OUTPUT
%    M = the 13x8 matrix of aggregate information

% agg=  [3/4";1/2";3/8';4;8;16;30;50;100;200;Gsb;Loose;Rodded]

three4= [100;100;100;100;100;100;100;100;100;100;1   ;1      ;1      ];
half=   [100;95;48;5 ;3  ;2  ;2  ;1  ;1   ;0.9 ;2.619;1501.57;1625.78];
three8= [100;100;99;27;9 ;6  ;3  ;2  ;1   ;1.0 ;2.588;1510.61;1616.49];
grits=  [100;100;100;96;83;61;33 ;14 ;7.0 ;3.1 ;2.556;1573.60;1713.62];
dust=   [100;100;100;100;85;67;51;36 ;23.0;13.0;2.607;1502.65;1772.63];
scrsand=[100;100;100;97;91;75;45 ;17 ;6.0 ;2.2 ;2.543;1541.50;1691.32];
bhf=    [100;100;100;100;100;100;100;99 ;95.0;80.0;1   ;1     ;1     ];
rap=    [100;100;100;100;100;100;100;100;100 ;100 ;1   ;1     ;1     ];

M=[three4,half,three8,grits,dust,scrsand,bhf,rap];

return
```

CONTINENTAL.M

```
function M=continental(x)

% This matlab function makes a 13 row by 8 column matrix of aggregate
% info.
% Aggregate origin: Continental Paving in Londonderry, NH
```

```
% Each line makes a column for one stockpile with percent passing in
% rows 1-10, Gsb in row 11, loose unit weight in 12, and rodded unit
% wt. in 13
% INPUTS
%    x = anything; without some input, I could not get this to work
% OUTPUT
%    M = the 13x8 matrix of aggregate information

% agg=  [3/4";1/2";3/8";4;8;16;30;50;100;200;Gsb;Loose;Rodded]

three4= [95.4;33.6;9.6;1.1;0.8;0.8;0.8;0.7;0.7;0.6;2.691;1492.53;1636.28];
half=   [100;98.0;42.7;1.4;0.9;0.8;0.7;0.7;0.6;0.5;2.722;1518.89;1638.49];
three8= [100;100;96.7;34.0;7.0;2.8;1.4;1.1;0.8;0.7;2.707;1556.70;1667.15];
WMS=    [100;100;100;98.0;68.1;38.0;20.9;11.0;6.6;4.9;2.710;1567.40;1740.43];
DSS=    [100;100;100;97.9;93.2;80.3;55.7;24.5;7.6;2.3;2.687;1548.24;1696.35];
none=   [100;100;100;100;100;100;100;100;100;100;1   ;1      ;1      ];
bhf=    [100;100;100;100;100;100;100;99.8;96.7;87.1;1;1      ;1      ];
rap=    [100;100;100;100;100;100;100;100;100;100;1   ;1      ;1      ];

M=[three4,half,three8,WMS,DSS,none,bhf,rap];

return
```

FARMINGTON.M

```
function M=farmington(x)

% This matlab function makes a 13 row by 8 column matrix of aggregate
% info.
% Aggregate origin: Pike Industries in Farmington, NH
% Each line makes a column for one stockpile with percent passing in
% rows 1-10, Gsb in row 11, loose unit weight in 12, and rodded unit
% wt. in 13
% INPUTS
%    x = anything; without some input, I could not get this to work
% OUTPUT
%    M = the 13x8 matrix of aggregate information

% agg=  [3/4";1/2";3/8';4;8;16;30;50;100;200;Gsb;Loose;Rodded]

three4= [100;100;100;100;100;100;100;100;100;100;1   ;1      ;1      ];
half=   [100;96;43;4 ;3  ;2  ;2  ;2  ;2   ;0.7 ;2.645;1580.38;1689.01];
three8= [100;100;99;32;5 ;3  ;3  ;2  ;2   ;0.9 ;2.616;1615.78;1691.25];
wasand= [100;100;100;100;91;72;49;21 ;5.0 ;2.0 ;2.565;1544.39;1686.94];
dust=   [100;100;100;100;85;67;51;36 ;23.0;12.0;2.598;1609.88;1809.01];
scrsand=[100;100;100;94;86;71;50 ;29 ;12.0;5.1 ;2.566;1604.48;1797.73];
bhf=    [100;100;100;100;100;100;100;99;95.0;80.0;1   ;1     ;1      ];
rap=    [100;100;100;81 ;63 ;50 ;35 ;23 ;14 ;9.3 ;1   ;1     ;1      ];

M=[three4,half,three8,wasand,dust,scrsand,bhf,rap];

return
```

BAILEYEVALUATION.M

```
function bestinput=baileyevaluation(Agg,NMSA,TargetBlend)
```

```
% This Matlab function finds the input values that generate a blend that is
closest to
% the target blend.  "Closest" means the sum of the absolute differences
between the
% calculated and target blends is as small as possible.
% Adjust the limits on the for loops as needed to cut down run time.


currentinput=zeros(1,9);
bestinput=currentinput;
prevTotal=100;

n=0;
for cuw=75:85
   for dd=3.5:0.1:6.0
      for ca2=27:47
         for fa1=43:63
            for fa2=16:36
               currentinput(1)=cuw;
               currentinput(2)=dd;
               currentinput(3)=0;
               currentinput(4)=ca2;
               currentinput(5)=100-ca2;
               currentinput(6)=fa1;
               currentinput(7)=fa2;
               currentinput(8)=100-fa1-fa2;
               currentinput(9)=14.4;
               [blend,grad,ratios,tests]=bailey(Agg,NMSA,currentinput);
               n=n+1;
               CA1=abs(TargetBlend(1)-blend(1));
               CA2=abs(TargetBlend(2)-blend(2));
               CA3=abs(TargetBlend(3)-blend(3));
               FA1=abs(TargetBlend(4)-blend(4));
               FA2=abs(TargetBlend(5)-blend(5));
               FA3=abs(TargetBlend(6)-blend(6));
               MF=abs(TargetBlend(7)-blend(7));
               Totaldiff=CA1+CA2+CA3+FA1+FA2+FA3+MF;
               if (Totaldiff<prevTotal)
                  bestinput=currentinput;
                  prevTotal=Totaldiff;
               end
               if (Totaldiff<0.3)
                  bestinput=currentinput;
                  disp('cool beans');
                  disp('Total difference =');
                  disp(Totaldiff);
                  disp('number of itterations =');
                  disp(n);
                  return
               end
            end
         end
      end
   end
end

disp('GOOD ENOUGH!');
```

```
disp('Total difference =');
disp(prevTotal);
disp('number of itterations =');
disp(n);

return
```

APPENDIX B: SPECIMEN VOLUMETRICS

The bricks are listed in the order in which they were laid in the test bed (meaning the first brick in the list was the first one to feel the tire). There were no bricks fabricated for the Farm-Bailey mix because it failed most of the Superpave criteria when the asphalt content was designed. The data files containing the volumetric measurements on most of the Oss 12.5-Bailey samples were lost. However, the volumetrics of each brick was measured right after fabrication and only those bricks with acceptable air voids, between 3.5% and 4.5%, were marked for testing; all other bricks were destroyed.

Table B1: Volumetrics for Oss 12.5

Brick ID	Gmm	Gmb	V_a	VMA	Thickness (mm)
O12.5M-7B	2.425	2.336	3.7	14.8	57.91
O12.5M-8T	2.425	2.333	3.8	14.9	57.32
O12.5M-6T	2.425	2.328	4.0	15.1	56.08
O12.5M-8B	2.425	2.338	3.6	14.7	55.78
O12.5M-5T	2.425	2.340	3.5	14.6	55.69
O12.5M-7T	2.425	2.324	4.2	15.2	55.39
O12.5M-4T	2.425	2.323	4.2	15.3	55.14
Average	2.425	2.332	3.9	15.0	56.19

Table B2: Volumetrics for Oss 19

Brick ID	Gmm	Gmb	V_a	VMA	Thickness (mm)
O19M-11T	2.466	2.361	4.3	13.6	57.02
O19M-6B	2.466	2.366	4.0	13.4	56.95
O19M-7T	2.466	2.360	4.3	13.7	55.61
O19M-7B	2.466	2.375	3.7	13.1	55.18
O19M-6T	2.466	2.366	4.0	13.4	54.93
O19M-10B	2.466	2.363	4.1	13.5	54.39
O19M-11B	2.466	2.366	4.0	13.4	53.69
Average	2.466	2.365	4.1	13.5	55.40

Table B3: Volumetrics for Cont 12.5

Brick ID	Gmm	Gmb	V_a	VMA	Thickness (mm)
C12.5M-2B	2.483	2.373	4.4	17.1	52.46
C12.5M-3B	2.483	2.385	3.9	16.7	51.81
C12.5M-4B	2.483	2.384	4.0	16.7	52.95
C12.5M-5B	2.483	2.390	3.7	16.5	52.76
C12.5M-6B	2.483	2.374	4.4	17.1	51.98
C12.5M-8T	2.483	2.377	4.2	17.0	52.67
C12.5M-8B	2.483	2.382	4.0	16.8	52.42
Average	2.483	2.381	4.1	16.8	52.44

Table B4: Volumetrics for Cont 19

Brick ID	Gmm	Gmb	V_a	VMA	Thickness (mm)
C19M-1	2.514	2.409	4.2	15.4	56.77
C19M-2	2.514	2.413	4.0	15.3	56.80
C19M-4	2.514	2.424	3.6	14.9	56.60
C19M-5	2.514	2.414	4.0	15.2	56.80
C19M-6	2.514	2.424	3.6	14.9	56.99
C19M-7	2.514	2.408	4.2	15.4	*
C19M-9	2.514	2.419	3.8	15.1	56.99
Average	2.514	2.416	3.9	15.2	56.83

* Data file lost

Table B5: Volumetrics for Farm

Brick ID	Gmm	Gmb	V_a	VMA	Thickness (mm)
FM-7	2.467	2.366	4.1	14.1	57.28
FM-8	2.467	2.356	4.5	14.5	57.39
FM-10	2.467	2.365	4.1	14.2	57.42
FM-6	2.467	2.369	4.0	14.0	58.24
FM-11	2.467	2.367	4.0	14.1	57.46
FM-12	2.467	2.358	4.4	14.4	57.31
FM-9	2.467	2.363	4.2	14.2	57.18
Average	2.467	2.364	4.2	14.2	57.47

Table B6: Volumetrics for Hook

Brick ID	Gmm	Gmb	V_a	VMA*	Thickness (mm)
HM-11	2.439	2.346	3.8		58.11
HM-16	2.439	2.345	3.8		58.63
HM-17	2.439	2.339	4.1		58.59
HM-15	2.439	2.333	4.3		58.90
HM-19	2.439	2.337	4.2		58.67
HM-18	2.439	2.351	3.6		58.43
HM-20	2.439	2.335	4.2		58.24
Average	2.439	2.341	4.0		58.51

* Gsb data was not available for the aggregate stockpiles, so VMA could not be calculated.

Table B7: Volumetrics for Oss 12.5-Bailey

Brick ID	Gmm	Gmb	AV	VMA	Thickness (mm)
OMB 2	2.456	2.366	3.7	13.3	58.39
OBM 4	2.456	2.365	3.7	13.3	58.69
OBM 5	2.456				58.80
OBM 6	2.456				58.70
OBM 7	2.456				58.69
OBM 8	2.456				58.80
OBM 9	2.456				58.78
Average	2.456	2.366	3.7	13.3	58.69

Table B8: Volumetrics for Cont 19-Bailey

Brick ID	Gmm	Gmb	AV	VMA	Thickness (mm)
CBM 13	2.511	2.416	3.8	15.8	58.89
CBM 14	2.511	2.414	3.9	15.9	58.87
CBM 16	2.511	2.421	3.6	15.6	58.88
CBM 17	2.511	2.415	3.8	15.8	58.89
CBM 19	2.511	2.408	4.1	16.1	58.99
CBM 23	2.511	2.403	4.3	16.2	59.98
CBM 25	2.511	2.410	4.0	16.0	59.98
Average	2.511	2.412	3.9	15.9	59.21

APPENDIX C: MMLS3 TEST RESULTS

Profile Data

Oss 12.5

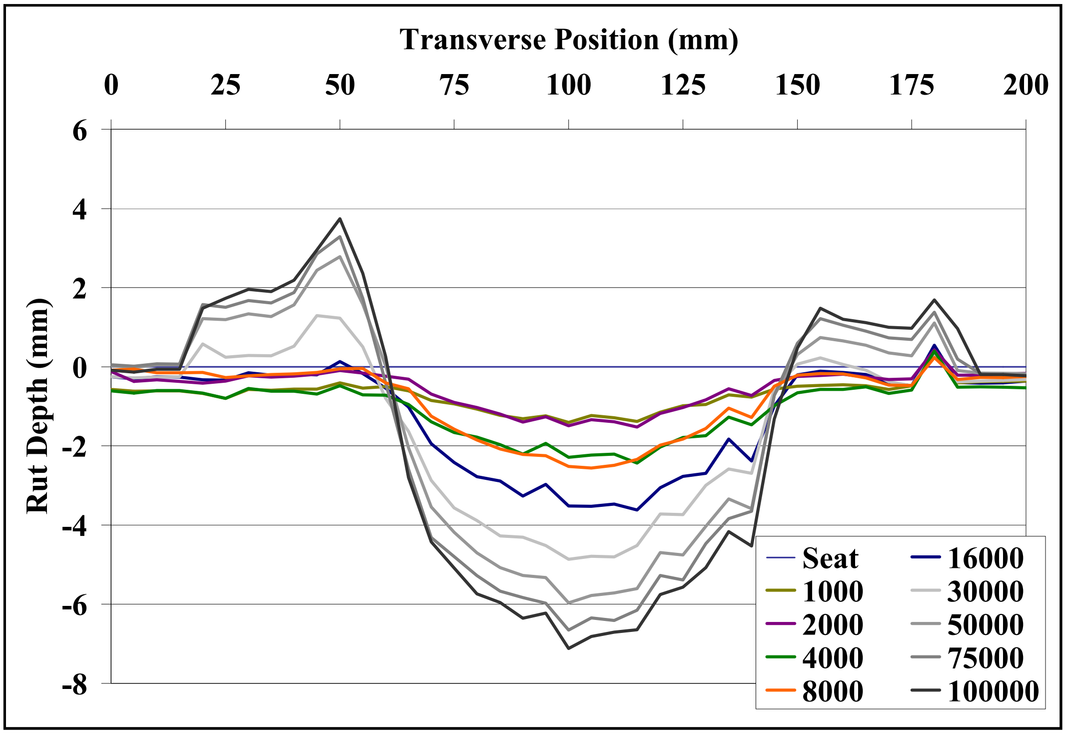


Figure C1: Oss 12.5 Brick 1 Transverse Profiles

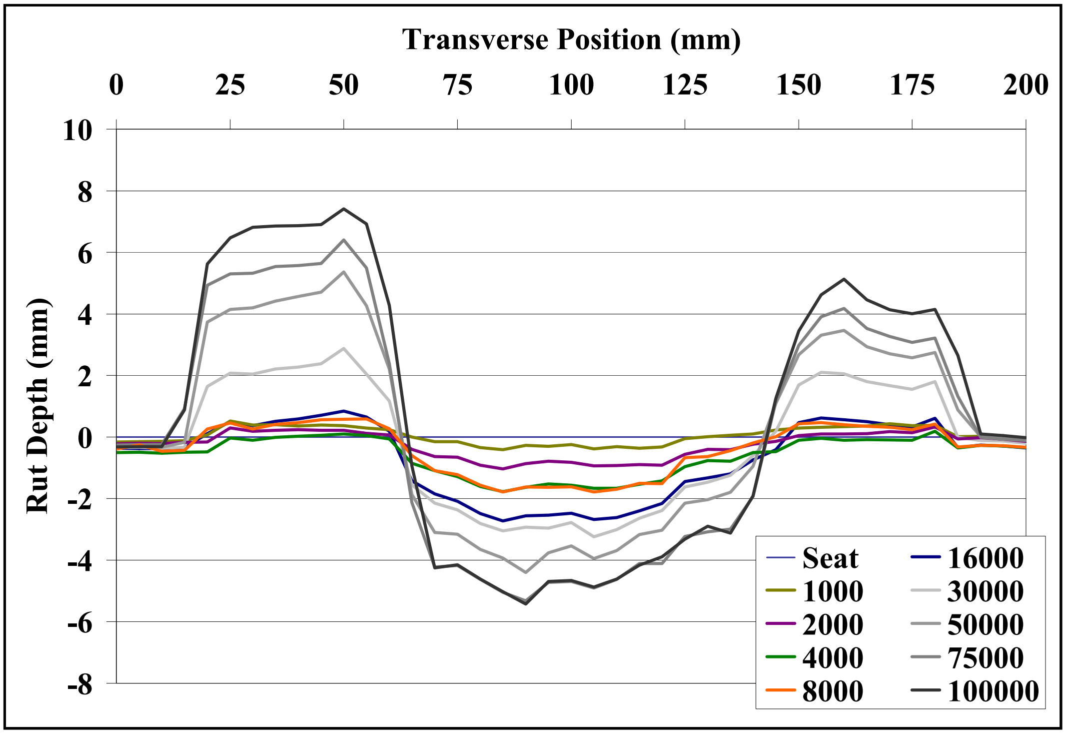


Figure C2: Oss 12.5 Brick 2 Transverse Profiles

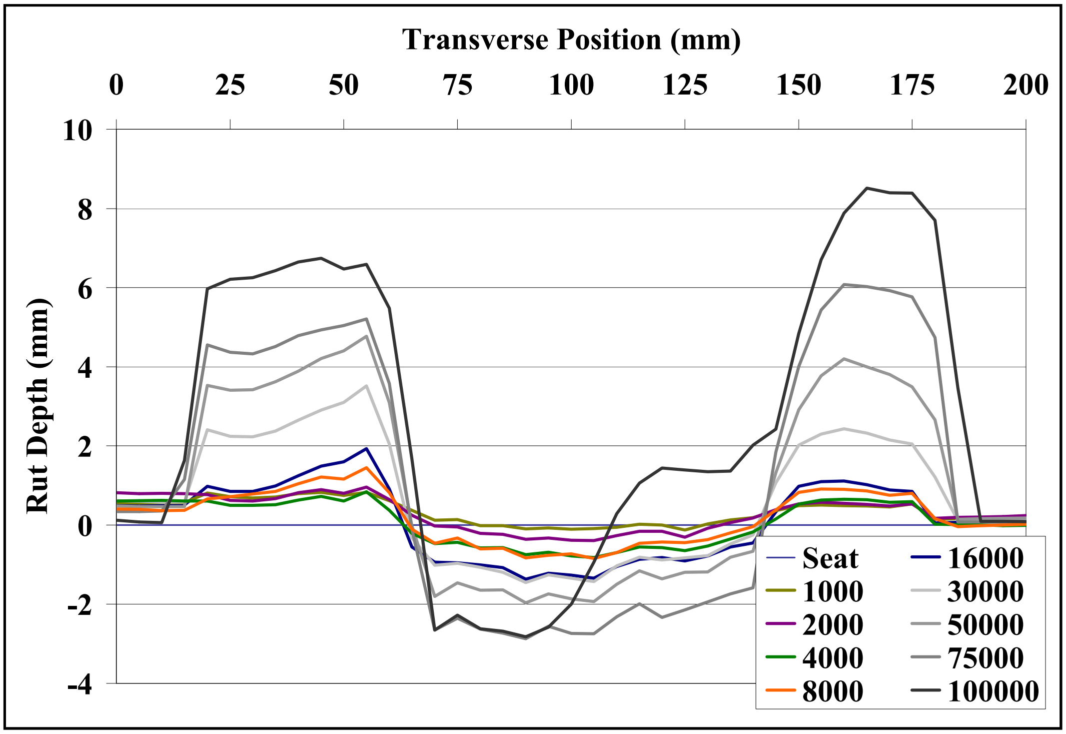


Figure C3: Oss 12.5 Brick 3 Transverse Profiles

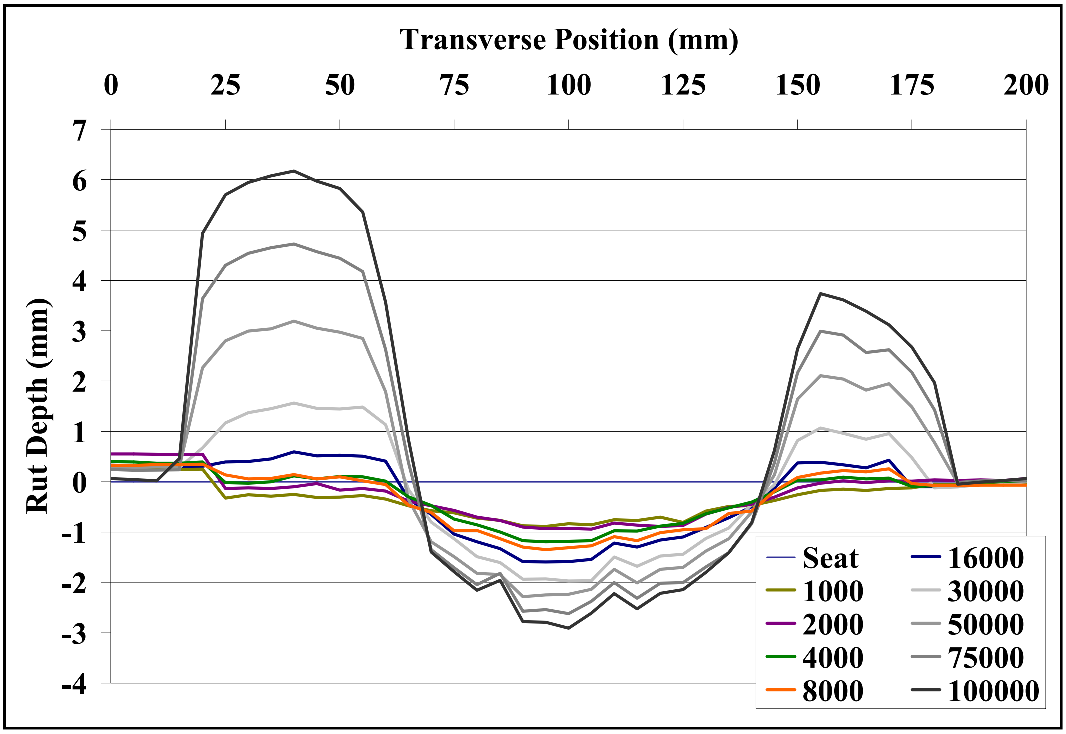


Figure C4: Oss 12.5 Brick 4 Transverse Profiles

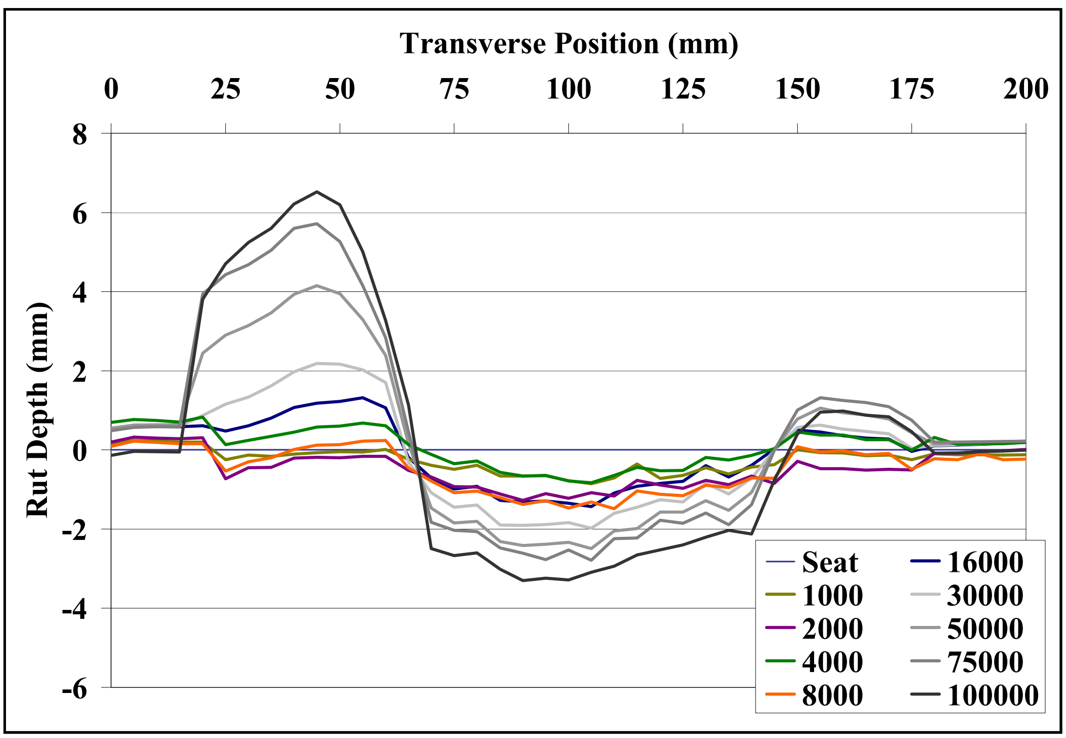


Figure C5: Oss 12.5 Brick 5 Transverse Profiles

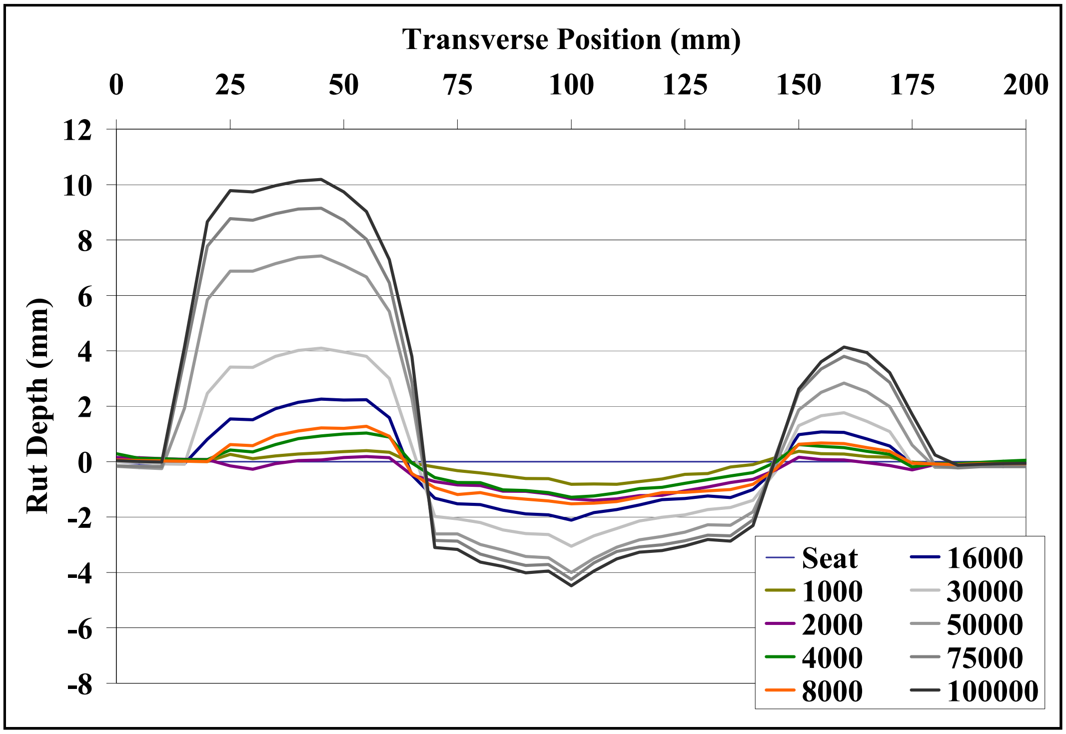


Figure C6: Oss 12.5 Brick 6 Transverse Profiles

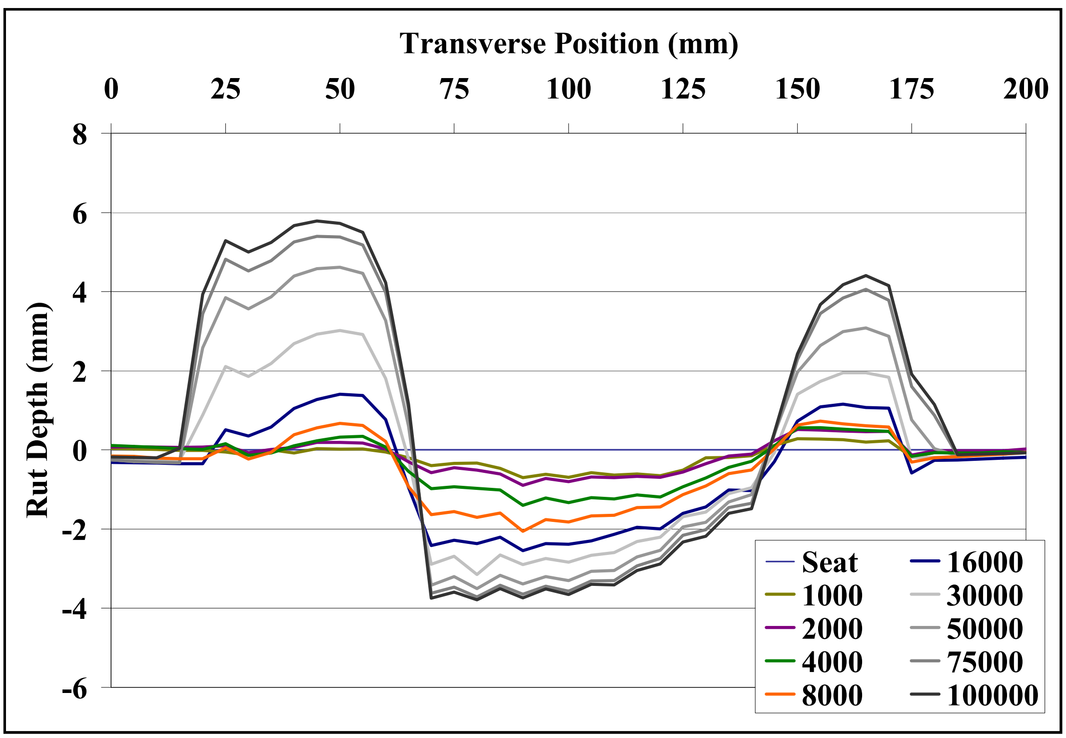


Figure C7: Oss 12.5 Brick 7 Transverse Profiles

Table C1: Oss 12.5 Avg Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	1.20	1.24	2.06	2.15	3.14	4.22	5.17	5.77	6.18
2	262.5	0.27	0.82	1.47	1.46	2.31	2.63	3.39	4.41	4.38
3	367.5	0.05	0.26	0.65	0.61	1.06	1.10	1.56	2.45	2.61*
4	472.5	0.78	0.84	0.99	1.14	1.32	1.65	1.92	2.18	2.38
5	577.5	0.63	1.03	0.55	1.22	1.06	1.58	2.02	2.27	2.84
6	682.5	0.62	1.15	0.99	1.29	1.66	2.35	3.09	3.37	3.60
7	787.5	0.55	0.65	1.12	1.56	2.12	2.48	2.88	3.11	3.22
Avg		0.58	0.86	1.12	1.35	1.81	2.29	2.86	3.37	3.60

* Brick 3 used a modified range for the average rut at 100,000 cycles

Table C2: Oss 12.5 Max Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	1.41	1.53	2.43	2.56	3.62	4.87	5.96	6.65	7.12
2	262.5	0.42	1.04	1.78	1.79	2.73	3.24	4.40	5.32	5.42
3	367.5	0.13	0.39	0.82	0.84	1.36	1.45	1.97	2.87	2.82
4	472.5	0.89	0.94	1.20	1.35	1.60	1.97	2.29	2.62	2.91
5	577.5	0.86	1.27	0.83	1.49	1.43	1.98	2.49	2.79	3.30
6	682.5	0.81	1.39	1.28	1.52	2.11	3.05	4.00	4.25	4.48
7	787.5	0.70	0.89	1.40	2.05	2.54	3.15	3.51	3.72	3.79
Avg		0.74	1.07	1.39	1.66	2.20	2.82	3.52	4.03	4.26

Table C3: Oss 12.5 Max Rut Depth from Max Heave

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	1.71	1.95	2.83	2.79	4.16	6.16	8.74	9.93	10.86
2	262.5	0.93	1.36	1.97	2.38	3.57	6.11	9.75	11.73	12.83
3	367.5	0.95	1.35	1.66	2.29	3.29	4.97	6.74	8.95	11.33
4	472.5	1.13	1.50	1.59	1.69	2.19	3.54	5.48	7.35	9.08
5	577.5	1.09	1.59	1.66	1.72	2.76	4.16	6.64	8.51	9.82
6	682.5	1.21	1.58	2.32	2.80	4.37	7.15	11.43	13.40	14.67
7	787.5	0.98	1.41	1.97	2.78	3.95	6.17	8.12	9.12	9.58
Avg		1.14	1.53	2.00	2.35	3.47	5.46	8.13	9.85	11.17

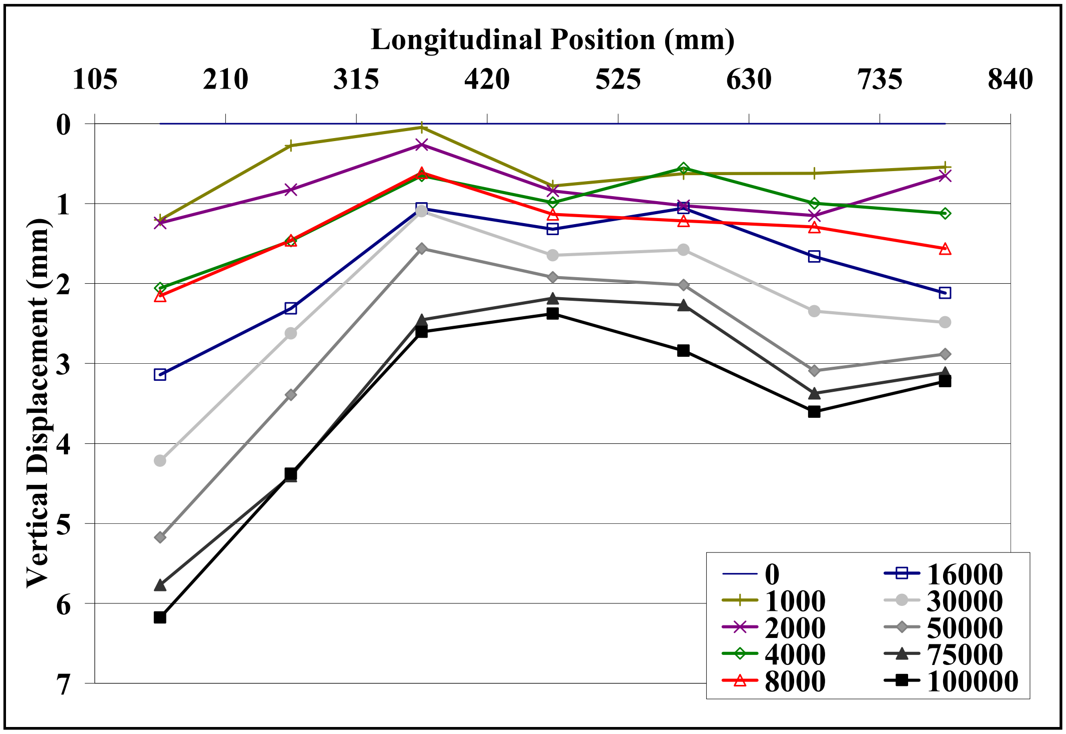


Figure C8: Oss 12.5 Avg Rut from Base Line Longitudinal Profiles

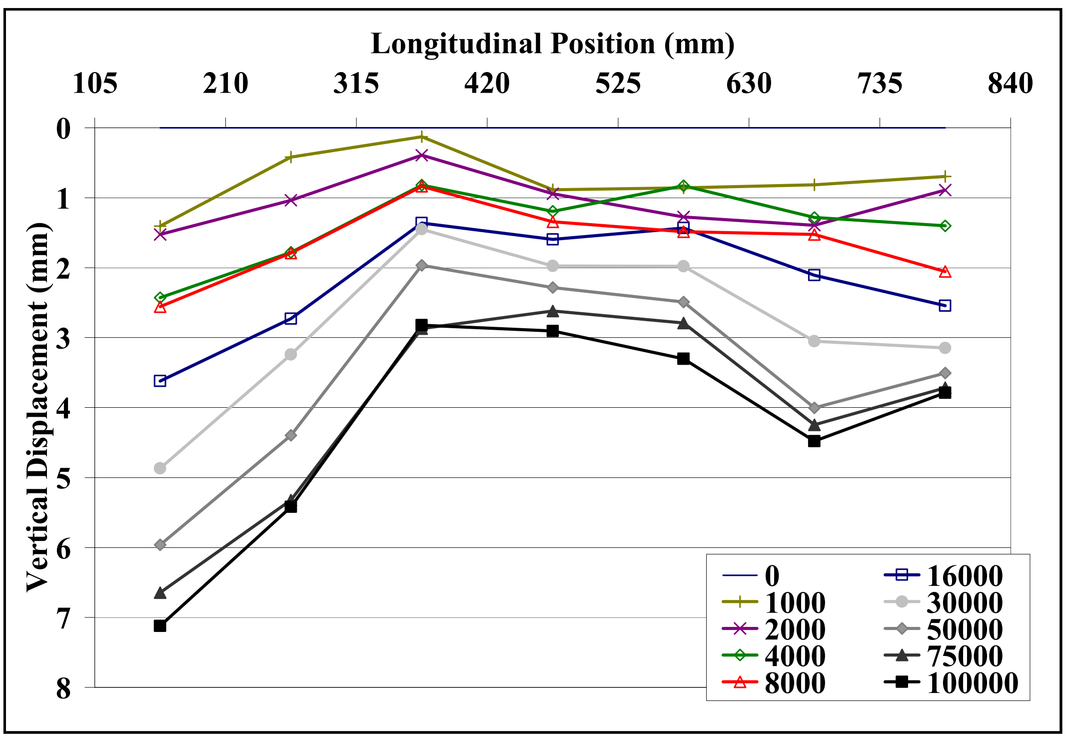


Figure C9: Oss 12.5 Max Rut from Base Line Longitudinal Profiles

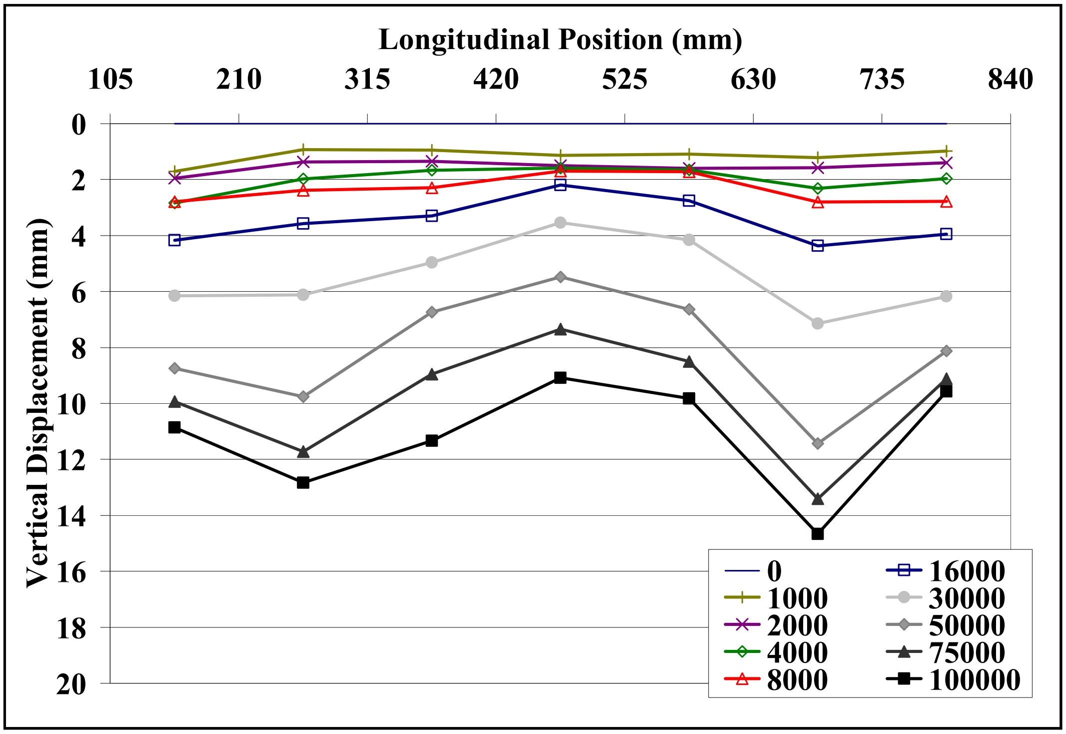


Figure C10: Oss 12.5 Max Rut from Max Heave Longitudinal Profiles

<u>**Oss 19**</u>

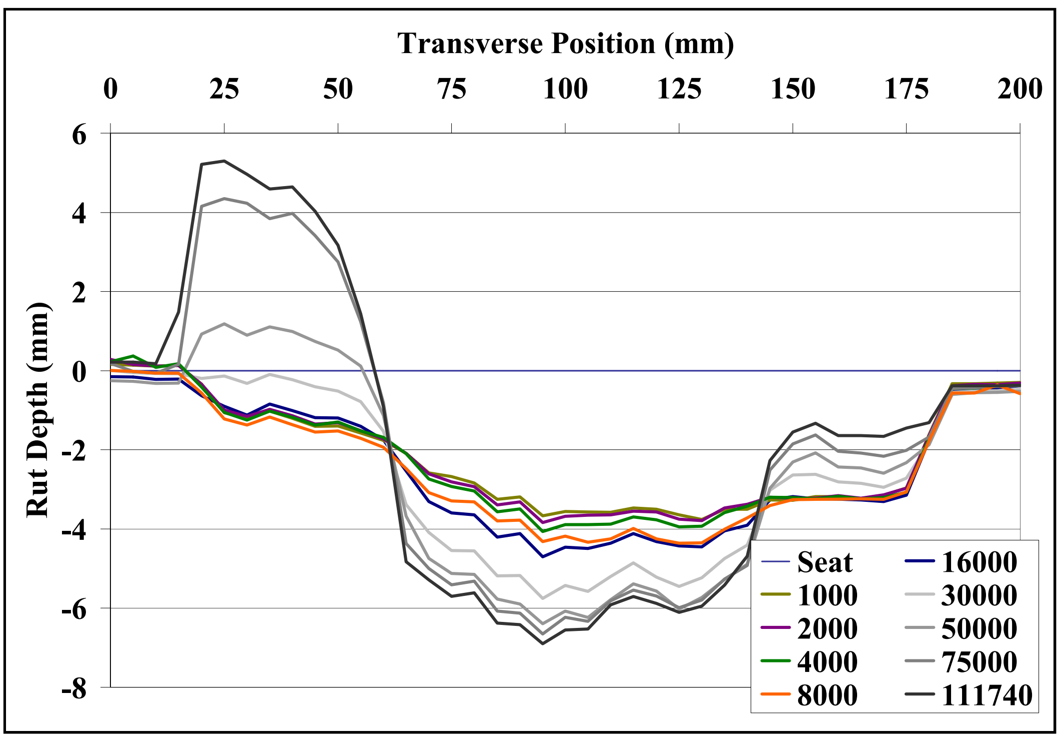


Figure C11: Oss 19 Brick 1 Transverse Profiles

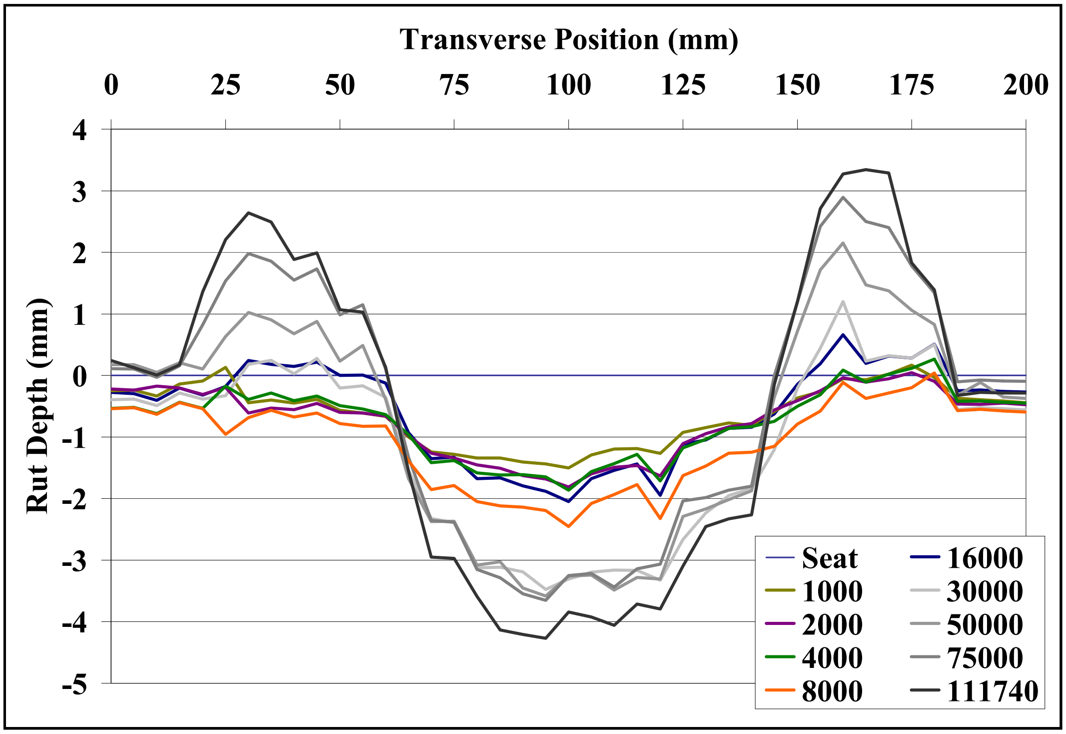


Figure C12: Oss 19 Brick 2 Transverse Profiles

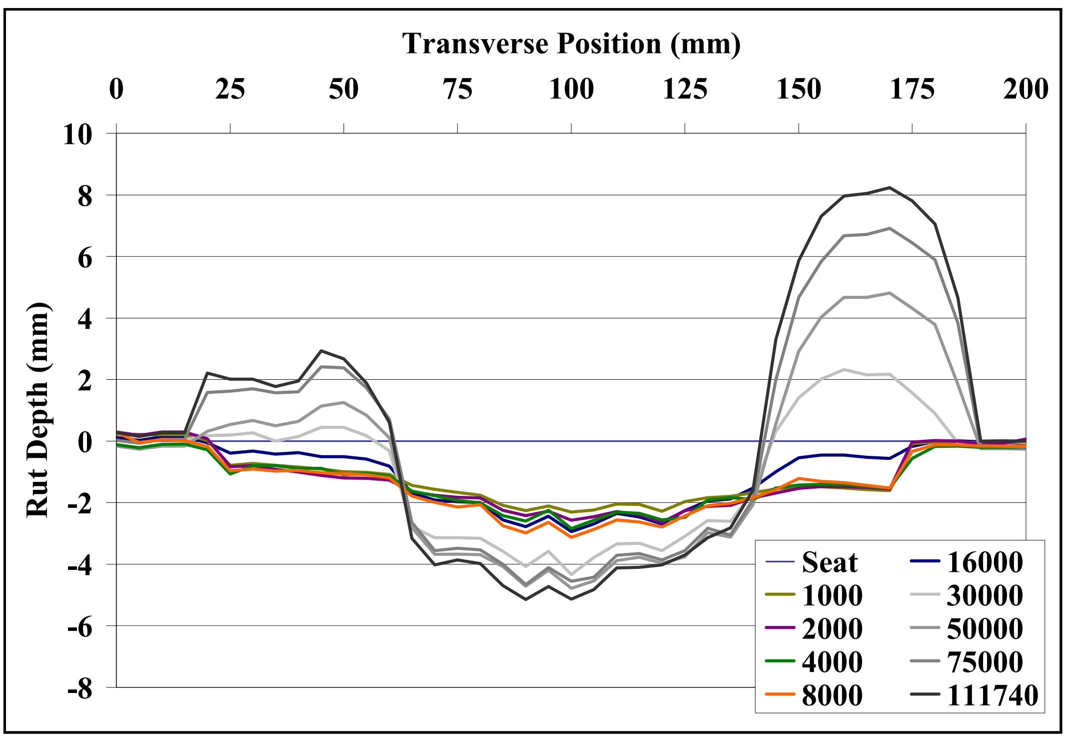


Figure C13: Oss 19 Brick 3 Transverse Profiles

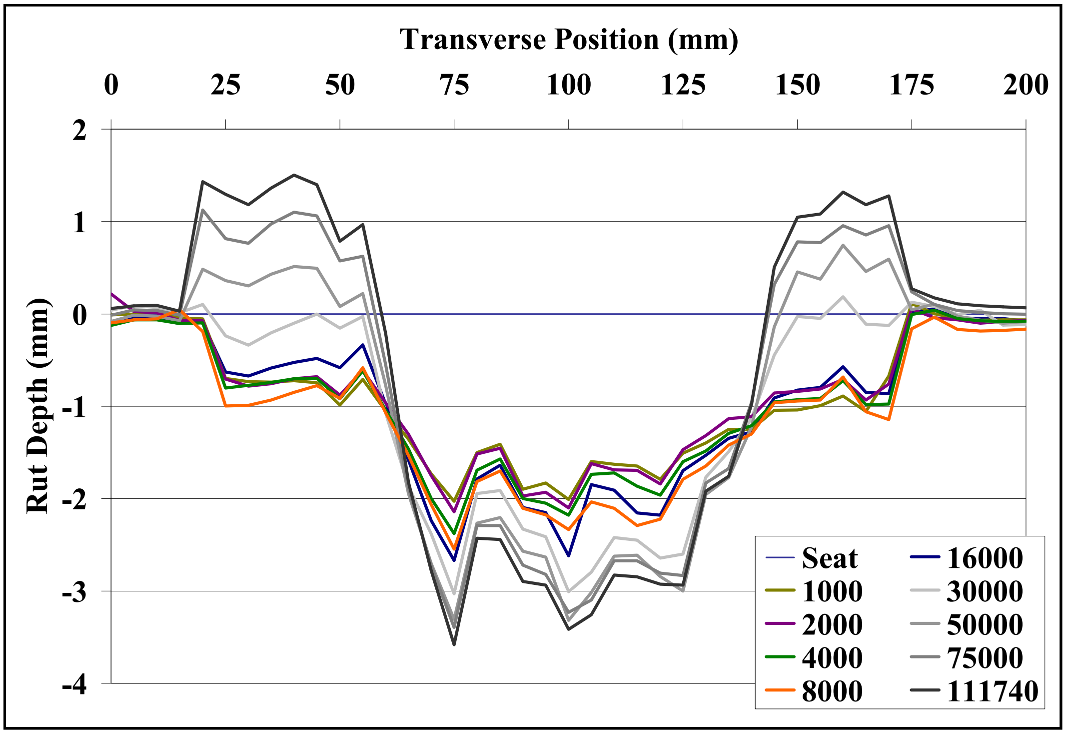


Figure C14: Oss 19 Brick 4 Transverse Profiles

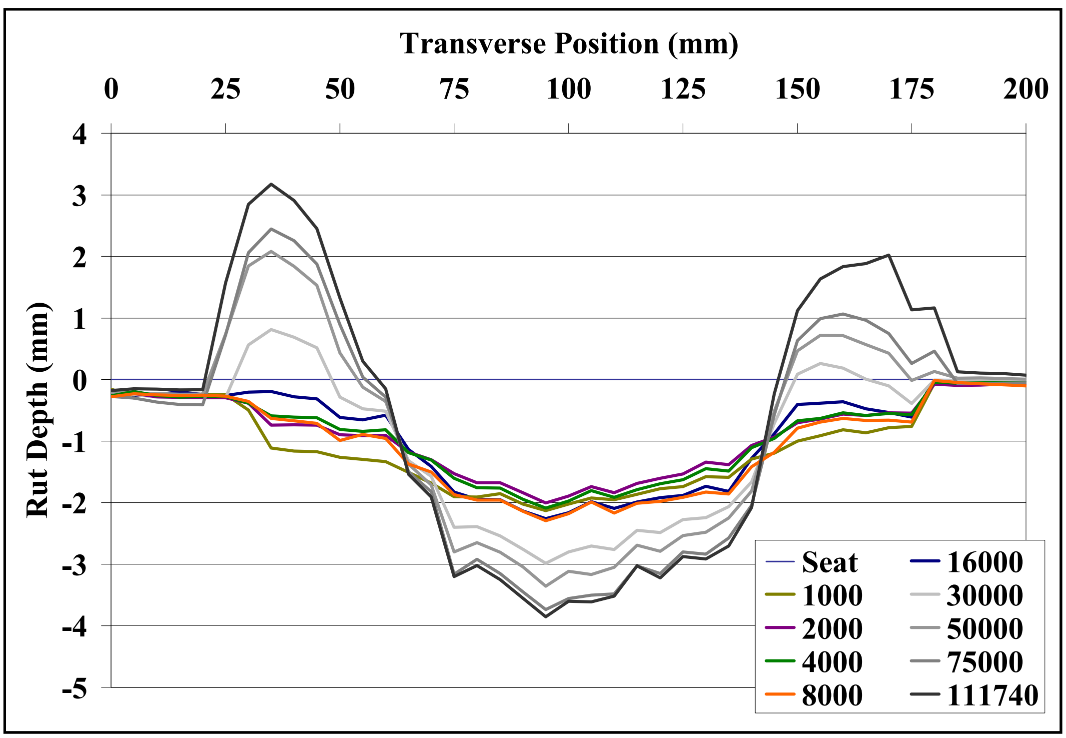


Figure C15: Oss 19 Brick 5 Transverse Profiles

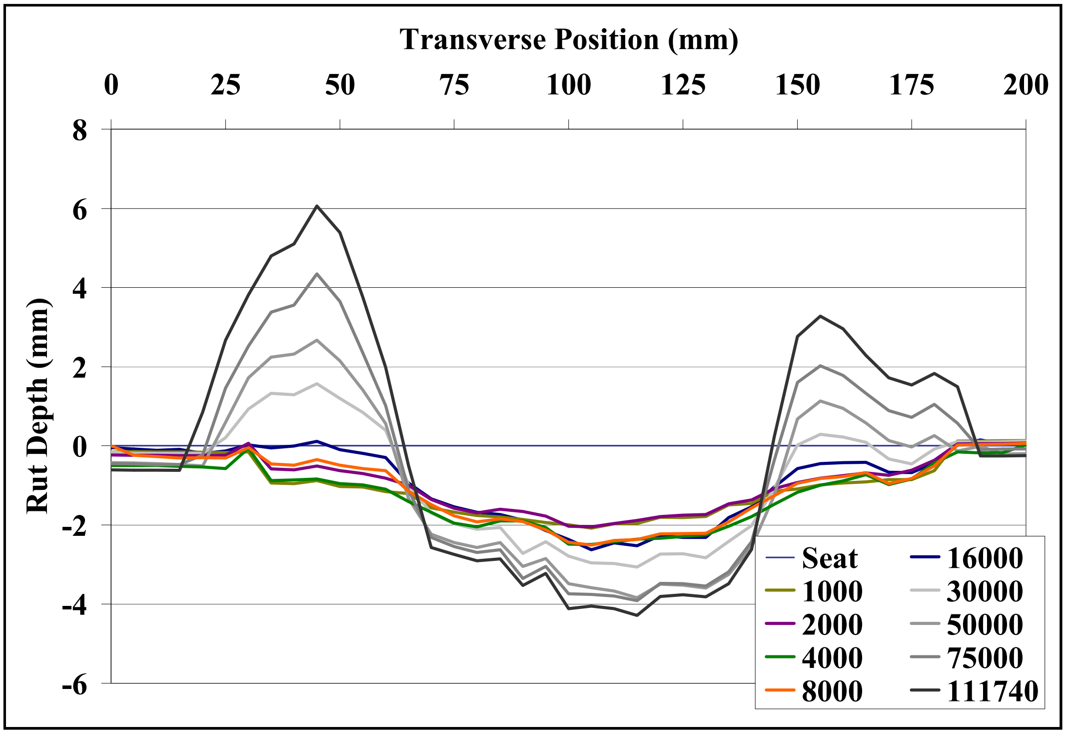


Figure C16: Oss 19 Brick 6 Transverse Profiles

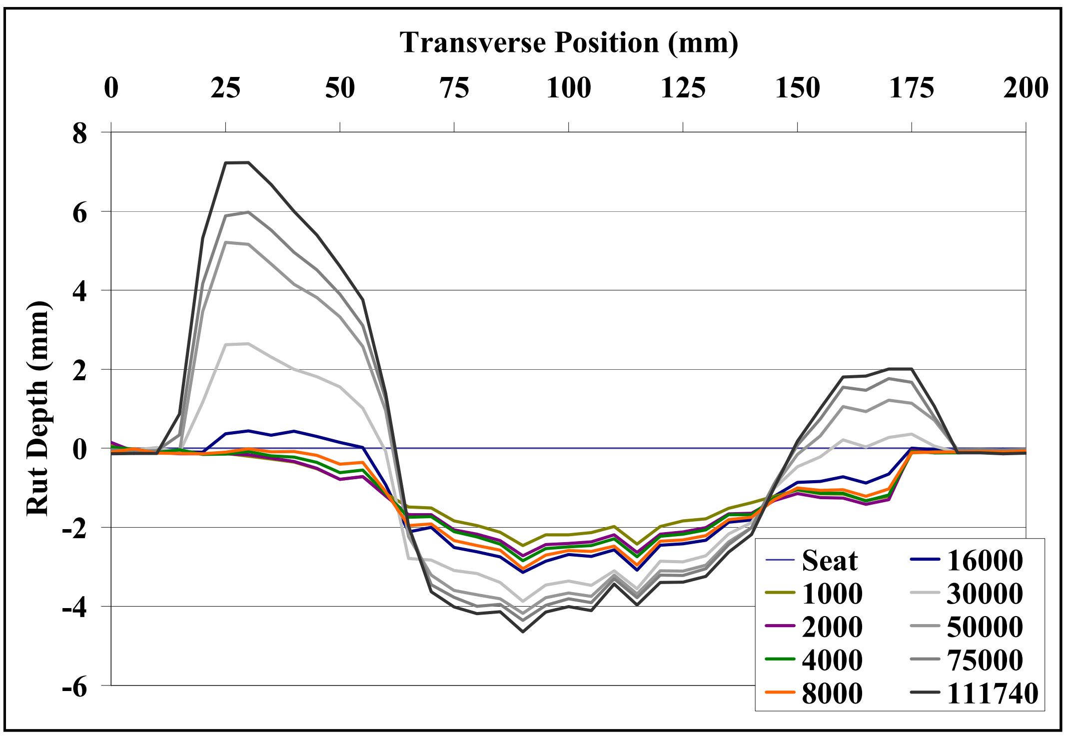


Figure C17: Oss 19 Brick 7 Transverse Profiles

Table C4: Oss 19 Avg Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	3.46	3.56	3.74	4.08	4.30	5.24	5.82	5.96	6.18
2	262.5	1.25	1.48	1.50	2.02	1.62	3.09	3.11	3.07	3.73
3	367.5	2.09	2.32	2.39	2.63	2.46	3.49	4.03	3.90	4.33
4	472.5	1.66	1.69	1.81	2.02	1.97	2.39	2.64	2.66	2.80
5	577.5	1.89	1.71	1.80	2.04	2.00	2.58	2.88	3.24	3.31
6	682.5	1.89	1.81	2.23	2.20	2.21	2.67	3.28	3.40	3.68
7	787.5	2.09	2.32	2.41	2.57	2.69	3.26	3.54	3.68	3.88
Avg		2.05	2.13	2.27	2.51	2.47	3.25	3.61	3.70	3.99

Table C5: Oss 19 Max Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	3.76	3.84	4.07	4.36	4.70	5.75	6.39	6.65	6.90
2	262.5	1.50	1.81	1.86	2.45	2.05	3.48	3.58	3.65	4.27
3	367.5	2.31	2.64	2.84	3.13	2.94	4.34	4.78	4.66	5.14
4	472.5	2.03	2.14	2.38	2.55	2.67	3.03	3.32	3.40	3.58
5	577.5	2.13	2.00	2.09	2.30	2.26	2.98	3.36	3.74	3.85
6	682.5	2.08	2.05	2.50	2.51	2.62	3.06	3.84	3.91	4.29
7	787.5	2.46	2.72	2.84	3.05	3.14	3.88	4.18	4.36	4.64
Avg		2.32	2.46	2.65	2.91	2.91	3.79	4.21	4.34	4.67

Table C6: Oss 19 Max Rut Depth from Max Heave

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	3.92	4.12	4.44	4.36	4.55	5.75	7.58	10.99	12.20
2	262.5	1.67	1.86	2.13	2.50	2.71	4.67	5.74	6.54	7.61
3	367.5	2.54	2.93	2.75	3.41	3.09	6.66	9.59	11.57	13.38
4	472.5	2.14	2.36	2.42	2.59	2.73	3.22	4.06	4.52	5.09
5	577.5	2.07	1.93	2.05	2.28	2.26	3.80	5.44	6.18	7.03
6	682.5	2.21	2.12	2.52	2.57	2.78	4.63	6.51	8.26	10.34
7	787.5	2.53	2.88	2.88	3.04	3.58	6.52	9.39	10.33	11.87
Avg		2.44	2.60	2.74	2.96	3.10	5.04	6.90	8.34	9.64

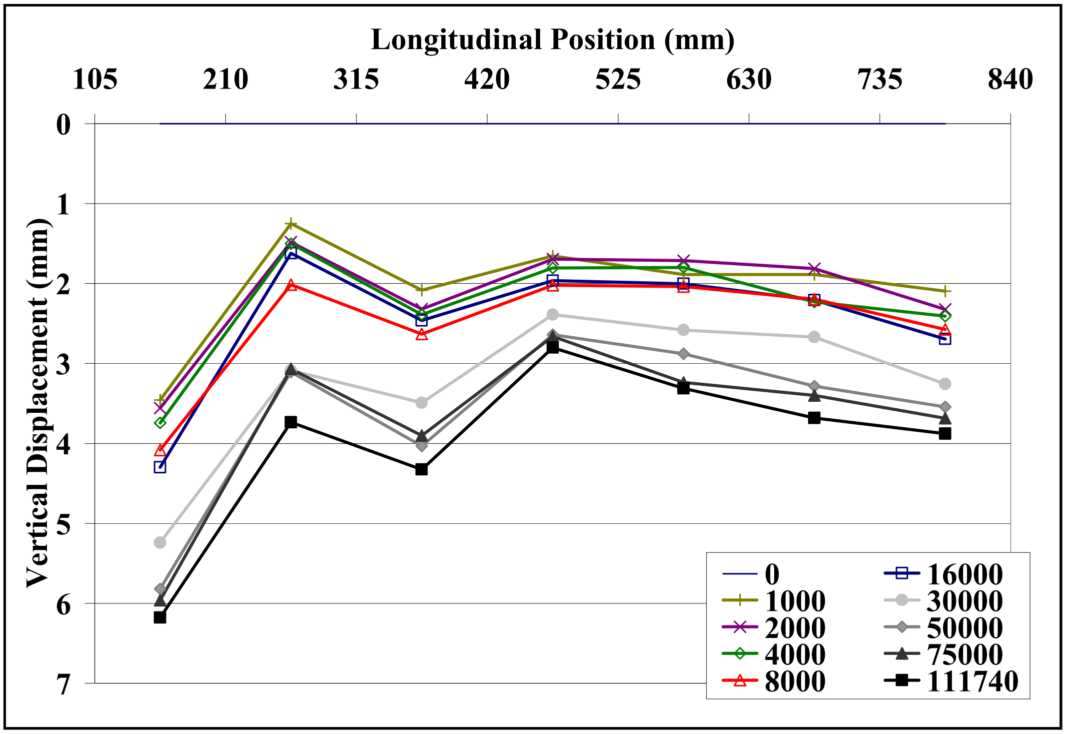


Figure C18: Oss 19 Avg Rut from Base Line Longitudinal Profiles

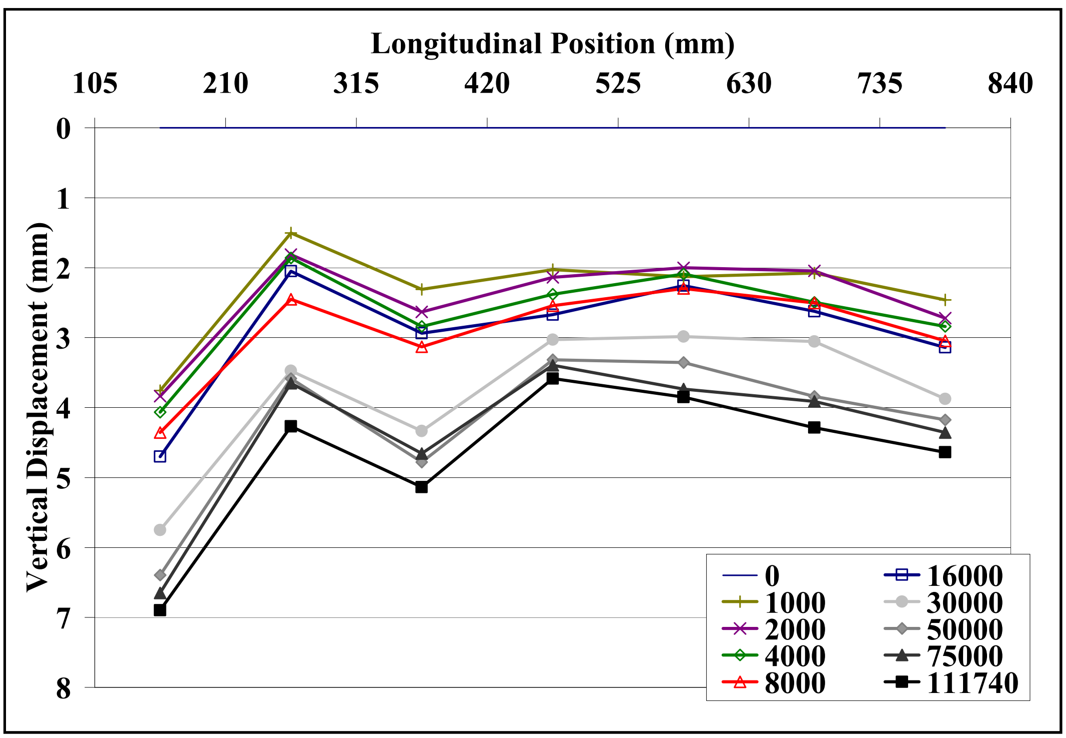


Figure C19: Oss 19 Max Rut from Base Line Longitudinal Profiles

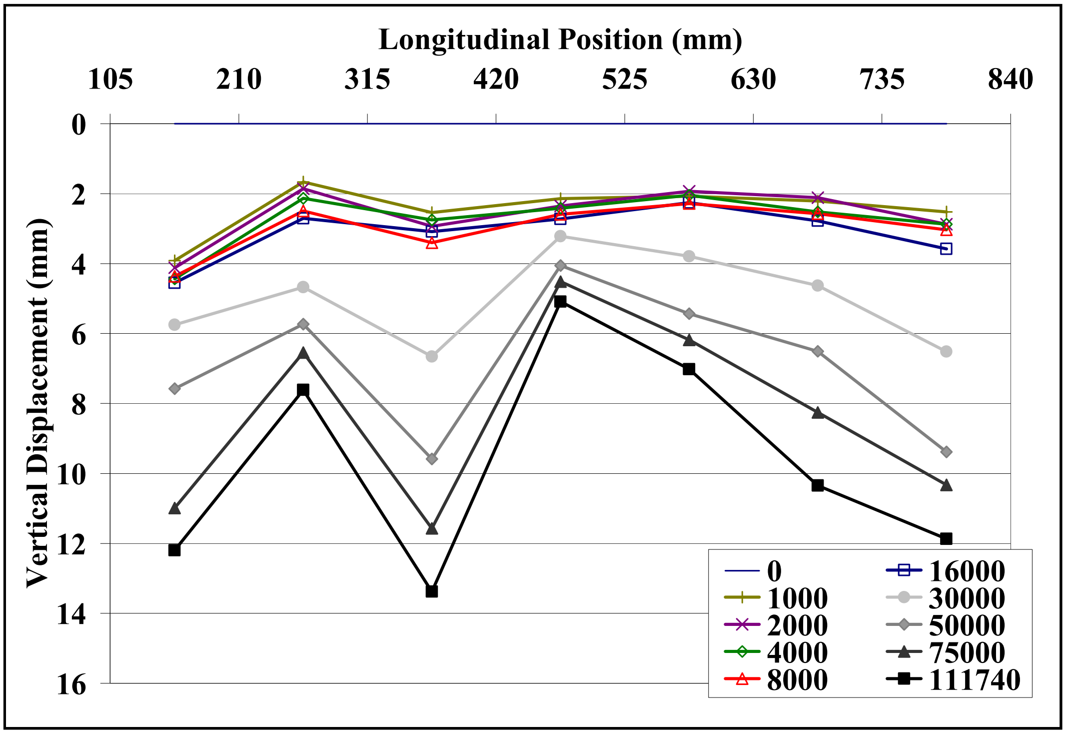


Figure C20: Oss 19 Max Rut from Max Heave Longitudinal Profiles

Cont 12.5

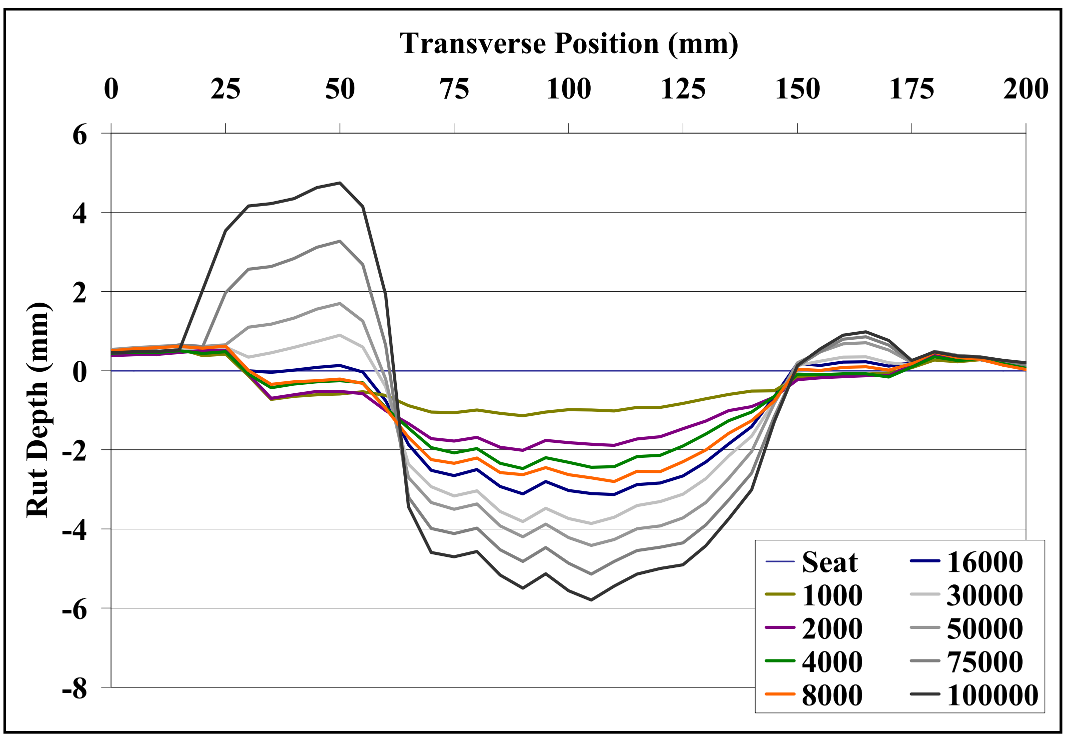


Figure C21: Cont 12.5 Brick 1 Transverse Profiles

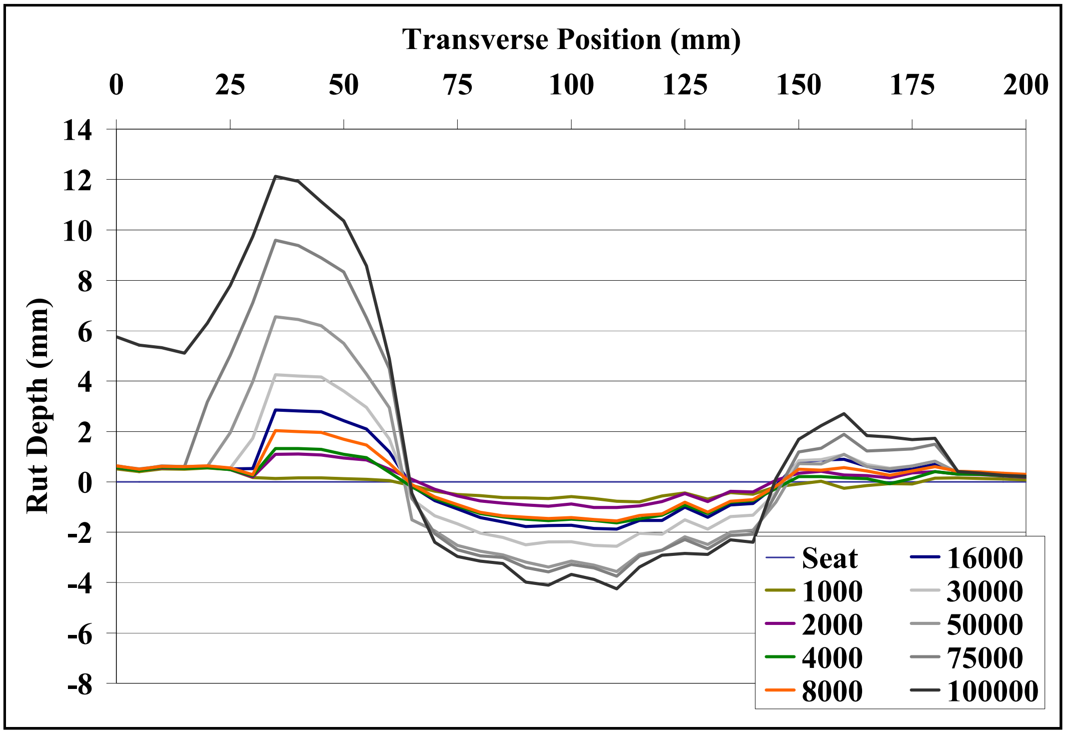


Figure C22: Cont 12.5 Brick 2 Transverse Profiles

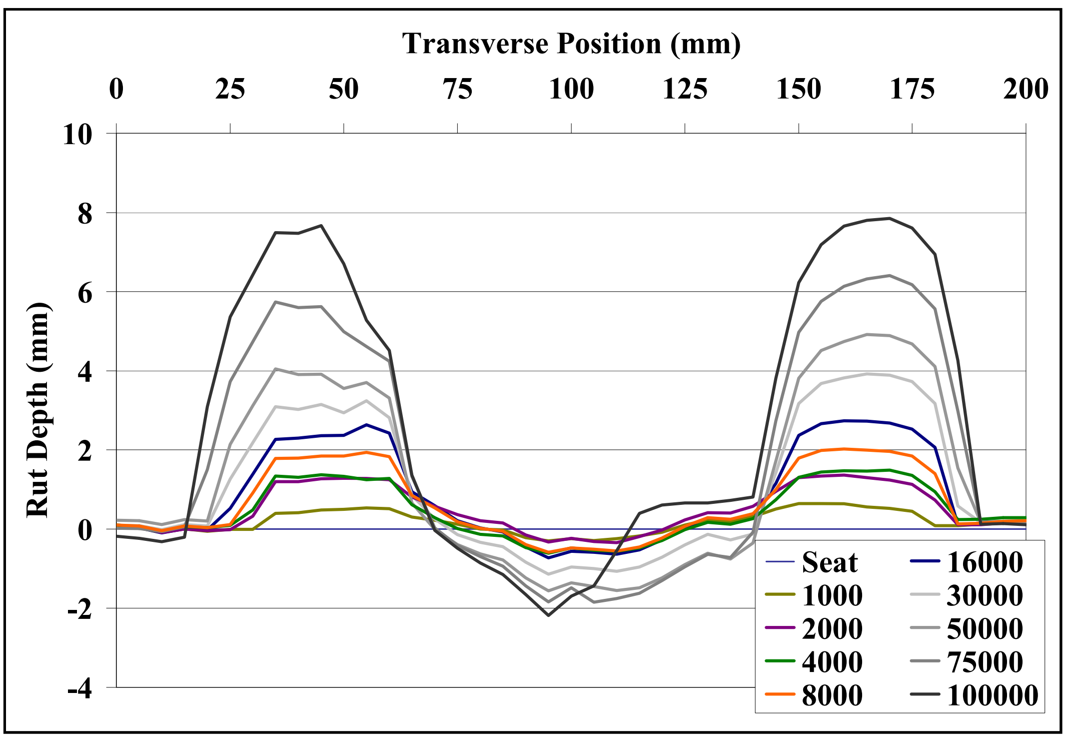


Figure C23: Cont 12.5 Brick 3 Transverse Profiles

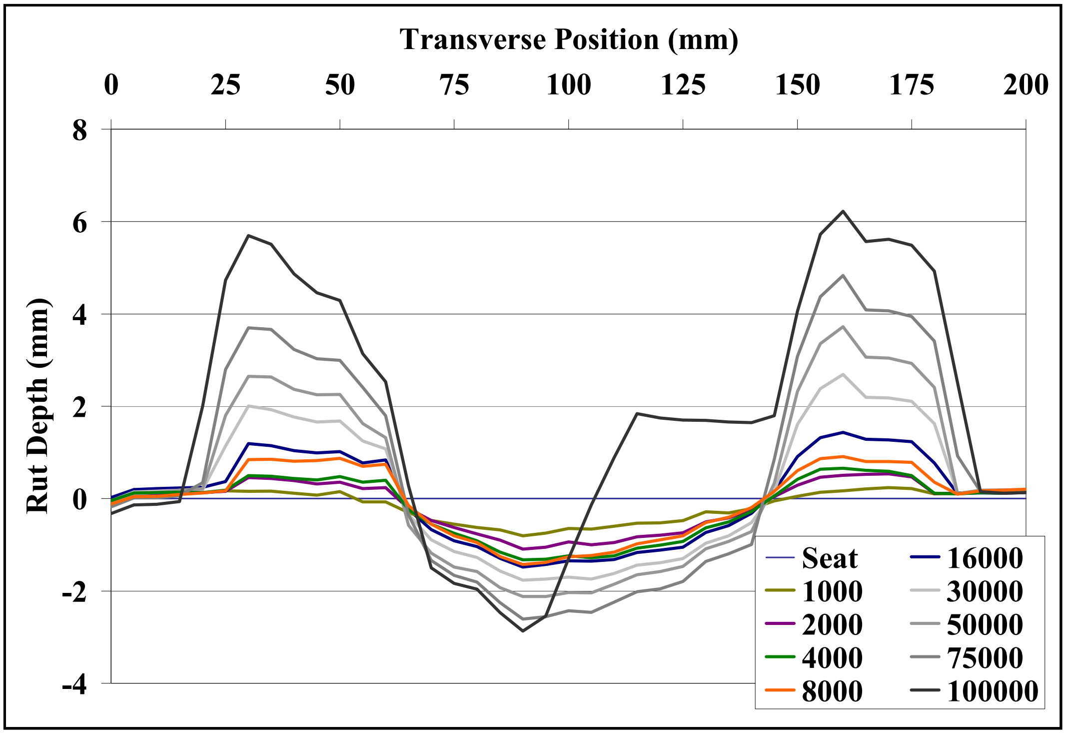


Figure C24: Cont 12.5 Brick 4 Transverse Profiles

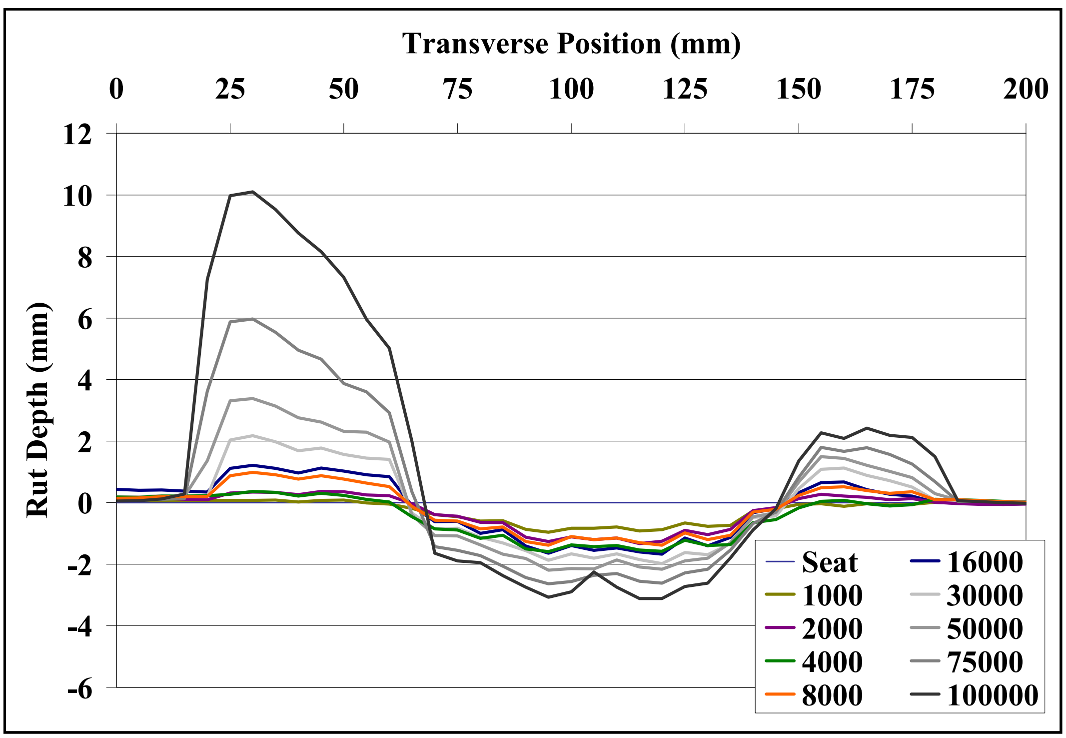


Figure C25: Cont 12.5 Brick 5 Transverse Profiles

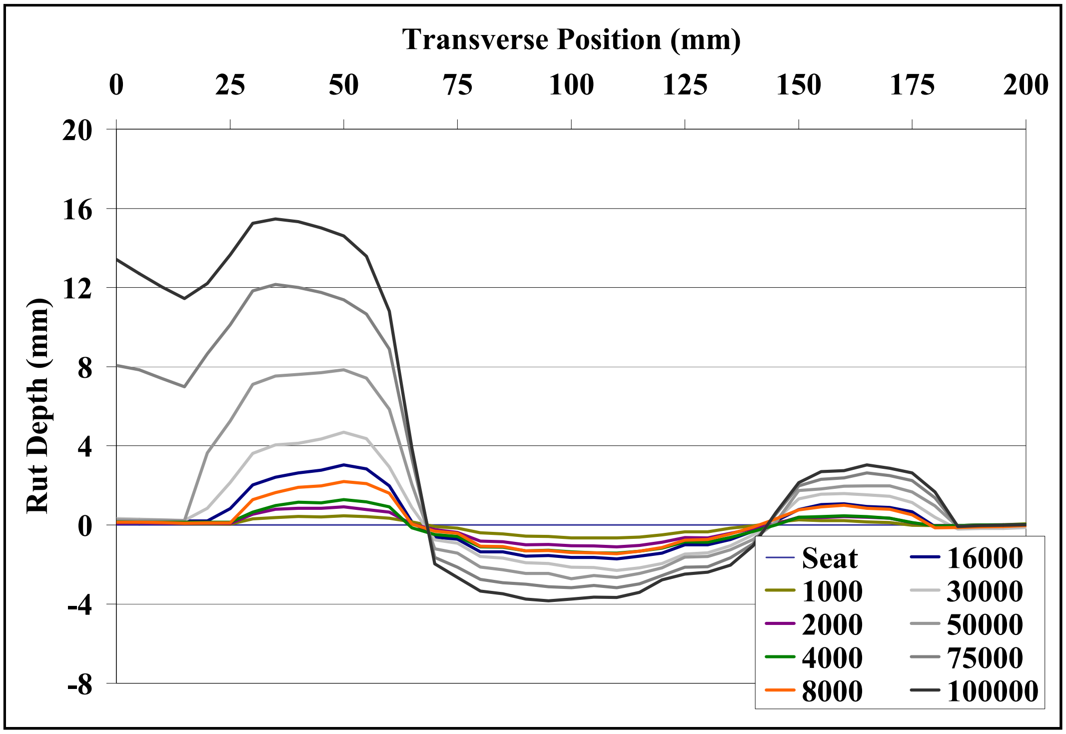


Figure C26: Cont 12.5 Brick 6 Transverse Profiles

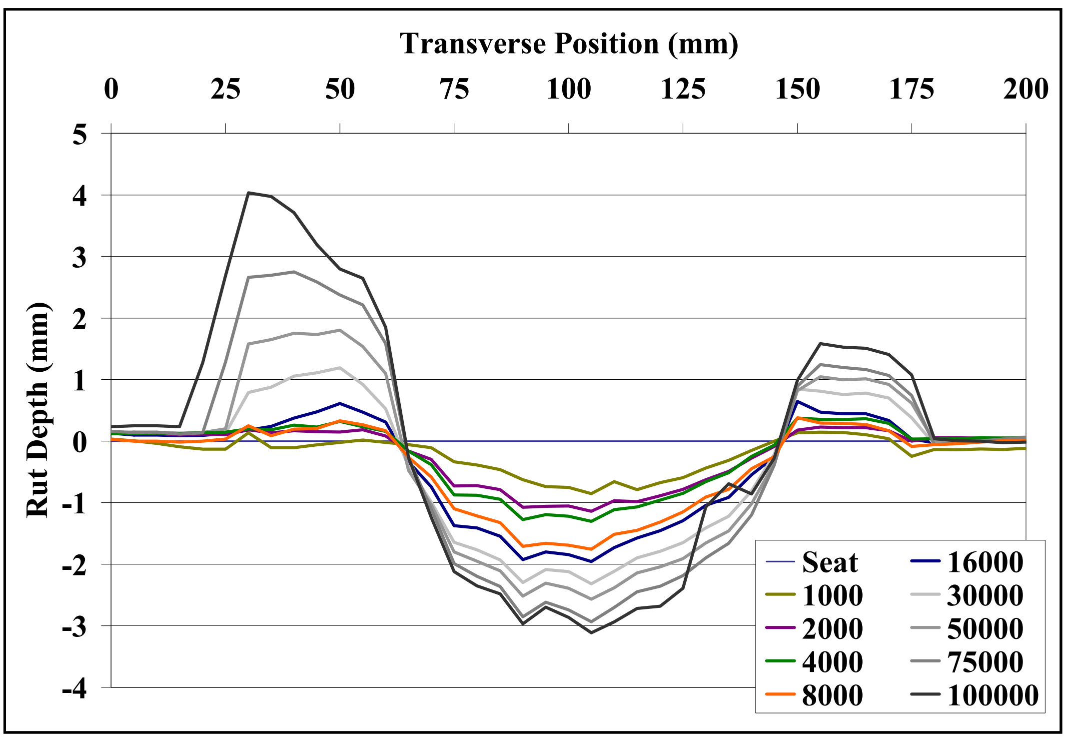


Figure C27: Cont 12.5 Brick 7 Transverse Profiles

Table C7: Cont 12.5 Avg Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	0.97	1.74	2.18	2.49	2.84	3.43	3.93	4.53	5.15
2	262.5	0.64	0.86	1.39	1.32	1.59	2.19	2.96	3.09	3.48
3	367.5	0.11	0.05	0.32	0.26	0.32	0.73	1.16	1.32	1.06*
4	472.5	0.60	0.87	1.10	1.08	1.21	1.50	1.77	2.14	2.20*
5	577.5	0.79	1.06	1.38	1.14	1.38	1.65	1.92	2.33	2.69
6	682.5	0.52	0.91	1.20	1.18	1.44	1.88	2.28	2.81	3.32
7	787.5	0.63	0.92	1.04	1.43	1.60	1.94	2.18	2.48	2.57
Avg		0.61	0.91	1.23	1.27	1.48	1.90	2.31	2.67	2.92

* Bricks 3 and 4 used a modified range for the average rut at 100,000 cycles

Table C8: Cont 12.5 Max Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	1.14	2.01	2.47	2.80	3.13	3.86	4.41	5.14	5.80
2	262.5	0.80	1.02	1.63	1.56	1.88	2.56	3.57	3.74	4.25
3	367.5	0.30	0.34	0.61	0.58	0.72	1.14	1.56	1.85	2.18
4	472.5	0.81	1.10	1.33	1.43	1.48	1.77	2.12	2.61	2.87
5	577.5	0.96	1.33	1.59	1.38	1.67	1.99	2.19	2.63	3.11
6	682.5	0.66	1.10	1.42	1.45	1.71	2.29	2.71	3.17	3.84
7	787.5	0.85	1.14	1.30	1.76	1.96	2.32	2.57	2.93	3.12
Avg		0.79	1.15	1.48	1.57	1.79	2.27	2.73	3.15	3.60

Table C9: Cont 12.5 Max Rut Depth from Max Heave

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	1.69	2.53	2.98	3.42	3.77	4.76	6.11	8.41	10.54
2	262.5	1.36	2.13	2.95	3.59	4.73	6.81	10.12	13.33	16.38
3	367.5	0.94	1.71	2.09	2.61	3.46	5.06	6.48	8.25	10.03
4	472.5	1.04	1.63	1.98	2.34	2.91	4.46	5.85	7.45	9.09
5	577.5	1.04	1.70	1.95	2.37	2.89	4.17	5.57	8.60	13.21
6	682.5	1.12	2.02	2.69	3.64	4.75	6.99	10.55	15.32	19.30
7	787.5	1.00	1.37	1.68	2.14	2.60	3.51	4.37	5.68	7.15
Avg		1.17	1.87	2.33	2.87	3.59	5.11	7.01	9.58	12.24

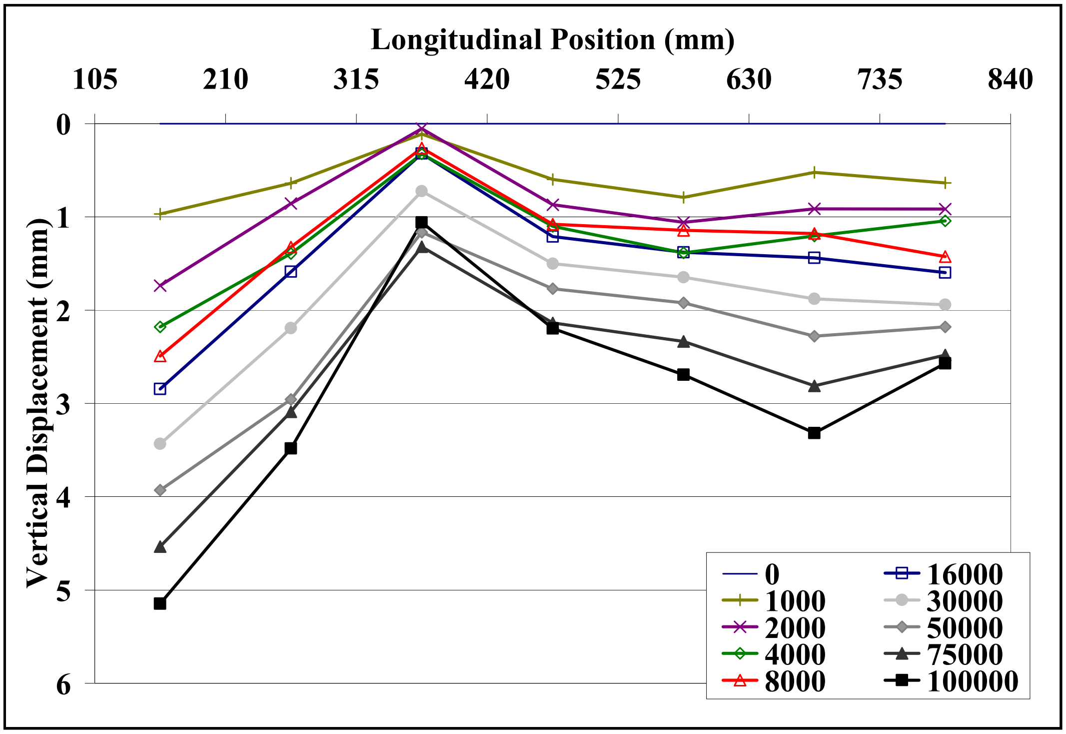


Figure C28: Cont 12.5 Avg Rut from Base Line Longitudinal Profiles

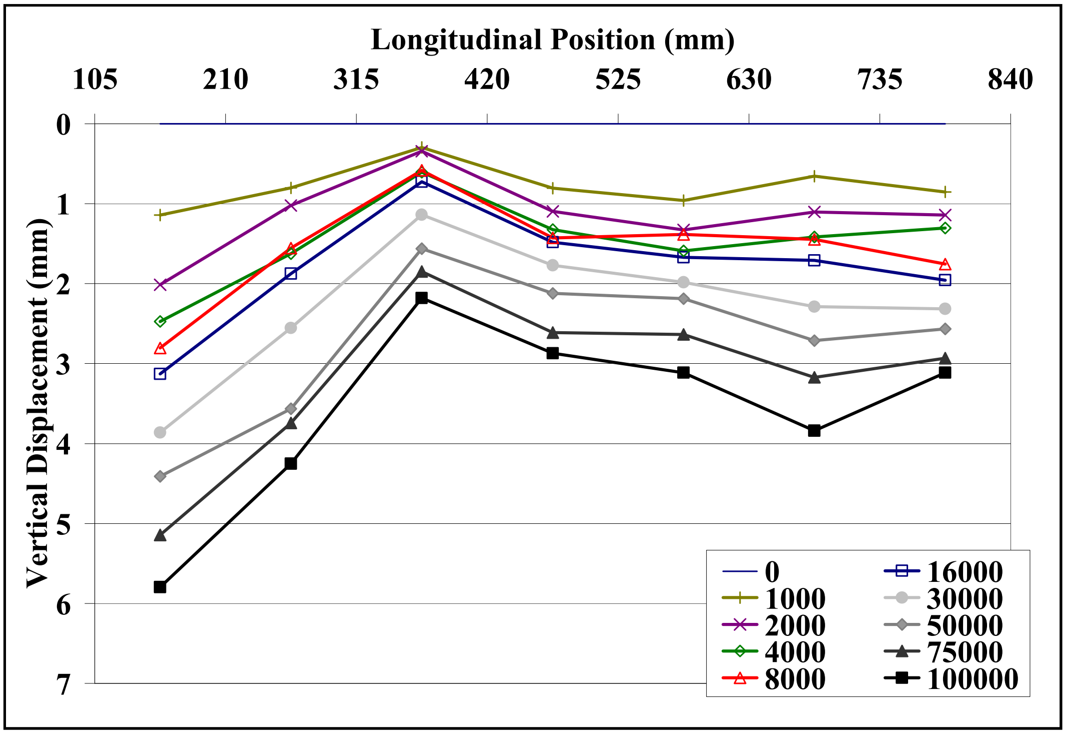


Figure C29: Cont 12.5 Max Rut from Base Line Longitudinal Profiles

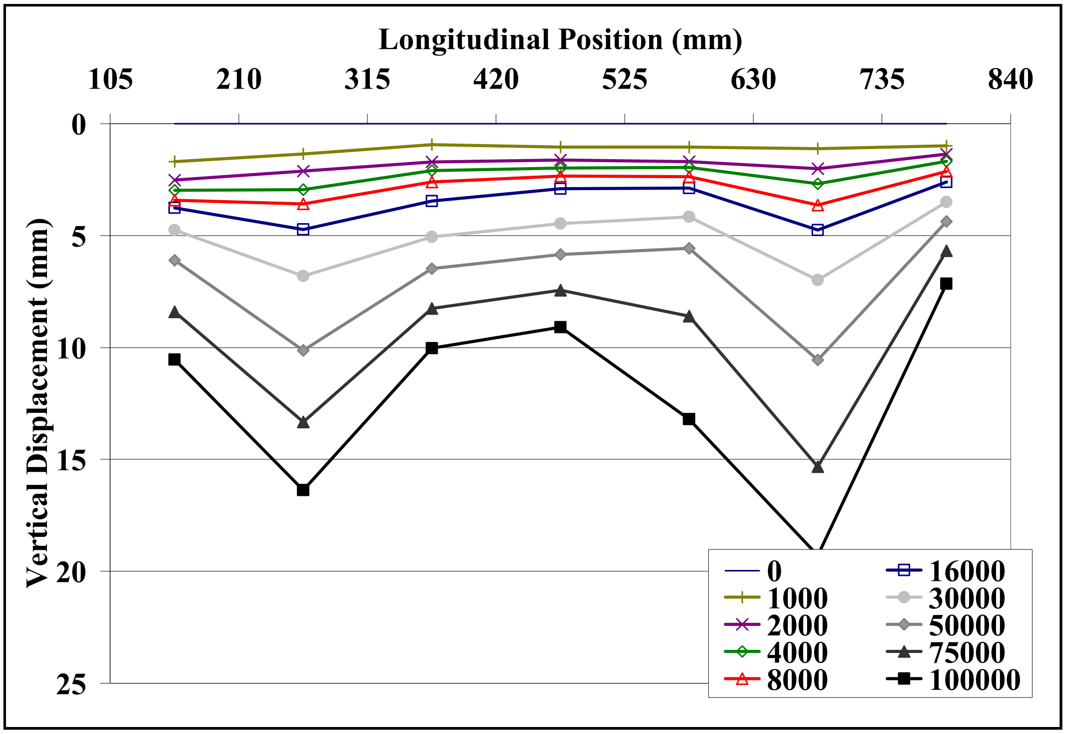


Figure C30: Cont 12.5 Max Rut from Max Heave Longitudinal Profiles

Cont 19

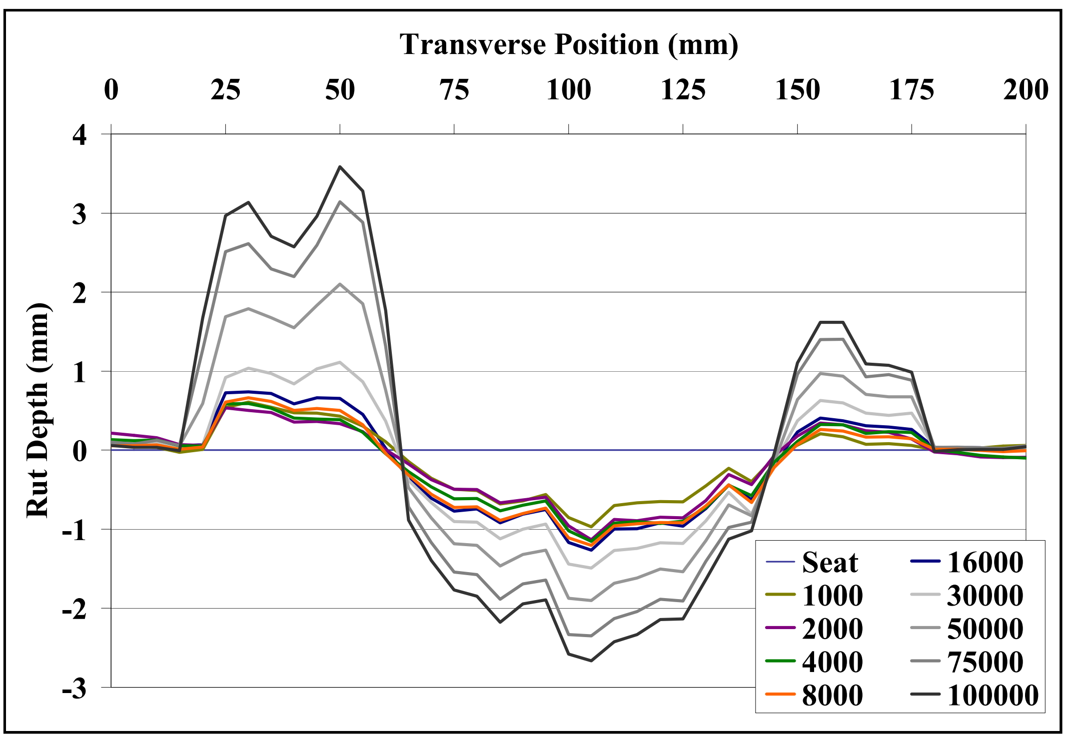


Figure C31: Cont 19 Brick 1 Transverse Profiles

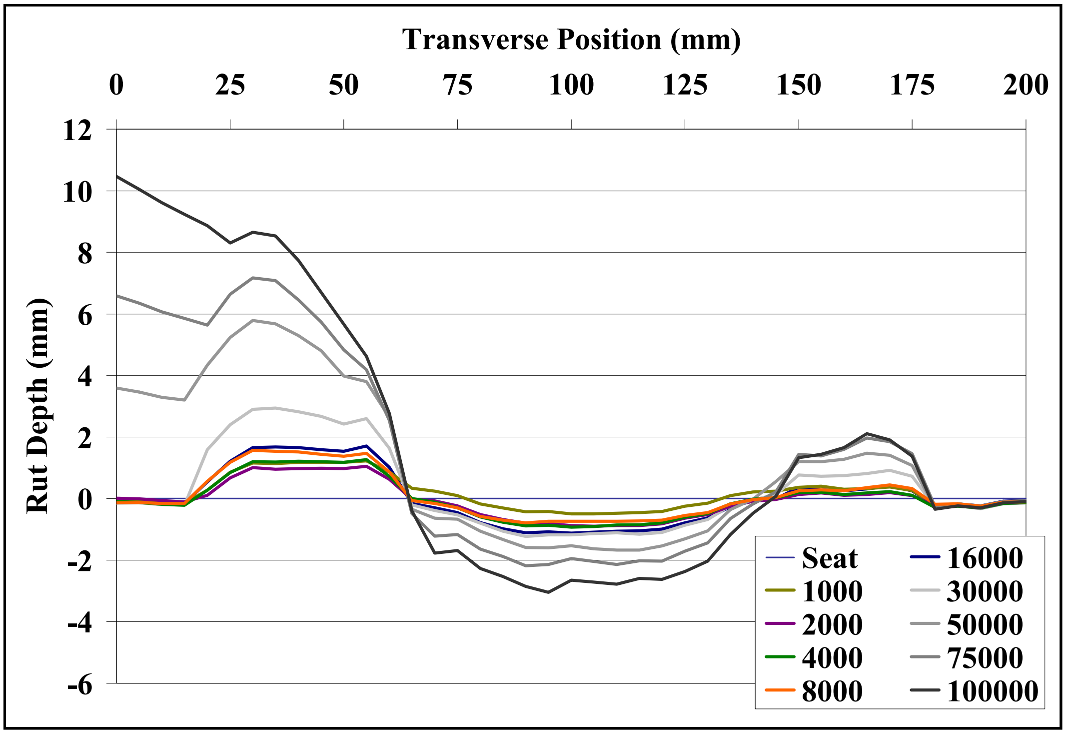


Figure C32: Cont 19 Brick 2 Transverse Profiles

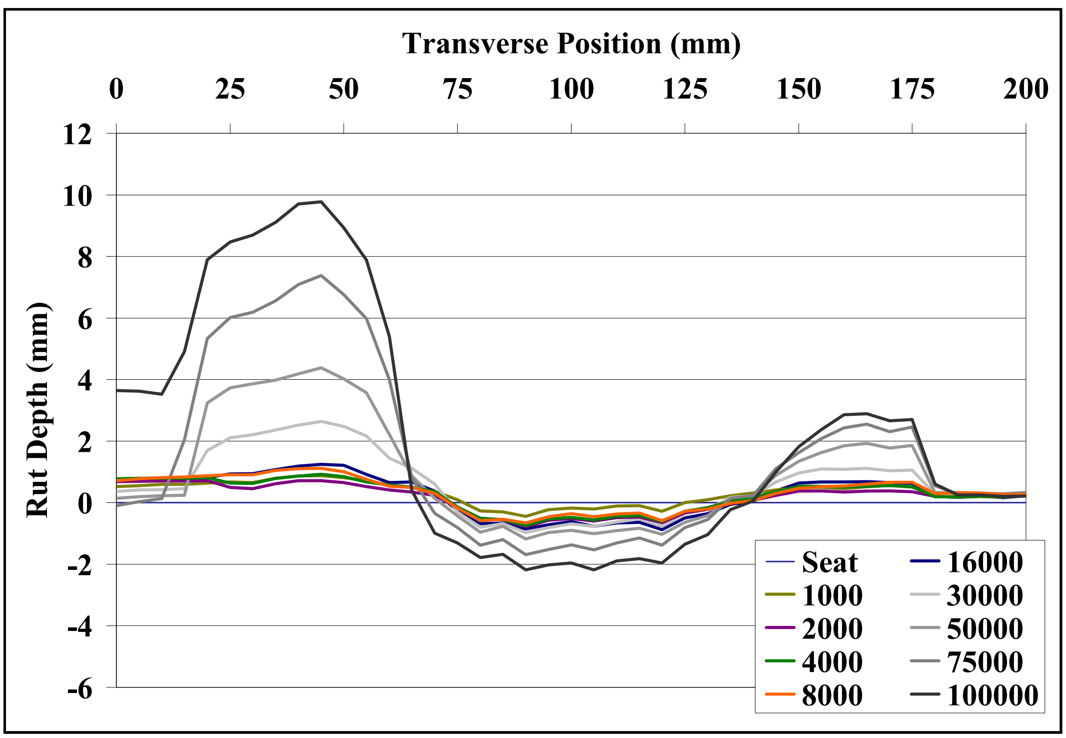


Figure C33: Cont 19 Brick 3 Transverse Profiles

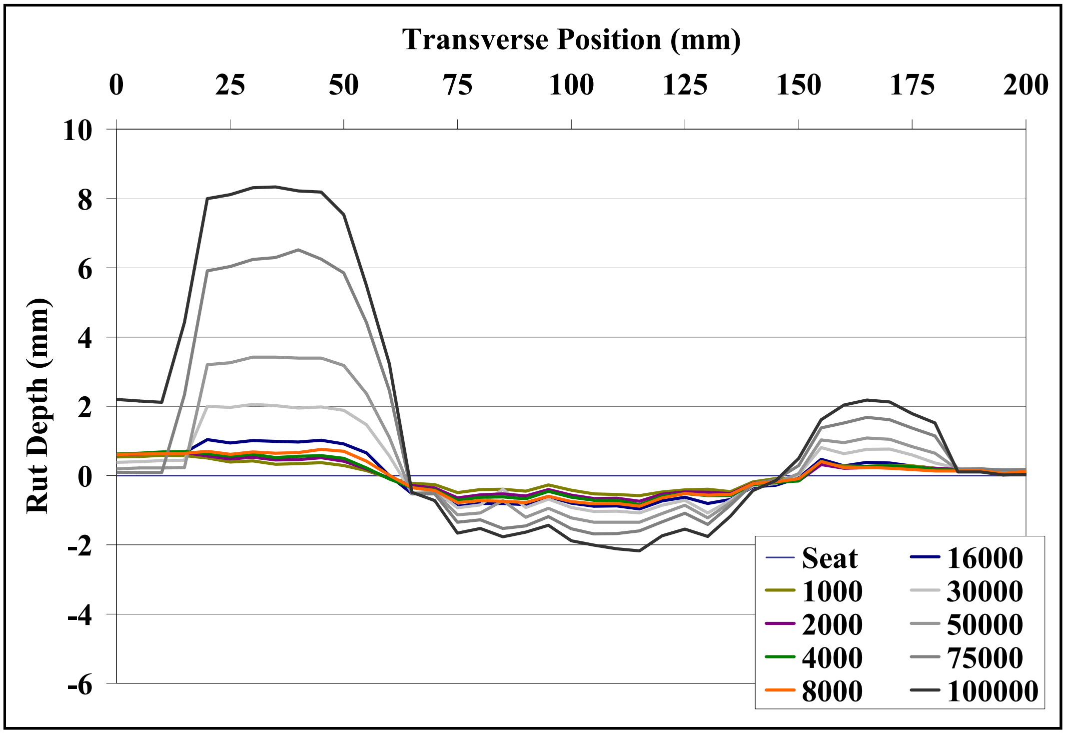


Figure C34: Cont 19 Brick 4 Transverse Profiles

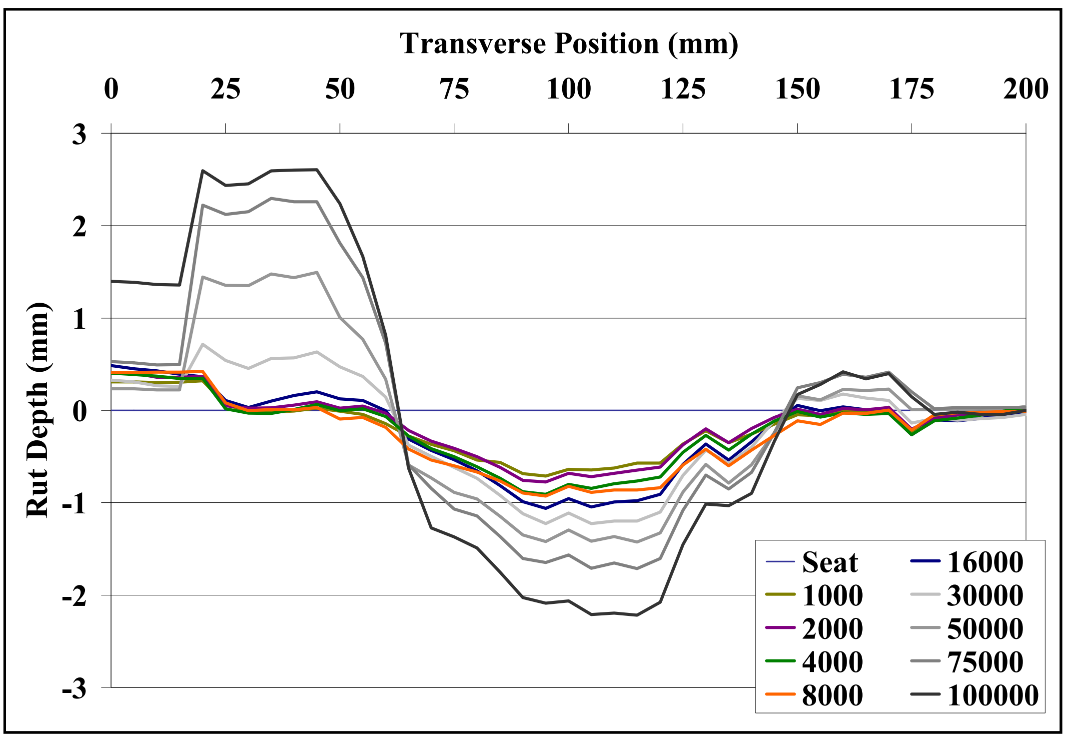


Figure C35: Cont 19 Brick 5 Transverse Profiles

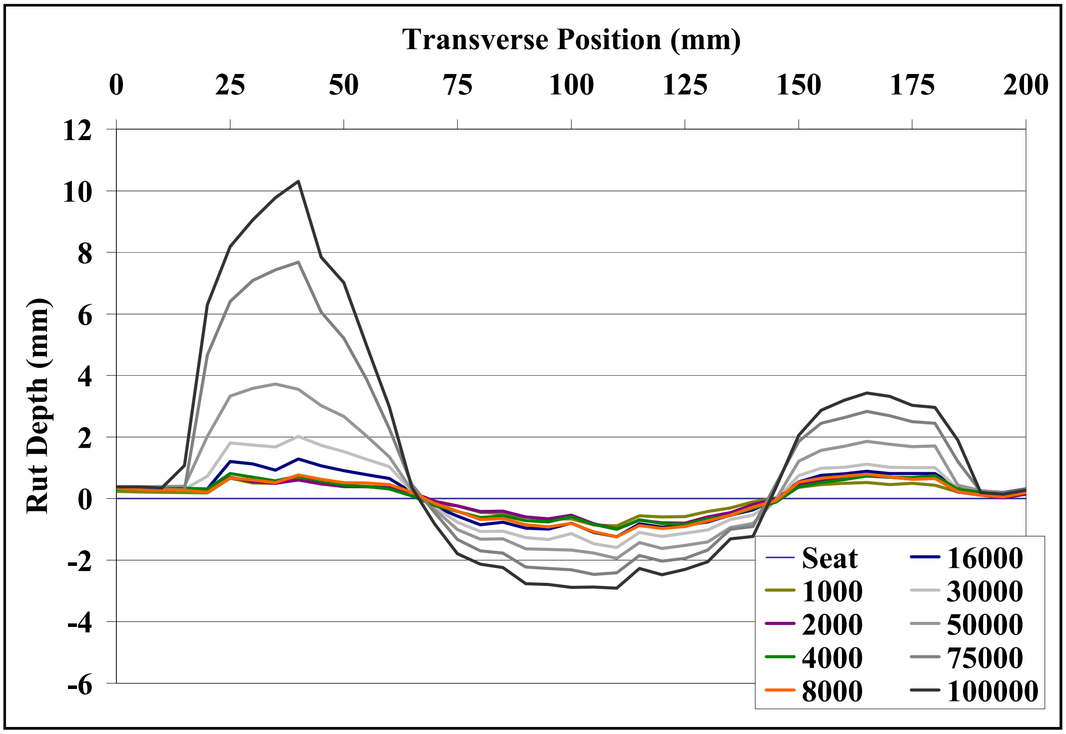


Figure C36: Cont 19 Brick 6 Transverse Profiles

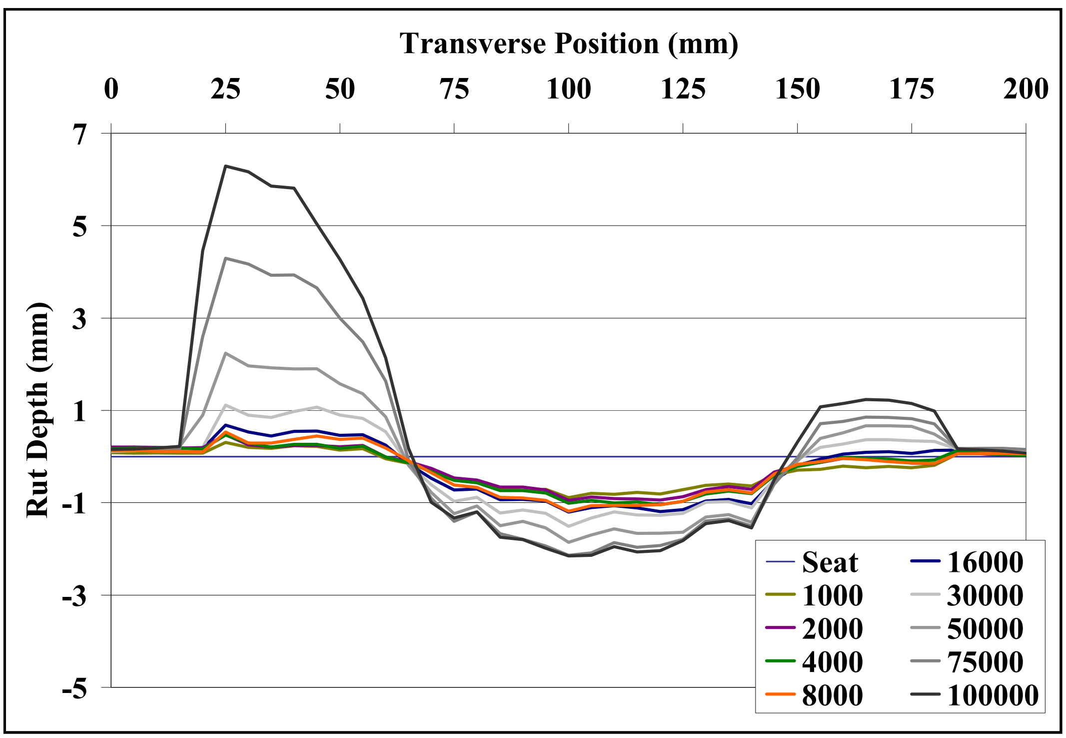


Figure C37: Cont 19 Brick 7 Transverse Profiles

Table C10: Cont 19 Avg Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	0.67	0.78	0.84	0.90	0.93	1.15	1.50	1.90	2.16
2	262.5	0.37	0.76	0.78	0.68	0.97	1.05	1.45	1.92	2.59
3	367.5	0.18	0.52	0.48	0.44	0.67	0.66	0.87	1.26	1.81
4	472.5	0.45	0.56	0.64	0.71	0.80	0.87	1.13	1.44	1.78
5	577.5	0.56	0.60	0.71	0.78	0.85	1.00	1.20	1.44	1.87
6	682.5	0.62	0.66	0.73	0.88	0.92	1.22	1.57	2.06	2.52
7	787.5	0.74	0.80	0.87	0.96	1.03	1.21	1.54	1.80	1.85
Avg		0.51	0.67	0.72	0.76	0.88	1.02	1.32	1.69	2.08

Table C11: Cont 19 Max Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	0.97	1.13	1.15	1.21	1.26	1.49	1.90	2.35	2.67
2	262.5	0.50	0.90	0.93	0.79	1.12	1.23	1.67	2.18	3.04
3	367.5	0.45	0.78	0.75	0.66	0.88	0.97	1.18	1.69	2.18
4	472.5	0.59	0.74	0.84	0.89	0.96	1.08	1.35	1.69	2.18
5	577.5	0.71	0.78	0.91	0.93	1.06	1.23	1.43	1.72	2.22
6	682.5	0.89	0.98	1.00	1.24	1.24	1.59	1.94	2.46	2.91
7	787.5	0.89	0.95	1.04	1.19	1.21	1.51	1.86	2.14	2.15
Avg		0.71	0.89	0.95	0.99	1.10	1.30	1.62	2.03	2.48

Table C12: Cont 19 Max Rut Depth from Max Heave

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	1.58	1.67	1.74	1.87	2.00	2.60	4.00	5.50	6.25
2	262.5	1.72	1.95	2.19	2.36	2.82	4.17	7.46	9.35	13.50
3	367.5	1.32	1.49	1.67	1.78	2.12	3.61	5.56	9.06	11.96
4	472.5	1.17	1.41	1.53	1.64	2.00	3.13	4.77	8.21	10.52
5	577.5	1.04	1.18	1.32	1.35	1.55	1.94	2.92	4.01	4.82
6	682.5	1.56	1.72	1.81	2.04	2.53	3.61	5.66	10.14	13.22
7	787.5	1.20	1.42	1.51	1.72	1.89	2.62	4.09	6.44	8.44
Avg		1.37	1.55	1.68	1.82	2.13	3.10	4.92	7.53	9.82

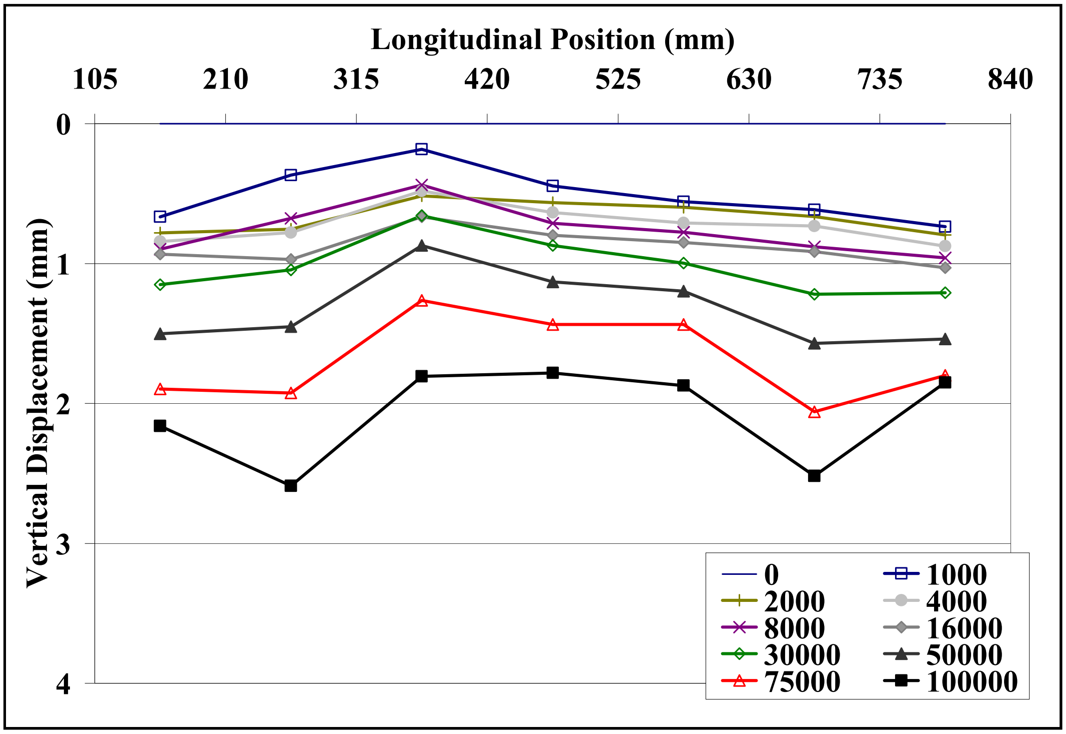


Figure C38: Cont 19 Avg Rut from Base Line Longitudinal Profiles

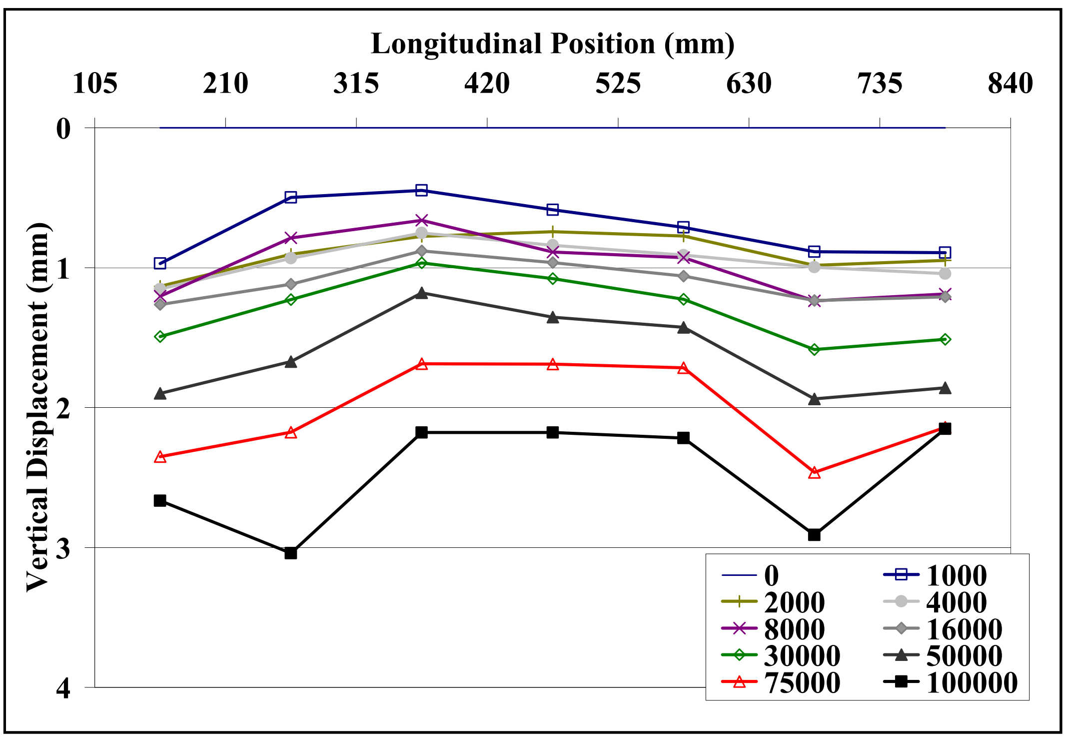


Figure C39: Cont 19 Max Rut from Base Line Longitudinal Profiles

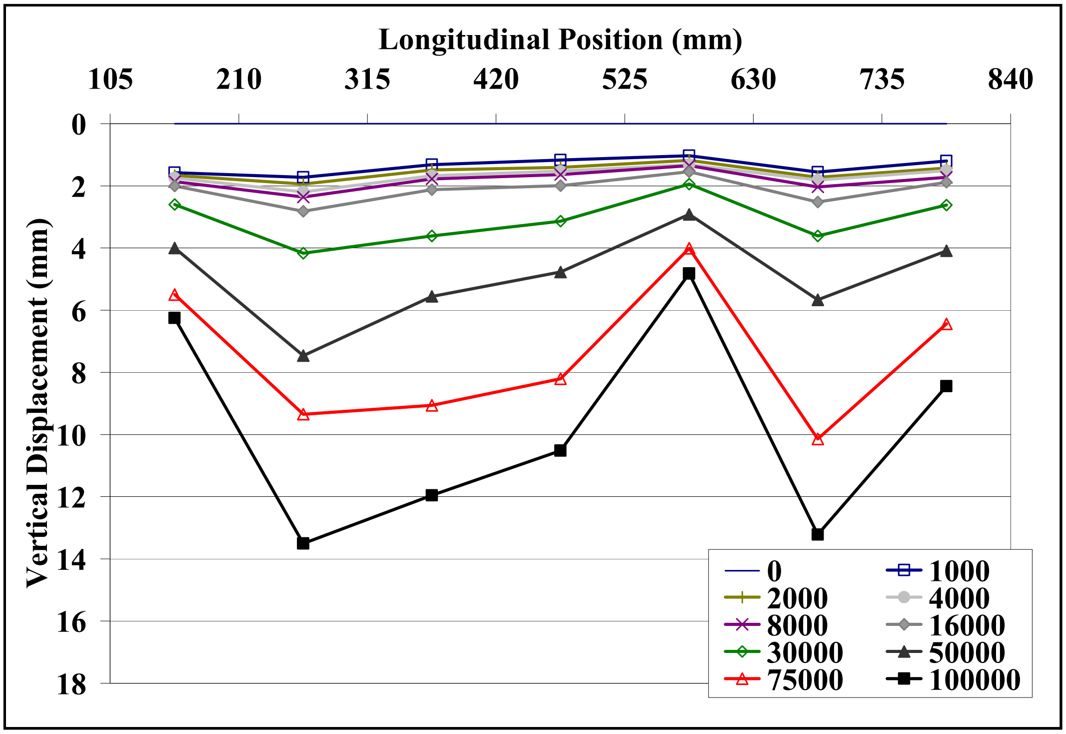


Figure C40: Cont 19 Max Rut from Max Heave Longitudinal Profiles

Farm

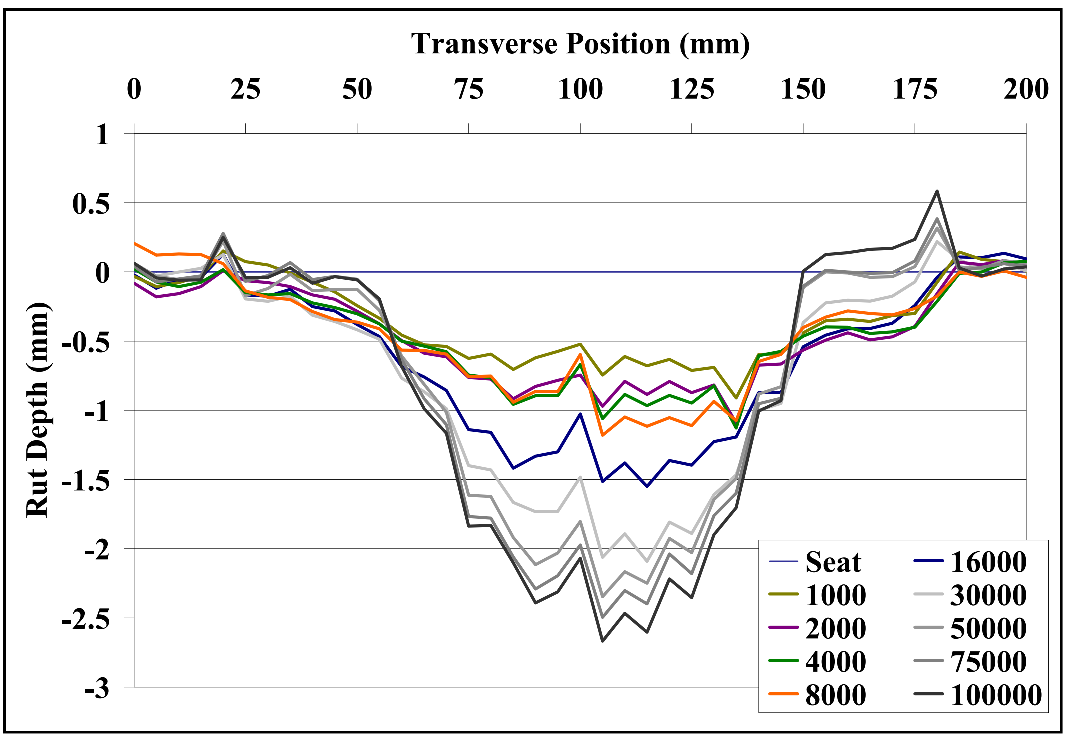


Figure C41: Farm Brick 1 Transverse Profiles

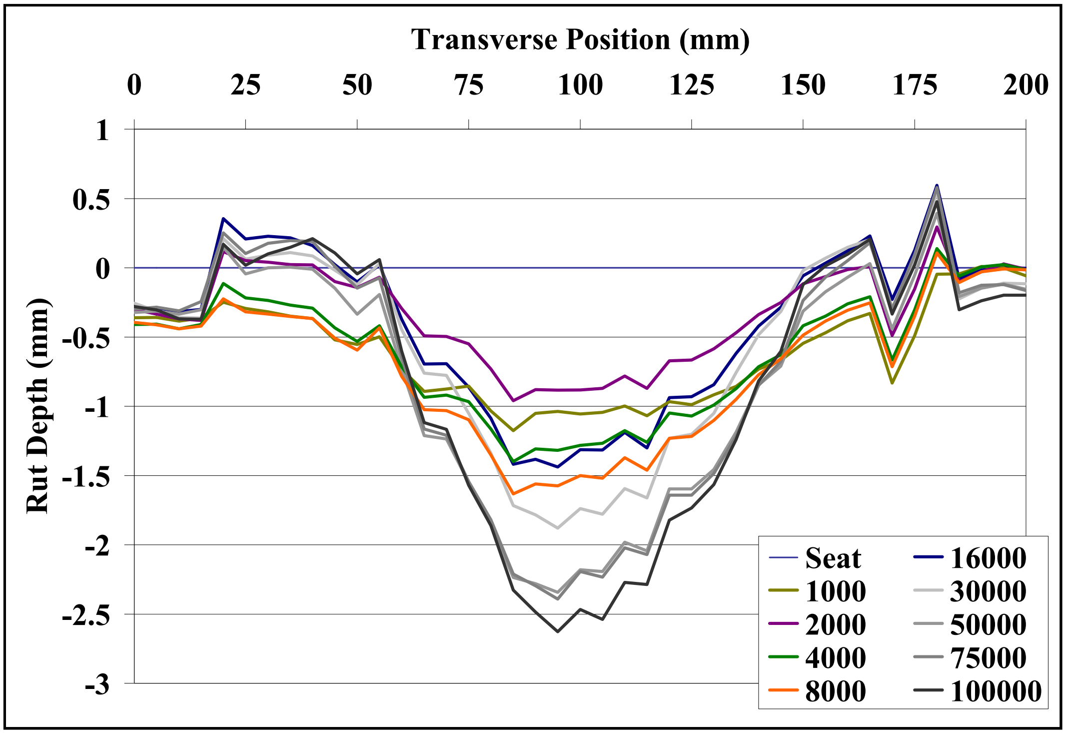


Figure C42: Farm Brick 2 Transverse Profiles

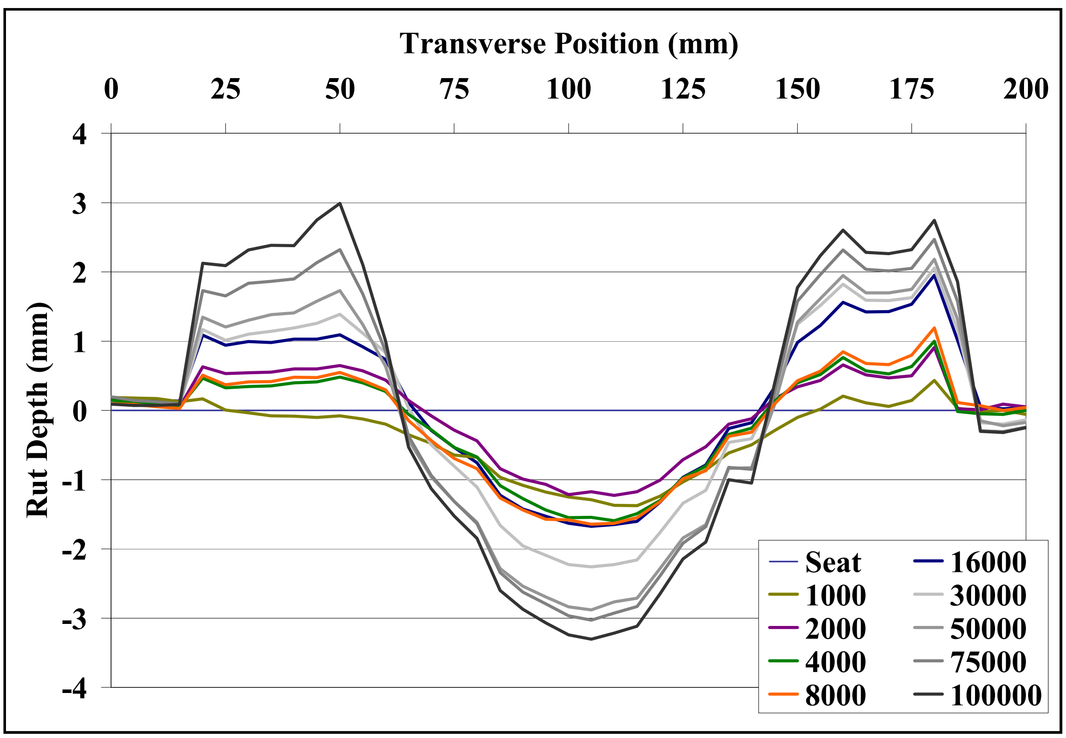


Figure C43: Farm Brick 3 Transverse Profiles

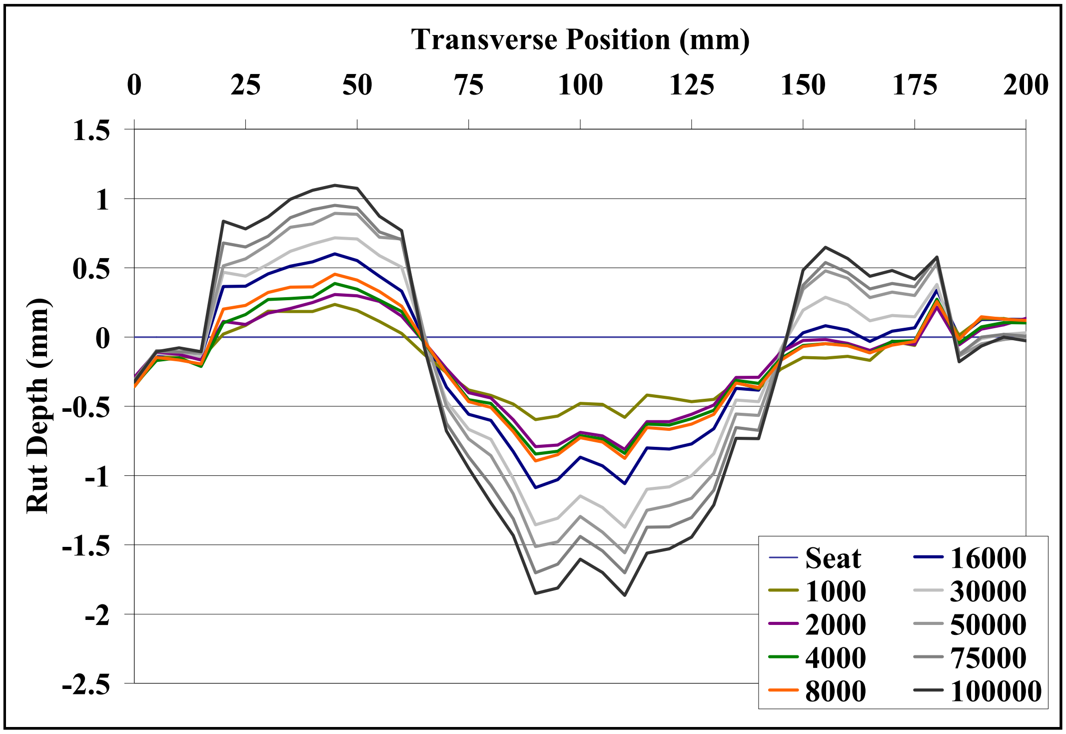


Figure C44: Farm Brick 4 Transverse Profiles

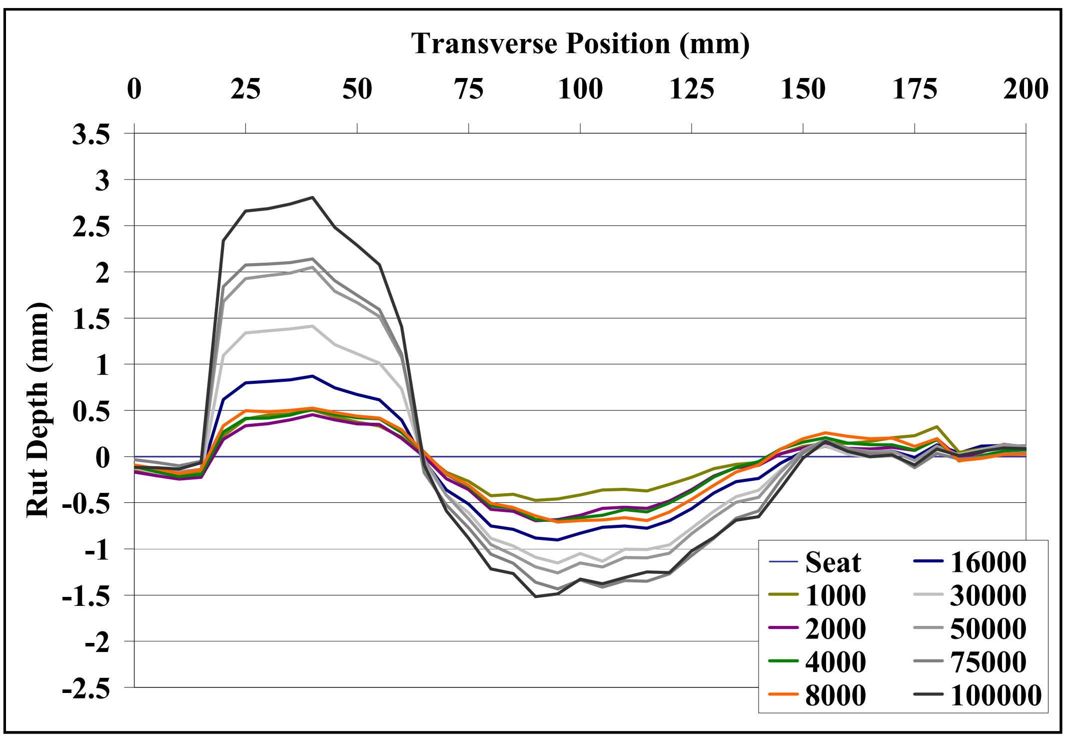


Figure C45: Farm Brick 5 Transverse Profiles

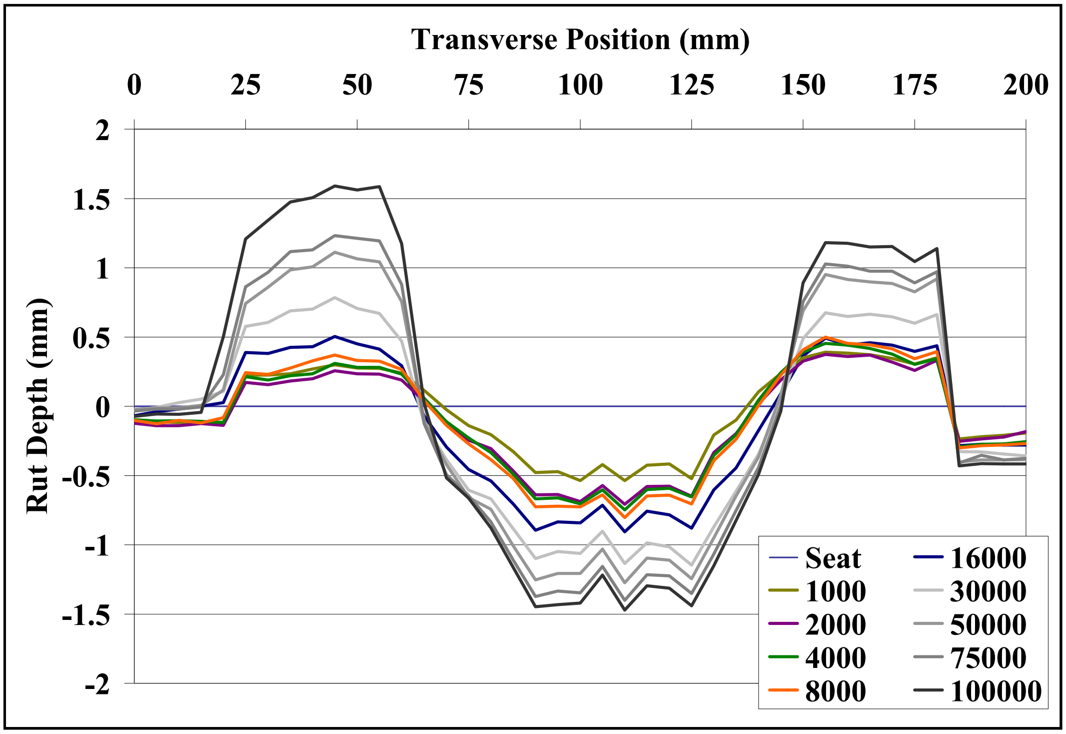


Figure C46: Farm Brick 6 Transverse Profiles

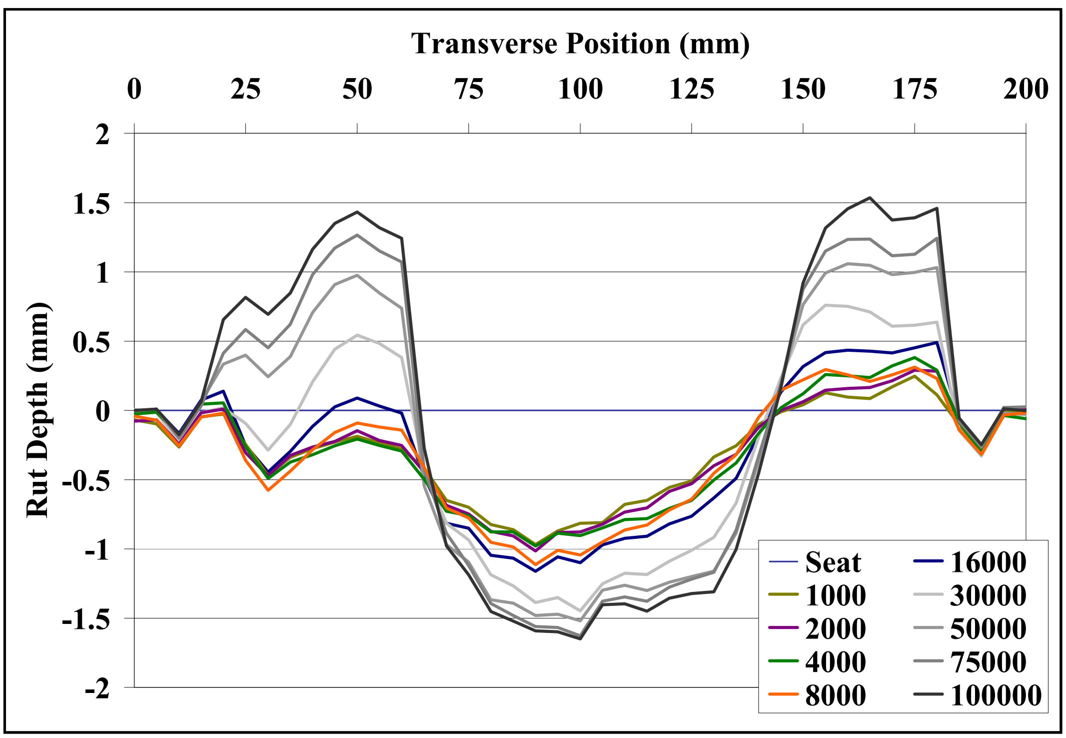


Figure C47: Farm Brick 7 Transverse Profiles

Table C13: Farm Avg Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	0.64	0.83	0.89	0.95	1.33	1.76	1.99	2.13	2.27
2	262.5	1.03	0.80	1.21	1.41	1.20	1.54	1.98	2.00	2.18
3	367.5	1.12	0.94	1.25	1.34	1.32	1.81	2.37	2.47	2.72
4	472.5	0.49	0.65	0.68	0.71	0.86	1.11	1.26	1.41	1.57
5	577.5	0.36	0.54	0.55	0.59	0.74	0.97	1.05	1.24	1.26
6	682.5	0.41	0.56	0.58	0.63	0.77	0.98	1.10	1.22	1.29
7	787.5	0.72	0.76	0.80	0.87	0.95	1.21	1.34	1.40	1.46
Avg		0.68	0.73	0.85	0.93	1.02	1.34	1.58	1.70	1.82

Table C14: Farm Max Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	0.91	1.09	1.13	1.18	1.55	2.09	2.35	2.50	2.67
2	262.5	1.18	0.96	1.40	1.63	1.44	1.88	2.34	2.39	2.63
3	367.5	1.38	1.23	1.60	1.64	1.68	2.26	2.88	3.03	3.31
4	472.5	0.60	0.81	0.85	0.90	1.09	1.37	1.56	1.70	1.87
5	577.5	0.48	0.70	0.70	0.71	0.90	1.15	1.26	1.43	1.52
6	682.5	0.54	0.71	0.75	0.80	0.91	1.15	1.27	1.40	1.47
7	787.5	0.97	1.02	0.98	1.11	1.16	1.45	1.52	1.63	1.65
Avg		0.86	0.93	1.06	1.14	1.25	1.62	1.88	2.01	2.16

Table C15: Farm Max Rut Depth from Max Heave

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	1.06	1.17	1.21	1.39	1.68	2.31	2.67	2.88	3.25
2	262.5	1.18	1.26	1.54	1.74	2.03	2.43	2.74	2.97	3.10
3	367.5	1.81	2.14	2.59	2.83	3.63	4.31	5.07	5.50	6.30
4	472.5	0.85	1.12	1.23	1.35	1.69	2.09	2.45	2.65	2.96
5	577.5	0.98	1.15	1.21	1.23	1.78	2.57	3.31	3.57	4.32
6	682.5	0.93	1.08	1.20	1.30	1.41	1.93	2.38	2.63	3.06
7	787.5	1.22	1.30	1.36	1.43	1.65	2.21	2.58	2.90	3.19
Avg		1.15	1.32	1.48	1.61	1.98	2.55	3.03	3.30	3.74

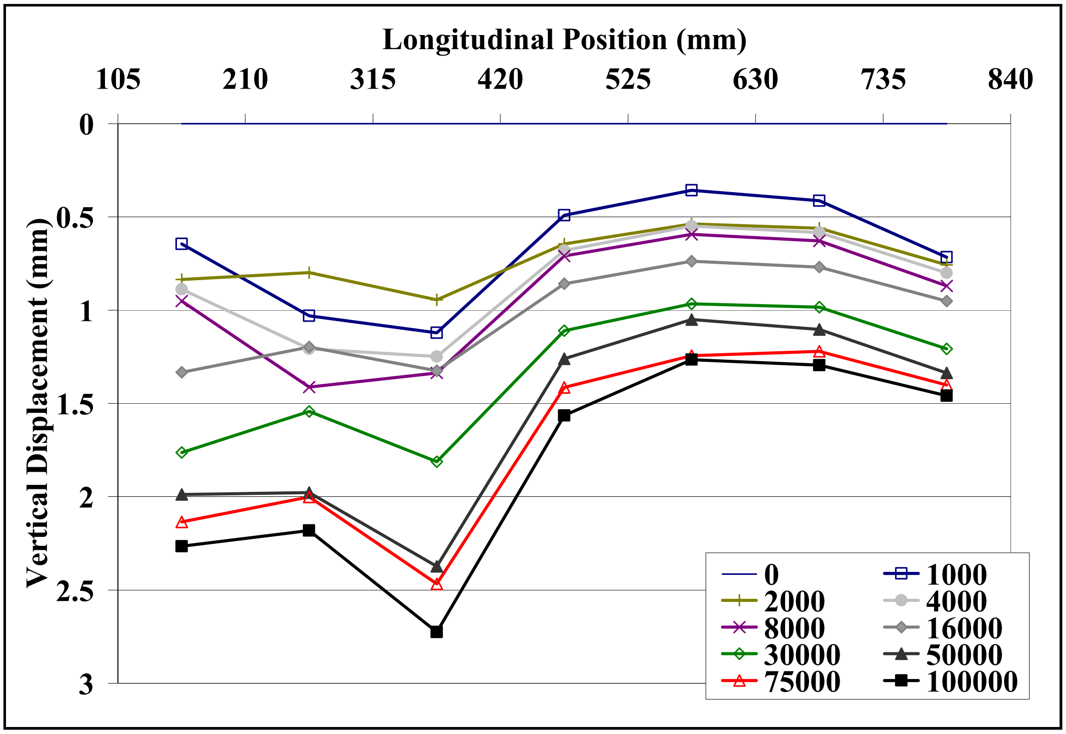


Figure C48: Farm Avg Rut from Base Line Longitudinal Profiles

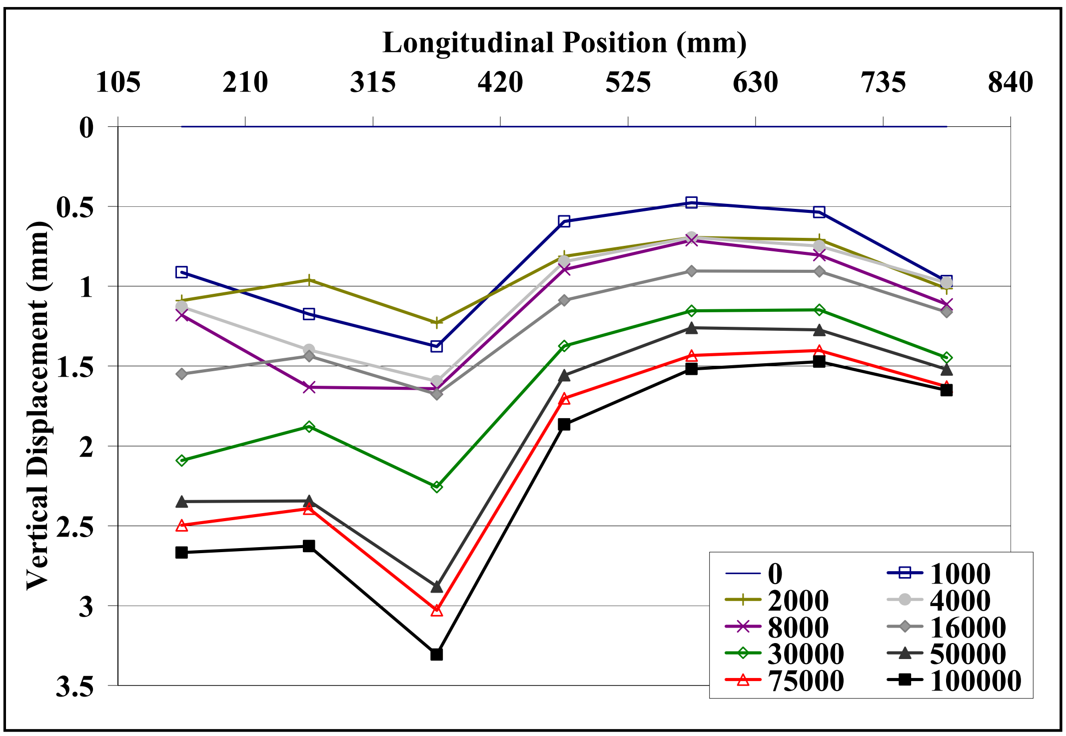


Figure C49: Farm Max Rut from Base Line Longitudinal Profiles

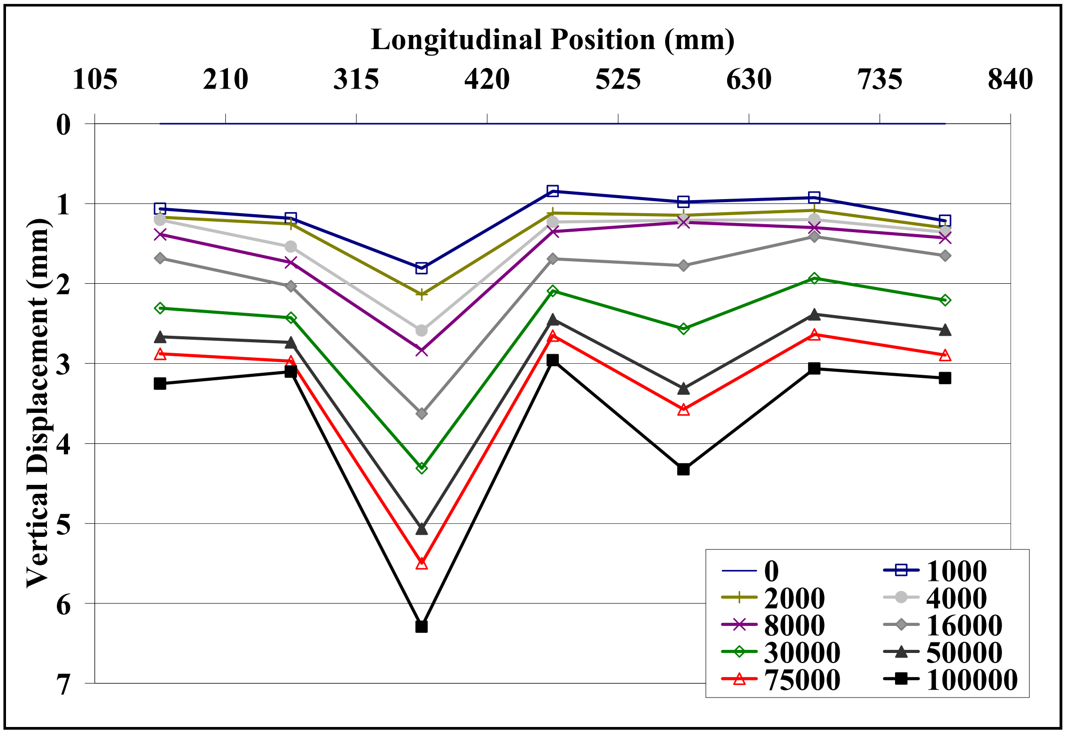


Figure C50: Farm Max Rut from Max Heave Longitudinal Profiles

<u>**Hook**</u>

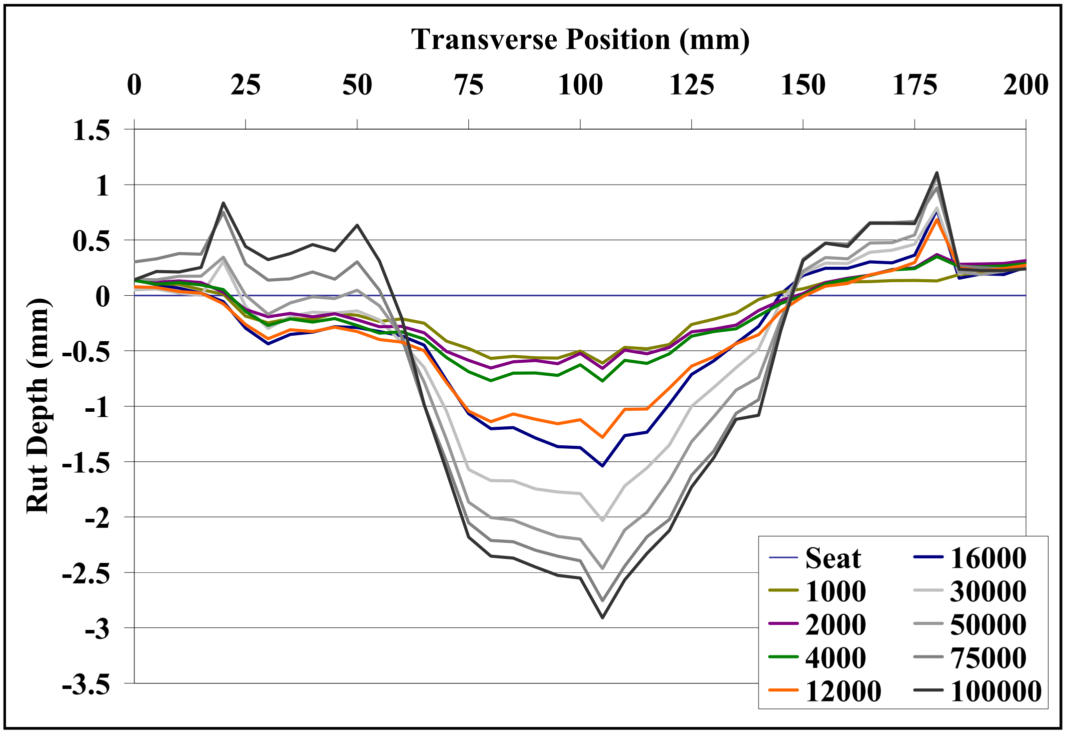


Figure C51: Hook Brick 1 Transverse Profiles

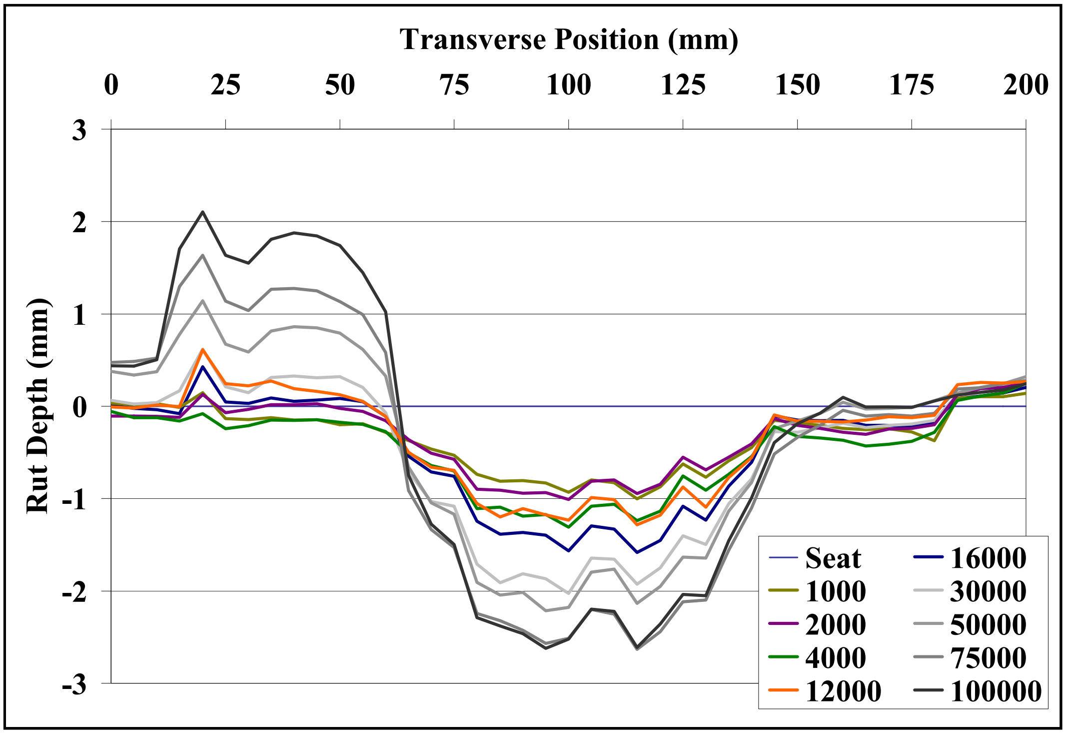


Figure C52: Hook Brick 2 Transverse Profiles

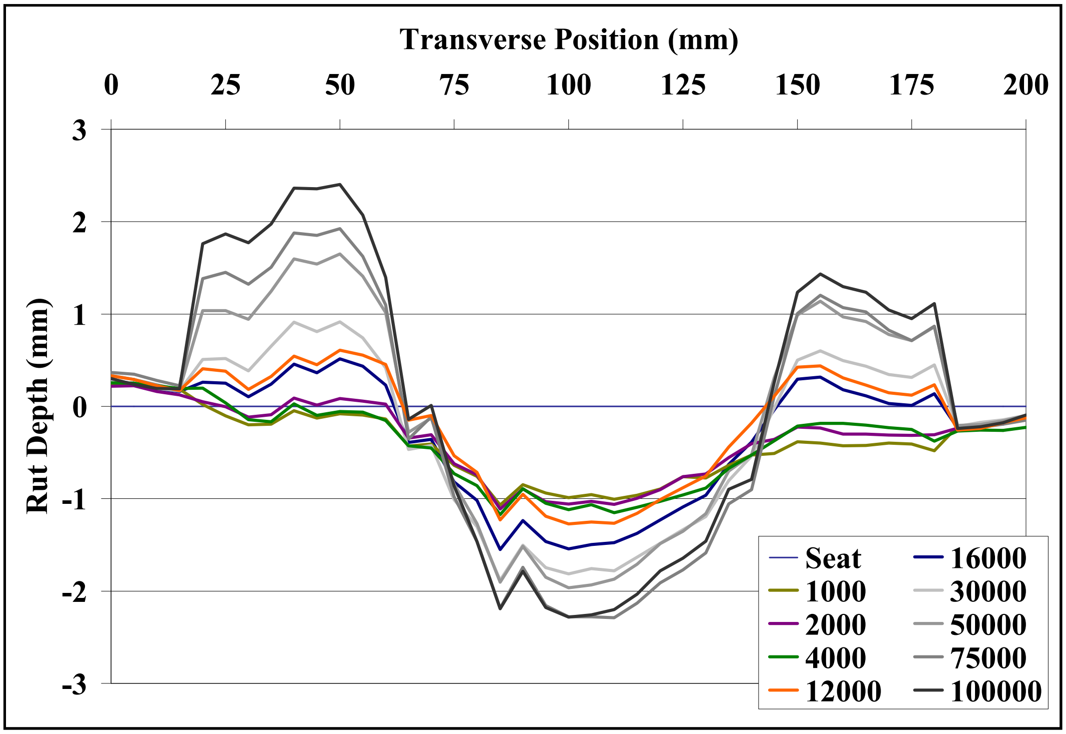


Figure C53: Hook Brick 3 Transverse Profiles

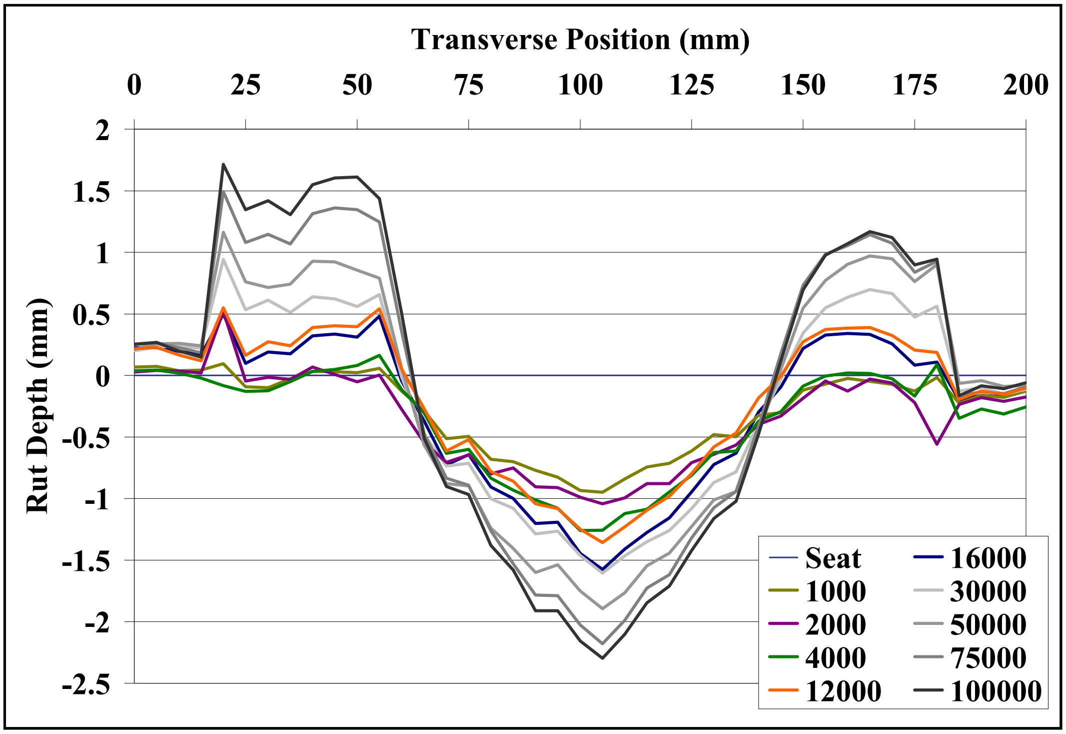


Figure C54: Hook Brick 4 Transverse Profiles

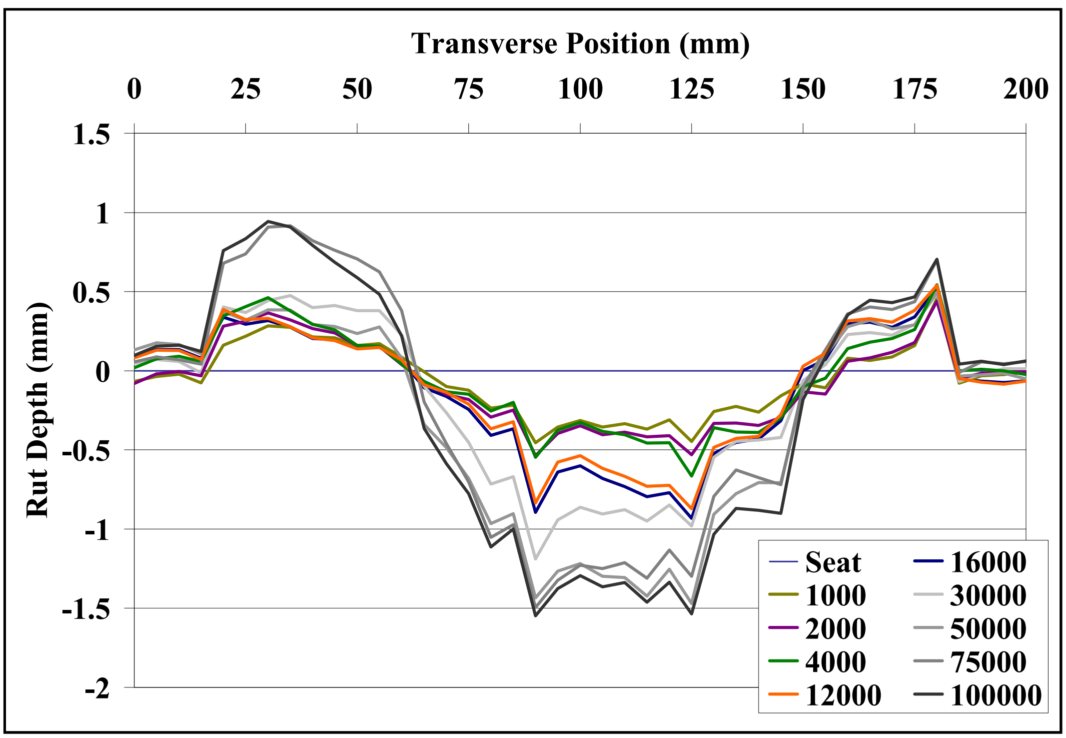


Figure C55: Hook Brick 5 Transverse Profiles

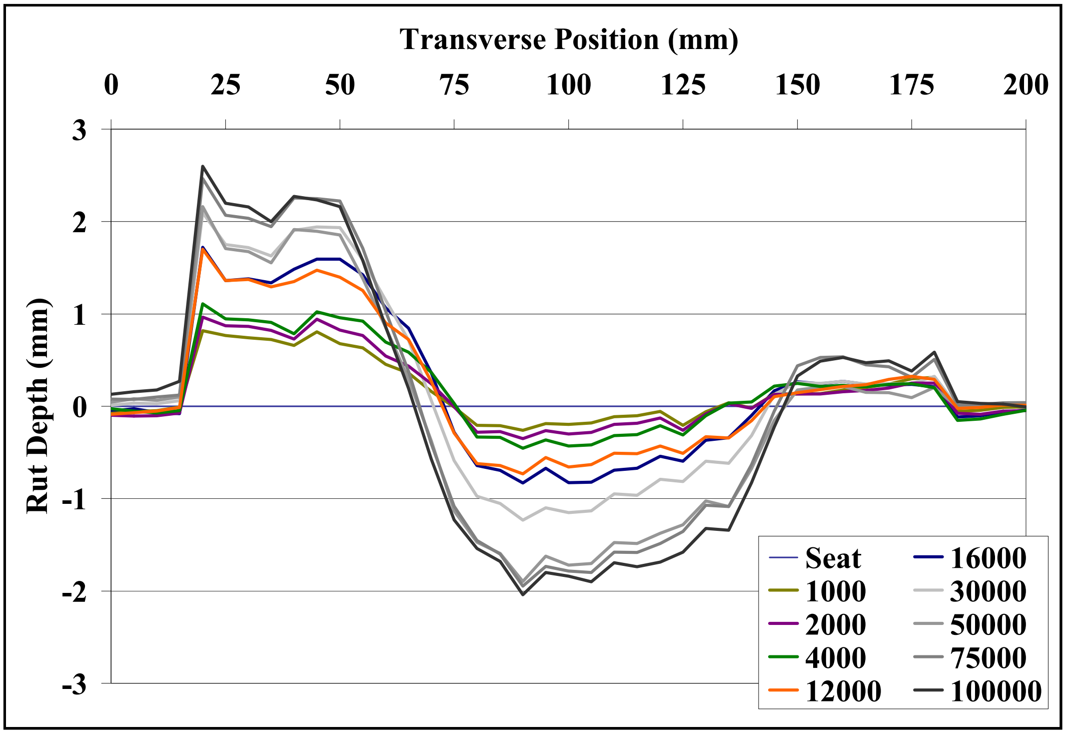


Figure C56: Hook Brick 6 Transverse Profiles

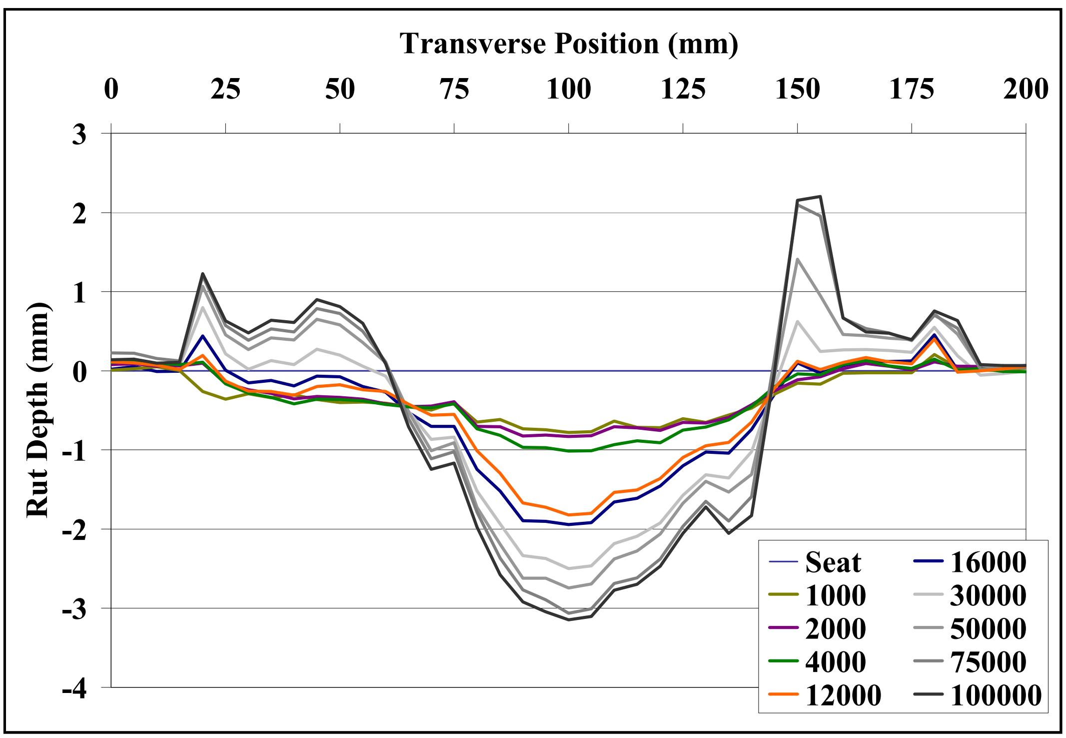


Figure C57: Hook Brick 7 Transverse Profiles

Table C16: Hook Avg Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	12	16	30	50	75	100
1	157.5	0.48	0.52	0.61	1.00	1.16	1.56	1.92	2.17	2.31
2	262.5	0.82	0.85	1.10	1.11	1.36	1.75	1.94	2.35	2.34
3	367.5	0.91	0.94	1.02	1.06	1.31	1.58	1.64	1.98	1.93
4	472.5	0.75	0.86	1.00	1.00	1.17	1.25	1.49	1.66	1.77
5	577.5	0.33	0.39	0.40	0.61	0.67	0.86	1.22	1.19	1.31
6	682.5	0.16	0.24	0.33	0.56	0.67	0.98	1.51	1.58	1.71
7	787.5	0.69	0.74	0.88	1.43	1.58	2.02	2.22	2.47	2.59
Avg		0.59	0.65	0.76	0.97	1.13	1.43	1.71	1.92	1.99

Table C17: Hook Max Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	12	16	30	50	75	100
1	157.5	0.61	0.66	0.77	1.28	1.54	2.03	2.47	2.75	2.91
2	262.5	1.00	1.01	1.31	1.28	1.58	2.03	2.21	2.63	2.62
3	367.5	1.07	1.11	1.17	1.27	1.55	1.89	1.96	2.29	2.28
4	472.5	0.95	1.04	1.26	1.36	1.58	1.61	1.89	2.18	2.30
5	577.5	0.45	0.54	0.66	0.87	0.93	1.19	1.47	1.50	1.55
6	682.5	0.26	0.35	0.46	0.73	0.83	1.23	1.90	1.95	2.04
7	787.5	0.78	0.83	1.01	1.82	1.94	2.50	2.74	3.07	3.15
Avg		0.73	0.79	0.95	1.23	1.42	1.78	2.09	2.34	2.41

Table C18: Hook Max Rut Depth from Max Heave

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	12	16	30	50	75	100
1	157.5	0.87	1.03	1.12	1.97	2.31	2.82	3.55	3.72	4.02
2	262.5	1.15	1.26	1.56	1.90	2.01	2.65	3.36	4.27	4.73
3	367.5	1.31	1.33	1.43	1.88	2.07	2.80	3.61	4.21	4.69
4	472.5	1.04	1.56	1.42	1.91	2.07	2.55	3.06	3.67	4.01
5	577.5	0.91	0.98	1.21	1.41	1.46	1.68	1.97	2.41	2.49
6	682.5	1.08	1.32	1.57	2.43	2.55	3.33	4.06	4.41	4.64
7	787.5	0.99	0.94	1.16	2.22	2.40	3.30	4.15	5.16	5.35
Avg		1.05	1.20	1.35	1.96	2.12	2.73	3.39	3.98	4.27

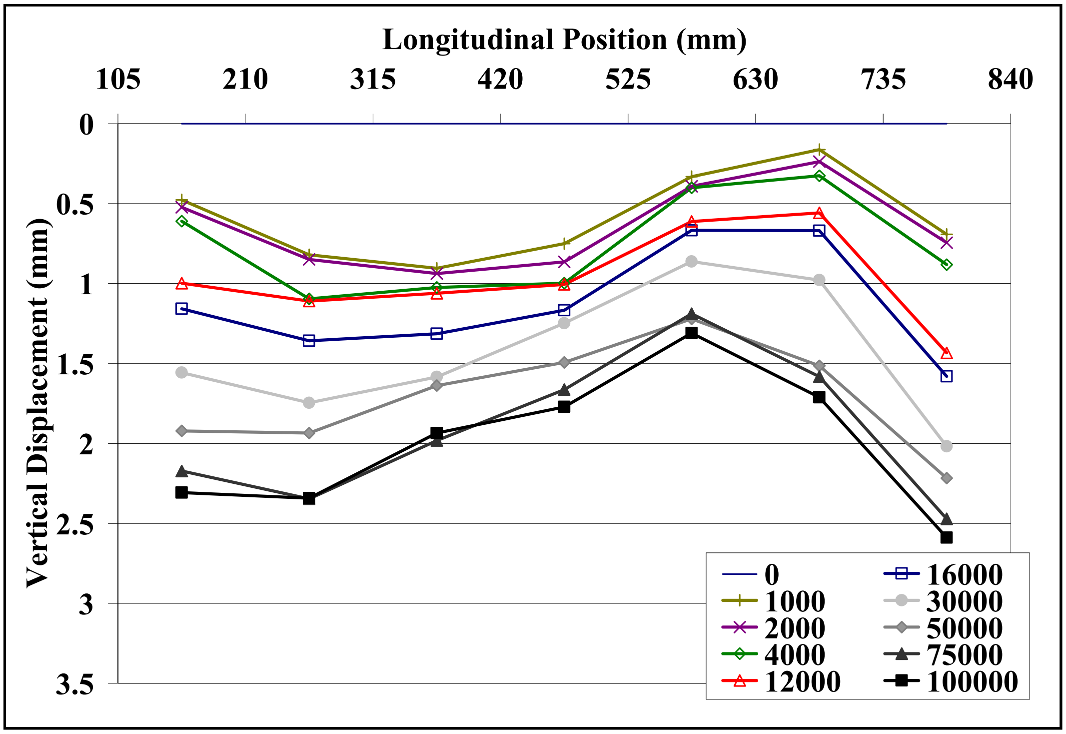


Figure C58: Hook Avg Rut from Base Line Longitudinal Profiles

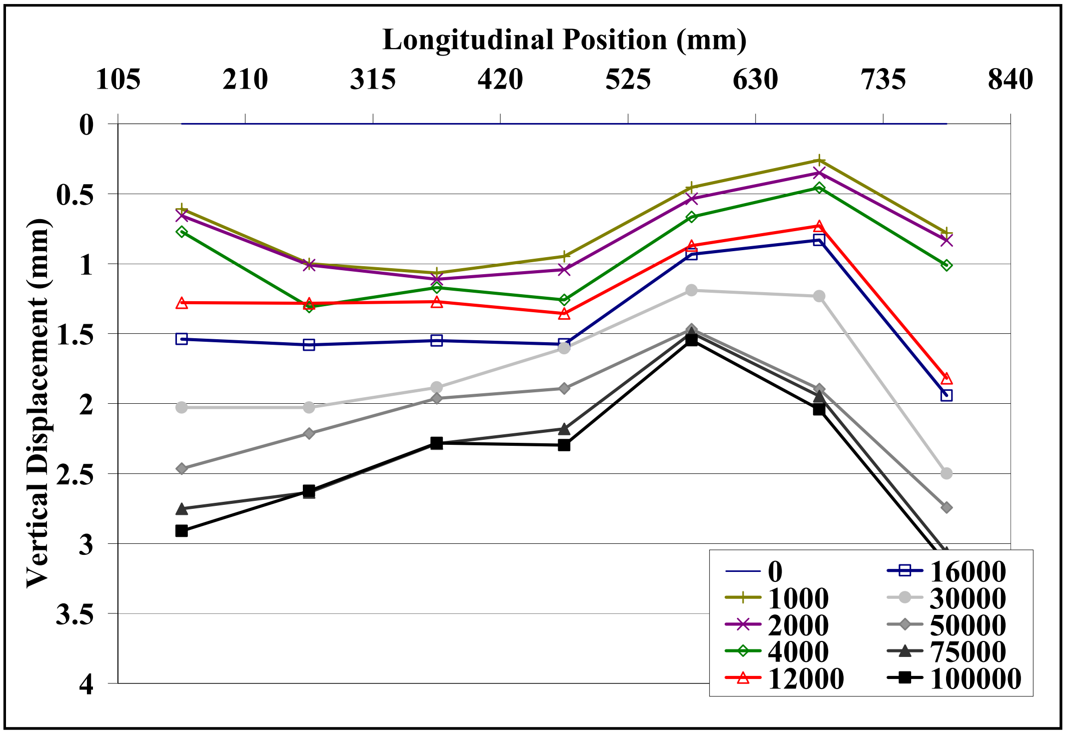
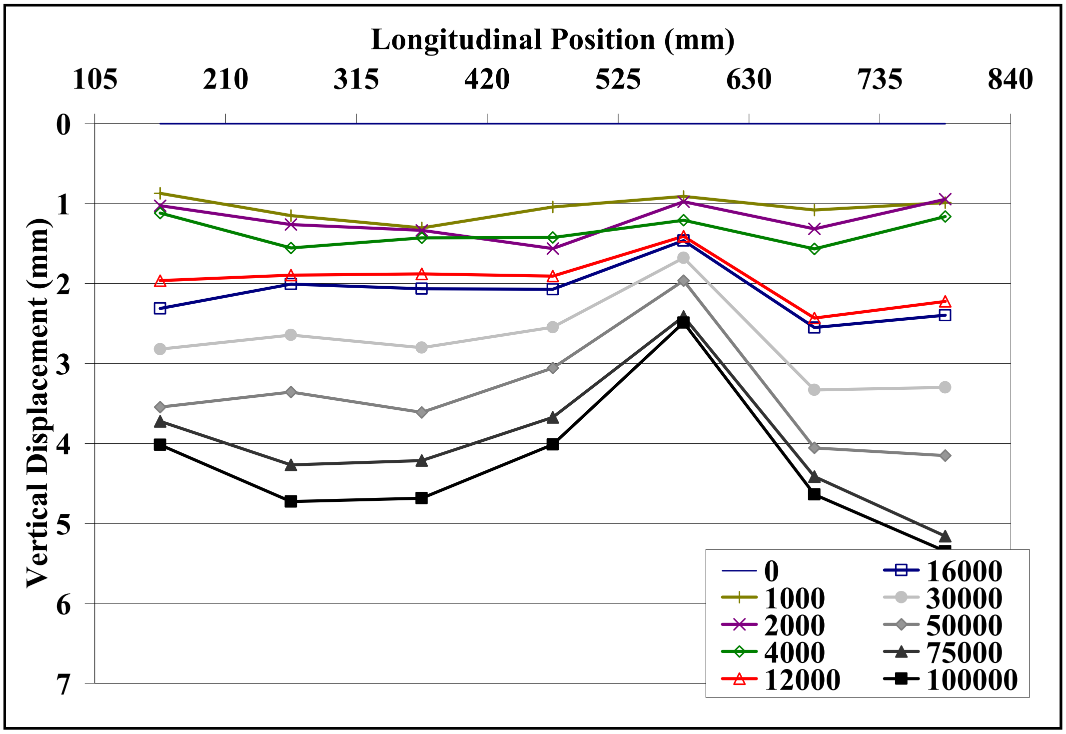


Figure C59: Hook Max Rut from Base Line Longitudinal Profiles



FigureC60: Hook Max Rut from Max Heave Longitudinal Profiles

__Oss 12.5 Bailey__

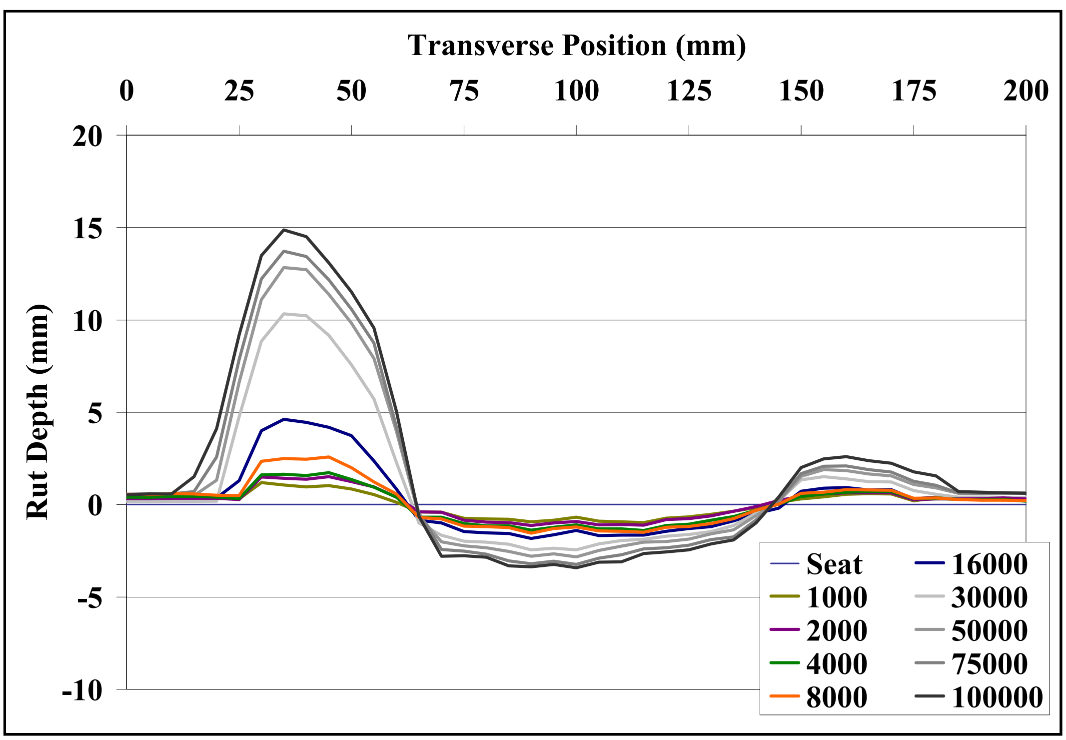


Figure C61: Oss 12.5 Bailey Brick 1 Transverse Profiles

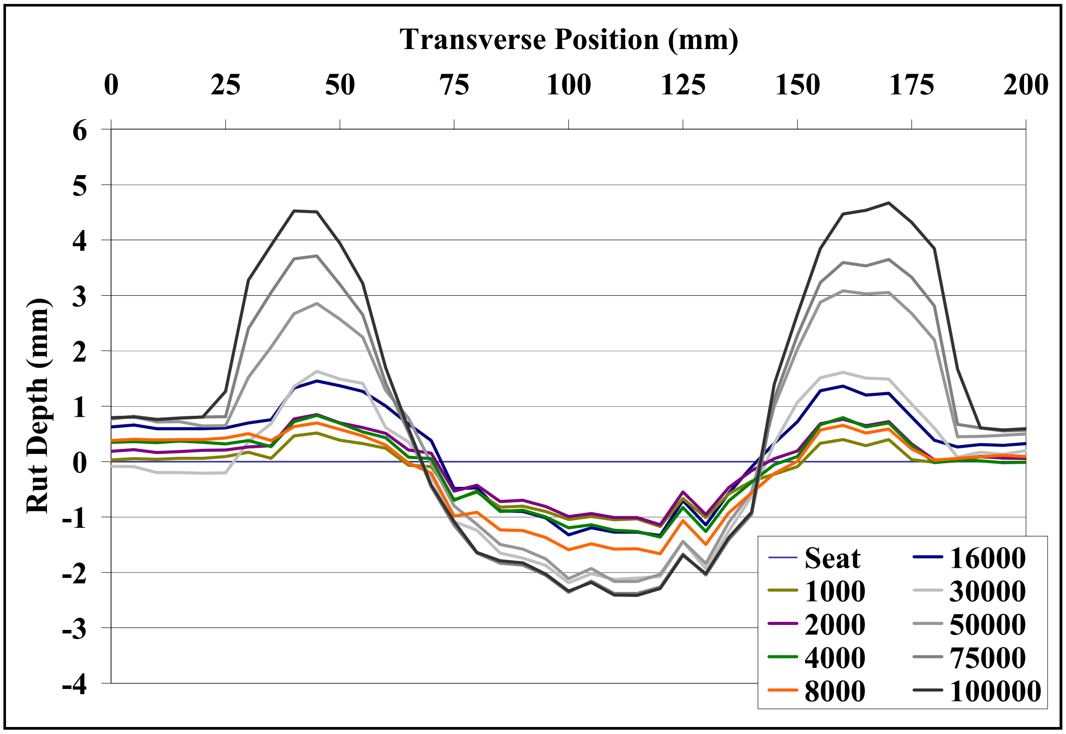


Figure C62: Oss 12.5 Bailey Brick 2 Transverse Profiles

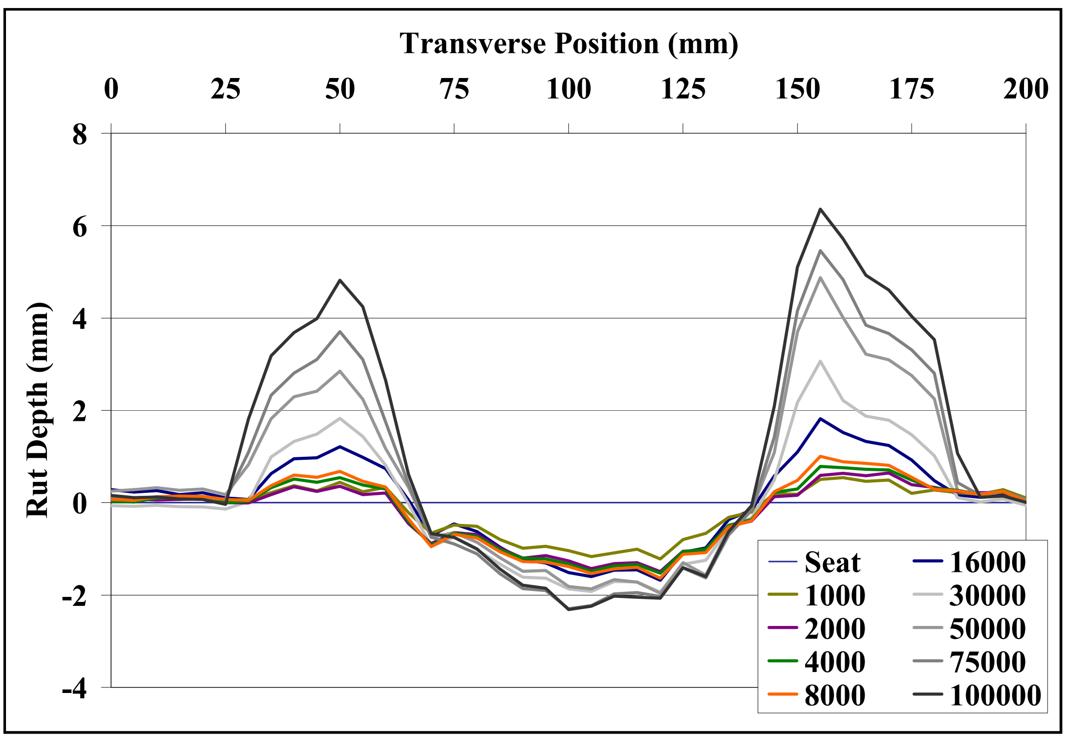


Figure C63: Oss 12.5 Bailey Brick 3 Transverse Profiles

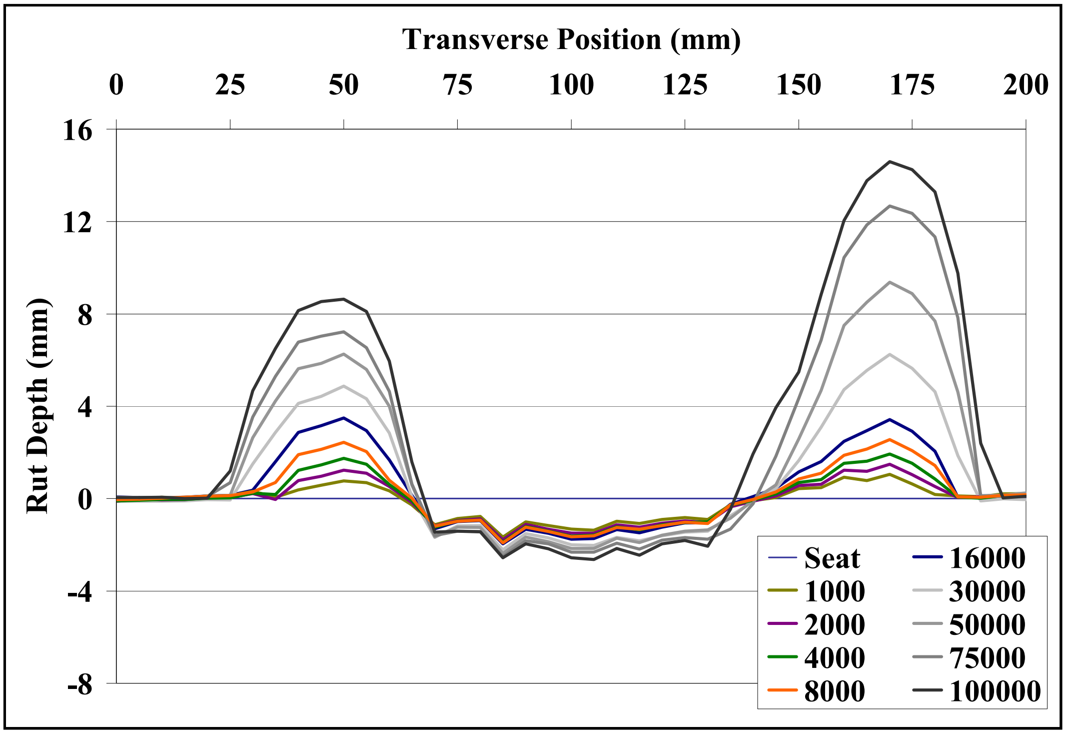


Figure C64: Oss 12.5 Bailey Brick 4 Transverse Profiles

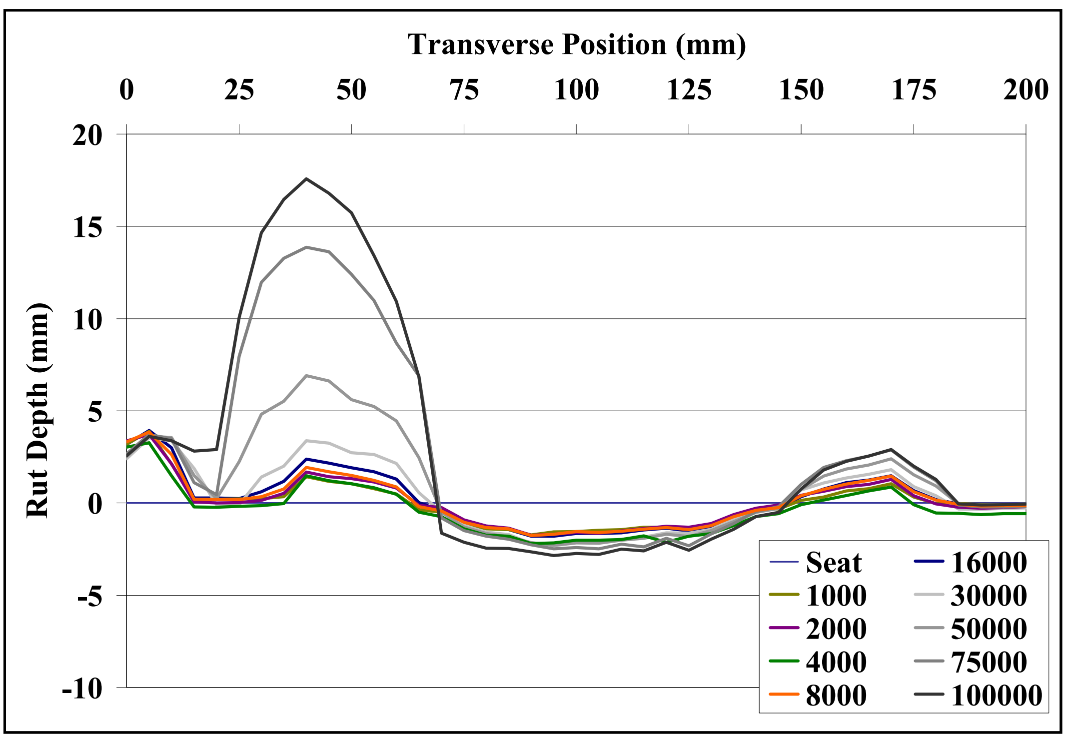


Figure C65: Oss 12.5 Bailey Brick 5 Transverse Profiles

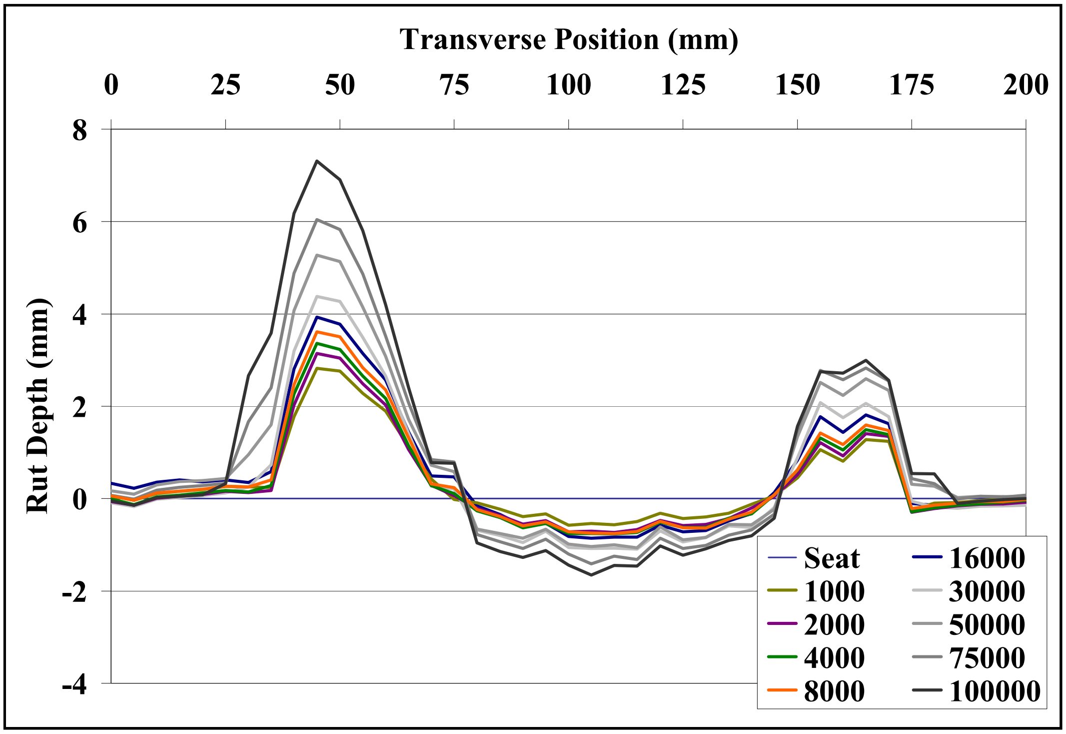


Figure C66: Oss 12.5 Bailey Brick 6 Transverse Profiles

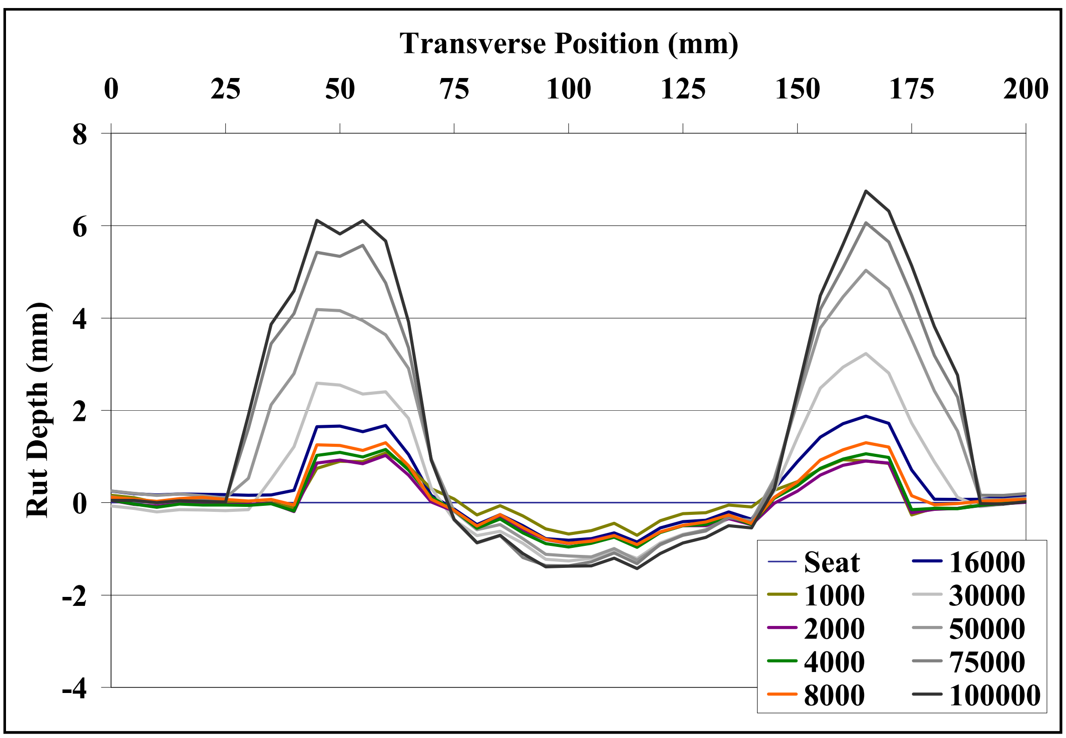


Figure C67: Oss 12.5 Bailey Brick 7 Transverse Profiles

Table C19: Oss 12.5 Bailey Avg Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	0.80	0.95	1.19	1.30	1.54	2.02	2.31	2.70	2.93
2	262.5	0.91	0.84	1.05	1.38	1.05	1.85	1.79	2.06	2.06
3	367.5	0.93	1.17	1.21	1.27	1.26	1.58	1.54	1.81	1.80
4	472.5	1.09	1.23	1.31	1.33	1.40	1.69	1.77	1.98	2.16
5	577.5	1.44	1.44	1.94	1.48	1.54	1.85	1.93	2.18	2.52
6	682.5	0.40	0.55	0.60	0.58	0.63	0.90	0.85	1.07	1.26
7	787.5	0.41	0.65	0.69	0.63	0.59	0.94	0.88	1.04	1.11
Avg		0.85	0.98	1.14	1.14	1.14	1.55	1.58	1.83	1.98

Table C20: Oss 12.5 Bailey Max Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	0.99	1.13	1.40	1.55	1.83	2.46	2.83	3.23	3.42
2	262.5	1.17	1.14	1.36	1.66	1.33	2.18	2.16	2.38	2.41
3	367.5	1.22	1.49	1.53	1.63	1.68	1.94	1.96	2.29	2.31
4	472.5	1.66	1.79	1.90	1.92	1.96	2.22	2.37	2.51	2.64
5	577.5	1.74	1.74	2.20	1.76	1.80	2.20	2.30	2.48	2.85
6	682.5	0.58	0.73	0.76	0.76	0.86	1.10	1.06	1.42	1.65
7	787.5	0.71	0.93	0.96	0.91	0.86	1.26	1.25	1.37	1.43
Avg		1.15	1.28	1.44	1.46	1.47	1.91	1.99	2.24	2.39

Table C21: Oss 12.5 Bailey Max Rut Depth from Max Heave

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	2.17	2.64	3.12	4.12	6.43	12.78	15.66	16.94	18.30
2	262.5	1.68	1.99	2.19	2.36	2.79	3.81	5.24	6.09	7.09
3	367.5	1.77	2.14	2.31	2.64	3.50	5.00	6.84	7.75	8.67
4	472.5	2.70	3.27	3.83	4.48	5.45	8.46	11.74	15.19	17.24
5	577.5	5.61	5.46	5.46	5.61	5.73	5.72	9.21	16.35	20.42
6	682.5	3.40	3.88	4.13	4.37	4.79	5.47	6.34	7.46	8.97
7	787.5	1.78	1.96	2.12	2.21	2.73	4.49	6.28	7.44	8.18
Avg		2.73	3.05	3.31	3.68	4.49	6.53	8.76	11.03	12.69

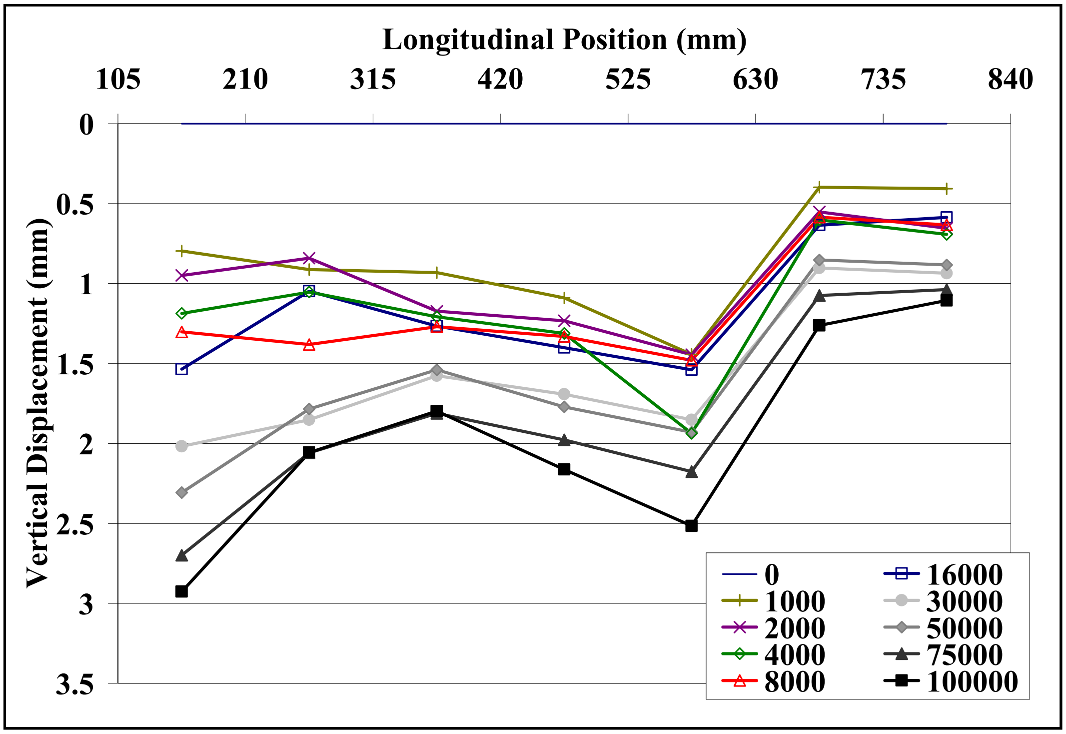


Figure C68: Oss 12.5 Bailey Avg Rut from Base Line Longitudinal Profiles

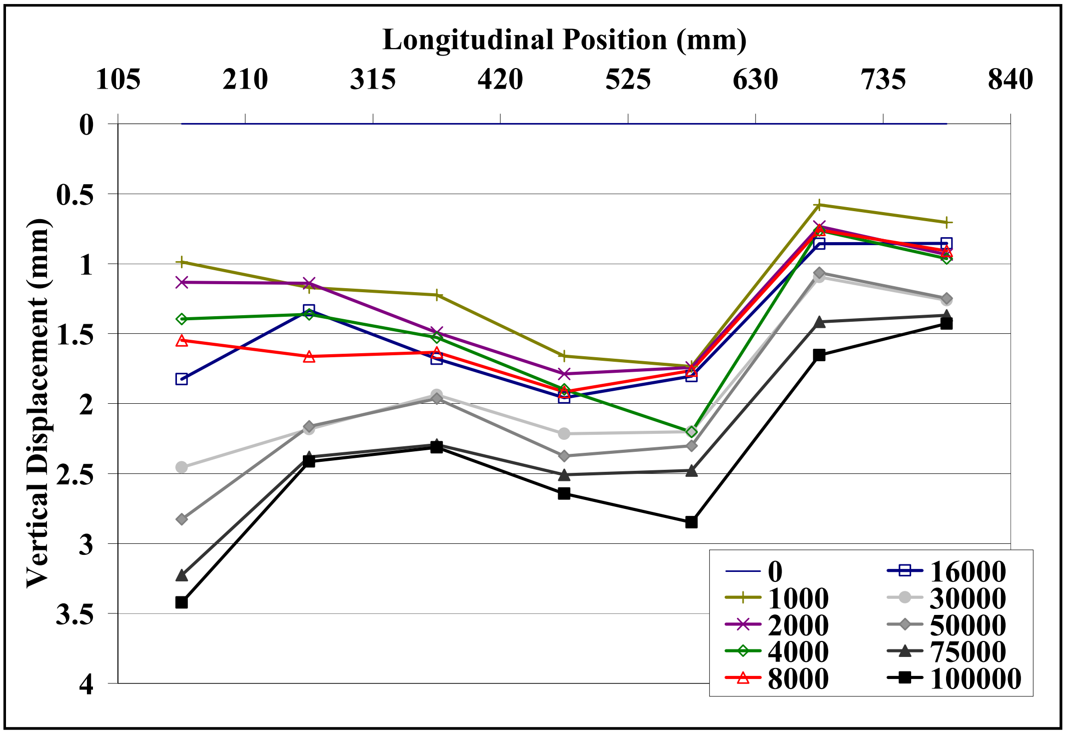


Figure C69: Oss 12.5 Bailey Max Rut from Base Line Longitudinal Profiles

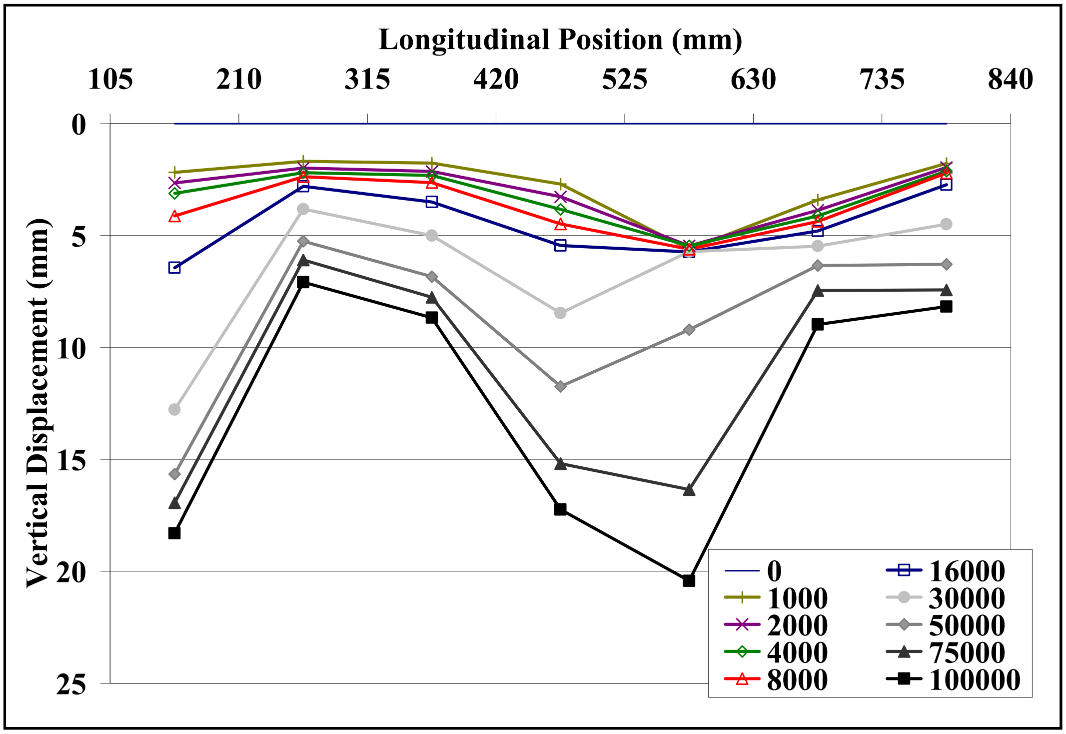


Figure C70: Oss 12.5 Bailey Max Rut from Max Heave Longitudinal Profiles

<u>Cont 19 Bailey</u>

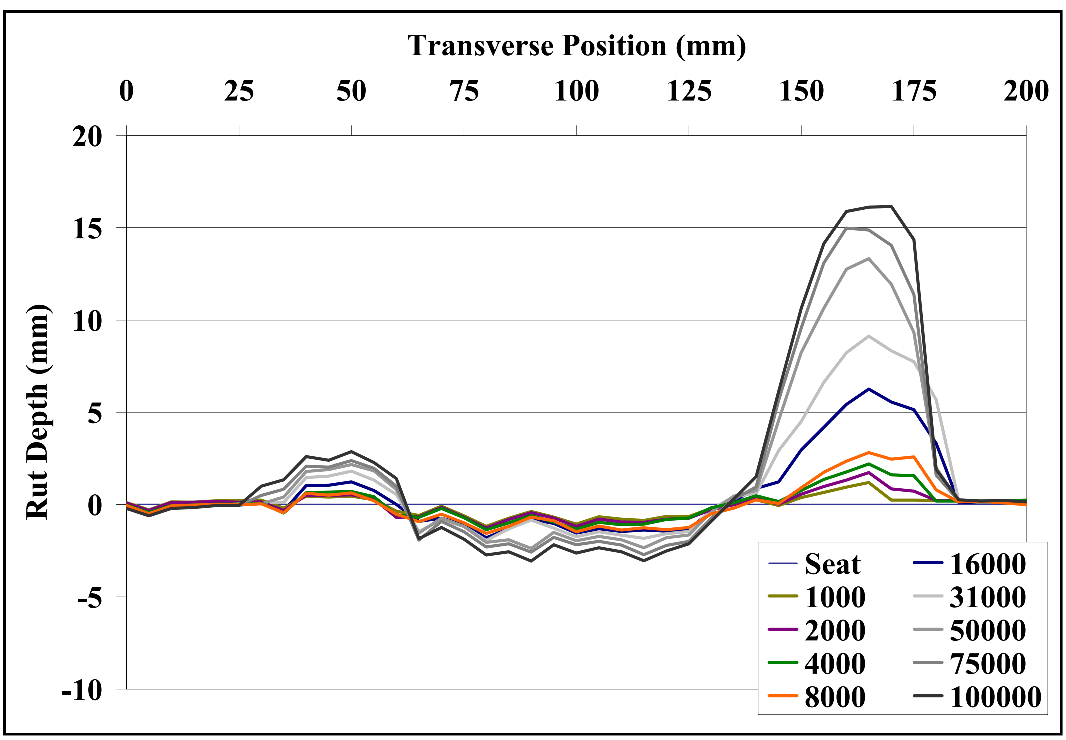


Figure C71: Cont 19 Bailey Brick 1 Transverse Profiles

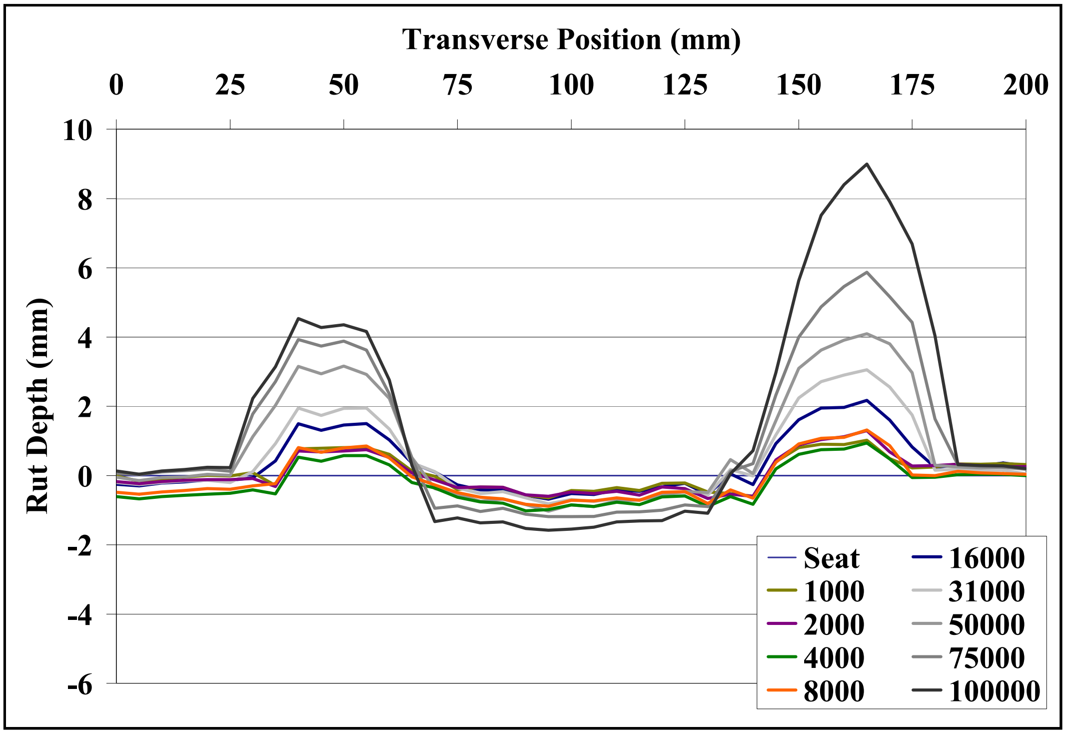


Figure C72: Cont 19 Bailey Brick 2 Transverse Profiles

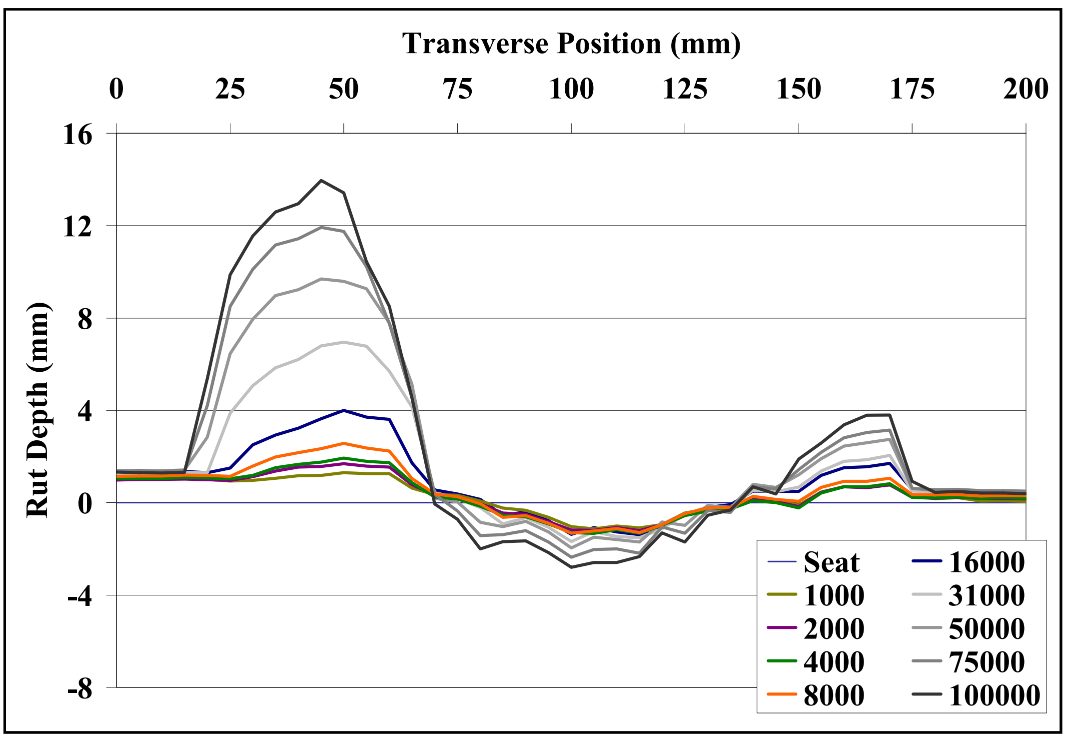


Figure C73: Cont 19 Bailey Brick 3 Transverse Profiles

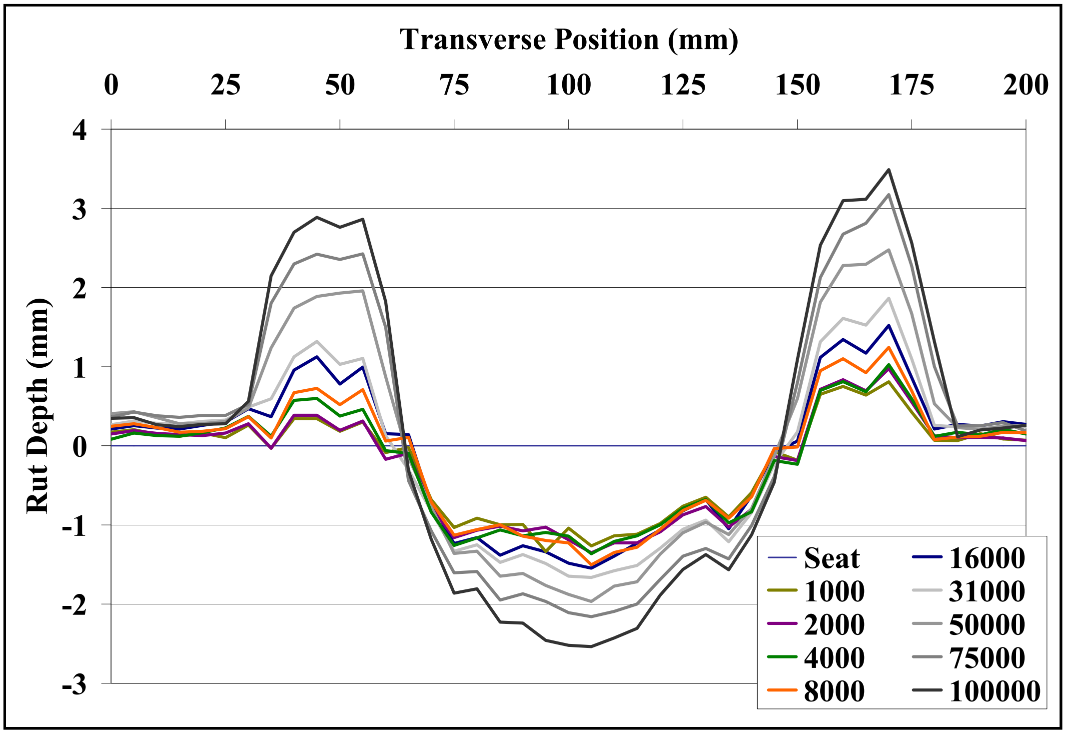


Figure C74: Cont 19 Bailey Brick 4 Transverse Profiles

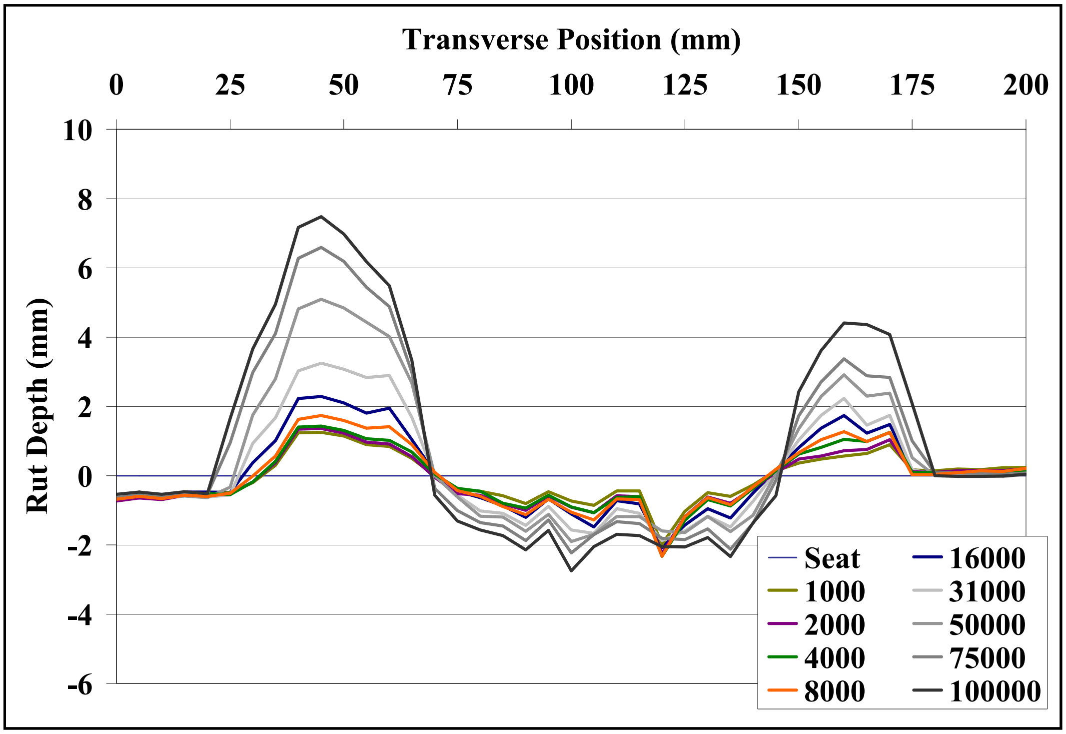


Figure C75: Cont 19 Bailey Brick 5 Transverse Profiles

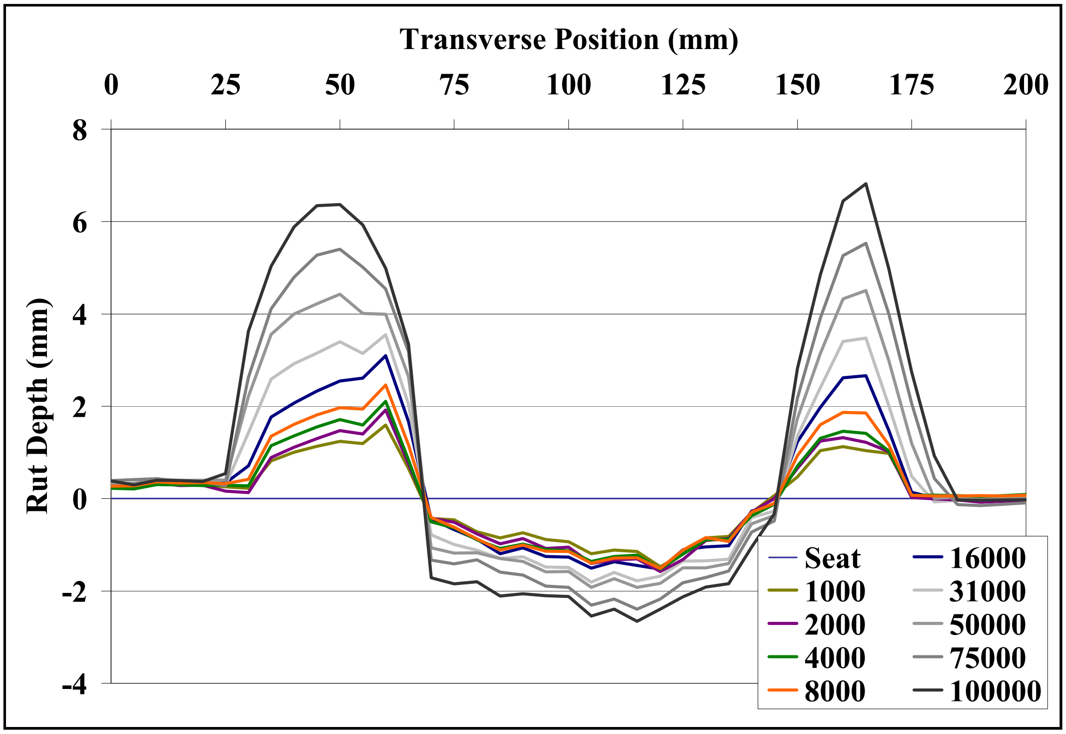


Figure C76: Cont 19 Bailey Brick 6 Transverse Profiles

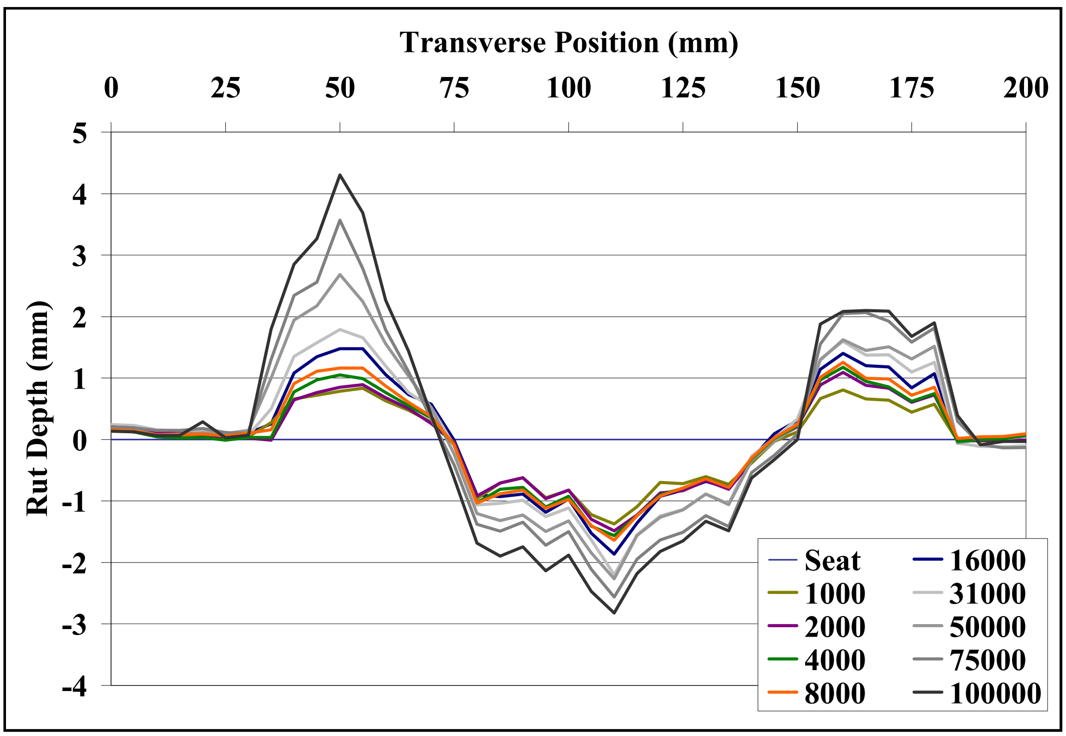


Figure C77: Cont 19 Bailey Brick 7 Transverse Profiles

Table C22: Cont 19 Bailey Avg Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	0.72	0.82	0.91	1.16	1.25	1.40	1.79	2.08	2.43
2	262.5	0.41	0.48	0.82	0.69	0.47	0.63	0.73	1.05	1.36
3	367.5	0.64	0.75	0.84	0.79	0.77	0.96	1.15	1.55	1.94
4	472.5	1.02	1.08	1.07	1.12	1.21	1.39	1.56	1.83	2.12
5	577.5	0.75	0.93	0.93	1.01	1.09	1.31	1.41	1.62	1.92
6	682.5	1.01	1.15	1.15	1.16	1.24	1.47	1.58	1.91	2.20
7	787.5	0.89	0.95	1.02	1.04	1.10	1.28	1.41	1.68	1.97
Avg		0.78	0.88	0.96	1.00	1.02	1.21	1.38	1.67	1.99

Table C23: Cont 19 Bailey Max Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	1.18	1.28	1.37	1.57	1.80	1.95	2.39	2.71	3.06
2	262.5	0.65	0.66	1.02	0.89	0.68	0.81	1.03	1.19	1.58
3	367.5	1.13	1.21	1.34	1.33	1.39	1.68	1.95	2.37	2.81
4	472.5	1.33	1.35	1.36	1.51	1.55	1.66	1.97	2.16	2.54
5	577.5	1.98	2.25	2.33	2.33	2.08	1.87	1.90	2.23	2.74
6	682.5	1.47	1.58	1.53	1.52	1.53	1.81	1.92	2.39	2.66
7	787.5	1.37	1.49	1.57	1.64	1.86	2.20	2.27	2.56	2.82
Avg		1.30	1.40	1.50	1.54	1.56	1.71	1.92	2.23	2.60

Table C24: Cont 19 Bailey Max Rut Depth from Max Heave

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	2.37	3.00	3.57	4.39	8.06	11.08	15.71	17.68	19.20
2	262.5	1.67	1.96	1.96	2.20	2.85	3.87	5.12	7.06	10.57
3	367.5	2.42	2.90	3.26	3.90	5.39	8.63	11.65	14.30	16.77
4	472.5	2.14	2.33	2.39	2.75	3.07	3.53	4.45	5.33	6.03
5	577.5	3.24	3.60	3.76	4.06	4.37	5.12	7.00	8.82	10.22
6	682.5	3.07	3.51	3.63	3.98	4.63	5.36	6.43	7.92	9.47
7	787.5	2.21	2.58	2.74	2.90	3.34	3.99	4.95	6.13	7.13
Avg		2.45	2.84	3.04	3.45	4.53	5.94	7.90	9.60	11.34

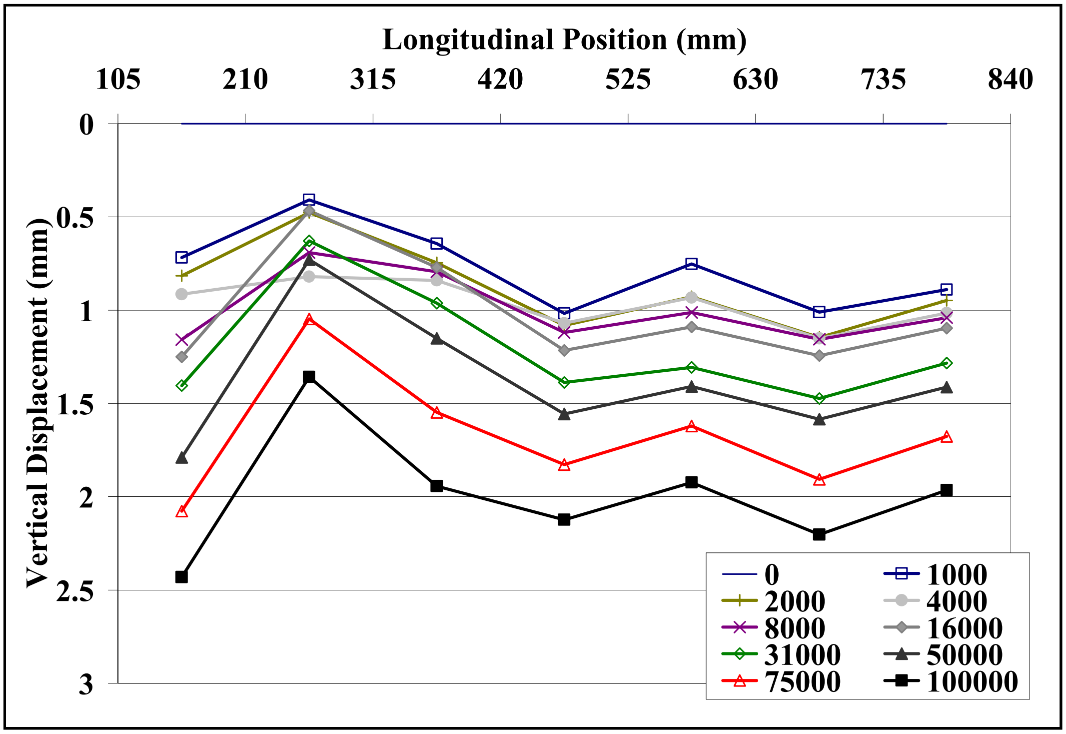


Figure C78: Cont 19 Bailey Avg Rut from Base Line Longitudinal Profiles

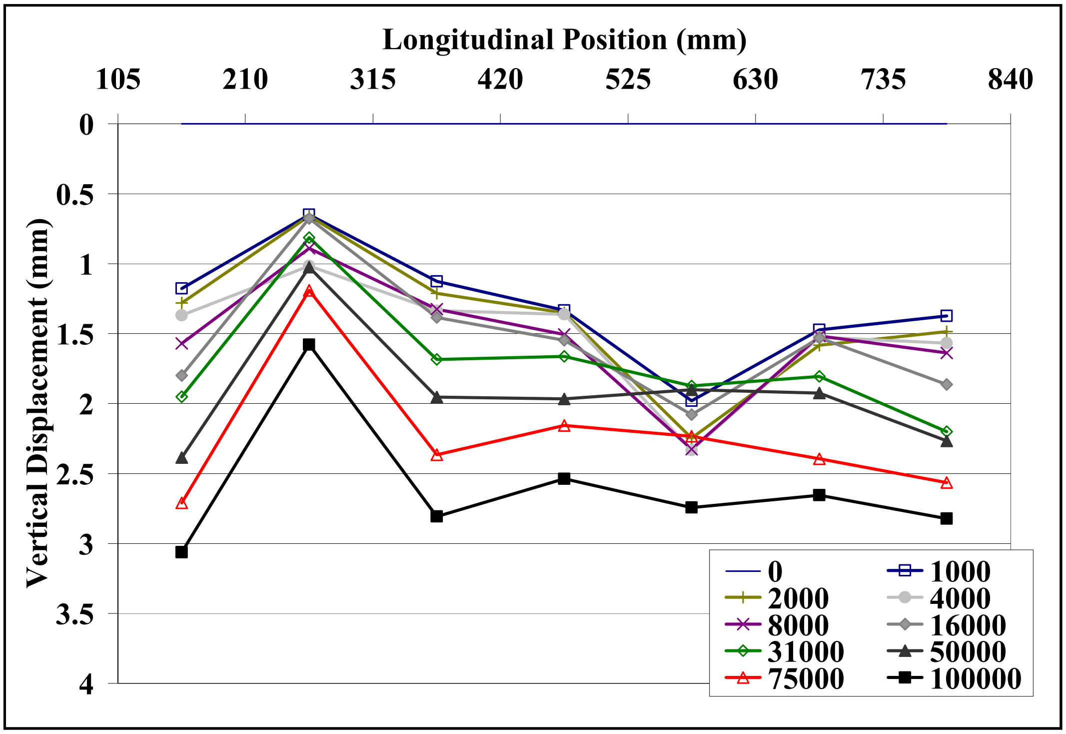


Figure C79: Cont 19 Bailey Max Rut from Base Line Longitudinal Profiles

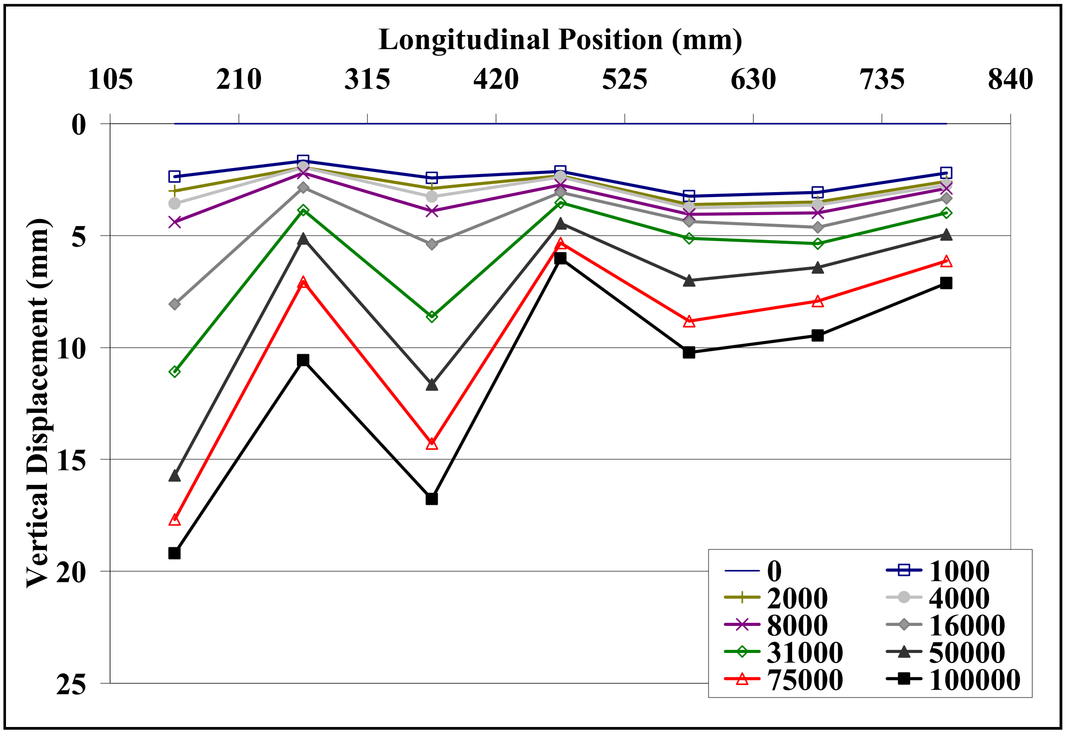


Figure C80: Cont 19 Bailey Max Rut from Max Heave Longitudinal Profiles

<u>**Oss 12.5 Field Cores**</u>

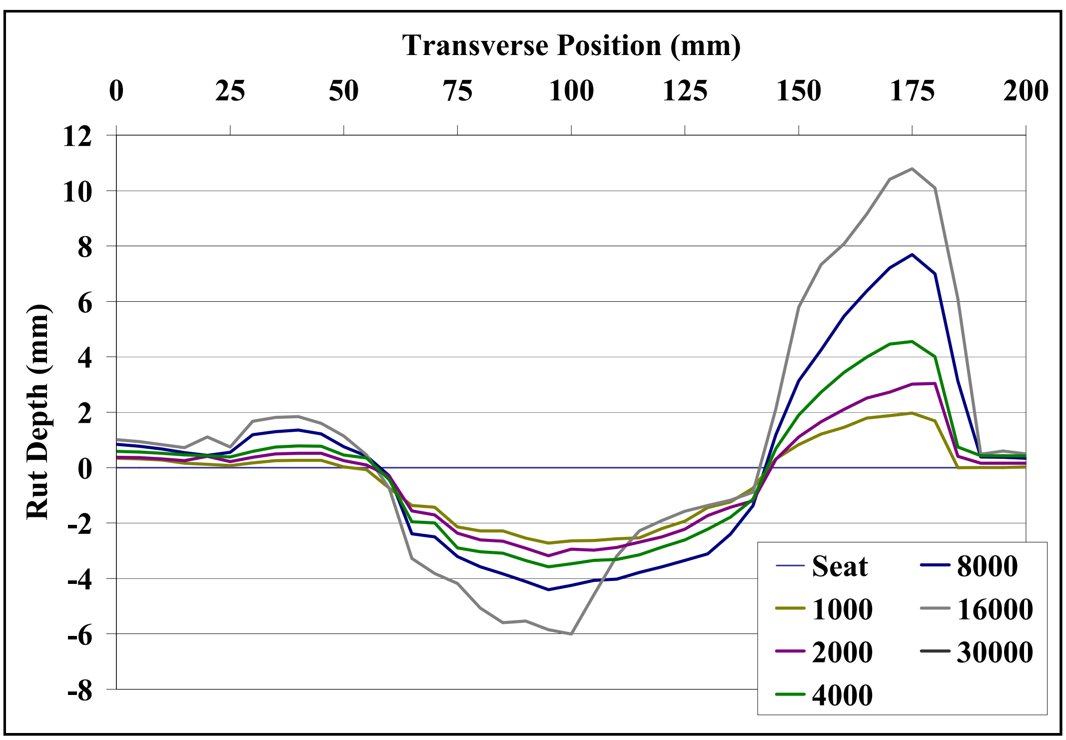


Figure C81: Oss 12.5 Field Cores Brick 1 Transverse Profiles

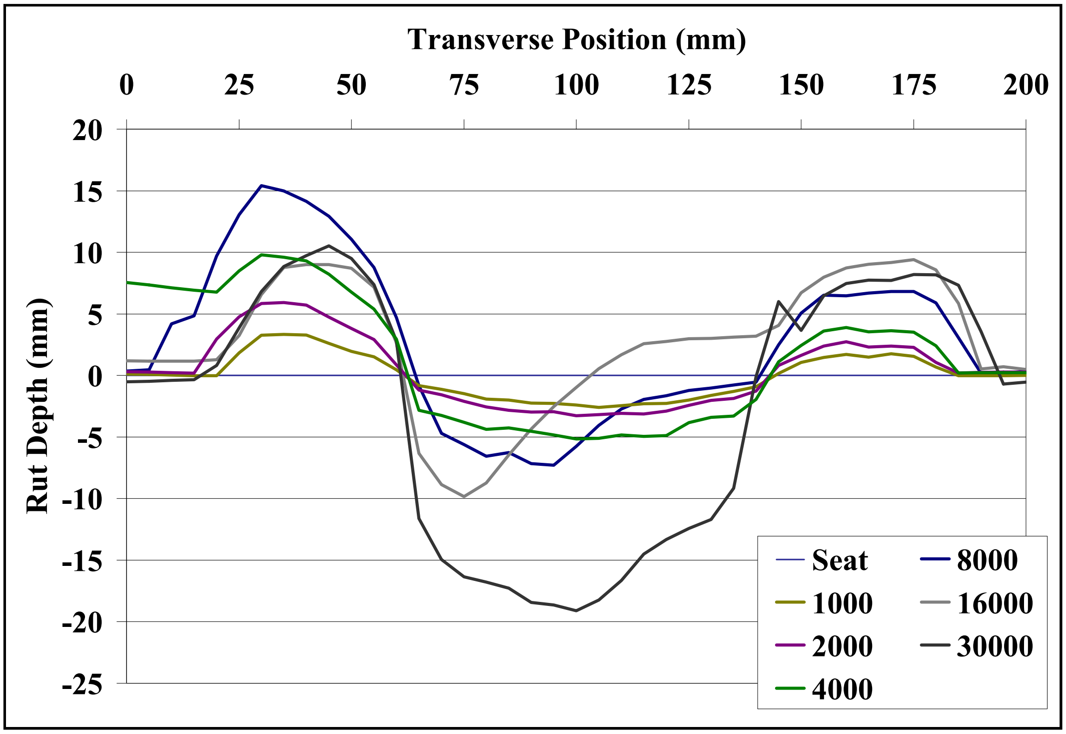


Figure C82: Oss 12.5 Field Cores Brick 2 Transverse Profiles

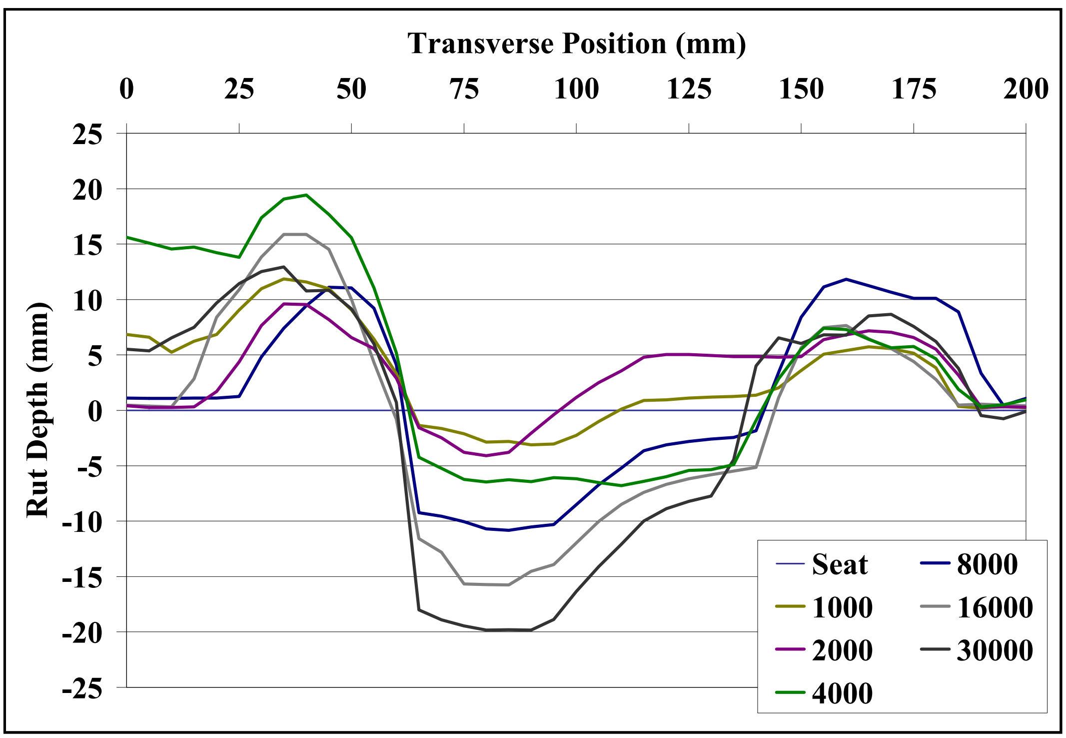


Figure C83: Oss 12.5 Field Cores Brick 3 Transverse Profiles

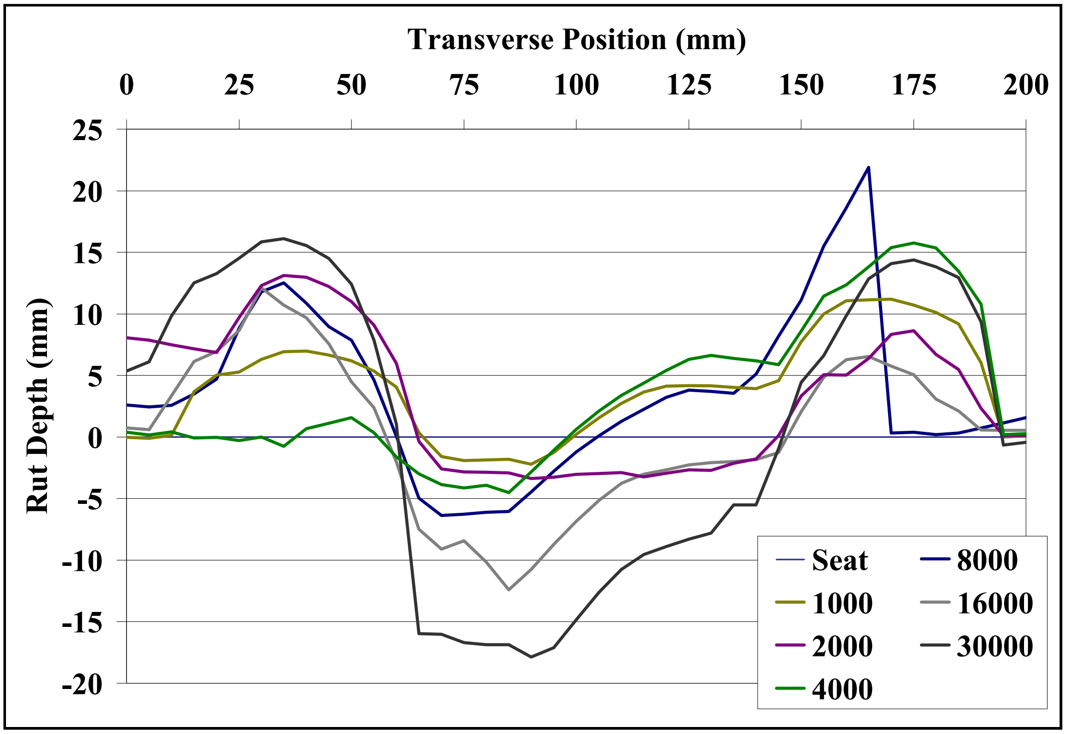


Figure C84: Oss 12.5 Field Cores Brick 4 Transverse Profiles

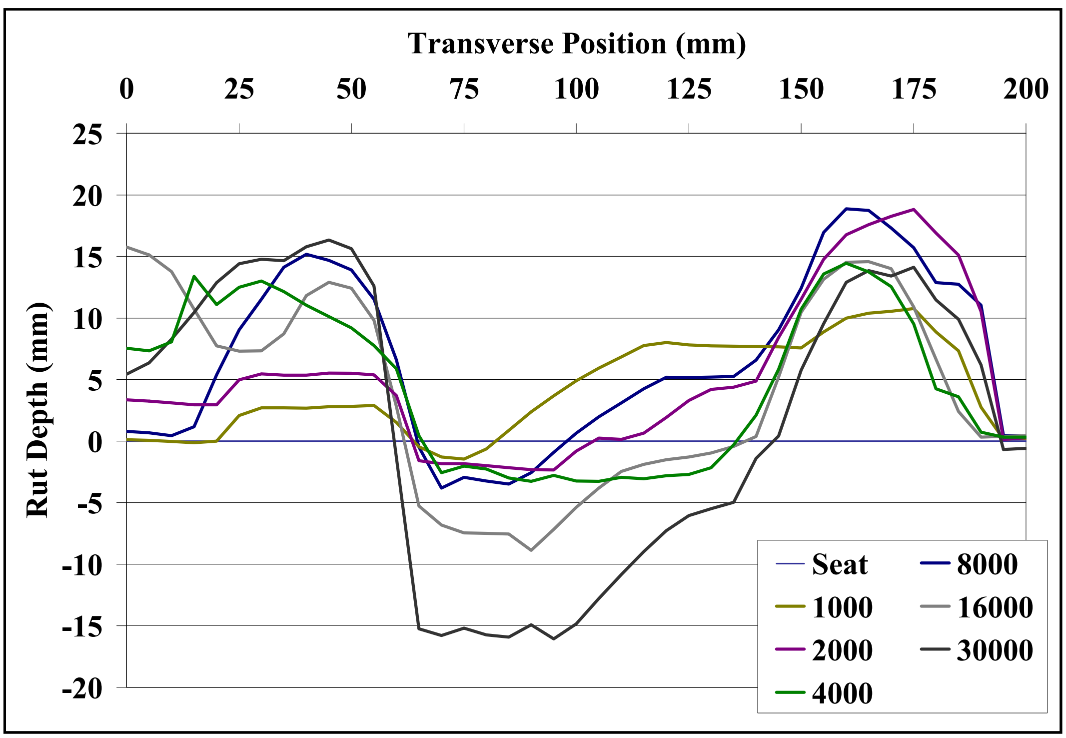


Figure C85: Oss 12.5 Field Cores Brick 5 Transverse Profiles

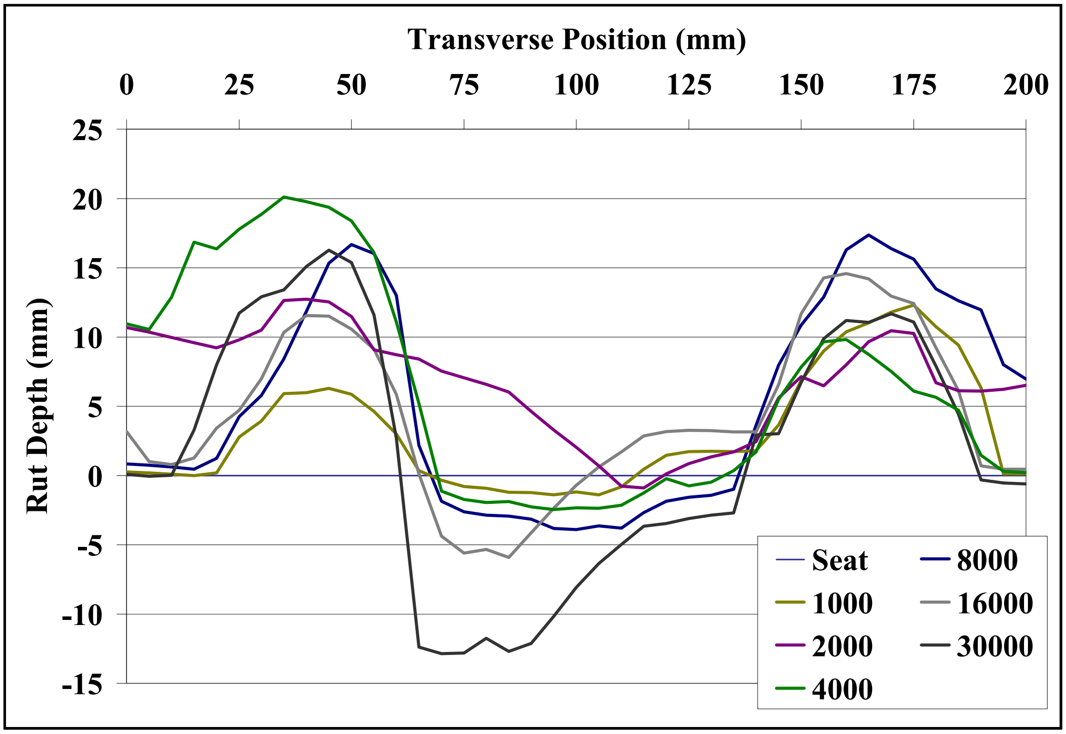


Figure C86: Oss 12.5 Field Cores Brick 6 Transverse Profiles

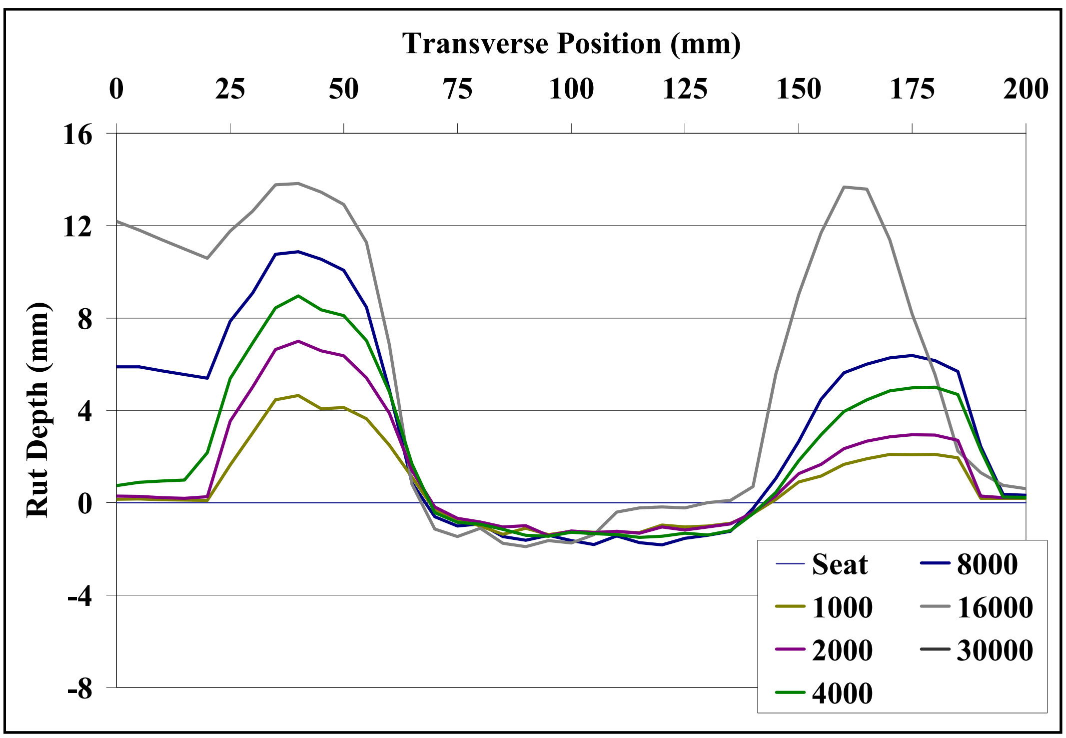
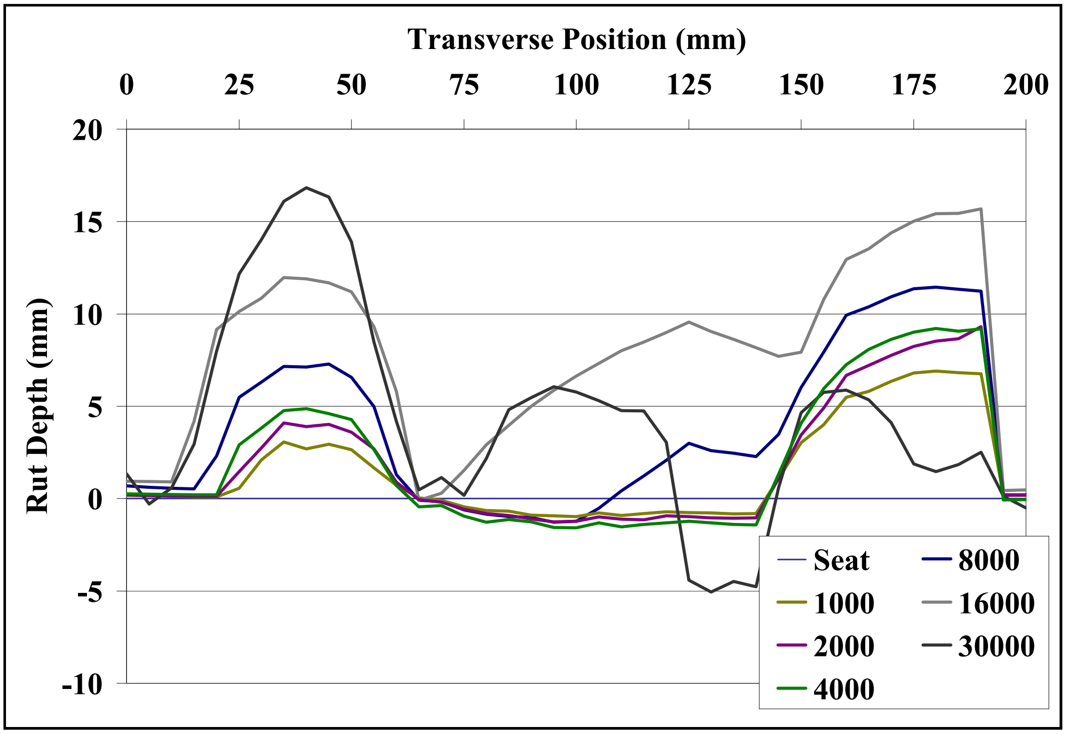


Figure C87: Oss 12.5 Field Cores Brick 7 Transverse Profiles



FigureC88: Oss 12.5 Field Cores Brick 8 Transverse Profiles

Table C25: Oss 12.5 Field Cores Avg Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles					
		1	2	4	8	16	30
1	52.5	2.34	2.66	3.09	3.83	4.92	*
2	157.5	2.19	2.84	4.56	6.26	8.45	16.10
3	262.5	0.98	3.14	6.17	10.17	14.29	19.24
4	367.5	1.87	2.98	3.88	5.96	9.52	16.77
5	472.5	0.96	2.07	2.86	2.79	7.25	15.46
6	577.5	1.06	0.52	1.65	2.88	5.07	12.12
7	682.5	1.18	1.15	1.33	1.53	1.52	*
8	787.5	0.81	1.05	1.36	0.75	0.09	**
Avg		1.51	2.20	3.36	4.77	7.29	15.94

* No profile could be measured
** Bad data
All the highlighted values used a modified range for the average rut

Table C26: Oss 12.5 Field Cores Max Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles					
		1	2	4	8	16	30
1	52.5	2.73	3.18	3.58	4.40	6.00	
2	157.5	2.60	3.27	5.16	7.30	9.84	19.11
3	262.5	3.13	4.09	6.80	10.84	15.76	19.82
4	367.5	2.21	3.36	4.51	6.38	12.41	17.86
5	472.5	1.46	2.32	3.27	3.81	8.88	16.05
6	577.5	1.39	0.90	2.45	3.91	5.90	12.87
7	682.5	1.39	1.43	1.50	1.83	1.90	
8	787.5	0.98	1.27	1.59	1.28	0.09	
Avg		2.13	2.65	3.90	5.49	8.67	17.14

Table C27: Oss 12.5 Field Cores Max Rut Depth from Max Heave

Brick	Long Pos	Thousands of Loading Cycles					
		1	2	4	8	16	30
1	52.5	4.69	6.22	8.13	12.09	16.79	
2	157.5	5.95	9.19	14.95	22.71	19.24	29.63
3	262.5	14.99	13.69	26.24	22.67	31.64	32.77
4	367.5	13.41	16.48	20.26	28.27	24.53	33.98
5	472.5	12.24	21.14	17.73	22.68	24.64	32.39
6	577.5	13.70	13.64	22.55	21.27	20.48	29.14
7	682.5	6.03	8.43	10.45	12.69	15.72	
8	787.5	7.88	10.58	10.79	12.73	15.78	
Avg		10.15	12.68	17.19	20.34	21.86	31.58

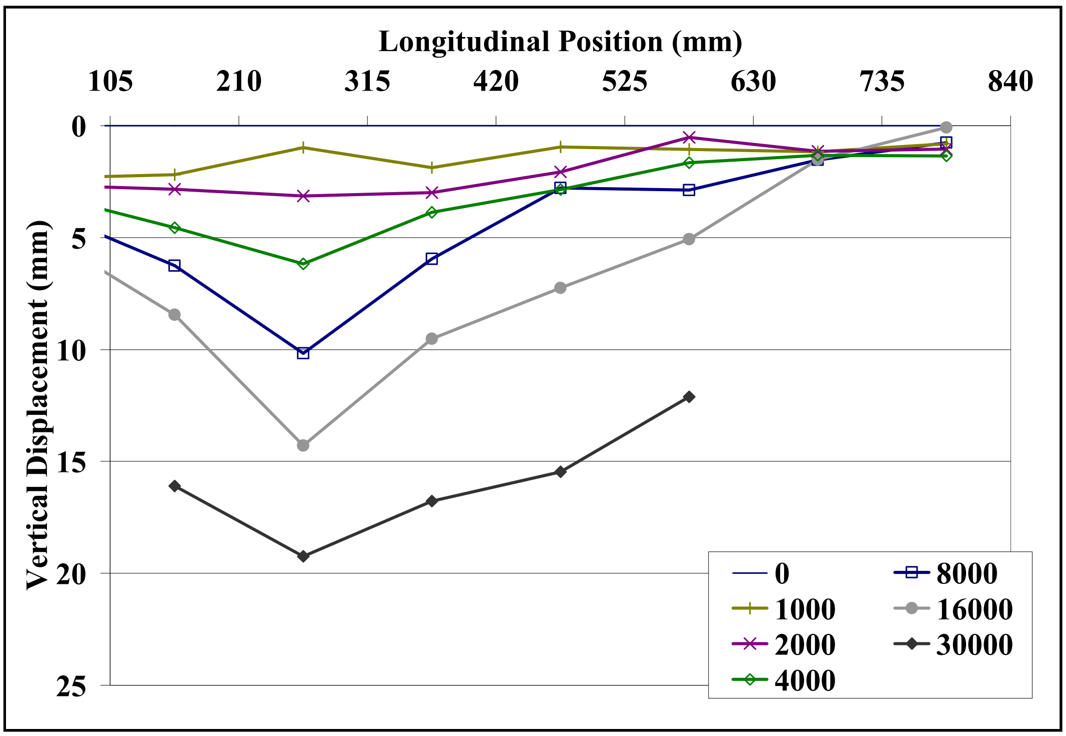


Figure C89: Oss 12.5 Field Cores Avg Rut from Base Line Longitudinal Profiles

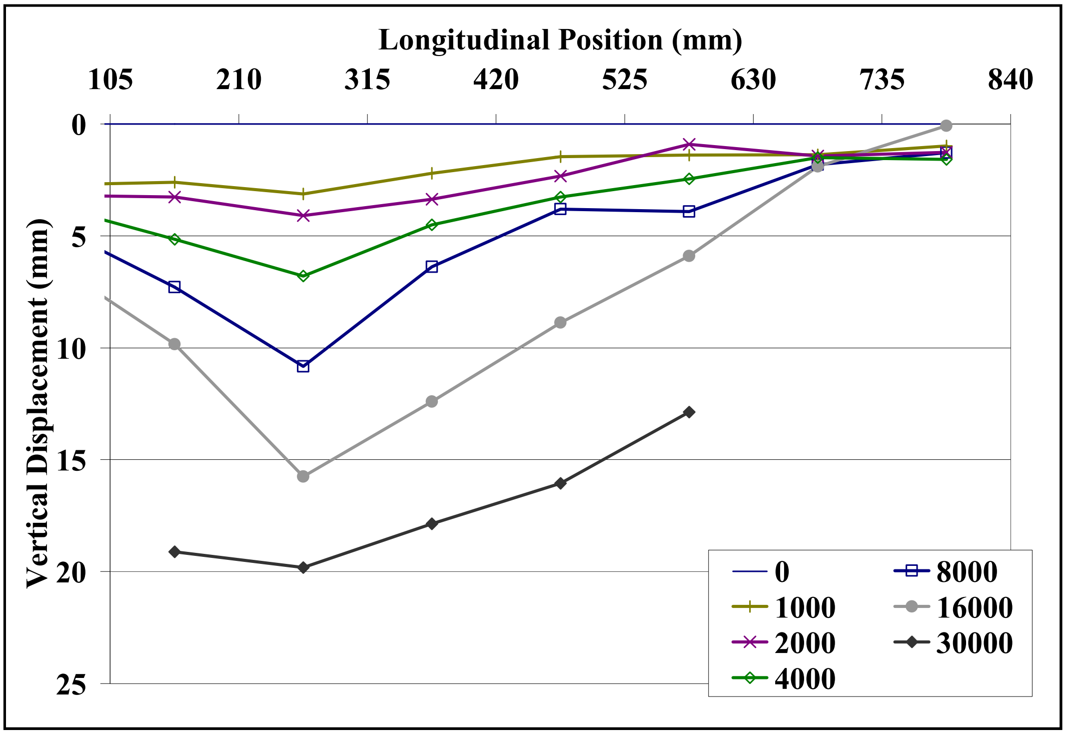


Figure C90: Oss 12.5 Field Cores Max Rut from Base Line Longitudinal Profiles

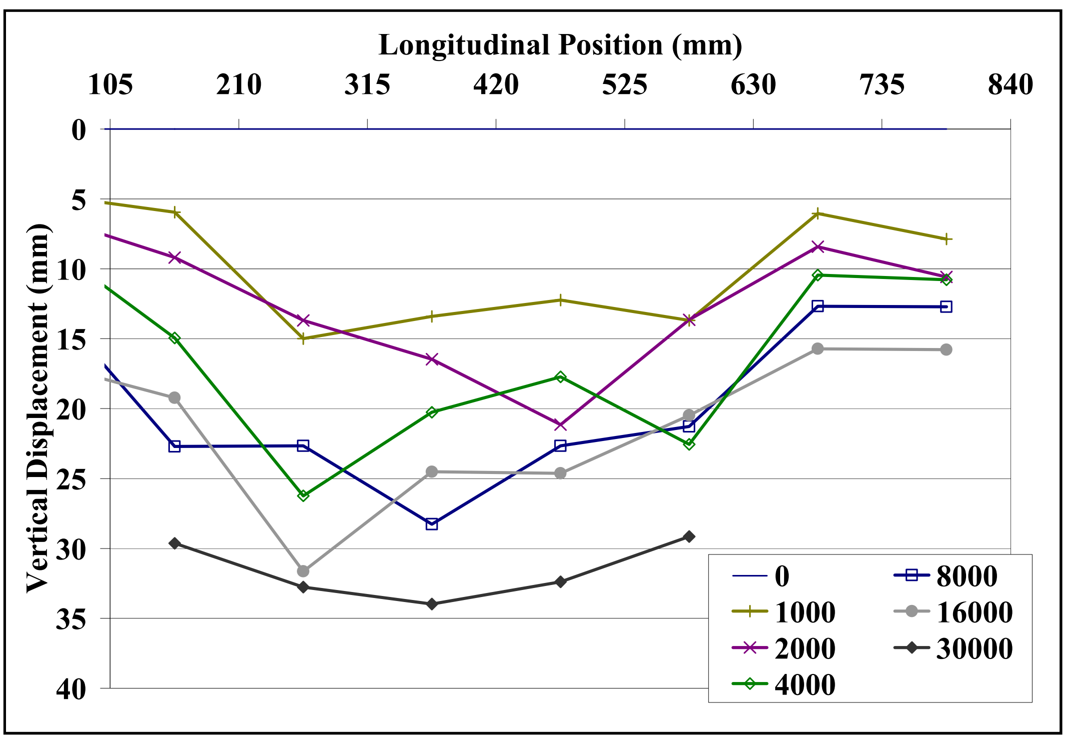
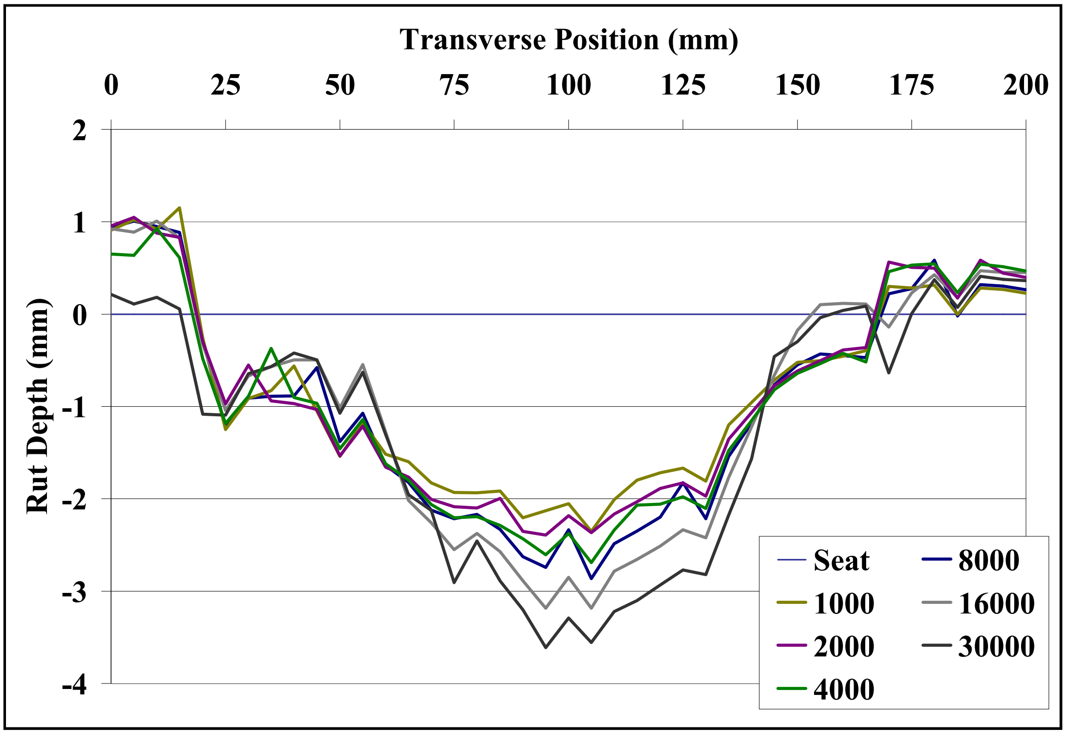


Figure C91: Oss 12.5 Field Cores Max Rut from Max Heave Longitudinal Profiles

Oss 19 Field Cores



FigureC92: Oss 19 Field Cores Brick 1 Transverse Profiles

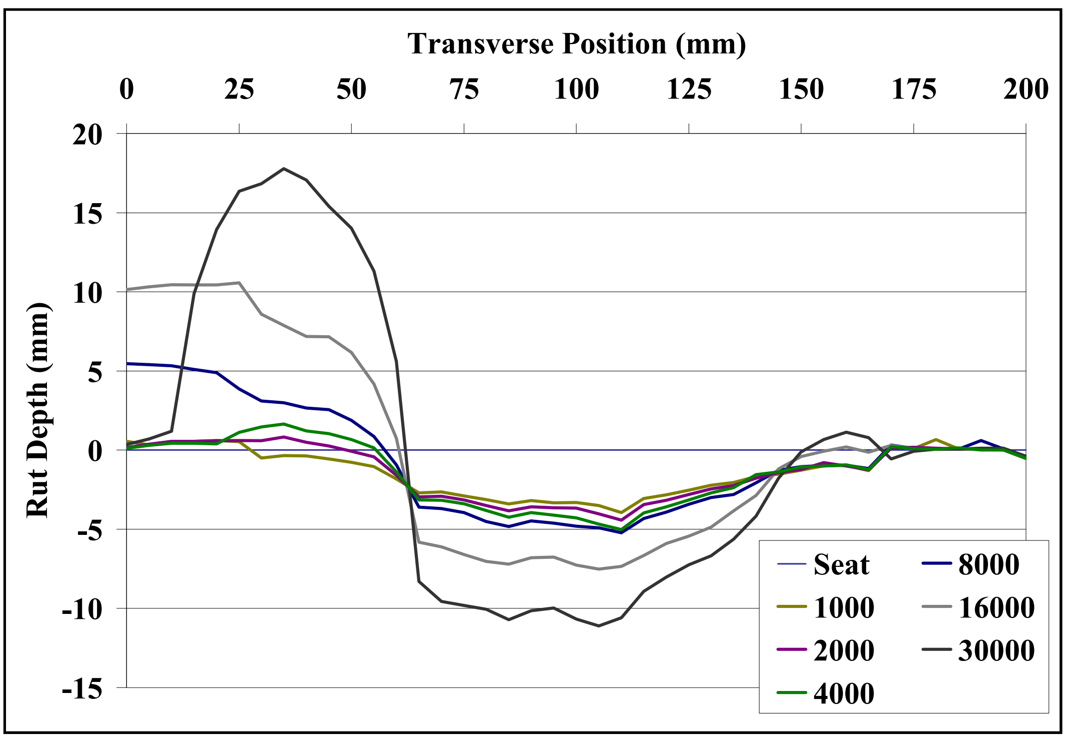


Figure C93: Oss 19 Field Cores Brick 2 Transverse Profiles

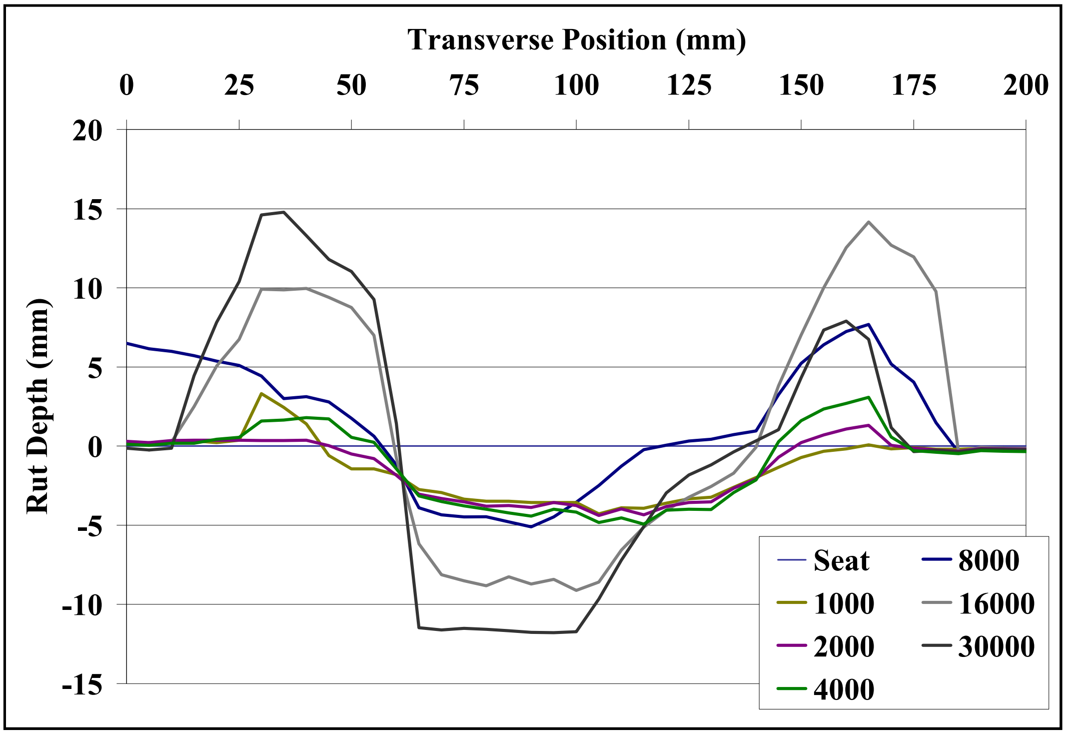


Figure C94: Oss 19 Field Cores Brick 3 Transverse Profiles

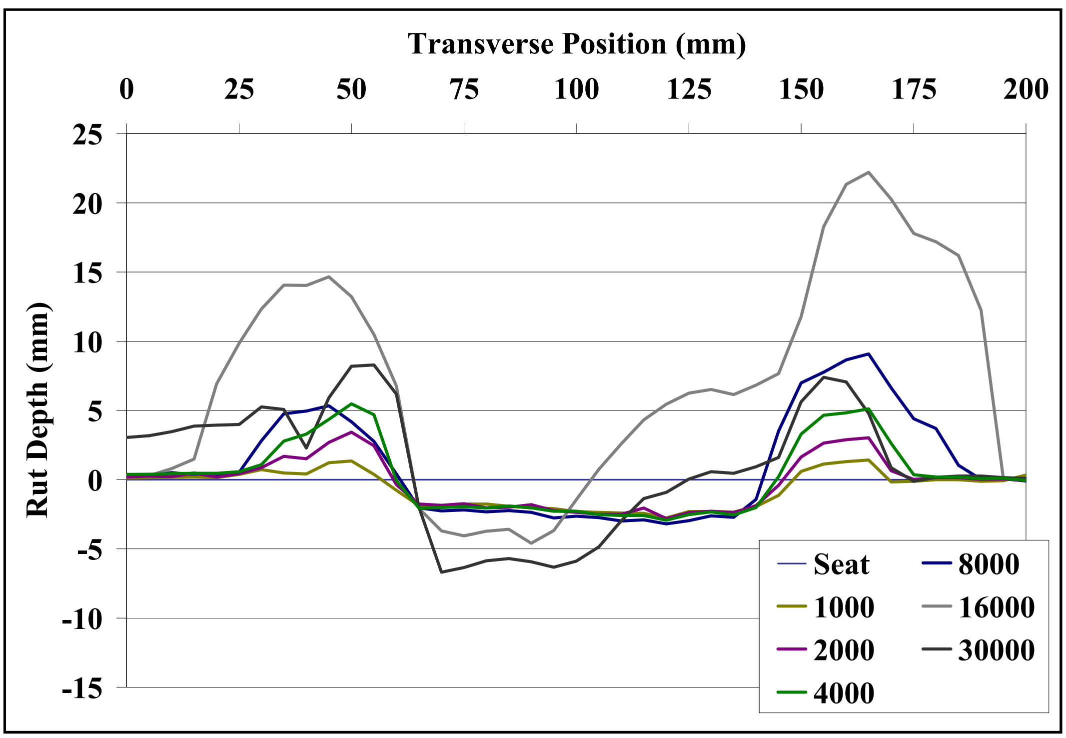


Figure C95: Oss 19 Field Cores Brick 4 Transverse Profiles

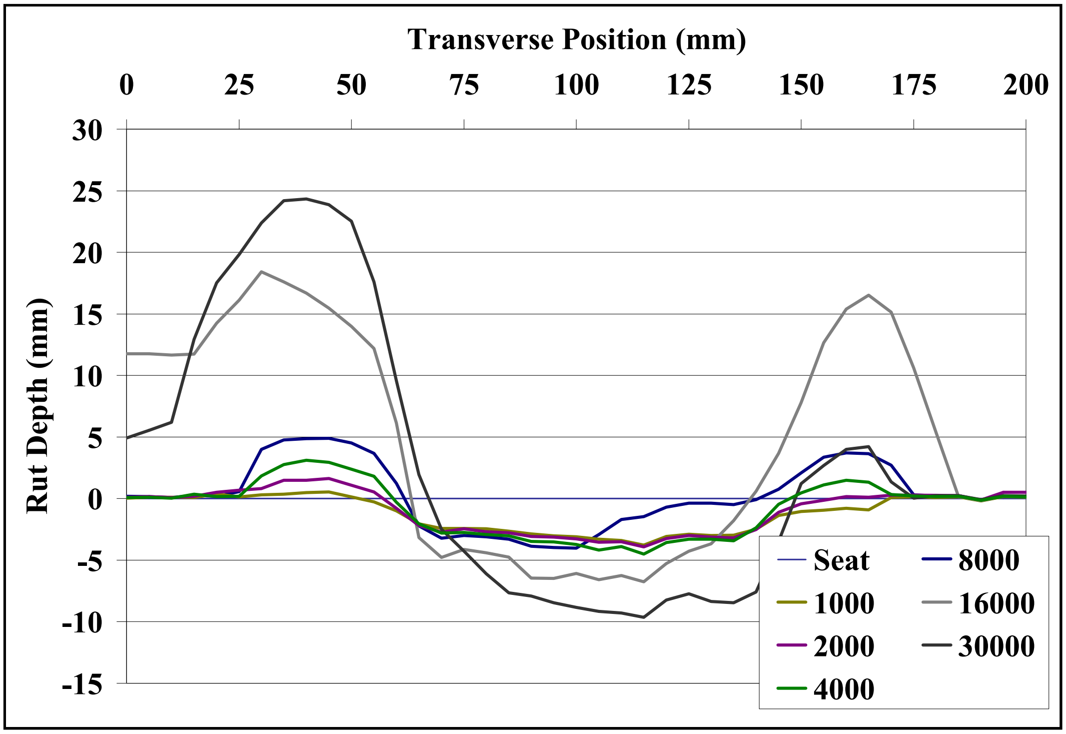


Figure C96: Oss 19 Field Cores Brick 5 Transverse Profiles

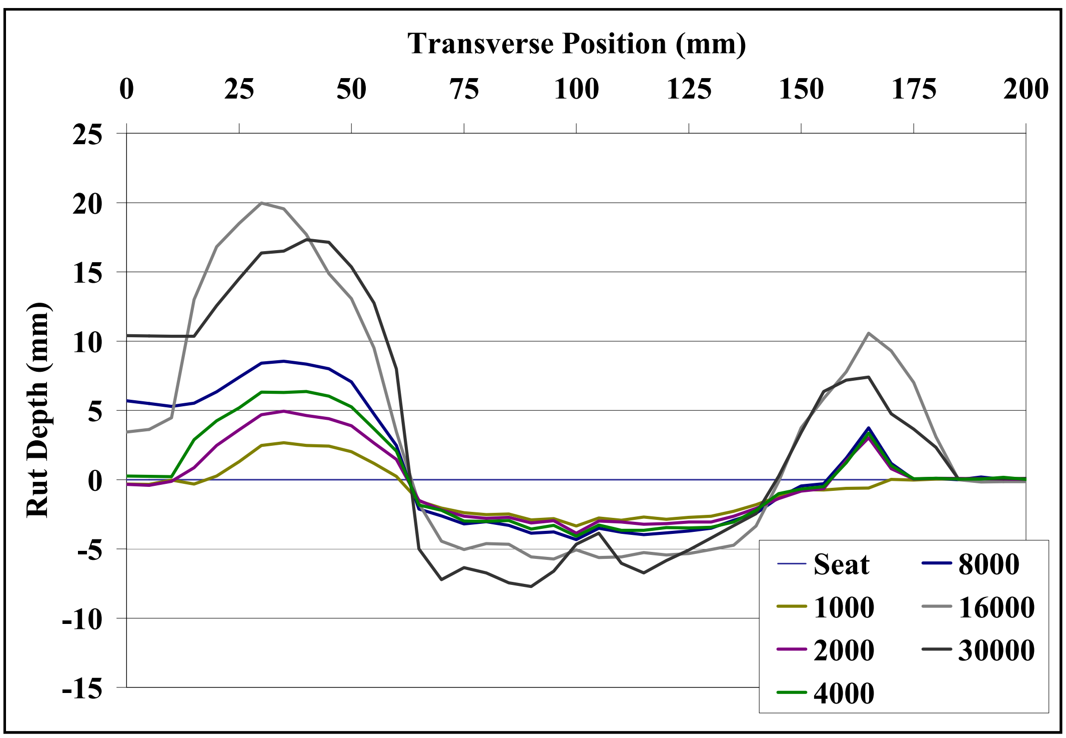


Figure C97: Oss 19 Field Cores Brick 6 Transverse Profiles

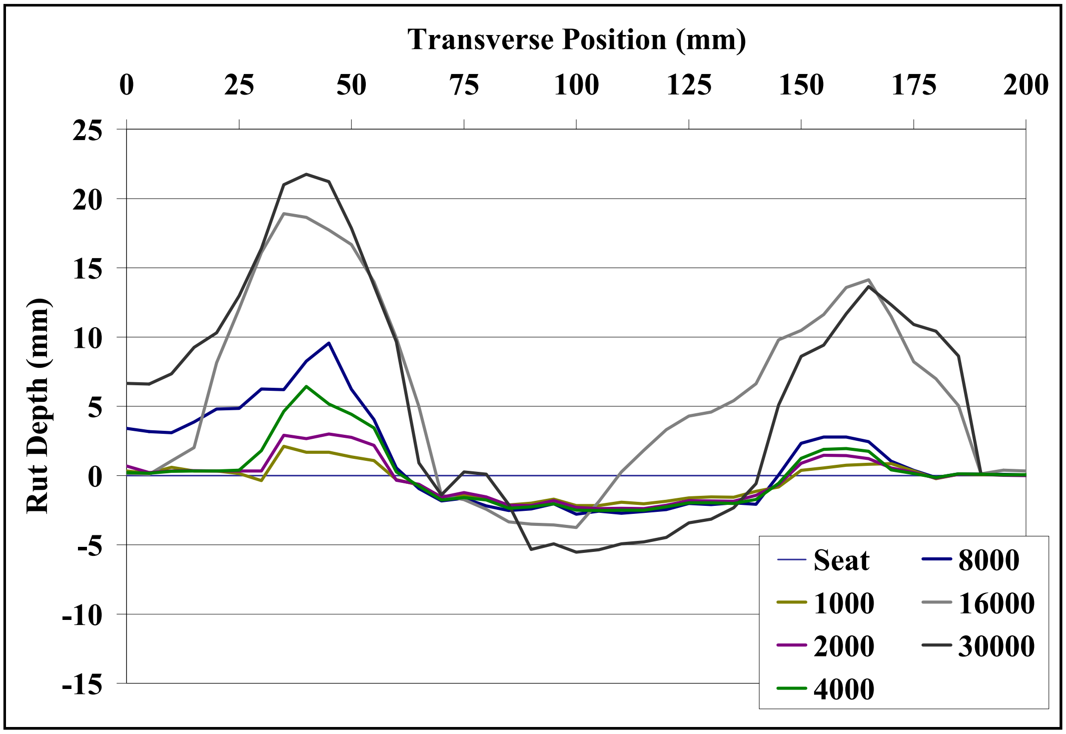


Figure C98: Oss 19 Field Cores Brick 7 Transverse Profiles

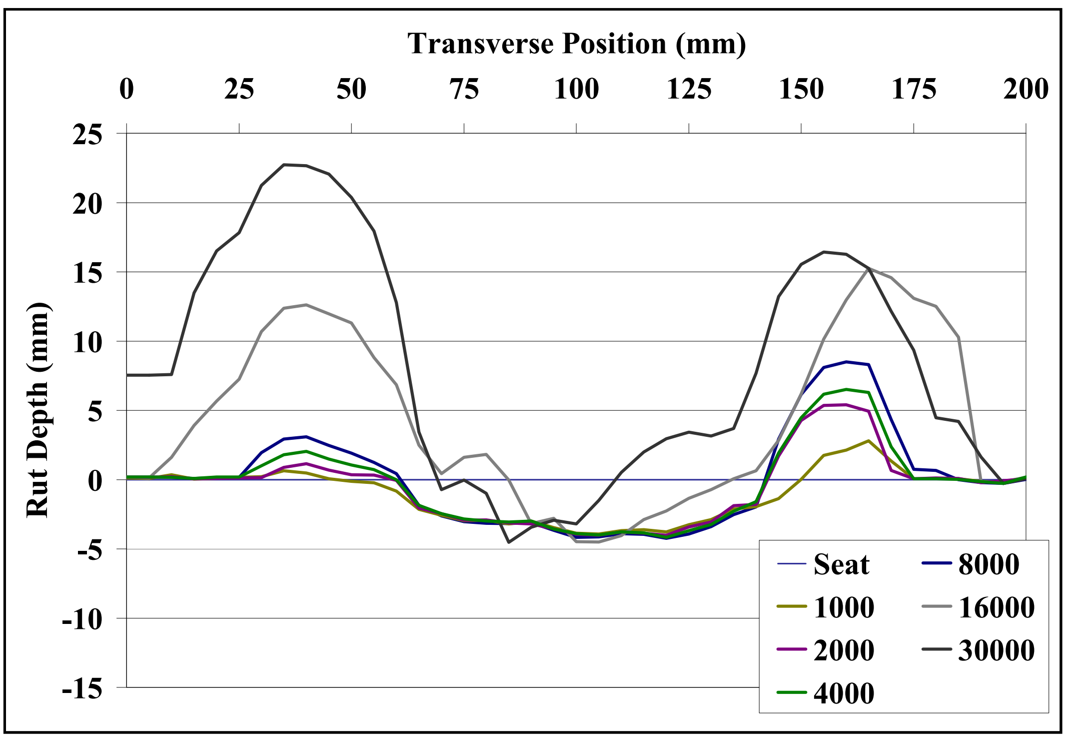


Figure C99: Oss 19 Field Cores Brick 8 Transverse Profiles

Table C28: Oss 19 Field Cores Avg Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles					
		1	2	4	8	16	30
1	52.5	1.96	2.12	2.29	2.38	2.71	3.08
2	157.5	3.13	3.50	3.95	4.36	6.62	9.46
3	262.5	3.63	3.85	4.29	4.51	8.27	11.64
4	367.5	2.25	2.28	2.37	2.71	3.89	5.96
5	472.5	3.05	3.21	3.58	3.50	5.55	8.31
6	577.5	2.79	3.10	3.45	3.69	5.26	5.91
7	682.5	1.89	2.09	2.24	2.40	2.83	4.66
8	787.5	3.42	3.53	3.57	3.71	3.80	4.54
Avg		2.67	2.88	3.17	3.36	5.02	7.00

All the highlighted values used a modified range for the average rut

Table C29: Oss 19 Field Cores Max Rut Depth from Base Line

Brick	Long Pos	Thousands of Loading Cycles					
		1	2	4	8	16	30
1	52.5	2.35	2.39	2.69	2.86	3.19	3.61
2	157.5	3.95	4.41	5.01	5.22	7.51	11.11
3	262.5	4.27	4.38	4.92	5.11	9.11	11.79
4	367.5	2.78	2.82	2.92	3.20	4.59	6.70
5	472.5	3.77	3.92	4.50	4.02	6.76	9.65
6	577.5	3.36	3.87	4.08	4.33	5.72	7.73
7	682.5	2.16	2.41	2.53	2.79	3.75	5.54
8	787.5	3.94	4.03	4.17	4.24	4.50	4.54
Avg		3.24	3.46	3.81	3.93	5.81	8.02

Table C30: Oss 19 Field Cores Max Rut Depth from Max Heave

Brick	Long Pos	Thousands of Loading Cycles					
		1	2	4	8	16	30
1	52.5	3.50	3.44	3.62	3.87	4.19	4.02
2	157.5	4.62	5.23	6.67	10.67	18.09	28.88
3	262.5	7.58	5.70	8.00	12.78	23.27	26.56
4	367.5	4.20	6.23	8.38	12.27	26.78	14.98
5	472.5	4.31	5.55	7.60	8.92	25.19	33.99
6	577.5	6.02	8.80	10.43	12.87	25.69	25.04
7	682.5	4.27	5.40	8.96	12.36	22.65	27.29
8	787.5	6.74	9.43	10.68	12.74	19.75	27.27
Avg		4.93	5.76	7.67	10.53	20.84	22.97

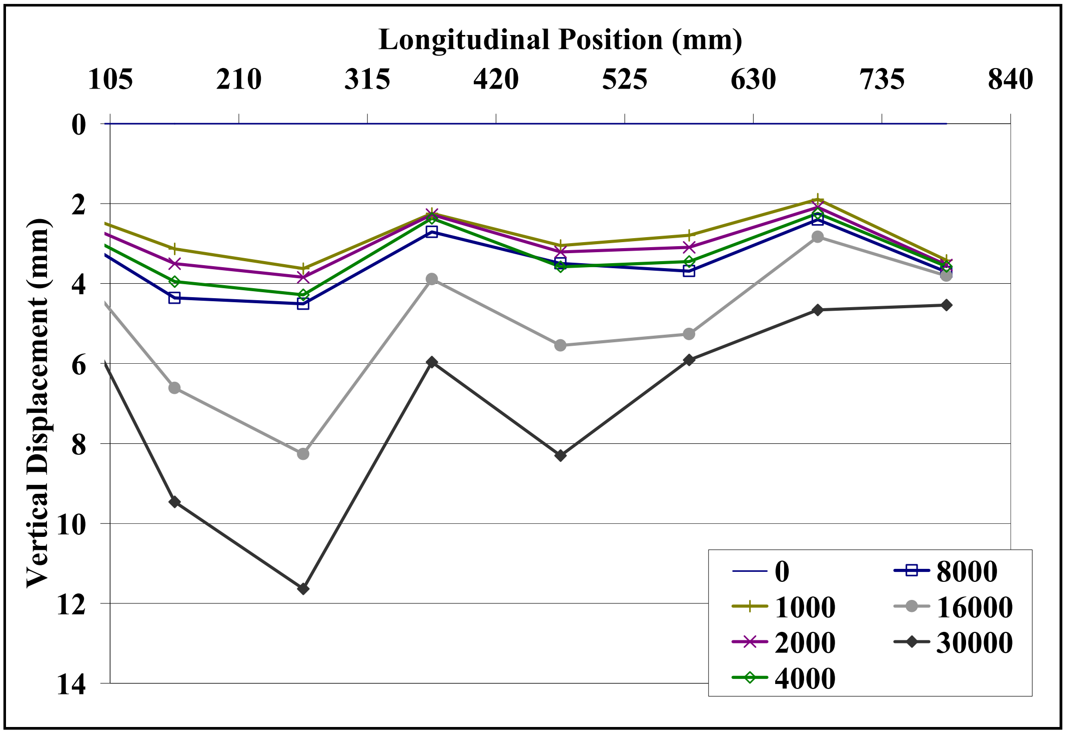


Figure C100: Oss 19 Field Cores Avg Rut from Base Line Longitudinal Profiles

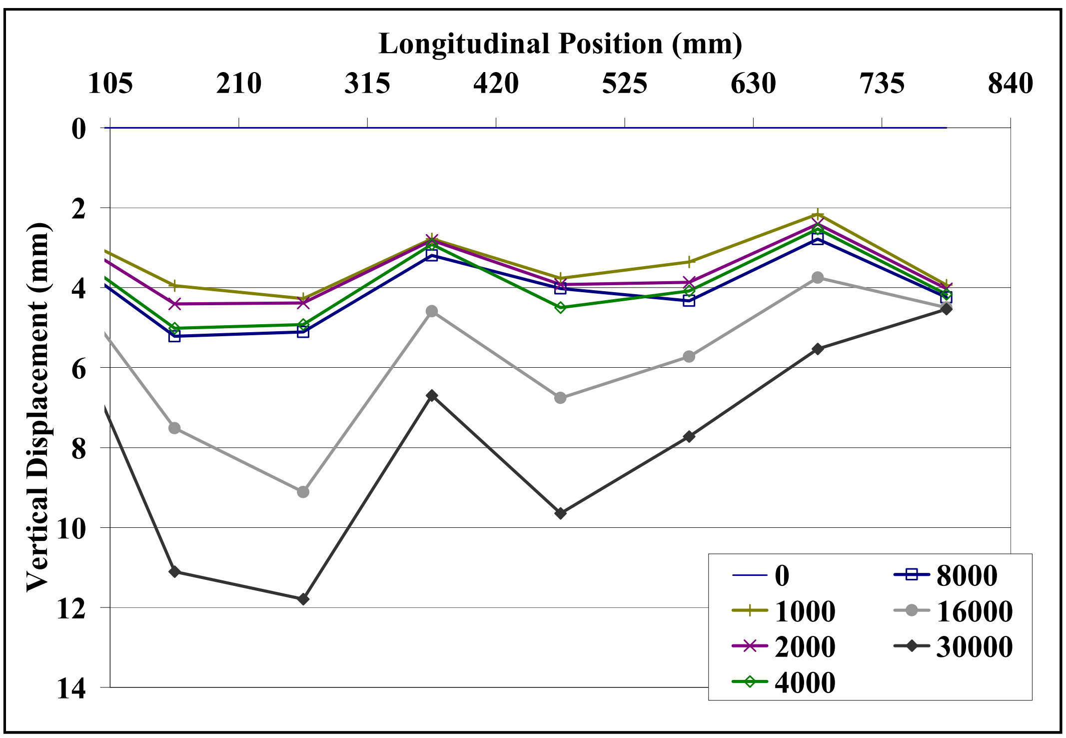


Figure C101: Oss 19 Field Cores Max Rut from Base Line Longitudinal Profiles

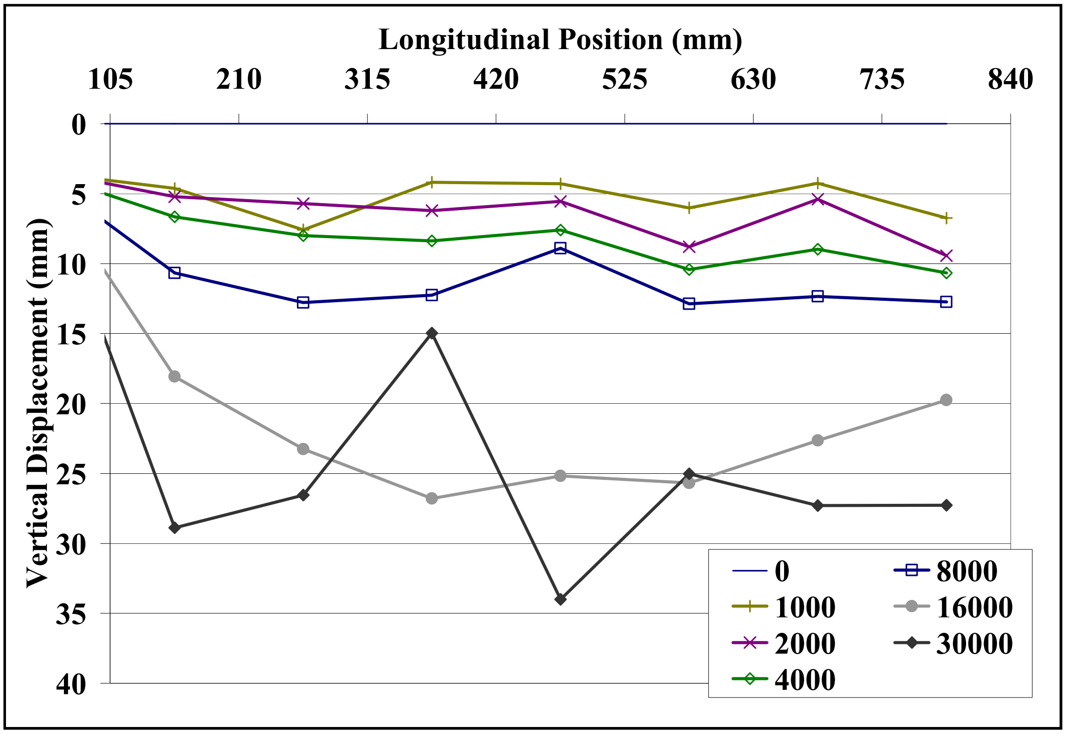


Figure C102: Oss 19 Field Cores Max Rut from Max Heave Longitudinal Profiles

Test Logs and Temperature Data

For all test logs, the Counter column shows the reading on the control box. Every time the control box was shut off and turned back on the counter increments by 1. The Relative column is the number of cycles run for that test only.

Oss 12.5

Table C31: Oss 12.5 MMLS3 Test Log

Action	Time	Date	Counter	Relative	Notes
Heat	1:44	1/12/2006	155482	0	
Profile	10:14		155482	0	
MMLS	10:42		155483	0	Seating load, no heat and vents off, approx 10 axles at 10 on the speed dial
Profile	10:42		155484	10	
Heat	11:10		155484	10	Heated to warm asphalt back up after first two profiles
MMLS	12:10		155485	10	
Profile	12:19		155585	1000	AIR thermocouple got caught under profilometer during #7 profile - screwed up profilometer for a bit
Demo	13:05		155586	1000	Demonstration, no heat and vents off
Heat	13:07		155600	1000	Search for Dr. Daniel
MMLS	13:30		155600	1000	
Profile	13:40		155700	2000	
Heat	14:05		155700	2000	Took a nap
MMLS	16:42		155700	2000	
Profile	17:00		155901	4000	
MMLS	17:28		155901	4000	
Profile	18:03		156300	8000	
MMLS	18:25		156300	8000	
Heat	19:34		157100	16000	Personal break
Profile	20:33		157100	16000	
MMLS	20:53		157100	16000	
Profile	22:54		158500	30000	
Heat	23:16		158500	30000	Personal break
MMLS	0:07	1/13/2006	158500	30000	
Profile	2:59		160500	50000	
MMLS	3:22		160500	50000	
Profile	7:00		163000	75000	
MMLS	7:27		163000	75000	
Profile	11:05		165500	100000	

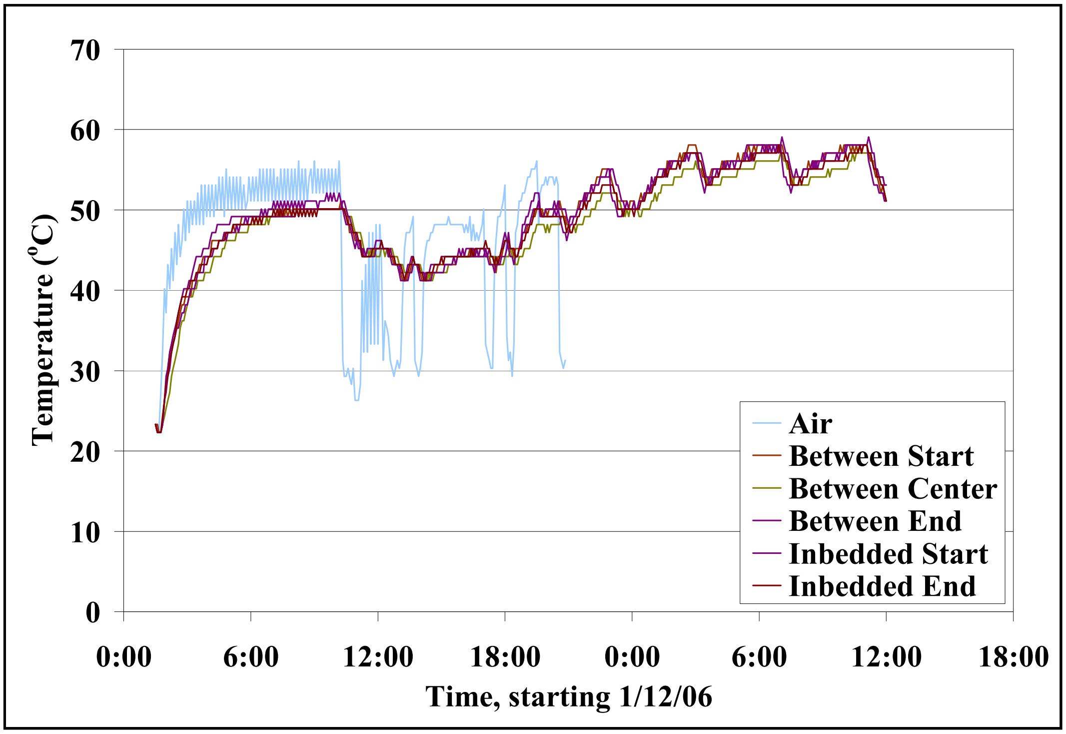


Figure C103: Oss 12.5 Temperature Readings

Oss 19

Table C32: Oss 19 MMLS3 Test Log

Action	Time	Date	Counter	Relative	Notes
Heat	00:25	10/30/05	144293	0	
Profile	15:43		144293	0	MMLS wouldn't start after the 0 load profile. I had to take off the envi. chamber and check connections and pull the track to make sure all small castor wheels were on the track. I tested it for a few cycles (~5 sec.) put envi. chamber back on and continued.
MMLS	16:34		144296	0	
Profile	16:42		144396	1000	
MMLS	17:07		144397	1000	
Profile	17:16		144497	2000	
MMLS	17:45		144498	2000	
Profile	18:02		144698	4000	
MMLS	18:27		144699	4000	
Profile	19:02		145099	8000	
MMLS	19:26		145100	8000	
Profile	20:36		145906	16000	I missed the turn-off time and stopped the MMLS at ~16060 cycles by mistake. I realized that during this last run I forgot to turn on the heater.

Table C32: Oss 19 MMLS3 Test Log (continued)

Action	Time	Date	Counter	Relative	Notes
					Also I forgot to tighten the jack screws on the End side. They did move by some unknown amount and there may have been heave on the End side due to this uneven loading.
Heat	21:00		145906	16000	
Off	22:42		145906	16000	Turned off heater to readjust jack screws on End side - no sure if they're perfect. I did it with a wheel resting on samples #6 and #7
Heat	22:56		145906	16000	
MMLS	00:48	10/31/05	145907	16000	I opened the end panels to lower jack screws with out turning heater off before starting the MMLS
Profile	02:49		147307	30000	
MMLS	03:15		147307	30000	
Profile	06:07		149307	50000	
Off	06:40		149307	50000	Everything was shut off because the room was needed by another class
Heat	18:35	11/01/05	149307	50000	Heat turned back on to finish the last 50k cycles of the test
MMLS	22:58		149308	50000	Again lowered jack screws without turning the heater off, before starting the MMLS.
Adjust	23:03		149361	50530	Noticed that there was a squeaking while the MMLS was running. I checked under the heater vent and found it was shaking due to uneven legs.
					I stopped the MMLS and raised the jack screws on the Start side until it was "OK".
MMLS	23:10		149361	50530	Squeaking persists - I will let it continue and will lubricate the machine after the test
Profile	02:34	11/02/06	151808	75000	
MMLS	02:57		151808	75000	
Off	08:15		155482	111740	I turned off the MMLS late. I left the machine raised to take the profile later on
Profile	17:45		155482	111740	for future reference: if you miss a stop point by a lot, let it run to a full 1000 cycle increment before stopping for convenience sake.

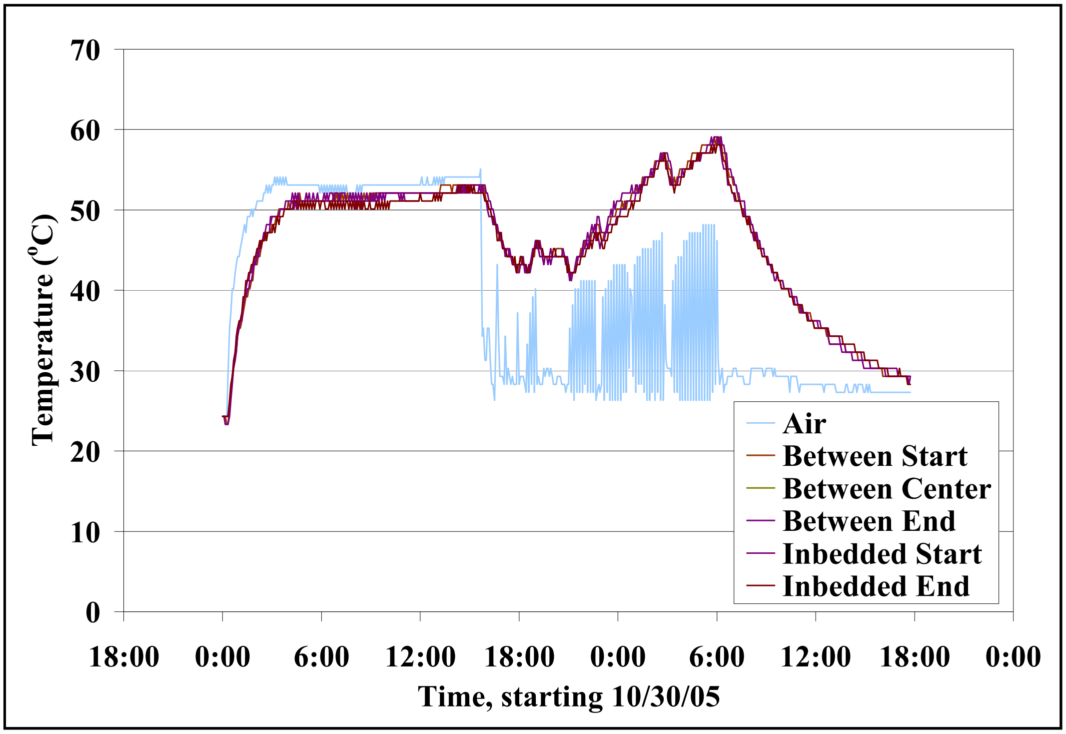


Figure C104: Oss 19 Temperature Readings, Part 1

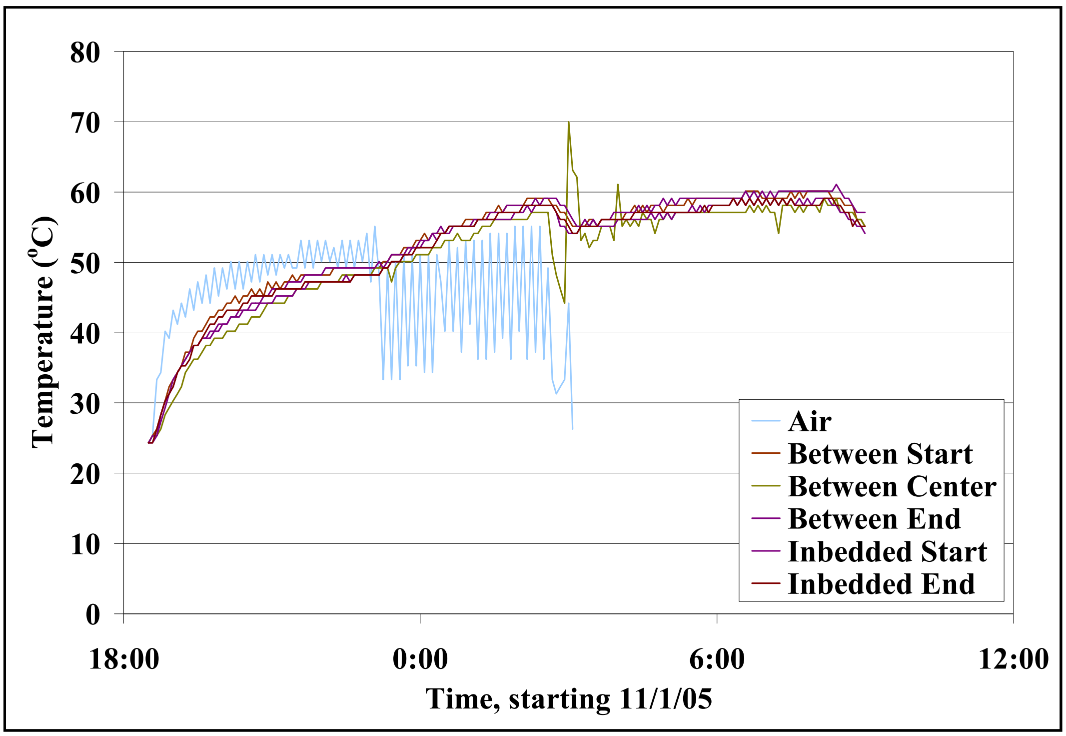


Figure C105: Oss 19 Temperature Readings, Part 2

Cont 12.5

Table C33: Cont 12.5 MMLS3 Test Log

Action	Time	Date	Counter	Relative	Notes
Profile	20:00	3/14/2006	165500	0	
MMLS	17:00	3/15/2006	165501	0	seating load, specimens cold, approx 10 axles at 10 on the speed dial
Profile	17:05		165503	20	
Heat	23:25		165503	20	beginning of heat, tried using the orange cover only instead of the white environmental chamber
Check	9:55	3/16/2006	165503	20	checked the heat, the heater read 44 C, the inb_strt thermocouple read ~43 C, set heater to 77.5 C
Stop	10:35		165504	20	the MMLS wouldn't start, so I stopped the heater to check things out
Heat	10:42		165505	20	MMLS display: oL3, would not go away even after pushing STOP and flipping off switches.
					I unplugged it, waited 10 sec. and replugged it and started it up and it worked; now heating specimens back up
MMLS	11:00		165505	20	
Profile	11:11		165603	1000	
Heat	12:00		165603	1000	using the orange vinyl cover was too difficult because the MMLS cannot be raised perfectly straight up and down with the crane and it is impractically difficult for one person to do the job, so I put the envi. chamber back on and will raise and lower the jack screws
MMLS	18:51		165603	1000	opened sides to lubricate jack screws before starting MMLS
Profile	18:59		165703	2000	
MMLS	19:22		165703	2000	
Profile	19:39		165903	4000	
MMLS	20:04		165903	4000	
Profile	20:39		166303	8000	
MMLS	21:09		166303	8000	
Heat	22:20		167103	16000	Personal break
Profile	23:45		167103	16000	
MMLS	0:07	3/17/2006	167103	16000	
Profile	2:11		168503	30000	
MMLS	2:44		168504	30000	
Profile	5:37		170504	50000	
MMLS	6:07		170504	50000	
Profile	9:43		173004	75000	
MMLS	10:10		173004	75000	

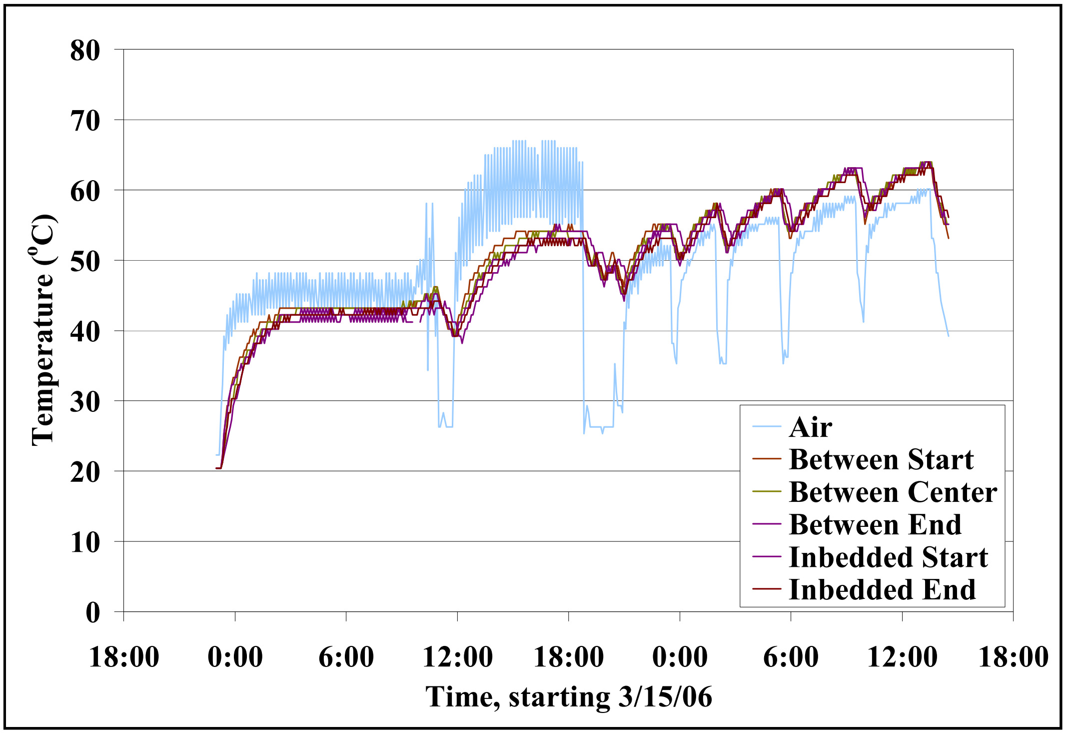


Figure C106: Cont 12.5 Temperature Readings

Cont 19

Table C34: Cont 19 MMLS3 Test Log

Action	Time	Date	Counter	Relative	Notes
Profile	2:45	3/25/2006	175504	0	
MMLS	3:08		175505	0	seating load, specimens cold, approx 10 axles at 18 on the speed dial
Profile	3:09		175506	10	not much change in profile, probably because I tightened the specimens in so much
Heat	3:52		175506	10	beginning of heat
MMLS	11:23		175506	10	
Profile	11:32		175606	1000	mistake on profile #3: the red line is bad (accidentally took #4 profile), overwrote file
MMLS	12:09		175606	1000	
Profile	12:18		175706	2000	
MMLS	12:46		175708	2000	
Profile	13:16		175908	4000	
MMLS	13:49		175908	4000	
Profile	14:39		176308	8000	
MMLS	15:06		176309	8000	
Profile	16:22		177115	16000	went a few extra axles on this one; should have stopped at 177109
MMLS	17:12		177116	16000	

Table C34: Cont 19 MMLS3 Test Log (continued)

Action	Time	Date	Counter	Relative	Notes
Profile	19:15		178510	32000	
Heat	19:43		178510	32000	took time to fix markings on profilometer bar
MMLS	20:07		178510	32000	
Profile	23:28		180587	50000	went a few extra axles on this one; should have stopped at 180510
MMLS	0:01	3/26/2006	180588	50000	
Profile	3:33		183011	75000	
MMLS	4:11		183012	75000	
Profile	7:55		185512	100000	

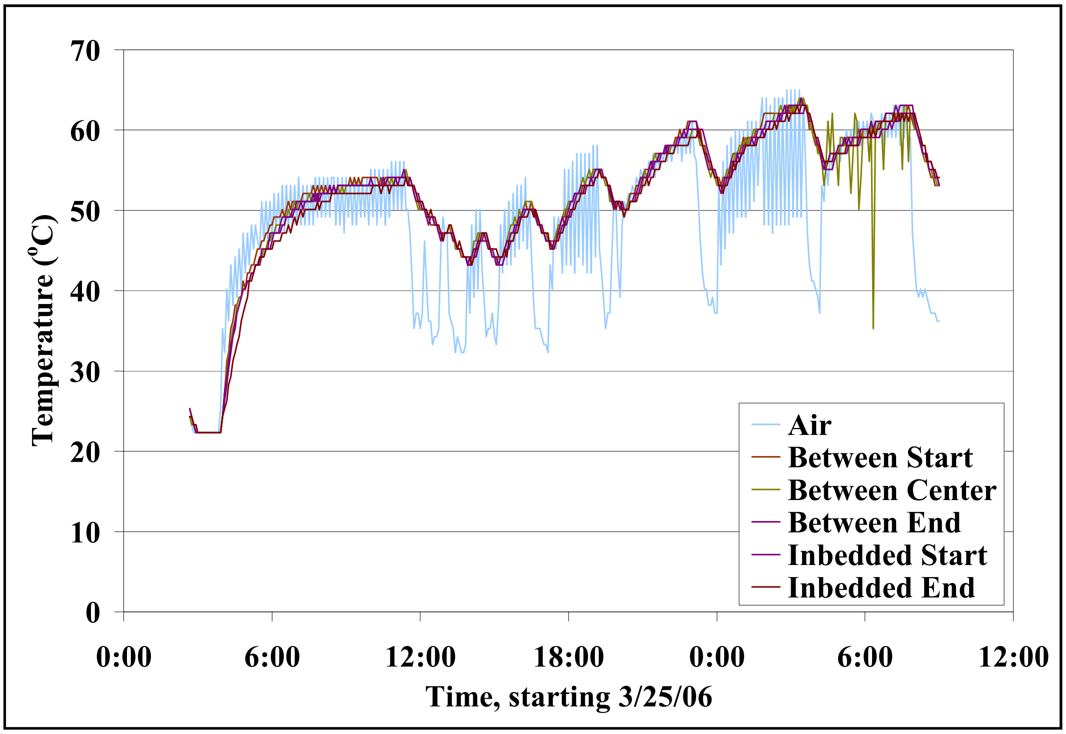


Figure C107: Cont 19 Temperature Readings

Farm

The original test log for the Farm MMLS3 test was lost. The log shown is extrapolated from the profile and temperature data files.

Table C35: Farm MMLS3 Test Log

Action	Time	Date	Counter	Relative	Notes
Heat	13:45	5/30/2006			
Profile	14:20			0	
MMLS	14:42				
Profile	14:45			10	
Heat	16:30				
MMLS	21:51				
Profile	22:00			1000	
Heat	22:45				
MMLS	23:32				
Profile	23:40			2000	
MMLS	0:13	5/31/2006			
Profile	0:30			4000	
MMLS	1:18				
Profile	1:50			8000	
MMLS	2:13				
Profile	3:20			16000	
MMLS	3:57				
Profile	6:00			30000	
MMLS	6:30				
Heat	9:17				
Profile	10:05			50000	
MMLS	10:45				
Profile	14:15			75000	
MMLS	14:55				
Stop	18:25				
Profile	19:20			100000	

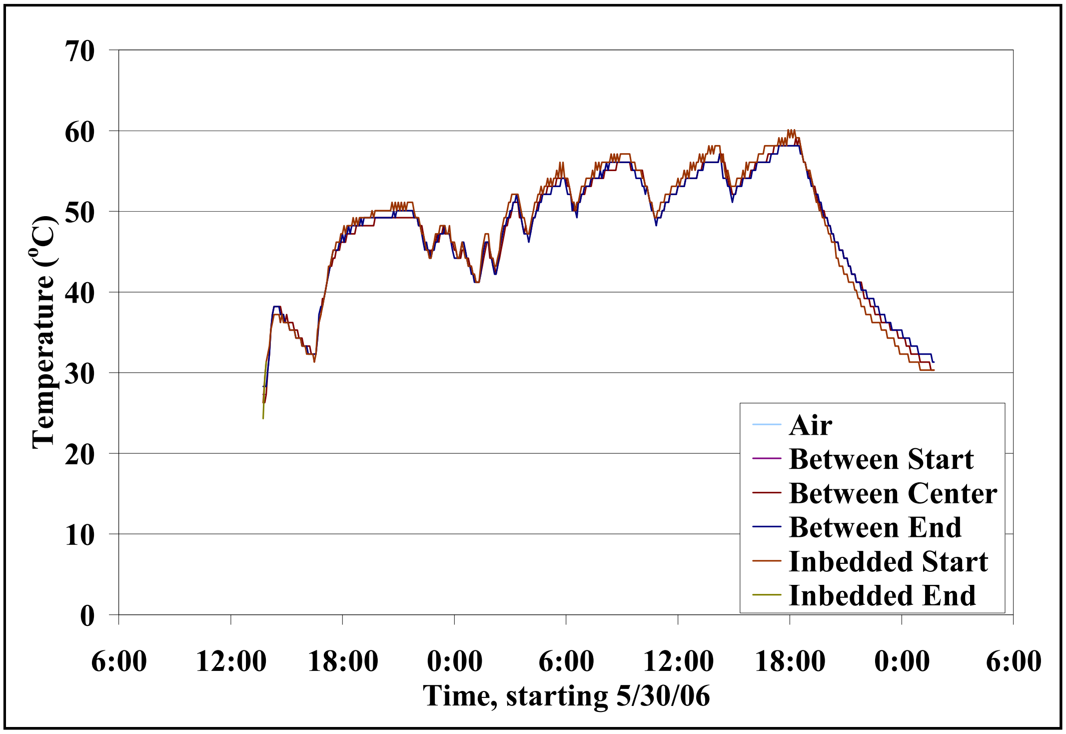


Figure C108: Farm Temperature Readings

<u>Hook</u>

Table C36: Hook MMLS3 Test Log

Action	Time	Date	Counter	Relative	Notes
Profile	11:35	6/13/2006	195519	0	
MMLS	11:40		195520	0	
Profile	11:45		195521	10	
Heat	12:14		195521	10	
MMLS	18:16		195522	10	
Profile	18:29		195623	1000	
MMLS	18:55		195624	1000	
Profile	19:04		195724	2000	
MMLS	19:27		195725	2000	
Profile	19:44		195925	4000	
MMLS	20:03		195926	4000	
Profile	21:12		196726	12000	
MMLS	21:56		196727	12000	
Profile	21:33		197127	16000	
MMLS	23:10		197128	16000	
Profile	1:12	6/14/2006	198528	30000	
MMLS	1:38		198529	30000	
Profile	4:32		200529	50000	
MMLS	4:56		200529	50000	
Profile	8:34		203029	75000	
MMLS	9:12		203030	75000	
Profile	12:50		205530	100000	

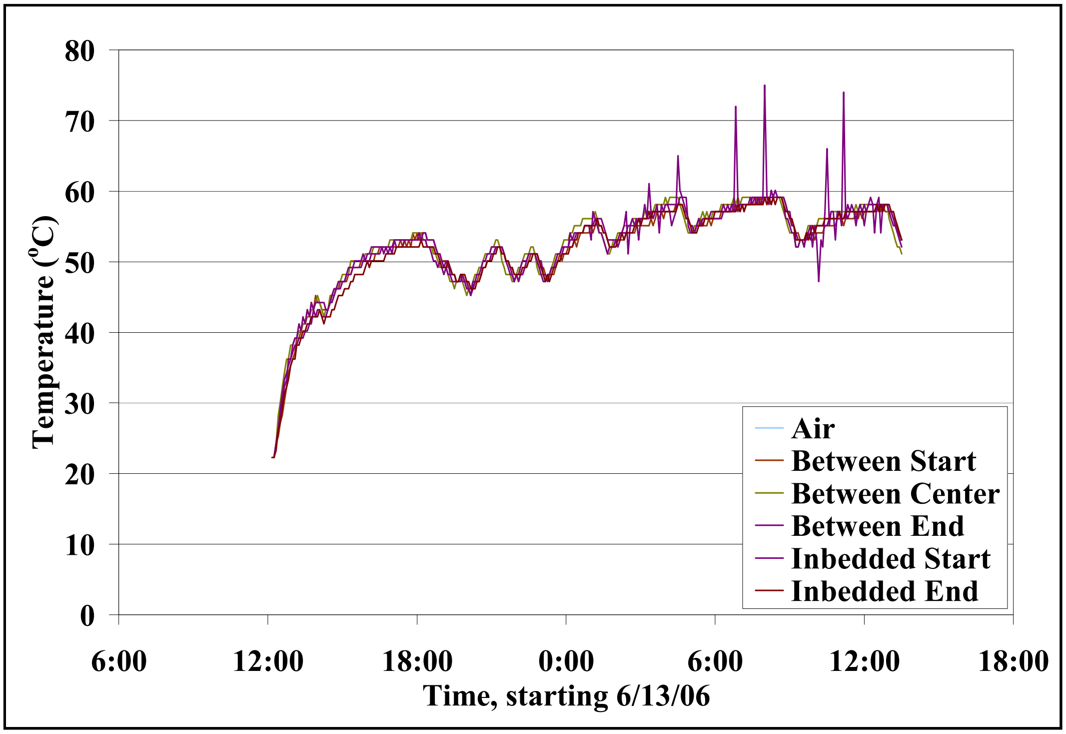


Figure C109: Hook Temperature Readings

<u>Oss 12.5 Bailey</u>

Table C37: Oss 12.5 Bailey MMLS3 Test Log

Action	Time	Date	Counter	Relative	Notes
Profile	18:00	05/19/08	475260	0	
MMLS	18:27		475261		
Profile	18:30		475263	20	
Heat	19:15		475263		
MMLS	23:31		475263		
Profile	23:39		475363	1000	
MMLS	00:00	05/20/08	475363		
Profile	00:08		475463	2000	
MMLS	00:29		475463		
Profile	00:46		475663	4000	
MMLS	01:10		475663		
Profile	01:43		476063	8000	
MMLS	02:05		476063		
Profile	03:12		476863	16000	
MMLS	03:37		476863		
Stop	05:30		478213	29500	tire #4 blew, will replace and restart test this evening
Profile	20:00		478213		
Heat	20:21		478213		
MMLS	01:00	05/21/08	478213		

Profile	03:50		480263	50000	

Table C37: Oss 12.5 Bailey MMLS3 Test Log (continued)

Action	Time	Date	Counter	Relative	Notes
MMLS	04:14		480263		
Profile	07:42		482771	75000	
MMLS	08:05		482771		
Stop	11:32		485263		Heather stopped and raised MMLS at 11:32am, she left heater going
Heat	11:32		485263		
Profile	20:44		485263	100000	

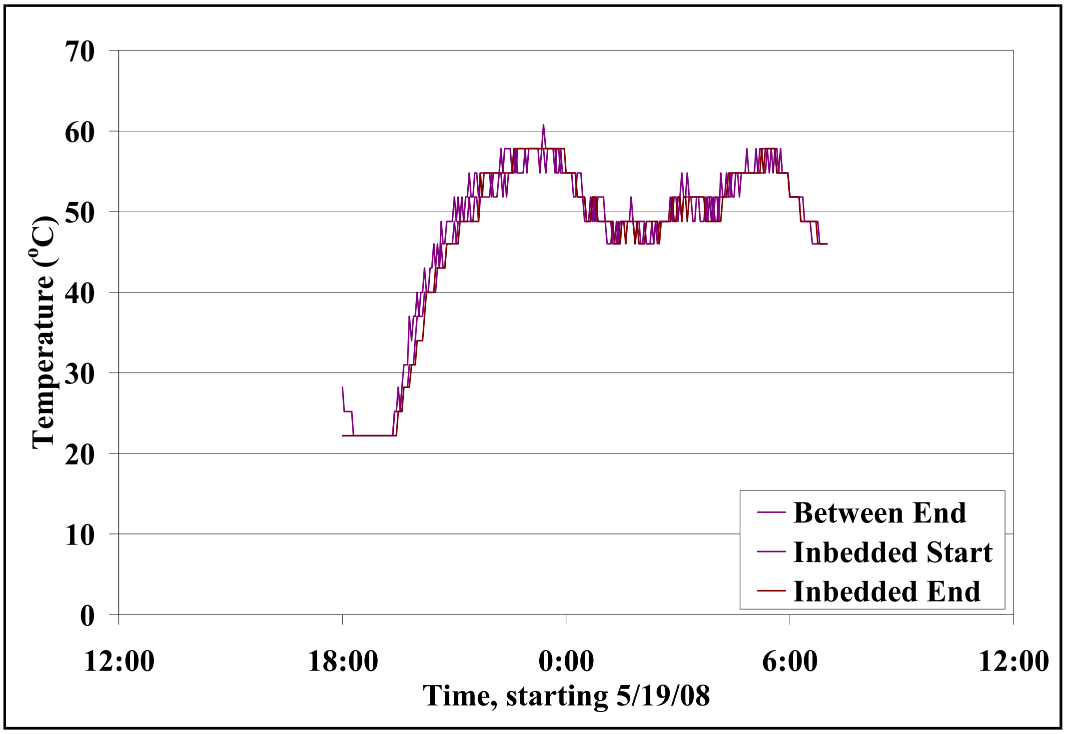


Figure C110: Oss 12.5 Bailey Temperature Readings, Part 1

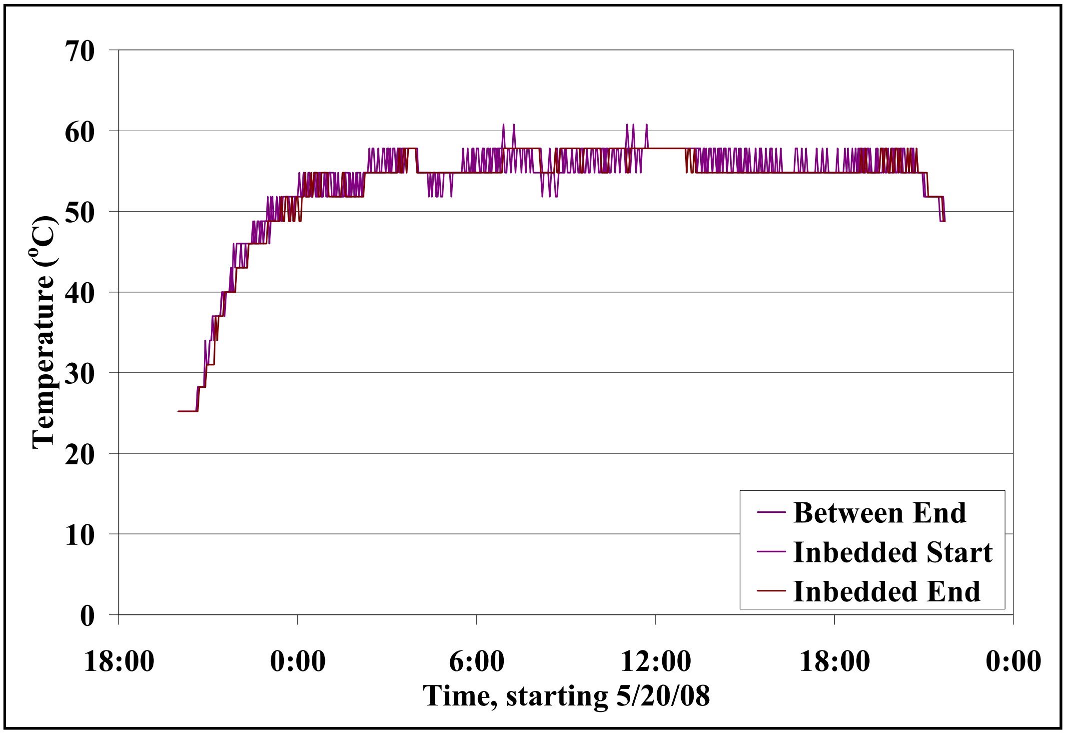


Figure C111: Oss 12.5 Bailey Temperature Readings, Part 2

Cont 19 Bailey

Table C38: Cont 19 Bailey MMLS3 Test Log

Action	Time	Date	Counter	Relative	Notes
Profile	18:20	06/19/08	505268	0	
MMLS	19:05		505269		
Profile	19:06		505271	20	
Heat	19:52		505271		
MMLS	01:01	06/20/08	505271		
Profile	01:09		505371	1000	
MMLS	01:33		505371		
Profile	01:41		505471	2000	
MMLS	02:02		505471		
Profile	02:18		505671	4000	
MMLS	02:38		505671		
Profile	03:10		506071	8000	
MMLS	03:30		506071		
Profile	04:35		506871	16000	
MMLS	04:56		506871		
Profile	06:59		508371	31000	Over slept a little
MMLS	07:28		508371		
Profile	10:04		510272	50000	
MMLS	10:25		510272		
Profile	13:51		512771	75000	

MMLS	14:13		512771		
Profile	17:39		515271	100000	

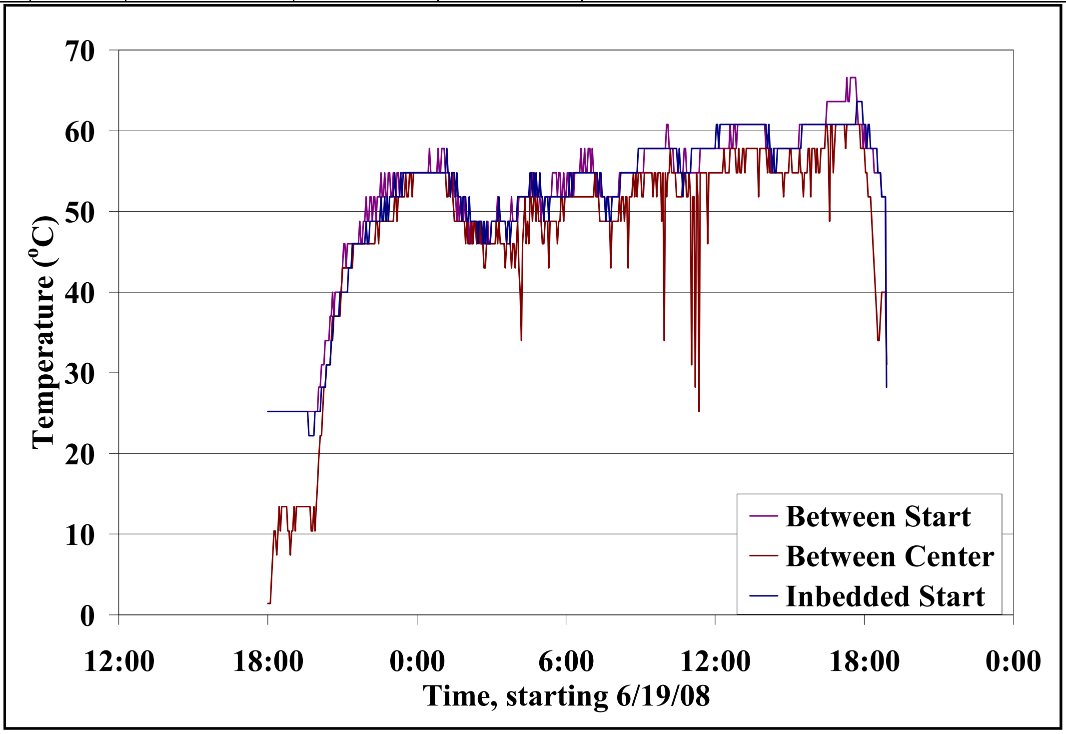


Figure C112: Cont 19 Bailey Temperature Readings

Oss 12.5 Field Cores

Table C39: Oss 12.5 Field Core MMLS3 Test Log

Action	Time	Date	Counter	Relative	Notes
Start	5:00	9/11/05			Started data collectors, some were not plugged in right away. Inbed Center was put off to the side
Heat	5:30				Started heater
Heat	22:25				Checked Air and Inbed End, readings were approx 50 to 55 C, increased heater setting to 70 C and decided to give it more time to heat up
Profile	2:25	9/12/2005			Checked Inbed End and found it to be 55 C, decided to begin testing with taking profile No. 1 at 0 cycles

The rest of the log file was lost.

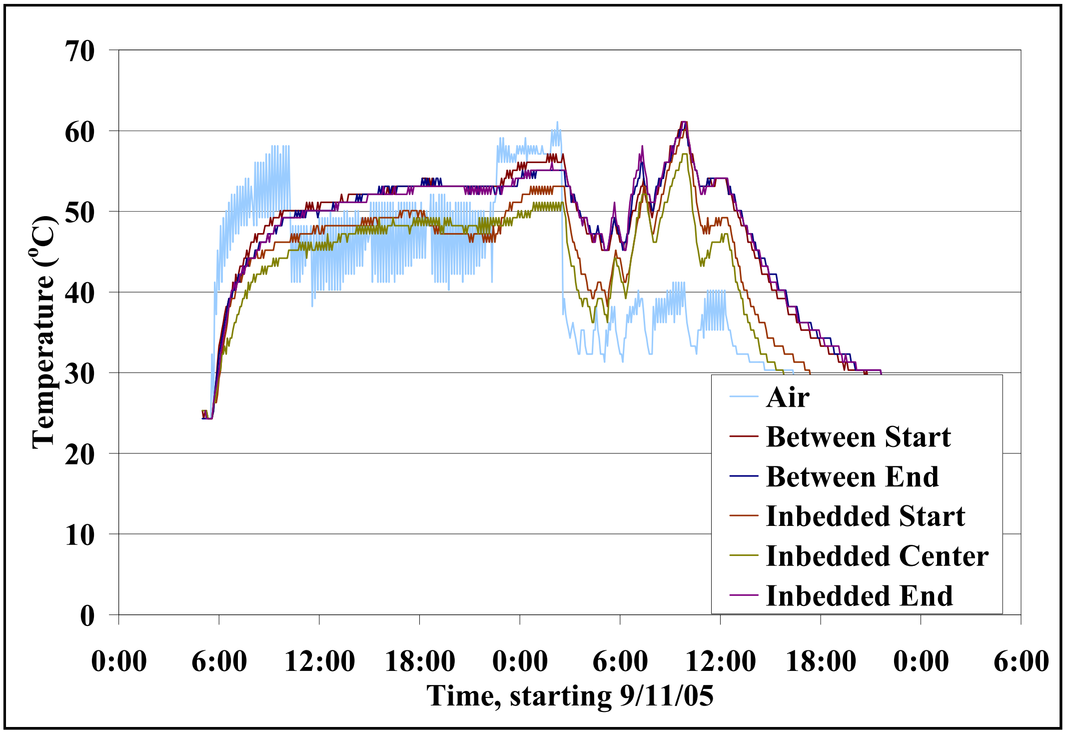


Figure C113: Oss 12.5 Field Core Temperature Readings

Oss 19 Field Cores

Table C40: Oss 19 Field Core MMLS3 Test Log

Action	Time	Date	Counter	Relative	Notes
Profile	16:00	9/18/05	141290	0	
Heat	19:20		141290	0	started heater
Off	2:20	9/19/2005	141290	0	turned off heater - will start test tomorrow
Heat	15:40		141290	0	Heater turned on - set to 70 C
Heat	21:55			0	checked temperature - was 55 C, increased heater to 75 C
MMLS	1:57	9/20/2005	141291	0	cranked down the MMLS 10 cranks, checked gap and found to be < 10 mm, cranked 2 more and gap was > 10 mm on a 14 1/2 wheel, started run.
					Noticed that when I turn on orange power box, counter increases by 1
Profile	2:05		141391	1000	After initial lowering of machine, I forgot to lock the jack screws, they were out of place after 1000 cycles. I put they back - gap seems OK - not sure they are in the right spots/ heights
MMLS	2:33		141391	1000	

Table C40: Oss 19 Field Core MMLS3 Test Log (continued)

Action	Time	Date	Counter	Relative	Notes
Profile	2:42		141491	2000	During 0840 profile, a piece of asphalt seemed to interfere w/ profile. Looked like large heave.
					Upon inspection I found a broken piece - I removed it and retook the profile
					NOTE: Lift profilometer to move, do not slide or drag
MMLS	3:08		141491	2000	
Profile	3:26		141691	4000	Personal break
MMLS	4:07		141691	4000	
Profile	4:42		142091	8000	Personal break
Heat	5:08		142091	8000	turned heater back on, left MMLS raised
MMLS	6:59		142092	8000	
Profile	8:08		142892	16000	retook the #7 profile because it looked horrible – was the same.
					the #5 profile topped out due to debris
					C-01 16000 cycles -> didn't work
					raised profilometer 10 mm
Heat	10:14		142892	16000	Heat back on
MMLS	12:01		142893	16000	lowered MMLS 1 crank to give 10 mm gap; gap was just at 10mm
Profile	14:02		144293	30000	

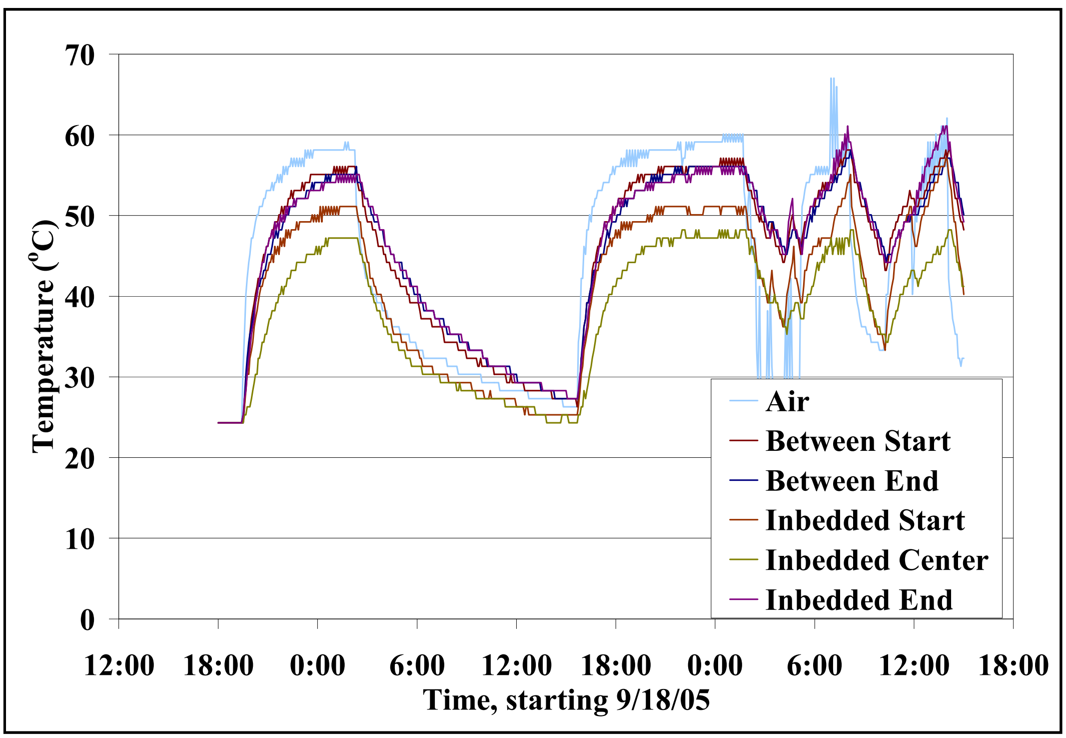


Figure C114: Oss 19 Field Core Temperature Readings

APPENDIX D: TEMPERATURE ADJUSTMENT METHOD

Temperatures during the testing varied within approximately ±5°C of the target temperature. In this relatively small temperature range, the permanent deformations measured are assumed to be inversely proportional to the stiffness, measured by dynamic modulus, of the mixture. The dynamic modulus of the mixtures at the various temperatures was estimated using the Hirsch Model as proposed by Christensen et.al (2003) and shown below:

$$|E^*|_{mix} = P_c\left[4{,}200{,}000(1\text{-}VMA/100) + 3|G^*|_{binder}\left(VFA\times VMA/10{,}000\right)\right] + \left(1\text{-}P_c\right)\left[\left(1\text{-}VMA/100\right)/4{,}200{,}000 + VMA/\left(3VFA\times|G^*|_{binder}\right)\right]^{-1} \quad \text{(D1)}$$

$$P_c = \left(3 + VFA\times|G^*|_{binder}/VMA\right)^{0.678}\Big/\left(396 + \left(VFA\times|G^*|_{binder}/VMA\right)^{0.678}\right)$$

Where P_c = contact factor
$|G^*|$ = Dynamic Complex Shear Modulus of asphalt binder in psi
VMA = Voids in Mineral Aggregates in %
VFA = Voids Filled with Asphalt in %

For the adjustment of deformation profiles, the deformation in each specimen at a temperature of 50°C must be predicted. If E_t is the |E*| value at temperature t and permanent deformation for some load cycles is d_t, then predicted value of deformation at 50°C under same number of load cycles is given by Equation (D2) as

$$d_{50} = d_t\times E_t/E_{50} \quad \text{(D2)}$$

As E_t can be computed using the Hirsch Model, deformation value at any temperature t can be transformed to 50°C.

As the deformation was measured several times during loading cycles, and temperature was continuously changing between two profile measurements, for the adjustment work, each loading interval between two profile measurements was divided into n parts where the temperature was observed for n times during that loading time. As the loading was applied at a constant rate and temperature observations were also taken at regular intervals, it was assumed that at each temperature value recorded, the number of loading cycles applied was N/n where N is the total number of loading cycles applied during that loading interval.

For each temperature value, |G*| and hence |E*|, was calculated and the ratio E_t/E_{50} was computed. |G*| values were obtained from a master curve for a typical PG 64-28 binder. Some G* values had to be interpolated or extrapolated from the master curve because of limited data.

If the measured deformation during i^{th} part of that loading cycle is $d_i(t)$ then predicted deformation is given by Equation (D3)

$$d_i(50) = d_i(t) \times E(t)_i / E_{50} \qquad \text{(D3)}$$

If total measured deformation during i^{th} loading interval is d then deformation that occurred in each of the i segments can be assumed to be inversely proportional to their respective |E*| values.

$$d_i(t) = \left(d \times 1/E(t)i\right) / \Sigma(1/E(t)i) \qquad \text{(D4)}$$

Combining Equations (D3) and (D4) gives:

$$d_i(50) = d / \Sigma(E_{50}/E(t)i) \qquad \text{(D5)}$$

This quantity doesn't depend on any parameter specific to that i^{th} segment only so we can say that

$$d(50) = n \times d / \Sigma(E_{50}/E(t)i)$$

$$\text{or } d(50) = d/(1/n)\Sigma(E_{50}/E(t)i) \qquad \text{(D6)}$$

$$\text{or } d(50) = d/k$$

where

$$k = (1/n)\, \Sigma(E_{50}/E(t)i) \qquad \text{(D7)}$$

The way profile was taken by the profilometer, the cumulative value of deformation beginning from the first cycle is obtained. To get the deformation d in a loading interval, cumulative deformation up to the previous loading interval was subtracted from the cumulative deformation up to that particular interval. After transforming each individual specimen to predicted value at 50^0C, again a cumulative variation can be obtained by averaging for all the specimens.

This process was carried out for all the specimens and deformation curves were adjusted for all of them. Also an average deformation curve over all the specimens was obtained and compared with the measured one.

An example of adjusted deformation curves for different specimens of Continental 19mm mix is shown in Figure D1. Also an example of comparison of averages of the measured deformation curves versus adjusted ones for Continental 19 mm mix is shown in Figure D2. The curves for all mixes can be found in Appendix C.

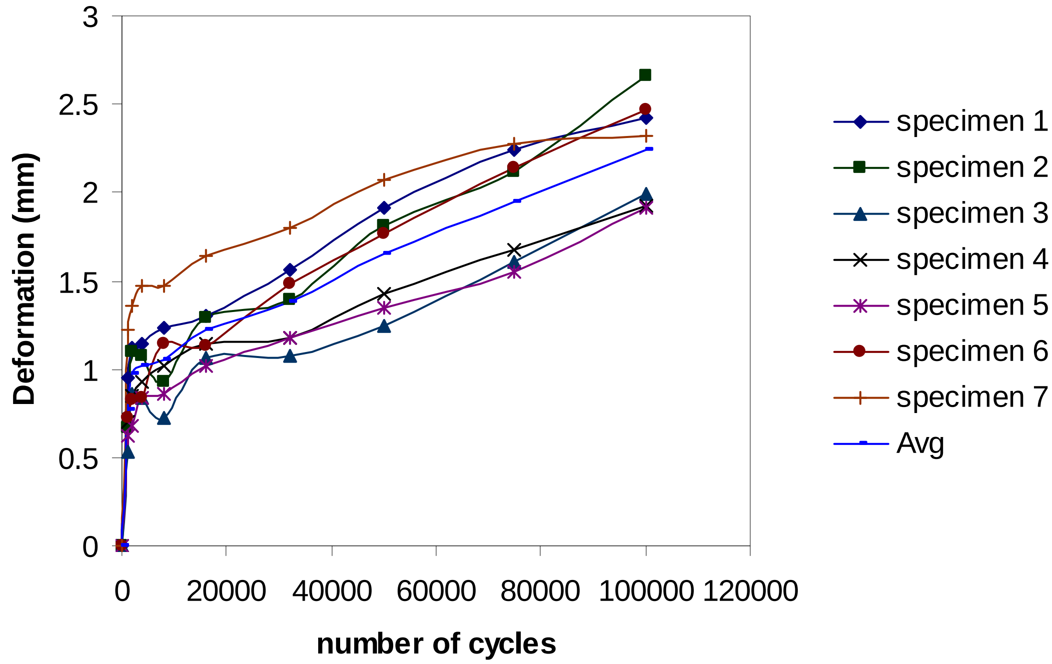


Figure D1: Adjusted deformation curve for Continental 19mm specimens

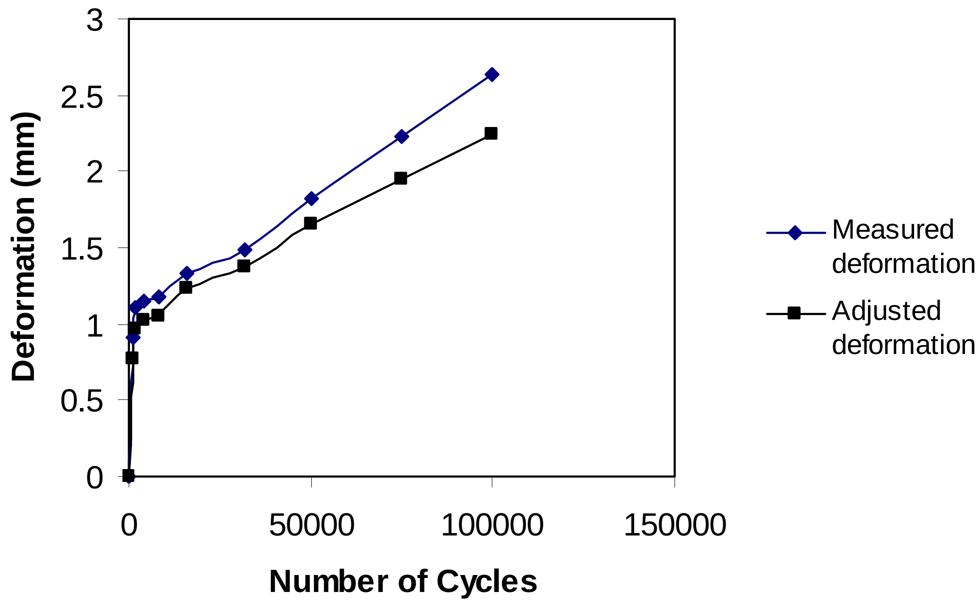


Figure D2: Adjusted versus measured deformation curves for Continental 19mm specimens

APPENDIX E: STATISTICAL COMPARISONS

The statistical test used for this project was the Mann-Whitney/Wilcoxon Rank Sum Test. The average rut depths for the Oss 12.5-Original and the Oss 12.5-Bailey MMLS3 tests will be used to explain how the test works. Tables A7.1 and A7.2 show the average rut depth measurements for these tests.

Table E1: Oss 12.5-Original Avg Rut Depth

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	1.20	1.24	2.06	2.15	3.14	4.22	5.17	5.77	6.18
2	262.5	0.27	0.82	1.47	1.46	2.31	2.63	3.39	4.41	4.38
3	367.5	0.05	0.26	0.65	0.61	1.06	1.10	1.56	2.45	2.61
4	472.5	0.78	0.84	0.99	1.14	1.32	1.65	1.92	2.18	2.38
5	577.5	0.63	1.03	0.55	1.22	1.06	1.58	2.02	2.27	2.84
6	682.5	0.62	1.15	0.99	1.29	1.66	2.35	3.09	3.37	3.60
7	787.5	0.55	0.65	1.12	1.56	2.12	2.48	2.88	3.11	3.22

Table E2: Oss 12.5-Bailey Avg Rut Depth

Brick	Long Pos	Thousands of Loading Cycles								
		1	2	4	8	16	30	50	75	100
1	157.5	0.80	0.95	1.19	1.30	1.54	2.02	2.31	2.70	2.93
2	262.5	0.91	0.84	1.05	1.38	1.05	1.85	1.79	2.06	2.06
3	367.5	0.93	1.17	1.21	1.27	1.26	1.58	1.54	1.81	1.80
4	472.5	1.09	1.23	1.31	1.33	1.40	1.69	1.77	1.98	2.16
5	577.5	1.44	1.44	1.94	1.48	1.54	1.85	1.93	2.18	2.52
6	682.5	0.40	0.55	0.60	0.58	0.63	0.90	0.85	1.07	1.26
7	787.5	0.41	0.65	0.69	0.63	0.59	0.94	0.88	1.04	1.11

A separate statistical comparison was done at each measuring point in the tests. Therefore, a total of nine separate comparisons are calculated for these two data sets. For a single comparison, the first step is to combine the values from both data sets into a single list. This list is then arranged in order from highest to lowest while keeping a tab on which data set each value originally came from. Once the values are in order, each is assigned a rank; the highest is rank 1 and the lowest is rank 14. An example using the rut depths at 4,000 loading cycles is shown in Table E3.

Table E3: Combined Rut Values at 4,000 Loading Cycles

Data Set	Rut Value	Rank
Original	2.06	1
Bailey	1.94	2
Original	1.47	3
Bailey	1.31	4
Bailey	1.21	5
Bailey	1.19	6
Original	1.12	7

Bailey	1.05	8
Original	0.99	9
Original	0.99	10
Bailey	0.69	11
Original	0.65	12
Bailey	0.60	13
Original	0.55	14

At this point, the values with their assigned rank are split up into their respective data sets again. Then, ranks in each data set are totaled. The sums of the ranks from each data set are the test statistics for the comparison. Table E4 shows the two data sets with their sums of ranks.

Table E4: Sum of Ranks

Brick	Oss 12.5 Original		Oss 12.5 Bailey	
	Rut Value	Rank	Rut Value	Rank
1	2.055	1	1.186	6
2	1.468	3	1.053	8
3	0.654	12	1.208	5
4	0.989	10	1.312	4
5	0.554	14	1.937	2
6	0.994	9	0.602	13
7	1.122	7	0.693	11
Sum		56		49

In this example, the sums, 56 and 49, differ by 7. The p-value for these two test statistics is 0.7104. This means that there is approximately a 71% chance that one would get two sums of ranks at least 7 apart if the ranks were randomly assigned to each data set. For a p-value this high, the null hypothesis is not rejected. In this case the null hypothesis says that the two data sets are not significantly different. For the rut values measured 46,000 cycles later, the two rank sums are 70 and 35. The probability that one would get two sums 35 apart by random chance with only ranks 1 through 14 to work with is about 3%. The limit for the p-value is 0.05, which is 5%. Therefore, at 50,000 loading cycles the null hypothesis is rejected, meaning that the two data sets are significantly different.

Sometimes, two or more values tie for the same rank in the combined list. In such a case, an average rank is assigned to all of the values. However, if this happens too much, the results can be skewed. This is especially true when working with a low number of data points. When there were too many ties in the data, the statistical analysis used for this project employed an assumed normal distribution, which yielding a single value for the test statistic that could be positive or negative. The larger the absolute value of this test statistic, the smaller the p-value.

For each pair of mix designs, two sets of comparisons were calculated. The first used the average rut depth measured from the base line and the second used the maximum rut depth measured from the base line. Tables E5 through E13 show the results from the statistical comparisons. The first column is the number of thousands of loading cycles applied up to the set of profiles that were statistically compared. The test statistics labeled W are sums of ranks. The test statistics labeled Z are the normal distribution approximations. If the null hypothesis, H_0, is rejected, then the two data sets are significantly different at the corresponding number of loading cycles.

Table E5: Oss 12.5 verses Oss 19

	Avg Rut Depth			Max Rut Depth		
Cycles	Test Statistics	P-Value	Reject H_0?	Test Statistics	P-Value	Reject H_0?
1	W = 28, 77	0.0006	Yes	W = 28, 77	0.0006	Yes
2	W = 28, 77	0.0006	Yes	W = 28, 77	0.0006	Yes
4	W = 31, 74	0.0041	Yes	W = 31, 74	0.0041	Yes
8	W = 31, 74	0.0041	Yes	W = 32, 73	0.007	Yes
16	W = 42, 63	0.2086	No	W = 64, 41	0.1649	No
30	W = 68, 37	0.053	No	W = 42, 63	0.2086	No
50	W = 42, 63	0.2086	No	W = 60, 45	0.3829	No
75	W = 60, 45	0.3829	No	W = 59, 46	0.4557	No
100	Z = -0.9594	0.3374	No	W = 59, 46	0.4557	No

Table E6: Oss 12.5 verses Cont 12.5

	Avg Rut Depth			Max Rut Depth		
Cycles	Test Statistics	P-Value	Reject H_0?	Test Statistics	P-Value	Reject H_0?
1	W = 56, 49	0.7104	No	W = 52, 53	1	No
2	W = 56, 49	0.7104	No	W = 50, 55	0.8048	No
4	W = 58, 47	0.535	No	W = 58, 47	0.535	No
8	W = 48, 57	0.62	No	W = 56, 49	0.7104	No
16	W = 48, 57	0.62	No	W = 48, 57	0.62	No
30	W = 59, 46	0.4557	No	W = 58, 47	0.535	No
50	Z = -0.7035	0.4817	No	W = 59, 46	0.4557	No
75	W = 60, 45	0.3829	No	W = 61, 44	0.3176	No
100	W = 60, 45	0.3829	No	W = 58, 47	0.535	No

Table E7: Oss 12.5 verses Farm

	Avg Rut Depth			Max Rut Depth		
Cycles	Test Statistics	P-Value	Reject H_0?	Test Statistics	P-Value	Reject H_0?
1	W = 49, 56	0.7104	No	W = 58, 47	0.535	No
2	W = 63, 42	0.2086	No	W = 60, 45	0.3829	No
4	W = 60, 45	0.3829	No	W = 62, 43	0.2593	No
8	W = 65, 40	0.1282	No	W = 66, 39	0.0973	No
16	W = 69, 36	0.0379	Yes	W = 70, 35	0.0262	Yes
30	W = 68, 37	0.053	No	W = 70, 35	0.0262	Yes
50	W = 70, 35	0.0262	Yes	W = 70, 35	0.0262	Yes
75	W = 31, 74	0.0041	Yes	W = 31, 74	0.0041	Yes
100	W = 75, 30	0.0023	Yes	W = 31, 74	0.0041	Yes

Table E8: Oss 19 verses Cont 19

	Avg Rut Depth			Max Rut Depth		
Cycles	Test Statistics	P-Value	Reject H_0?	Test Statistics	P-Value	Reject H_0?
1	W = 28, 77	0.0006	Yes	W = 28, 77	0.0006	Yes
2	W = 28, 77	0.0006	Yes	W = 28, 77	0.0006	Yes
4	W = 28, 77	0.0006	Yes	W = 28, 77	0.0006	Yes
8	W = 28, 77	0.0006	Yes	W = 28, 77	0.0006	Yes
16	W = 28, 77	0.0006	Yes	W = 28, 77	0.0006	Yes
30	W = 28, 77	0.0006	Yes	W = 28, 77	0.0006	Yes
50	W = 28, 77	0.0006	Yes	W = 28, 77	0.0006	Yes
75	Z = -3.07	0.0021	Yes	W = 28, 77	0.0006	Yes
100	W = 28, 77	0.0006	Yes	Z = -3.07	0.0021	Yes

Table E9: Cont 12.5 verses Cont 19

	Avg Rut Depth			Max Rut Depth		
Cycles	Test Statistics	P-Value	Reject H_0?	Test Statistics	P-Value	Reject H_0?
1	W = 59, 46	0.4557	No	W = 56, 49	0.7104	No
2	W = 35, 70	0.0262	Yes	W = 38, 67	0.0728	No
4	W = 70, 35	0.0262	Yes	W = 70, 35	0.0262	Yes
8	W = 70, 35	0.0262	Yes	W = 70, 35	0.0262	Yes
16	W = 70, 35	0.0262	Yes	W = 70, 35	0.0262	Yes
30	W = 71, 34	0.0175	Yes	W = 72, 33	0.0111	Yes
50	W = 72, 33	0.0111	Yes	W = 32, 73	0.007	Yes
75	Z = 2.3025	0.0213	Yes	W = 32, 73	0.007	Yes
100	W = 38, 67	0.0728	No	Z = 2.3025	0.0213	Yes

Table E10: Cont 12.5 verses Hook

	Avg Rut Depth			Max Rut Depth		
Cycles	Test Statistics	P-Value	Reject H_0?	Test Statistics	P-Value	Reject H_0?
1	W = 52, 53	1	No	W = 56, 49	0.7104	No
2	W = 65, 40	0.1282	No	W = 66, 39	0.0973	No
4	W = 69, 36	0.0379	Yes	W = 70, 35	0.0262	Yes
8	W = 64, 41	0.1649	No	W = 65, 40	0.1282	No
16	W = 65, 40	0.1282	No	W = 62, 43	0.2593	No
30	W = 62, 43	0.2593	No	W = 61, 44	0.3176	No
50	Z = 1.3431	0.1792	No	W = 42, 63	0.2086	No
75	W = 66, 39	0.0973	No	Z = 1.471	0.1413	No
100	W = 66, 39	0.0973	No	W = 68, 37	0.053	No

Table E11: Farm verses Hook

	Avg Rut Depth			Max Rut Depth		
Cycles	Test Statistics	P-Value	Reject H_0?	Test Statistics	P-Value	Reject H_0?
1	W = 56, 49	0.7104	No	W = 48, 57	0.62	No
2	W = 56, 49	0.7104	No	W = 59, 46	0.4557	No
4	W = 56, 49	0.7104	No	W = 56, 49	0.7104	No
8	W = 56, 49	0.7104	No	W = 58, 47	0.535	No
16	W = 50, 55	0.8048	No	W = 60, 45	0.3829	No
30	W = 50, 55	0.8048	No	W = 58, 47	0.535	No
50	W = 56, 49	0.7104	No	W = 58, 47	0.535	No
75	W = 46, 59	0.4557	No	W = 61, 44	0.3176	No
100	W = 60, 45	0.3829	No	W = 58, 47	0.535	No

Table E12: Oss 12.5 Original verses Oss 12.5 Bailey

	Avg Rut Depth			Max Rut Depth		
Cycles	Test Statistics	P-Value	Reject H_0?	Test Statistics	P-Value	Reject H_0?
1	W = 42, 63	0.2086	No	W = 65, 40	0.1282	No
2	W = 48, 57	0.62	No	W = 59, 46	0.4557	No
4	W = 49, 56	0.7104	No	W = 50, 55	0.8048	No
8	W = 49, 56	0.7104	No	W = 50, 55	0.8048	No
16	W = 66, 39	0.0973	No	W = 65, 40	0.1282	No
30	W = 64, 41	0.1649	No	W = 64, 41	0.1649	No
50	W = 70, 35	0.0262	Yes	W = 36, 69	0.0379	Yes
75	W = 31, 74	0.0041	Yes	W = 31, 74	0.0041	Yes
100	W = 32, 73	0.007	Yes	W = 32, 73	0.007	Yes

Table E13: Cont 19 Original verses Cont 19 Bailey

	Avg Rut Depth			Max Rut Depth		
Cycles	Test Statistics	P-Value	Reject H_0?	Test Statistics	P-Value	Reject H_0?
1	W = 36, 69	0.0379	Yes	W = 32, 73	0.007	Yes
2	W = 38, 67	0.0728	No	W = 70, 35	0.0262	Yes
4	W = 32, 73	0.007	Yes	W = 75, 30	0.0023	Yes
8	W = 36, 69	0.0379	Yes	W = 32, 73	0.007	Yes
16	W = 41, 64	0.1649	No	W = 70, 35	0.0262	Yes
30	W = 65, 40	0.1282	No	W = 70, 35	0.0262	Yes
50	W = 49, 56	0.7104	No	W = 68, 37	0.053	No
75	Z = 0	1	No	W = 42, 63	0.2086	No
100	W = 51, 54	0.9015	No	Z = -0.6396	0.5224	No

APPENDIX F: BAILEY SUPERPAVE MIX DESIGNS

Oss 12.5 Bailey

NMSA: 12.5 mm (0.5 in.)
Binder: Gb = 1.026

Table F1: Oss 12.5-Bailey Aggregate Data

Aggregate	Blend %	Gsb	Gsa
1/2" Gravel	27.0	2.619	2.686
3/8" Gravel	41.5	2.588	2.666
Grits	27.7	2.556	2.618
Dust	0	2.607	2.651
Scr. Sand	0	2.543	2.62
BHF	3.8	2.607	2.651
Total	100	2.588	2.657

Table F2: Oss 12.5-Bailey Calculation Results for Pbi and Pb,est

Pbi		Pb,est	
Gse	2.643	Gmm	2.444
Vba	0.0181	Gmb - 1	2.351
Vbe	0.101	Gmb - 2	2.355
Ws	2.235	%Gmm@Nini, avg	88.8
Pbi	5.2	%Gmm@Ndes, avg	96.3
		Va	3.7
		VMA	13.8
		Pb,est	5.1

Table F3: Oss 12.5-Bailey Volumetrics of Design Specimens

Parameter	Pb,est – 1.0	Pb,est – 0.5	Pb,est	Pb,est + 0.5
Pb	4.6	5.1	5.6	6.1
Gmm	2.470	2.452	2.434	2.417
Gmb #1	2.330	2.365	2.376	2.377
Gmb #2	2.319	2.349	2.370	2.375
Gse	2.650	2.650	2.650	2.650
%Gmm@Nini avg	86.8	88.5	89.7	90.4
%Gmm@Ndes avg	94.1	96.1	97.5	98.3
Va	5.9	3.9	2.5	1.7
VMA	14.3	13.6	13.4	13.8
VFA	58.7	71.3	81.3	87.8
Pbe	3.7	4.2	4.7	5.2
DP	1.2	1.1	1.0	0.9

Table F4: Oss 12.5-Bailey Final Volumetrics

Parameter	Value	Limits	Pass/Fail
Pb	5.1		
Gmm	2.456		
Gmb - 1	2.347		
Gmb - 2	2.358		
Gse	2.655		
%Gmm@Nini avg	88.0	<89	OK
%Gmm@Ndes avg	95.8		
Va	4.2	=4.0	IN LIMITS
VMA	13.7	>14.0	UNDER LIMIT
VFA	69.4	65 - 75	OK
Pbe	4.2		
DP	1.1	0.6 - 1.2	OK

Cont 19 Bailey

NMSA: 19 mm (0.75 in.)
Binder: Gb = 1.020

Table F5: Cont 19-Bailey Aggregate Data

Aggregate	Blend %	Gsb	Gsa
3/4" Frac	23.1	2.691	2.749
1/2" Frac	30.4	2.722	2.768
3/8" Frac	18.3	2.707	2.756
WMS	19.5	2.71	2.825
DSS	6.3	2.687	2.707
BHF	2.4	2.763	2.763
Total	100	2.708	2.768

Table F6: Cont 19-Bailey Calculation Results for Pbi and Pb,est

Pbi		Pb,est	
Gse	2.756	Gmm	2.551
Vba	0.0148	Gmb - 1	2.408
Vbe	0.089	Gmb - 2	2.403
Ws	2.317	%Gmm@Nini, avg	86.2
Pbi	4.4	%Gmm@Ndes, avg	94.3
		Va	5.7
		VMA	15.1
		Pb,est	5.1

Table F7: Cont 19-Bailey Volumetrics of Design Specimens

Parameter	Pb,est – 1.0	Pb,est – 0.5	Pb,est	Pb,est + 0.5
Pb	4.6	5.1	5.6	6.1
Gmm	2.547	2.527	2.508	2.488
Gmb #1	2.385	2.391	2.409	2.415
Gmb #2	2.383	2.378	2.409	2.427
Gse	2.745	2.745	2.745	2.745
%Gmm@Nini avg	85.3	86.1	88.0	88.6
%Gmm@Ndes avg	93.6	94.4	96.1	97.3
Va	6.4	5.6	3.9	2.7
VMA	16.0	16.4	16.0	16.1
VFA	60.1	65.8	75.5	83.1
Pbe	4.1	4.6	5.1	5.6
DP	0.9	0.8	0.7	0.6

Table F8: Cont 19-Bailey Final Volumetrics

Parameter	Value	Limits	Pass/Fail
Pb	5.6		
Gmm	2.511		
Gmb - 1	2.401		
Gmb - 2	2.407		
Gse	2.750		
%Gmm@Nini avg	87.0	<89	OK
%Gmm@Ndes avg	95.7		
Va	4.3	=4.0	IN LIMITS
VMA	16.2	>13.0	OK
VFA	73.7	65 - 75	OK
Pbe	5.1		
DP	0.7	0.6 - 1.2	OK

Farm Bailey

NMSA: 12.5 mm (0.5 in.)
Binder: Gb = 1.026

Table F9: Farm-Bailey Aggregate Data

Aggregate	Blend %	Gsb	Gsa
1/2" Gravel	33.13	2.645	2.617
3/8" Gravel	25.04	2.616	2.703
Wa. Sand	4.59	2.565	2.625
Dust	22.23	2.598	2.68
Scr. Sand	0	2.566	2.642
BHF	0.02	2.607	2.651
RAP	15		
Total	100	2.620	2.659

Table F10: Farm-Bailey Calculation Results for Pbi and Pb,est

Pbi		Pb,est	
Gse	2.651	Gmm	2.508
Vba	0.0101	Gmb - 1	2.402
Vbe	0.101	Gmb - 2	2.406
Ws	2.240	%Gmm@Nini, avg	89.3
Pbi	4.85	%Gmm@Ndes, avg	95.9
		Va	4.1
		VMA	12.7
		Pb,est	4.90

Table F11: Farm-Bailey Volumetrics of Design Specimens

Parameter	Pb,est – 1.0	Pb,est – 0.5	Pb,est	Pb,est + 0.5
Pb	4.40	4.90	5.40	5.90
Gmm	2.526	2.507	2.488	2.470
Gmb #1	2.387	2.408	2.426	2.439
Gmb #2	2.399	2.413	2.437	2.439
Gse	2.709	2.709	2.709	2.709
%Gmm@Nini avg	88.4	89.4	88.0	92.2
%Gmm@Ndes avg	94.7	96.1	97.7	98.8
Va	5.3	3.9	2.3	1.2
VMA	12.7	12.5	12.2	12.4
VFA	58.3	69.2	81.3	89.9
Pbe	3.2	3.7	4.2	4.7
DP	1.5	1.3	1.1	1.0

Table F12: Farm-Bailey Final Volumetrics

Parameter	Value	Limits	Pass/Fail
Pb	4.85		
Gmm	2.506		
Gmb - 1	2.415		
Gmb - 2	2.418		
Gse	2.705		
%Gmm@Nini avg	89.6	<89	OVER LIMIT
%Gmm@Ndes avg	96.4		
Va	3.6	=4.0	IN LIMITS
VMA	12.2	>14.0	UNDER LIMIT
VFA	70.8	65 - 75	OK
Pbe	3.7		
DP	1.3	0.6 - 1.2	OUTSIDE LIMITS