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Effects of Various HMA Material Properties on Pavement Performance

Stacy G. Williams, Julia K. Foreman

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16. Abstract

During HMA mixture design, mineral aggregates and asphalt binder are combined according to specifications with the expectation that if all requirements are met, the mix will be resistant to premature failure in the field. The volumetric properties of a mix are known to affect performance, although the specific nature of these relationships is difficult to quantify.

In this study, four aggregate sources were selected including limestone, sandstone, gravel, and syenite. From each aggregate source, two gradations (coarse-graded and fine-graded) surface mixtures were designed at three levels of VMA (low, medium, and high). For each of the 24 mix designs, rutting and stripping performance was measured using the University of Arkansas' Evaluator of Rutting and Stripping in Asphalt (ERSA) and Pine's AFW1A Rotary Asphalt Wheel Tester (RAWT). The results of these tests were used to quantify the effects of VMA and gradation type on rutting resistance. Also, qualitative trends were developed relating other volumetric and gradation properties to performance.

The results of the study indicate that VMA affects rutting performance more significantly than gradation type. Each aggregate type exhibited a "natural" range of VMA, and mixtures designed with lower levels of VMA within this range were more resistant to rutting. Stripping characteristics were affected by both VMA and gradation, such that the coarse-graded mixtures of low VMA were the best performers. Overall, it is recommended that both fine- and coarse-graded mixtures be designed with lower VMA, with possible adjustments for the bulk specific gravity of the aggregate source.

With respect to mix design, additional emphasis should be placed on ensuring that mixtures are designed at the "bottom of the VMA curve". Adjusting binder content to create an increase in VMA is likely to reduce performance. Instead, changes in VMA should be made by adjusting the structure of the aggregate blend.

Regression analyses were used in an attempt to mathematically correlate volumetric properties with mixture performance. While definitive models remained elusive, several trends were noted. Film thickness was calculated according to the traditional surface area factors, and this method exhibited only a moderate trend with respect to rutting performance. It is believed that restrictions on this property, if accurately determined, could be used in addition to VMA to better manage the binder content of a mix design. Methods for the measurement of film thickness should be studied further.

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EFFECTS OF VARIOUS HMA MATERIAL PROPERTIES ON PAVEMENT PERFORMANCE TRC-0301

by

Stacy G. Williams, Ph.D., P.E.
Research Assistant Professor
Department of Civil Engineering
University of Arkansas
700 Research Center Blvd.
Fayetteville, AR 72701
479-575-2220
479-575-7639 (FAX)
sgwill@uark.edu

and

Julia K. Foreman, E.I.
Civil Engineer
CEI Engineering Associates, Inc.
3317 Southwest "I" St.
Bentonville, AR 72712
479-273-9472
479-273-0844 (FAX)
jforeman@ceieng.com

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ABSTRACT

During HMA mixture design, mineral aggregates and asphalt binder are combined according to specifications with the expectation that if all requirements are met, the mix will be resistant to premature failure in the field. The volumetric properties of a mix are known to affect performance, although the specific nature of these relationships is difficult to quantify. The ability to alter mixture properties, such as VMA and gradation, in order to produce a desired outcome is perhaps one of the most useful tools a mix designer can possess.

In this study, four aggregate sources were selected including limestone, sandstone, gravel, and syenite. From each aggregate source, two gradations (coarse-graded and fine-graded) surface mixtures were designed at three levels of VMA (low, medium, and high). For each of the 24 mix designs, rutting and stripping performance was measured using the University of Arkansas' Evaluator of Rutting and Stripping in Asphalt (ERSA) and Pine's AFW1A Rotary Asphalt Wheel Tester (RAWT). The results of these tests were used to quantify the effects of VMA and gradation type on rutting resistance. Also, qualitative trends were developed relating other volumetric and gradation properties to performance.

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INTRODUCTION

Permanent deformation, or rutting, is a primary failure mode of hot-mix asphalt (HMA) pavements. Rutting is the accumulation of small deformations caused by repeated heavy loads, and appears as longitudinal depressions in the wheel paths of the roadway. Asphalt mixture rutting is the result of accumulated unrecoverable strain in the asphalt layers due to either densification and/or repeated shear deformations under applied wheel loads. This type of deformation is caused by consolidation, lateral movement, or both, of the HMA under traffic. *(1)* When rutting occurs as a result of mixture shear failure, it is necessary to determine what mixture properties caused the failure, and what measures can be taken during design to provide a solution for the problem.

During HMA mixture design, mineral aggregates and asphalt binder are combined to according to specifications with the expectation that if all requirements are met, the mix will be resistant to premature failure in the field. Most specifications involve the volumetric properties of the mixture. During production, these volumetric properties are used to monitor production for quality control and quality assurance purposes. In Arkansas, the volumetric properties used during production are air voids, binder content, and voids in the mineral aggregate (VMA). These properties play a significant role in the rutting characteristics of asphalt pavements. The ability to alter such properties in order to produce a desired outcome is perhaps one of the most useful tools a mix designer can possess.

BACKGROUND

Traditional mix design methods were based upon the premise that if the volumetric properties met a set of specifications, the mix would perform well. However, very little testing was done to validate these claims in terms of performance. In the 1990s, the Superpave (*Su*perior *Per*forming Asphalt *Pave*ments) mix design procedure gained recognition by many state agencies. In the Superpave mix design protocol, a combination of aggregates, binder, and voids is determined based on the expected climatic conditions and expected traffic levels for the pavement. Superpave combines the volumetric specifications of traditional methods with a more contemporary focus on performance. New equipment was developed specifically for this design method with the expressed purpose of obtaining a measure of predicted pavement performance. By considering material and mixture properties that directly influence performance, the mixture should possess a strong aggregate skeleton and void structure that will resist failure by permanent deformation, and binder characteristics that will help to prevent fatigue and low temperature cracking.

Mixture Properties

The components of a mixture are integral to its performance. In order to improve HMA pavement quality, it is important to understand the relationships of these components to performance.

Air Voids

Air voids are known to affect pavement rutting performance. In general, a mixture is most stable at an air void content between 3 and 7 percent. Below 3 percent and above 7 percent, the likelihood of rutting increases. *(2)* Very low air void contents indicate that the mixture has experienced premature densification either during construction or under traffic loads, increasing the probability of instability and shear deformation within the mix. At very high air void contents, the mix is more permeable to external detrimental factors such as air and water. Exposure to air promotes oxidation of the asphalt binder, which leads to weak, brittle pavements. The presence of water increases the ability of the mix to strip, meaning that the asphalt cement physically separates from the mineral aggregate surfaces. In the early stages, stripping failure may be seen as "fat spots", or resemble rutting failures.

During design, asphalt mixes are designed at an air void content that will produce a tight, stable mix, while also allowing for some variation during construction. In Arkansas, mixes are currently designed at 4.0 and 4.5 percent air voids (depending on binder grade), with an acceptable field tolerance of 3 to 5 percent. *(3)*

Binder Content

Binder content is also known to affect the rutting potential of an asphalt mixture. The asphalt binder is the "glue" used to bond the aggregate structure, or skeleton, together. During compaction, the binder acts as a lubricant, and aids in consolidation, thereby reducing the spaces between aggregate particles. When the binder content is too high, it fills the void spaces and forces the aggregate particles to separate, which reduces the stone-to-stone contact. As a result, the rutting resistance is also reduced. Alternatively, a binder content that is too low can leave the aggregate particles thinly coated, reducing the level of adhesion and making the HMA susceptible to stripping and raveling. *(4)*

<u>VMA</u>

Increasing binder content increases mixture durability, but also increases the rutting potential of a mix. Thus, appropriate binder contents must be selected in order to reach a balance of acceptable performance with respect to multiple failure modes. Voids in the mineral aggregate (VMA) is a property that can help a designer to achieve this balance, though its relationship to performance has not been clearly defined. VMA is the portion of the volume in the compacted asphalt mixture that is not occupied by aggregate or absorbed binder. By definition, VMA includes the effective volume of asphalt binder plus the volume of air, and is expressed as a percent of total volume. *(5)* It is calculated according to Equation 1.

$$VMA = 100 - \left(\frac{Gmb * Ps}{Gsb} \right) \qquad \textit{Equation 1}$$

where: VMA = voids in the mineral aggregate

Gmb = bulk specific gravity of the compacted HMA sample

Ps = percent stone

Gsb = bulk specific gravity of the aggregate blend

The relationship between VMA and binder content is a critical part of HMA mixture design. As binder content increases, VMA decreases to a minimum value. If the binder content increases past the point of minimum VMA, the air void spaces become displaced by asphalt binder films. As these film thicknesses increase, the aggregate particles are forced apart and the VMA volume increases. This relationship is illustrated in Figure 1. The optimum binder content for a mixture is that which corresponds with the minimum VMA. Asphalt mixes designed with binder contents less than that which generates minimum VMA are said to be designed "on the dry side of the VMA curve". Such mixes have smaller film thickness and are susceptible to durability problems in the field. Mixes designed with binder contents greater than that which generates the minimum VMA are said to be designed "on the wet side of the VMA curve", which is also undesirable. Excessive binder causes these mixes to be prone to rutting, bleeding, and flushing.

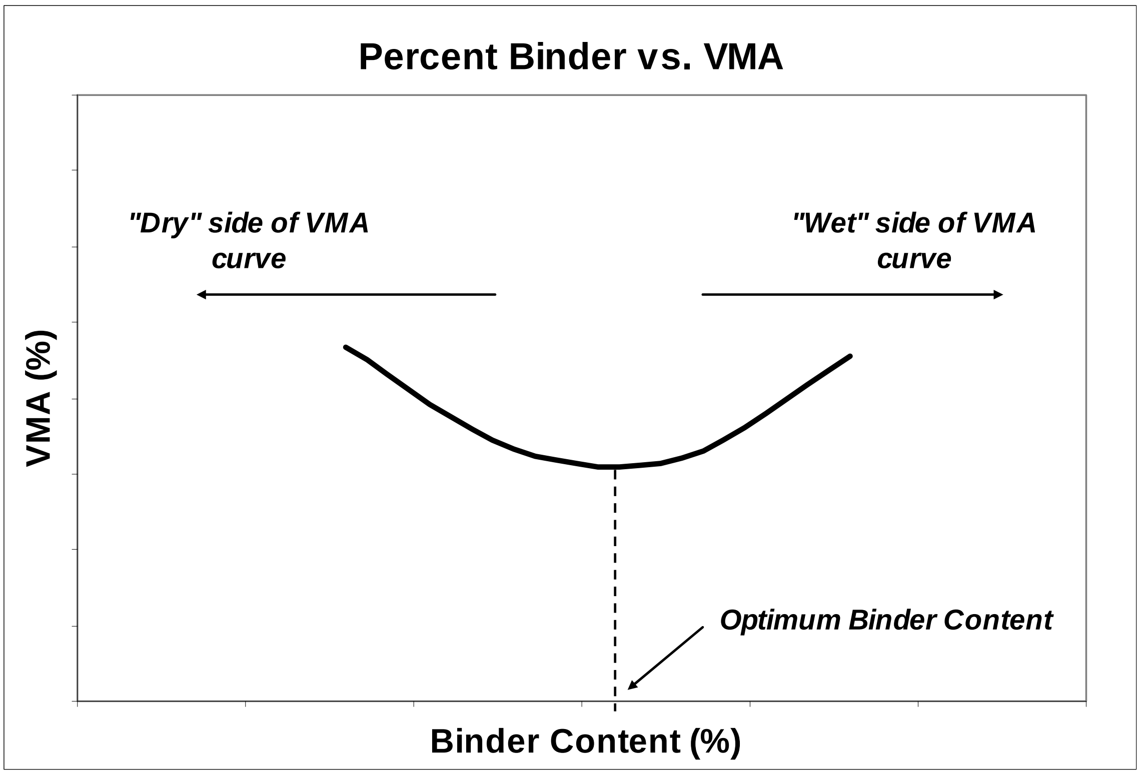

Figure 1. Typical relationship of VMA and binder content

Early studies of VMA were performed in the 1950s by McLeod, who defined VMA in its current form. He suggested that minimum VMA criteria should be used during the mix design process and based on nominal maximum aggregate size (NMAS).

McLeod's definition of VMA was adopted by the Asphalt institute in 1962, and it has remained unchanged since that time. *(6)*

Superpave mixture design procedures incorporated VMA criteria as a means to ensure that the mixture contains adequate binder as well as a proper air void content. By meeting minimum requirements for VMA, it is believed that bleeding and rutting will be minimized, and mix durability will be provided. *(7)* One notable problem with the Superpave mix design protocol relates to the VMA of coarse-graded mixes. Although Superpave procedures recommend the use of coarse-graded mixtures, such mixtures have less surface area and typically exhibit lower VMA. Thus, some coarse-graded mixes do not meet the minimum design criteria though they may demonstrate acceptable performance. *(8)*

Several aggregate properties, such as gradation, texture, and shape, are known to affect VMA. *(9)* Aggregates must be combined in such a way that adequate space will remain between the particles, allowing for air and sufficient binder film thickness. Changing the gradation, or particle size distribution, will affect the space available within the aggregate skeleton. For instance, a gap-graded aggregate blend does not pack as tightly as a dense-graded blend, thereby increasing VMA. The texture of the aggregate also affects the manner in which the particles pack together. Friction causes rough aggregate textures to be more resistant to compaction efforts. A blend made up of crushed particles will generate more friction, and therefore more VMA, than a non-crushed aggregate. Aggregate shape plays an important role in the VMA of a mixture. Block-shaped particles resist compaction in the gyratory compactor more readily than thin, flat particles. Therefore, cubical-shaped aggregates tend to increase VMA in a mix.

Although it is generally accepted that VMA and pavement performance are related, the specific nature of this relationship has yet to be defined, and thus has been a great topic of debate among researchers. *(7, 10)*

Film Thickness

Film thickness is a property related to VMA that describes the thickness of the binder coatings on the individual aggregate particles. Adequate film thickness is necessary to provide mixture durability and to limit moisture susceptibility. Coatings that are too thin can allow air and water to permeate the sample, and may not provide enough cohesion to the mix. *(11)* Because of its dependency on aggregate surface area, this property is difficult to measure. The most common method used to determine film thickness is outlined by the Asphalt Institute in MS-2. *(12)* It is calculated by dividing the effective volume of asphalt binder by total estimated surface area of the aggregate particles. It has been suggested that a minimum film thickness may be a more appropriate criteria for durability concerns than VMA. *(13)*

VFA

Voids filled with asphalt (VFA) is a property relating VMA and air voids. It represents the percent of VMA volume that is occupied by the effective binder, and is calculated according to Equation 2. Some mix design procedures use VFA as a specification requirement, and others do not. It seems reasonable that if VMA and air voids are both restricted, then a restriction on VFA is thereby implied.

$$VFA = \left(\frac{VMA - P_{air}}{VMA} \right) * 100$$ *Equation 2*

where: VFA = voids filled with asphalt
VMA = voids in the mineral aggregate
P_{air} = percent air voids

Dust Proportion

Dust proportion is the ratio of the percent of aggregate passing the #200 sieve to the effective binder content expressed as a percentage. Because the material passing the #200 sieve is so small, it combines with the binder and can make a major contribution to the mix cohesion. In general, this material has the ability to stiffen the binder, although different types of materials will display varying degrees of this effect. Thus, the material passing the #200 sieve, as well as dust proportion, can affect the rutting potential of a mix. *(14)*

Aggregate Properties

It has long been recognized that aggregate gradation, shape, texture, fine aggregate angularity, and dust proportion affect the packing characteristics of the aggregate in an asphalt mixture. Cubical, rough-textured aggregates tend to produce greater particle interlock, forming a strong aggregate skeleton for the mix. *(12, 15)*

Aggregate characteristics relate not only to the volumetric properties of a mix, but also to its performance. For this reason, Superpave mix design procedures incorporate the use of source and consensus properties of aggregate. These requirements provide additional assurance that a mixture will perform adequately.

Source Properties

Source properties of aggregates are believed to be critical to pavement performance, but are "source-specific". Thus, critical values for these properties are typically established by local agencies, and vary based upon the source. These properties include toughness, soundness, and deleterious materials.

Toughness is a measure of the resistance of coarse aggregate to abrasion and mechanical breakdown that can occur in the field during the handling and construction of pavement materials. It is typically measured according to the Los Angeles Abrasion test (AASHTO T 96), but the Micro-Deval method (AASHTO T 327) is gaining popularity for the measurement of this property. *(16)* The current AHTD requirement is a maximum of 40 percent loss as determined by AASHTO T 96. *(3)*

Soundness tests estimate the resistance of an aggregate to degradation due to environmental and weathering effects. This property is regulated as a maximum percent loss, and is measured by the sodium or magnesium sulfate soundness test (AASHTO T 104). *(16)* The AHTD specification currently requires that aggregates have no more than 12 percent loss. *(3)*

Deleterious materials are defined as contaminants to the aggregate source such as clay lumps, shale, and friable particles. Procedures for determining the percent of deleterious materials are detailed in methods AASHTO T 112 and AHTD 302. *(16, 17)*

Consensus Properties

Consensus properties are those which are believed to be critical to HMA performance, and the specification limits are not dependent on aggregate source. They are intended to be determined for the aggregate blend, and more stringent requirements are often specified for mixes that are to be used in high traffic situations. The consensus properties are coarse aggregate angularity, fine aggregate angularity, flat and elongated particles, and clay content. *(5)*

Coarse aggregate angularity is usually described as the percentage of crushed particles in an aggregate blend. Since crushed aggregates generate greater internal friction in a mixture, this requirement helps to minimize the use of smooth and rounded aggregates, which are known to reduce mixture stability.

Fine aggregate angularity, detailed in AASHTO T 304, is used to ensure a high degree of internal friction for fine aggregate, and aids in rutting resistance. *(5, 12, 16, 18)* Specifications for this property aid in limiting the use of natural sands, which are known to create "tender" mixes.

Flat and elongated particles are undesirable because they have a tendency to break under construction and traffic loadings. This test is performed on coarse aggregate according to test method ASTM D 4791. *(19)*

Clay content is measured according to the sand equivalent method as described in ASTM D 2419. *(19)* The clay content for an aggregate blend must be limited because clay particles can prevent asphalt binder from adhering properly to aggregate surfaces.

Gradation

The structure of an aggregate blend greatly affects mixture performance. Quantifying this relationship, however, is quite a difficult task. Although many recommendations are available for adjusting the gradation of an aggregate blend in order to create the desired effect on VMA and air voids, these suggestions are largely based on experience with the materials being used. *(12)*

A great deal of research intended to correlate VMA and aggregate gradation focused on the relationship between the aggregate gradation and the Maximum Density Line (MDL). In mix design, the MDL is defined as a straight line drawn from the origin to the maximum aggregate size on the 0.45-power gradation chart, as shown in Figure 2. The MDL represents the theoretical aggregate gradation that would produce the tightest packing characteristics, thus producing the lowest VMA. Aggregate gradations that plot above the MDL are considered to be "fine-graded" while those that plot below the MDL are considered to be "coarse-graded". *(5)* In general, it has been demonstrated that aggregate gradations that closely follow the MDL have lower VMA than those that plot further away from the MDL.

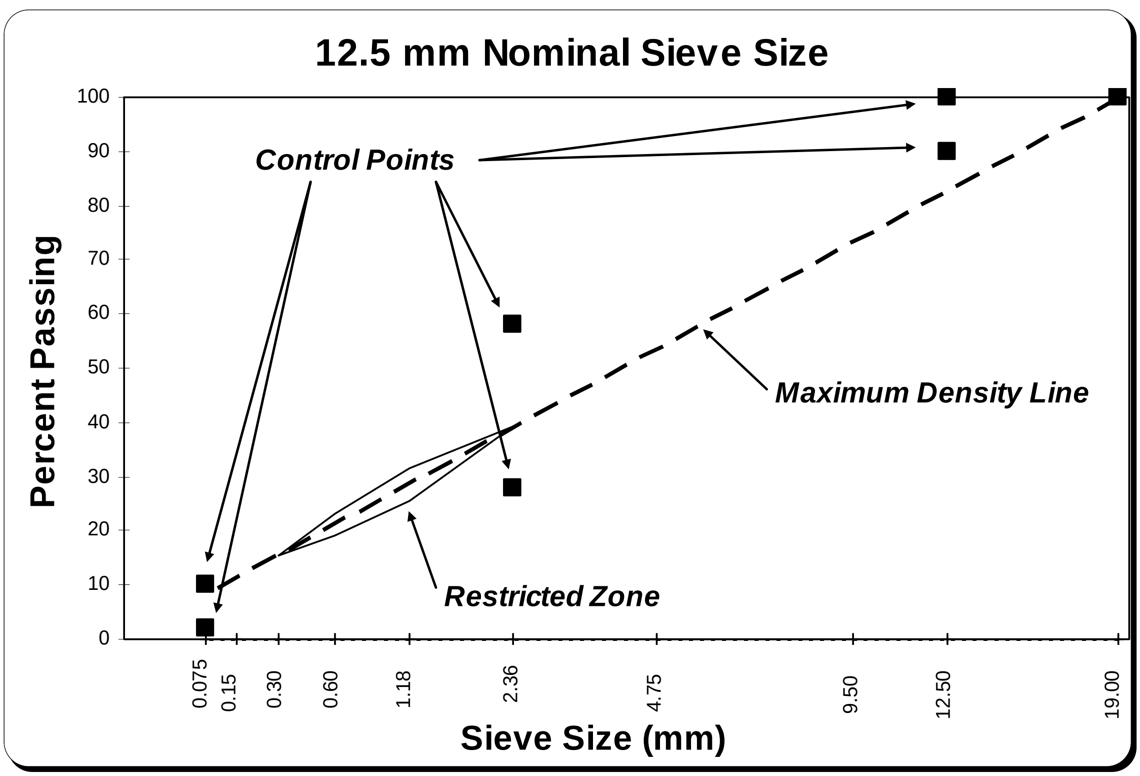

Figure 2. Superpave gradation specification for 12.5mm mixture

In the original Superpave mix design procedure, the gradation of the aggregate blend was required to pass between control points at the NMAS, an intermediate size (#8 sieve), and the smallest size (#200 sieve), while avoiding an area called the restricted zone. This concept is given in Figure 2. The intention of the restricted zone was to avoid mixtures that have a high proportion of fine sand relative to total sand, and to prevent a gradation from following the MDL in the fine aggregate sieves. Gradations that closely follow the MDL often have inadequate VMA to allow room for sufficient asphalt binder, which is necessary for the durability of the mix. Thus, the Asphalt Institute recommends that in order to increase VMA, aggregate gradations should not plot near the MDL. *(12)*

Superpave design procedures recommended that gradations avoid the restricted zone, preferably passing below. However this was not a requirement. *(5)* Several highway agencies have successfully used gradations that pass above the restricted zone (ARZ), below the restricted zone (BRZ), and through the restricted zone (TRZ). Thus, most current mix design procedures have eliminated the use of a restricted zone. While some states allow only ARZ or BRZ mix designs, the majority of states accept both coarse- and fine-graded Superpave mix designs – provided they meet volumetric property criteria. *(14, 20, 21)*

Pavement Performance

In order to compare mixture characteristics to pavement performance, an appropriate laboratory performance test method must be chosen. The Superpave procedure originally intended for performance testing to be incorporated into the design procedure for mixes serving high traffic volumes. However, the devices developed for those tests have come under great scrutiny and have not been widely accepted. Proof tests, specifically wheel-tracking tests, have become increasingly popular as one of the most acceptable options for measuring rutting susceptibility.

Wheel-Tracking Tests

All wheel-tracking tests operate under the same general premise – a loaded wheel applies a dynamic load to the sample in order to simulate rutting. Depressions, or ruts, are created in the sample, and the magnitudes of the ruts are measured and analyzed.

ERSA

The Evaluator of Rutting and Stripping in Asphalt (ERSA), shown in Figure 3, is a wheel-tracking device that was developed at the University of Arkansas in the 1990s. It is based on the German Hamburg wheel-tracking device, but also has the capability of performing a loaded wheel test similar to that of the Asphalt Pavement Analyzer (APA). In the standard ERSA testing configuration, two separate samples can be tested at one time while subjected to a steel wheel loaded at 132 lb and submerged at a temperature of 50 C. *(22)* A complete test lasts 20,000 cycles, which takes just over 18 hours. A computer-based data acquisition system employs linear variable differential transducers (LVDTs) to collect vertical deformation measurements at 75 locations along the sample profile. Average rut depths are computed so that edge effects are eliminated.

Figure 3. Evaluator of Rutting and Stripping in Asphalt (ERSA)

Results from an ERSA test (shown graphically in Figure 4) include initial consolidation, rut depth, rutting slope, stripping slope, and stripping inflection point. A typical sample will experience some initial consolidation, or post-compaction, then deform at a rate known as the creep slope, or rutting slope. The rutting slope relates to rutting from plastic flow. It is defined as the inverse of the rate of deformation in the linear region of the deformation curve after initial consolidation effects have ended and before the onset of stripping. In other words, it is the number of cycles (after the initial consolidation) required to create a 1-mm rut. Thus, larger values of this variable are desirable. If the sample is susceptible to moisture damage, it will strip, which means that the asphalt films have separated from the aggregate surfaces in the presence of moisture. When stripping occurs, the sample begins to deteriorate at a higher rate. The stripping slope is the inverse of the rate of deformation in the linear region of the deformation curve, after stripping begins and until the end of the test. It is the number of cycles required to create a 1-mm impression from stripping. The stripping slope is related to the severity of moisture damage. The stripping inflection point is the number of cycles at the intersection of the rutting slope and the stripping slope. It is the point where rutting begins to be dominated by moisture damage, and is related to the resistance of the HMA to moisture damage. *(22)*

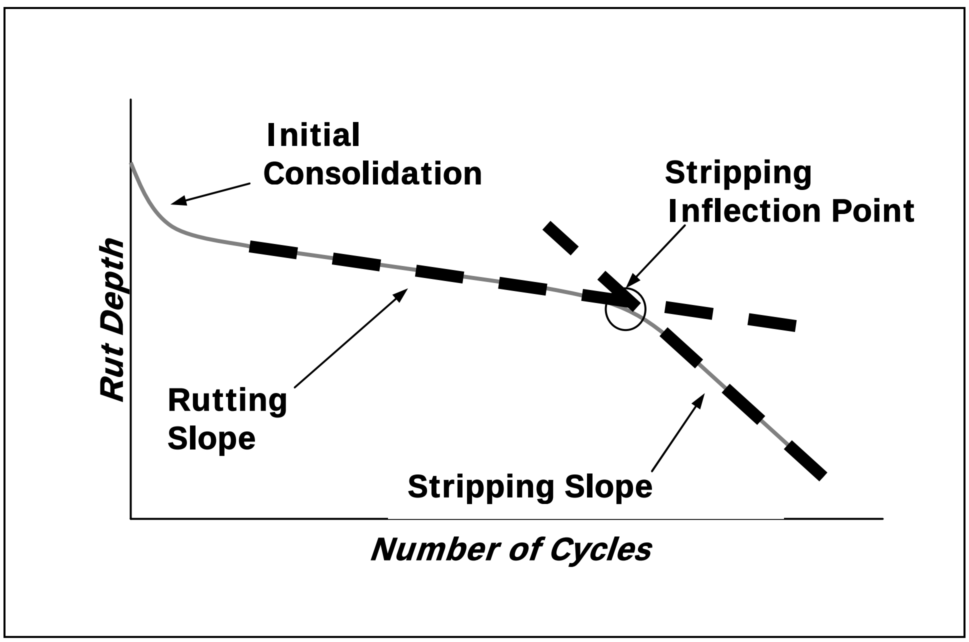

Figure 4. Schematic of Typical ERSA Data

In 1998, a round robin study was conducted by the Texas Department of Transportation to assess the repeatability of testing with the Hamburg and other similar wheel-tracking devices. The University of Arkansas participated in this study. The repeatability of ERSA and similar devices was determined to be acceptable. *(23)*

<u>RAWT</u>

The Rotary Asphalt Wheel Tester (RAWT), Model AFW1A, was developed by the Pine Instrument Company in 2003, and the University of Arkansas was among the first to use the device. The RAWT, shown in Figure 5, was developed specifically for testing the rutting and stripping susceptibility of individual gyratory-compacted specimens.

Figure 5. Pine Rotary Asphalt Wheel Tester – AFW1A

Most conventional wheel-tracking tests apply a load using a single wheel traveling lengthwise along the flat surface of the sample. However, the loading mechanism of the RAWT is unique in that the sample is loaded about the circumference of the specimen by three Hamburg-style wheels, and the specimen rotates continuously throughout the duration of the test. The RAWT testing configuration is illustrated in Figure 6.

Figure 6. RAWT testing configuration

In a typical test, a 75-lb load is applied to the circumference of the submerged specimen for up to 30,000 cycles, and the rut depth is recorded once every 30 cycles. A cycle is defined as one complete revolution of the specimen, which results in three applications of the testing load. The loading rate is adjustable in the range of 60 to 90 cycles per minute (CPM), but the manufacturer recommends a rate of 70 CPM. The water temperature is adjustable between 20 C and 60 C, and a one-hour preconditioning time is recommended to allow the water temperature to regulate and the sample to become saturated. The length of the test is adjustable from 300 to 30,000 cycles, however, the test will automatically terminate if the sample reaches a maximum rut depth or if specimen deterioration causes the wheels to no longer track smoothly. The maximum rut depth is selected by the user to a value within the range of 1 mm (0.04 in.) and 16 mm (0.63 in.). At the end of the test, the rut depth data is plotted versus the number of cycles. While stripping can be detected by the RAWT, resulting data graphs generally more curved in shape than those from ERSA, making it difficult to consistently determine stripping characteristics. A typical RAWT graph is shown in Figure 7. *(24)*

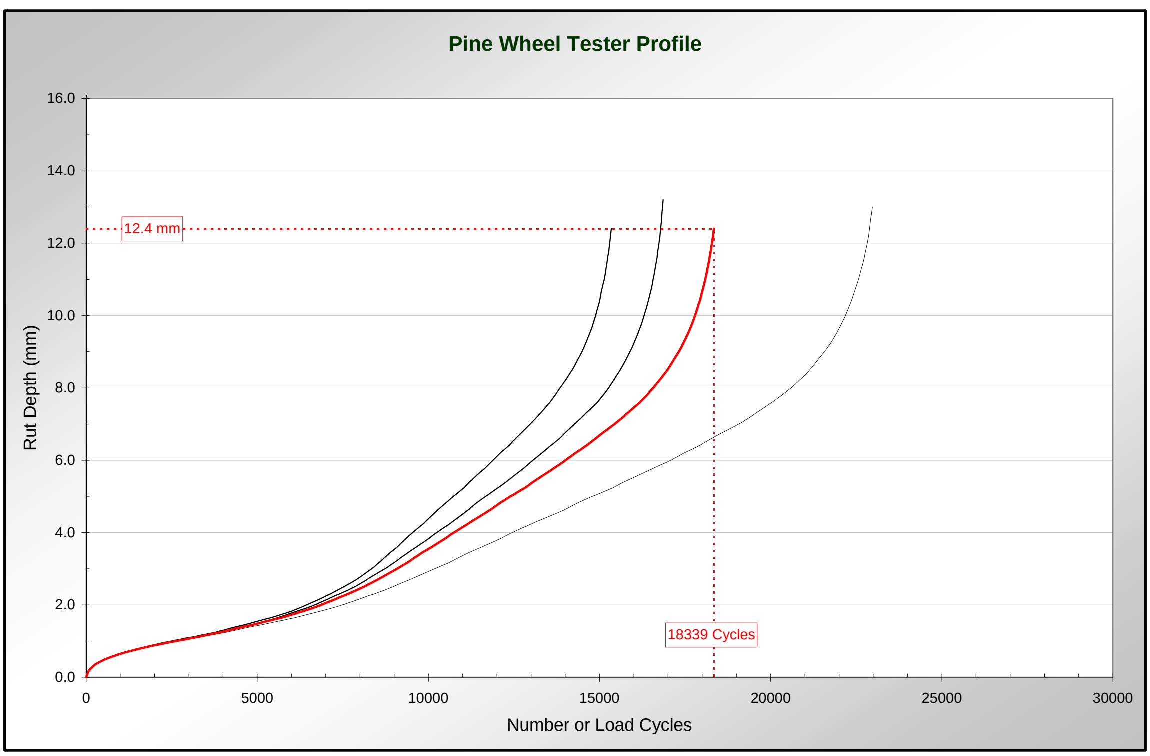

Figure 7. Typical RAWT Data

LITERATURE REVIEW

Although several volumetric property requirements are specified for mix design in order to assure quality, the relationship between VMA and performance is probably the least intuitive. The confounding effects of other quantities are inherent in the property of VMA. The concepts of VMA and mixture properties have been investigated for over one hundred years in order to identify and quantify HMA mixture characteristics and to improve pavement performance, yet there is still not a clear understanding of the relationship between VMA and rutting.

History of VMA

Early 1900s

Since the early 1900s, it has been recognized that a hot-mix asphalt (HMA) mixture must possess an appropriate combination of aggregates, binder, and air voids in order to exhibit adequate performance and durability. VMA is one mixture characteristic that helps to quantify this combination. One of the earliest declarations of the importance of VMA was made by F.J. Warren in his 1901 application for a patent on asphalt concrete. He believed that the upper limit of VMA should be 15 percent and also stressed the importance of minimizing VMA as a means to ensure that the mixture would have good stability. *(8)*

In 1907, Cliff Richardson emphasized that the surface area of the aggregate in the asphalt mixture was important because it affected the film thickness on the aggregate particles. Understanding the concept of VMA and film thickness, he recognized that an increase in surface area resulting from an increase in the use of fine aggregates would require the use of additional asphalt cement. *(8)*

The work of Warren and Richardson led to what are now considered to be traditional methods of mix design. Perhaps the most notable 'traditional' mix design methods were the Marshall and Hveem methods. However, neither method incorporated VMA as an original specification requirement. In developing his mix design protocol, Francis Hveem believed that it was not appropriate to determine the mix design properties based solely on the volume of voids. *(8)* Early Marshall mix design did not specify a range for VMA because Marshall believed that the many types and gradations of aggregate made it an unrealistic requirement. *(15)*

1950s

VMA gained popularity as a mix design parameter during the 1950s, mainly due to the work of Dr. Norman W. McLeod. In 1956, he suggested that the design and analysis of asphalt mixtures should be based on volume rather than weight. He established volumetric mix design criteria based on specimens compacted to 75 blows with a Marshall hammer, an aggregate bulk specific gravity of 2.65, and an asphalt specific gravity of 1.01. Asphalt absorption was not considered at this time. He suggested that VMA should be a minimum of 15 percent and air voids should be between three and five percent. Both parameters were expressed as percent by volume of a compacted specimen. The VMA and air void contents suggested by McCleod automatically set the minimum asphalt content to 10 percent by volume, or 4.5 percent by weight. *(25)* McLeod believed that 4.5 percent asphalt binder (which was greater than that typically used at the time) would provide adequate mixture durability. *(8)*

McLeod identified several factors that significantly impact VMA, including:

- Moving the aggregate gradation curve away from the maximum density line should increase VMA.
- Adding fine aggregate should increase the void space between the coarse aggregate and thereby increase VMA.
- Significantly reducing the fine aggregate in a mix should create an "open" gradation and thus increase VMA.
- Adding mineral filler should significantly decrease VMA.

In 1957, Lefebvre recognized that VMA was a property that should be considered during mix design. He realized that the suggestions of 15 percent VMA and three to five percent air voids was difficult to achieve in practice. He studied the effects of coarse aggregate, fine aggregate, fine sand, and mineral filler on the performance of a mixture, and found that fine aggregate had the largest influence on the VMA and stability of an asphalt mixture. *(8, 15)* He suggested that, in order to achieve the recommended minimum VMA of 15 percent, a mixture should have a high percentage of angular fine aggregate and a small percentage of fine sand. He also determined that coarse aggregate provided stability, but created difficulties in achieving the minimum VMA. *(8)*

In 1959, McLeod added to his previous research on volumetric properties of asphalt mixtures. He related critical minimum VMA and nominal maximum aggregate size for dense-graded mixtures. He stressed the importance of using aggregate bulk specific gravity to calculate VMA and air voids. He also took into consideration the absorption of the asphalt binder in the volumetric analysis of a mix design. *(8, 26)*

Hudson and Davis developed a method for computing the VMA from the aggregate gradation. During this study, several factors were found to significantly influence VMA. They were particle arrangement, degree of compaction, range of size between coarse and fine aggregates, the relationship between the percentage passing adjacent sieves, and aggregate shape. *(8)*

Other research performed in the 1950s led to the conclusion that because the tests performed in order to calculate VMA were highly variable, other laboratory tests should be developed in order to more directly predict the durability of a trial mixture. Unfortunately, no other method was found to be acceptable at that time, and thus VMA remained the best method for determining the design binder content that would produce acceptable mixture durability. *(15)*

Following the significant research done in the 1950s, the Asphalt Institute incorporated McLeod's recommendation for VMA as a required mixture design parameter in 1962. *(27)* The VMA requirement replaced the VFA specification which had been used previously. A VFA requirement was not used again until 1994 when the Asphalt Institute re-introduced it, using it in addition to the requirement for VMA. It is interesting to note that although McLeod's minimum VMA and asphalt content recommendations have been used for many years, they were originally made without any performance data to prove them. *(25)*

Recent Studies

Despite the history of difficulty achieving minimum design values, the VMA requirement was carried over from the traditional design methods to the Superpave mix design method. The Superpave method utilizes the volumetric property requirements similar to that of traditional mix design procedures, but also incorporates an emphasis on specific properties of the aggregate and binder that directly influence performance.

The VMA requirement in Superpave restricts both the asphalt content and the aggregate gradation of a mixture. *(8)* Recently, mix designers and researchers have repeatedly noted that the restrictive VMA requirement causes the rejection of economical mix designs that meet all of the required performance properties. *(8, 10, 25, 26, 27)*

It has been shown that for the same design air void content, coarse- and fine-graded mixtures meeting the same VMA requirement will have different film thickness. Because of greater aggregate surface area, the fine-graded mixture will require more binder to create the same film thickness as a coarse-graded mixture. Thus, to provide the same level of durability, the VMA requirement for a fine-grader mixture should be greater than that for a coarse-graded mixture of the same NMAS. This belief is based on the premise that film thickness is more directly related to mixture durability than is VMA.

Factors Affecting VMA

Many studies have been performed to try and determine the specific influence of VMA on rutting performance. However, since VMA incorporates several factors relating to the mixture components, it is first necessary to investigate the binder and aggregate properties that affect VMA.

<u>Binder</u>

Adding binder to an asphalt mixture can either increase or decrease the VMA, depending on whether the binder content is on the "dry" or "wet" side of the VMA curve. HMA mixes should be designed at the minimum VMA. Thus, simply changing the binder content is not an appropriate method for changing the VMA of a mix design.

Instead, the combination of aggregates should be adjusted in order to effect a desired change in VMA characteristics. Difficulties in selecting an aggregate gradation that will result in meeting the VMA requirement is often the most time consuming part of the mix design process.

Aggregates

The current VMA requirements included in the Superpave mixture design specification are based solely upon NMAS, yet it is recognized that additional aggregate properties such as gradation, shape, texture, and fine aggregate angularity affect the packing characteristics of the aggregate in an asphalt mixture.

Aschenbrener and MacKean studied the relationship between gradation and VMA. *(28)* In part of their research, they investigated alternative definitions for the maximum density line. They drew a series of MDLs through the gradations of mix designs with known properties to find the definition for MDL that could be used to best correlate VMA to gradation. They found that VMA correlated best to the distances between the #8 and #200 sieves and a MDL drawn from the origin to the actual percent passing the NMAS. They concluded that gradation certainly affects VMA, but were unable to develop a practical statistical correlation between the two.

Huber and Shuler conducted similar research in an attempt to relate VMA to the sum of the distances between the MDL and the actual gradation. *(29)* They found that the correlation was poor when the sum was small (i.e., the gradation was close to the MDL), but good when the sum was large (i.e., the gradation was not close to the MDL). They concluded that when the gradation plotted close to the MDL, factors other than gradation had a greater impact on the resulting VMA. Ultimately, they recommended that the MDL could be used by mix designers as a general method for affecting VMA, but again no clear relationship was defined.

Aggregate angularity is a consensus property specified by Superpave as a method for creating adequate internal friction of the aggregate particles, which increases the rutting resistance of a mix. Angularity has also been identified as a property that affects VMA. *(5)* Because natural sands have been shown to create stability and durability problems, the Asphalt Institute recommends the use of angular aggregate. *(12)*

Aschenbrener and MacKean investigated the effects of angularity on VMA. Angular aggregates yield mixtures with higher VMA because the rough texture of the aggregate creates more friction between the aggregate particles, thus reducing how tightly the particles will pack together. They discovered that coarse-graded mixtures were more sensitive to the addition of fine aggregate with high angularity than were fine-graded mixtures. *(28)*

Another study investigating the effects of VMA and aggregate properties on pavement performance determined that the relationship between VMA and fine aggregate angularity (FAA) was found to be poor. *(30)* While high FAA values do not necessarily produce high VMA in mixes, there was a general trend of increasing VMA with increasing FAA. It was also suggested that the potential of mixes failing due to excessive VMA was increased with high FAA values.

Aggregate shape also influences VMA. Aggregates that are cubical in shape do not compact as tightly as flat and/or elongated particles. Increasing the use of cubical particles in blend gradations will result in mixtures with higher VMA. *(9)*

A research project was conducted at Iowa State University to relate aggregate gradation and shape characteristics to “critical” VMA. *(26)* They used the Nottingham Asphalt Tester to perform triaxial tests on a variety of mixes. They defined “critical” VMA as the VMA at the point in the test where the mixtures became plastic. They showed that the “critical” VMA did follow the trend of Superpave criteria in that mixes of larger NMAS require less VMA. However, the “critical” VMA for each NMAS was determined to be less than that required by Superpave procedures. They also showed that factors other than NMAS affected the minimum required VMA for a mixture. Fineness modulus, crushed coarse aggregate, and fine aggregate angularity were better indicators of the “critical” VMA than NMAS. *(15, 26)* Overall, they concluded that Superpave VMA criteria could exclude mixtures that perform satisfactorily.

Because aggregates are a natural resource, each source is likely to be unique in some way. Research has been conducted in order to investigate the effects of aggregate source and type on VMA. In one such study, crushed limestone, crushed basalt, and crushed granite were used to develop five difference aggregate gradations. Researchers concluded that aggregates with higher specific gravities have higher VMA. *(4)* This is reasonable since the definition of VMA is based directly on the bulk specific gravity of the aggregate blend. This conclusion brings to light the fact that some variation in adequate VMA should be expected simply because not all aggregate sources are the same.

Aggregates and Performance

In 2002, the National Center for Asphalt Technology (NCAT) reported on a research project that investigated the relationship between rutting resistance and aggregate gradation. *(14)* They tested 14 mixtures, seven having gradations above the restricted zone (ARZ) and seven having gradations below the restricted zone (BRZ). The mixes were designed according to Superpave criteria and had a NMAS of 9.5mm and 19.0mm. Three tests were used to quantify the rutting potential: the Asphalt Pavement Analyzer (APA), the Superpave Shear Tester (SST), and the repeated load confined creep test (RLCC). The 9.5mm granite coarse aggregate/limestone fine aggregate combinations exhibited the smallest rut depths. Interestingly, these two mixes actually failed the Superpave VMA criteria. The highest rut depths were demonstrated by the 19.0mm crushed gravel coarse aggregate/granite fine aggregate combinations. Based on rut depth magnitudes, there appeared to be little difference in the ARZ and BRZ mixes. Statistically, the BRZ and ARZ gradations performed similarly for all three performance tests. Practically, the BRZ gradations had lower rutting potential for some aggregate combinations, and the ARZ gradations had lower rutting potential for other aggregate combinations. The primary conclusion of the study was that both ARZ and BRZ gradations can be designed to be rut-resistant, as long as some type of rut test is used to prove the rutting resistance of the mixture.

In another study, researchers sought to evaluate the impact of aggregate gradation on permanent deformation. *(31)* Two aggregate sources, four aggregate gradations, and two binder sources were used to design mixes according to the Hveem method. Rutting potential was measured using the standard and repeated load triaxial tests. The rutting potential of the coarser mixes was not influenced as much by binder type as their finer counterparts. Also, the performance of the various gradation types was dependent upon aggregate source. One source had the best rutting resistance with a fine gradation, and the other with a coarse gradation.

Yet another study was performed to study the effects of aggregate gradation, aggregate type, and NMAS on mixture resistance to permanent deformation. *(32)* The Superpave design method was employed to create 12.5mm and 19.0mm NMAS mixes ARZ, TRZ, and BRZ for three aggregate types, and the mixes were tested for rutting susceptibility in the APA. Granite mixes exhibited less rutting than the gravel and limestone mixes, indicating that rutting performance is affected by aggregate source. With respect to gradation, results varied by source. For the granite and limestone sources, the BRZ mixes showed the highest amount of rutting, the TRZ mixes showed the lowest amount of rutting, and the ARZ mixes showed an intermediate amount of rutting. For the gravel source, the BRZ mixes showed the least rut depths, the ARZ mixes had the greatest rut depths, and the TRZ mixes had rut depths similar (but slightly higher than) the BRZ mixes. Statistically, the effect of gradation was significant for granite and limestone mixes, but not for the gravel mixes. When analyzed separately, the ARZ and TRZ rut depths were similar for all but one mix.

A similar study was performed using Purdue University's APT, PURWheel, and triaxial testing. *(21)* Limestone sand, 12.5mm limestone, and 19.0mm limestone mixes were designed with ARZ, TRZ, and BRZ gradations. In all three performance tests, the ARZ gradations performed better than BRZ gradations. The ARZ mixes were denser than their BRZ counterparts, and also had lower asphalt contents. Similar results were discussed in another report, and additional conclusions were made regarding asphalt binder content. *(33)* When shear strength was plotted as a function of asphalt content, a transition from a stable condition to an unstable condition was evident, typically occurring at or below the optimum asphalt content. For 65% of the mixtures evaluated, the asphalt content corresponding to peak shear strength was approximately 0.5% less than the optimum determined by the Superpave mix design process.

In an effort to aid mix designers in meeting Superpave's minimum VMA criteria, 128 mixtures from the Asphalt Institute's extensive database of Superpave mixture designs were analyzed with respect to gradation and performance. Performance, as measured by frequency sweep at constant height (FSCH) and repeated shear at constant height (RSCH) tests, was less for BRZ gradations than for ARZ gradations. Thus, the previous assumption that ARZ mixtures possessed weaker aggregate structures was unfounded. This conclusion has been confirmed in numerous studies, and was perhaps most convincing when full-scale performance tests conducted at WesTrack clearly indicated reduced performance for mixes designed with BRZ gradations. *(20, 34)* Although some research studies have concluded that the performance of BRZ gradations is dependent upon aggregate type *(20)*, it has been established that BRZ mixes exhibit more variability in performance, and may thus be more affected by construction variability. *(33)*

Other factors believed to affect a pavement's performance include aggregate roughness, aggregate size and shape, fineness modulus, and angularity. One researcher reported that aggregate roughness was the most important characteristic, while aggregate size and shape were less important than generally believed. *(15)*

VMA and Performance

The value of VMA is an indication of the potential durability of an asphalt mixture, and has been shown to affect mixture performance. *(26)* One philosophy regarding VMA and performance is that mixtures possessing high VMA are more advantageous than those with low VMA because they exhibit a lower stiffness modulus at lower temperatures, which reduces reflection and thermal cracking. Higher levels of VMA have also been associated with increased rutting resistance. Additionally, high VMA mixes are also more desirable because they are less affected by variations in the asphalt binder and dust content during field production. *(8)* However, there is strong sentiment that the current minimum VMA criteria may be too stringent for some coarse-graded mixtures. Several studies have been performed to relate VMA and aggregate properties to performance.

One such study focused specifically on the relationship between VMA requirements and aggregate type. It was found that the minimum VMA required to provide protection against rutting failures was, in fact, related to the type of aggregate being used in the mixture. They found that for granite and limestone mixtures, an increase in VMA caused an increase in rutting. However, for gravel mixtures, an increase in VMA caused a decrease in rutting. *(32, 35)*

Another study analyzed the effect of gradation and VMA on pavement performance, paying particular attention to the rate of binder age-hardening. It was determined that fine-graded mixtures were generally more susceptible to binder age-hardening than coarse-graded mixtures. Also, fine-graded mixtures with low VMA and low film thickness were found to have a reduction in performance. At lower levels of VMA, these mixtures exhibited poor rutting performance. Coarse-graded mixtures with low VMA did not exhibit the same reduction in performance. For coarse-graded mixes, gradation, film thickness, and void structure played a larger role in indicating the resistance to binder age-hardening, fracture, and rutting. The ultimate conclusion of the study was that low VMA was detrimental to the rutting performance of fine-graded mixtures, but not to that of the coarse-graded mixtures. Thus, each type of gradation should be considered separately when determining the appropriate design criteria for volumetric properties. *(27)*

Further research on this topic reinforced the earlier findings that fine-graded mixtures with high VMA had higher strain tolerance, lower stiffness, lower density, and higher creep compliance. With respect to coarse-graded mixes, it was noted that coarse mixtures that meet the high VMA requirements specified in the Superpave mix design protocol may exhibit low shear resistance and may, therefore, be highly susceptible to rutting. *(34)*

In a separate study, the Asphalt Institute conducted a study designed to determine the effects of aggregate gradation and VMA on the mechanical properties of an asphalt mixture. The research consisted of aggregate from a single source, and all mixes had a NMAS of 12.5mm. The estimated rut depths of fine-graded mixtures were greater than those of coarse-graded mixtures containing the same level of VMA. The data indicated that as VMA increased, the shear stiffness decreased and the shear strain increased. The shear stiffness of coarse-graded mixtures was found to be much more affected by the increase in VMA than that of fine-graded mixtures. At low VMA, the fine-graded mixture had lower shear stiffness than the coarse-graded mixture having the same VMA. At higher VMA, the fine-graded mixture had higher shear stiffness than the coarse-graded mixture of the same VMA. In other words, the performance of the fine-graded mixture was better at the high level of VMA, and the performance of the coarse-graded mixture was better that the low level of VMA. For the fine-graded mixtures, VMA significantly impacted rutting performance. However, VMA did not significantly influence the rutting performance of the coarse-graded mixtures. Thus, it was concluded that a reduction in VMA for coarse-graded mixtures should not negatively impact performance with respect to rutting. *(36)* This result supports industry concerns that high VMA requirements may be unnecessary and can even be detrimental to pavement performance.

In a project sponsored by the AHTD (TRC-9804), seven coarse-graded mixes were tested, representing both 12.5mm and 25.0mm NMAS. Plant mix was tested in the laboratory with respect to rutting. Due to variation in production, the mixes exhibited a range of VMA levels. In general, the mixes exhibited a slight trend toward increased rutting as VMA increased, showing some sensitivity to construction variability. *(37)*

In response to continuing skepticism concerning the applicability of the VMA requirements as set forth by the Superpave mixture design procedures, the National Cooperative Highway Research Program (NCHRP) initiated an investigation (Project 9-25) to determine the suitability of the criteria. This project is currently underway and has an anticipated completion date of July 31, 2006. *(38)*

VMA Criteria

A survey of states was conducted by the AHTD in order to compile a summary of VMA requirements used around the nation. A total of 37 states responded to the questionnaire, with 95 percent of those responding indicating that VMA is a required design criterion for HMA. A vast majority of those states claim to use the VMA design criteria as outlined by Superpave design methods. *(5, 39)* When this project began, Arkansas required minimum VMA during design to be 0.5 percent higher than that given by Superpave. Since that time, the VMA specification has been revised to reflect the Superpave criteria as presented in AASHTO M 323. *(16)* A comparison of current

AHTD and AASHTO mix design specifications for the 12.5mm NMAS is presented in Table 1.

		AASHTO M 323 *(16)*		AHTD Specification *(3)*
% Passing 3/4" Sieve		100		100
% Passing 1/2" Sieve		90 – 100		90 – 100
% Passing 3/8" Sieve		90 max.		90 max.
% Passing #8 Sieve		38 – 58		28 - 58
% Passing #200 Sieve		2 – 10		2 – 10
% Air Voids		4.0		4.5[1]
% VMA		14.0 minimum[2]		14.0 – 16.0
% VFA		65 - 75[3]		NA
Dust Proportion		0.60 – 1.2		0.6 – 1.6
Water Sensitivity Ratio (%) (method AHTD 455)		NA		80.0 minimum
Tensile Strength Ratio (AASHTO T 283)		0.80 minimum		NA
Wheel Tracking Test Maximum Rut depth (method AHTD 480)		NA		8.000mm (low traffic) 5.000mm (high traffic)

Table 1. Comparison of AHTD and AASHTO Design Specifications (NMAS=12.5mm)

[1]For binder grades of PG 70-22 and PG 64-22

[2]Design values more than 2% above the minimum are not recommended

[3]Depending on traffic level - the maximum increases for low design traffic levels

VMA Collapse

One possible justification for elevating minimum VMA specifications is VMA collapse. This term is used to refer to the reduction in VMA that occurs during HMA production, resulting in lower levels of VMA than were generated during the mix design process. Several factors relating to aggregate degradation and asphalt absorption have been identified as possible contributors to this phenomenon. *(11)*

During plant production, the operating temperature can vary. If the mixing temperature is elevated, the viscosity of the binder is reduced. This allows for more asphalt absorption, creates lower effective binder contents, and reduces VMA. During paving, elevated temperatures create softer mixtures, which have fewer air voids, and thus, less VMA. Hauling time can also affect VMA. If hauling times are increased, asphalt absorption is increased, generating lower effective binder contents and lower VMA.

Aggregate handling can also significantly affect the VMA of field mixes. As more steps are included in aggregate handling, there is a greater potential for aggregate degradation. As aggregates interact, the abrasive actions allow points and edges to break free from larger particles. These textural components are the very features that create internal friction and increase shear resistance. The broken portions create additional fine aggregate, leaving coarse particles in a smoother, rounder state. Rounded aggregate particles and additional fines are associated with lower VMA. *(11)*

Baghouse fines include the "dust" that is trapped during production. An efficient use of these fines is to add them back to a mix. The addition of such materials increases the dust proportion, which generally decreases VMA. Because the small particles generate an overall increase in surface area, the average film thickness and effective binder content of the mix are reduced, often lowering the VMA.

Several general causes of VMA collapse have been noted, however definitive relationships have not yet been established. More research should be performed to determine possible test methods and procedures that could be used to predict VMA collapse for a given mix during design.

Film Thickness

The purpose of specifying a minimum value for VMA in an asphalt mix design is to ensure that the binder content is sufficient for providing the durability needed under traffic loading. However, VMA is based on a conglomeration of interrelated factors, and trends relating VMA to performance have not been successfully established. *(20)*

Critics of the minimum VMA requirements feel that a new way to ensure adequate film thicknesses should be implemented. This is especially important for mixtures with coarse gradations because mix designers are encountering difficulties in meeting the minimum VMA requirement though the film thickness is believed to be adequate. *(25)* VMA is calculated from two tests conducted in the laboratory – aggregate bulk specific gravity and mixture bulk specific gravity. These tests have a high level of variability, which could cause a mixture that meets the VMA requirement in the contractor's laboratory to not meet the VMA requirement in the governing agency's laboratory. *(10)* In fact, considering the variability of the constituent test methods comprising a VMA value, the standard deviation for VMA is 1.3 percent, which means that the D2S range (i.e., acceptable range of two results) is 3.8%. *(8, 10)* So, a contractor reporting 15.6 percent VMA and an agency reporting 12.2 percent VMA for the same material would, in a statistical sense, be considered valid since both values fall within the acceptable range. Practically, this is a very significant difference. Therefore the addition of some other criterion for mix design, such as film thickness, could prove beneficial.

It has been found in many studies that the film thickness, or thickness of asphalt coating on the aggregate, is a better predictor of mixture durability than VMA, and can also be a valuable indicator of moisture susceptibility. *(11, 25)* Film thickness is a function of the amount of asphalt binder added to a mixture and the total surface area of the aggregate in the mixture. There has been a movement toward rewriting the current mix design specifications to include a minimum film thickness requirement. *(20)*

In the 1950s and 1960s, some researchers felt that film thickness, rather than VMA was important in achieving adequate mixture performance properties, and that mixtures were more flexible and durable as film thickness increased. *(40)* It was shown that as the surface area of the aggregate increased, the film thickness decreased for constant binder contents. It was also demonstrated that the VMA could be the same for different aggregate blends, but the film thickness would differ depending on the surface area of the aggregate particles. However, no direct relationship was established. The recommended film thickness at that time was 6 to 8 microns.

In 1965, Goode and Lusfey took a slightly different approach in recommending a minimum film thickness for HMA mixtures. They recognized that all aggregate in a mixture may not be coated with a uniform film thickness, and therefore developed the idea of a "bitumen index". *(41)* The bitumen index was defined as pounds of asphalt cement per square foot of aggregate surface area. A minimum value of 0.00123 was suggested as a means to resist binder aging and hardening. In addition, a maximum ratio of voids to bitumen index of 4 was recommended.

In the 1970s, Kumar and Goetz related film thickness to permeability in dense-graded mixtures. They developed a "film thickness factor" that was defined as the ratio of the percent asphalt content available for coating the aggregate to the surface area of the aggregate. They concluded that the accuracy of methods used to generate average film thickness were, at best, suspect. *(42)*

More recently, the relationship between film thickness and aging for dense-graded asphalt mixtures was revisited. Kandhal and Chakraborty demonstrated that when compacted to 8 percent air voids, mixtures having a film thickness less than 9 microns aged more quickly. Thus, a minimum film thickness of 8 microns was recommended for use in design. *(7)* Later, the minimum VMA required to reach this minimum was investigated. Based on the results, it was concluded that the minimum VMA required for coarse mixtures was unnecessary. *(25)*

Although film thickness shows much promise as a valuable component of mix design, using this parameter in mix design presents its own set of challenges. For instance, there are several flaws in the equations used for its calculation. The first is that the surface area factors are based only on the aggregate gradation, and do not consider shape or texture. In fact, these factors were developed based on rounded aggregate shapes, which are not recommended for use in current mix design procedures. *(7)* Also, the film thickness equation appears to be sensitive to the specific gravity of the aggregate. The value for VMA that is back-calculated for a given film thickness should not change, but it actually changes more than one percent over a change in specific gravity of 0.3. *(10)* Another issue pertaining to film thickness measurements is that the coatings are not likely to be consistent for all aggregate particles in a mix. Depending on particle orientation during compaction, fine aggregate particles may have thicker coatings than the coarse particles, and very fine aggregates may not even be coated, but rather embedded within the coatings. *(25)*

OBJECTIVES

The overall objective of this project was to evaluate various properties of HMA mixtures and to quantify the relationships of these properties to performance, specifically focusing on permanent deformation, or rutting. Detailed objectives follow.

Establish the effects of VMA on rutting performance of HMA mixes. Voids in the mineral aggregate (VMA) is believed to affect the performance of asphalt mixes. VMA represents the portion of volume in a mixture not occupied by the mineral aggregate or the absorbed asphalt contained in its pores. It has long been believed that maintaining a VMA percentage greater than some minimum value would increase mixture durability and help to prevent rutting failures. In other words, increased VMA may provide increased rutting resistance. Recent research has indicated that this trend may not always be correct. This primary objective of this research was to establish trends and/or relationships between rutting and VMA for HMA mixes containing typical Arkansas aggregates.

Analyze the effects of other mixture characteristics on rutting performance. Factors other than VMA are known to affect pavement rutting performance, including binder content, VFA, film thickness, and aggregate characteristics. Most of the factors are interrelated, making it difficult to assess only the effects of the individual properties. For that reason, varying the level of VMA for various mix designs caused the other factors in question to be varied as well. These factors were investigated with respect to rutting performance. Aggregate properties such as bulk specific gravity and gradation, and the gradation of fines in the blend, were also analyzed to determine how these properties may affect the rutting performance of the mix using ERSA. The focal points of this objective were to develop performance trends for a variety of mixture properties and to form a basis for the determination of optimal mixture design properties with respect to rutting.

Investigate issues associated with binder film thickness. The property of film thickness is believed to be an important indicator of mixture performance. Aggregate surface area is a major component involved in the calculation of film thickness, but is difficult to measure. A secondary objective of this research was to examine alternative methods for measuring aggregate surface area and/or calculating film thickness. Currently there are several methods available for characterizing film thickness. A common procedure was developed by the Asphalt Institute to describe average film thickness. *(12, 43)* This method was used to calculate film thickness and the results used to investigate the relationship of film thickness and rutting susceptibility.

SCOPE

This research study investigated various mixture properties and the relationships of those properties to the rutting performance of the HMA mixture. In order to assess the applicability of conclusions to a variety of aggregate types, a selection of aggregate sources were chosen to represent the typical range of materials found in the state of Arkansas. Four aggregate sources were selected including limestone (LS), sandstone (SS), gravel (GR), and syenite (SY). From each aggregate source, two gradations (coarse-graded and fine-graded) surface mixtures were designed at three levels of VMA (low, medium, and high). A summary of the experimental design is presented in Table 2.

Factors	Level of Variation
Aggregate Source	4 (Sandstone, Syenite, Gravel, Limestone)
Gradation	2 (Fine, Coarse)
VMA	3 (Low, Medium, High)
Response Variables – ERSA 4 Replicates	Rut Depth at 10,000 Cycles, Rut Depth at 20,000 Cycles, Rutting Slope, Stripping Slope, Stripping Inflection Point
Response Variables – RAWT 3 Replicates	Final Rut Depth, Rut per Cycle

Table 2. Experimental Design Summary

The medium VMA level was chosen as a value that was in the “natural” range for the particular aggregate source. As the aggregate bulk specific gravity increased, the medium VMA increased. The low and high VMA levels were set as approximately one percent below and above that determined for the medium VMA, respectively. Because mixture rutting is typically most prevalent in the upper three inches of a pavement structure, only surface mixtures having a nominal maximum aggregate size of 12.5mm were tested. *(22)* All mixes were compacted to 100 design gyrations, designed at approximately 4.5 percent air voids, and contained a PG 70-22 binder. No antistrip or additives were used. Summaries for the 24 mix designs are given in Tables 3 - 6, and gradations are illustrated in Figures 8 - 11. As near as possible, all mixtures were designed according to current AHTD volumetric specifications with the exception, of course, of the VMA criteria.

In order to assess performance, two wheel-tracking devices were utilized. The Evaluator of Rutting and Stripping in Asphalt (ERSA) was used to test four samples of each of the 24 mixes. The Rotary Asphalt Wheel Tester (RAWT) was used to test triplicate samples of each of the 24 mixes.

ERSA tests were performed according to the standard testing configuration. Each ERSA sample was comprised of two cylindrical specimens that were compacted in the gyratory compactor to an air void content of approximately 7.0 percent. The samples were tested at 50 C in the submerged condition while subjected to a 132-lb load. After a four hour pre-conditioning period, the samples were tested for 20,000 cycles or to a maximum rut depth of 20mm, whichever occurred first.

Samples tested in the RAWT were also compacted to approximately 7.0 percent air voids in the gyratory compactor. Single specimens were used for each test result. All RAWT tests were performed at the manufacturer's recommended operating conditions of 70 cycles per minute, a 75-lb load, and a one-hour pre-conditioning cycle. Samples were tested in the submerged condition at 40 C. Early RAWT testing indicated that a 50 C test temperature was too high. Samples tested at this temperature degraded so quickly that test results were difficult to interpret. While this temperature is less than the ERSA testing temperature, it was felt that a 40 C test temperature was more able to discriminate between samples of different performance qualities, resulting in more meaningful conclusions.

	Sandstone					
Gradation	Coarse	Coarse	Coarse	Fine	Fine	Fine
VMA Level	Low	Medium	High	Low	Medium	High
% Passing						
3/4"	100	100	100	100	100	100
1/2"	95	91	95	95	97	98
3/8"	87	80	86	89	93	95
#4	63	52	54	70	76	77
#8	35	30	28	44	47	47
#16	24	20	19	30	31	31
#30	19	16	15	23	24	24
#50	16	14	13	19	20	20
#100	11	9	9	12	13	13
#200	6.3	5.4	5.1	6.7	7.0	6.7
% Binder	6.0	6.2	6.3	5.8	6.6	6.7
% Air Voids	4.2	4.2	4.6	4.8	4.3	4.4
% VMA	12.8	13.7	14.3	12.8	13.9	14.4
% VFA	67.2	69.3	67.8	61.7	69.1	69.4
Gsb	2.467	2.473	2.466	2.463	2.461	2.459
Gmm	2.396	2.376	2.365	2.388	2.369	2.362
DP	1.6	1.3	1.2	1.8	1.6	1.5
Film Th.	6.2	8.2	8.9	5.5	6.2	6.5
FAA	44.9	43.7	47.0	46.8	43.8	44.0

Table 3. Mix design summary for sandstone aggregate source.

	Syenite					
Gradation	Coarse	Coarse	Coarse	Fine	Fine	Fine
VMA Level	Low	Medium	High	Low	Medium	High
% Passing						
3/4"	100	100	100	100	100	100
1/2"	91	93	95	94	97	98
3/8"	81	83	86	87	91	94
#4	58	59	61	65	69	78
#8	39	39	39	45	47	55
#16	26	26	25	31	33	39
#30	18	17	17	23	23	29
#50	12	11	10	15	15	18
#100	7	6	6	8	9	10
#200	4.2	3.9	3.3	5.1	5.7	5.9
% Binder	5.8	6.0	6.2	5.7	6.0	6.5
% Air Voids	4.4	4.5	4.8	4.8	4.4	4.2
% VMA	15.7	16.5	17.1	15.5	16.3	17.1
% VFA	72.0	72.7	71.9	68.4	73.0	75.4
Gsb	2.586	2.586	2.586	2.585	2.584	2.581
Gmm	2.420	2.404	2.401	2.416	2.407	2.390
DP	0.8	0.7	0.6	0.9	1.0	0.9
Film Th.	10.8	12.1	13.4	9.0	8.8	8.7
FAA	48.3	48.3	48.5	47.5	47.0	47.6

Table 4. Mix design summary for syenite aggregate source.

	Gravel					
Gradation	Coarse	Coarse	Coarse	Fine	Fine	Fine
VMA Level	Low	Medium	High	Low	Medium	High
% Passing						
3/4"	100	100	100	100	100	100
1/2"	90	95	98	96	96	96
3/8"	77	85	89	89	89	88
#4	53	54	56	64	74	63
#8	36	34	35	44	56	43
#16	25	24	23	31	41	29
#30	19	17	17	23	31	20
#50	12	11	10	15	19	12
#100	6	6	5	8	11	6
#200	3.9	3.8	3.6	4.9	6.3	3.9
% Binder	5.5	5.6	6.4	5.5	6.0	6.3
% Air Voids	4.2	4.7	4.6	4.6	4.7	4.8
% VMA	14.5	15.5	16.8	14.8	15.8	16.7
% VFA	71.0	69.7	72.6	68.9	70.3	71.3
Gsb	2.562	2.561	2.560	2.560	2.560	2.572
Gmm	2.424	2.406	2.386	2.420	2.405	2.390
DP	0.9	0.8	0.7	1.1	1.3	0.7
Film Th.	10.1	11.2	13.3	8.2	7.2	11.8
FAA	44.3	44.2	44.0	44.2	44.4	44.4

Table 5. Mix design summary for gravel aggregate source.

	Limestone					
Gradation	Coarse	Coarse	Coarse	Fine	Fine	Fine
VMA Level	Low	Medium	High	Low	Medium	High
% Passing						
3/4"	100	100	100	100	100	100
1/2"	94	95	95	94	97	96
3/8"	83	85	84	89	90	90
#4	51	52	48	66	68	73
#8	36	37	33	50	51	56
#16	25	25	23	34	35	38
#30	17	17	15	23	23	25
#50	11	10	9	14	15	15
#100	7	6	6	9	9	9
#200	5.2	4.7	4.0	6.6	6.7	6.4
% Binder	5.9	6.3	6.5	5.9	6.6	6.7
% Air Voids	4.8	4.8	4.5	4.5	4.3	4.5
% VMA	13.5	14.8	15.5	13.3	14.5	15.2
% VFA	64.4	67.6	71.0	66.2	70.3	70.4
Gsb	2.509	2.514	2.518	2.503	2.504	2.507
Gmm	2.397	2.403	2.384	2.416	2.393	2.387
DP	1.2	1.1	0.8	1.7	1.5	1.3
Film Th.	8.5	9.7	12.3	6.2	7.2	7.6
FAA	44.9	44.8	45.4	44.4	44.7	45.0

Table 6. Mix design summary for limestone aggregate source.

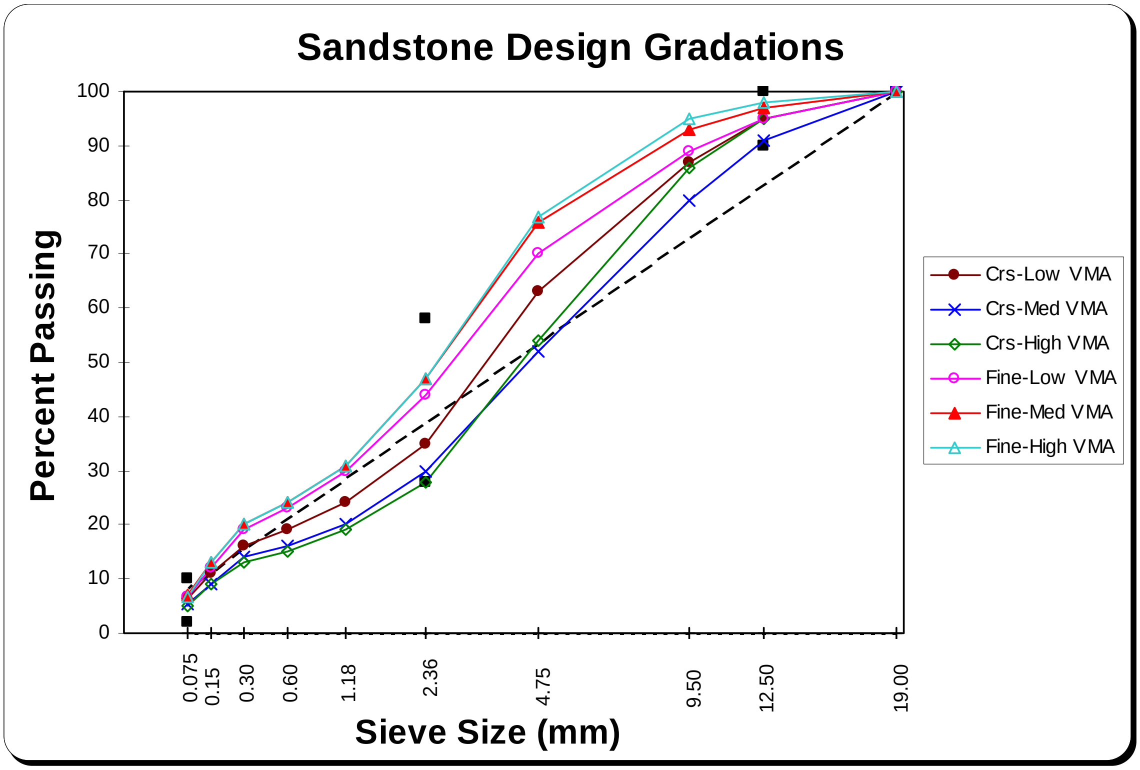

Figure 8. Gradation comparison for sandstone mixes.

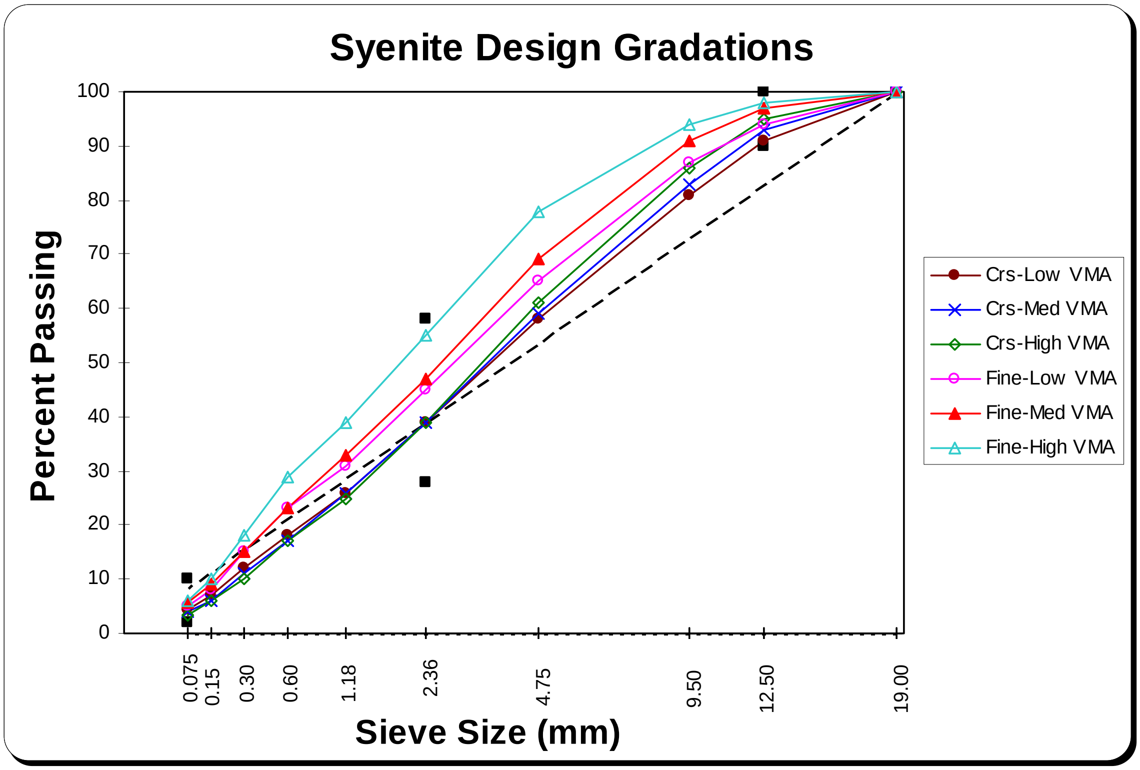

Figure 9. Gradation comparison for syenite mixes.

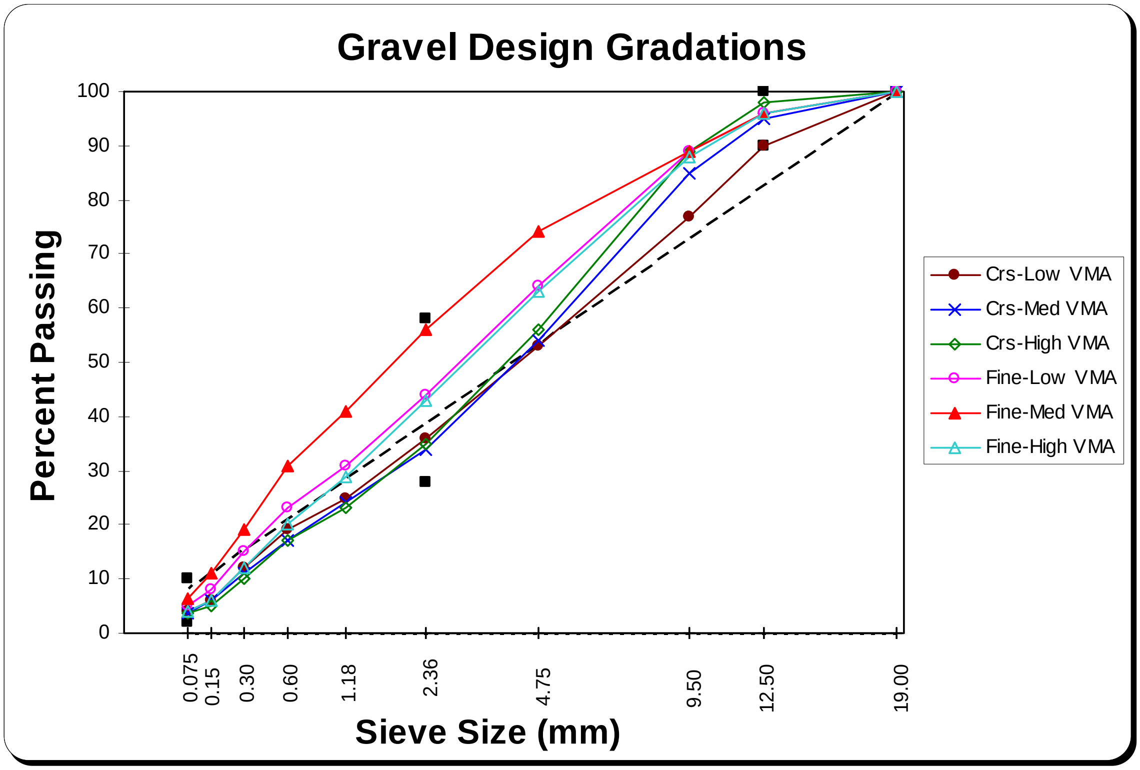

Figure 10. Gradation comparison for gravel mixes.

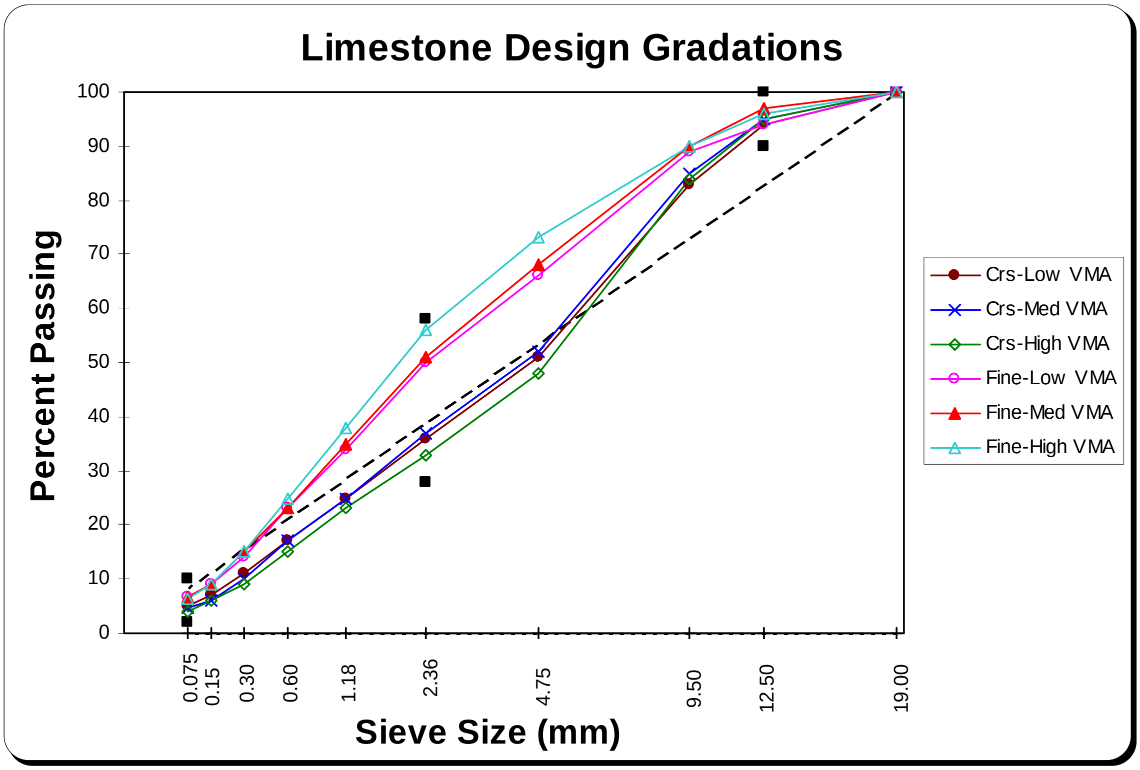

Figure 11. Gradation comparison for limestone mixes.

TEST RESULTS AND ANALYSIS

A comprehensive review of data is presented in this section of the report. Statistical analyses were completed using SAS statistical software. A five percent level of significance (alpha = 0.05) was used in all cases.

A total of 96 ERSA tests and 72 RAWT tests were performed on the 24 mix designs. Sample graphs showing individual results from the ERSA tests are presented in Appendix A, and sample graphs of individual results from the RAWT tests are presented in Appendix B. A comprehensive summary of numerical data resulting from the testing regimen is presented in Table 7. In this table, the values shown represent the average results for all replicates of a given combination of factors. The summaries are perhaps more easily interpreted when presented in graphical form as shown in Figures 12 - 19. The graphs are compiled for each testing method and for each aggregate source.

By visual classification, conclusions were drawn regarding the relative performance of each mix type. Based on this inspection, the mixture types from each aggregate source were ranked from best to worst in terms of rutting resistance. The rankings are shown in Table 8. In this table, mixtures are designated according to gradation type – coarse (C) and fine (F), and VMA level - low (L), medium (M), and high (H). In the top section, mixtures having a coarse gradation are shaded. This section indicates that, in general, coarse-graded mixes tend to have greater rutting resistance as measured by the ERSA test. However, the RAWT appears to rank fine mixtures as having better rutting performance. In the middle section, the same rankings are presented, but the mixtures with high VMA are shaded. According to ERSA, the high VMA mixes exhibit poor rutting performance. For the RAWT, results are mixed, but a slight preference is given to the high VMA mixes. In the bottom portion of the table, mixtures with low VMA are shaded. According to ERSA, low VMA tends to produce greater rutting resistance. The RAWT suggests the opposite trend, with low VMA mixtures exhibiting poorer performance. It is important to consider that these cursory observations were based solely on visual interpretation. Statistically sound analysis procedures should also be used in order to draw more accurate conclusions.

			ERSA					RAWT		
Source	Gradation	VMA	Rut10k Avg	Rut20k Avg	Rslope Avg	SIP Avg	Sslope Avg	Avg Final Rut	Avg Cycles	Avg RutperCyc
Sandstone	Coarse	Low	12.70	16.95	1528	4075	623	8.07	14901	0.000545
		Med	11.35	17.35	1818	4375	741	12.56	22206	0.000585
		High	10.75	17.55	2375	7012.5	435	14.15	22839	0.000630
	Fine	Low	14.20	18.68	3144	4800	502	9.12	16278	0.000566
		Med	14.38	16.70	1323	3075	561	11.13	23522	0.000461
		High	13.60	14.48	1554	3050	434	9.07	25289	0.000390
Syenite	Coarse	Low	8.53	13.75	1931	7525	957	15.41	16952	0.000929
		Med	12.05	17.93	1662	4375	800	14.93	10233	0.001546
		High	12.95	15.15	1225	4925	459	14.22	9721	0.001480
	Fine	Low	8.08	14.15	2777	6250	810	12.54	25223	0.000528
		Med	11.80	16.10	2663	5350	689	12.96	18454	0.000722
		High	20.13	20.63	800	2275	295	15.50	19010	0.000919
Gravel	Coarse	Low	4.95	10.23	3991	40000	3991	14.12	12244	0.001186
		Med	4.45	6.13	4300	40000	4300	15.98	8274	0.001957
		High	8.58	17.65	1512	9875	573	16.03	10021	0.001611
	Fine	Low	5.25	10.93	3140	18750	1599	14.42	12573	0.001245
		Med	5.95	13.33	2896	14375	763	15.52	19249	0.000900
		High	8.30	14.20	2427	10625	888	16.03	14901	0.001146
Limestone	Coarse	Low	13.35	17.03	1642	6850	562	14.08	12102	0.001162
		Med	15.35	17.23	1124	5175	413	11.98	9709	0.001236
		High	17.00	17.93	1484	5425	360	14.26	8767	0.001643
	Fine	Low	12.83	19.48	1700	6175	429	13.42	20108	0.000676
		Med	16.93	16.98	890	3175	266	16.02	19716	0.000837
		High	15.20	15.28	637	2650	285	15.25	17789	0.000867

Table 7. Summary of performance data

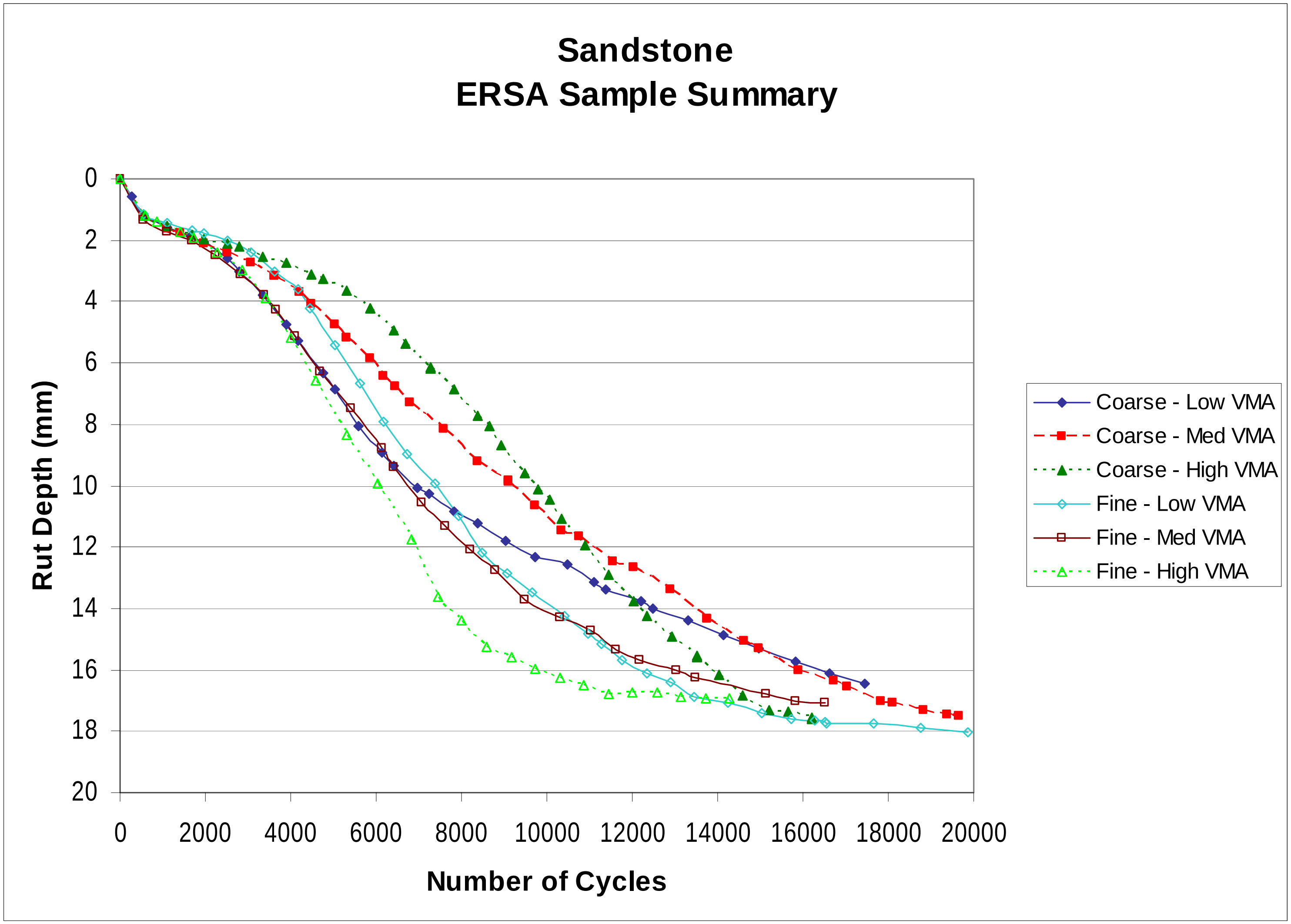

Figure 12. Summary of average performance for sandstone mixtures tested in ERSA

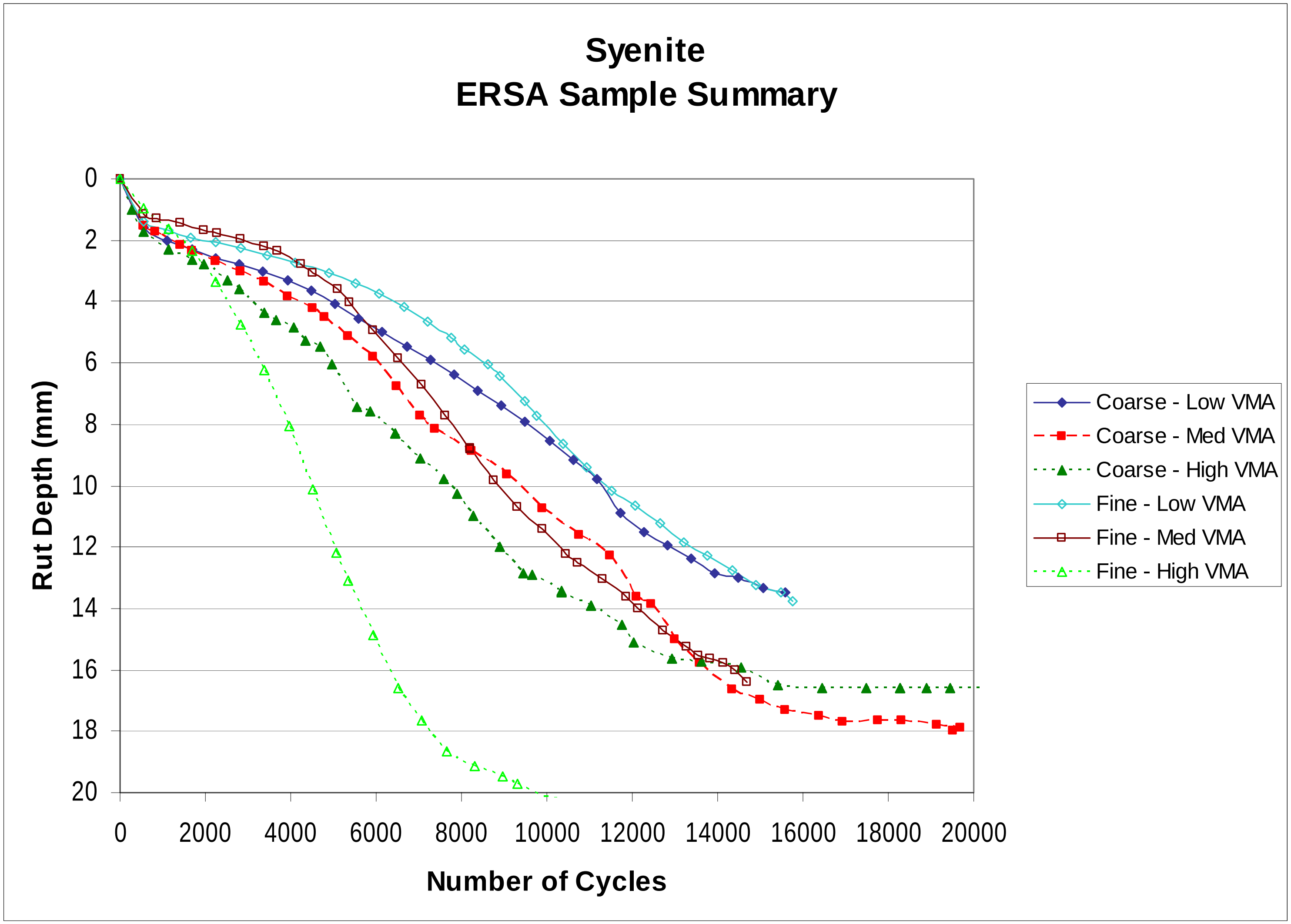

Figure 13. Summary of average performance for syenite mixtures tested in ERSA

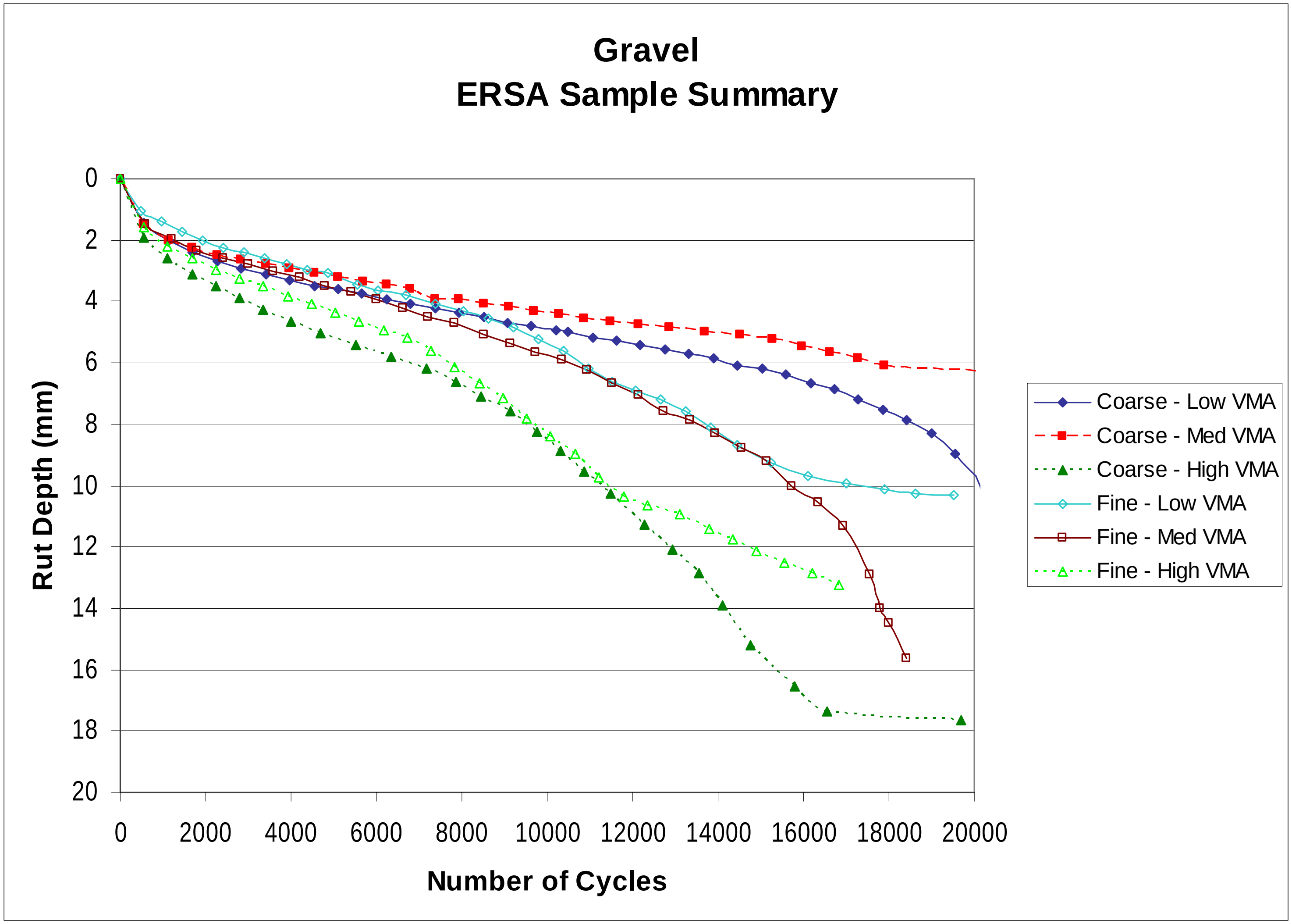

Figure 14. Summary of average performance for gravel mixtures tested in ERSA

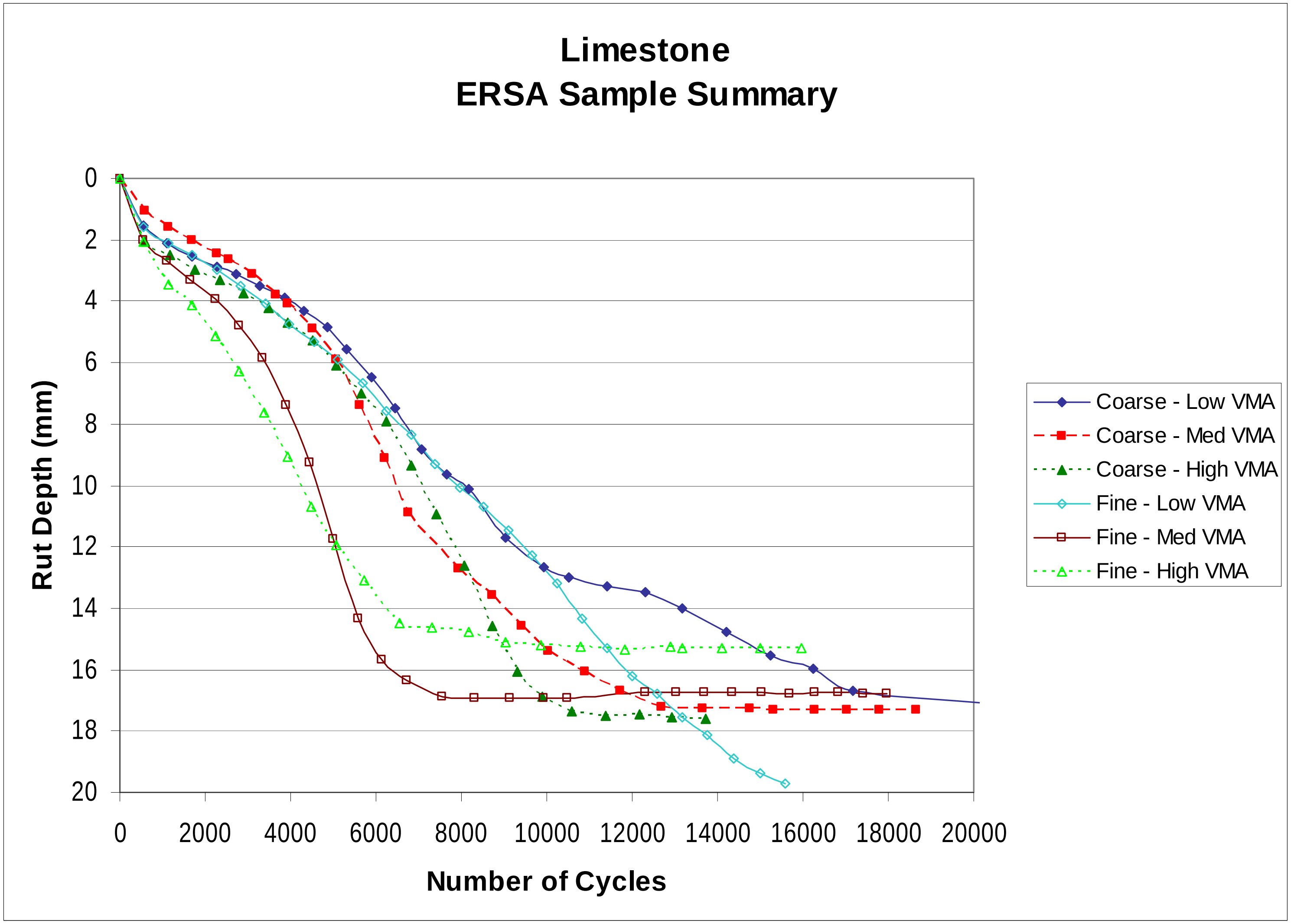

Figure 15. Summary of average performance for limestone mixtures tested in ERSA

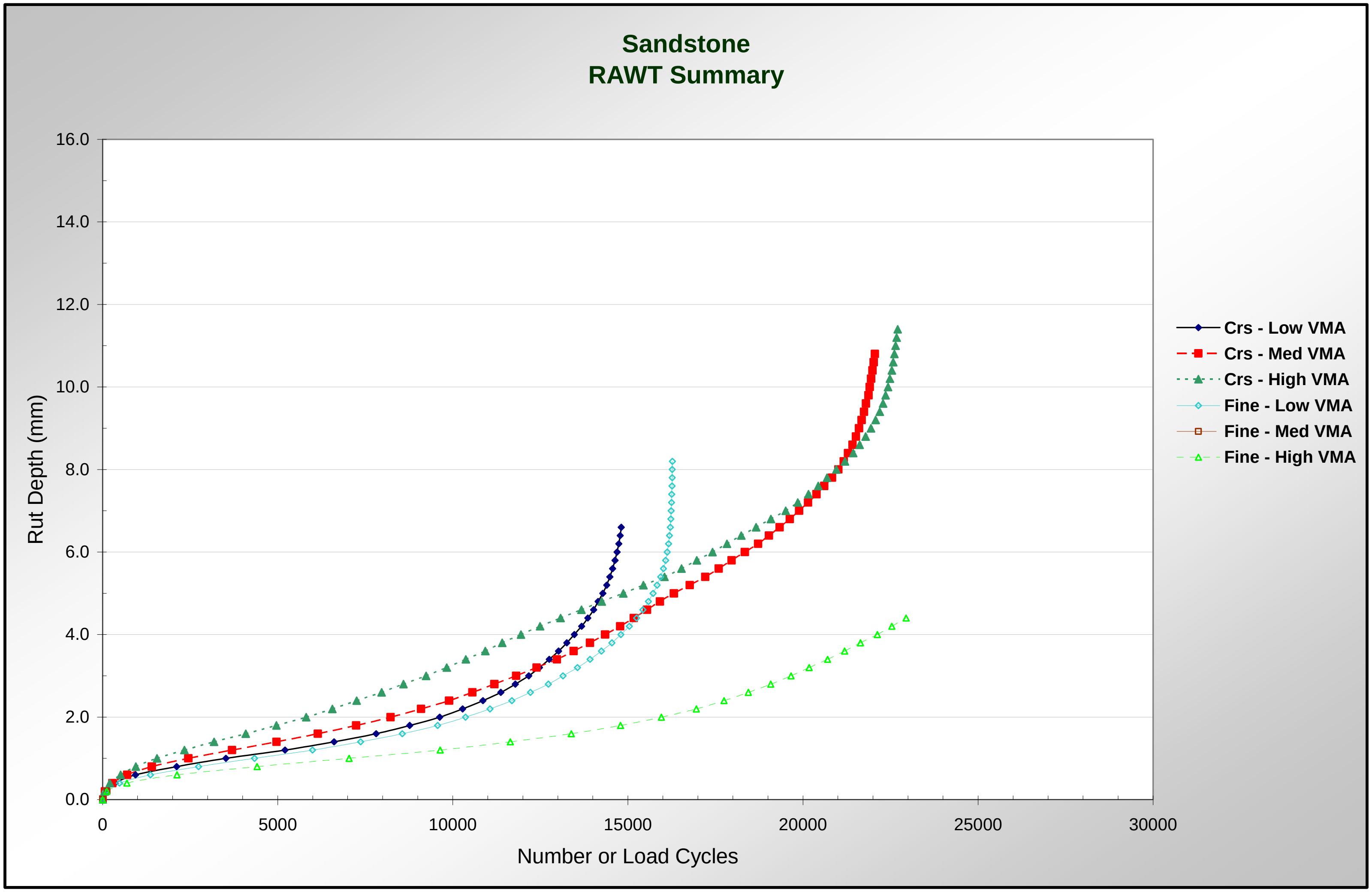

Figure 16. Summary of average performance for sandstone mixtures tested in RAWT

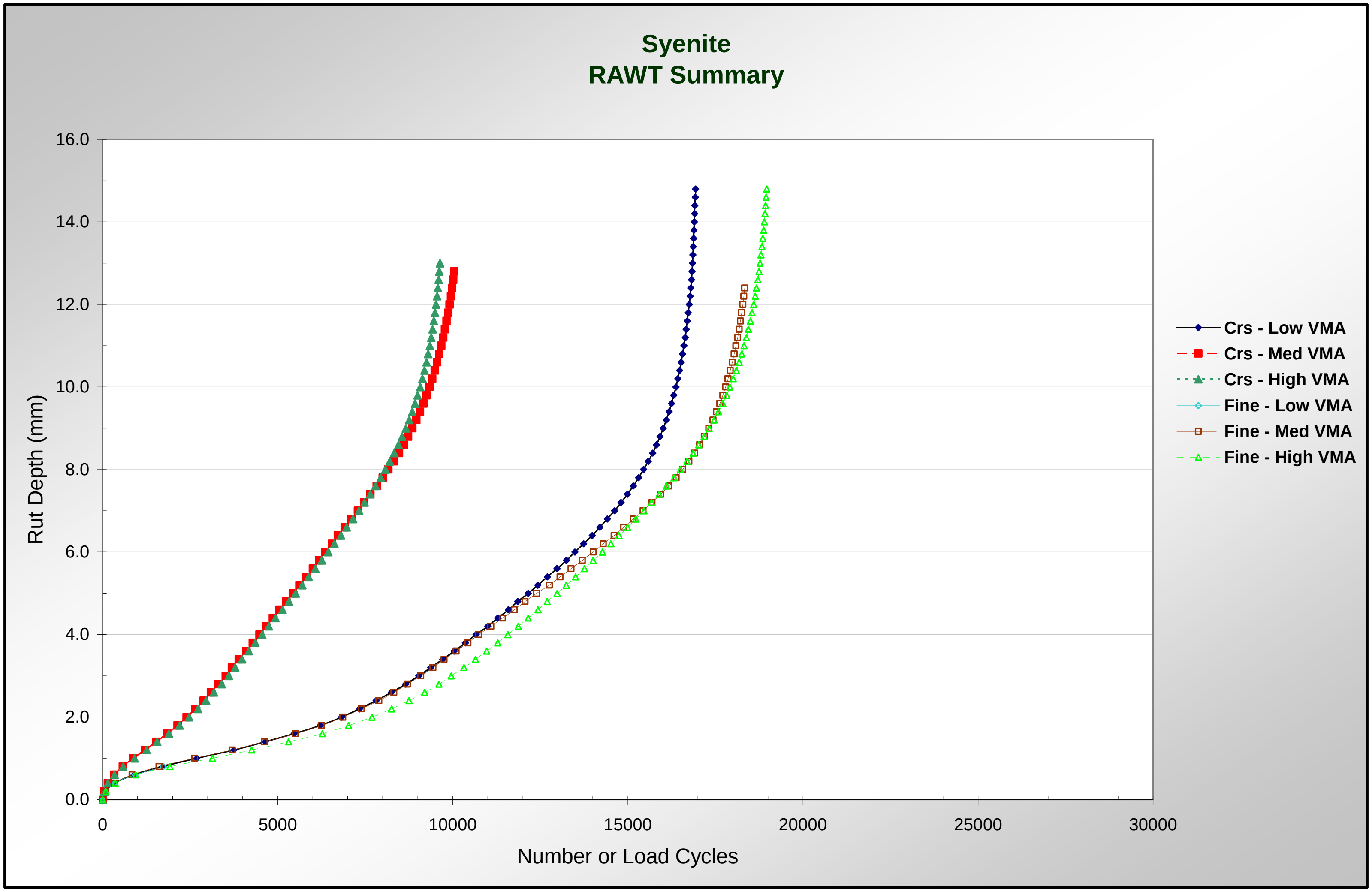

Figure 17. Summary of average performance for syenite mixtures tested in RAWT

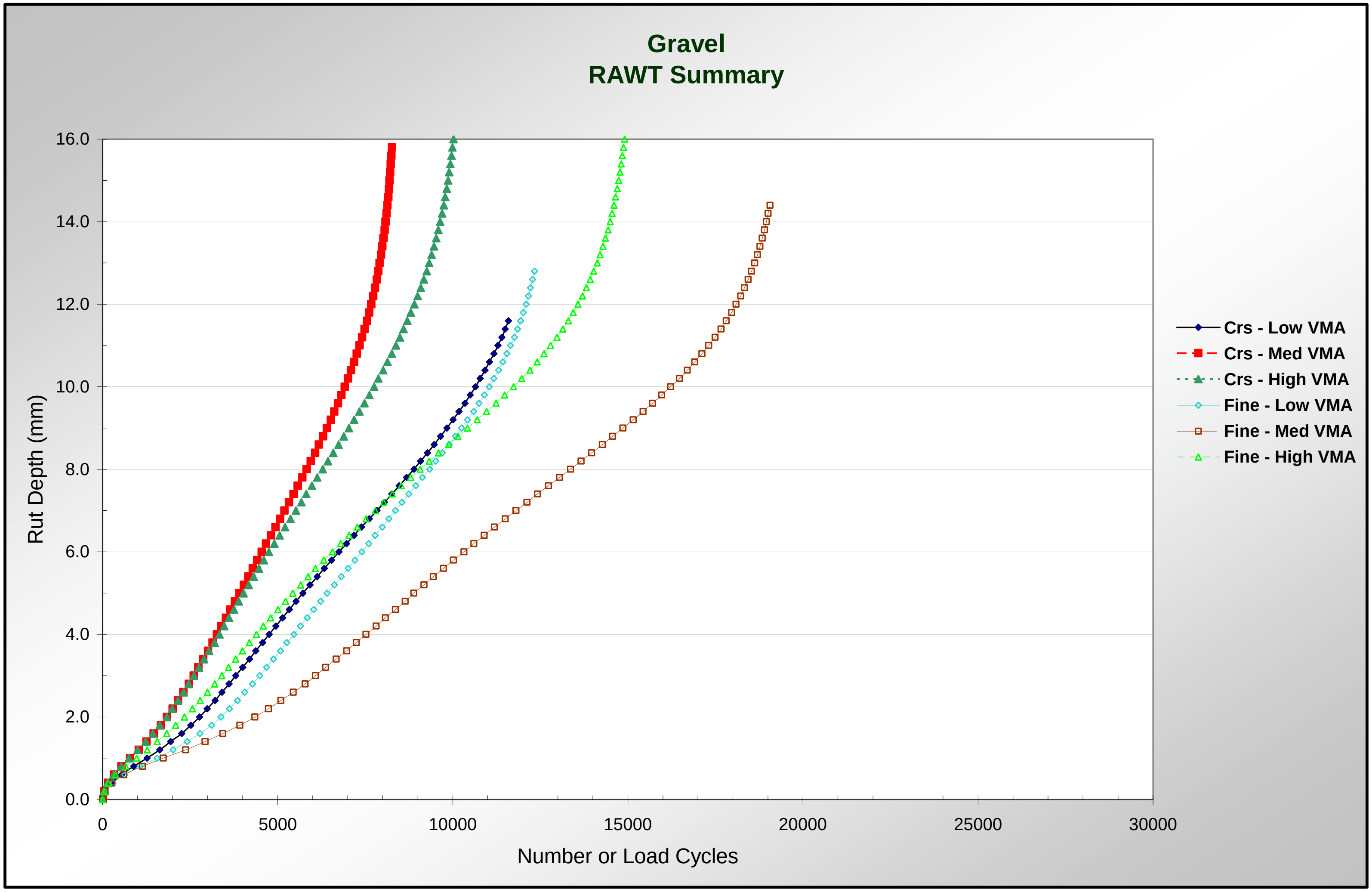

Figure 18. Summary of average performance for gravel mixtures tested in RAWT

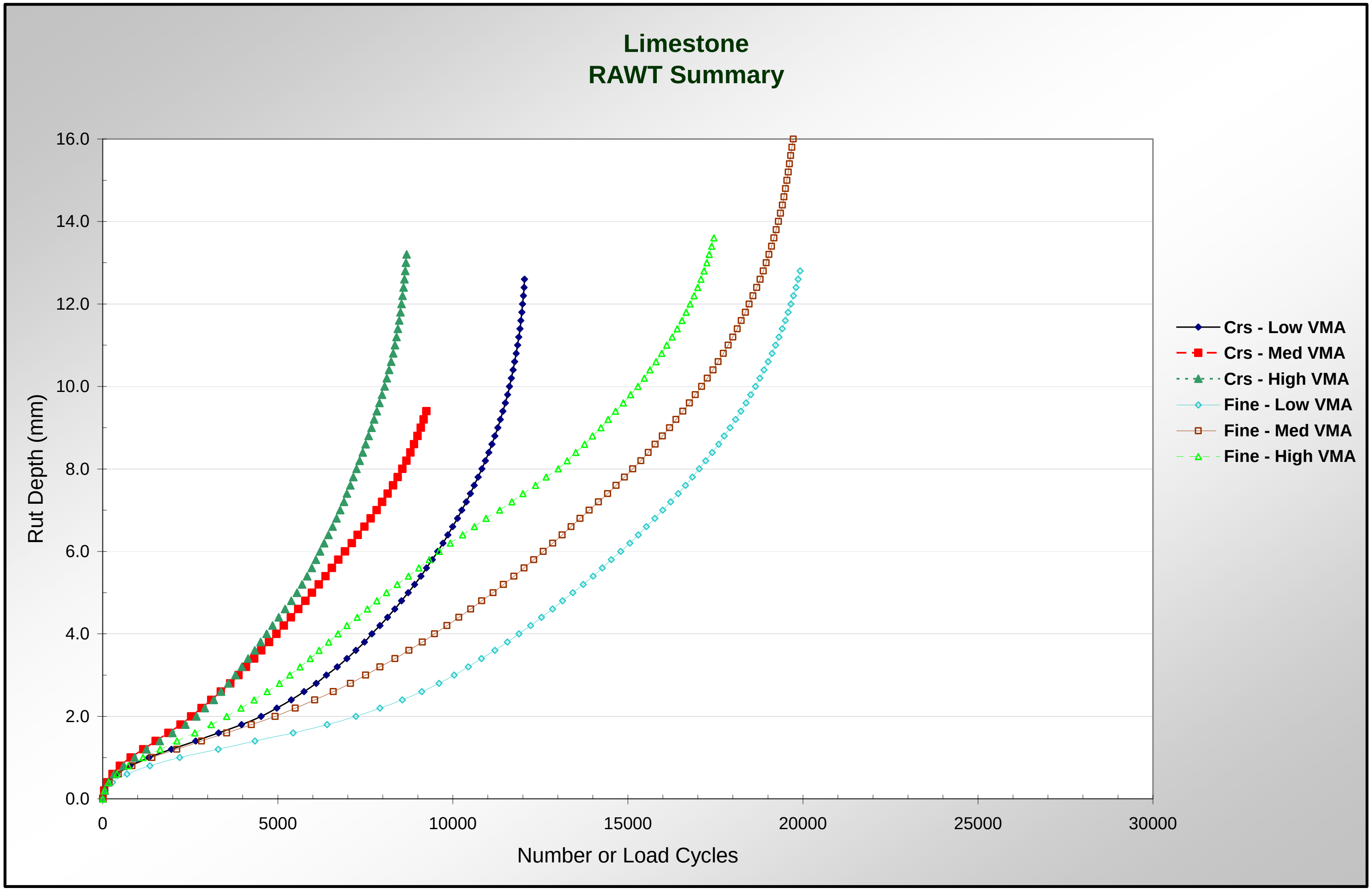

Figure 19. Summary of average performance for limestone mixtures tested in RAWT

ERSA				RAWT			
Sandstone	Syenite	Gravel	Limestone	Sandstone	Syenite	Gravel	Limestone
CH	FL	CM	CL	FH	FH	FM	FL
CM	CL	CL	FL	CM	FM	FH	FM
CL	FM	FL	CH	CH	CL	FL	FH
FM	CM	FM	CM	FM	FL	CL	CL
FL	CH	FH	FH	FL	CM	CH	CM
FH	FH	CH	FM	CL	CH	CM	CH

Coarse-graded mixtures are shaded.

ERSA				RAWT			
Sandstone	Syenite	Gravel	Limestone	Sandstone	Syenite	Gravel	Limestone
CH	FL	CM	CL	FH	FH	FM	FL
CM	CL	CL	FL	CM	FM	FH	FM
CL	FM	FL	CH	CH	CL	FL	FH
FM	CM	FM	CM	FM	FL	CL	CL
FL	CH	FH	FH	FL	CM	CH	CM
FH	FH	CH	FM	CL	CH	CM	CH

Mixtures with high VMA are shaded.

ERSA				RAWT			
Sandstone	Syenite	Gravel	Limestone	Sandstone	Syenite	Gravel	Limestone
CH	FL	CM	CL	FH	FH	FM	FL
CM	CL	CL	FL	CM	FM	FH	FM
CL	FM	FL	CH	CH	CL	FL	FH
FM	CM	FM	CM	FM	FL	CL	CL
FL	CH	FH	FH	FL	CM	CH	CM
FH	FH	CH	FM	CL	CH	CM	CH

Mixtures with low VMA are shaded.

Table 8. Mixture rankings (visual) and factor shading

Statistical Analysis of VMA and Gradation

Analysis of variance (ANOVA) was used to statistically analyze the effects of VMA and gradation on rutting performance. A rank transformation was used as a non-parametric alternative when the underlying assumptions of the AVOVA were not met. Four replicate ERSA tests were performed on each of the 24 mixes from the four aggregate sources, which allowed four replicates. A summary of factors and levels is contained in Table 9.

Factor	# of Levels	Levels
Source	4	Sandstone (SS), Syenite (SY), Gravel (GR), Limestone (LS)
Gradation	2	Coarse, Fine
VMA Level	3	High, Medium, Low

Table 9. Summary of ANOVA factors for ERSA analysis.

For this ANOVA, a complete randomized block design was used to isolate the variability associated with aggregate source. Since the results of the analysis are likely to be affected by aggregate type, this factor must be considered even though it is not the variable of interest and has no practical bearing on factor interactions. The effects of Gradation, VMA Level, and their interaction were analyzed for significance with respect to the five response variables generated from the ERSA test – rut depth at 20,000 cycles (RUT20K), rut depth at 10,000 cycles (RUT10K), rutting slope (RSLOPE), stripping slope (SSLOPE), and stripping inflection point (SIP). A summary of results is given in the following tables, including the degrees of freedom, calculated F-statistic, and P-value for each parameter. The P-value is the smallest level of significance at which the data are significant. In other words, if the P-value is less than alpha (0.05), then the factor or interaction is significant.

RUT20K			
Factor	df	F-calc	P-value
Source	3	11.97	<0.0001
Gradation	1	0.52	0.4741
VMA	2	1.84	0.1651
Gradation*VMA	2	1.05	0.3559
Error	87		

Table 10. ANOVA results for rut depth at 20,000 cycles in ERSA

Relative to rut depth at 20,000 cycles, the data presented in Table 10 indicates that source had a significant effect, meaning that it was beneficial to separate the significant amount of variability created by that factor. No other factors or interactions were significant. By close examination of the data, it is evident that most samples exhibited a large rut depth at the end of the test. However, some samples reached a maximum rut depth early in the test and others reached their maximum rut depth more gradually. Thus, RUT20K was not descriptive enough to truly explain sample behavior. For this reason, the rut depth at 10,000 cycles (RUT10K) was investigated next. By examining rut depths that occurred earlier in the test, greater discrimination between testing factor combinations was obtained. Results are presented in Table 11.

RUT10K			
Factor	df	F-calc	P-value
Source	3	26.10	<0.0001
Gradation	1	2.71	0.1033
VMA	2	6.75	0.0019
Gradation*VMA	2	0.51	0.6026
Error	87		

Duncan's Test		
VMA Level	Mean	Rank
High	13.31	A
Medium	11.53	AB
Low	9.98	B

Table 11. ANOVA results for rut depth at 10,000 cycles in ERSA

Again, source was significant, so separating this source of variability was beneficial for the analysis. Relative to rut depth at 10,000 cycles, VMA level was the only significant factor. Duncan's Multiple Range Test was used to determine which means caused the significance, and these results are also included in Table 11. Means with the same letter grouping were ranked similarly. Overall, mixes with low VMA performed better than mixes with high VMA, and this trend was unrelated to gradation type.

Next, the rutting slope was analyzed. Rutting slope is an important value to consider because it describes the rate of rutting and is not affected by the amount of initial consolidation of the mix. ANOVA results for this property are presented in Table 12.

RSLOPE			
Factor	df	F-calc	P-value
Source	3	16.87	<0.0001
Gradation	1	0.09	0.7701
VMA	2	9.73	0.0002
Gradation*VMA	2	1.67	0.1948
Error	87		

Duncan's Test		
VMA Level	Mean	Rank
High	1501.8	A
Medium	2084.5	B*
Low	2481.5	C*

Table 12. ANOVA results for rutting slope in ERSA
*Note: The significance between low and medium VMA was marginal.

With respect to rutting slope, source was a significant block and VMA level was a significant main effect. Duncan's Multiple Range Test indicated that the medium and low VMA mixes showed better rutting performance than the high VMA mixes. This trend was again unrelated to gradation type.

Next, the stripping characteristics were analyzed. Stripping properties describe the mixture's resistance to moisture damage. The stripping inflection point is a relative measure of how quickly moisture damage affects the sample, and the stripping slope indicates the rate of deterioration after stripping begins. ANOVA results for these properties are presented in Tables 13 and 14.

SIP			
Factor	df	F-calc	P-value
Source	3	42.81	<0.0001
Gradation	1	13.59	0.0004
VMA	2	7.27	0.0012
Gradation*VMA	2	1.16	0.3190
Error	87		

Duncan's Test					
VMA Level	Mean	Rank	Gradation	Mean	Rank
High	5730	A	Coarse	11634	A
Medium	9988	B	Fine	6713	B
Low	11803	B			

Table 13. ANOVA results for stripping inflection point in ERSA

After separating the significant effects of aggregate source, the stripping inflection point was determined to be significantly affected by both gradation and VMA level. However, the interaction of the two terms was not significant. Coarse gradations provided greater resistance to stripping than did fine gradations, and mixes with low and medium VMA exhibited better stripping performance than mixes with high VMA.

SSLOPE			
Factor	df	F-calc	P-value
Source	3	22.33	<0.0001
Gradation	1	23.31	0.0007
VMA	2	7.82	0.0008
Gradation*VMA	2	3.57	0.0322
Error	87		

Table 14. ANOVA results for stripping slope in ERSA

Stripping slope was the only ERSA response variable significantly affected by an interaction of factors. A significant interaction means that the conclusions for one factor are dependant on another factor, and can be seen as non-parallel lines on an interaction plot. When a significant interaction exists, conclusions regarding the effects of the individual main effects should not be made. In this case, the stripping slope of the coarse-graded mixes is much more affected by VMA than the fine-graded mixes. The medium and low VMA coarse-graded mixes were the best performers. The high VMA mixes of both gradation types performed poorly, and the fine-graded low VMA mix showed mediocre performance. The interaction is illustrated in Figure 20.

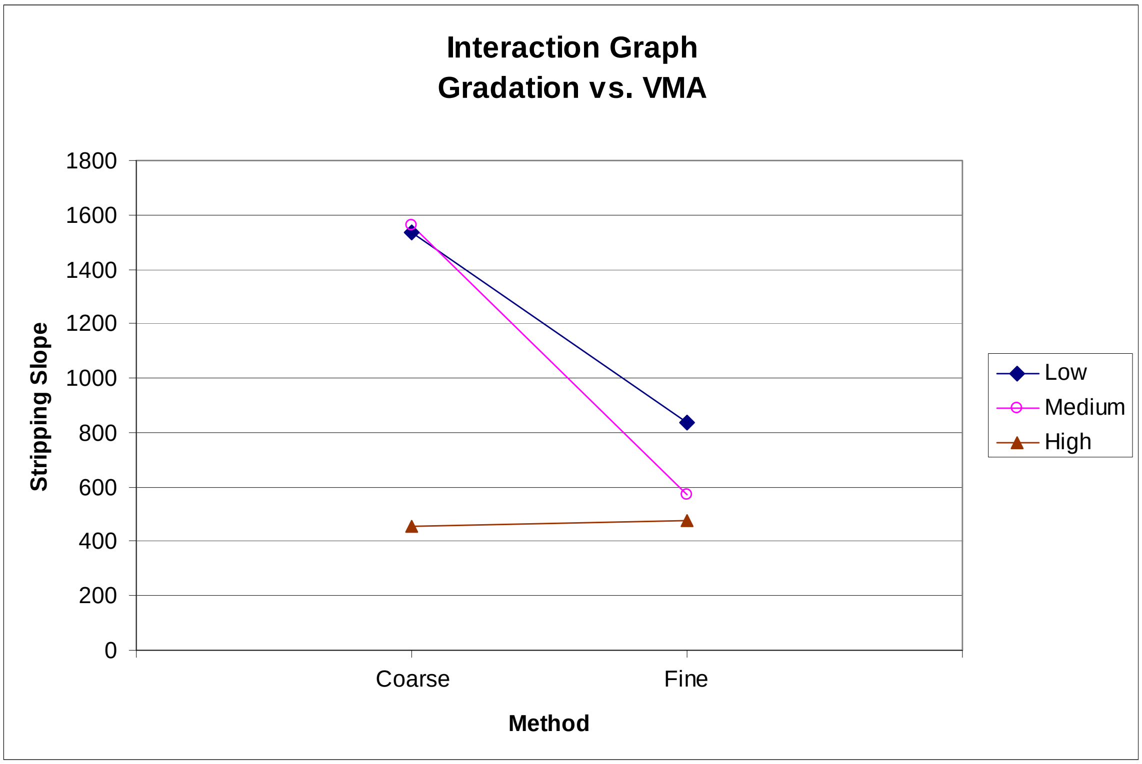

Figure 20. Interaction of Gradation and VMA based on stripping slope in ERSA

Similar analyses were performed for the data generated by the RAWT test. In this case, two response variables were analyzed. The first was the final rut depth. The ANOVA results are contained in Table 15.

FINALRUT			
Factor	df	F-calc	P-value
Source	3	16.27	<0.0001
Gradation	1	0.45	0.5036
VMA	2	4.25	0.0189
Gradation*VMA	2	0.18	0.8328
Error	60		

Duncan's Test		
VMA Level	Mean	Rank
High	14.32	A
Medium	14.00	A
Low	12.53	B

Table 15. ANOVA results for final rut depth in RAWT

According to final rut depths in the RAWT, source was a significant block and VMA was a significant factor. Mixes with low VMA showed the best rutting performance. Mixes with medium and high VMA performed similarly, but rutted more than those with low VMA. Gradation was not a significant factor in these test results.

From a RAWT test, the final rut depth and number of cycles to reach that final rut depth are reported. The final rut depth is indicative of the mixture's performance, but does not account for the rate at which this rut depth was achieved. From this data alone, the performance of samples that reach a high rut depth early in the test cannot be differentiated from those that reach a high rut depth late in the test. (This is similar to the situation described earlier for the RUT20K response in ERSA.) Also, a test may be terminated early for samples that develop a rough wheel-track. So although a sample may have a small final rut depth, that amount of rutting could have been generated very quickly. To alleviate this discrepancy, an additional response variable was calculated in order to describe the rate of rutting. This variable, RutperCycle, is the final rut depth divided by the total number of cycles applied during the test. ANOVA results are given in Table 16.

RUTPERCYCLE			
Factor	df	F-calc	P-value
Source	3	24.91	<0.0001
Gradation	1	40.12	<0.0001
VMA	2	3.35	0.0417
Gradation*VMA	2	3.49	0.0367
Error	87		

Table 16. ANOVA results for RutperCycle in RAWT

For this measure of rutting rate, RAWT responses were significantly affected by the interaction of gradation and VMA level. This interaction, shown in Figure 21, indicates that the rate of rutting for the coarse-graded mixes is much more affected by VMA than the fine-graded mixes. For the coarse-graded mixes, those with low VMA have greater rutting resistance than those with medium or high VMA. For the fine-graded mixes, all levels of VMA appeared to produce similar performance, and were more resistant to rutting than their coarse-graded counterparts. This is contrary to the results of the previous ANOVA according to the RAWT final rut depth, as well as the results generated by ERSA. Overall, the RAWT seemed to indicate that fine-graded mixtures exhibit greater resistance to rutting and stripping than coarse-graded mixes. This contradicting conclusion may be explained by sample degradation during testing.

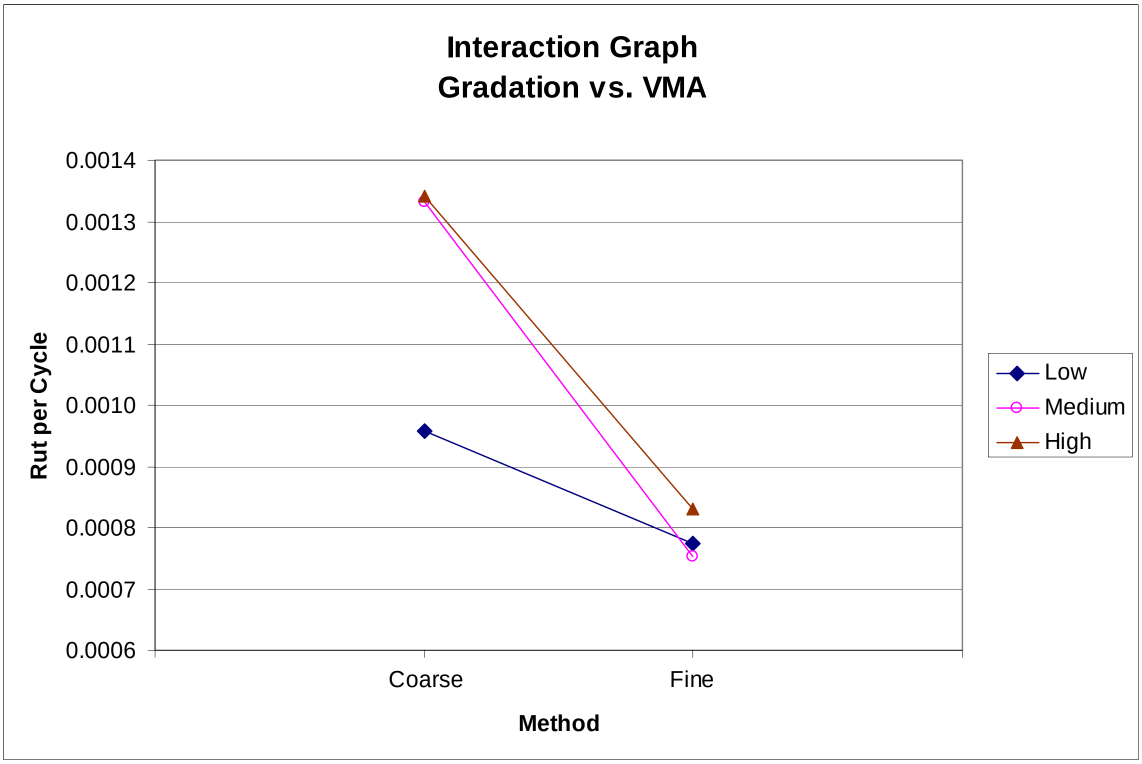

Figure 21. Interaction of Gradation and VMA based on rut per cycle in RAWT

In general, ERSA rutting results favored mixes with low VMA, and were relatively unaffected by gradation type. Stripping characteristics were affected by both gradation and VMA in that coarse-graded mixes were most resistant to moisture damage when designed with low or medium VMA. In terms of stripping slope, fine-graded mixtures did not perform as well as coarse-graded ones, but were much less affected by changes in VMA. Overall, it appeared that coarse-graded mixtures with low VMA provide the greatest resistance to rutting and stripping.

Final rut depths obtained from the RAWT test suggested that, again, resistance to permanent deformation was significantly affected by VMA level, but not by gradation type. Mixtures designed with lower levels of VMA exhibited better performance. However, in a practical sense, these results may be inconclusive because they are based merely upon the final rut depth with no regard for the number of cycles that were applied to create the rut depth. To remedy this discrepancy, the rate of rutting was analyzed. According to this parameter, rutting results were affected by both gradation type and VMA level, such that fine-graded mixes showed better rutting resistance, and were less affected by changes in VMA than the coarse mixes.

Relationships to Material Properties

Gradation and level of VMA were the primary material properties investigated with respect to permanent deformation performance. However, each of these properties is based on several other properties. For example, VMA is calculated based on the properties of mixture bulk specific gravity, aggregate bulk specific gravity, and binder content. Gradation type is based on series of percentages passing individual sieves. While trends relating to these two factors can be extremely valuable to mix designers, they do not represent the most basic properties of the mix. By relating the components of VMA or gradation to performance, a mix designer can more effectively create desired mixture properties. Thus, relating fundamental properties to performance would provide a more efficient tool for mix designers.

A number of mixture properties were determined for each mixture designed in the study. A series of regression analyses was performed in order to determine which property, or combination of properties was best related to performance. First, each property was tested to determine which displayed the significant relationships to the various measures performance-related response variables. The predictor variables are described in Table 17. The analyses were performed for the entire dataset, and then again for the data when separated by aggregate source. In Table 18, an "X" indicates that a particular parameter significantly affected the response.

Predictor	Description
VMA	Design VMA
VFA	Design VFA
Pb	Design binder content
Pbe	Effective binder content (design)
Pair	Design air content
Gmm	Theoretical Maximum Specific Gravity
Gsb	Aggregate bulk specific gravity
Gse	Aggregate effective specific gravity
DP	Dust proportion
FilmTh	Film thickness
FAA	Fine aggregate angularity
P34	% Passing the ¾" sieve
P12	% Passing the ½" sieve
P38	% Passing the 3/8" sieve
P4	% Passing the #4 sieve
P8	% Passing the #8 sieve
P16	% Passing the #16 sieve
P30	% Passing the #30 sieve
P50	% Passing the #50 sieve
P100	% Passing the #100 sieve
P200	% Passing the #200 sieve
MDL4	Distance between the MDL and #4 sieve
MDL8	Distance between the MDL and #8 sieve
MDL16	Distance between the MDL and #16 sieve
MDL30	Distance between the MDL and #30 sieve
MDL50	Distance between the MDL and #50 sieve
MDL100	Distance between the MDL and #100 sieve
MDL200	Distance between the MDL and #200 sieve
MDL4200	Sum of distances between the MDL and all sieves from the #4 to the #200
MDL8200	Sum of distances between the MDL and all sieves from the #8 to the #200
MDL16200	Sum of distances between the MDL and all sieves from the #16 to the #200
MDL30200	Sum of distances between the MDL and all sieves from the #30 to the #200
MDL50200	Sum of distances between the MDL and all sieves from the #50 to the #200
MDL100200	Sum of distances between the MDL and all sieves from the #100 to the #200
MDL4100	Sum of distances between the MDL and all sieves from the #4 to the #100
MDL8100	Sum of distances between the MDL and all sieves from the #8 to the #100
MDL16100	Sum of distances between the MDL and all sieves from the #16 to the #100
MDL30100	Sum of distances between the MDL and all sieves from the #30 to the #100
MDL50100	Sum of distances between the MDL and all sieves from the #50 to the #100
MDL450	Sum of distances between the MDL and all sieves from the #4 to the #50
MDL850	Sum of distances between the MDL and all sieves from the #8 to the #50
MDL1650	Sum of distances between the MDL and all sieves from the #16 to the #50
MDL3050	Sum of distances between the MDL and all sieves from the #30 to the #50
MDL430	Sum of distances between the MDL and all sieves from the #4 to the #30
MDL830	Sum of distances between the MDL and all sieves from the #8 to the #30
MDL1630	Sum of distances between the MDL and all sieves from the #16 to the #30
MD416	Sum of distances between the MDL and all sieves from the #4 to the #16
MDL816	Sum of distances between the MDL and all sieves from the #8 to the #16
MDL48	Sum of distances between the MDL and all sieves from the #4 to the #8

Table 17. Description of predictor variables used in regression analyses

Upon careful consideration of the information presented in Table 18, the following observations are made.

- Syenite mixes were sensitive to many of the predictor variables
- Sandstone mixes were relatively insensitive to all variables.
- Design binder content (Pb) was a relatively significant predictor. Interestingly, it was significant in more cases than the effective binder content (Pbe).
- When considering data from all sources, RAWT results were more affected by changes in VMA and VFA than were the ERSA results.
- Overall, aggregate bulk specific gravity was more significant than aggregate effective specific gravity.
- The properties of dust proportion, film thickness, and fine aggregate angularity were more closely related to stripping than to rutting, as measured by ERSA.
- In ERSA, gradation was a more significant predictor of stripping than of rutting.
- In the RAWT, gradation had a greater affect on rutting rate than on final rut depth.
- In ERSA, rutting and stripping responses were more closely related to the coarse fraction (i.e., 3/4″ to #16) of the blend gradation.
- In the RAWT, performance was more closely related to the fine fraction (i.e., #4 to #200) of the blend gradation.
- Distances and sums of distances to the maximum density line seemed to be most indicative of performance in ERSA when the #4 sieve is included.

- RAWT results were more sensitive to distances and sums of distances to the maximum density line when fine sieves (i.e. #16 to #200) are included.

While many of the parameters displayed significant effects, no relationships were strong enough to use for predictive purposes. In most cases, the R^2 values were less than 10 percent. This means that though a parameter did *affect* the response, that parameter was not able to explain enough of the variability in the relationship to *predict* a specific response. It was also noted that the range of values for several of the predictor variables were not large enough to generate robust statistical correlations. However, these observations did provide valuable guidance for further analysis.

	ERSA																									RAWT									
	RUT20K					RUT10K					RSLOPE					SSLOPE					SIP					FINALRUT					RUTPERCYCLE				
Predictor	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS
VMA			X	X				X	X				X	X	X			X	X	X			X	X		X			X		X				X
VFA			X	X				X	X			X	X	X	X			X		X			X		X	X					X				
Pb	X	X	X	X		X		X	X		X	X	X	X	X	X		X	X	X	X		X	X	X				X						
Pbe			X	X				X	X				X	X	X			X	X	X			X	X	X	X			X		X				X
Pair								X			X	X							X	X				X					X	X	X				
Gmm	X		X	X	X	X		X	X		X		X	X		X		X	X		X		X	X					X		X				X
Gsb	X		X			X		X			X					X	X	X			X		X			X					X				X
Gse						X					X											X	X			X	X		X		X			X	X
DP	X															X					X					X	X				X		X	X	X
FilmTh																X					X	X				X	X				X		X	X	X
FAA												X	X			X					X	X											X	X	X
P34								X						X	X		X	X	X	X			X	X	X										
P12						X		X			X			X	X	X	X	X	X	X	X		X	X	X										
P38	X					X		X			X			X	X	X		X	X	X	X		X	X	X						X				X
P4			X			X		X							X	X		X	X	X	X	X	X	X	X						X			X	X
P8			X			X		X								X		X	X	X	X	X	X	X	X						X			X	X
P16								X								X		X	X	X		X	X		X						X		X	X	X
P30								X														X			X						X		X	X	X
P50								X								X					X	X				X					X		X	X	X
P100	X					X										X					X	X				X	X				X		X	X	X
P200	X					X					X					X					X	X				X	X				X		X	X	X

Table 18. Factors representing individual significance with respect to ERSA and RAWT

	ERSA																									RAWT									
	RUT20K					RUT10K					RSLOPE					SSLOPE					SIP					FINALRUT					RUTPERCYCLE				
Predictor	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS
MDL4			X			X		X			X				X	X		X	X	X	X	X	X	X	X					X	X	X		X	X
MDL8			X			X		X							X	X		X		X			X		X		X			X	X				X
MDL16			X					X					X		X			X		X		X	X		X	X	X			X					
MDL30			X					X					X					X				X	X			X	X	X							X
MDL50													X																		X		X		X
MDL100	X					X										X					X					X	X				X		X	X	X
MDL200	X					X					X					X					X	X				X	X				X		X	X	X
MDL4200			X			X		X			X		X		X	X		X	X	X	X		X		X					X					
MDL8200			X					X					X					X					X			X	X								
MDL16200								X					X					X				X				X	X	X			X		X		X
MDL30200													X			X					X					X	X				X		X		X
MDL50200																X					X					X	X				X		X	X	X
MDL100200	X					X										X					X	X				X	X				X		X	X	X
MDL4100	X		X			X		X			X		X		X	X		X	X	X	X		X		X					X	X				
MDL8100			X					X					X					X		X			X			X	X								
MDL16100			X					X					X					X					X			X	X	X			X				X
MDL30100													X								X					X	X	X			X		X		X
MDL50100																X					X					X					X		X	X	X

Table 18. (cont.) Factors representing individual significance with respect to ERSA and RAWT

	ERSA																									RAWT									
	RUT20K					RUT10K					RSLOPE					SSLOPE					SIP					FINALRUT					RUTPERCYCLE				
Predictor	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS	All	SS	SY	GR	LS
MDL450	X		X			X		X			X				X	X		X	X	X	X		X		X					X	X				
MDL850			X			X		X					X					X		X			X		X	X	X								
MDL1650			X					X					X					X					X			X	X	X							X
MDL3050								X					X														X	X			X		X		X
MDL430	X		X			X		X			X				X	X		X	X	X	X		X		X					X	X				X
MDL830			X					X							X	X		X		X			X		X	X	X			X					
MDL1630			X					X					X					X				X	X			X	X								
MD416	X		X			X		X			X				X	X		X	X	X	X	X	X		X					X	X	X			X
MDL816			X			X		X							X	X		X		X			X		X		X			X	X				X
MDL48			X			X		X			X				X	X		X	X	X	X	X	X	X	X					X	X	X		X	X

Table 18. (cont.) Factors representing individual significance with respect to ERSA and RAWT

The fact that no individual predictor variable was able to explain mixture performance is not unreasonable, given that there are many interrelated factors involved. Therefore, the next stage in the analysis was to determine how many and what combinations of mixture properties possess the greatest likelihood of predicting pavement performance. A complicating factor in this effort was that most of the predictor variables were related to each other in some way. For instance, VMA and VFA are calculated from other properties, and are obviously related. In order to provide the greatest degree of accuracy, the independent variables in a regression analysis should be free of multicollinearity. In other words, they should not be mathematically related.

To minimize the risk of multicollinearity, the predictor variables for the regression analysis were separated into groups and in various combinations such that the most descriptive variables were included and anticipated interdependencies were minimized.

This step in the statistical analysis involved series of stepwise regression procedures as a means for selecting the most valuable combinations of predictor variables. Forward selection, backward selection, and best R^2 procedures were employed in this effort.

In general, as terms are added to a statistical model, the potential for error increases. In fact, for each additional term, the actual R^2 value is reduced due to the additional source of error. When selecting predictor variables, terms should only be added to the model if they provide an increase in R^2 large enough to positively offset the reduction in R^2 due its addition. Based on this concept, an optimum number of predictor variables can be determined.

For ERSA, rutting characteristics seemed to be best predicted using a combination of six to seven factors including binder content, VMA, VFA, and percents passing the #4 through the #30 sieves. When the MDL variables were used in place of gradation information, the distances from the MDL to the #4, #8, #16, #100, and #200 sieves emerged as most significant. Although the relationships were significant, R^2 values were in the range of 60 to 70 percent, and thus not adequate for predicting pavement performance.

Stripping characteristics in ERSA were less affected by VMA, but notably more affected by fine aggregate angularity. Six to seven variables were optimum for the relationships, and the most commonly chosen ones for predicting ERSA stripping performance were fine aggregate angularity, binder content, dust proportion, and percents passing the #8 through the #50 sieves. When the MDL variables were used in place of gradation information, the distances from the MDL to the #4, #8, #50, #100, and #200 sieves were most significant. R^2 values were slightly better for predicting stripping performance, and were in the range of 70 to 75 percent. However, multiple combinations of factors generated similar R^2 values, and thus the relationships were not believed to be adequate for predictive purposes.

Regression procedures for predicting performance in the RAWT were performed in a similar manner. Response variables were, in general, best predicted by effective binder content, film thickness, and the percents passing the #16, #30, #100, and #200 sieves. R^2 values were in the range of 50 to 60 percent. When using MDL predictor variables in place of actual gradation values, the relationship improved slightly (R^2 values of approximately 65 percent) and was highly dependent upon the inclusion of the MDL100 predictor.

Overall, the regression procedures indicated that approximately seven predictor variables would be optimum for providing the most significant relationships. In fact, several different combinations of predictors produced similar R^2 values, meaning that no single combination of mixture properties stood out as being uniquely significant for modeling pavement performance. However, several trends were noted to be of practical significance and will be discussed in the following section.

Trends

Based on the lack of suitable mathematical correlations for predicting pavement performance, practical trends were investigated. Graphs illustrating trends between mixture properties and performance response are given in Figures 22 through 65. For brevity, only a selection of these graphs is presented.

Upon consideration of the trend graphs given in Figures 22 - 65, the following conclusions were made.

- As binder content increased, rutting performance in ERSA decreased.
- As VMA increased, rutting performance in ERSA decreased. This trend was most evident when aggregate sources were considered separately. Also as VMA increased, resistance to stripping in ERSA decreased for some aggregate types.
- As VFA increased, the amount and rate of rutting in ERSA increased. However, the likelihood for stripping decreased with increased VFA, which was evident in the plot of VFA and stripping inflection point in ERSA.

- Greater theoretical maximum densities of the mixtures tended to provide greater resistance to stripping in ERSA. This trend was more evident when aggregate sources were considered separately.
- As fine aggregate angularity increased, stripping performance in ERSA increased. Stripping slopes were not consistently affected, but the stripping inflection points were delayed. Since several of the gravel mixes did not strip, this aggregate source should be considered separately with respect to stripping performance.
- Trends relating dust proportion to performance in ERSA were somewhat inconclusive, but appeared to be dependent upon aggregate source.
- As film thickness increased, stripping performance in ERSA improved slightly. This is reasonable since thicker binder coatings should be less penetrable by water.
- As the percent passing the 3/8" sieve increased, stripping performance in ERSA decreased. Thus, a greater amount of large aggregate was beneficial in resisting moisture damage. Again, the gravel mixes should be considered separately since several samples from that aggregate source did not strip.
- The plot of percent passing the #4 sieve vs. ERSA rut depth at 10,000 cycles was inconclusive, however mixes from the syenite source appeared to benefit from a smaller passing percentage.
- The percentage passing the #16 sieve appeared to be unrelated to rutting performance in ERSA.

- As the distance from the MDL to the percent passing the #4 sieve increased, stripping performance in ERSA decreased. This trend was slight, but was evident for all but the aggregate source.
- As the distance from the MDL to the percent passing the #8 sieve increased, stripping performance in ERSA was negatively impacted for all but the gravel source. Rutting performance appeared to be unrelated.
- As the distance from the MDL to the percent passing the #200 sieve increased, the stripping inflection point in ERSA increased for all but the gravel aggregate source. Rutting performance was inconclusive, except that the sandstone source appeared to benefit from the greater distances.
- In the RAWT, increased VMA led to an increase in rutting. This trend was weak, however, especially when considered for separate aggregate sources.
- Relative to the RAWT, no trends were noted with respect to changes in VFA.
- As effective binder content increased, the rutting performance decreased for samples tested in the RAWT. This trend was more clearly exhibited by the final rut depth than by rutting rate.
- As film thickness increased, rutting performance as measured by the RAWT decreased.
- As dust proportion increased, final rut depths and rutting rate in the RAWT decreased.

- The percent passing the #50 sieve did not appear to affect final rut depths in the RAWT, however the rate of rutting decreased as the percentage passing the #50 sieve increased.
- A slight trend toward decreased rutting in the RAWT was noted for an increase in the percentage passing the #100 sieve.
- As the distance between the MDL and percent passing the #100 sieve increased, the rate of rutting in the RAWT increased. A very slight trend toward increased rut depths was associated with this factor for some aggregate types.
- As the distance between the MDL and percent passing the #200 sieve increased, the rate of rutting in the RAWT increased. No trends were noted with regard to final rut depths.

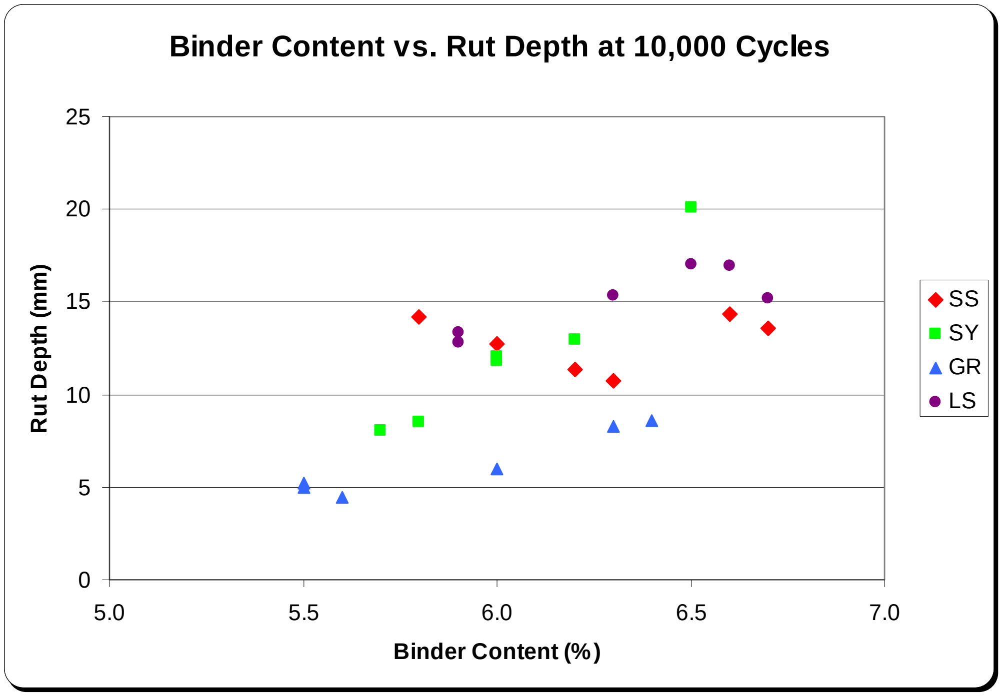

Figure 22. Trend graph - binder content vs. rut depth at 10,000 cycles in ERSA

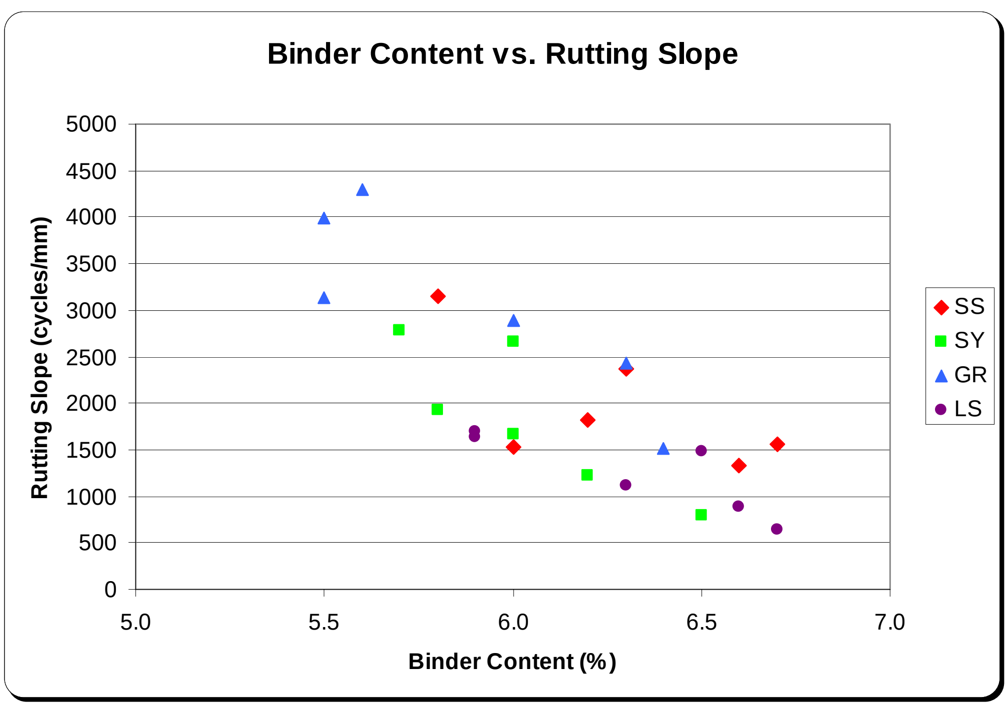

Figure 23. Trend graph - binder content vs. rutting slope in ERSA

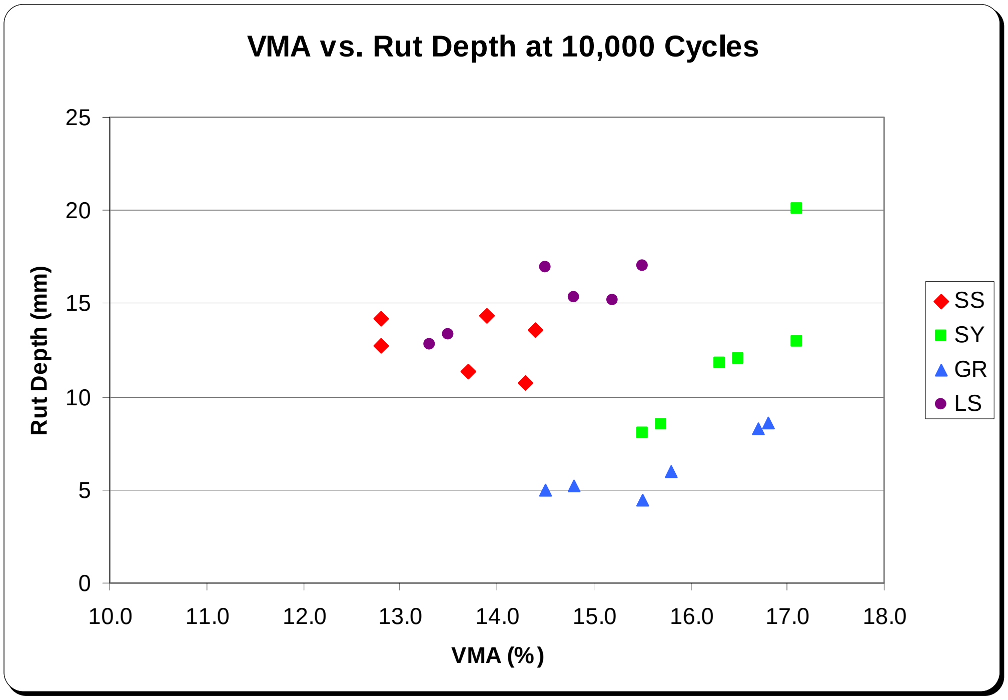

Figure 24. Trend graph - VMA vs. rut depth at 10,000 cycles in ERSA

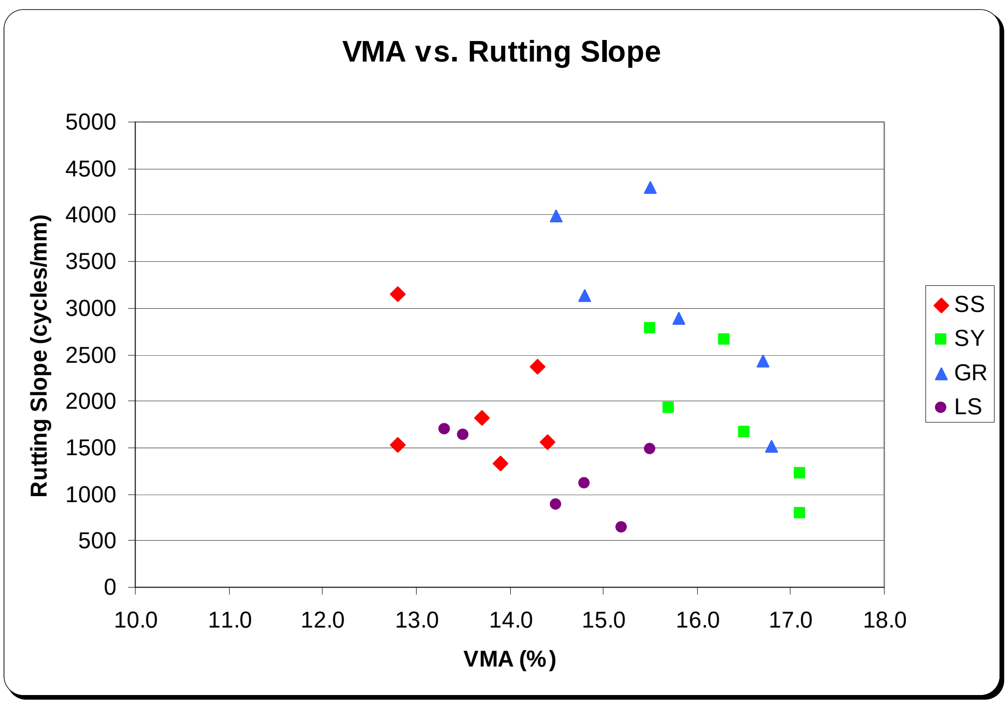

Figure 25. Trend graph - VMA vs. rutting slope in ERSA

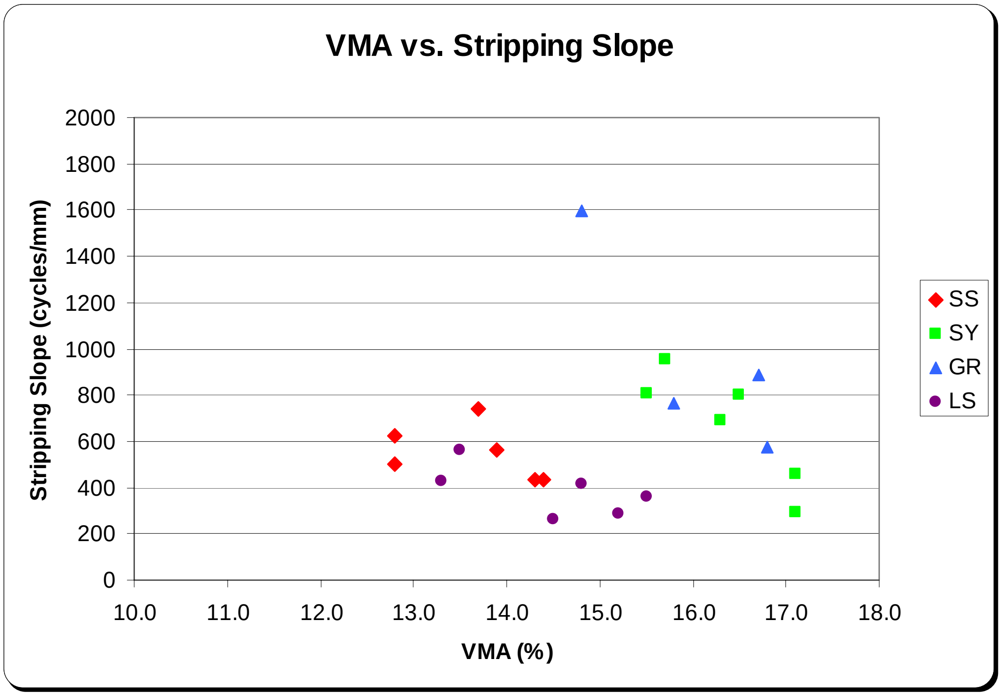

Figure 26. Trend graph - VMA vs. stripping slope in ERSA

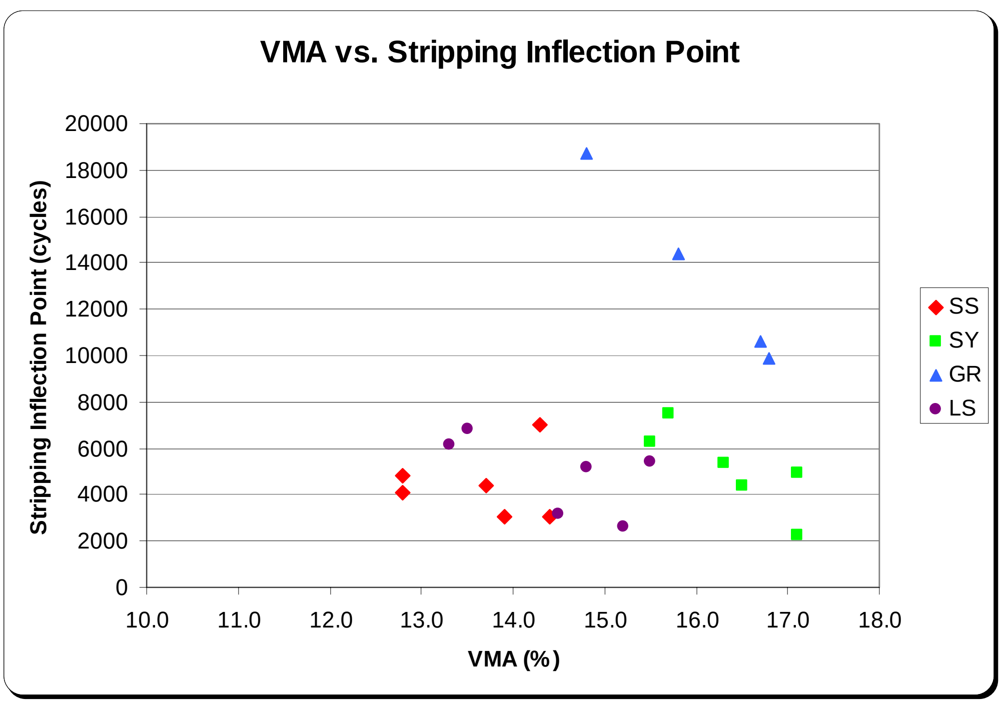

Figure 27. Trend graph - VMA vs. stripping inflection point in ERSA

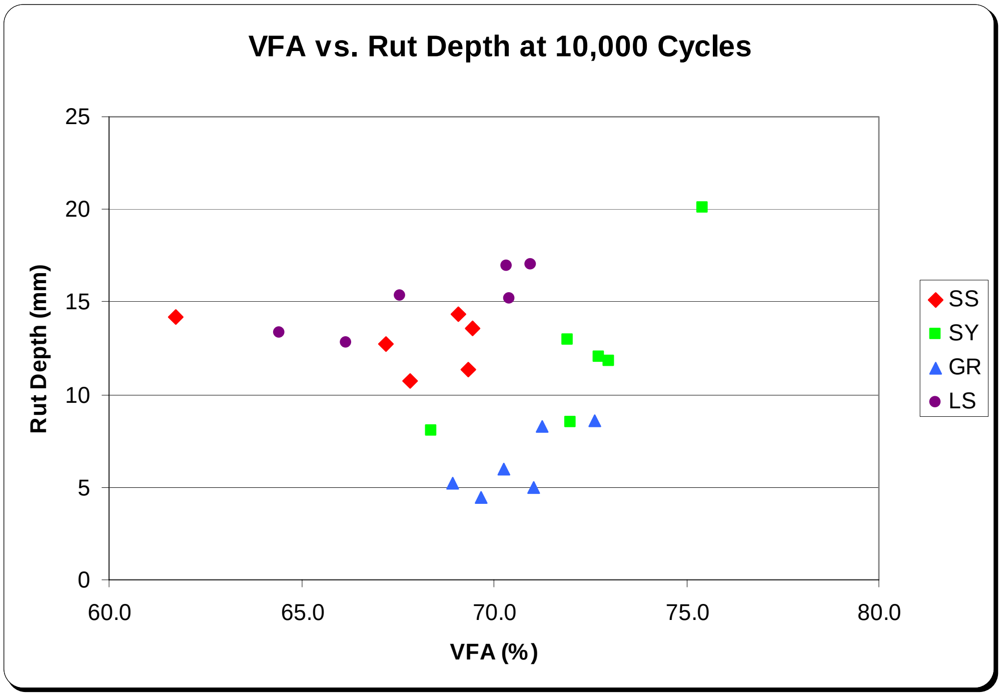

Figure 28. Trend graph - VFA vs. rut depth at 10,000 cycles in ERSA

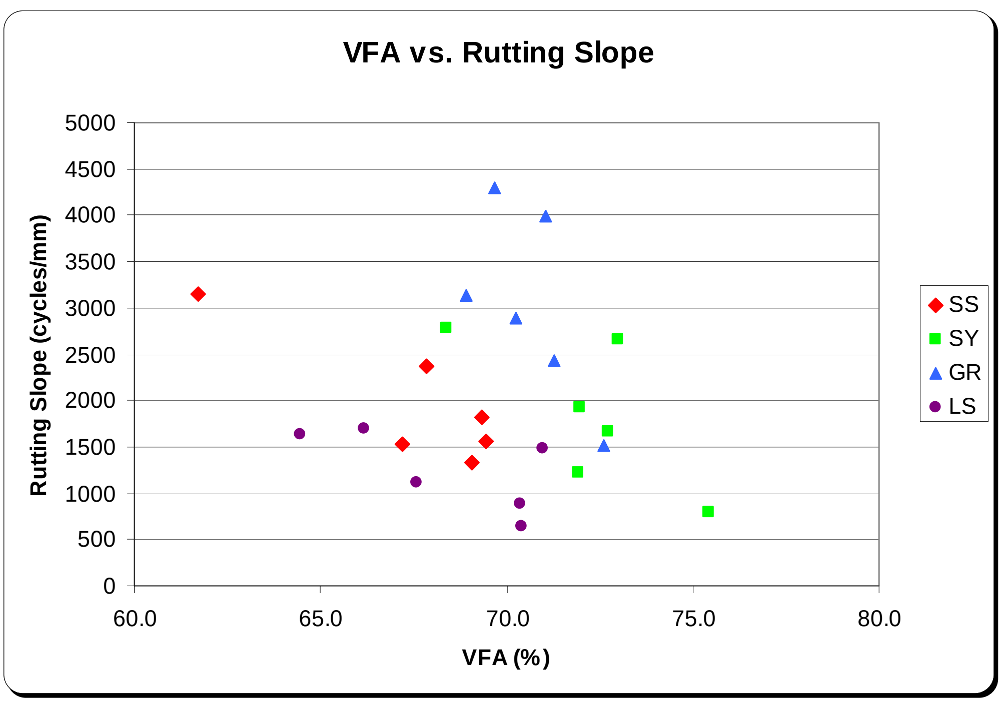

Figure 29. Trend graph - VFA vs. rutting slope in ERSA

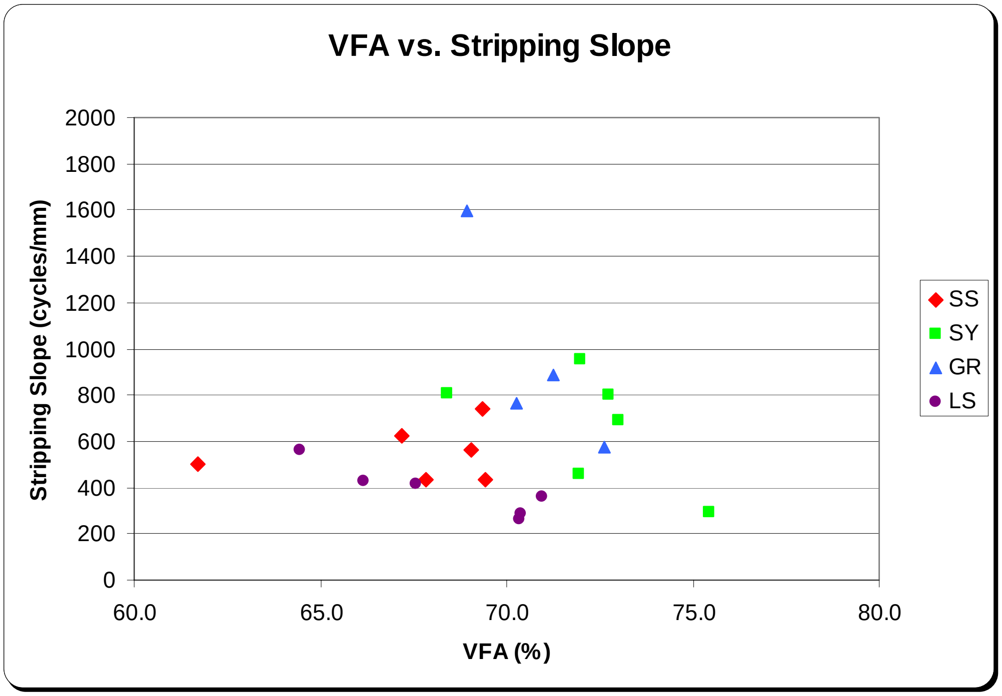

Figure 30. Trend graph - VFA vs. stripping slope in ERSA

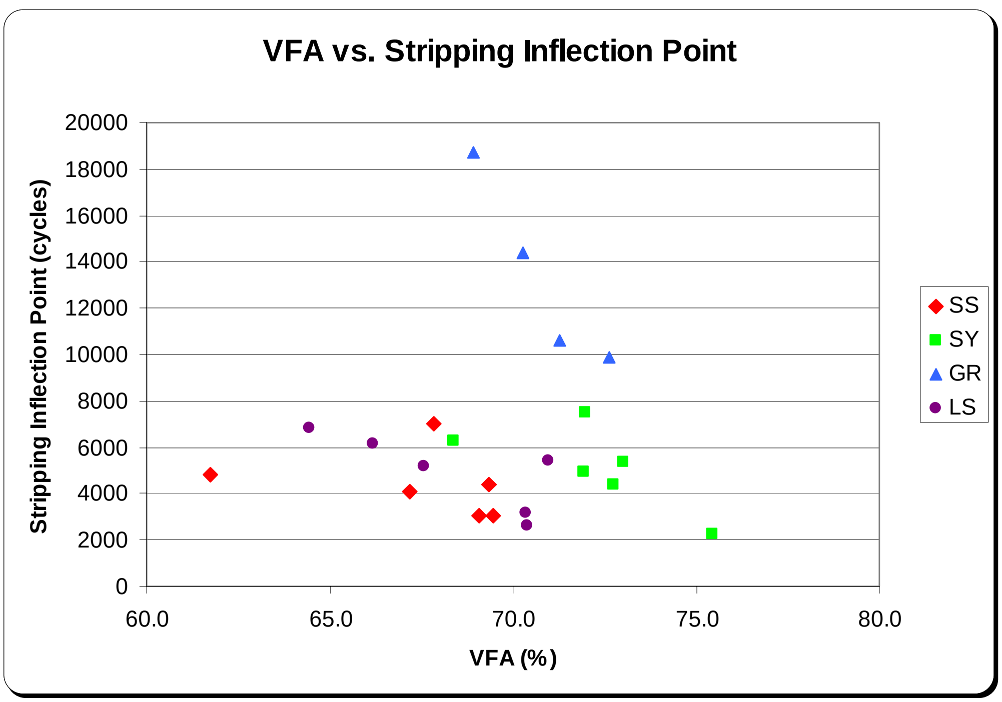

Figure 31. Trend graph - VFA vs. stripping inflection point in ERSA

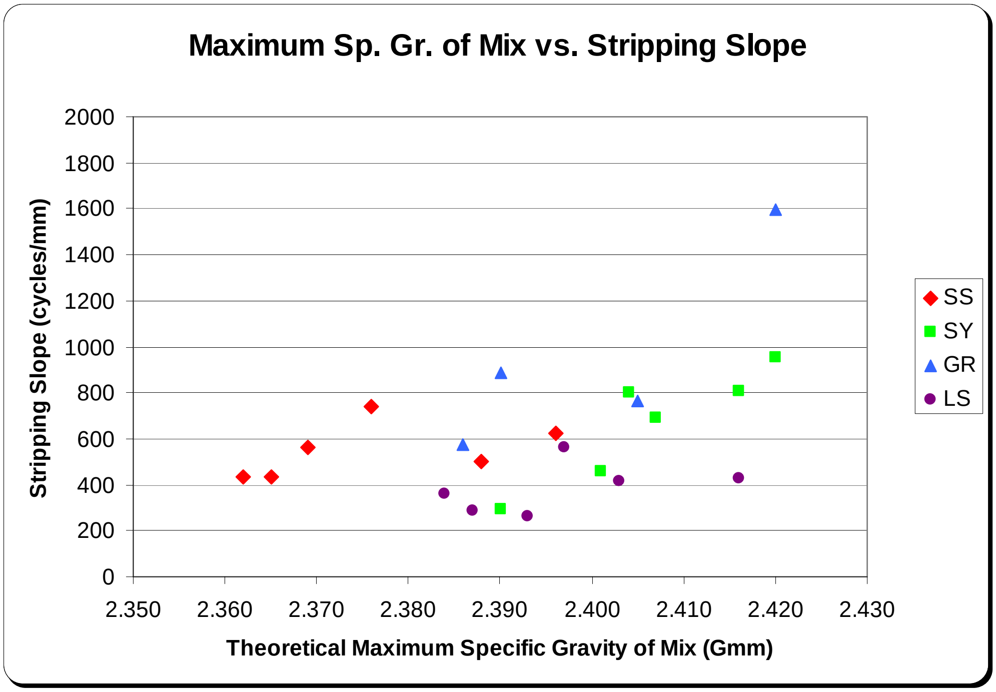

Figure 32. Trend graph – Gmm vs. stripping slope in ERSA

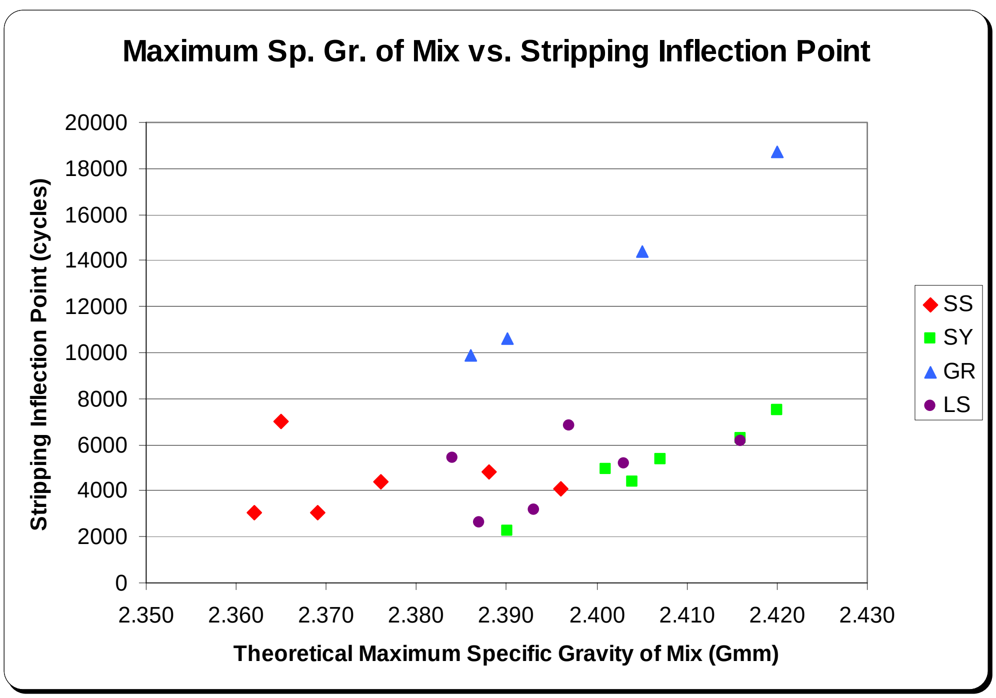

Figure 33. Trend graph – Gmm vs. stripping inflection point in ERSA

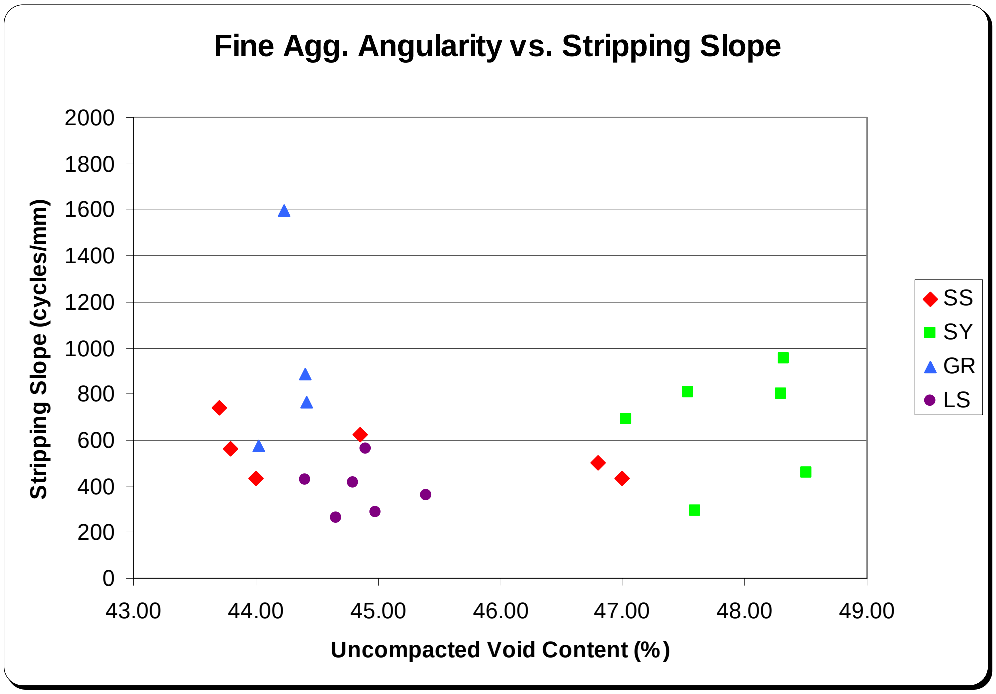

Figure 34. Trend graph – fine aggregate angularity vs. stripping slope in ERSA

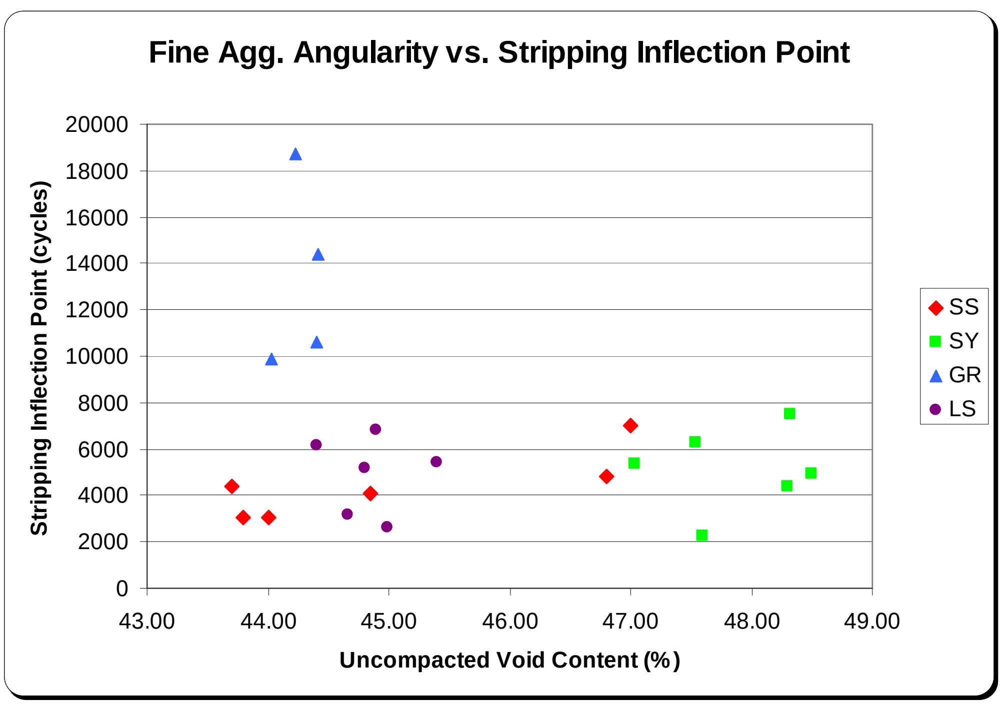

Figure 35. Trend graph – fine aggregate angularity vs. stripping inflection point in ERSA

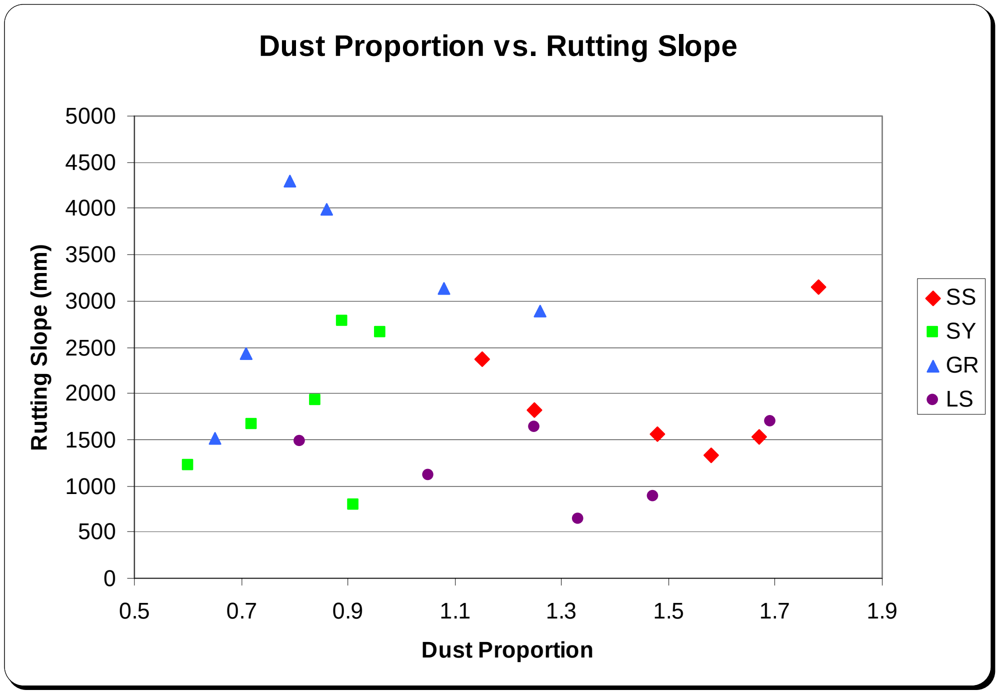

Figure 36. Trend graph – dust proportion vs. rutting slope in ERSA

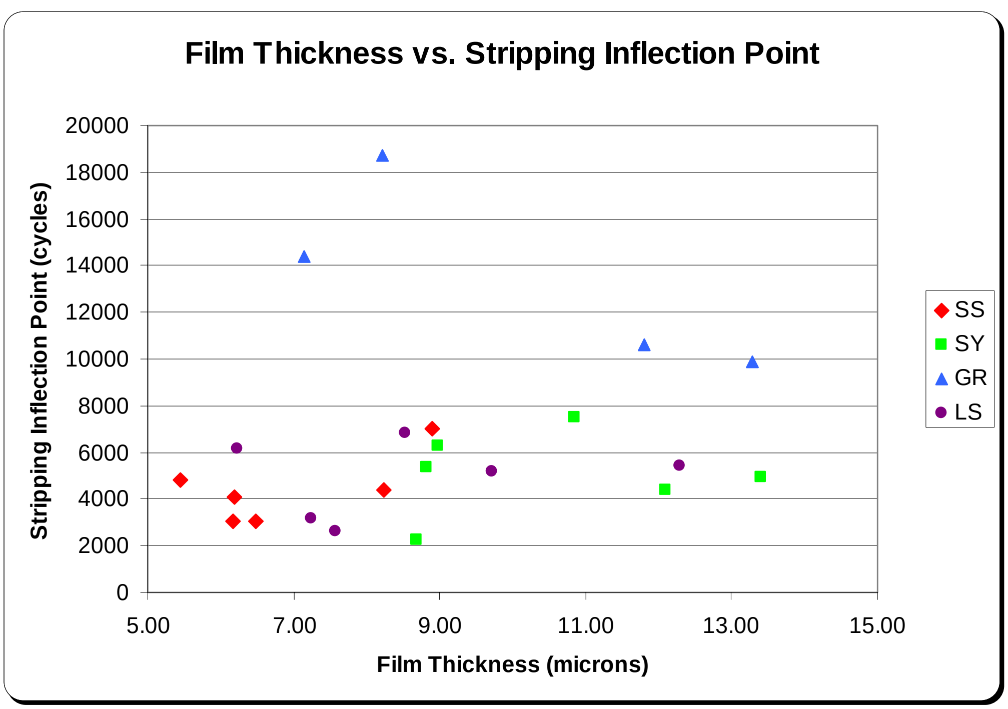

Figure 37. Trend graph – film thickness vs. stripping inflection point in ERSA

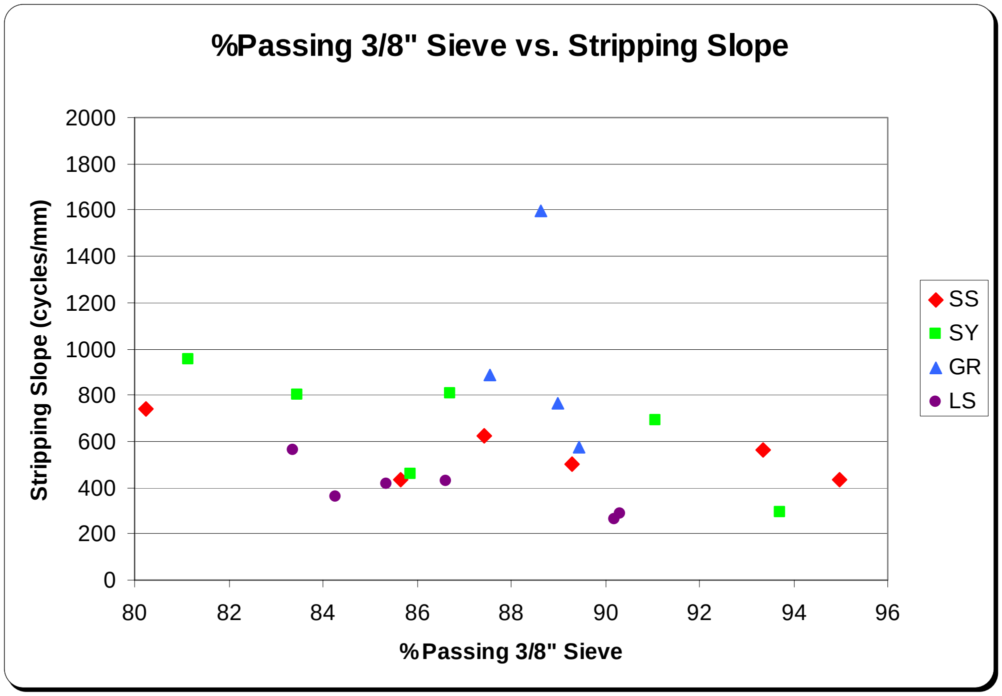

Figure 38. Trend graph – % passing 3/8″ sieve vs. stripping slope in ERSA

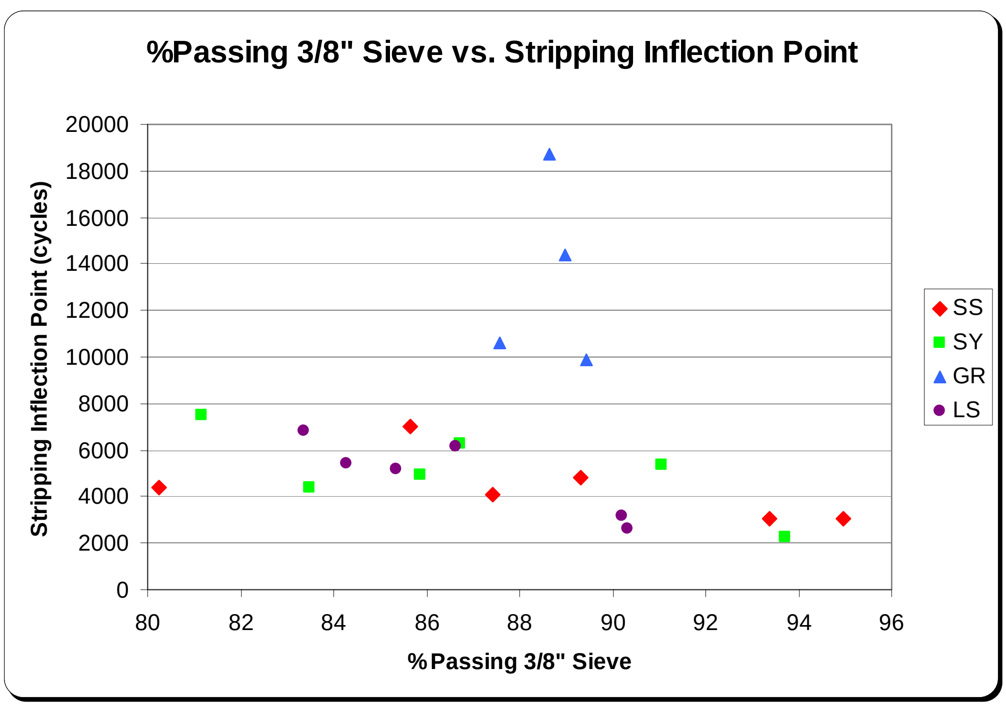

Figure 39. Trend graph – % passing 3/8″ sieve vs. stripping inflection point in ERSA

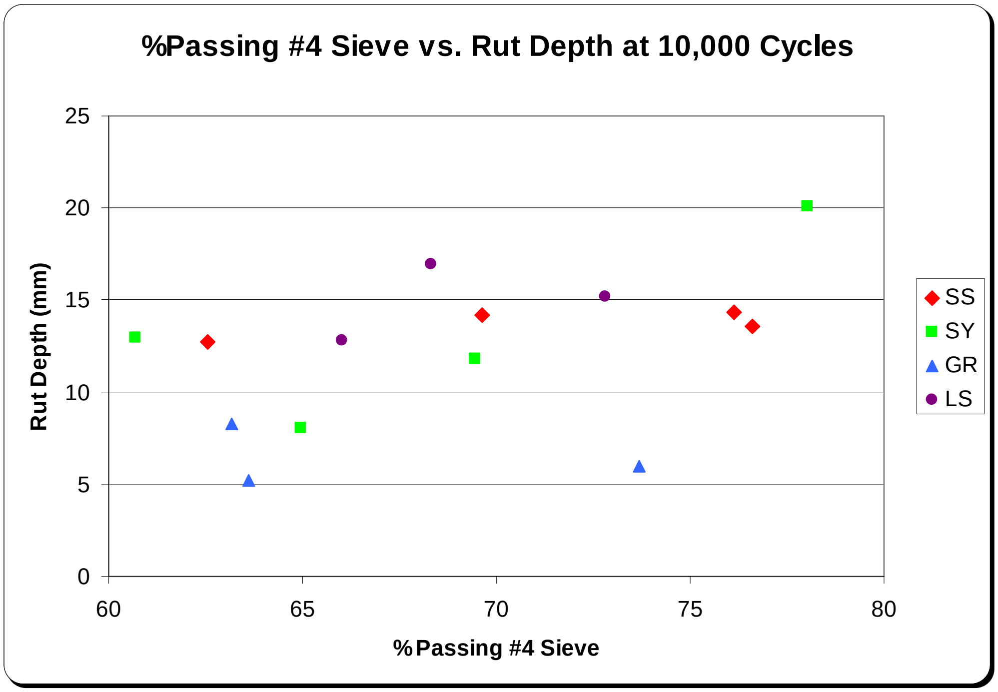

Figure 40. Trend graph – % passing #4 sieve vs. rut depth at 10,000 cycles in ERSA

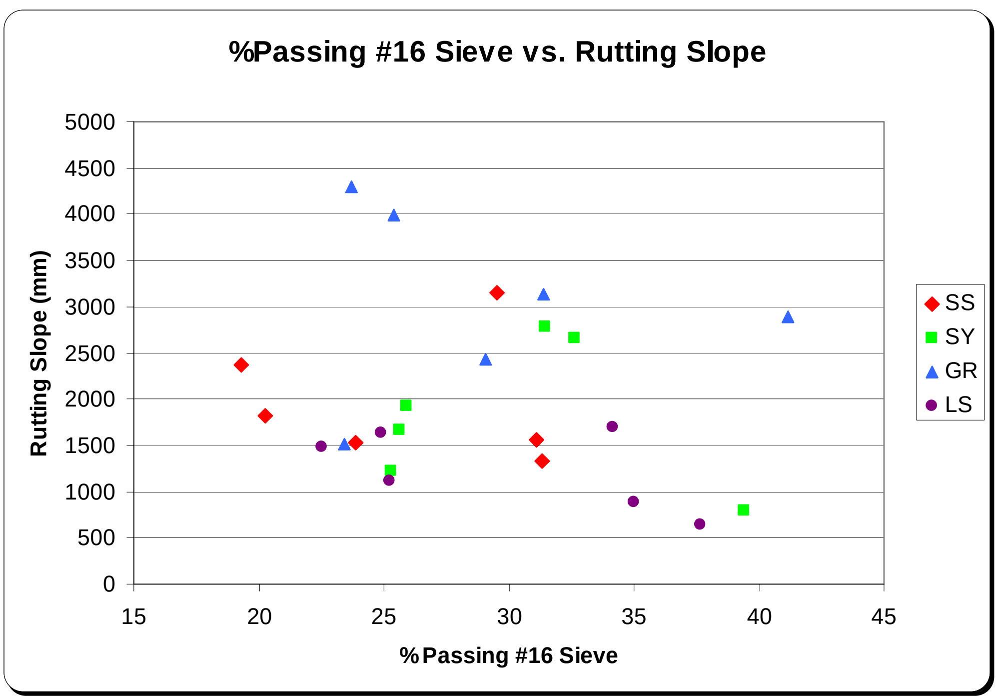

Figure 41. Trend graph – % passing #16 sieve vs. rutting slope in ERSA

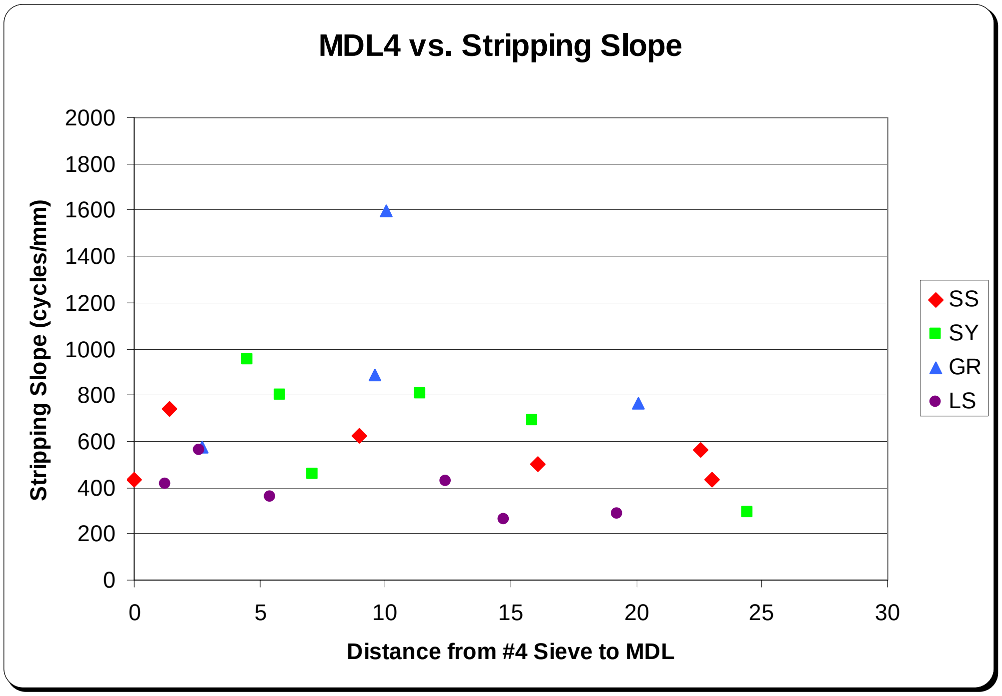

Figure 42. Trend graph – distance from MDL to #4 vs. stripping slope in ERSA

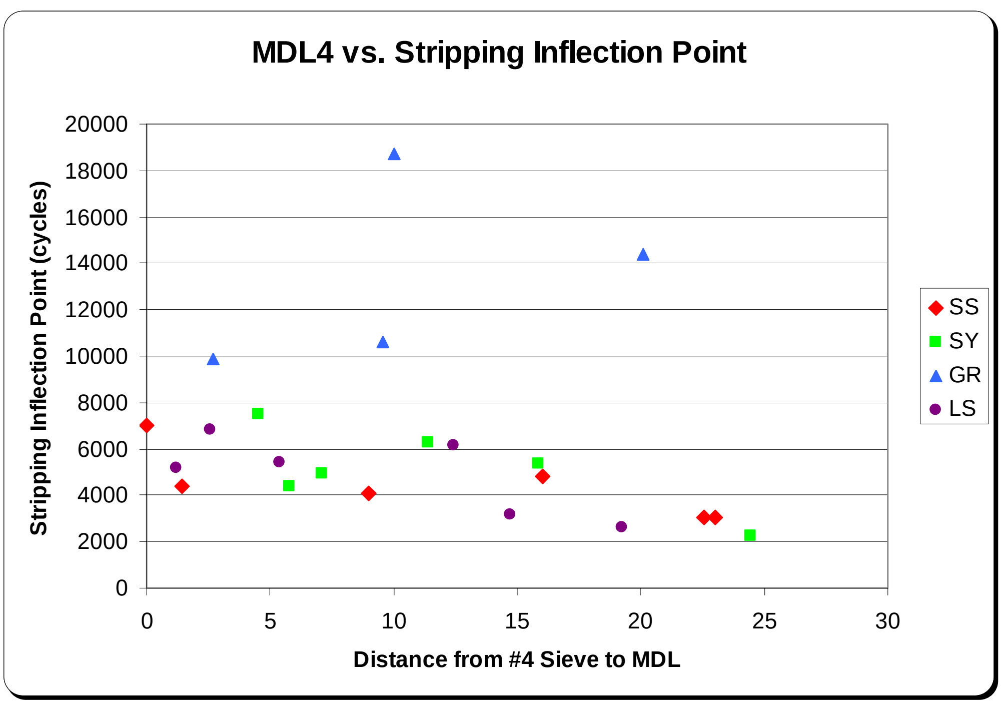

Figure 43. Trend graph – distance from MDL to #4 vs. stripping inflection point in ERSA

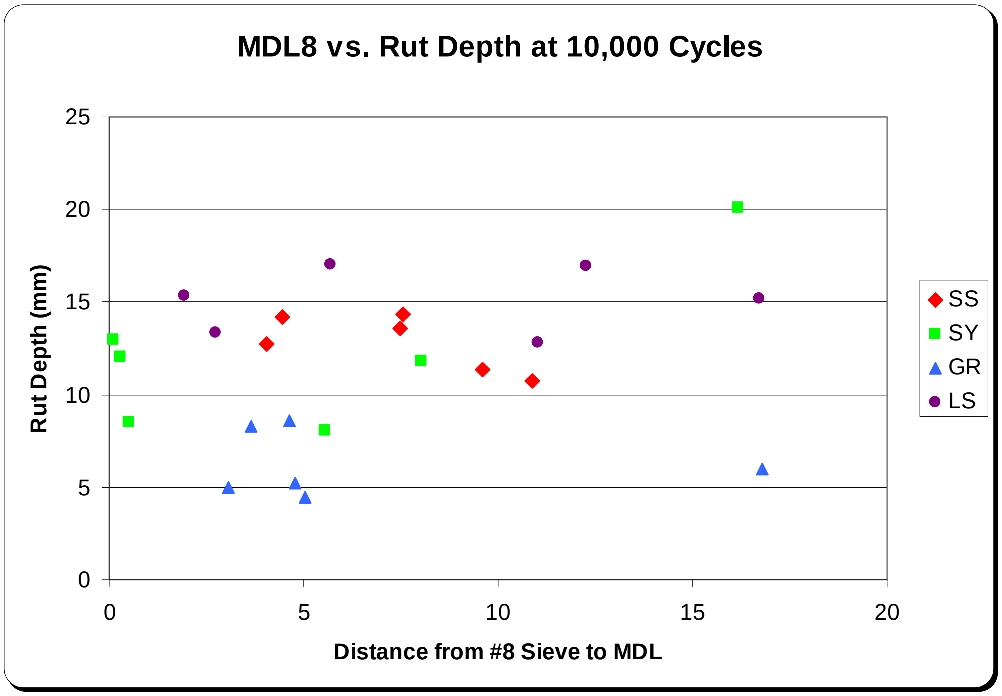

Figure 44. Trend graph – distance from MDL to #8 vs. rutting slope in ERSA

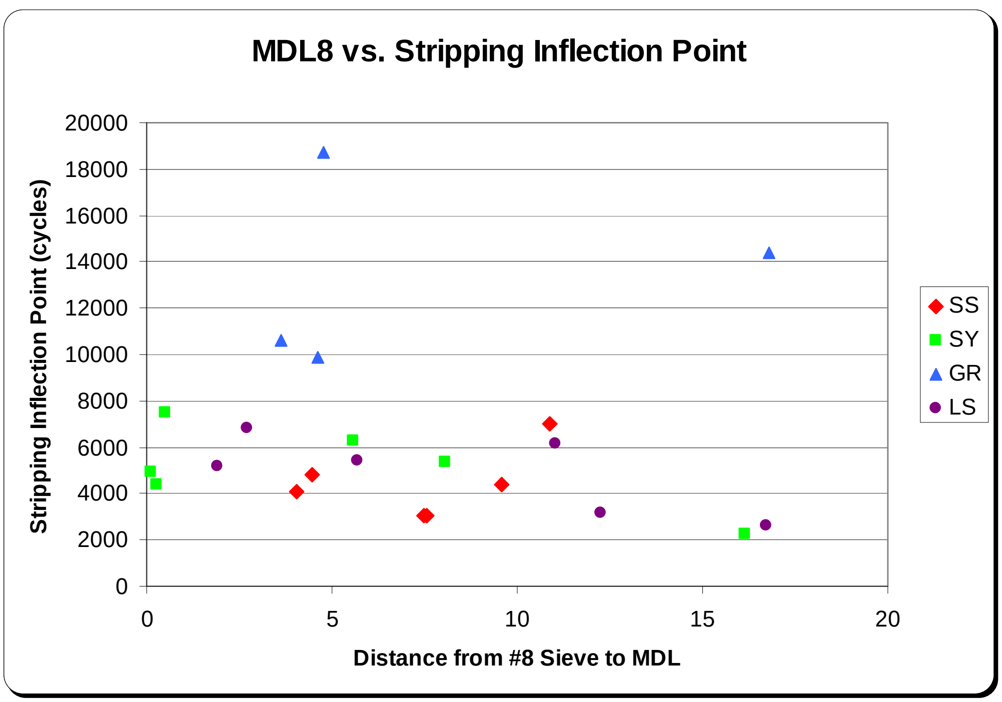

Figure 45. Trend graph – distance from MDL to #8 vs. stripping inflection point in ERSA

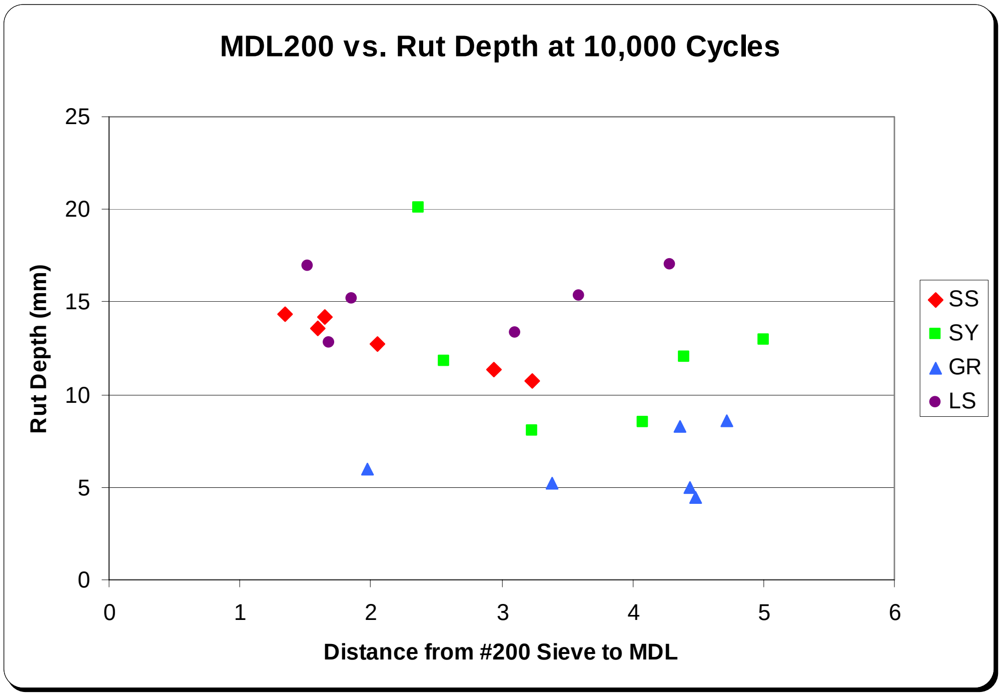

Figure 46. Trend graph – distance from MDL to #200 vs. rut depth at 10,000 cycles in ERSA

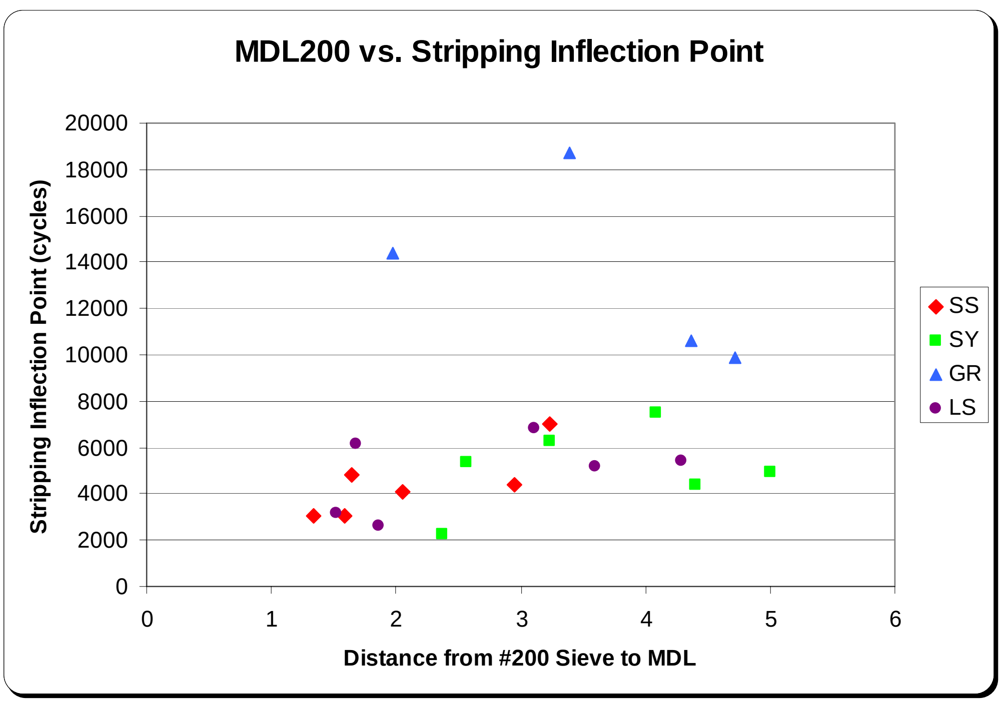

Figure 47. Trend graph – distance from MDL to #200 vs. stripping inflection point in ERSA

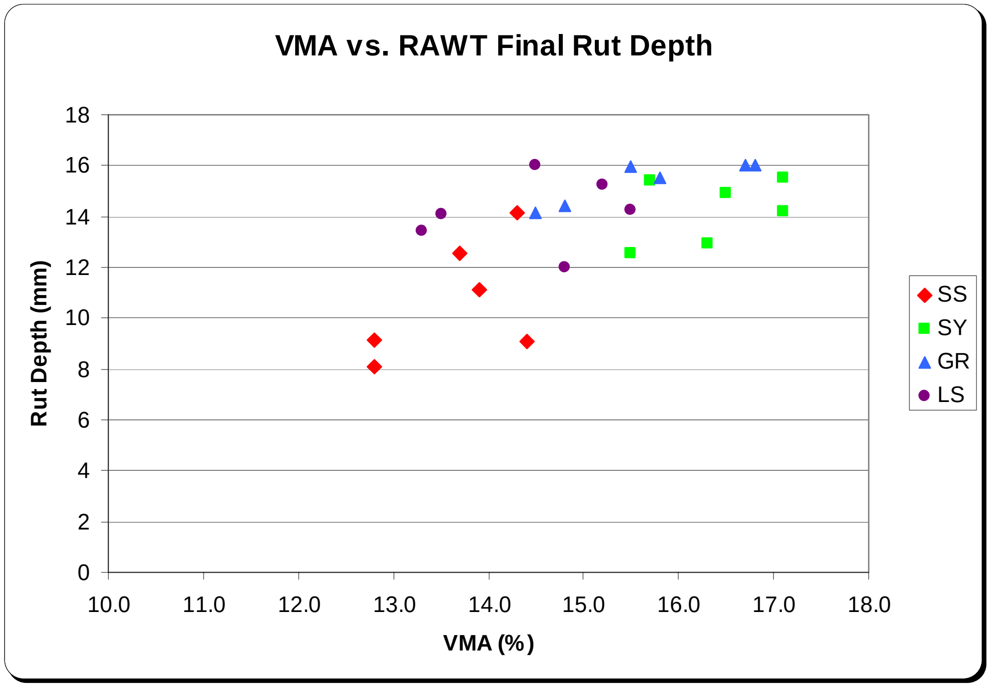

Figure 48. Trend graph – VMA vs. final rut depth in RAWT

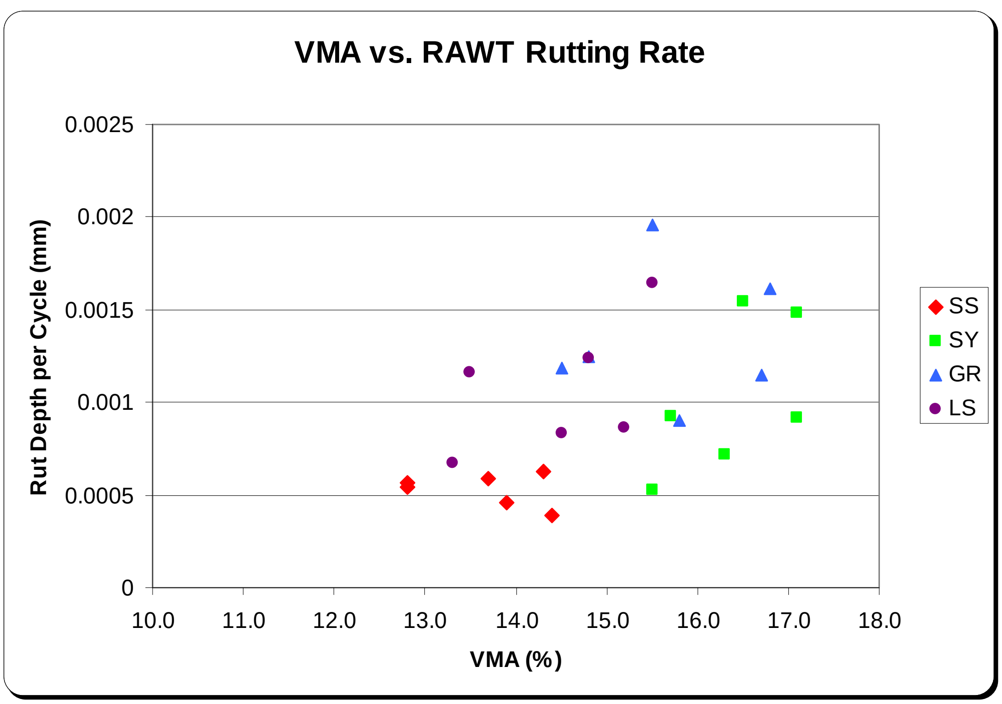

Figure 49. Trend graph – VMA vs. rutting rate in RAWT

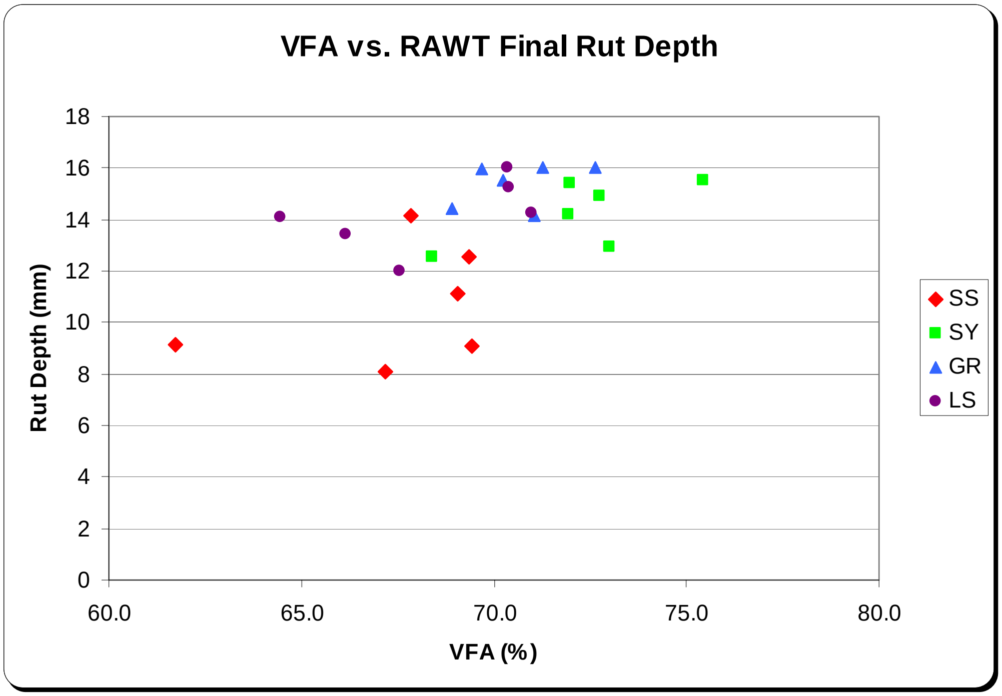

Figure 50. Trend graph – VFA vs. final rut depth in RAWT

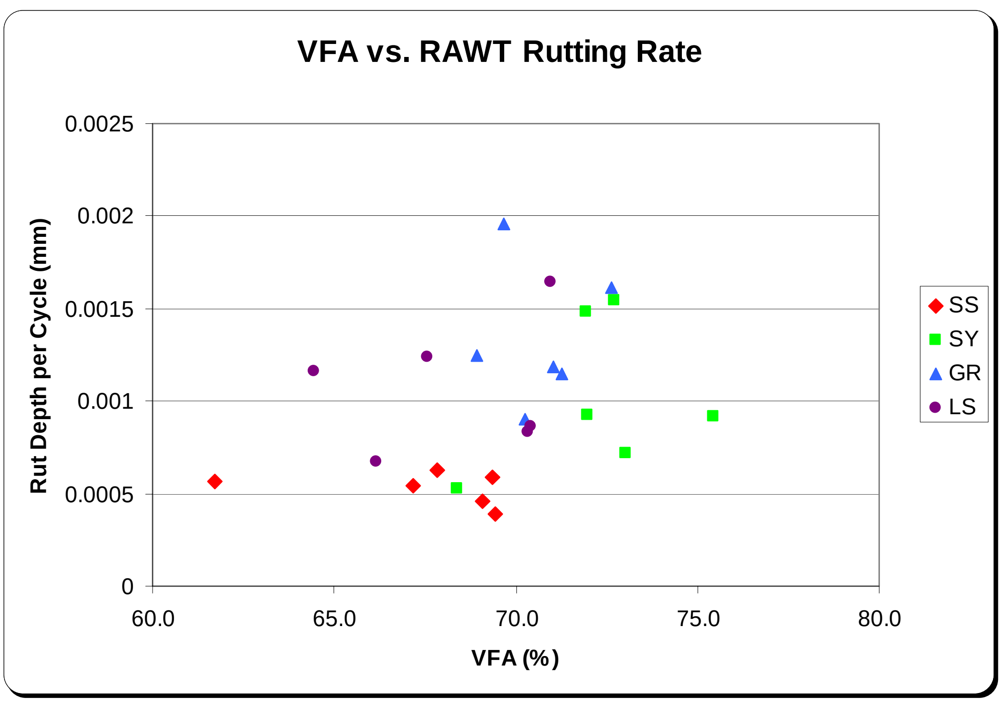

Figure 51. Trend graph – VMA vs. rutting rate in RAWT

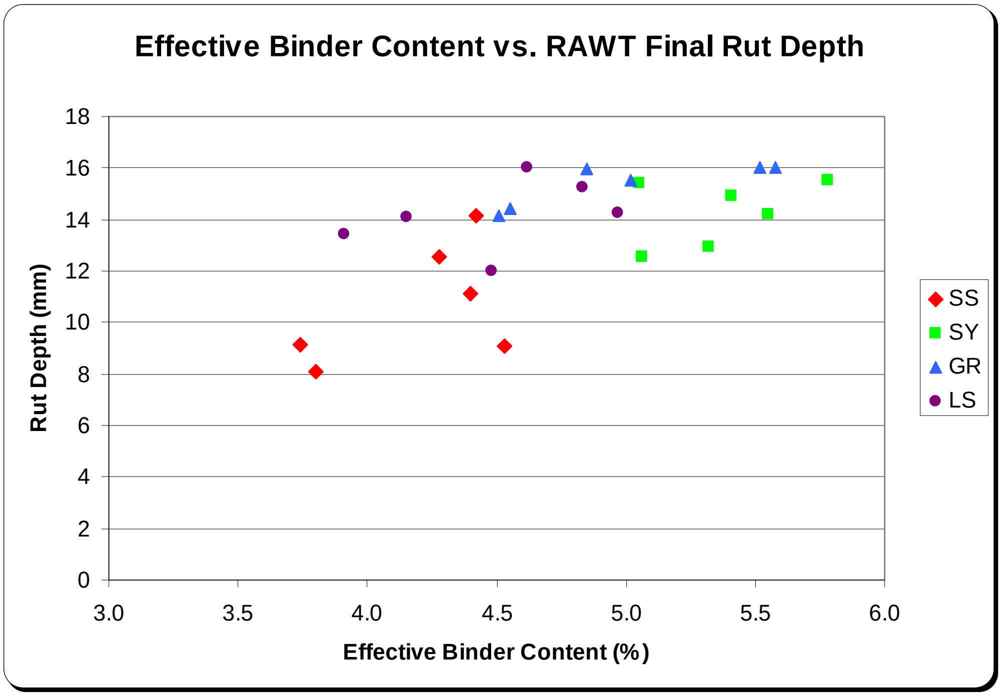

Figure 52. Trend graph – effective binder content vs. final rut depth in RAWT

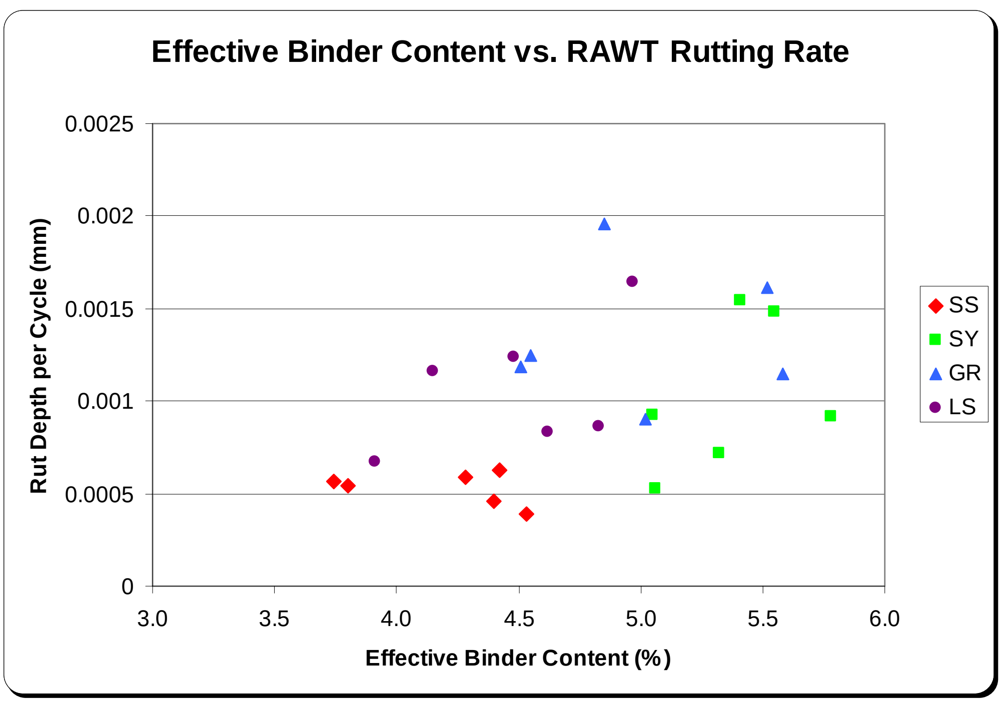

Figure 53. Trend graph – effective binder content vs. rutting rate in RAWT

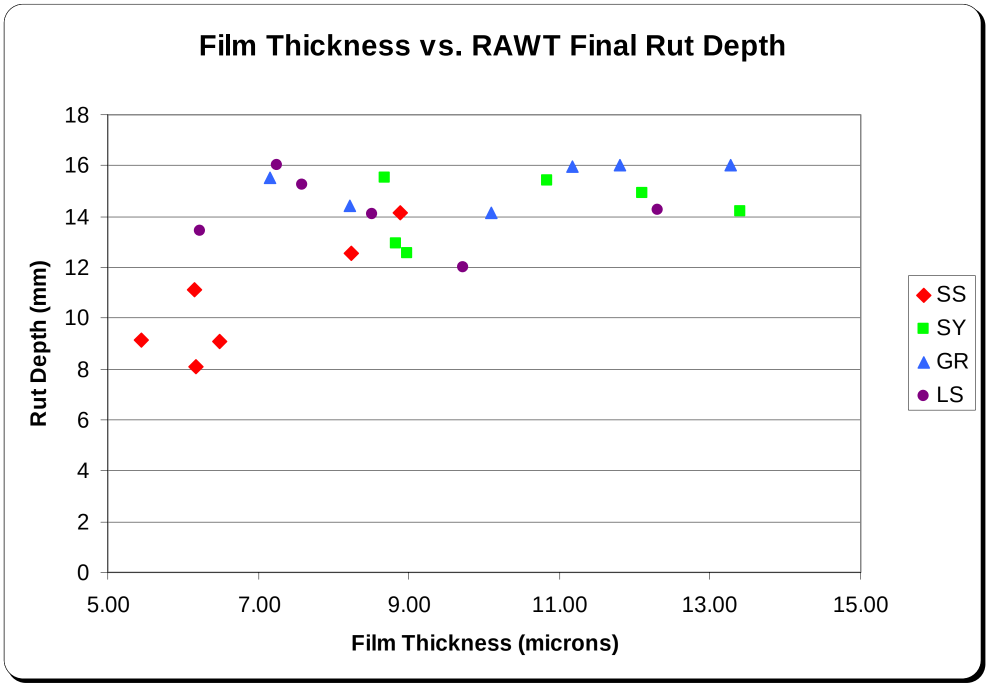

Figure 54. Trend graph – film thickness vs. final rut depth in RAWT

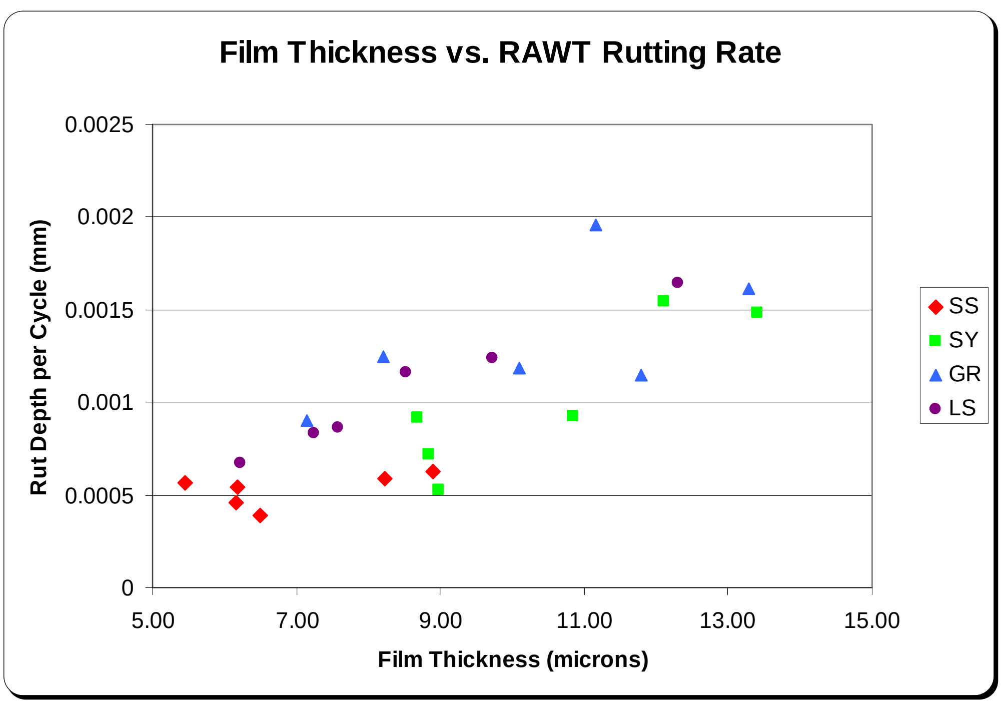

Figure 55. Trend graph – film thickness vs. rutting rate in RAWT

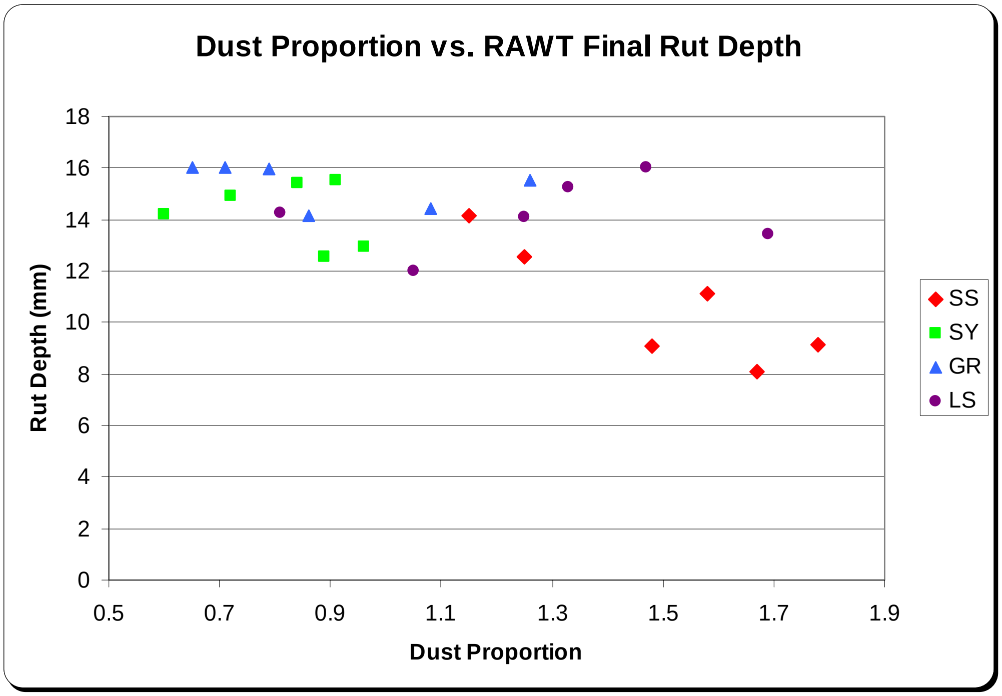

Figure 56. Trend graph – dust proportion vs. final rut depth in RAWT

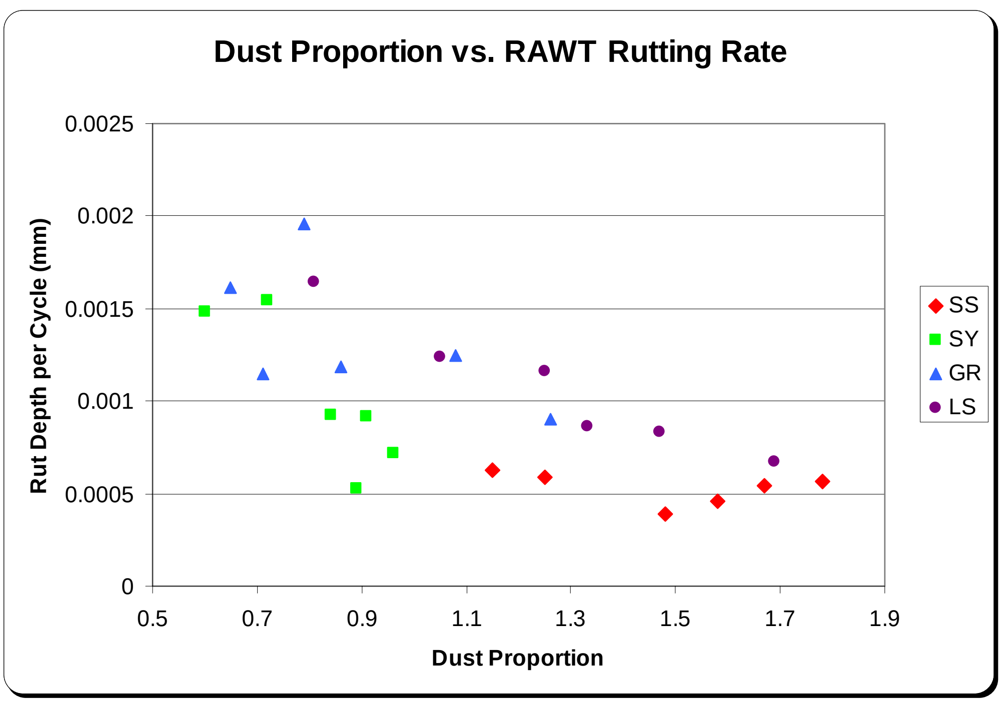

Figure 57. Trend graph – dust proportion vs. rutting rate in RAWT

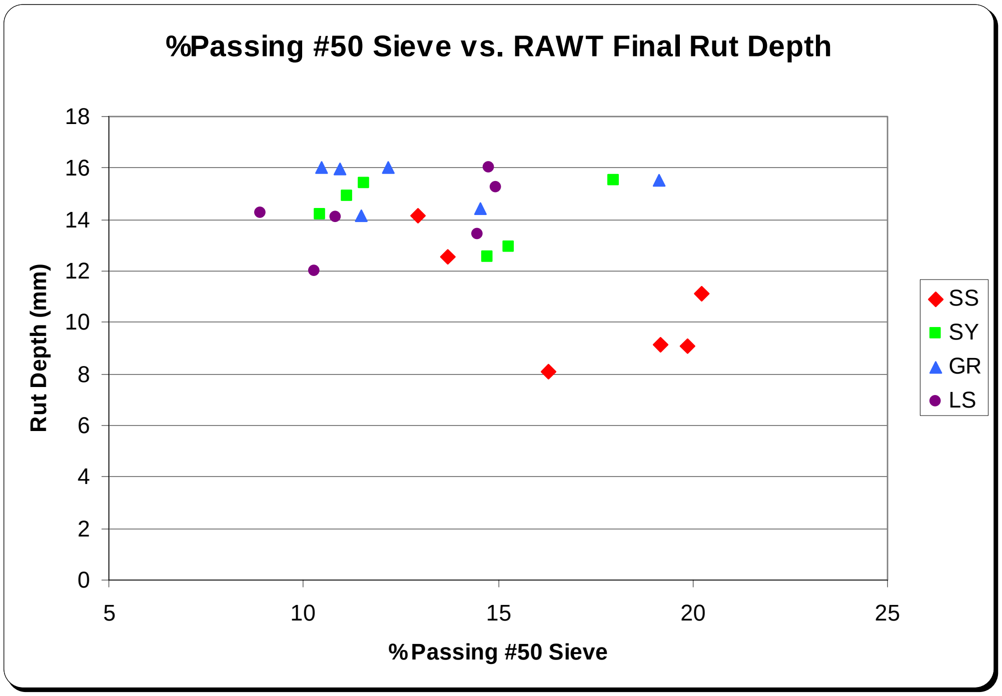

Figure 58. Trend graph – % passing #50 sieve vs. final rut depth in RAWT

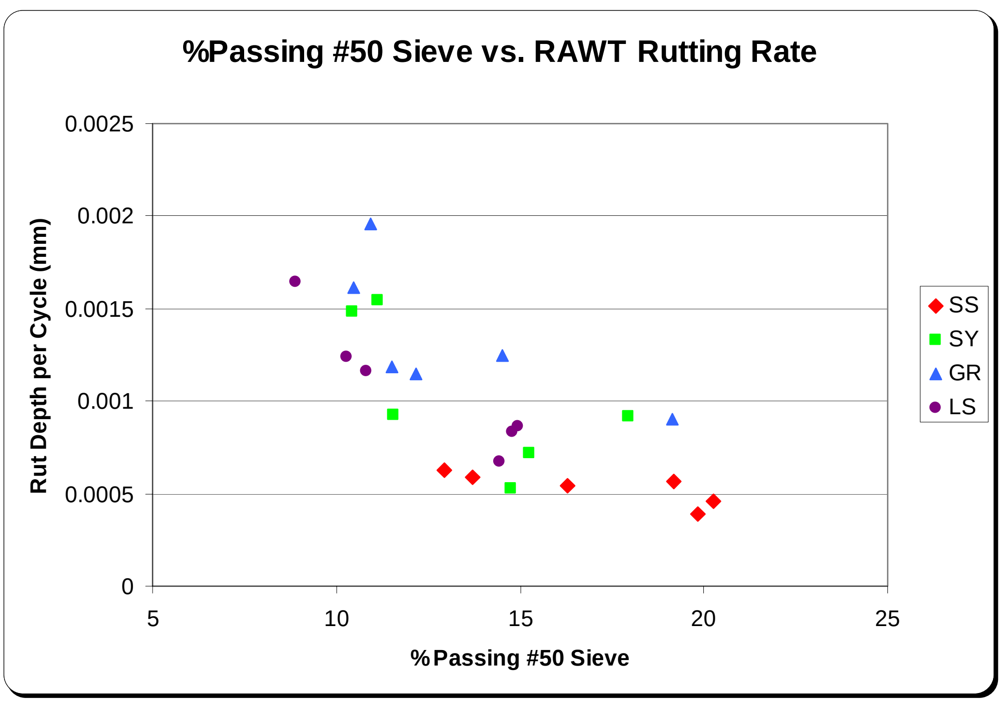

Figure 59. Trend graph – % passing #50 sieve vs. rutting rate in RAWT

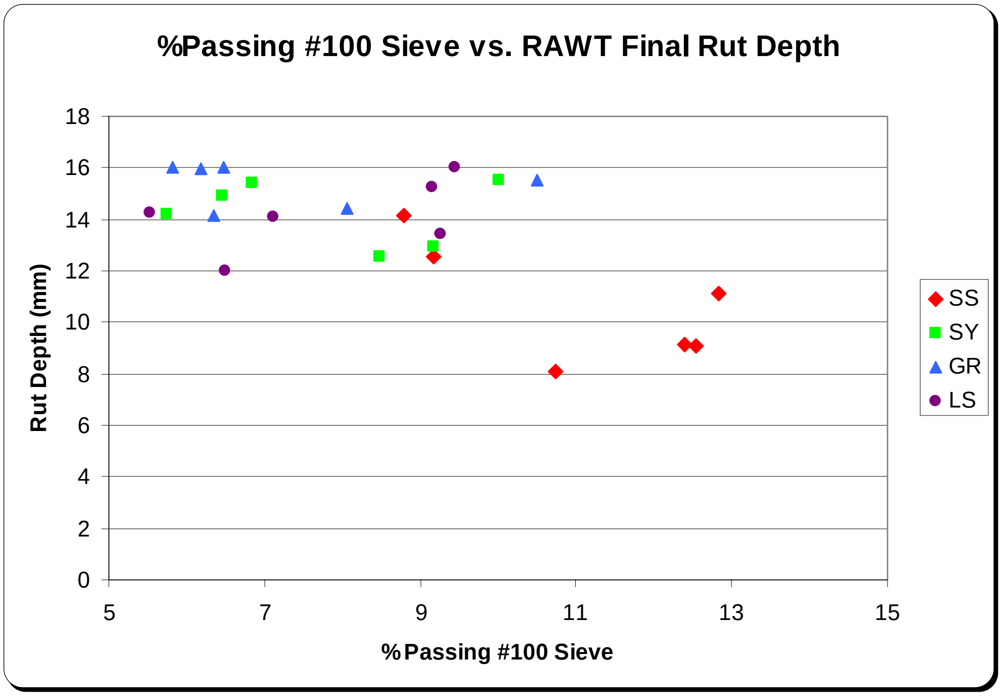

Figure 60. Trend graph – % passing #100 sieve vs. final rut depth in RAWT

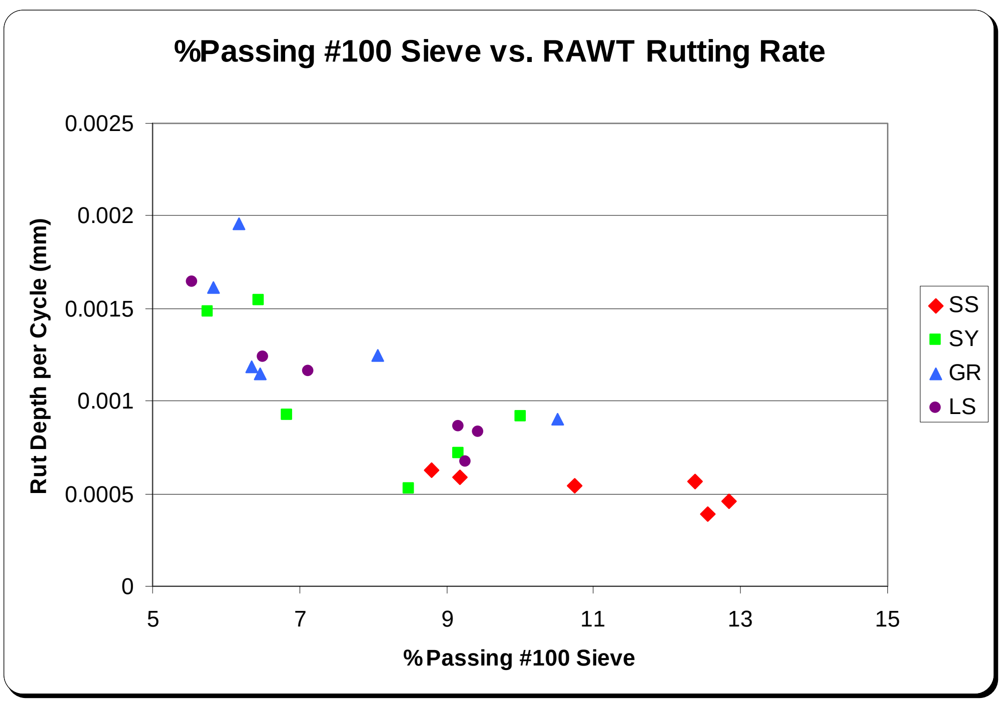

Figure 61. Trend graph – % passing #100 sieve vs. rutting rate in RAWT

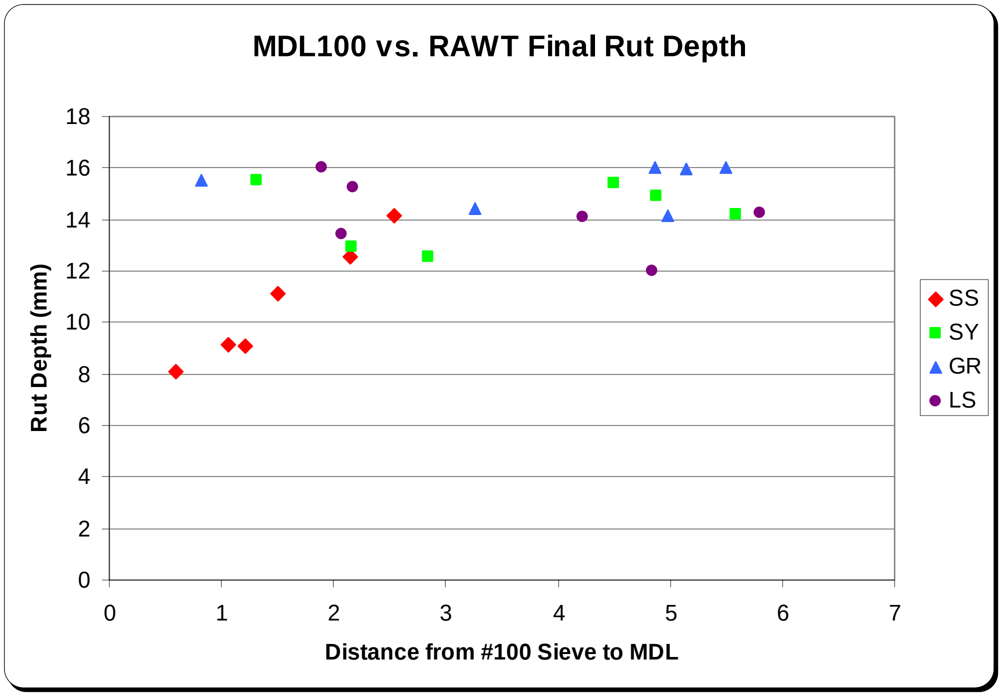

Figure 62. Trend graph – distance from MDL to #100 vs. final rut depth in RAWT

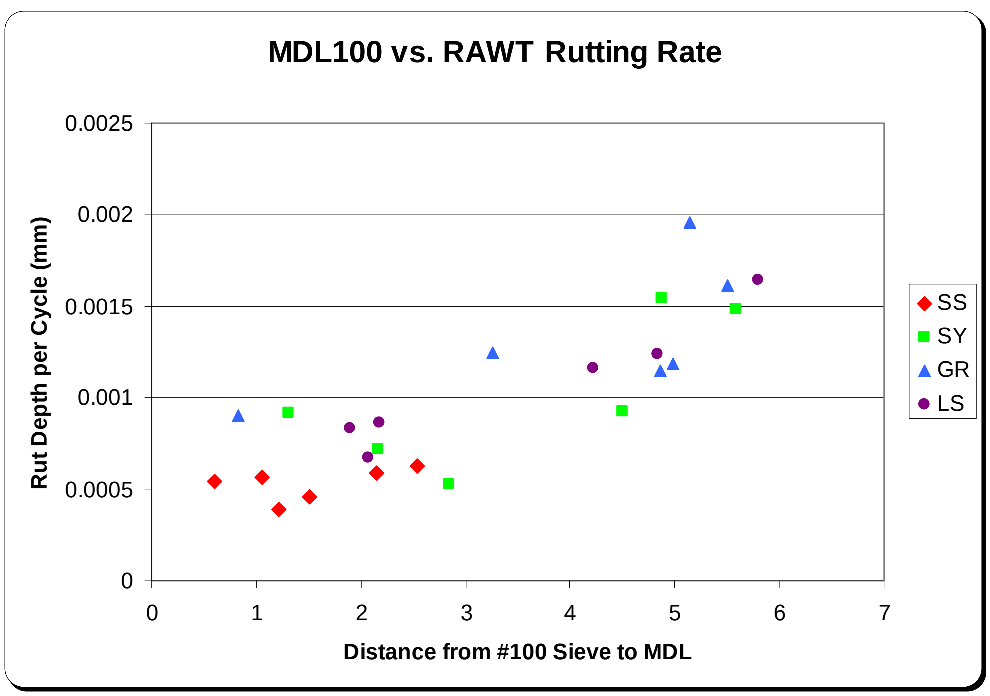

Figure 63. Trend graph – distance from MDL to #100 vs. rutting rate in RAWT

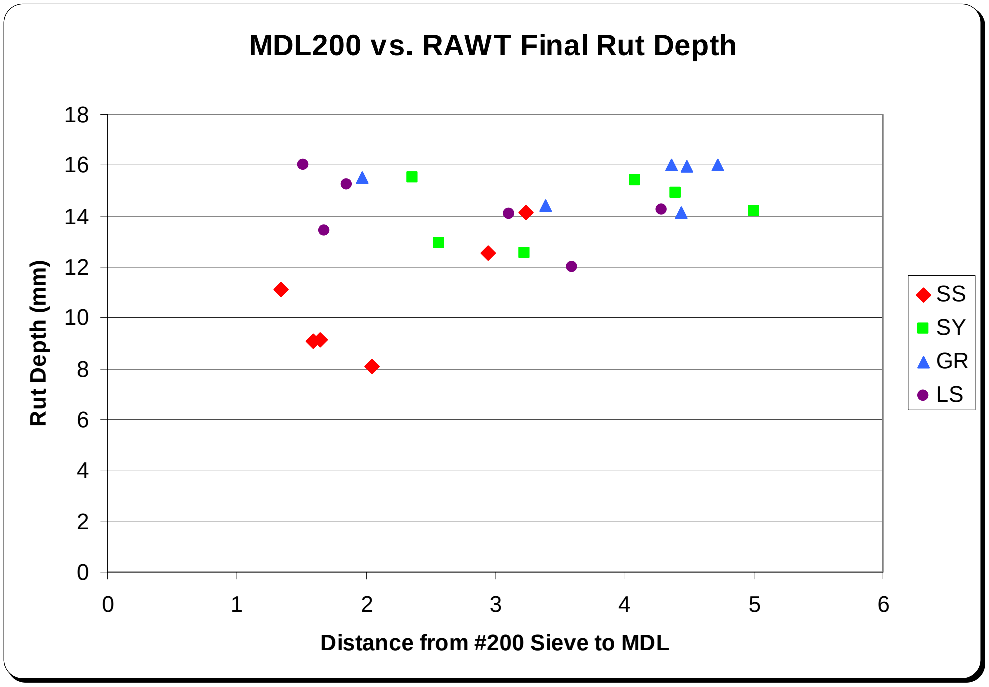

Figure 64. Trend graph – distance from MDL to #200 vs. final rut depth in RAWT

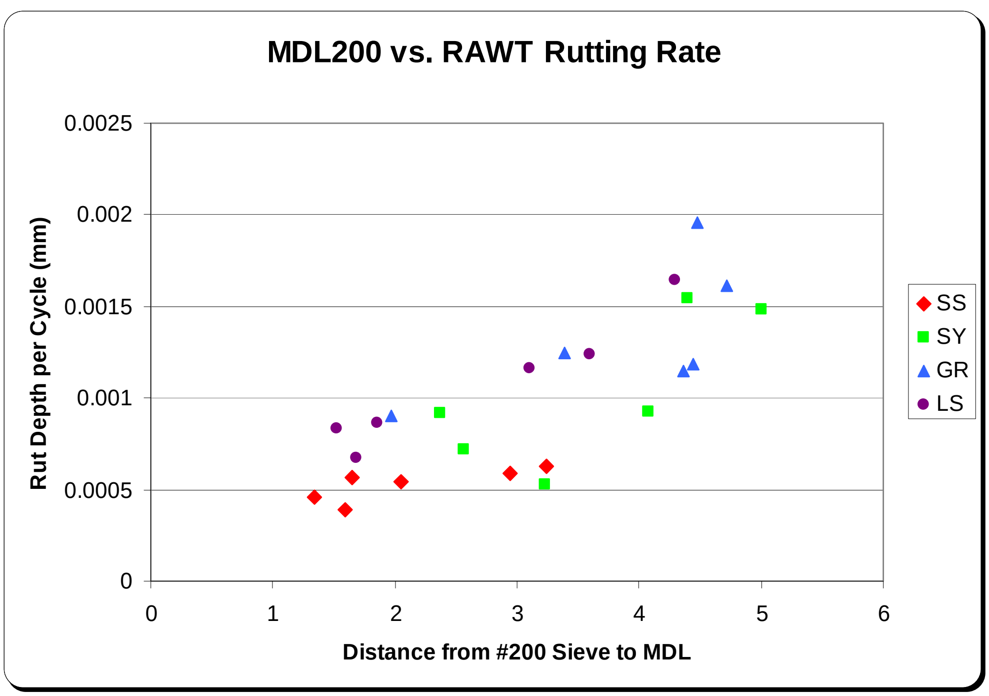

Figure 65. Trend graph – distance from MDL to #200 vs. rutting rate in RAWT

DISCUSSION

VMA

Perhaps the most difficult part of the mix design process is determining an aggregate structure that will allow for the desired volume of VMA while meeting all other volumetric property specifications. This was certainly true for this project, since mixtures were purposely designed with such a wide range of VMA. The different VMA values were derived by changing the aggregate structure, not by simply changing the binder content. This was an important step in creating the most optimum conditions for each mix type because merely adjusting the binder content to increase VMA is likely to negatively impact performance. Thus, the results of this study were based on the true effects of changes in design VMA rather than the effects of construction variation.

Early in the design process, it became apparent that the various aggregate sources seemed to have a "natural range" of VMA. The original target values were a low VMA of 13.5 percent, a medium VMA of 14.5 percent, and a high VMA of 15.5 percent. However, this was not possible to achieve for all aggregate sources. Some mixes easily achieved a low level of VMA while others easily achieved a high level of VMA. This difference was based, in part, on the aggregate bulk specific gravity. As the aggregate density increased, the natural range of VMA also increased. Thus, the target ranges were adjusted accordingly. Also, the "correct" value for VMA is source-dependent. For this reason, general minimum and maximum values for required VMA may not be as effective in a design specification as originally hoped. An adjustment for the VMA specification range based on aggregate specific gravity could be beneficial in allowing flexibility to mix designers without sacrificing quality. Additional emphasis should be placed on ensuring that mixes are designed at "the bottom" or "slightly on the dry side" of the VMA curve. A performance test should then be used to screen mixes with respect to rutting and stripping.

Aggregate Bulk Specific Gravity

Another point of discussion is the issue of aggregate bulk specific gravity. The published precision values for this property are such that the precision for VMA is quite large. A difference of just 0.02 in aggregate bulk specific gravity will create a difference in VMA of approximately 0.7 percent. Acceptable differences could actually be much larger, since the acceptable range of two results for different operators is reported to be 0.066 for fine aggregate and 0.038 for coarse aggregate. *(16)* Additionally, aggregate specific gravity tests are performed on individual aggregates, or portions of aggregate, then combined mathematically to generate a "blend" value. Thus, a systematic error in the determination of this property for each material could translate into an even larger error for the gravity of the blend of aggregates, further perpetuating the error in VMA. Fluctuations in the density of stockpiled aggregates can also exacerbate this problem. For these reasons, it seems that more frequent aggregate testing could be beneficial to the consistency of HMA material properties.

According to current AHTD specifications, VMA is calculated based on the effective specific gravity of the aggregate, then corrected for the difference in the effective and bulk specific gravity of the aggregate. Since the aggregate's effective specific gravity can be easily obtained from the maximum theoretical specific gravity of the mix (which is tested regularly for quality control purposes), changes in aggregate density can be detected. However, additional aggregate testing during production would provide a more direct method for detecting stockpile variation.

RAWT Tests

Most of the samples tested in this study exhibited some amount of stripping. When a sample strips, the binder separates from the aggregate particles, and mixture cohesion is reduced such that individual particles are loosened from the sample. In the ERSA test, and similar to field conditions, small stripped particles may wash away, but larger and heavier particles remain near their original location, and are usually with the sample at the end of a test. In the RAWT, the sample orientation is such that when a particle loosens from the sample, it falls to the bottom of the testing chamber. When emptying the water bath after a RAWT test, particles of all sizes may be present. In contrast, sample particles in the bottom of the ERSA water bath (after testing) are generally smaller than the #50 sieve. Thus, the loss of large particles during a RAWT test is more likely for a coarse-graded sample, and the loss of such particles translates to a smaller sample dimension (i.e., greater rut depths) than would be measured if the loose particles had remained with the sample. Thus, for samples that exhibit significant stripping potential (as was the case in this study), the RAWT may over-estimate rut depths for coarse-graded mixes. A ruggedness study could be beneficial to the future of the RAWT.

Another challenge associated with the RAWT device was the fact that the test would terminate early if the sample developed a rough wheel path. This was a beneficial feature when a sample had experienced a significant amount of rutting and the test was near completion. However, some RAWT tests were terminated early, yet had experienced only a small amount of actual rutting. Thus, the results were fairly inconclusive. For this reason, test results from RAWT samples that experience early termination should be considered very carefully or disregarded altogether.

Film Thickness

The property of film thickness was included in this study, however, no significant conclusions were drawn. Since film thickness is based on aggregate surface area factors that do not account for the shape or texture of the particles, this calculation is suspect. In fact, the Asphalt Institute warns against the use of these factors for the calculation of film thickness. *(12)* Thus, the lack of conclusion regarding this value is also insignificant.

There are many practical reasons that film thickness should be valuable predictor of mixture rutting performance, and many researchers have suggested that innovative methods for the measurement of this property be investigated further. One possible method is to use technologically advanced optical measurement systems. In Figure 66, a photo of an enlarged mixture particle is shown. The particle was approximately ¼” in length, and was fractured so that the varying thicknesses of asphalt films could be viewed. With current digital imaging capabilities, analysis programs are available that could be adapted for the determination of average film thickness. This technology should be further investigated as a means for measuring film thickness. If this property could be accurately determined, mix design specifications could use film thickness, in addition to VMA, as a means to more efficiently control the balance of a mixture’s constituent materials.

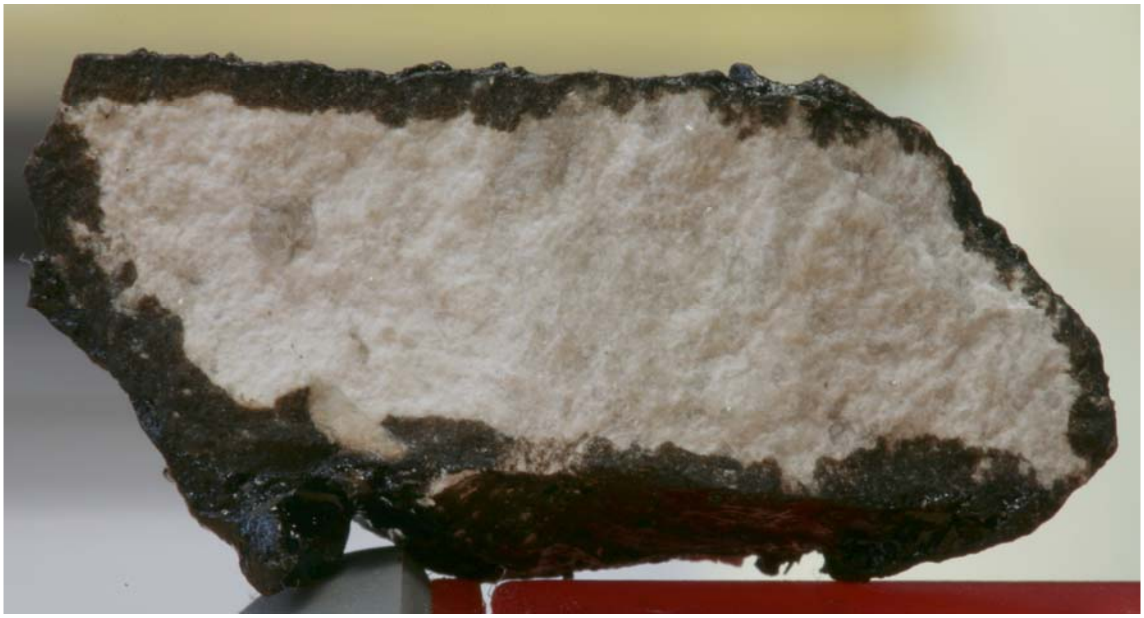

Figure 66. Fractured face of ¼" aggregate particle showing film thickness

Baghouse Fines

For each of the mix designs, a small portion (approximately one percent) of baghouse fines was included in the blend gradation. This helped the laboratory mixes to more closely simulate those in the field. In an effort to determine what effects, if any, that these fines had on performance, specific gravity and hydrometer analyses were performed on duplicate samples of baghouse fines from each aggregate source. The syenite baghouse fines exhibited the coarsest grading, and the limestone baghouse fines were very finely graded. Baghouse fines from the sandstone and gravel sources displayed similar, and intermediate gradings. No significant relationships were found between the specific characteristics of these fines and mixture performance.

CONCLUSIONS

Twenty-four mix designs were created to examine the effects of VMA and gradation type, as well as other mixture characteristics, on the rutting and stripping potential of four aggregate sources. Based on the performance of the mixes as tested in the ERSA and the RAWT, the following conclusions were made.

VMA and Gradation

The Evaluator of Rutting and Stripping in Asphalt (ERSA)

- Based on ERSA tests, VMA had a greater influence on pavement rutting performance than did gradation.
- Mixtures with low VMA were more resistant to rutting than those with high VMA.
- Gradation type was a more important factor relating to stripping performance than for rutting performance.
- Coarse-graded mixtures were less susceptible to stripping than fine-graded mixtures.
- Coarse-graded mixes were more sensitive to the testing variables than fine-graded mixes.

The Rotary Asphalt Wheel Tester (RAWT)

- In terms of rut depth, the RAWT was significantly affected by VMA. Mixes with low VMA showed smaller rut depths.
- In terms of rutting rate, both gradation and VMA significantly affected rutting performance, with preference being given to fine-graded mixes.

- Fine-graded mixes had lower rutting rates than their coarse-graded counterparts, and coarse-graded mixes with low and medium VMA had poorer performance than coarse-graded mixes with high VMA.
- Overall, the results of the RAWT testing program were mixed.

It is recommended that both fine- and coarse-graded mixtures be allowed as per current AHTD specifications. Coarse-graded mixtures should be designed with low VMA. A reduction in the current VMA criteria would not be detrimental to pavement rutting performance, especially for coarse-graded mixtures.

HMA Mixture Properties

- No mathematical models were determined to be adequate for predicting pavement rutting and stripping performance based solely on the volumetric properties determined during mixture design.
- Several trends relating mixture properties to performance were established.
- As binder content increased, rutting and stripping performance decreased.
- As VMA increased, rutting and stripping performance decreased.
- As VFA increased, rutting increased and stripping decreased.
- As film thickness increased, rutting susceptibility increased, while stripping susceptibility decreased slightly.
- As fine aggregate angularity increased, stripping susceptibility decreased for some aggregate sources.
- Dust proportion did not appear to consistently affect rutting or stripping performance, but may be related to aggregate source.
- Gradation had more influence on stripping than on rutting.

- Increasing the amount of the coarse portions in a blend gradation improved stripping performance.
- Gradation affected the performance of mixtures from some aggregate sources more than others.
- Increasing the distance between the #4 sieve and the maximum density line decreased stripping performance slightly.
- Increasing the distance between the #200 sieve and the maximum density line provided greater rutting and stripping resistance for some aggregate sources.

In order to enhance the rutting performance of HMA mixtures, the following guidelines should be followed: binder content should be reduced, VMA should be minimized, VFA should be reduced, fine aggregate angularity should be increased, the amount of coarse aggregate should be increased, and the distance between the percent passing the #200 sieve and the maximum density line should be increased. The benefit of these suggestions may vary according to aggregate type.

A <u>critical</u> step in the design of an HMA mixture is the determination of optimum binder content. Care should be exercised such that the optimum binder content of a mix is that which corresponds with, or is slightly less than, the minimum VMA. It is recommended that additional emphasis be placed on the accuracy of the VMA curve, as well as the appropriate selection of optimum binder content.

Additional Topics

- Errors in aggregate bulk specific gravity values were found to significantly affect calculated values of VMA.

It is recommended that the bulk specific gravity of the aggregate be tested regularly during production.

- For stripping-susceptible mixes, test results from the RAWT may be somewhat biased, favoring fine-graded mixtures.

It is recommended that a ruggedness study be performed to establish the effects of testing variables in the Rotary Asphalt Wheel Tester.

- Film thickness was not determined to have a statistically significant predictive correlation to pavement rutting or stripping performance, however the methods used for its calculation are known to be suspect.

It is recommended that further study be performed to investigate innovative methods for measuring binder film thickness. In this effort, digital alternatives should be considered.

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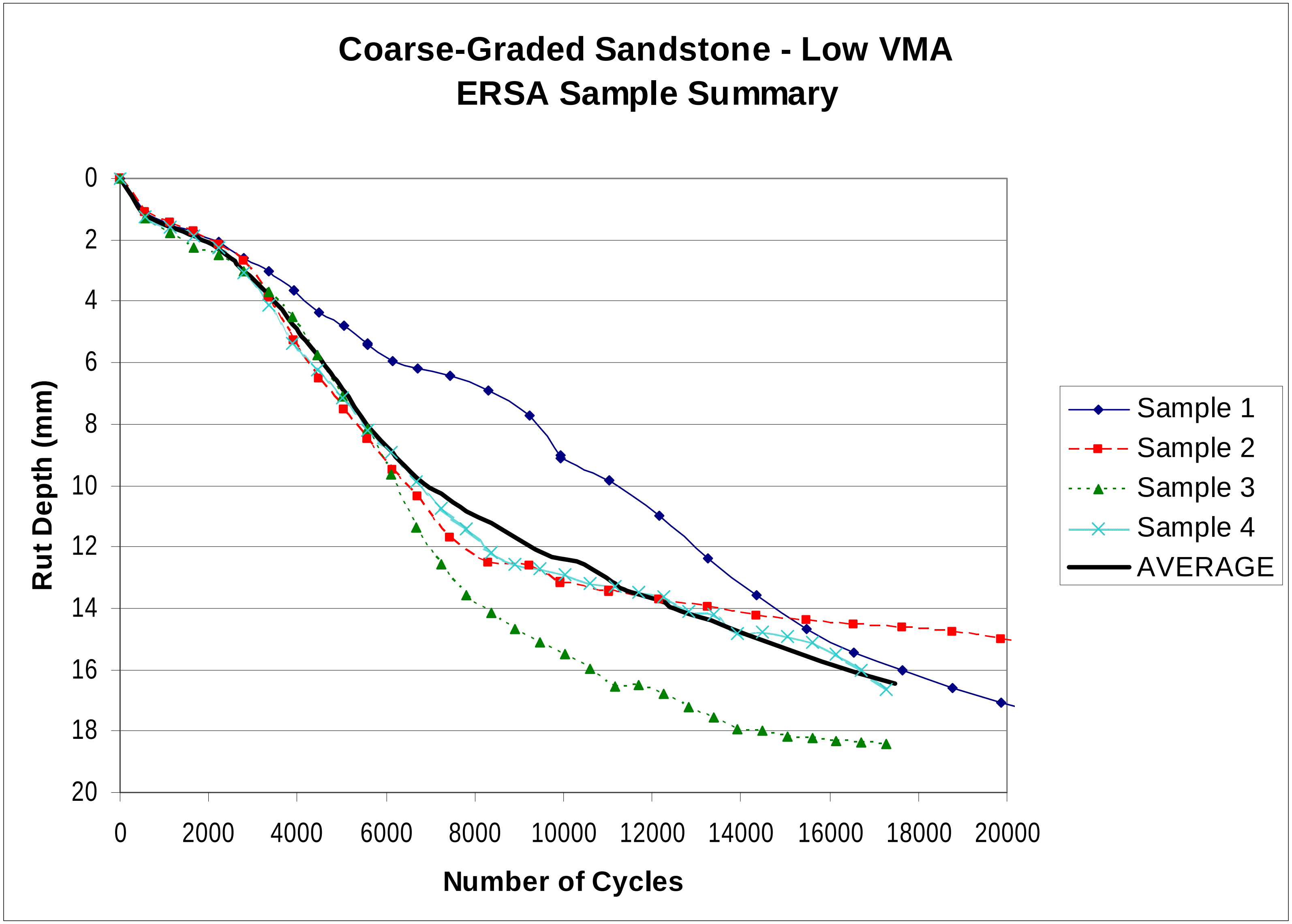
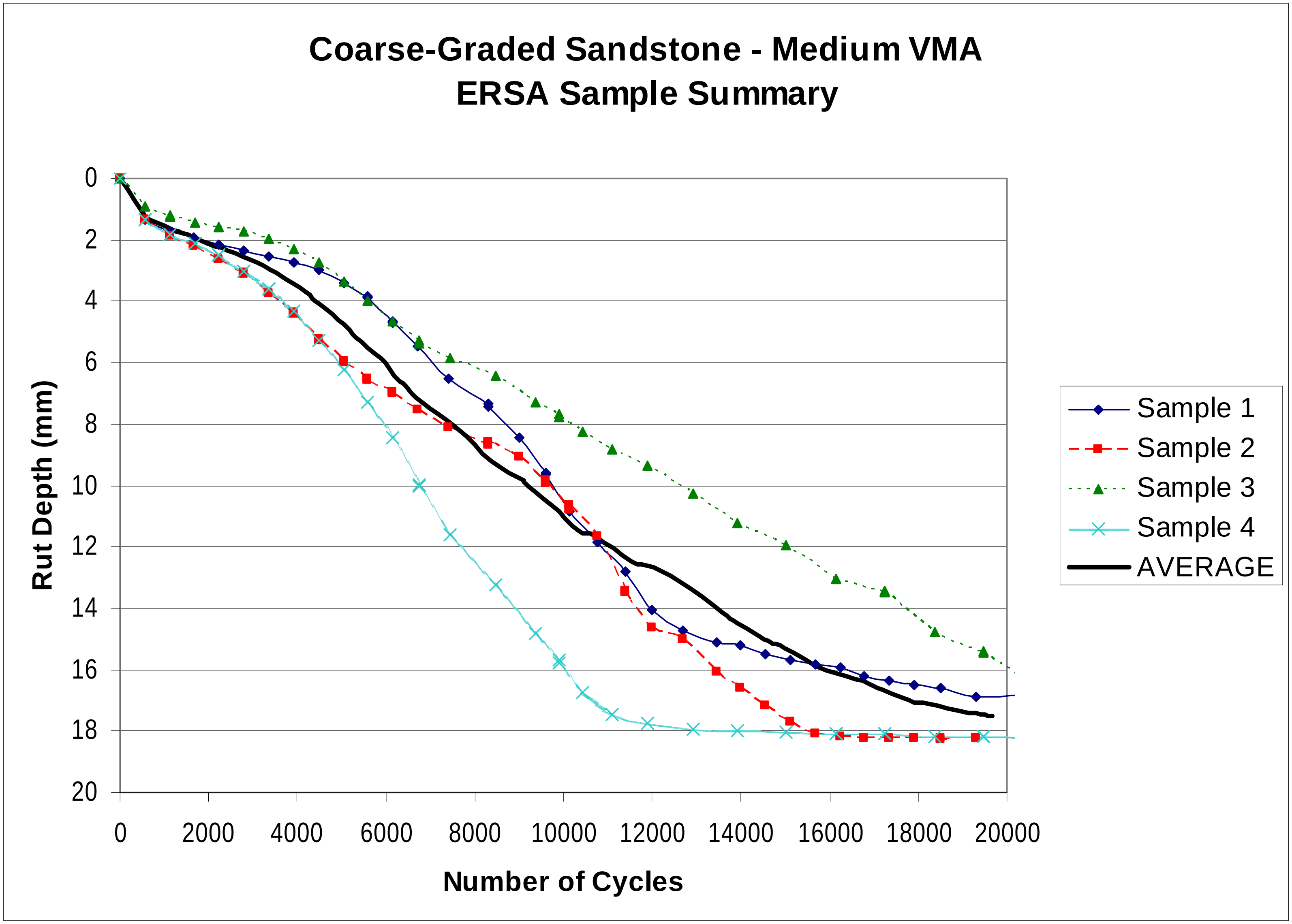
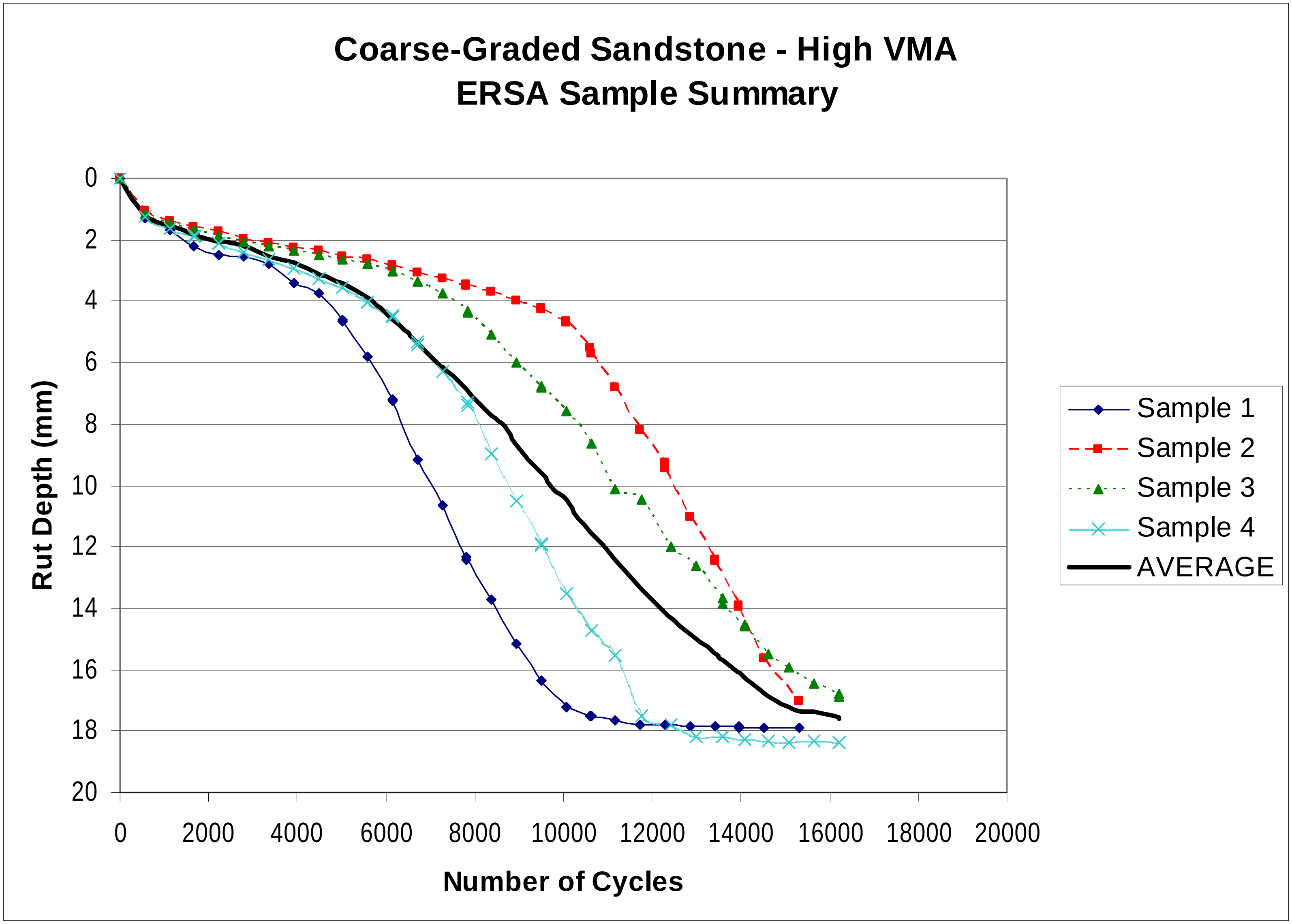
APPENDIX A

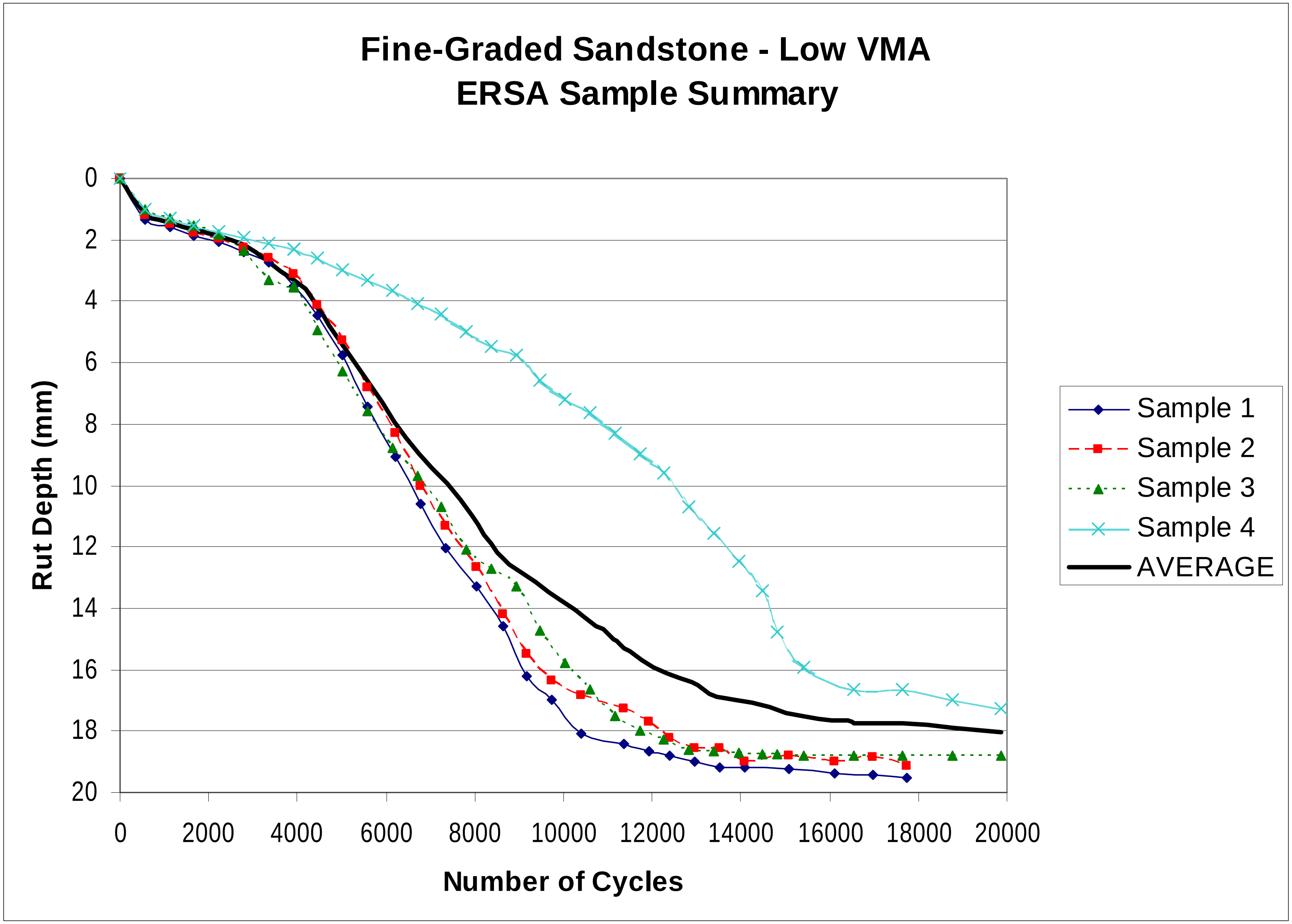
ERSA RESULTS

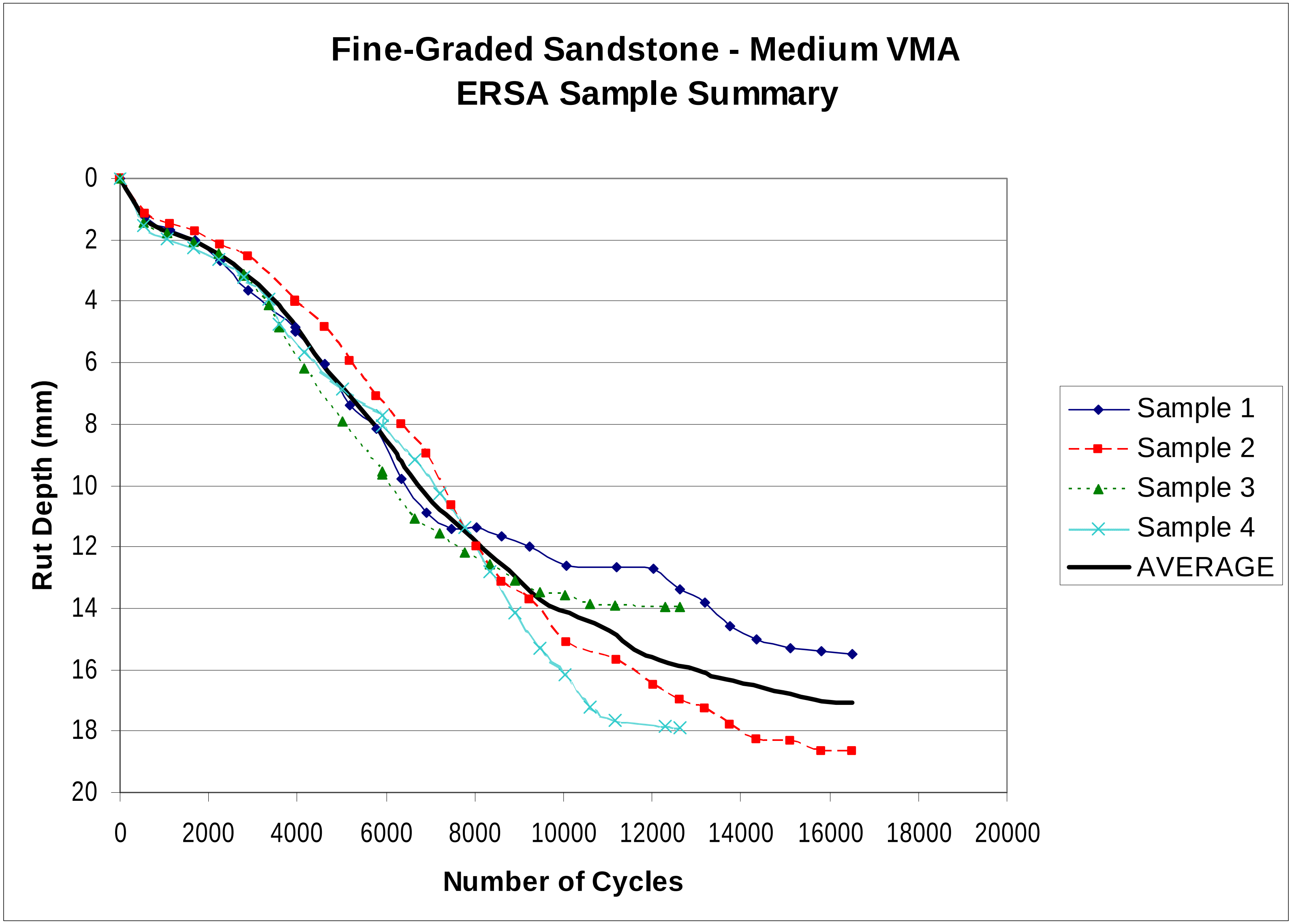


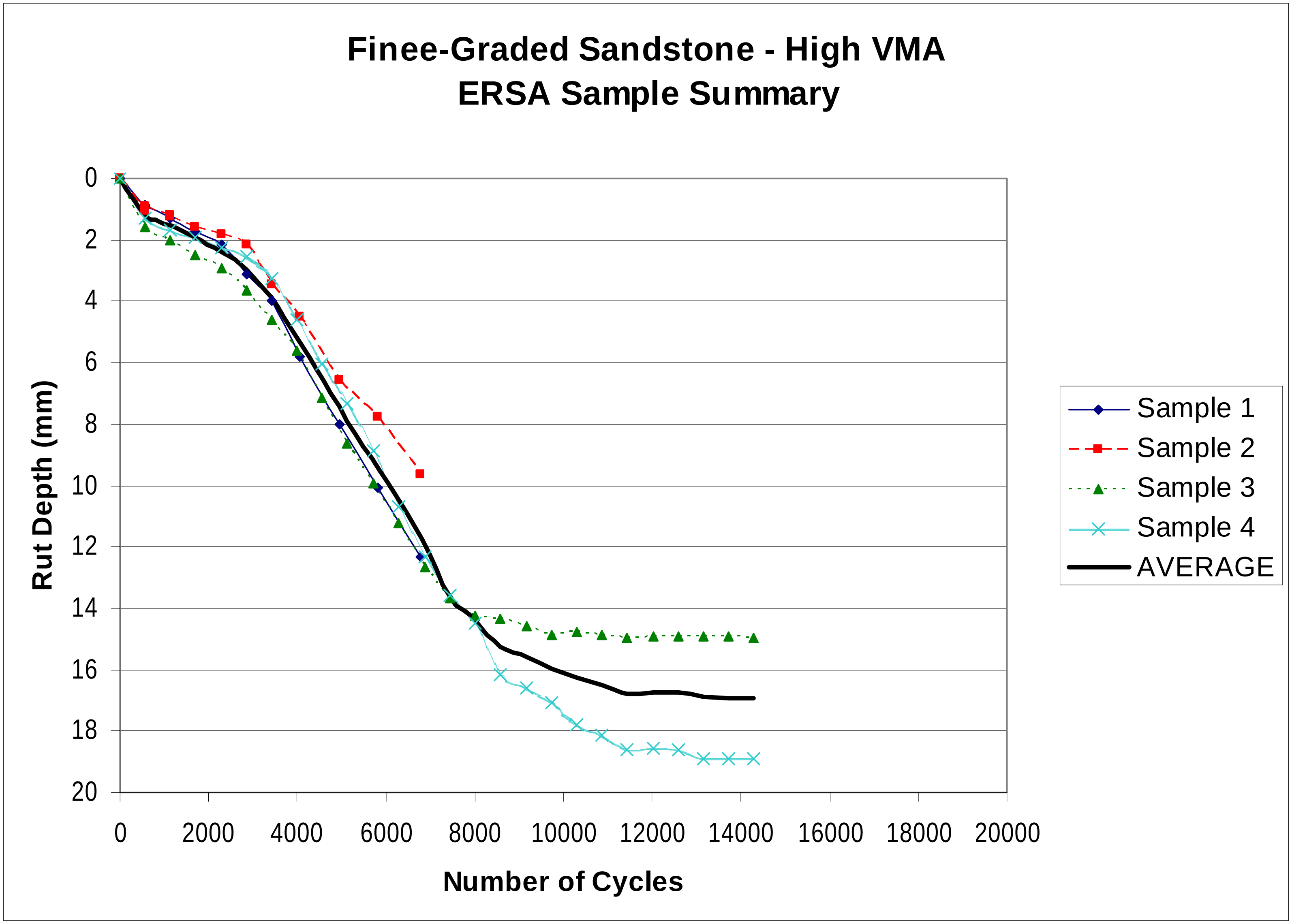
Coarse-Graded Sandstone - Low VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

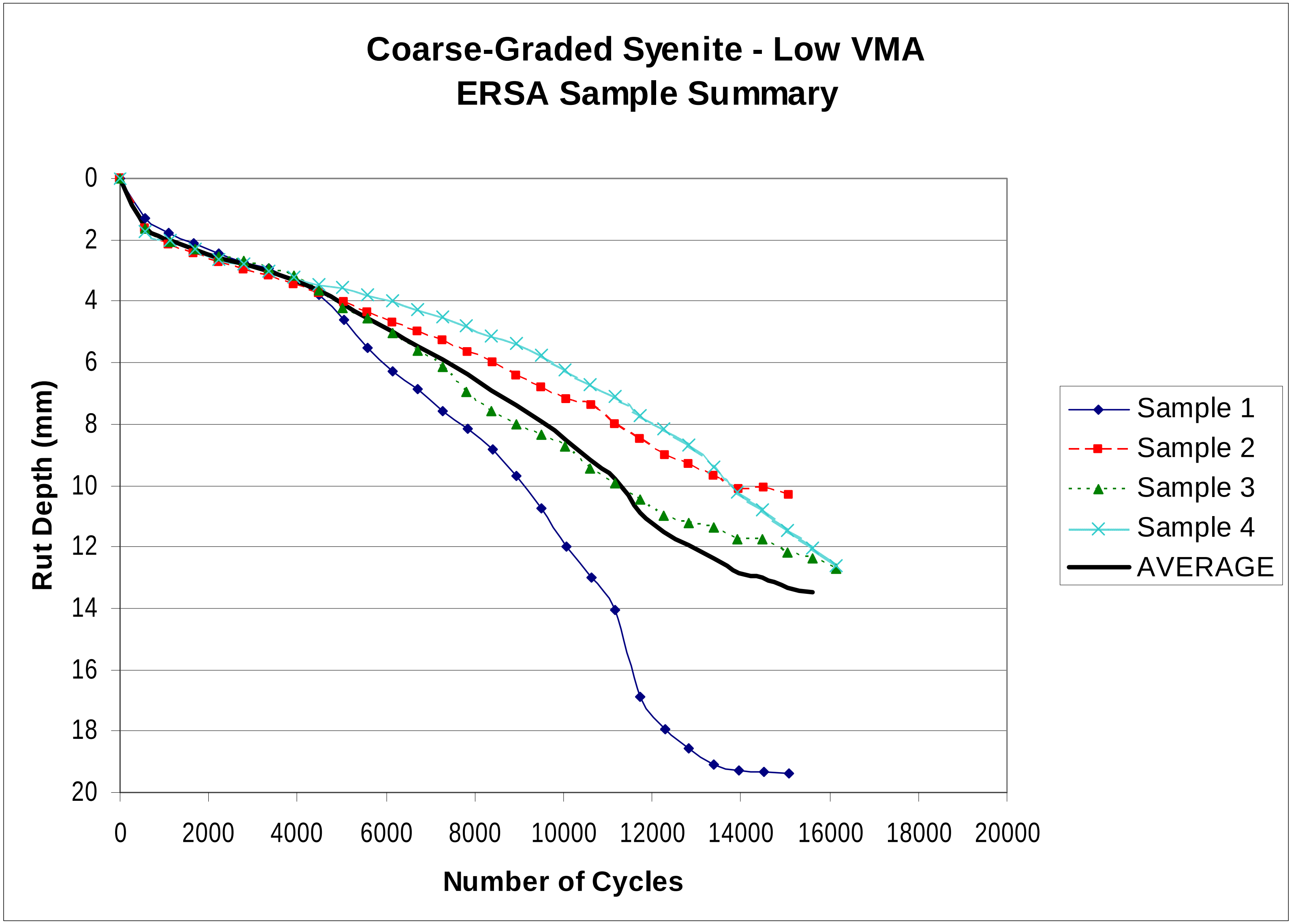

Coarse-Graded Sandstone - Medium VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

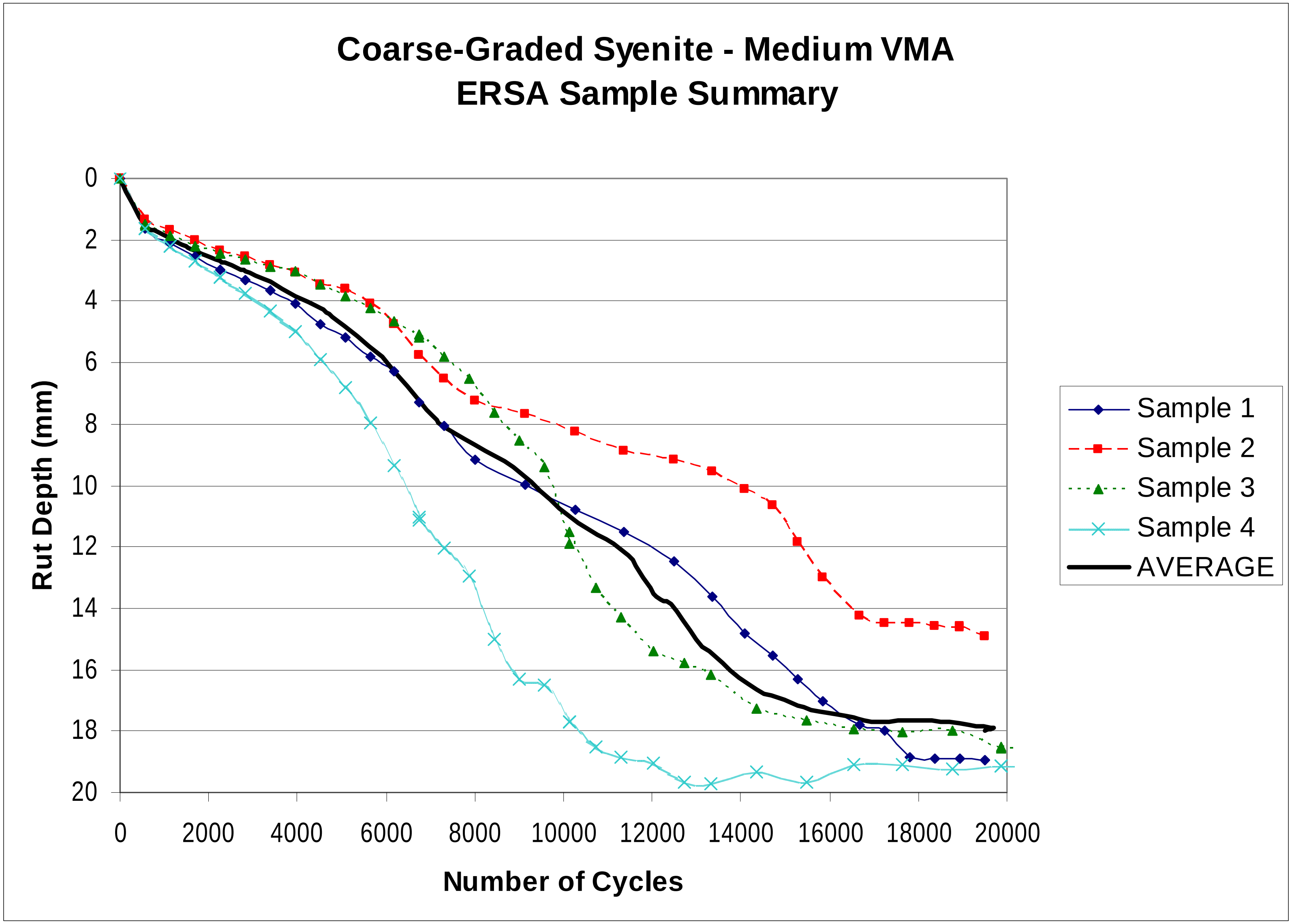

Coarse-Graded Sandstone - High VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

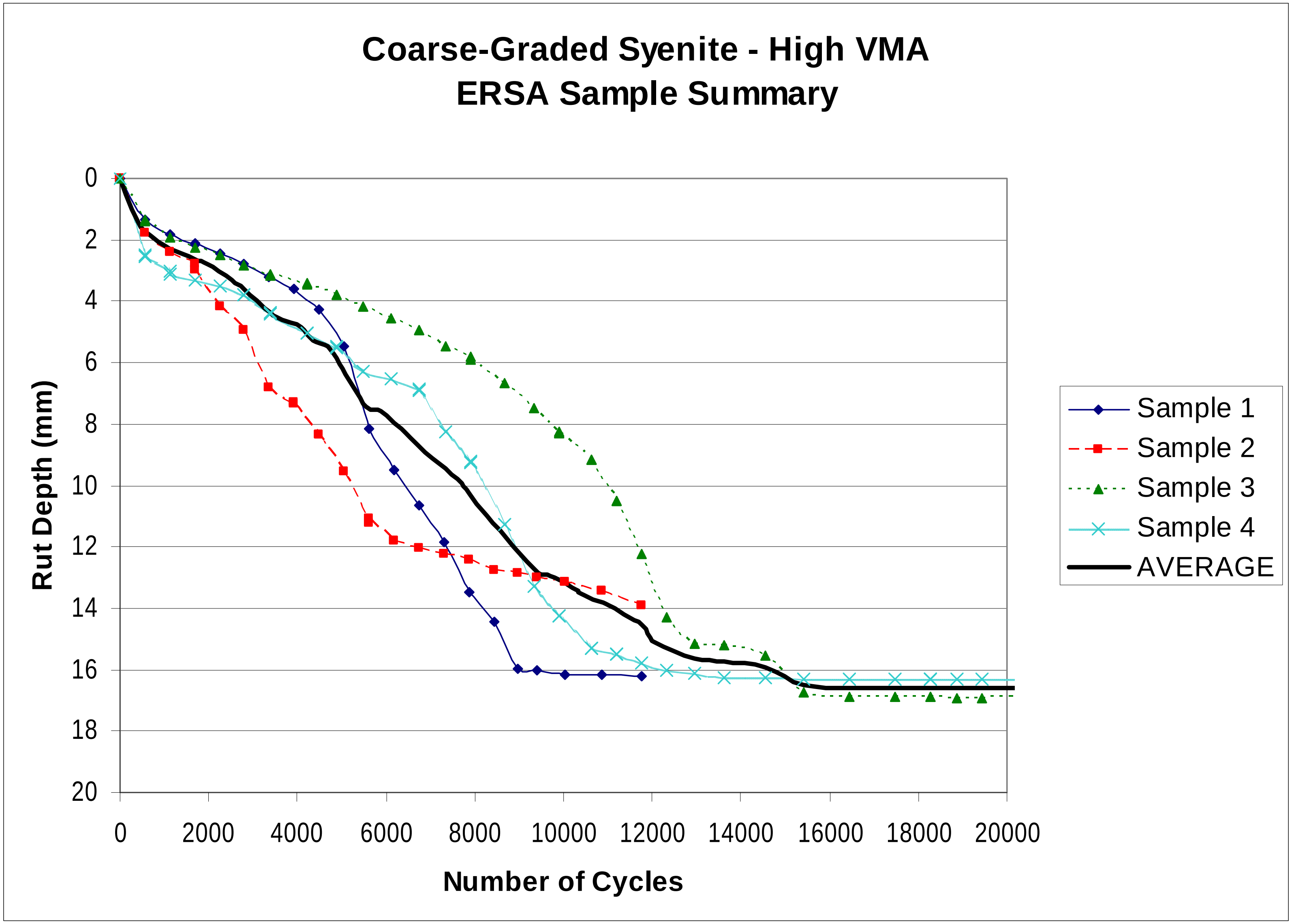

Fine-Graded Sandstone - Low VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

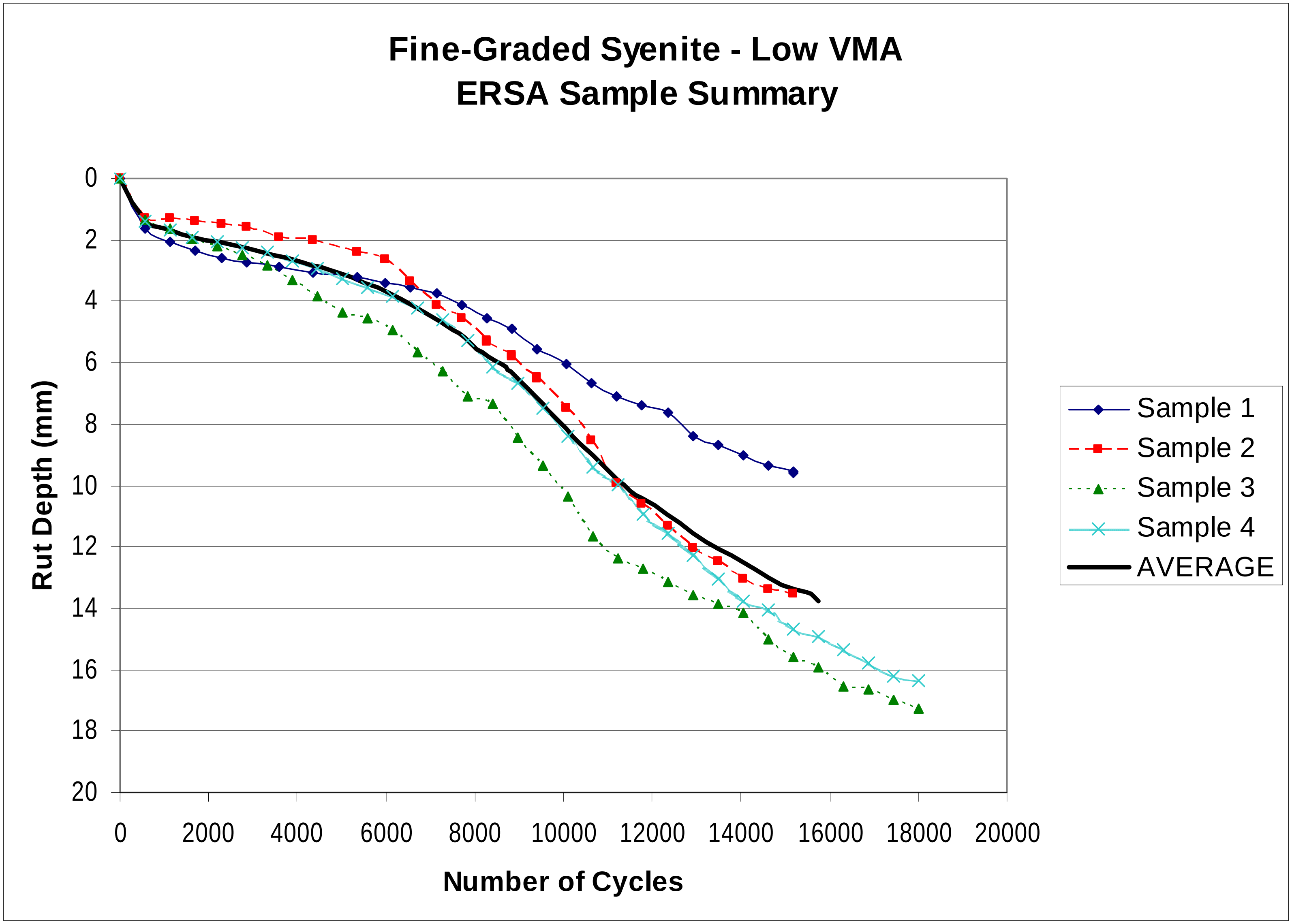

Fine-Graded Sandstone - Medium VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE


Finee-Graded Sandstone - High VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

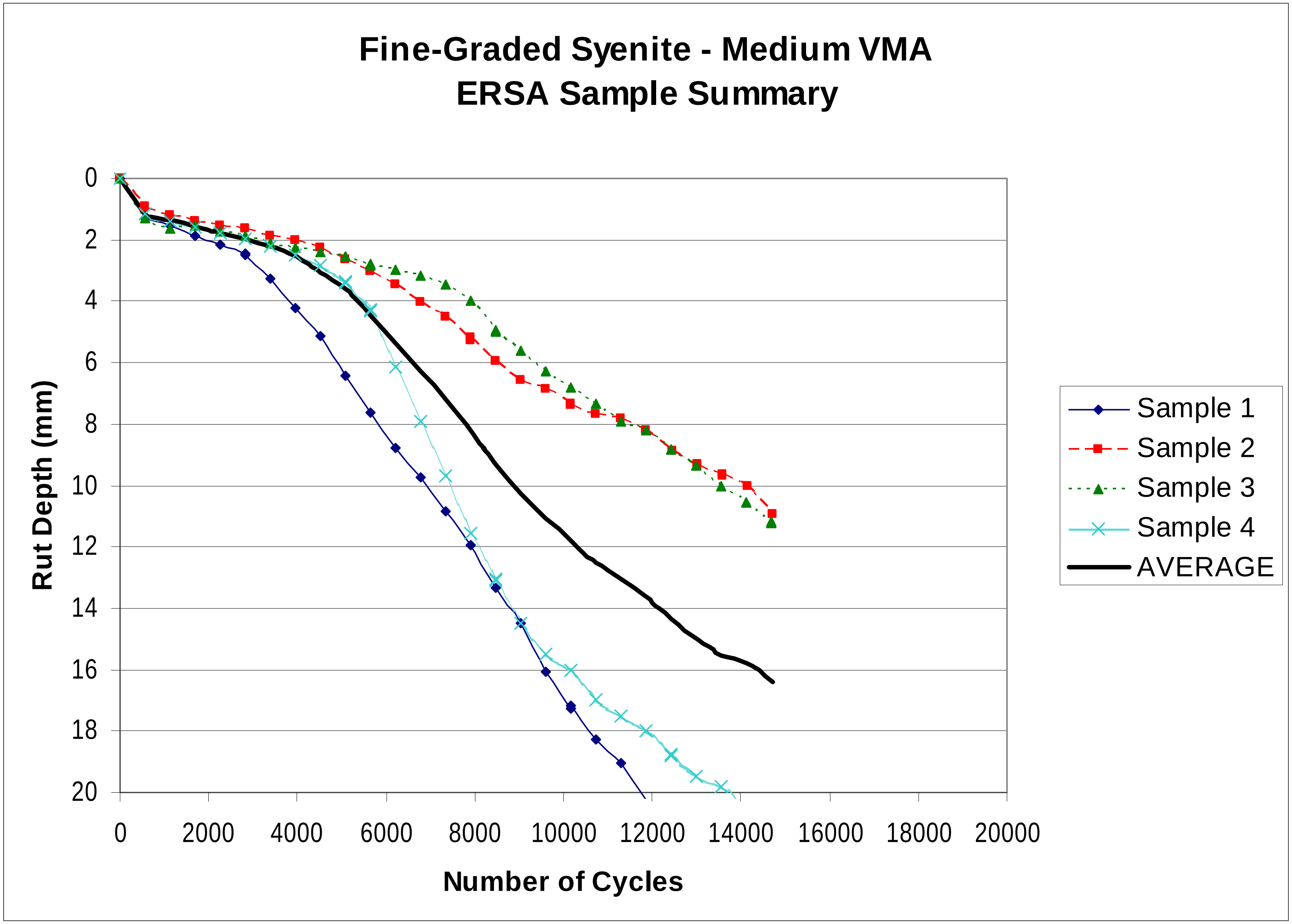

Coarse-Graded Syenite - Low VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE


Coarse-Graded Syenite - Medium VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

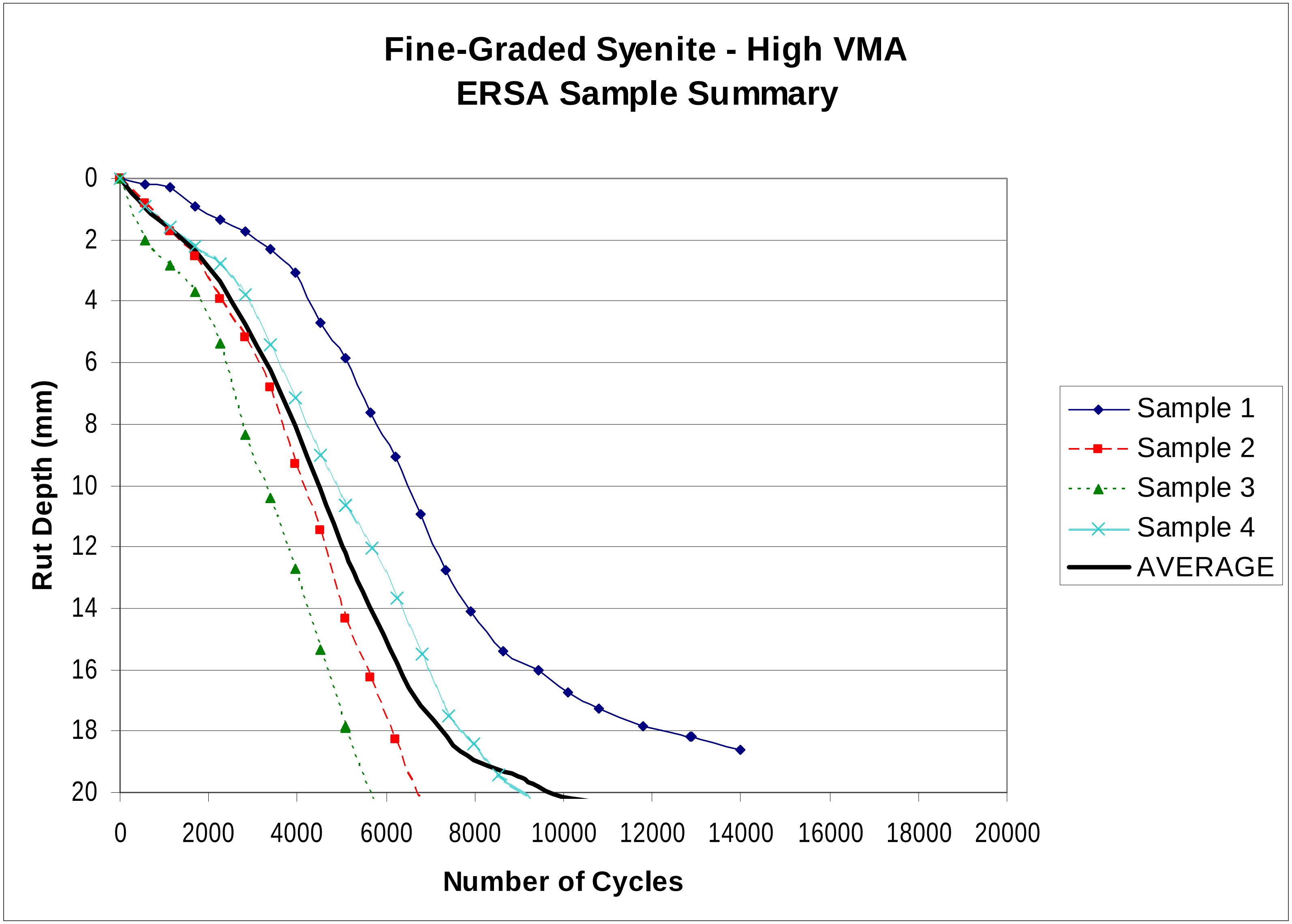

Coarse-Graded Syenite - High VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

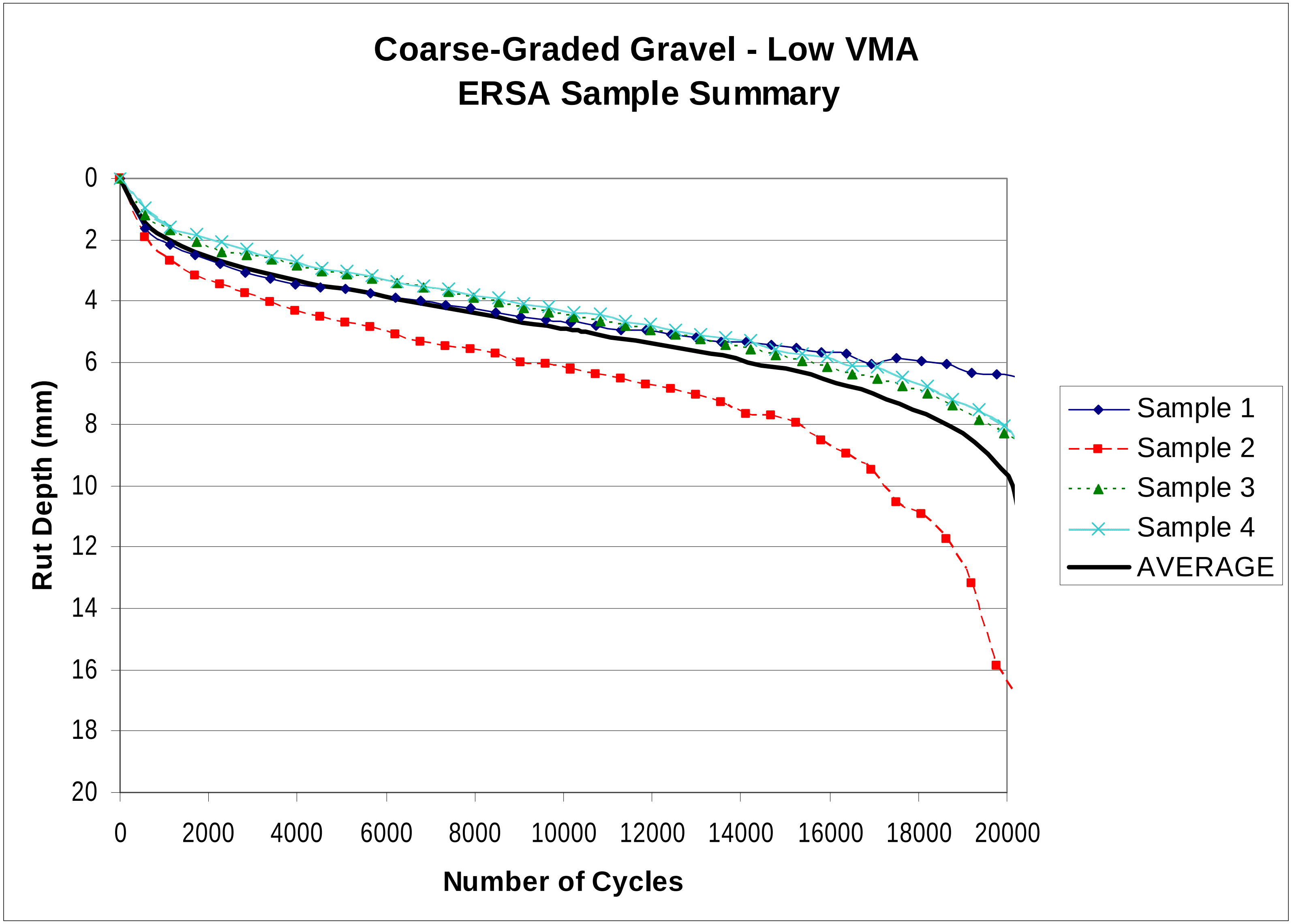


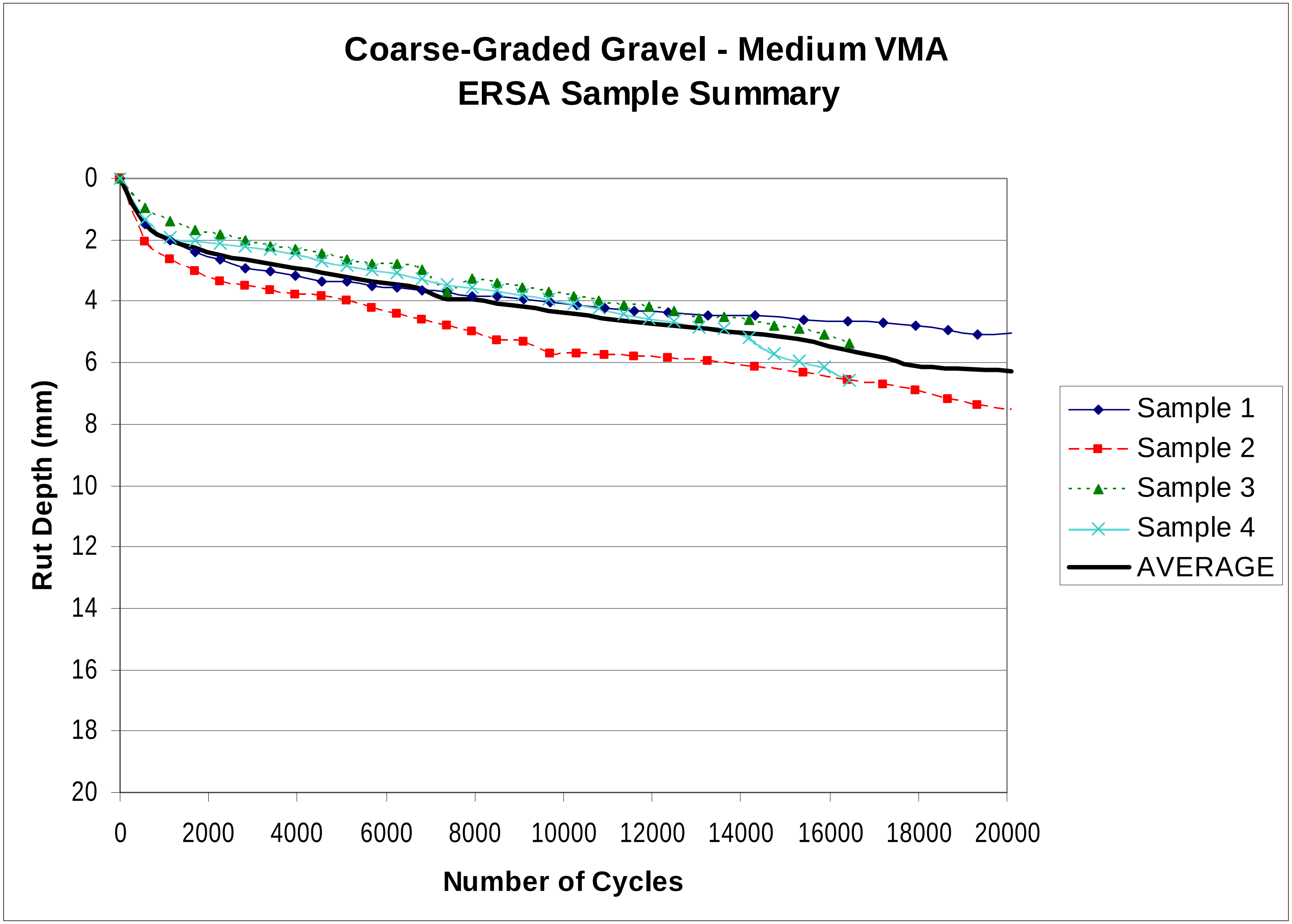
Fine-Graded Syenite - Low VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

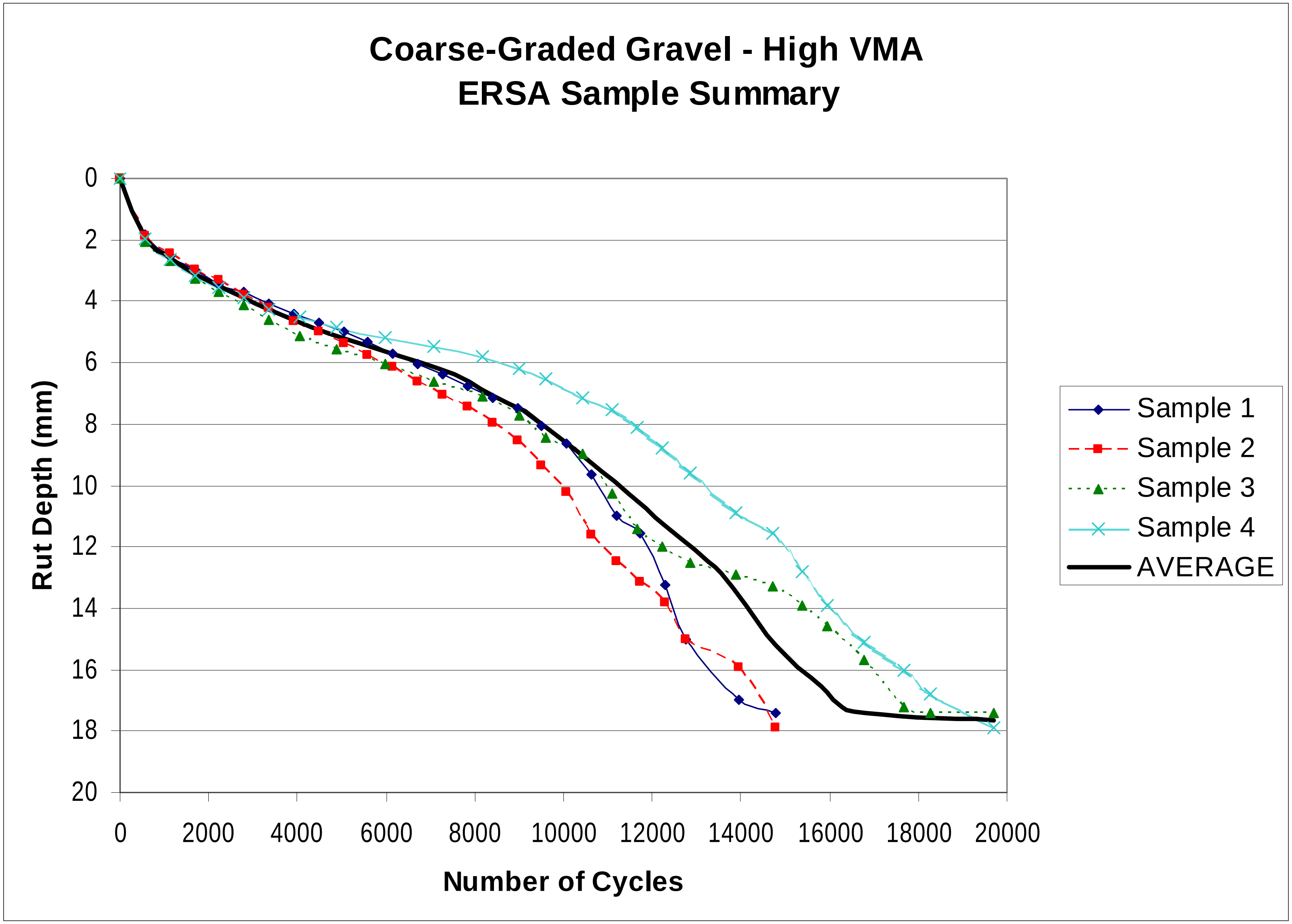


Fine-Graded Syenite - Medium VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

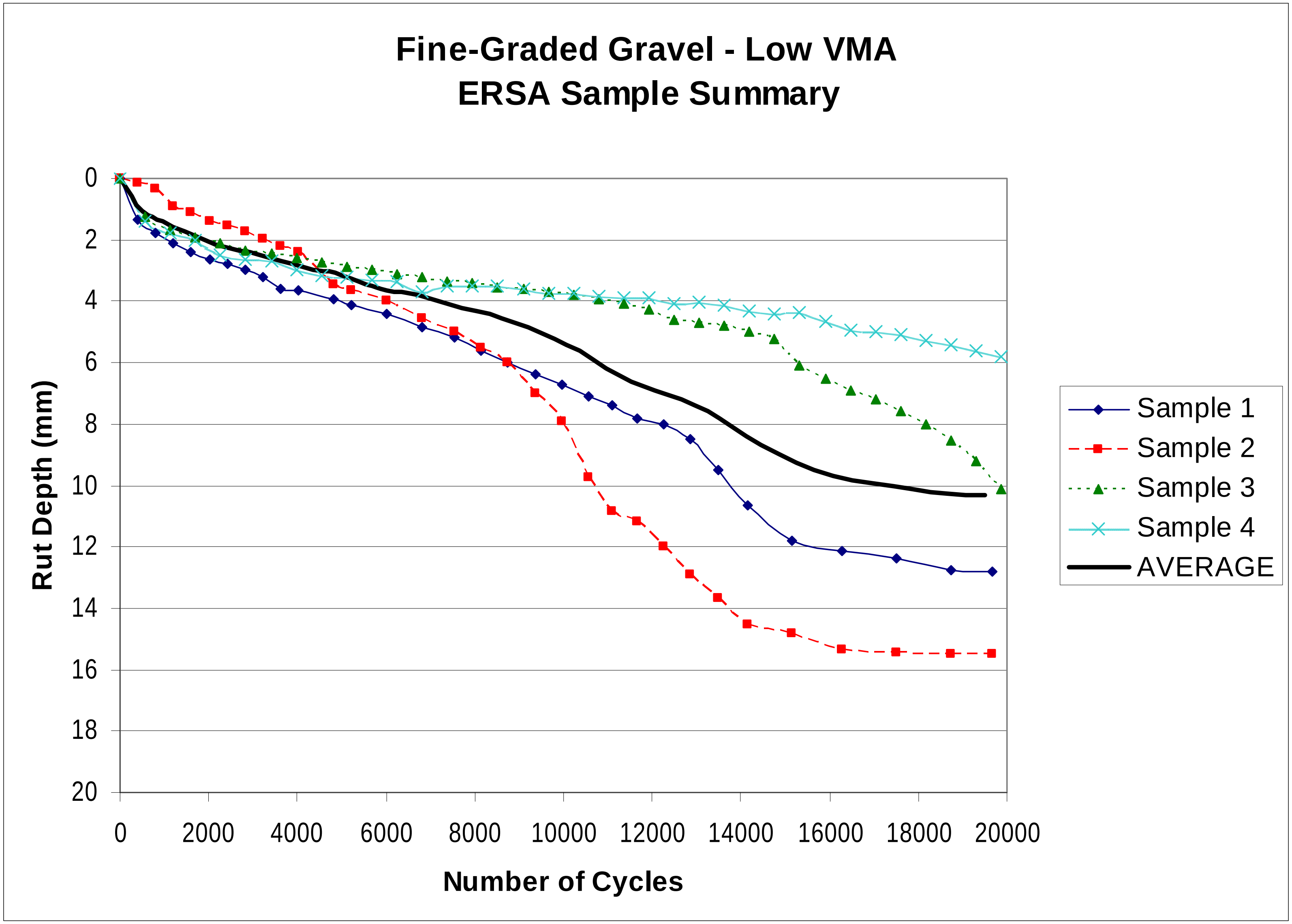

Fine-Graded Syenite - High VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

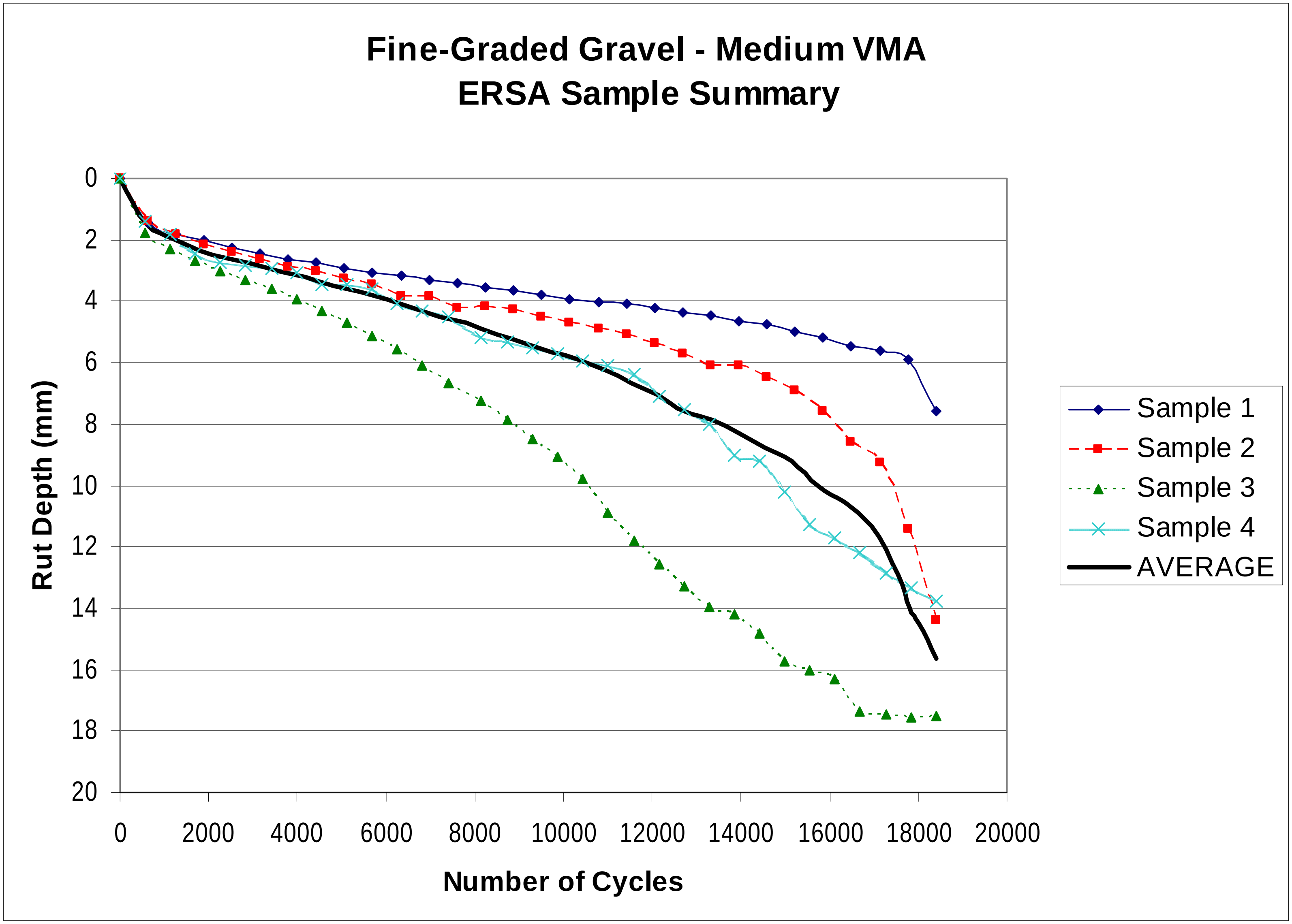

Coarse-Graded Gravel - Low VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

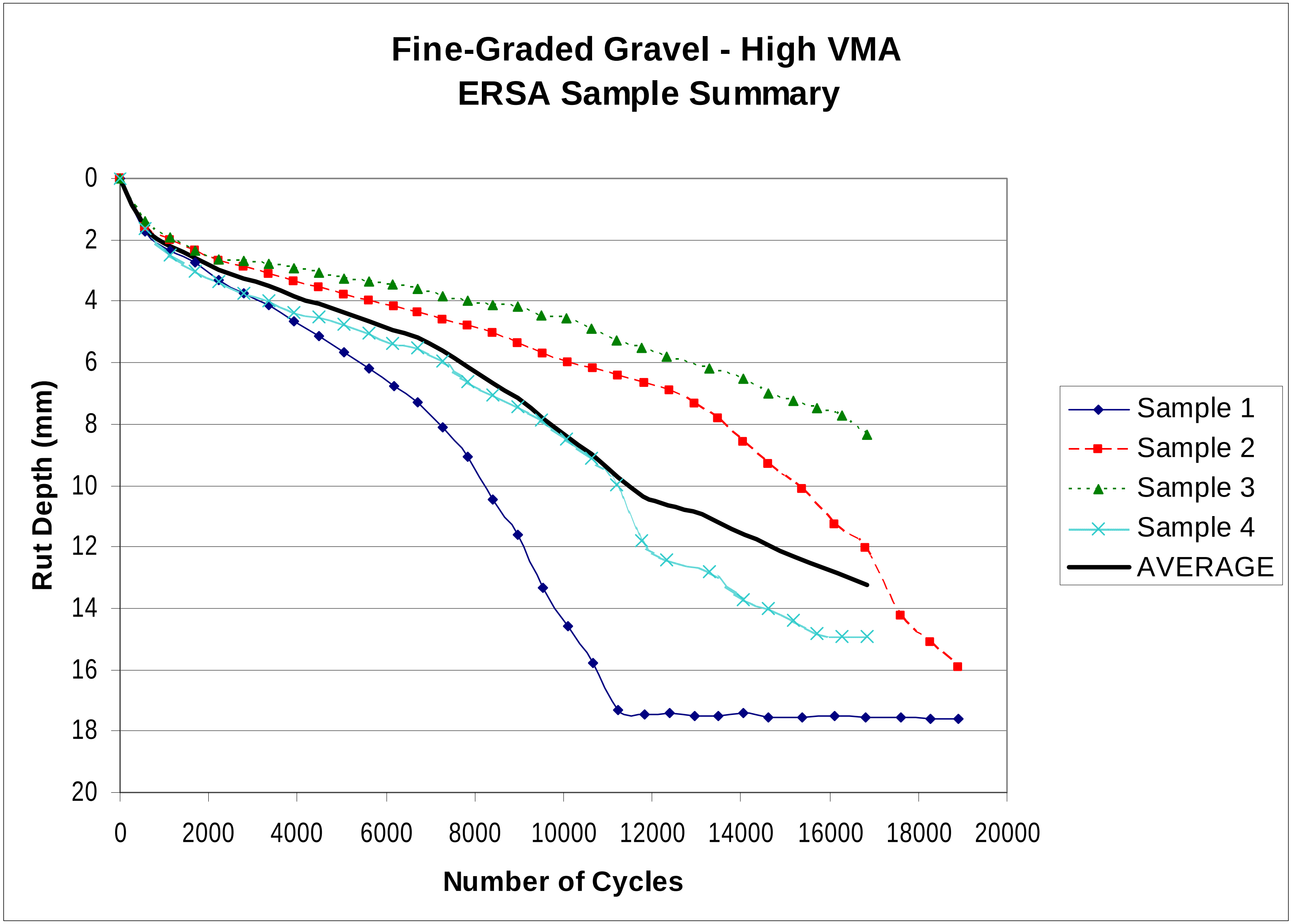

Coarse-Graded Gravel - Medium VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

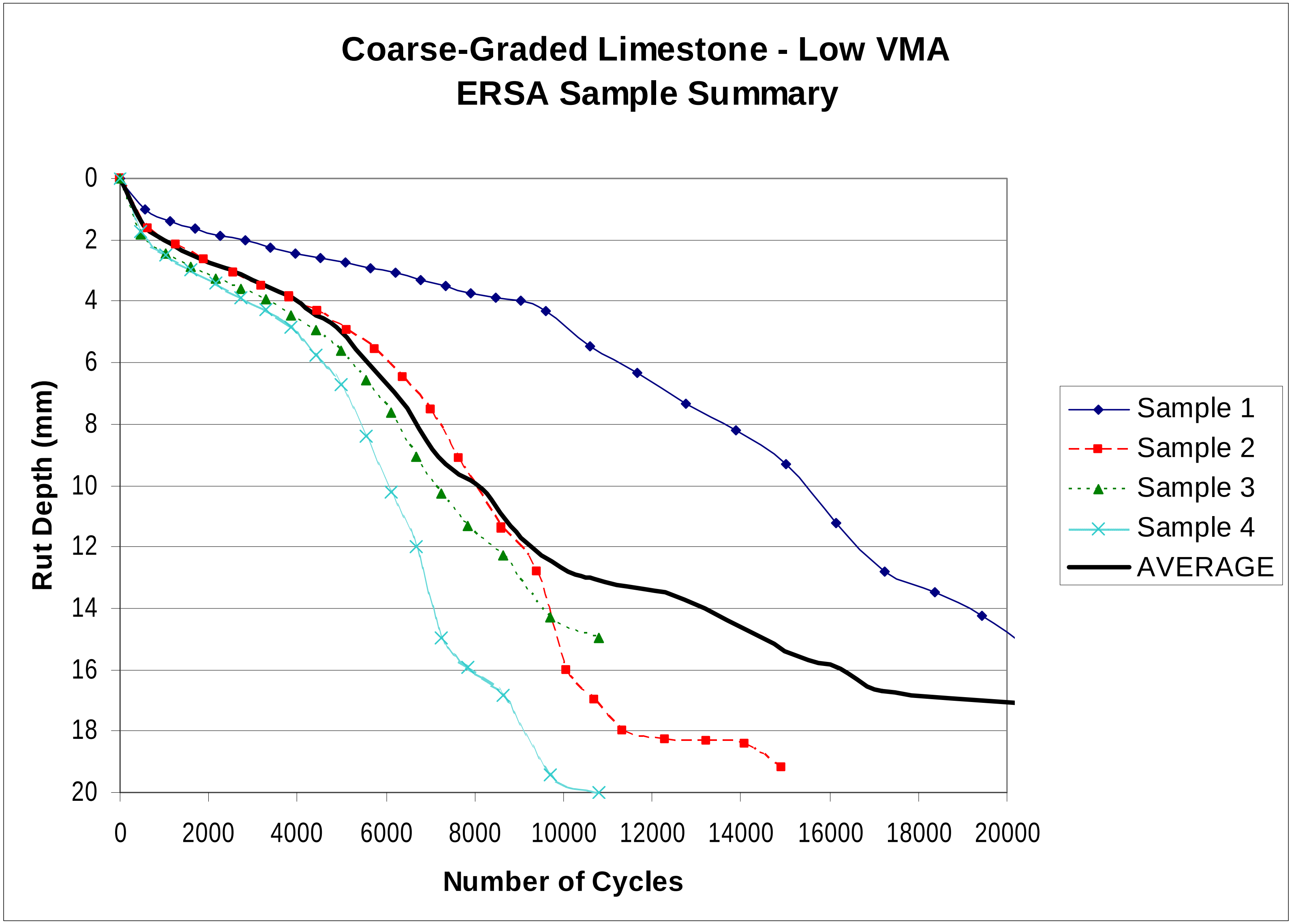


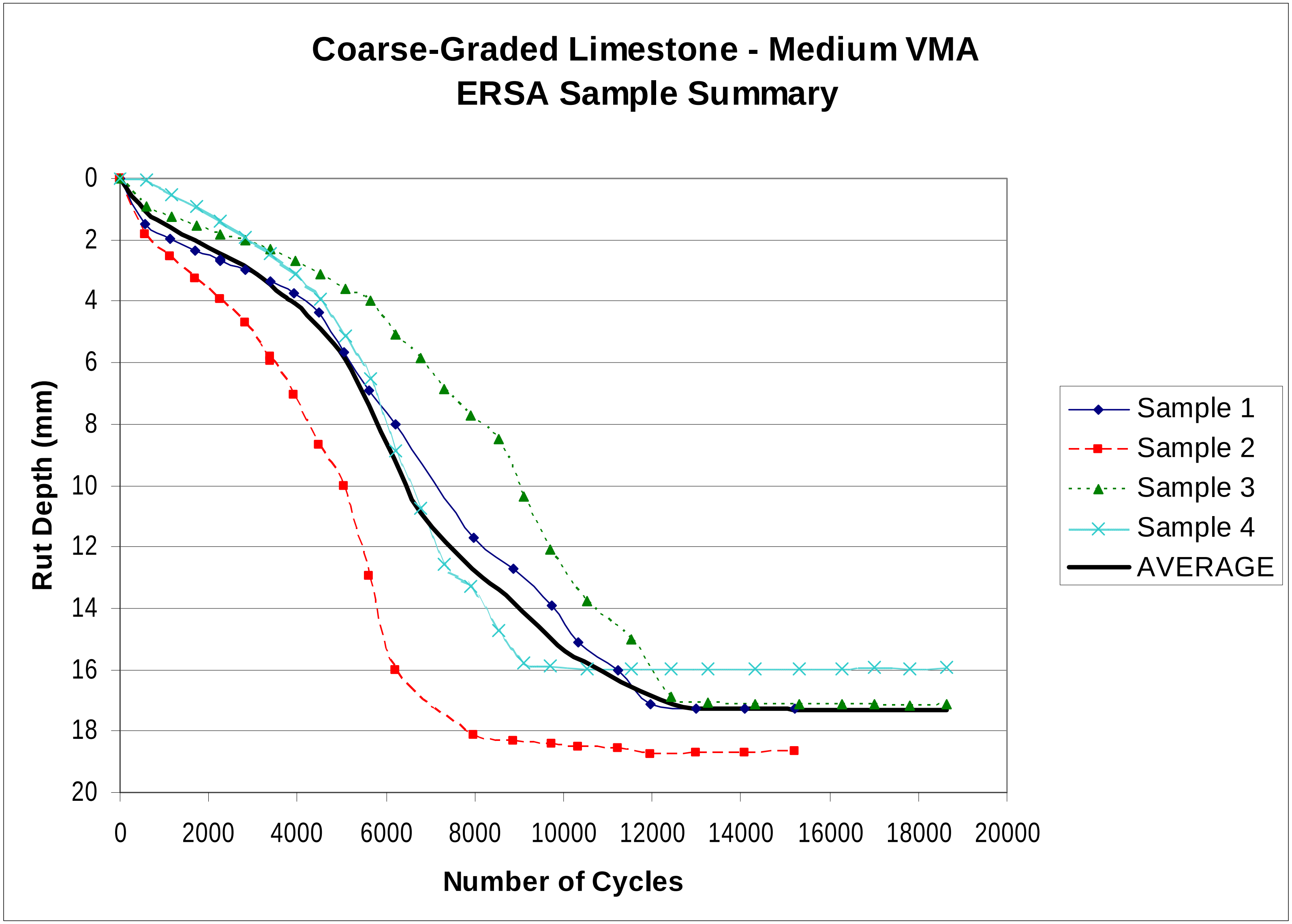
Coarse-Graded Gravel - High VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE


Fine-Graded Gravel - Low VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

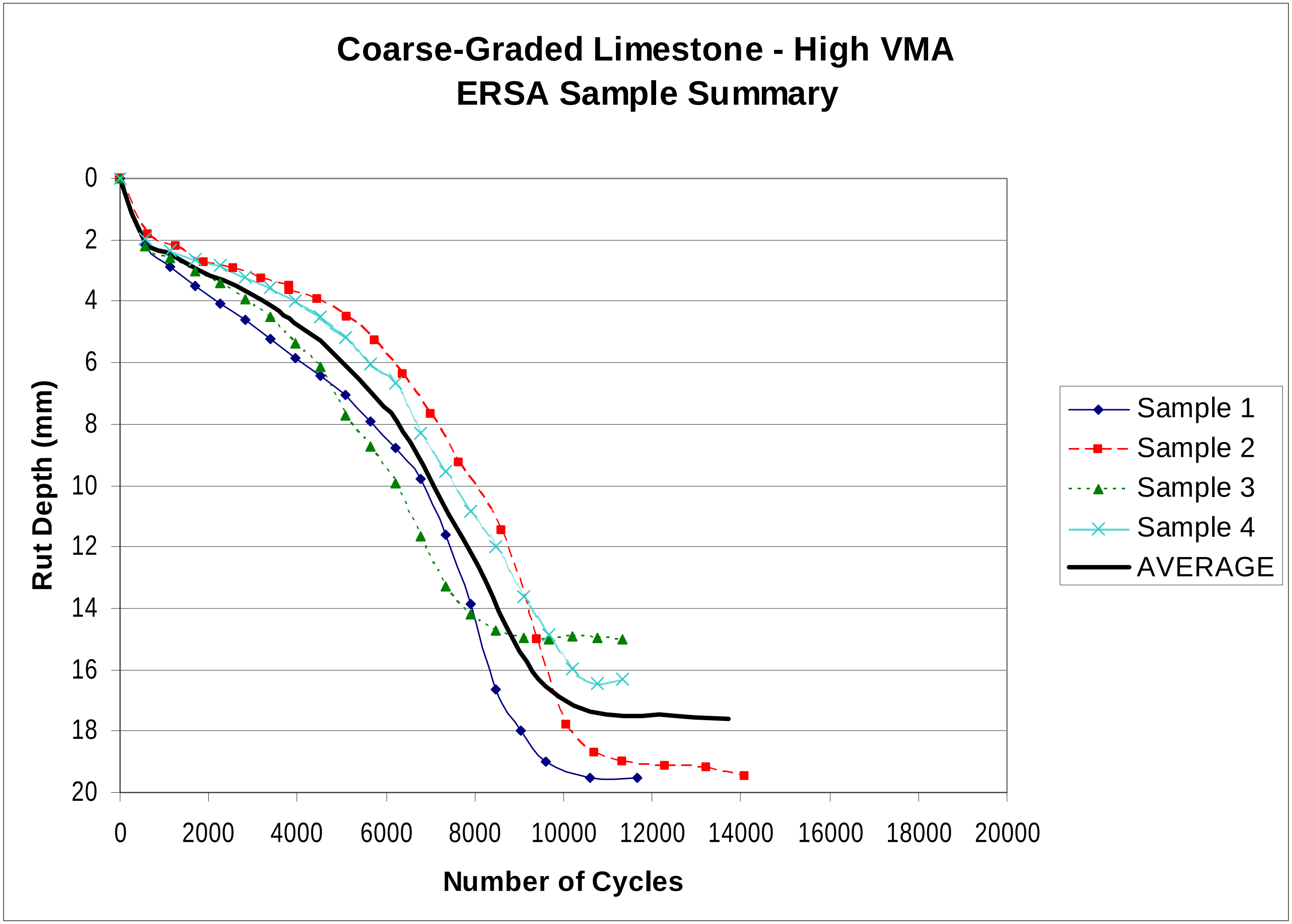

Fine-Graded Gravel - Medium VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

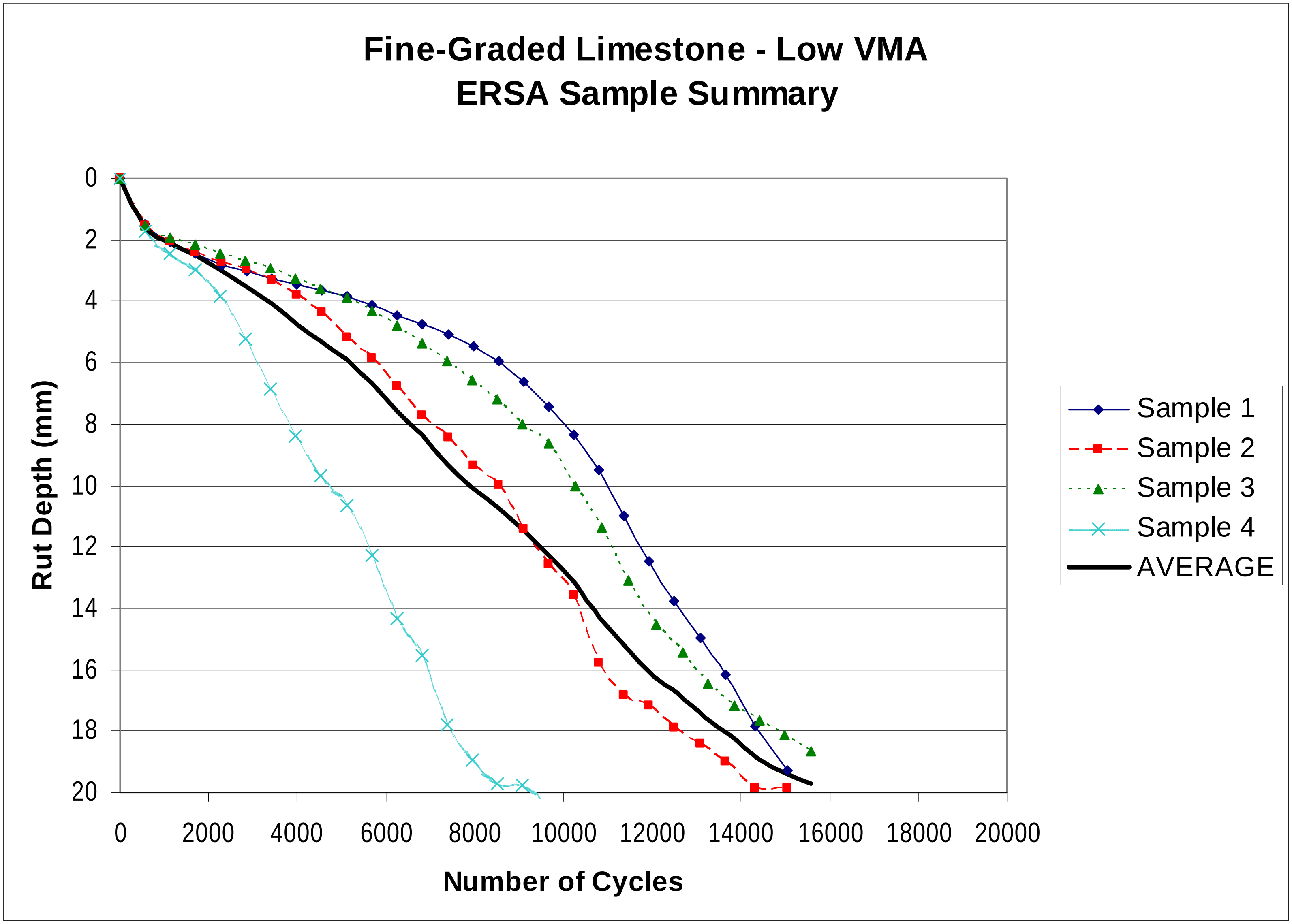

Fine-Graded Gravel - High VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

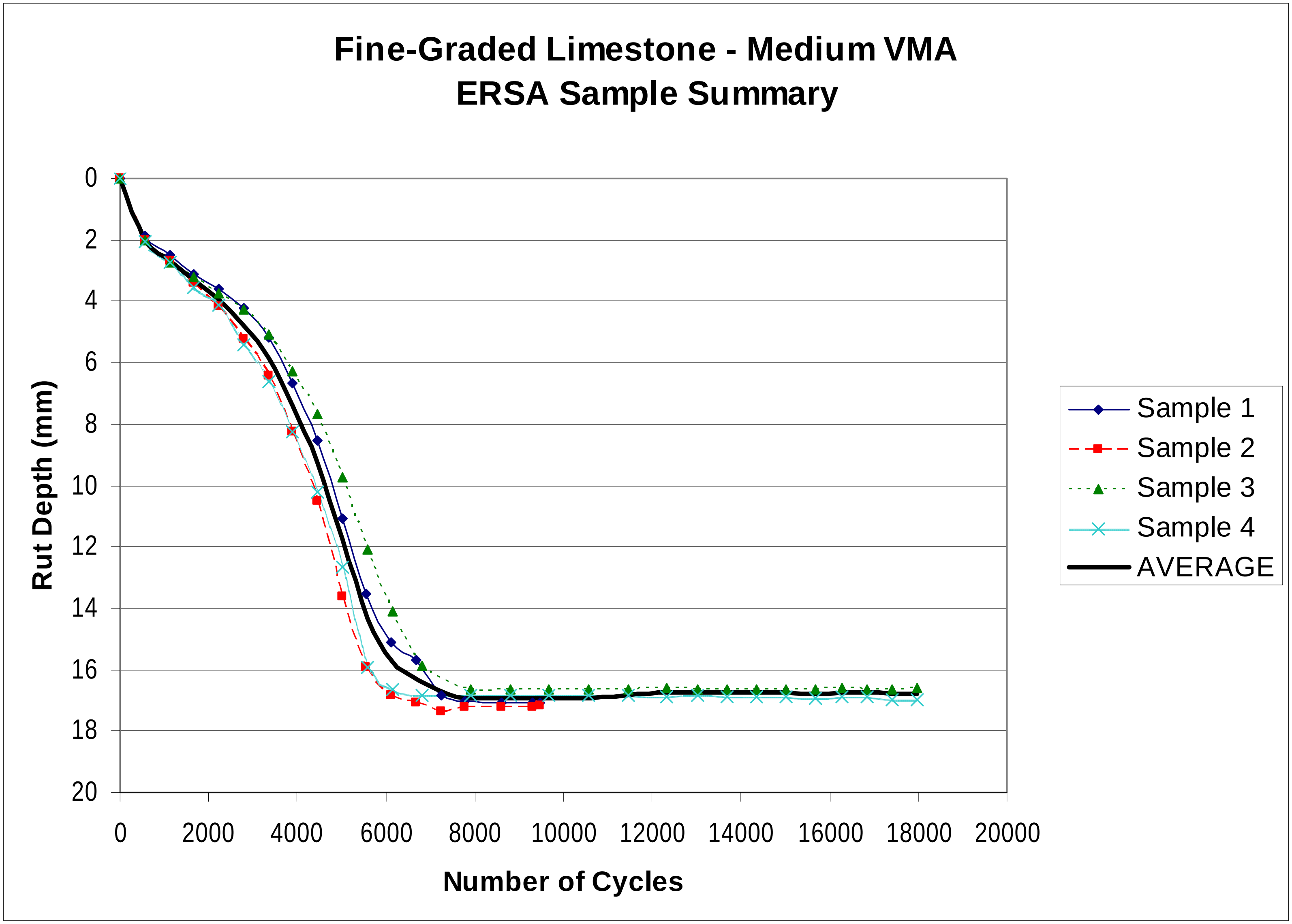

Coarse-Graded Limestone - Low VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE



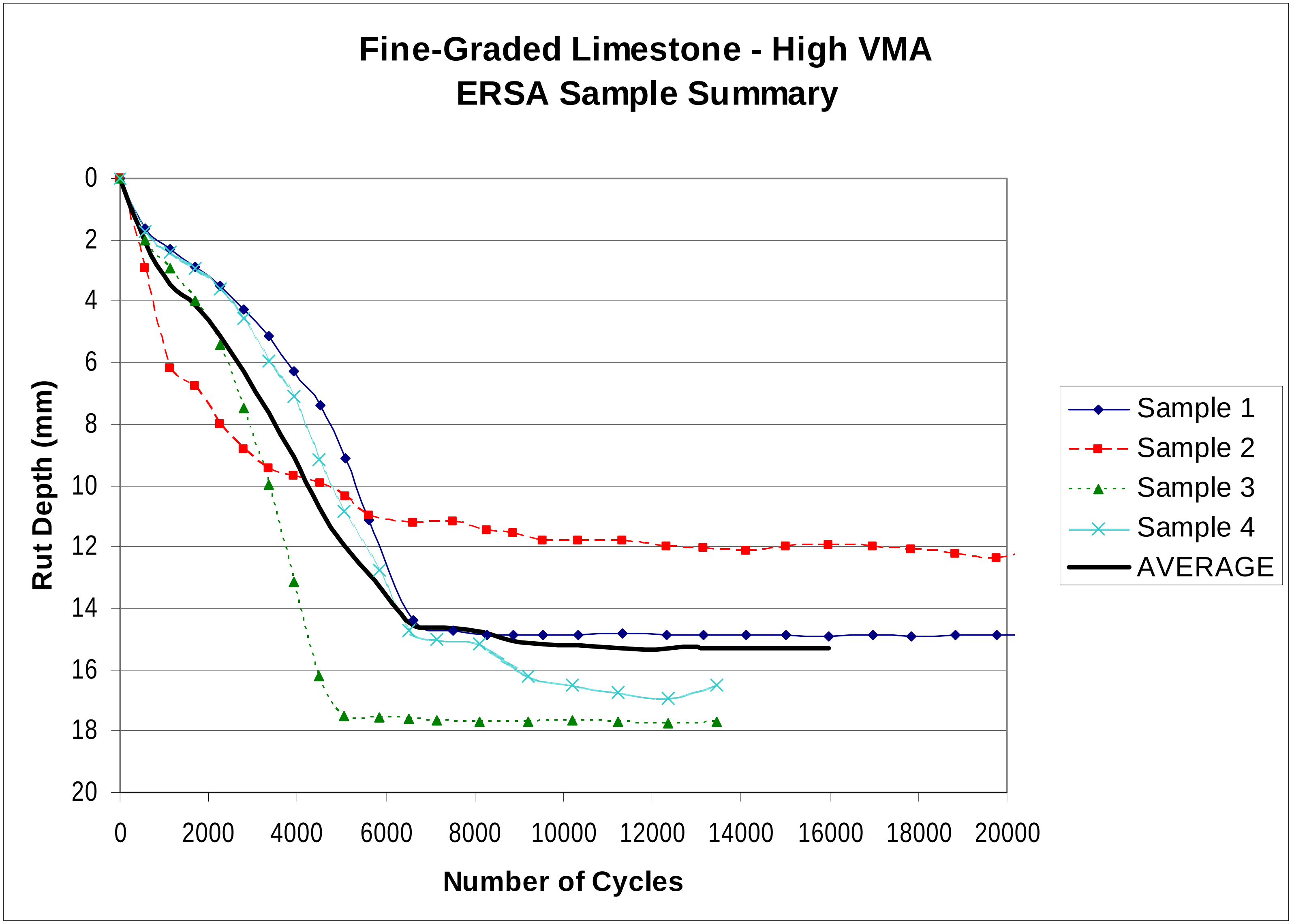
Coarse-Graded Limestone - Medium VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE


Coarse-Graded Limestone - High VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE


Fine-Graded Limestone - Low VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

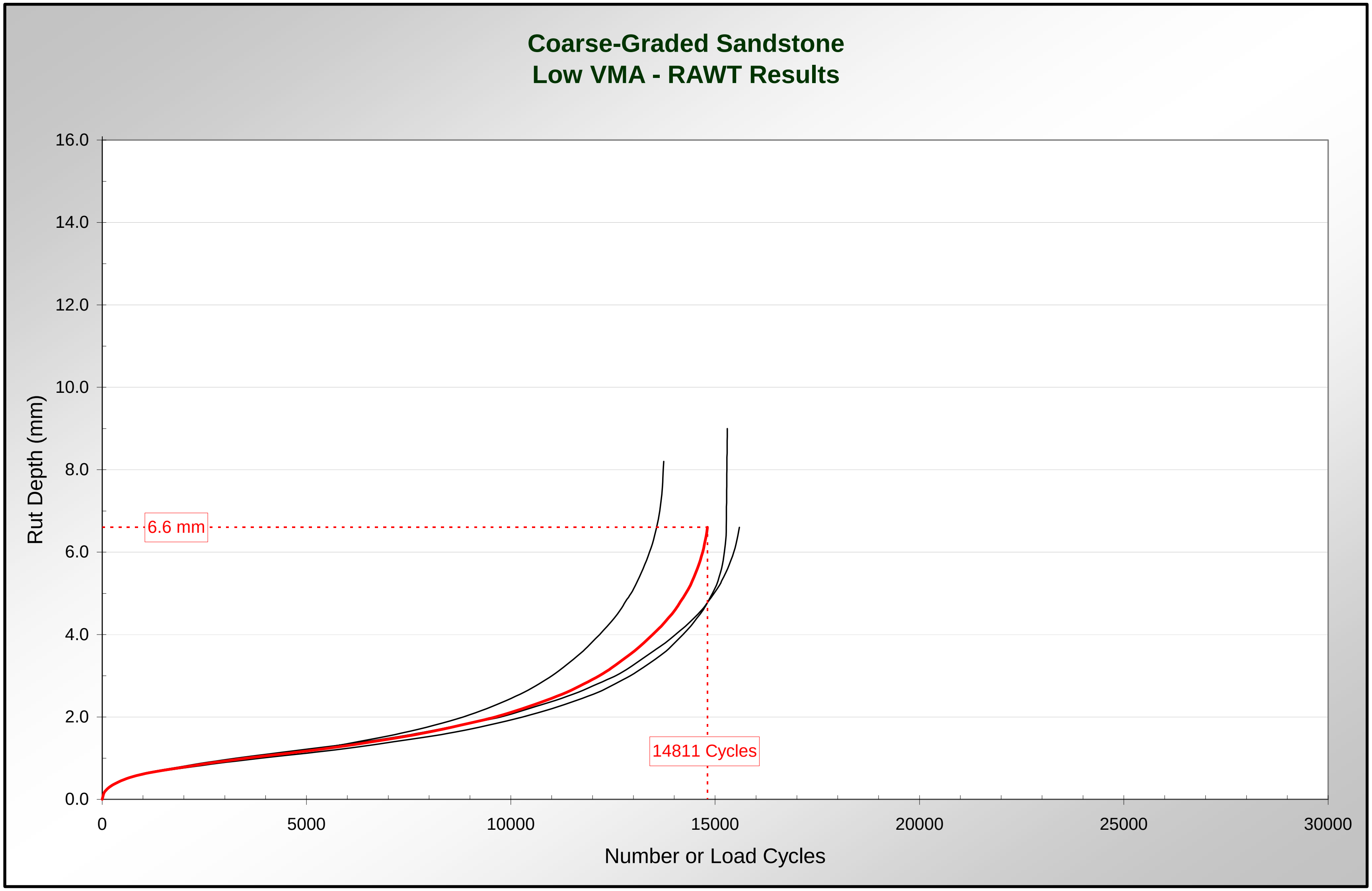


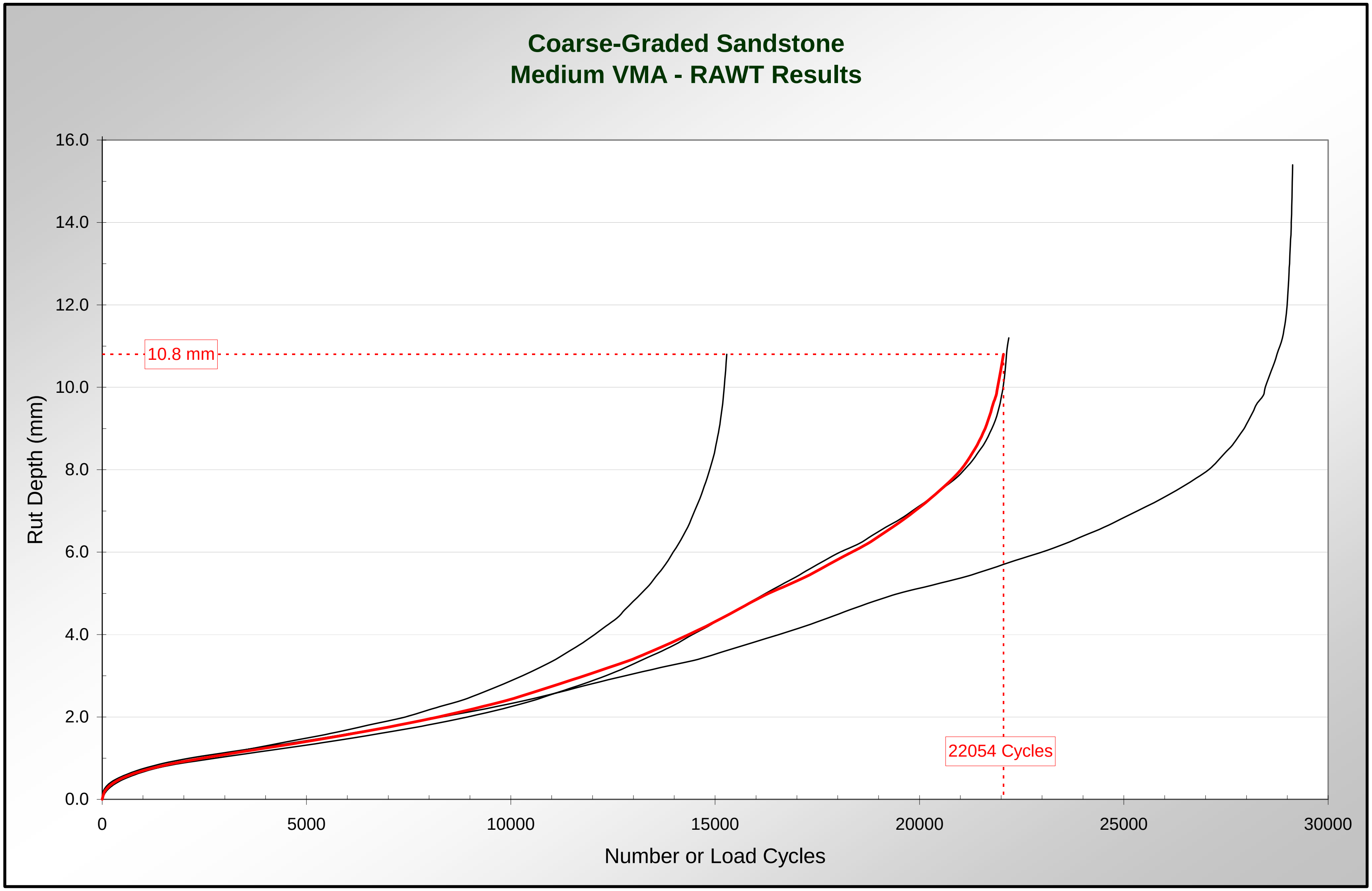
Fine-Graded Limestone - Medium VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE


Fine-Graded Limestone - High VMA
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

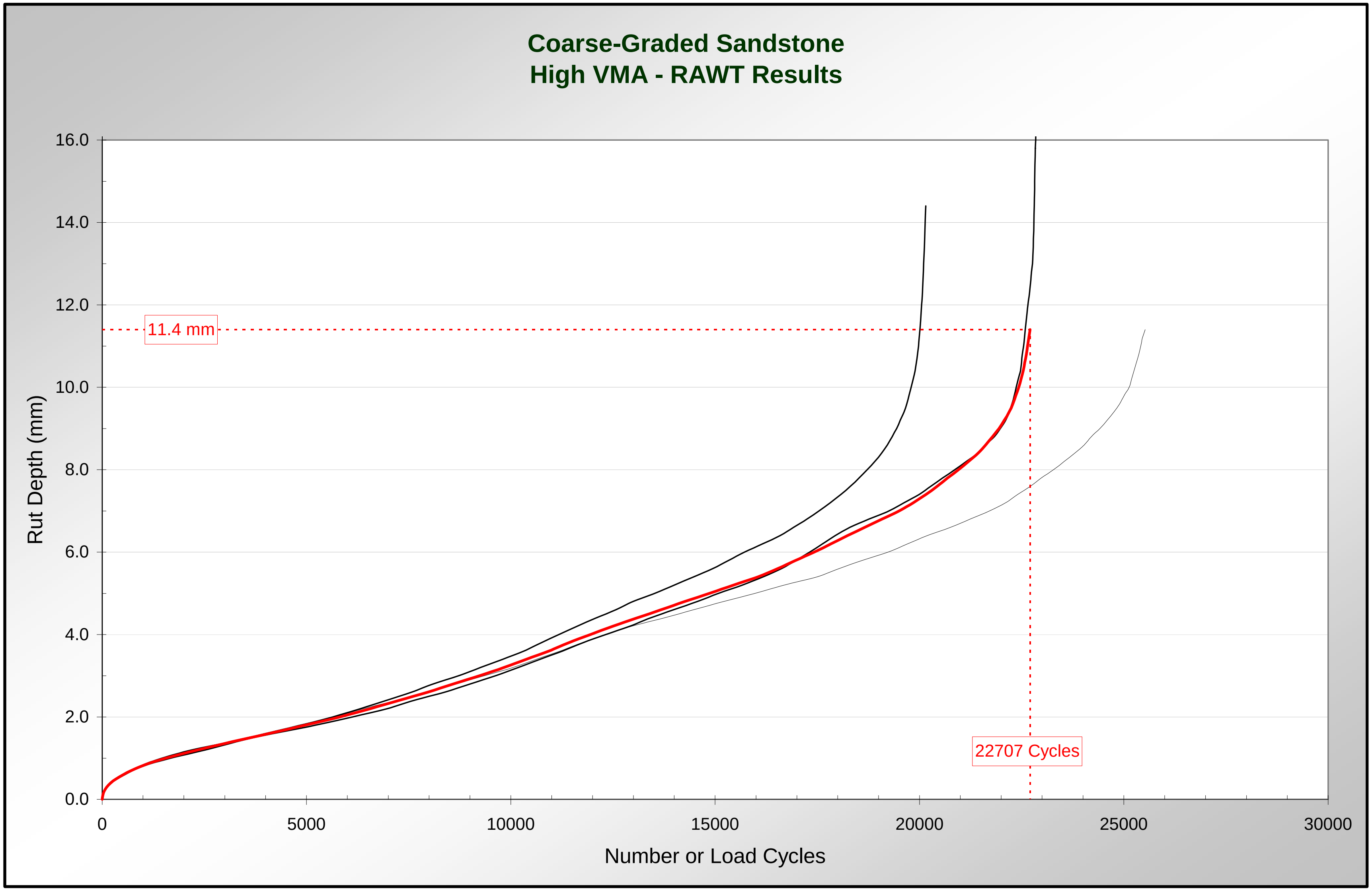
APPENDIX B

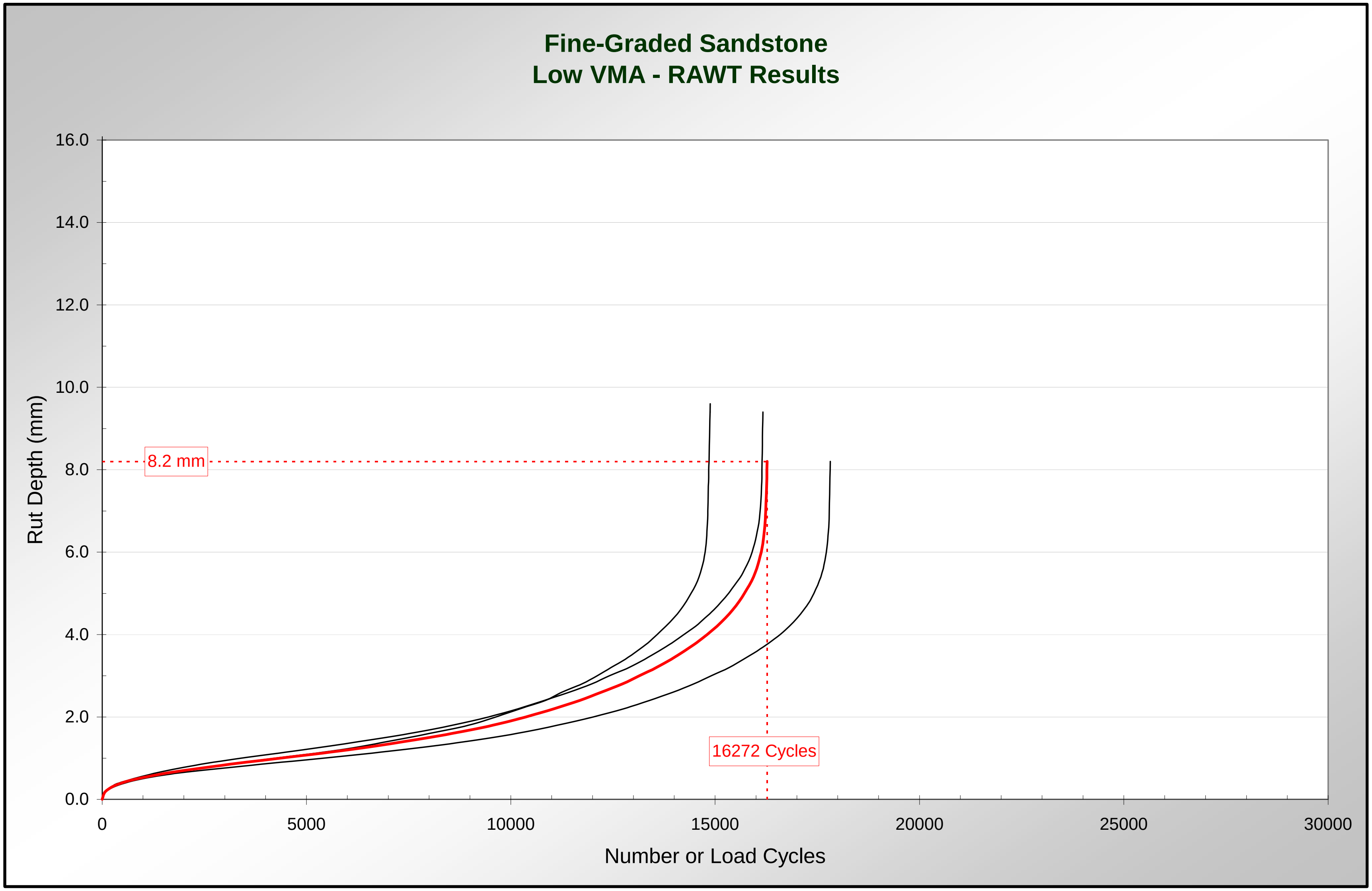
RAWT RESULTS

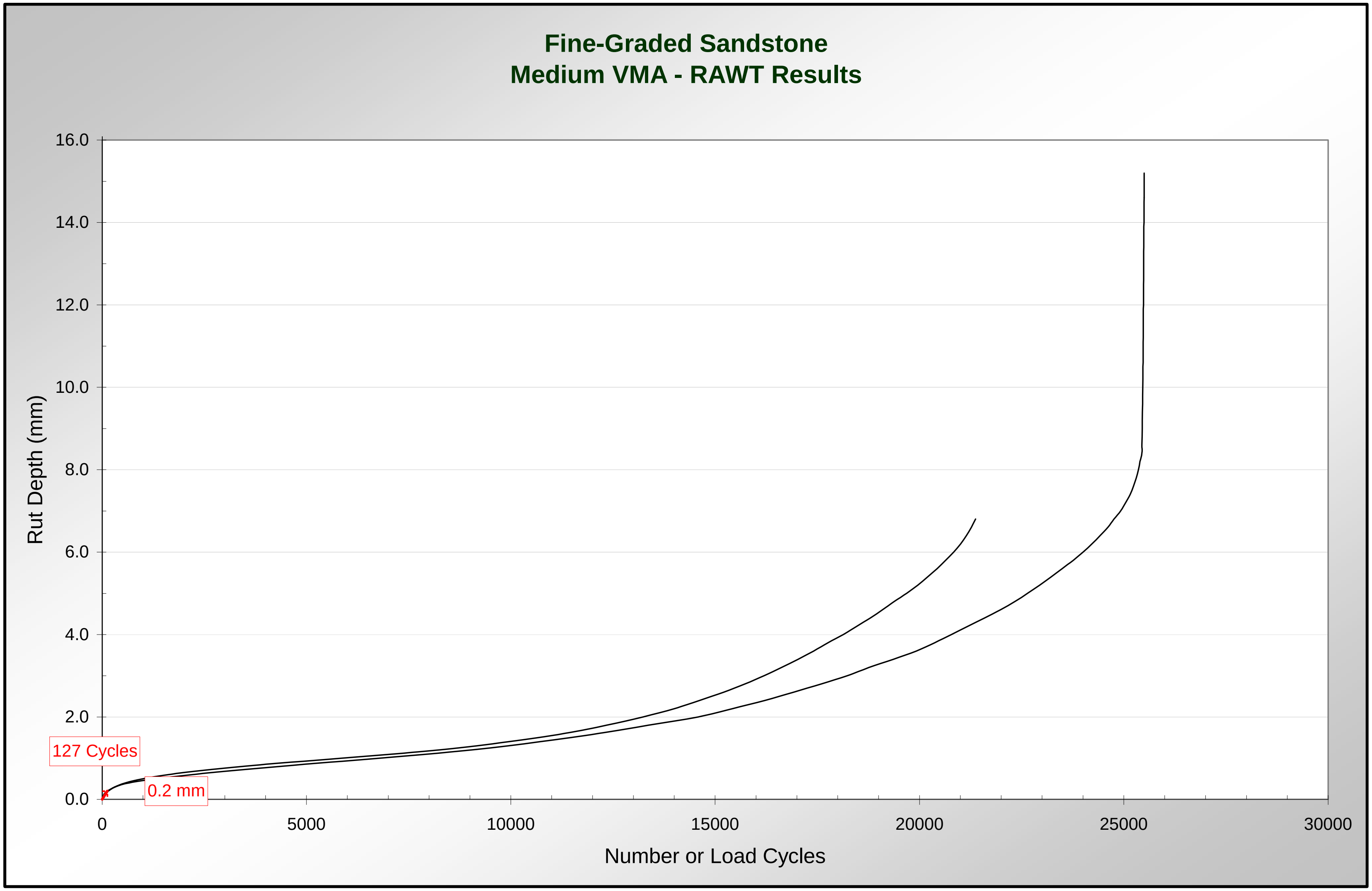

Coarse-Graded Sandstone
Low VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
6.6 mm
14811 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

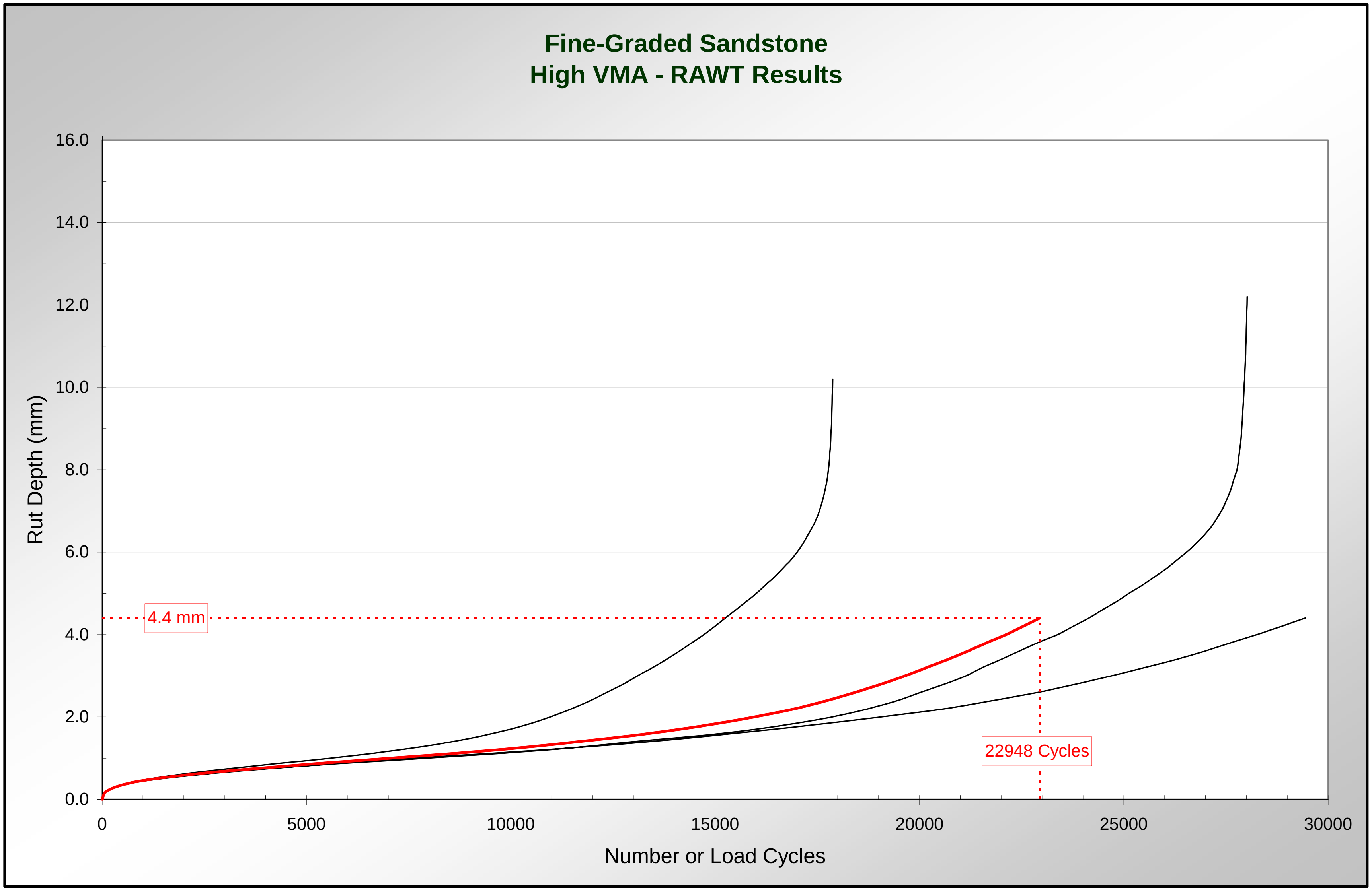


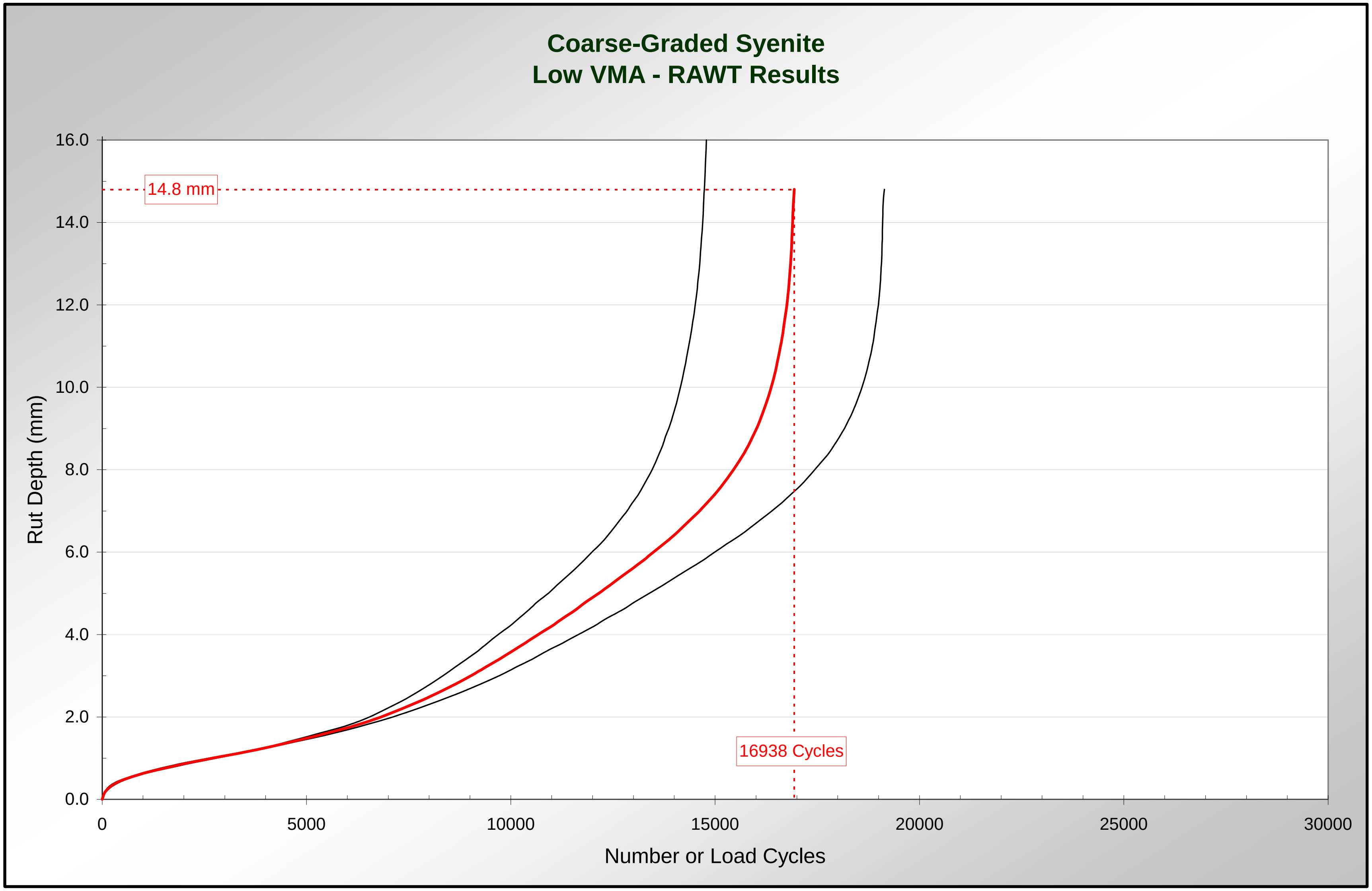
Coarse-Graded Sandstone
Medium VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
10.8 mm
22054 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

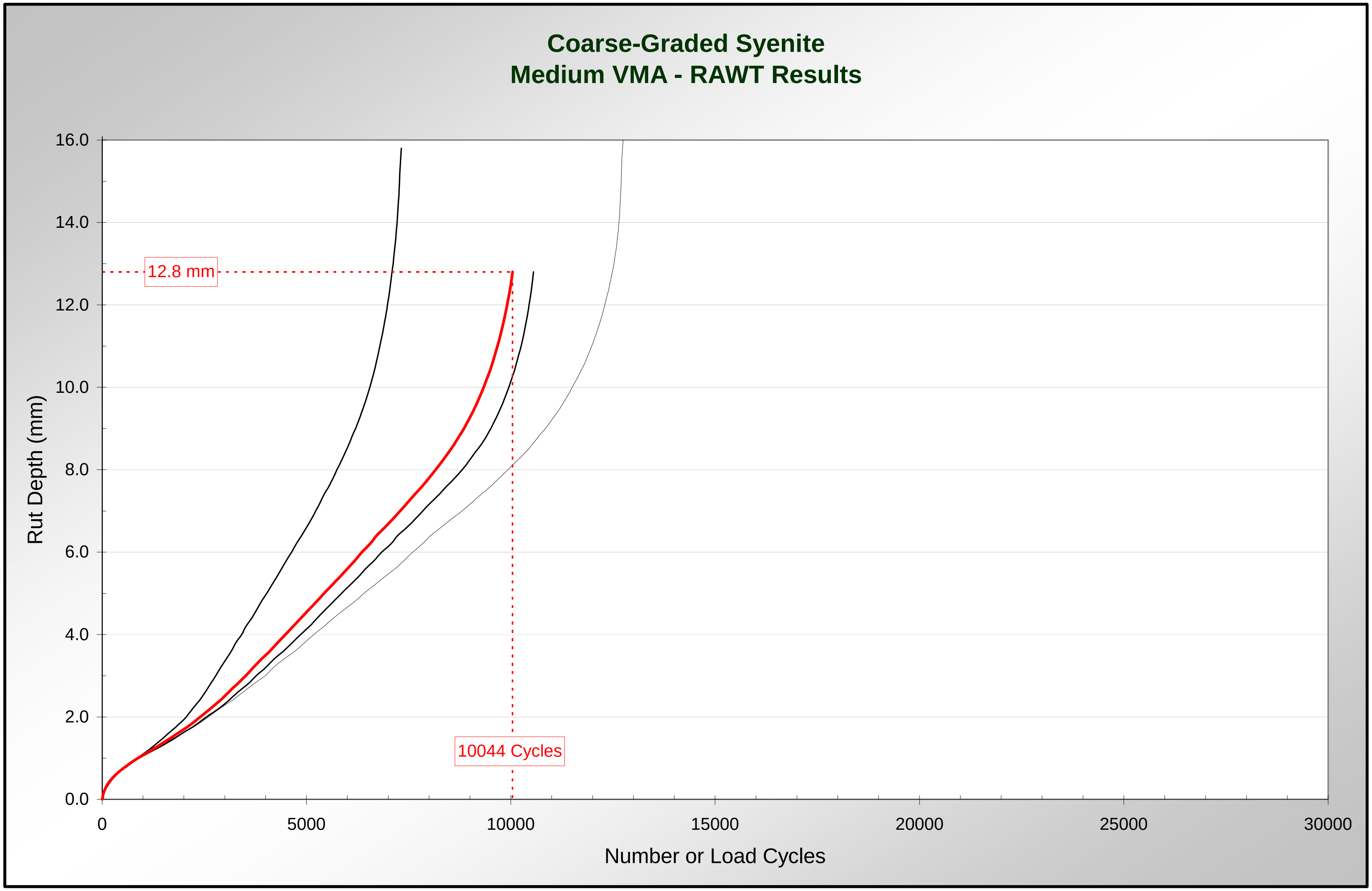

Coarse-Graded Sandstone
High VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
11.4 mm
22707 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

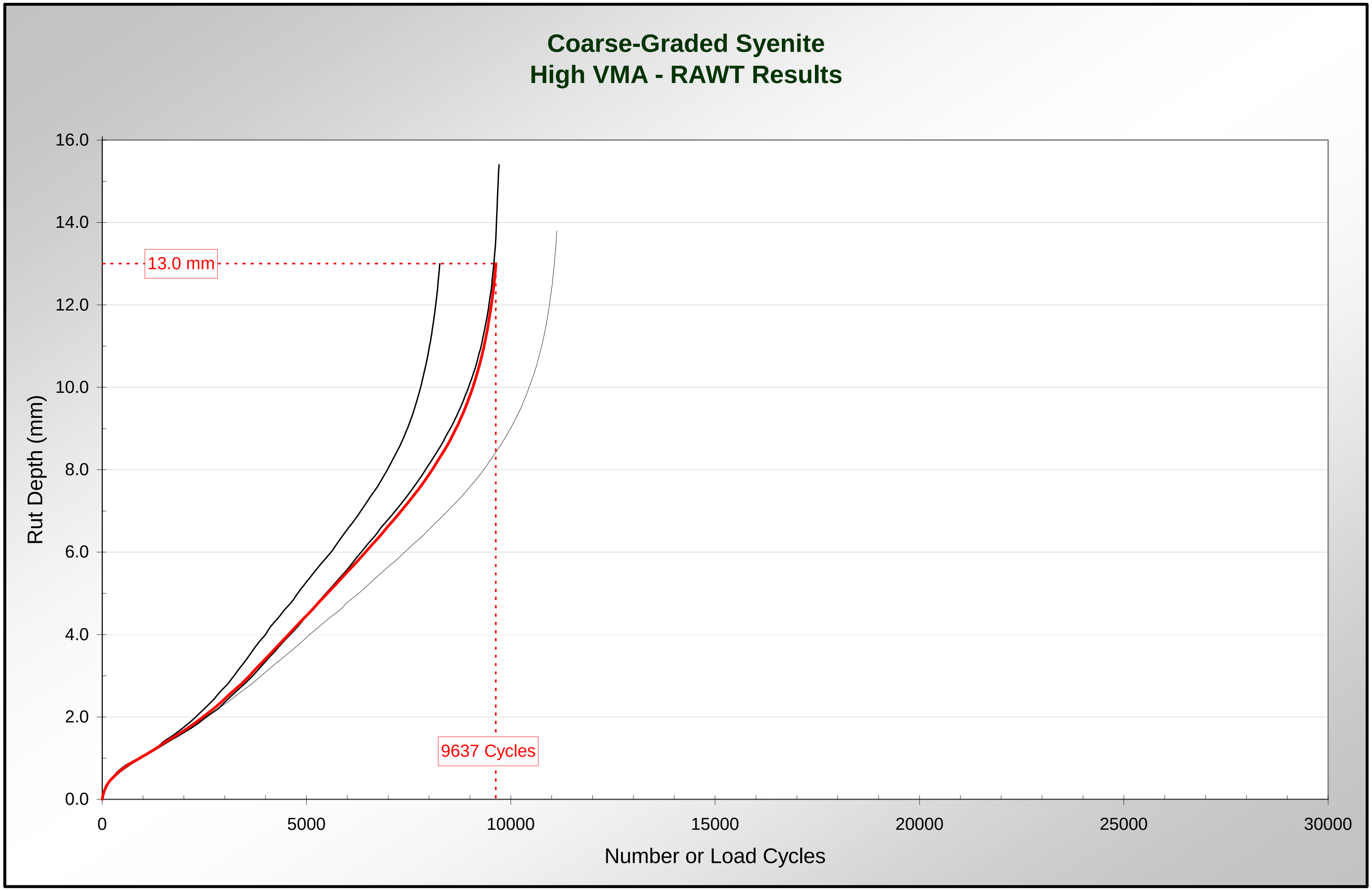

Fine-Graded Sandstone
Low VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles
8.2 mm
16272 Cycles

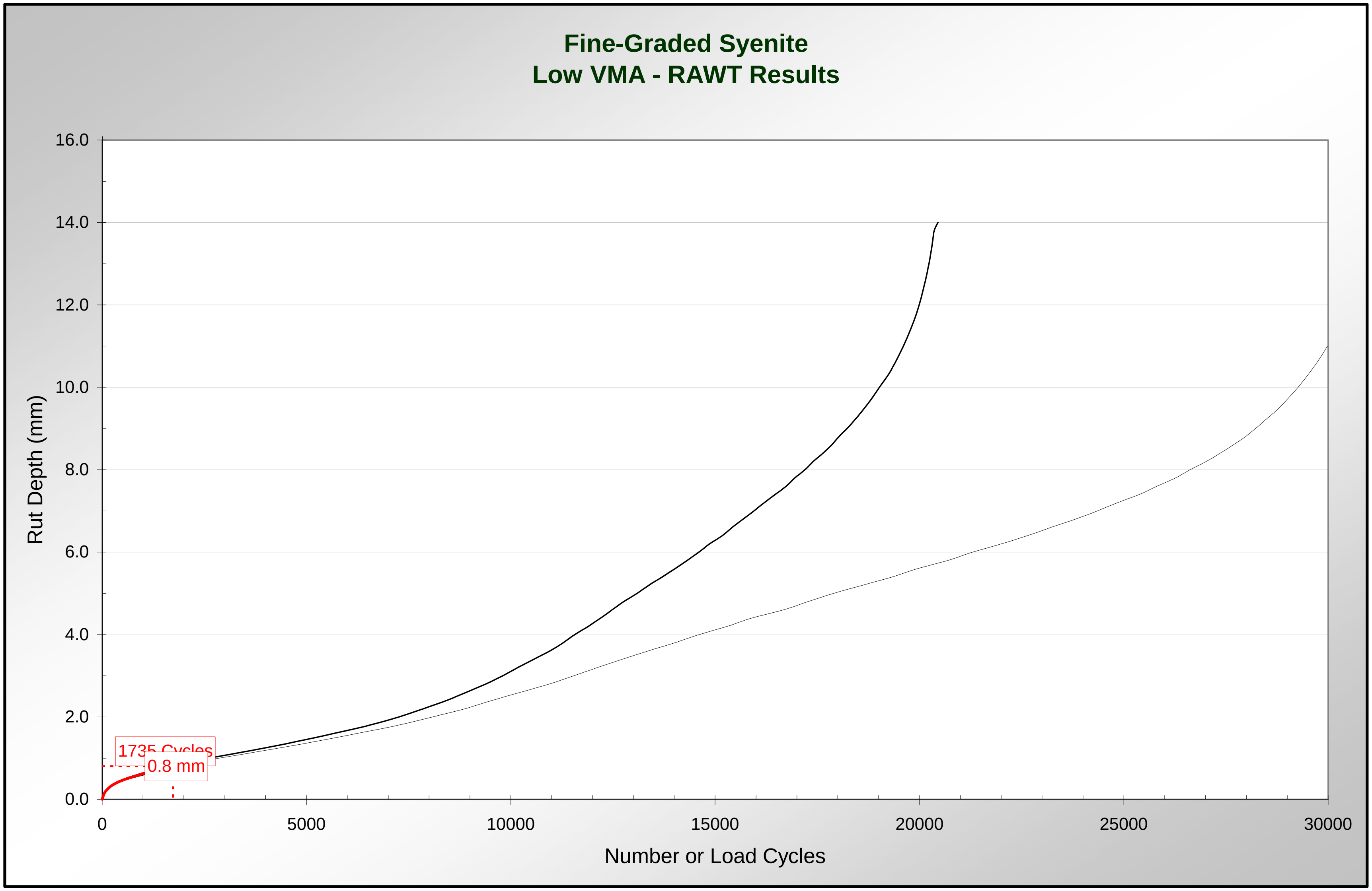

Fine-Graded Sandstone
Medium VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
127 Cycles
0.2 mm
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles


Fine-Graded Sandstone
High VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
4.4 mm
22948 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

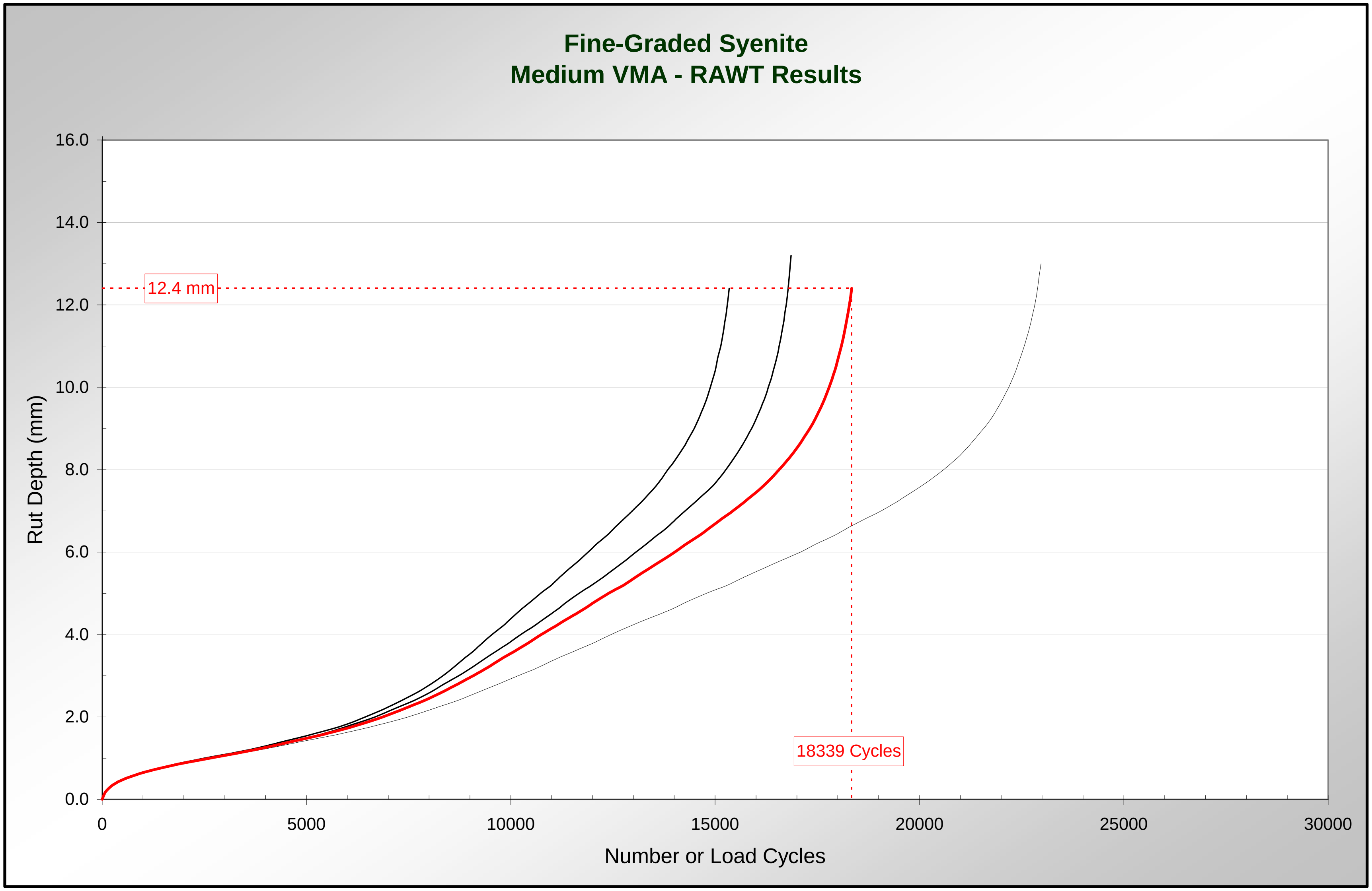

Coarse-Graded Syenite
Low VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
14.8 mm
16938 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

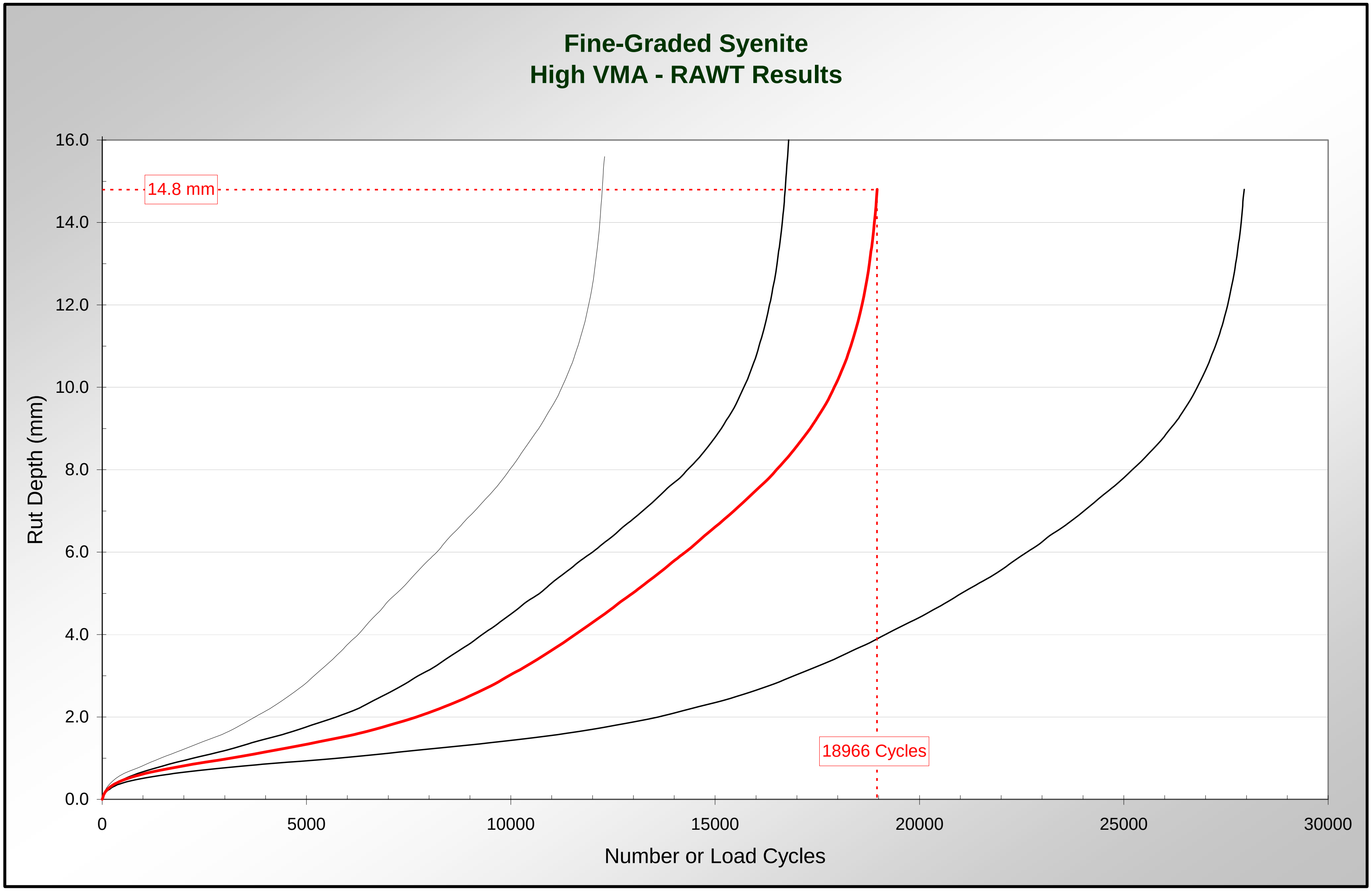

Coarse-Graded Syenite
Medium VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
12.8 mm
10044 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

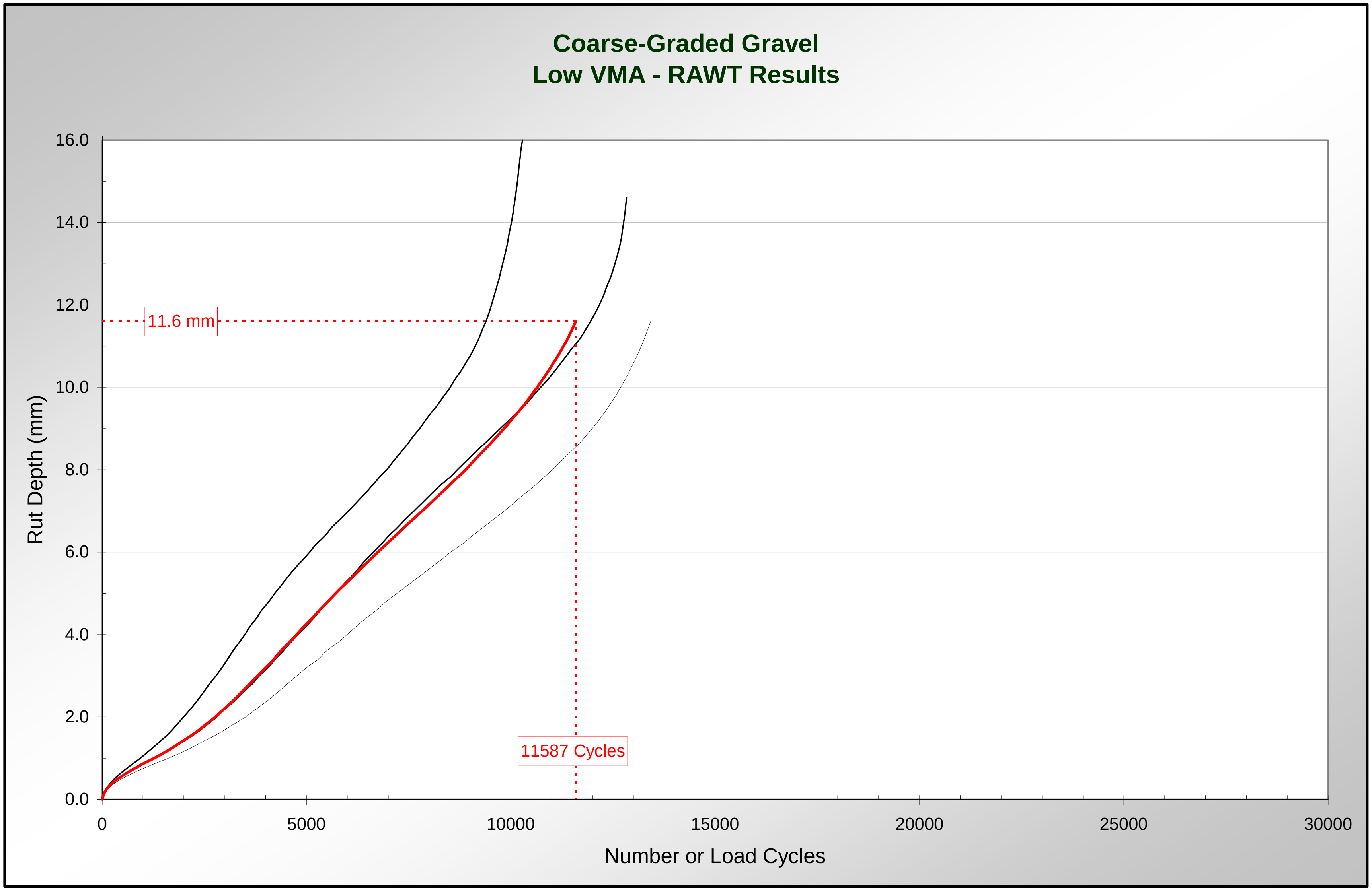

Coarse-Graded Syenite
High VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
13.0 mm
9637 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

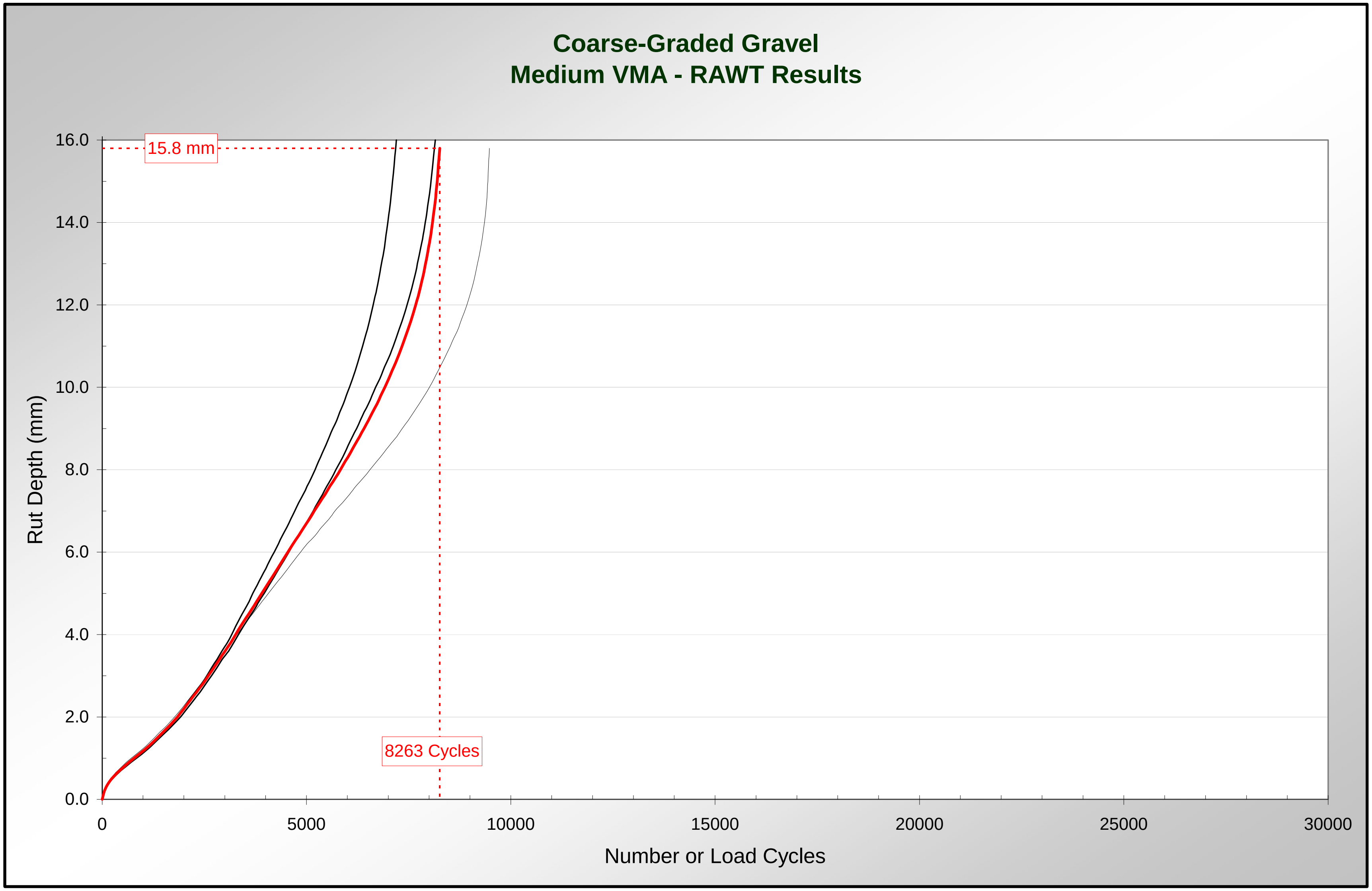


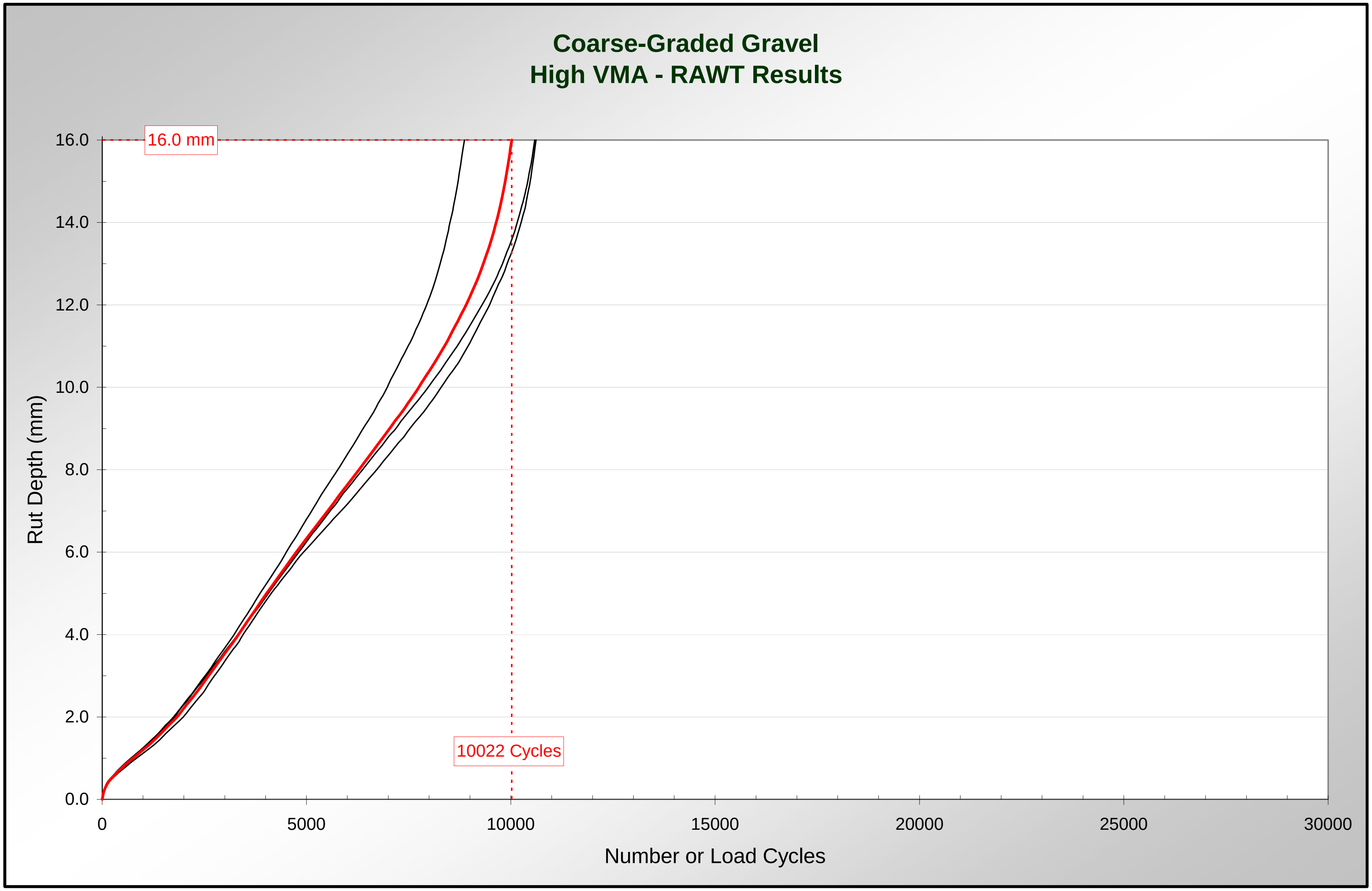
Fine-Graded Syenite
Low VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles
1735 Cycles
0.8 mm

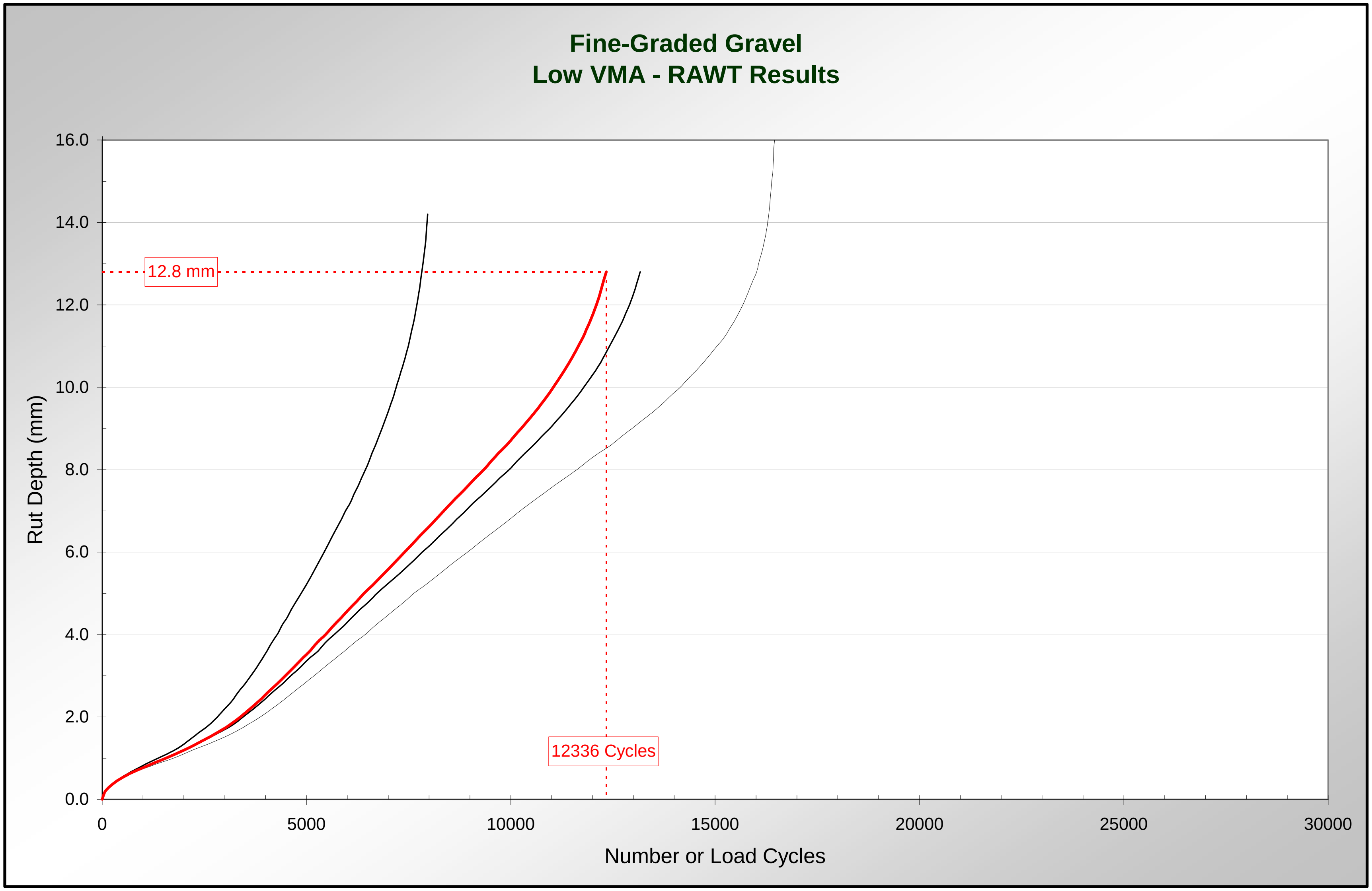

Fine-Graded Syenite
Medium VMA - RAWT Results
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Rut Depth (mm)
12.4 mm
18339 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles


Fine-Graded Syenite
High VMA - RAWT Results
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Rut Depth (mm)
14.8 mm
18966 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

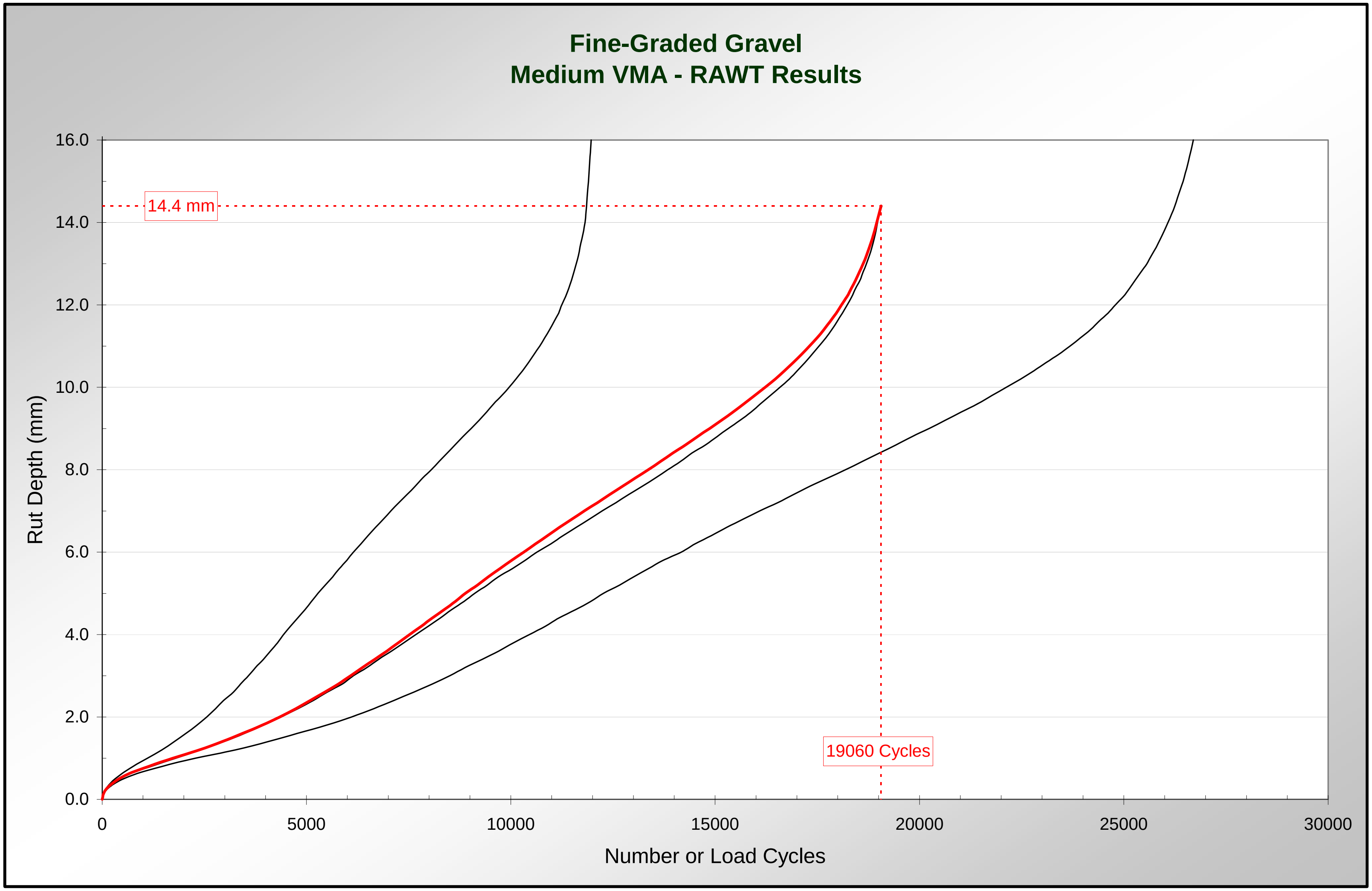

Coarse-Graded Gravel
Low VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
11.6 mm
11587 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

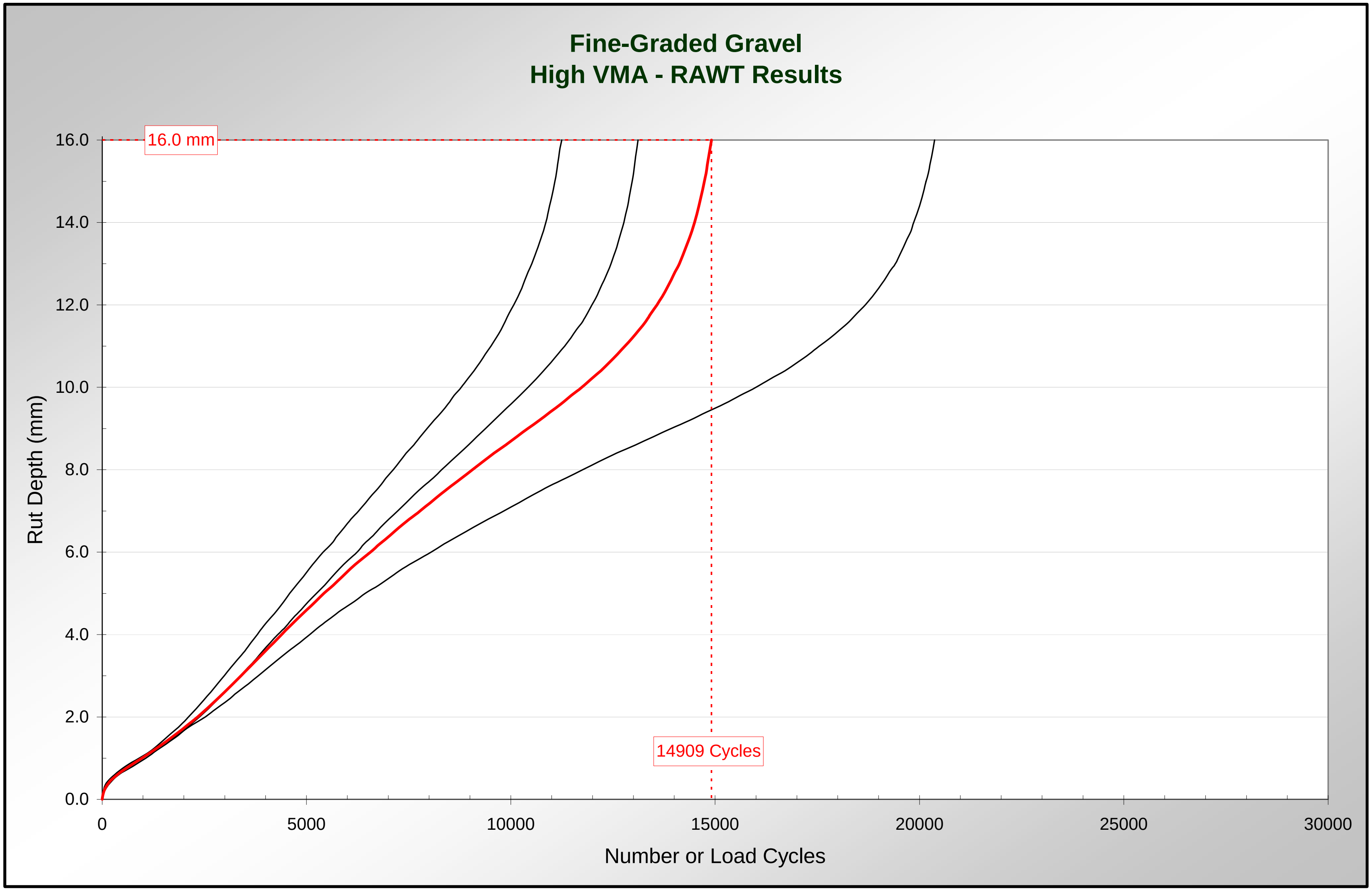

Coarse-Graded Gravel
Medium VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
15.8 mm
8263 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles


Coarse-Graded Gravel
High VMA - RAWT Results
16.0 mm
10022 Cycles
Rut Depth (mm)
Number or Load Cycles
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
0
5000
10000
15000
20000
25000
30000

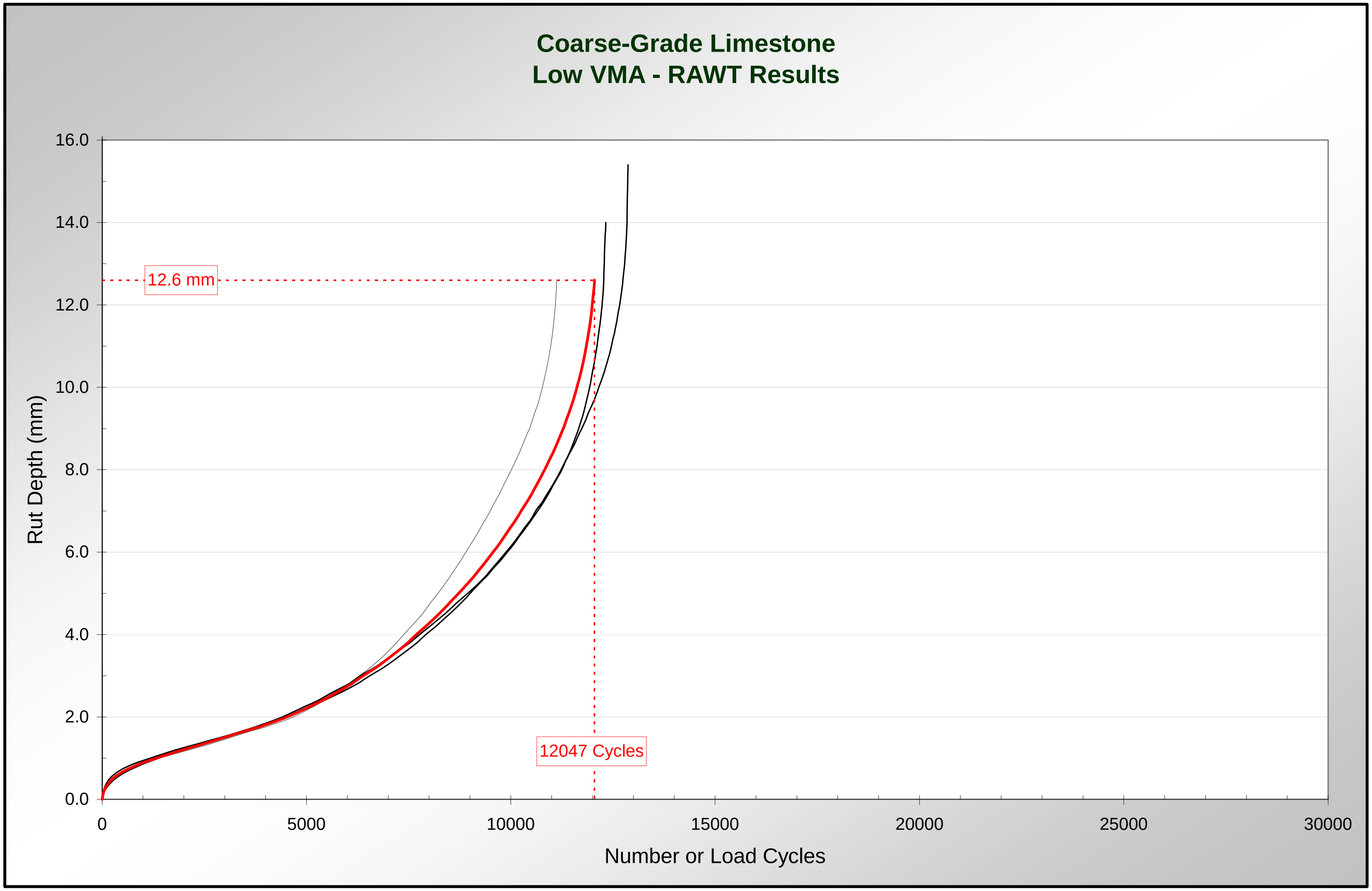


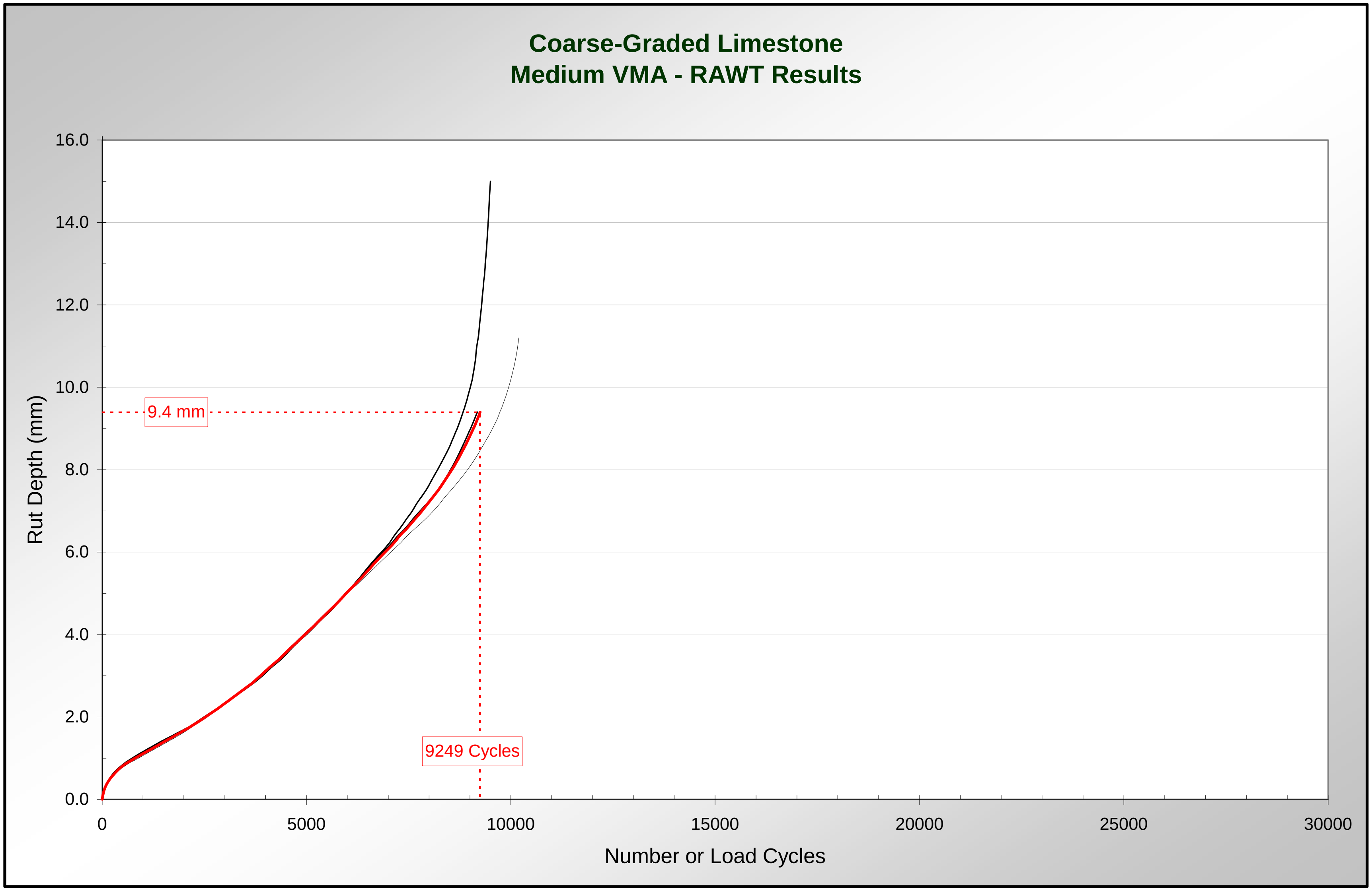
Fine-Graded Gravel
Low VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
12.8 mm
12336 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

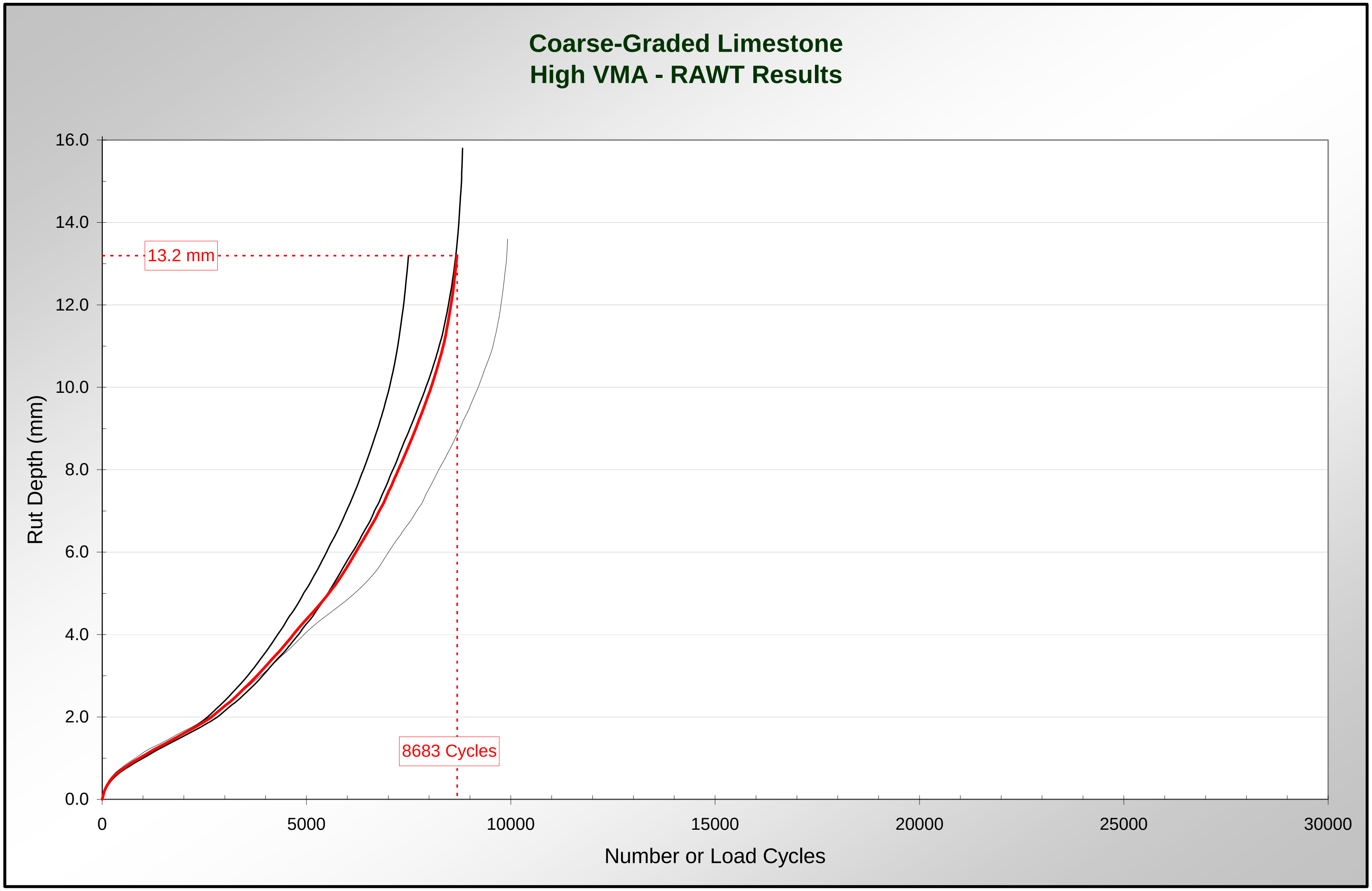

Fine-Graded Gravel
Medium VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
14.4 mm
19060 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

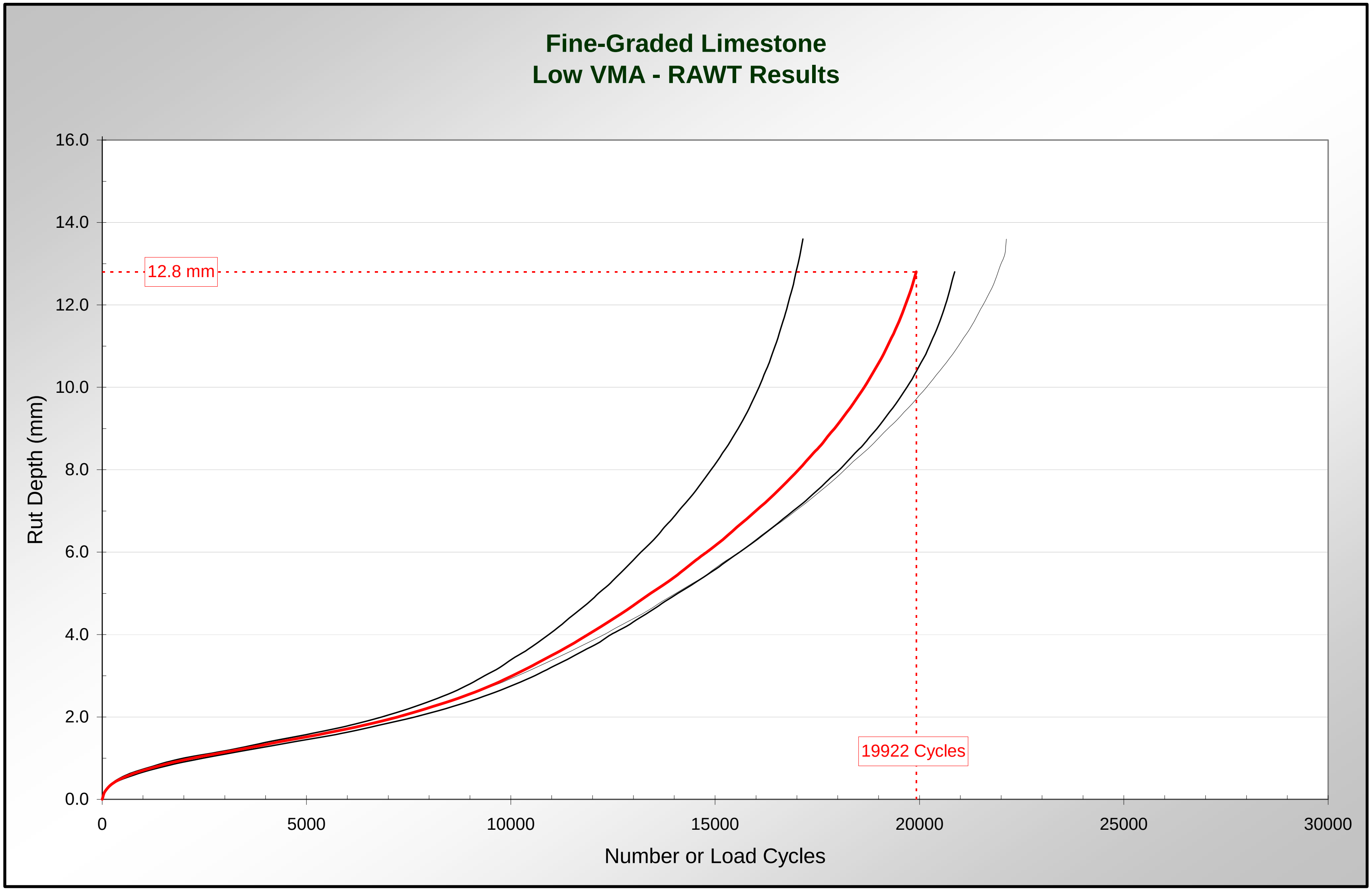


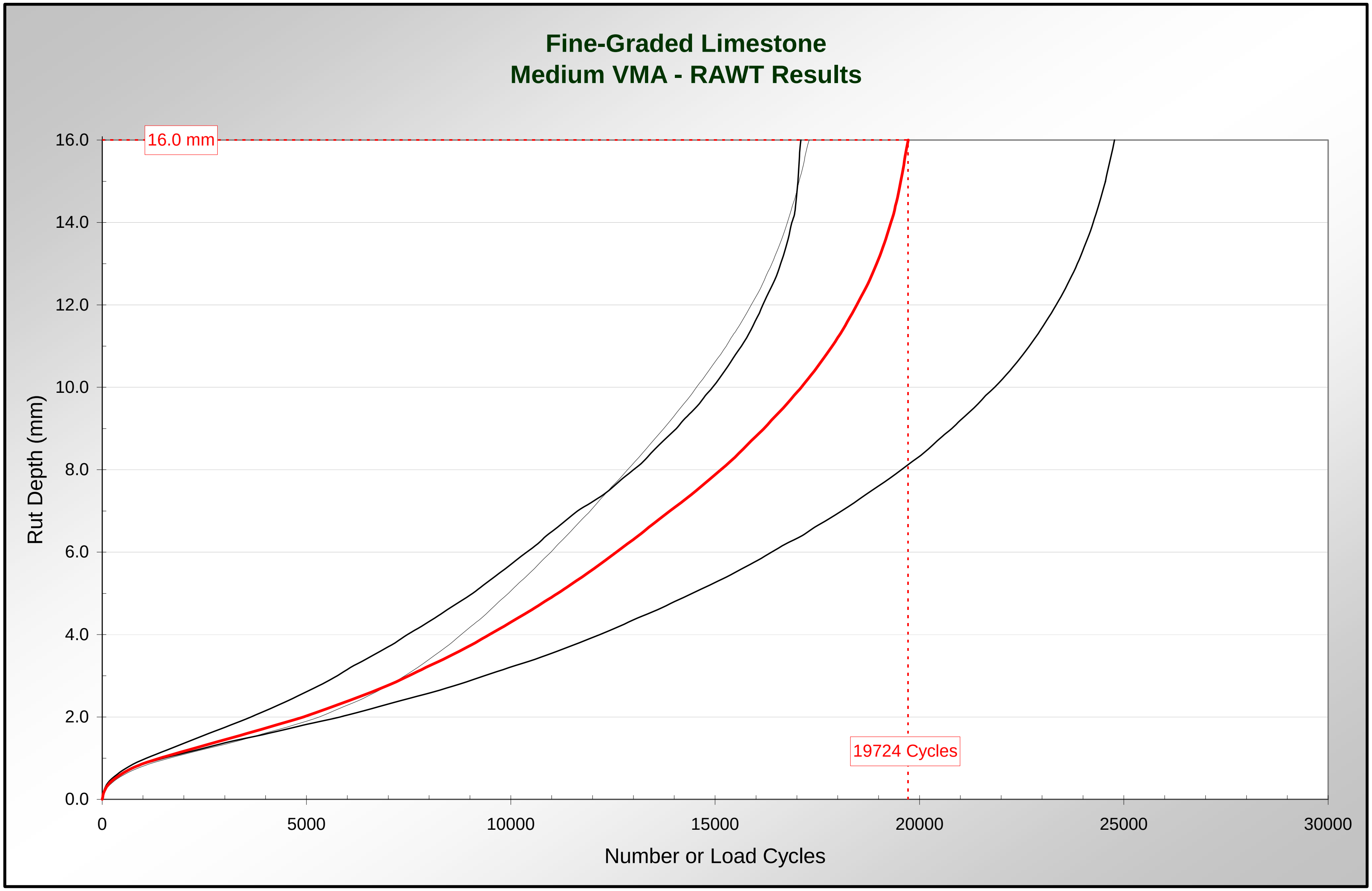
Fine-Graded Gravel
High VMA - RAWT Results
16.0 mm
14909 Cycles
Rut Depth (mm)
Number or Load Cycles
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
0
5000
10000
15000
20000
25000
30000

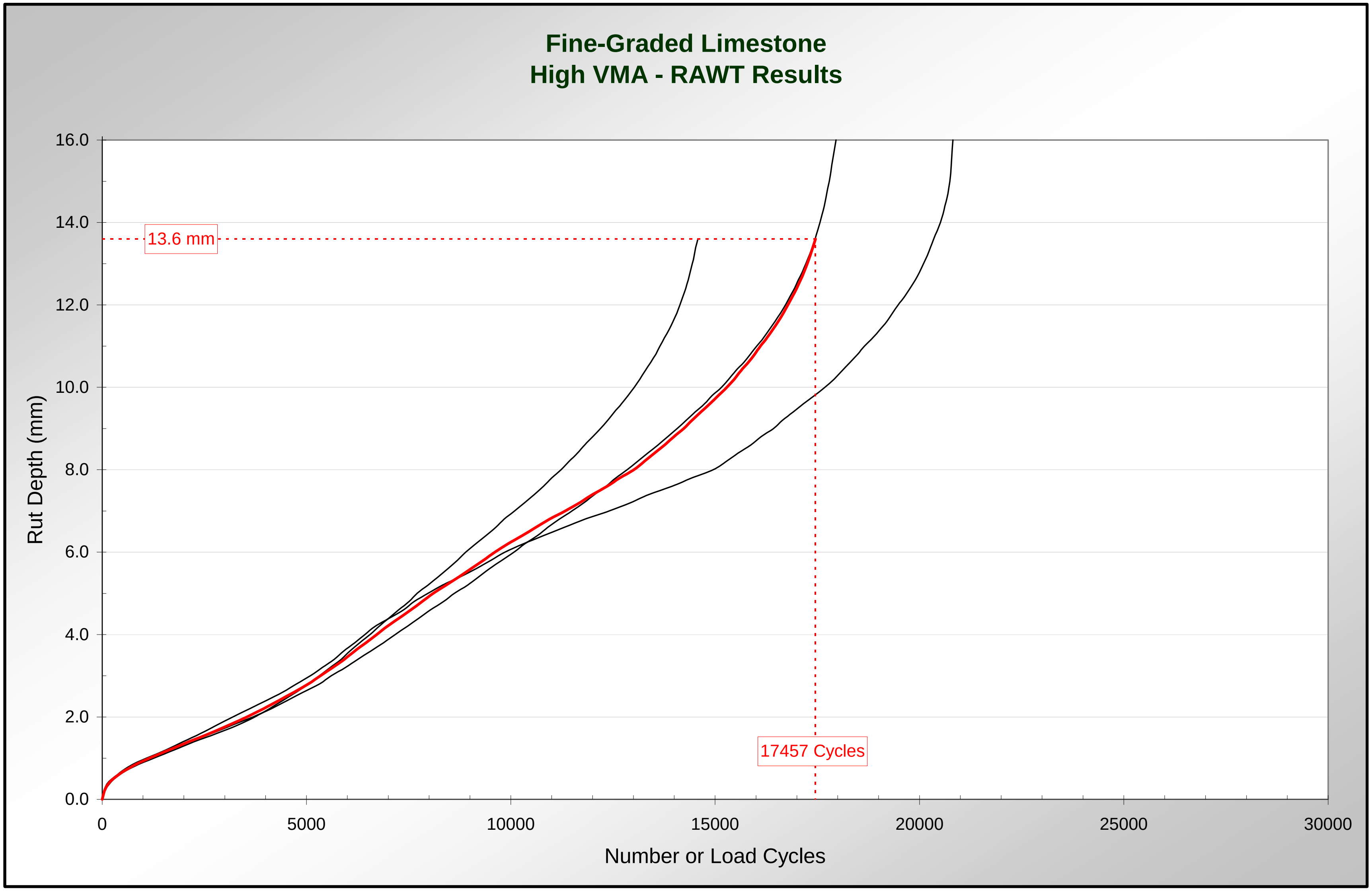

Coarse-Grade Limestone
Low VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
12.6 mm
12047 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles


Coarse-Graded Limestone
Medium VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
9.4 mm
9249 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles


Coarse-Graded Limestone
High VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
13.2 mm
8683 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles


Fine-Graded Limestone
Low VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
12.8 mm
19922 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles


Fine-Graded Limestone
Medium VMA - RAWT Results
16.0 mm
19724 Cycles
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles


Fine-Graded Limestone
High VMA - RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
13.6 mm
17457 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles