DEVELOPMENT OF 4.75mm SUPERPAVE MIXES

MBTC-2030

by

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May 2006

ABSTRACT

Until recently, the Superpave asphalt mix design specification did not include the 4.75mm nominal maximum aggregate size (NMAS). Such mixes have the potential to create a smooth riding surface, extend pavement life, improve ride quality, improve safety characteristics, enhance appearance, increase durability, reduce permeability, and reduce road-tire noise. Also, because of the ability to place these mixes in thin lifts, they can be used to correct surface defects, decrease construction time, decrease construction costs, and to extend maintenance dollars. The Arkansas State Highway and Transportation Department does not currently use a 4.75mm NMAS mix. Thus, the objectives of this project were to evaluate the benefits and impacts associated with 4.75mm mixture implementation.

In this study, three aggregate sources (limestone, sandstone, and syenite) were used to develop 4.75mm nominal maximum aggregate size (NMAS) mixtures. From each source, six mixtures were designed at varying design air void contents and design compaction levels. Two air void levels (4.5 and 6.0 percent) and three compaction levels (Ndes = 50, 75, and 100) were evaluated in order to determine the most advantageous design parameters with respect to rutting, stripping, and permeability. Also, the use of natural sand was investigated.

The results of the study indicate that 4.75mm mixes can be successfully designed using existing aggregate sources. In some cases, minor modifications to existing stockpile gradations improved design success. Design air voids and compaction level were both important to the performance of the mixes. The greatest resistance to rutting and stripping was provided for low- and medium-volume mixes when designed at 6.0 percent air voids, and for high-volume mixes when designed at 4.5 percent air voids.

Thus, different design air void levels were recommended for different applications. Some aggregate sources were able to tolerate the addition of natural sand. In general, however, rutting and stripping potential increased as the natural sand content increased. When compared to mixes with larger NMAS, the 4.75mm mixes exhibited rutting and stripping resistance similar to, and sometimes greater than, that of typical 12.5mm surface mixes. The permeability of the 4.75mm mixes was determined to be very low, and thus there is excellent potential for using these mixes to seal surfaces that may be prone to permeability problems.

Overall, the results of the study indicated that 4.75mm mixes have the potential to successfully provide many benefits. Thus, it was recommended that the 4.75mm NMAS be added to the Arkansas mix design specification.

ACKNOWLEDGMENTS

The author wishes to sincerely acknowledge the sponsorship of the Mack-Blackwell National Rural Transportation Study Center (MBTC) and the Arkansas State Highway and Transportation Department (AHTD) for funding this research effort. The talents of Ravi Vedantham, John T. Krentz, Artem Popov, Jonathan Strain, and Marcos Argote are also greatly appreciated. The personnel of AHTD RE 43, APAC-Arkansas (McClinton-Anchor and Arkhola Divisions), and Granite Mountian Quarries, are also recognized for their efforts and support.

INTRODUCTION

In the 1990s, the Superpave (Superior Performing Asphalt Pavements) mix design procedure gained recognition by many state agencies. In the Superpave protocol, focus is placed on mixture performance. Requirements are placed on the aggregates, binder, and voids of the mix based on climatic conditions and expected traffic levels for the pavement. The expectation is that if certain properties are met, the performance of the mix will be acceptable. The original Superpave mix design procedure included specifications for 9.5mm, 12.5mm, 19.0mm, 25.0mm, and 37.5mm nominal maximum aggregate size (NMAS) mixtures. However, the 4.75mm NMAS was not included. Prior to Superpave, many states used small aggregate mixes for various maintenance and low-volume applications. Thus, in order for a state to fully implement the Superpave system, it would be necessary to either eliminate a traditional product, or combine Superpave specifications with traditional or modified specifications.

Mixes with 4.75mm NMAS can be beneficial for many reasons. Such mixes have the potential to create a smooth riding surface, extend pavement life, improve ride quality, improve safety characteristics, enhance appearance, increase durability, reduce permeability, and reduce road-tire noise. Also, because of the ability to place these mixes in thin lifts, they can be used to correct surface defects, decrease construction time, decrease construction costs, and to extend maintenance dollars.

With the advent of Superpave, many agencies began to recommend the use of coarse-graded mixtures. Several agencies have also begun to utilize stone-matrix asphalt (SMA) mixes. In both situations, the stability of the mix is highly dependent upon the stone-to-stone contact of coarse particles, which in turn, limits the use of fine aggregate materials. As a result, excessive stockpiles of fine aggregate materials have accumulated. The implementation of 4.75mm mixes would aid in the reduction of these stockpiles, providing a use for materials that could otherwise become a "by-product" of the HMA industry.

This project examined the potential for using of 4.75mm Superpave mixtures for low-, medium-, and high-volume applications. Issues pertaining to the appropriate design of these mixtures were investigated, as well as resistance to permanent deformation and permeability.

BACKGROUND

In the late 1980's, the Strategic Highway Research Program (SHRP) began a significant research effort with the objective of creating an improved asphalt mixture design system. A prominent product of this research was Superpave, which stands for *Su*perior *Per*forming Asphalt *Pave*ments. Traditional mix design methods (such as the Marshall and Hveem methods) were based upon the premise that if the volumetric properties of the mixture met a set of specifications, then the mix would perform well. However, very little testing was done to validate these claims in terms of performance. The Superpave method uses the traditional methodologies in terms of volumetric property requirements, but also includes a performance component. Additional requirements were developed for the constituent materials of the mixture based on the relationship of material properties to the primary failure modes of permanent deformation, fatigue cracking, and low temperature cracking. *(1)*

One of the most significant changes brought about by the Superpave mixture design method was development of the Superpave Gyratory Compactor (SGC). The SGC, shown in Figure 1, was based on a combination of features of the Texas gyratory compactor and the French gyratory compactor. During sample compaction, the mold is tilted at an angle of 1.25 degrees and rotated at 30 gyrations per minute while subjected to 600 kPa of pressure. This compaction mechanism is believed to better simulate field compaction than the impact compaction method employed by the more traditional Marshall method. *(1)* Laboratory testing has shown that the SGC generates greater compaction than the Marshall hammer, thereby creating more stable mixes. *(2)*

Figure 1. Superpave Gyratory Compactor (Pine AFGC125X)

Compactive effort is incorporated into the design process by the number of gyrations (N) applied to the specimen. The amount of compactive effort applied to a particular mix is based on expected traffic loadings, expressed as design Equivalent Single Axle Loads (ESALs). Greater compactive effort is required for mixes that are intended to serve high traffic volumes. Compaction properties are determined early in the compaction process (percent density at $N_{initial}$), at the design compaction level (percent density at N_{design}), and late in the compaction process (percent density at $N_{maximum}$). These properties represent the density of the mix at different stages during the life of the pavement. If the density of a mix is too high early in the compaction process (N_{ini}), it may be prone to stability problems. If the density of a mix is too high at the end of the compaction process (N_{max}), it may be prone to bleeding or rutting. The density of the mix at N_{des} should correlate with the design air void content of the mix.

Another major change included in the Superpave method was the binder specification. Asphalt cement binders were "performance-graded", and specified based on their expected performance at a range of temperatures. For example, a PG 70-22 binder would be expected to perform well at a high pavement temperature of 70 C and a low pavement temperature of -22 C. By using this system, the mixture can be tailored to the environmental conditions of a particular region. *(3)*

Aggregate properties were also incorporated with respect to performance. A selection of source and consensus properties were chosen that were believed to most affect performance. Although many agencies already employed specifications for such properties, the inclusion of these requirements formalized the importance of aggregate characteristics.

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.

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. *(1)* 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. *(1, 4, 5)* Specifications for this property aid in limiting the use of natural sands, which are known to create "tender" mixes. Because 4.75mm mixes contain primarily fine aggregate, this property is important to the performance of such mixes.

The structure of an aggregate blend is also important to mixture performance. Traditional specifications typically included a "band" for acceptable gradations such that the entire gradation curve was required to plot within that band. Superpave gradations may take any shape, as long as they pass between control points at the maximum aggregate size (MAS), the nominal maximum aggregate size (NMAS), an intermediate sieve size (INT) and the #200 sieve size (0.075 mm). These elements are presented in Figure 2.

Early Superpave gradations were restricted by the control points as well as an area called the restricted zone. It was recommended that gradations avoid the restricted zone, preferably passing below, however this was not a requirement. *(1)* 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 closely following the Maximum Density Line (MDL) in the fine aggregate sieves. 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. *(6, 7)*

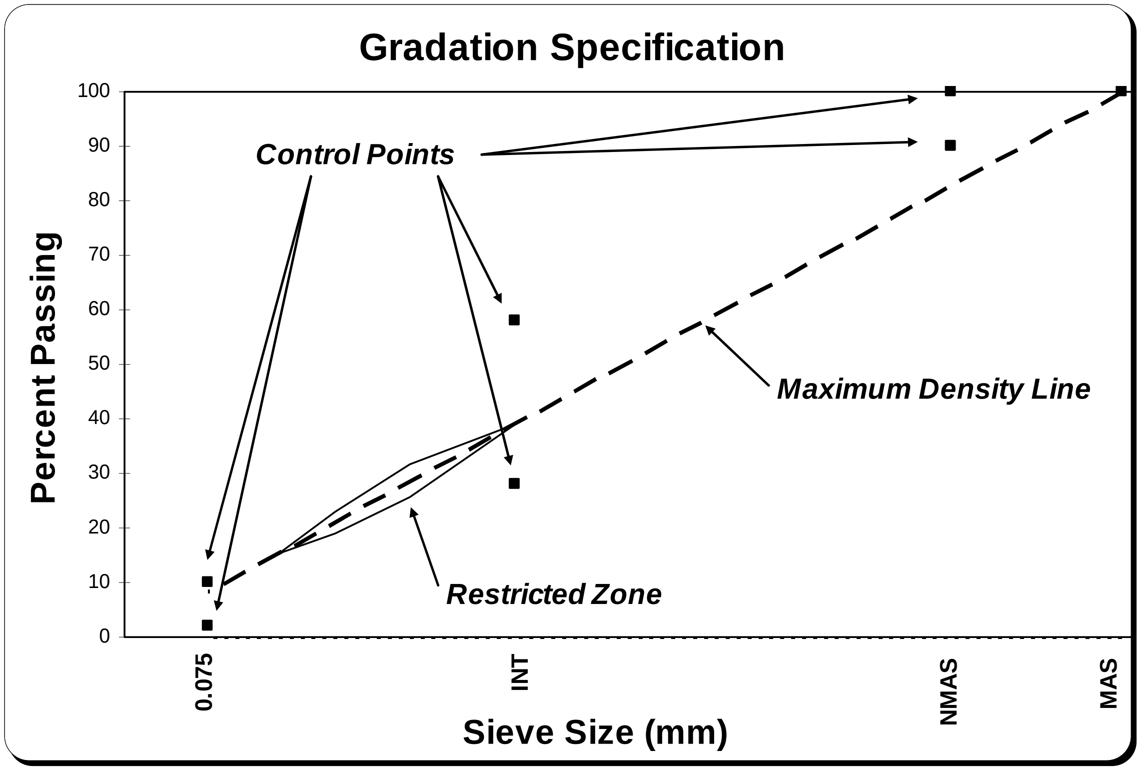

Figure 2. Superpave gradation specification

Volumetric requirements are a vital part of the Superpave mix design system. Similar to traditional mix design methods, the Superpave method has specified limiting values for many volumetric mix properties that are known to affect performance. A summary of the Superpave volumetric property requirements (not including the 4.75 mm NMAS) is presented in Table 1. *(5)*

Design ESALs[a] (Million)	Required %Density			Minimum VMA (%)					VFA Range[b] (%)	Dust to Binder Ratio
				Nominal Maximum Aggregate Size, mm						
	$N_{initial}$	N_{design}	N_{max}	37.5	25.0	19.0	12.5	9.5		
<0.3	≤91.5	96.0	≤98.0	11.0	12.0	13.0	14.0	15.0	70-80[c]	0.6-1.2
0.3 to <3	≤90.5	96.0	≤98.0	11.0	12.0	13.0	14.0	15.0	65-78	0.6-1.2
3 to <10	≤89.0	96.0	≤98.0	11.0	12.0	13.0	14.0	15.0	65-75[d]	0.6-1.2
10 to <30	≤89.0	96.0	≤98.0	11.0	12.0	13.0	14.0	15.0	65-75[d]	0.6-1.2
≥30	≤89.0	96.0	≤98.0	11.0	12.0	13.0	14.0	15.0	65-75[d]	0.6-1.2

[a] Design ESALs are the anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design ESALs for 20 years.
[b] For 37.5-mm NMAS mixtures, the specified lower limit of the VFA range shall be 64 percent for all design traffic levels.
[c] For 25.0-mm NMAS mixtures, the specified lower limit of the VFA range shall be 67 percent for design traffic levels <0.3 million ESALs.
[d] For design traffic levels >3 million ESALs, 9.5-mm NMAS mixtures, the specified VFA range shall be 73 to 76 percent.

Table 1. Superpave volumetric design specifications (not including 4.75 mm NMAS)

Air Voids

Air voids are known to affect pavement performance. In general, a mixture is most stable at an air void content between 3 and 8 percent. Below 3 percent and above 8 percent, the likelihood of rutting increases. *(8)* 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", and may resemble a rutting failure.

Binder Content

Binder content is also known to affect the performance 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.

Voids in the Mineral Aggregate

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 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. *(1)* 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. 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.

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). 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. *(9)*

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. *(10)* 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. *(11)* It is calculated by dividing the effective volume of asphalt binder by total estimated surface area of the aggregate particles.

Voids Filled with Asphalt

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.

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

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. *(6)*

Performance

While volumetric properties are related to performance, the relationships are rather empirical and are largely based on experience. In order to more directly assess the performance of designed mixtures, new equipment was developed for the Superpave system with the expressed purpose of obtaining a measure of *predicted* pavement performance, specifically targeting the failure modes of rutting, fatigue cracking, and low-temperature cracking. For determining resistance to permanent deformation and fatigue cracking, the Superpave Shear Tester (SST) was developed. The Indirect Tensile Tester (IDT) was developed for the purpose of determining susceptibility to low-temperature cracking. *(1)* Unfortunately, these devices were very expensive, were met with a great deal of scrutiny, and have not yet been widely accepted. As a surrogate procedure, proof tests, specifically wheel-tracking tests, have become increasingly popular as one of the most acceptable options for measuring rutting susceptibility.

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. *(12)* 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 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. *(12)*

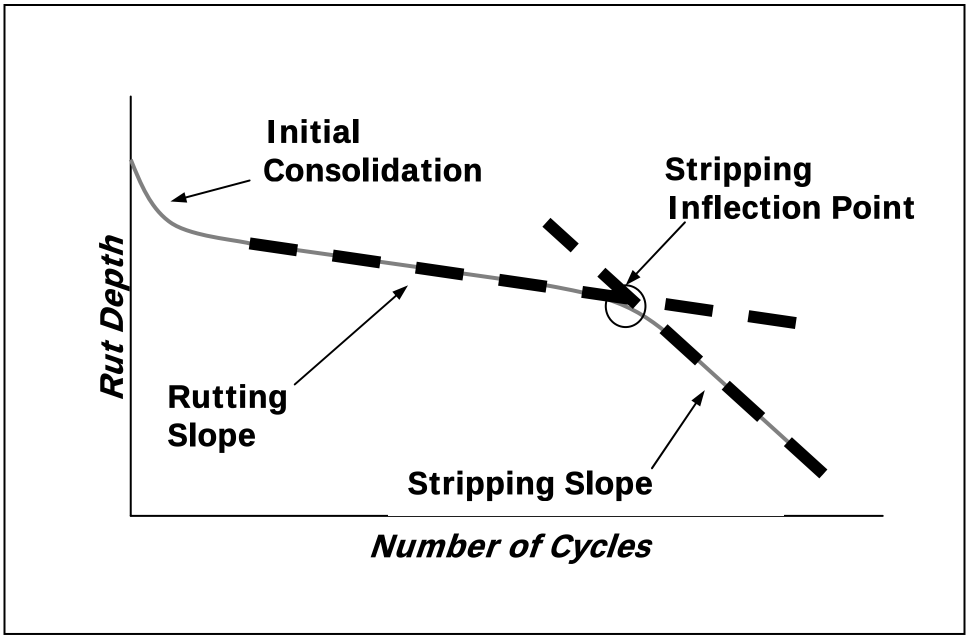

Figure 4. Schematic of Typical ERSA Data

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. *(13)*

RAWT

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.

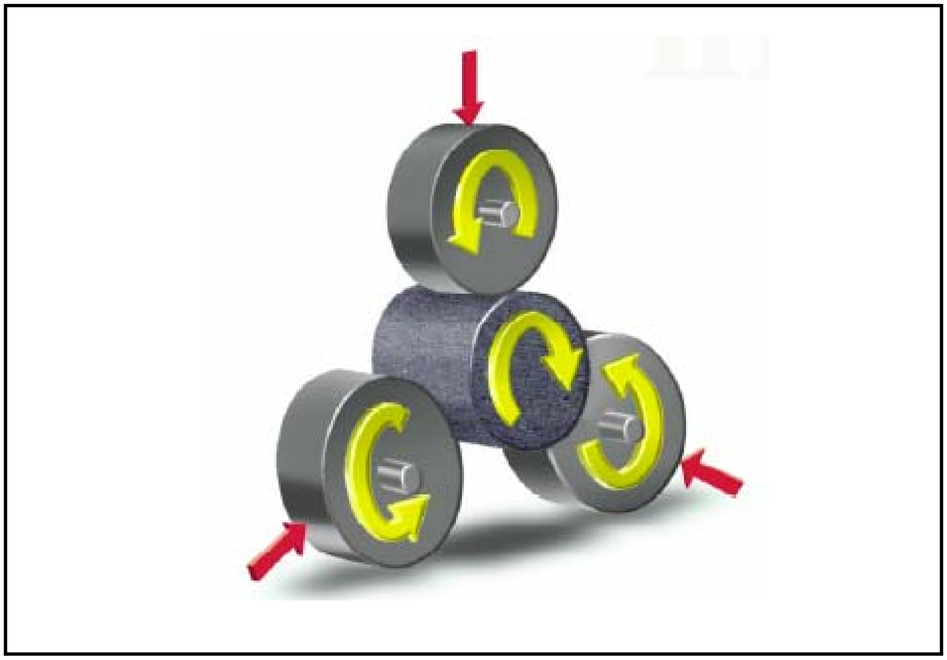

Figure 6. RAWT testing configuration

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. *(14)*

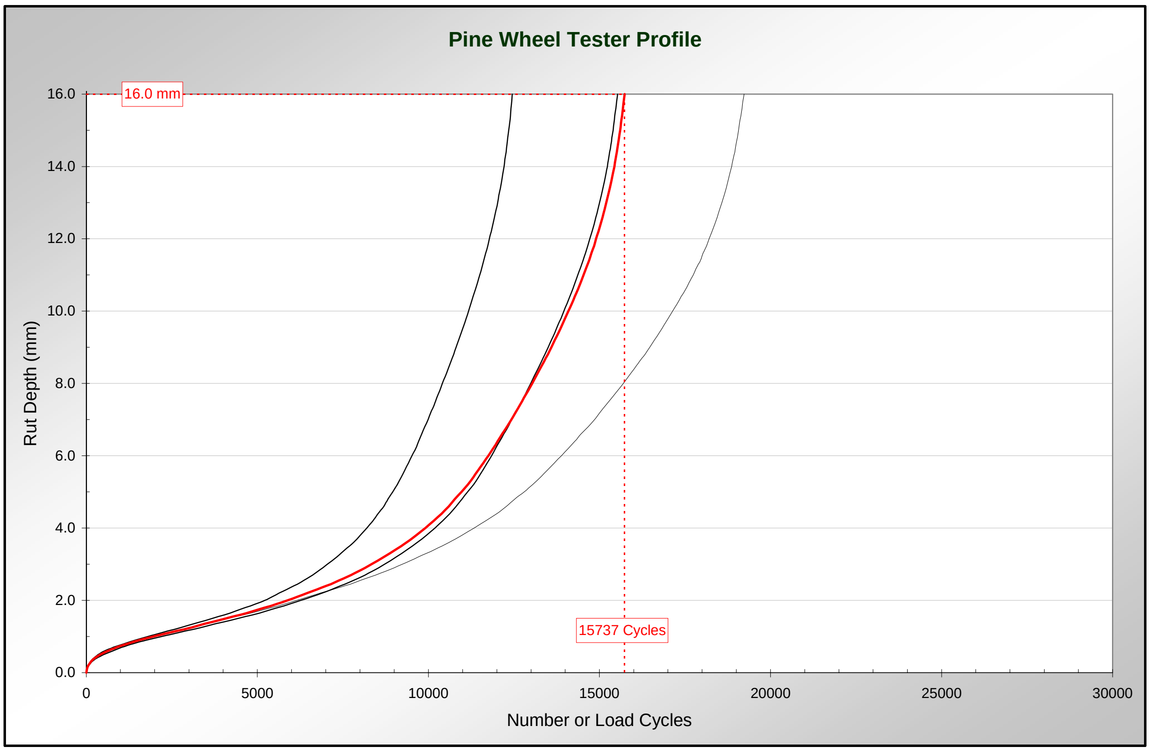

Figure 7. Typical RAWT Data

Permeability

One reported difficulty with Superpave mixtures is high permeability. *(15)* Since Superpave mixtures are coarser than their traditional counterparts, there are more large aggregate particles. Larger particles create larger voids (when designed to the same air void content), and larger voids lead to a greater likelihood of interconnected voids. Thus, there is a risk of greater permeability. Increased permeability allows oxidation and binder aging. This, in turn, leads to longitudinal and fatigue cracking, stripping, freeze-thaw problems, raveling, pop-outs, and surface weeping. *(16)*

Concern for permeability in Superpave mixes led to a great number of laboratory studies to investigate this phenomenon. In order to determine permeability in the laboratory, an asphalt permeameter was developed, and is marketed by Karol-Warner. This device is shown in Figure 8. The associated test method was outlined in the ASTM provisional standard PS-129, but inconsistencies with the method caused specification to be withdrawn. *(17)* In this falling head permeability test, a saturated asphalt sample is sealed on the sides and placed under a column of water so that water can only flow through the sample. The time required for the water column to experience a specified change in elevation is determined. The permeability coefficient, k, is calculated based on the time elapsed during the test and the drop in water level during that time period. The test is repeated until four consecutive readings do not differ by more than ten percent. This aids in verifying that the sample was, in fact, saturated. Otherwise, it would be unclear whether movement of the water column was due to water infiltrating void spaces or actual flow through the sample.

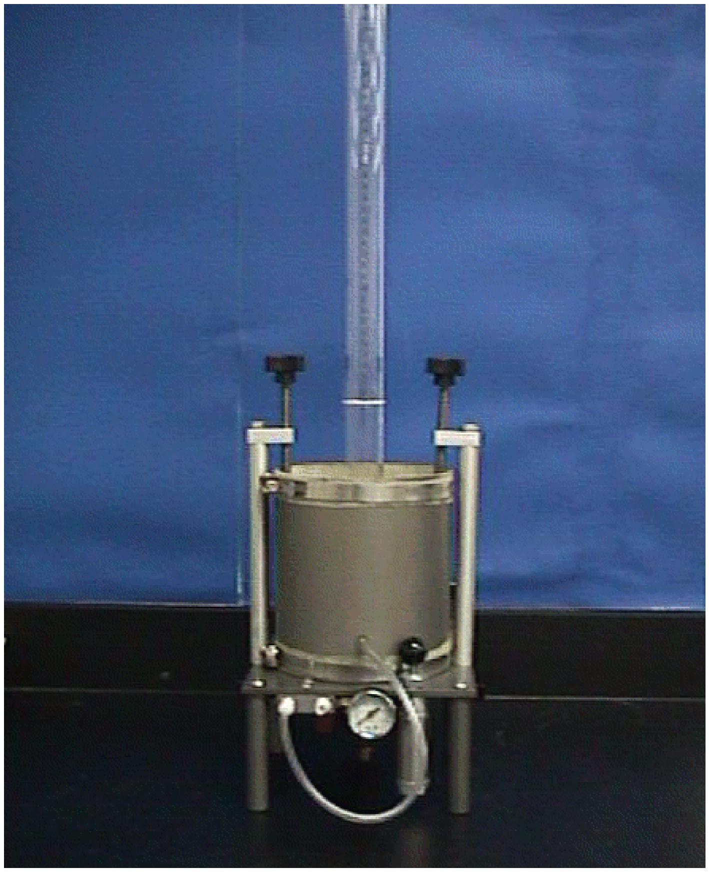

FIGURE 8. Karol-Warner flexible wall permeability device

Before Superpave

Prior to the Superpave design system, mixes were finely-graded and had a smooth appearance. This was largely due to differences in gradation, especially considering the recommendation that Superpave gradations pass below the restricted zone. Traditional gradations commonly passed above the MDL. A comparison of traditional and Superpave gradations for the 12.5mm NMAS is presented in Figure 9. The largest difference is evident in the percent of material passing the intermediate sieve (in this case the #8). The Superpave mix contains a significant amount of coarse aggregate and fine aggregate, but the intermediate size is limited. This allows for additional large stone particle interaction, thereby increasing the structural capacity of the mixture.

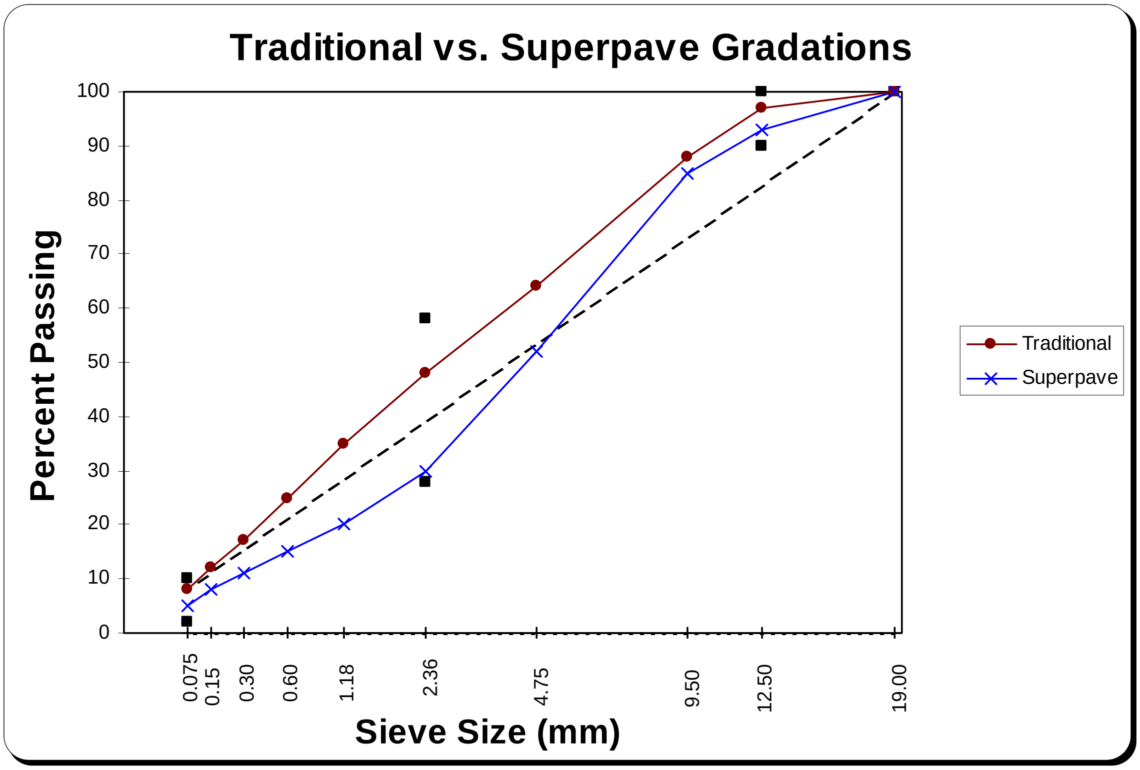

Figure 9. Traditional vs. Superpave gradation

Originally, Superpave included gradation specifications for 37.5mm, 25.0mm, 19.0mm, 12.5mm, and 9.5mm NMAS mixtures. However, many states had previously utilized smaller aggregate mixes with success. So, the lack of a 4.75mm Superpave specification caused a significant gap in implementation.

HMA mixes having smaller aggregates can be placed in thin lifts, and thus, are often termed "thin-lift" mixes. Such mixes have a multitude of potential uses, most commonly for maintenance and rehabilitation. When performing maintenance functions, it is often necessary to correct surface defects in the existing pavement surface before placing an overlay, especially in the presence of rutting. A fine-graded mixture is very well suited for leveling, shimming, or as a scratch course. In this case, the primary concerns are durability, workability, and smoothness.

Preventive maintenance is another excellent use for thin-lift mixtures. In this case, there is not usually a large concern with the structural integrity of the pavement, and only minor distresses are addressed. By placing mixtures in thin lifts (3/4" to 1"), maintenance dollars can be stretched, geometric tolerances of a roadway can be preserved, and milling or grinding can be minimized. For these applications, the primary concerns are durability, surface texture, smoothness, and ride quality. In addition, the permeability of the pavement structure can be reduced, and some level of crack healing may be achieved. Also, refreshing an asphalt surface allows for greater visibility of pavement markings, which helps to increase safety.

For low-volume roadways such as rural highways, county roads, city streets, and parking lots, thin lift asphalt mixes can provide many advantages. In these applications, the main concerns addressed are durability, workability, skid resistance, permeability, and appearance. Depending on the actual lift thickness and the condition of the underlying materials, the structural capacity could also be improved. It should be noted, however, that the structural capacity of these mixes is not adequate for truck parking and loading areas. In terms of performance and design, durability is more of a concern than rutting due to the low level of traffic loading. *(18)*

For medium and high volume roadways such as highways and arterials, thin-lift mixes can be used as a surface treatment to improve smoothness, promote crack healing, reduce road-tire noise, improve skid resistance, seal the surface, reduce permeability, and improve appearance. These mixes are not expected to improve the structural capacity of the roadway, and should only be placed on surfaces free of significant distress. Rutting should be considered during design for these applications since rutting is more of a concern when traffic levels are higher.

As states began to implement the Superpave system, it became apparent that the lack of a 4.75mm NMAS design was a significant disadvantage. Such mixes were still desired for use in leveling and maintenance applications, and were known to serve other functions as well. Also, the coarse nature of Superpave mixes had caused an abundance of screenings to accumulate. A 4.75mm NMAS mix would create a use for what is becoming a "waste" product of HMA production. Thus, the TRB Superpave Mixture and Aggregate Expert Task Group (ETG) appointed a Task Team to develop modifications to the AASHTO mix design specification (then AASHTO MP-2) to include the 4.75mm NMAS Superpave mix. *(19)*

A number of states have successfully used thin lift mixes for a variety of applications. Some of these mixes resemble a 4.75mm Superpave design, while others have considerable differences. A summary of the design parameters included in the AASHTO specification as well as other state specifications is presented in Table 2. *(5, 20, 21, 22, 23, 24, 25, 26, 27, 28)* Note that not all of the specifications presented are currently in use.

% Passing	AASHTO 4.75mm	MD	GA	NC	IN	MO	OH (Type A)	OH (Type B)	TN	AR Type III	AR Seal Crs.	ASTM	SMA
½"	100		100			100		100		100	95-100		
3/8"	95-100	100	90-100	100	100		100	95-100			86-100	100	100
No. 4	90-100	80-100	75-95	90-100	95-100	90-100	95-100	85-95	100	54-80	45-60	80-100	90-100
No. 8		36-76	60-65	65-90	70-90	65-95	90-100	53-63	95-100	32-64	29-44	65-100	28-65
No. 16	30-60				40-68		80-100	37-47		22-51		40-80	22-36
No. 30					20-50	20-40	60-90	25-35	50-80	14-43		25-65	18-28
No. 50			20-50		7-30		30-65	9-19	30-60	8-32	6-18	7-40	15-22
No. 100					1-20		10-30		8-25	5-21	4-14	3-20	
No. 200	6-12	2-12	4-12	4-8	0-5	3-10	3-10	3-8	2-10		2-10	2-10	12-15
Binder Content (%)		5.0-8.0	6.0-7.5				8.5 (Modified)	6.4 min.	7.0-11.0	4.5-7.5	4.5-7.5		
Air Voids (%)	4.0	4.0	4.0-7.0	7.0-15.0	6.0			4.0		4.0			4.0
VMA (%)	16.0 min.			20.0 min.	17.0 min.			15.0 min.		15.0 min.			17.0 min.
VFA (%)	75-78*		50-80										
DP	0.9-2.0									0.6-1.4			

*Depending on traffic level

Table 2. Comparison of design specifications for thin-lift type HMA mixes

Maryland has used thin HMA overlays as part of a preventive maintenance program, and these mixes have shown excellent resistance to rutting and cracking. The gradation requirement is such that the mixes could fit into either a 9.5mm or 4.75mm NMAS in the Superpave system, and a combination of approximately two-thirds manufactured screenings and one-third natural sand is typically used. The asphalt content is specified to be within the range of 5.0 to 8.0 percent, and the optimum design air void content is 4.0 percent. The mix is usually placed in lifts of 19 to 25 mm. *(20)*

The Georgia DOT has also successfully used a thin lift type of mix for over 30 years for leveling and for paving low-volume roadways. *(21)* These mixes are made up of mostly screenings and a small quantity of No. 89 sized stone. The resulting gradation contains approximately 60 to 65 percent passing the #8 sieve and roughly 8 percent passing the #200 sieve. The mixes are designed using the SGC and target an air voids range of 4 to 7 percent.

North Carolina is another state that has had success with thin lift HMA, having used a coarse sand asphalt mix for paving very low volume roadways. *(22)* This mix is designed with a high air void content and with a minimum VMA requirement of 20.0 percent. By designing at higher air voids, the optimum binder content is reduced, which aids in rutting resistance.

Other states such as Indiana, Missouri, Ohio, and Tennessee have similar specifications for the use of thin lift HMA mixtures. *(23, 24, 25, 26)* Ohio utilizes two types of a mixture known as Smoothseal. *(25)* Type A is an extremely fine mix used in medium traffic and urban applications. It is designed using 8.5 percent polymer modified binder, such that the stiffness added by the polymer modification serves as a substitute for aggregate strength. Type B Smoothseal is a coarser mix and is used for heavy-duty and high-speed applications. This mix has a gradation similar to that specified by AASHTO for 4.75mm Superpave mixtures. A minimum binder content of 6.4 percent is used with a minimum VMA of 15.0 percent and a 4.0 percent air void requirement.

Traditional mixture design specifications according to ASTM D 3515 included a gradation specification for a dense-graded sand asphalt mix. This gradation was somewhat finer than the AASHTO 4.75mm specification, allowing 100 percent to pass the No. 8 sieve. *(28)*

One other type of mixture having potential use in the 4.75mm NMAS is stone-matrix asphalt (SMA). This type of mixture is gap-graded, and appears to be a somewhat exaggerated form of the coarse-graded Superpave mix because it relies heavily on large particle stone-on-stone contact. Research has been conducted to assess the potential of this type of mixture for the 4.75mm NMAS. *(29, 30, 31, 32)*

Currently, Arkansas does not have a thin lift type of HMA in its construction specification. *(33)* Prior to current specifications, most low volume roadways were surfaced with a "Type III" mix. This mix was similar to a 9.5mm NMAS Superpave mixture, required 4.0 percent air voids, a minimum of 15 percent VMA, and a binder content in the range of 4.5 to 7.5 percent. A seal course was also included in the specification. This type of mix was also coarser than a 4.75mm NMAS Superpave mixture, but its specification was less restrictive than that of the Type III mix relative to other volumetric requirements. *(27, 33)*

The Superpave mix design system is more restrictive than most previously used specifications. If 4.75mm Superpave mixes are implemented for maintenance applications, then these mixes will be held to a standard similar to that of mixes used in new construction. These mixes might also perform well in other situations. Thus, the application of thin-lift mixes could be broadened.

In terms of performance, durability is usually thought to be the most important feature of a maintenance-type or low-volume mix. However, if 4.75mm Superpave mixes could be used for medium and high volume applications, rutting would become a greater concern.

LITERATURE REVIEW

4.75mm Mixtures

The majority of research work concerning 4.75mm mixtures has been performed by the National Center for Asphalt Technology (NCAT). One such study pertained to the development of mixture design criteria for 4.75mm Superpave mixes. *(34)* In this study, two aggregate sources (limestone and granite) were used to evaluate the effects of gradation, dust content, and design air void content on 4.75mm mixtures performance. Coarse, medium, and fine gradations (below, near, and above the MDL) were developed for each aggregate source, and designed to two air void contents (4 and 6 percent). Gradation was also evaluated by using three dust contents (6, 9, and 12 percent). The resulting 36 mix designs were tested in the Asphalt Pavement Analyzer (APA) for rutting susceptibility. All mixes were compacted to 75 design gyrations, and contained a PG 64/67-22 binder (a PG 64-22 that met the criteria for a PG 67-22).

For the 36 mixtures, design binder contents ranged from 4.2 to 8.0 percent. The granite mixes had higher average binder contents than the limestone mixes (approximately 0.5 percent higher). This was assumed to be due to the greater angularity and greater surface texture of the granite source. As the dust content increased, the optimum binder content decreased by an average of 0.5 percent for every three percent increase in dust. Fine gradations required the highest binder content, followed by the coarse, and then medium gradations. Mixes with lower design air void contents required more binder. This was sensible because the additional binder aided in compaction, thereby reducing the air void content.

Values of VMA for the mixes ranged from 14.2 to 20.8 percent. Aggregate type, dust content, and gradation shape (but not design air voids) were reported to affect the

VMA of the mix. The granite mixtures had higher levels of VMA, which was expected due to the greater angularity and surface texture. On average, the granite mixes contained 1.0 percent more VMA than the limestone mixes.

Relative to dust content, as the percent passing the No. 200 sieve increased, VMA decreased. The mixtures containing 6 percent dust had an average VMA of 18.3 percent, the mixes containing 9 percent dust had an average VMA of 16.7 percent, and the mixes containing 12 percent dust had an average VMA of 15.4 percent. Relative to gradation, the mixes with gradations near the MDL had the lowest levels of VMA, which was expected.

In order to assess performance and develop a specification, the experience of states already using these types of mixes was researched. Both Georgia and Maryland address durability by specifying a maximum dust content and a minimum binder content. By using these values, the average dust proportion was calculated to be 2.2 percent. Based on the relationships of dust proportion and VMA, a "critical" value for minimum VMA was determined to be 16.0 percent. This was a reasonable minimum because it follows the existing Superpave system in that as NMAS decreases, the required minimum VMA increases one percent per sieve size.

In terms of rut depth, the granite mixes rutted more than the limestone mixes. It was assumed that the higher binder contents of the granite mixtures were responsible for the rutting. Coarse gradations rutted (10.14 mm) slightly more than the fine gradations (9.72 mm) or medium gradations (6.29 mm). When dust contents were decreased, rut depths increased. This observation was also attributed to the fact that the mixes with smaller dust contents had higher design binder contents. Finally, the mixes with lower air void content rutted more than those at a higher air void content. Again, higher binder contents were blamed for their poorer performance. Statistically, the ANOVA revealed that there were some three-way interactions in the data and several two-way interactions, meaning that performance with respect to one factor was related to variations in another factor. For example, there was a significant interaction between aggregate type and dust content. This meant that the trend of performance as it related to dust content was dependent upon aggregate source. A significant interaction also existed between gradation dust content. There were large differences in the performance of the mixes having a fine gradation, and less variation in the test results for mixes having medium and coarse gradations.

This study resulted in several conclusions. First, the binder content of 4.75mm mixes should be limited in order to decrease rutting susceptibility. A minimum VMA of 16 percent and a maximum VMA of 18 percent was recommended, creating a range of two percent for acceptable VMA. These values agreed with the conclusions previously published from the WesTrack research. *(35)*

The mixes designed at 6.0 percent air voids exhibited better performance than those designed at 4.0 percent. However, a design air void content of 4.0 percent would provide consistency within the AASHTO specification. Therefore a design air void content of 4.0 percent was recommended. Based on an air void content of 4.0 percent and VMA values ranging from 16 to 18 percent, a recommended range of acceptable VFA results was calculated to be 75 to 78 percent, although it was believed that higher values could be tolerated for low traffic mixtures.

In terms of compaction requirements, none of the mixes failed the criteria as outlined for the 9.5 mm mixtures, and no problems were reported in achieving proper compaction. The range recommended for dust proportion was 0.9 to 2.2, which was based on the relationship of VMA and dust proportion, as well as the experience of the Maryland and Georgia Departments of Transportation.

Overall, the study indicated that 4.75 mm NMAS Superpave mixtures could be successfully designed, and that the 4.75mm NMAS should be added to the existing Superpave mixture design specification.

A similar study performed in West Virginia evaluated the same factors for different aggregate sources. *(36)* The results of the study were very similar to that determined in the NCAT study, with 4.75mm mixes being recommended for use. One additional feature in this research program was the evaluation of natural sand. As expected, the mixes containing higher percentages of natural sand did produce greater rut depths. This finding was consistent with previous recommendations by the Federal highway Administration (FHWA) that the use of natural sand be limited to approximately 15 to 20 percent for high volume pavements and 20 to 25 percent for low and medium volume pavements as a means to control the detrimental rutting effects of natural sand. *(37)*

Screenings

In another study, the focus was to assess the effects of aggregate source, binder grade, cellulose fiber, and design air void content on the use of screenings for 4.75mm Superpave mixes. Two single-source aggregate screenings (limestone and granite) and two binder grades (PG 64/67-22 and PG 76-22) were utilized in combination with three design air void contents (4, 5, and 6 percent). Finally, the presence of cellulose fiber was evaluated. Overall, all factors except binder grade were significant.

In general, the granite aggregate source required a significantly higher binder content than the limestone source. As in the previous study, this fact is attributed to the greater surface texture and finer gradation of the granite source. Thus, more compactive effort was required to compact the granite aggregate. The addition of fibers increased the demand for binder, causing an average increase of 0.7 percent.

On average, a one percent drop in air void content caused an average increase in binder content of 0.4 percent. Mixes designed at 5.0 and 6.0 percent air voids performed similarly with respect to rutting, and were slightly more rut resistant than those designed at 4.0 percent air.

VFA was concluded to be the most realistic option for ensuring durability, and 80 percent was believed to provide an appropriate limit. The final conclusion was that single-source screenings could successfully be used to make rut-resistant mixes.

4.75mm SMA

In another study of small aggregate mixes, 4.75mm SMA mixtures were evaluated. *(29)* Eight SMA mixtures were designed representing two aggregate sources (limestone and granite), two dust contents (9 and 12 percent), and two air void levels (4 and 6 percent). All mixes were compacted using 75 design gyrations and a PG 64/67-22 binder. Rutting susceptibility was determined by the APA.

Relative to design, the four limestone mixtures failed the 17.0 percent minimum VMA criteria by a considerable amount, though all four met the criteria for stone-on-stone contact. As in the other two studies, the granite mixes required greater binder contents than the limestone mixtures. As the percent passing the No. 200 sieve increased from 9 percent to 12 percent, optimum binder decreased by an average of 0.5 percent for the granite mixes, and by 0.2 percent for the limestone mixes.

Statistically, a three-way interaction was present between the factors of aggregate source, dust content, and air void level, meaning that the effects of individual factors were dependent upon each other. A significant interaction was present for aggregate type and dust content such that the limestone mixes were more sensitive to changes in dust content than the granite mixes. Overall, the rut depths were small, and it was concluded that 4.75mm SMA mixes do have potential for use as rut-resistant overlay mixes.

Similar research was performed to evaluate the potential for using 4.75mm SMA mixes in Mississippi. *(32)* Although difficulty was encountered in producing the mix designs for some sources, it was concluded that this type of mixture did provide rutting resistance and should be considered for use on problematic intersections.

Permeability

Due to the coarse nature of Superpave, permeability has become another topic of concern. Although a great deal of permeability testing has been reported for larger NMAS mixes, little has been published with respect to the permeability of 4.75mm mixtures.

A study in Florida reported that coarse-graded Superpave mixes can be excessively permeable to water even when containing in-place air voids of less than 8 percent. *(15)* This conclusion led to the suggestion that field density requirements be increased during the construction of Superpave mixtures. Typical specifications require a minimum field density of 92 percent, so increasing this value to approximately 94 percent could be a way to reduce the permeability problems associated with Superpave mixtures. A maximum acceptable permeability value of 100 x 10^{-5} cm/s was recommended.

This critical value was consistent with previous research performed in Arkansas, which had determined ranges of permeability as shown in Table 3. *(38)* The Arkansas study also determined that lift thickness was a significant factor relating to pavement permeability. For 12.5mm NMAS mixes, lift thicknesses of less than 2 inches had higher permeability. Thus, it was recommended that Superpave mixtures be placed with a minimum lift thickness of 4 times the NMAS.

Permeability Designation	Range of Permeability Coefficient, k
High Permeability	1 x 10^{-1} cm/s to 1 x 10^{-4} cm/s
Low Permeability	1 x 10^{-4} cm/s to 1 x 10^{-6} cm/s
Practically Impervious	1 x 10^{-6} cm/s to 1 x 10^{-9} cm/s

Table 3. Permeability ranges determined by Arkansas research

In a study at NCAT, the relationships of laboratory permeability, lift thickness, and density were investigated. *(39)* It was determined that permeability decreased as lift thickness increased. Also, smaller NMAS mixes were less permeable than larger NMAS at the same air void content. However, the 4.75mm NMAS was not included in this study.

In the NCAT study involving 4.75mm SMA mixes, the permeability of the 4.75mm SMA mixes was evaluated and compared to that of 9.5mm, 12.5mm, and 19.0mm mixtures. *(29)* Overall, the permeability of the 4.75mm mixes was lower than that of the others. Specifically, the 4.75mm mixtures were the only ones that did not exceed the critical permeability level of 100 x 10^{-5} cm/s. Thus, it was determined that 4.75mm SMA mixes exhibit desirably low levels of permeability.

OBJECTIVES

The overall objective of this project was to evaluate various aspects of the design of 4.75mm Superpave mixtures, and to assess the relative performance of these mixes with respect to traditional or typical surface mixes in terms of rutting resistance and permeability. Detailed objectives follow.

Develop guidelines for designing 4.75mm Superpave mixtures. Because a draft specification for 4.75mm Superpave mixtures was in circulation at the time this project began, the focus of this objective was primarily implementation-related. Using the anticipated requirements of the AASHTO specification as a basis for the study, the applicability of the design procedure was evaluated for typical Arkansas aggregate sources. Also, features affecting the AHTD's ability to implement the design specification were investigated.

Assess aggregate properties relating to the design of 4.75mm mixtures. Because 4.75mm mixtures are composed almost completely of fine aggregate, the specific characteristics of the aggregate which make it most applicable for use in 4.75mm mixtures should be determined. This would give guidance to aggregate producers regarding desirable qualities of aggregate screenings (relative to performance), potentially resulting in a more efficient collection and use of fine aggregate stockpiles.

Evaluate the applicability of 4.75mm mixtures for medium and high volume pavements. Although 4.75mm mixtures are typically perceived as being applicable to only low-volume roadways, there are many potential benefits for the use of such mixes on medium- and high-volume roadways. The goal of this portion of the study was to determine whether successful 4.75mm designs could be generated at higher levels of compactive effort.

Evaluate the level of design air voids for 4.75mm mixtures. Although four percent air voids was specified in the AASHTO specification for the design of 4.75mm mixtures, it was felt that a higher air void content could reduce the required binder content and make the mixtures more resistant to rutting. Too little binder, however, could reduce the durability of the mix. The effect of design air void content was evaluated to determine the appropriate value that would provide a balance of durability and rutting resistance.

Test the rutting and stripping susceptibility of 4.75mm mixtures. Rutting resistance is an important performance characteristic of asphalt pavements, especially for pavements that experience higher traffic volumes. Resistance to stripping is also important. Thus, before determining whether 4.75mm mixtures should be used for higher traffic applications, it was necessary to compare the rutting and stripping susceptibility of the 4.75mm mixtures to that of more traditional surface mixtures.

Determine the permeability of 4.75mm Superpave mixtures. Although asphalt mixtures containing smaller aggregates would be expected to have low permeability, existing Superpave mixtures have proven to be more open, and thus, more permeable. In this objective, the permeability of 4.75mm Superpave mixtures was assessed.

SCOPE

This research study investigated the development of 4.75mm Superpave mixtures using a variety of compactive efforts and design air void levels, and the relationships of those factors to the rutting and stripping performance and permeability of the mixtures. The performance of 4.75mm mixes was also compared to that of 12.5mm NMAS mixtures. In order to assess the applicability of the results to different aggregate types, a selection of aggregate sources was chosen to represent the typical range of materials found in the state of Arkansas.

In the first phase of the experiment, three aggregate sources were selected including limestone (LS), sandstone (SS), and syenite (SY). From each aggregate source, mixes were designed at three levels of compactive effort (Ndesign = 50, 75, and 100) and two design levels of air voids (4.5 and 6.0 percent). A total of 18 4.75mm NMAS mixes were designed, and the effects of the design factors were evaluated based on rutting, stripping, and permeability responses. Two additional mixtures were designed in order to determine the effects of natural sand.

Mixes were designed according to the AASHTO mix design procedure for 4.75mm NMAS, with the exception of air voids (which was purposely varied in the experimental design) and its associated properties. In Arkansas, mixes containing PG 64-22 and PG 70-22 binders are designed at an air void content of 4.5 percent and are required to meet the minimum VMA as outlined in the AASHTO specification. Air voids and VMA are integrally related. Thus, when the design air void content was increased to 6.0 percent, the minimum VMA had to also be increased. For design air void contents of 4.5 percent, the AASHTO-recommended minimum VMA of 16.0

percent was imposed. A minimum VMA of 18.0 percent was utilized for mixtures designed at an air void content of 6.0 percent.

The AASHTO criteria for VFA was also adjusted based on the changes in air void content and VMA. Assuming a 2.0 percent range in VMA, as recommended by AASHTO, the resulting VFA criteria were calculated based on the air void and VMA combinations as outlined in Table 4.

Air Voids (%)	Minimum VMA (%)	VFA Range (%)
4.5	16.0	71.9 – 75.0
6.0	18.0	66.7 – 70.0

Table 4. Calculated VFA ranges used in research project

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

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.

Permeability was determined using the Karol-Warner laboratory asphalt permeability device as outlined in ASTM PS-129(withdrawn). *(17)* Samples were compacted to approximately 7 percent air voids at a 75 mm height, then sawn so that each permeability specimen contained one compacted face and one sawn face. After sawing, each compacted sample resulted in two permeability specimens, one that was approximately 25 mm in height and one that was approximately 50 mm in height. Thus, the level of permeability and the effect of lift thickness could be assessed. Four permeability results were generated for each of the 18 mix designs.

In the second phase of the study, the 4.75mm mixtures were compared to more traditional surface mixtures. Two 12.5mm NMAS mixes were created from each of the three aggregate sources, and were designed at 4.5 percent air voids and 100 design gyrations. Thus, two levels of NMAS (4.75mm and 12.5mm) were investigated, and the effect of aggregate size was based on rutting and stripping responses. Six mixtures for each NMAS were tested. Again, the performance characteristics of each mix were determined by the ERSA and RAWT procedures. Four replicate samples were used for the ERSA procedure, and triplicate samples were used for the RAWT procedure.

A summary of the complete experimental design for the project is presented in Table 5. All mixtures were prepared using a PG 70-22 binder, and contained no anti-strip.

PHASE 1	
Factors	Level of Variation
Aggregate Source	3 (Limestone, Sandstone, Syenite)
Design Air Voids/VMA	2 (4.5% / 16.0%, 6.0% / 18.0%)
Compactive Effort	3 (Low, Medium, High)
Performance Measure	Response Variables
ERSA (2 Replicates)	Rut Depth at 20,000 Cycles
	Rut Depth at 10,000 Cycles
	Rut Depth at 5,000 Cycles
	Rutting Slope
	Stripping Inflection Point
	Stripping Slope
RAWT (3 Replicates)	Final Rut Depth
	Rut per Cycle
Permeability (4 Replicates)	Permeability Coefficient, k (x 10^{-5} cm/s)
PHASE 2	
Factors	Level of Variation
Aggregate Source	3 (Limestone, Sandstone, Syenite)
Aggregate NMAS	2 (4.75mm, 12.5mm)
Performance Measure	Response Variables
ERSA (4 Replicates)	Rut Depth at 20,000 Cycles
	Rut Depth at 10,000 Cycles
	Rut Depth at 5,000 Cycles
	Rutting Slope
	Stripping Inflection Point
	Stripping Slope
RAWT (3 Replicates)	Final Rut Depth
	Rut per Cycle

Table 5. Experimental Design Summary

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 95 percent level of significance (alpha = 0.05) was used in all cases.

Mix Design

The first task in the research effort was to create mix designs using the selected aggregates according to the AASHTO design procedure. From the limestone source, several materials were available that could be used in 4.75mm mixes. They were ½″ limestone (LS12), limestone screenings (LSsc), graded mine sand (LSgs), limestone block chat (LSbc), coarse lime (LScl), and manufactured limestone sand (LSms). All of the materials were limestone, except the mined material (LSgs). Mix designers often combine different material types in order to meet design requirements. The LSgs material was known to be commonly included in mix designs for larger NMAS limestone mixes, and therefore was also deemed appropriate in this case. From the sandstone source, three aggregates were applicable to the 4.75mm mix criteria. They were ¼″ sandstone screenings (SSsc), ¼″ washed screenings (SSws), and No. 4 gravel chips (SSgc). (The No. 4 gravel chips were created by scalping the plus No. 4 material from 3/8″ gravel chips.) Again, a varying aggregate type (SSgc) was included in the group as was common for this type of mix when used for larger NMAS designs. From the syenite source, three appropriate materials were available. They were ½″ syenite (SY12), syenite screenings (SYsc), and manufactured sand (SYms). In addition, natural sand (NS) was included in the study. A summary of properties of the aggregate sources, including gradation, bulk specific gravity, and fine aggregate angularity, is presented in Table 6.

	Limestone						Sandstone			Syenite			Natural Sand
%Passing	LS12	LSsc	LSgs	LSbc	LScl	LSms	SSsc	SSws	SSgc	SY12	SYsc	SYms	NS
½"	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/8"	86.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	94.4	100.0	100.0	100.0
No. 4	17.7	99.9	96.8	77.0	89.0	100.0	89.0	92.5	100.0	68.1	90.4	100.0	97.0
No. 8	3.0	79.2	76.9	17.0	62.0	92.0	59.7	58.8	58.1	42.8	61.7	100.0	89.0
No. 16	2.6	56.6	49.3	3.0	44.0	45.0	46.2	39.7	36.1	27.0	40.3	99.4	73.0
No. 30	2.5	42.1	28.2	3.0	31.0	15.0	40.0	31.0	24.9	17.6	25.5	90.1	48.3
No. 50	2.3	30.6	13.0	3.0	22.0	8.0	35.9	26.2	18.0	10.7	14.1	65.0	13.2
No. 100	2.2	22.0	5.1	3.0	16.0	6.0	25.1	16.5	10.3	5.9	6.4	43.0	0.9
No. 200	2.1	16.3	2.8	2.2	12.0	5.0	15.1	9.0	3.6	3.4	3.3	26.9	0.1
Gsb	2.527	2.447	2.543	2.600	2.519	2.588	2.516	2.459	2.443	2.600	2.576	2.606	2.600
FAA	NA	46.74	45.10	45.25	44.97	45.17	48.44	45.87	47.10	48.22	47.35	47.70	38.35

Table 6. Summary of Aggregate Properties

In order to determine whether individual sources of screenings could be used to create acceptable 4.75mm NMAS mixes, aggregates having appropriate gradations were identified. An examination of the gradations revealed that only one raw aggregate, SSws, met the 4.75mm gradation requirements as outlined in AASHTO M 323. However, if the lower limit of the percent passing the No. 200 sieve were disregarded, four others joined the group (LSgs, LSms, SSgc, and SYsc). Of these, the limestone aggregates were eliminated as a single-source option due their typical inability to meet the siliceous material requirements specified by AHTD. *(33)* The gravel chip aggregate (SSgc) from the sandstone source was eliminated because the gradation used for this aggregate was adjusted in the laboratory and was not truly representative of the aggregate stockpile. Thus, two individual aggregates (SSws and SYsc) were chosen for trial 4.75mm mix designs. Neither of the designs met the AASHTO 4.75mm volumetric criteria. The SSws mix contained inadequate VMA (approximately 1.5 percent below the recommended minimum). Thus, a gradation change (i.e., a combination of materials) was necessary to change the void structure of the mix. The SYsc mix had very high VMA (greater than 20 percent), which was attributed to the high angularity and surface texture for that source. This mix also failed to meet the minimum requirement for dust proportion. The low dust proportion was expected since the gradation did not actually meet the minimum requirement for the percent passing the No. 200 sieve. Again, a change in gradation was necessary to affect the void structure and desired volumetric properties for the mix.

Based on these initial mix design trials, it was evident that combinations of aggregates would be better able to generate the desired mixture properties. Since such combinations are often used for mixes of larger NMAS, this approach was reasonable for the 4.75mm mixes. Next, combinations of materials were used to design six mixes from each source, meeting the requirements of the AASHTO 4.75mm mix design specification and the experimental design factors as previously discussed. Gradation and volumetric properties of the 18 mix designs used in this phase of the study are summarized in Tables 7 - 9.

	Limestone					
Design Air	4.5	4.5	4.5	6.0	6.0	6.0
Design VMA	16.0	16.0	16.0	18.0	18.0	18.0
Ndes	50	75	100	50	75	100
Job Mix Formula (%)						
LS12				7	7	7
LSsc				43	43	43
LSgs				50	50	50
LSbc	5	5	5			
LScl	55	54	54			
LSms	30	41	41			
NS	10					
Blend Gradation						
% Passing						
½"	100.0	100.0	100.0	100.0	100.0	100.0
3/8"	100.0	100.0	100.0	99.0	99.0	99.0
No. 4	92.5	92.9	92.9	92.6	92.6	92.6
No. 8	71.5	72.1	72.1	72.7	72.7	72.7
No. 16	45.2	42.4	42.4	49.2	49.2	49.2
No. 30	26.5	23.0	23.0	32.4	32.4	32.4
No. 50	16.0	15.3	15.3	19.8	19.8	19.8
No. 100	10.8	11.3	11.3	12.2	12.2	12.2
No. 200	8.2	8.6	8.6	8.6	8.6	8.6
Binder Content (%)	7.2	7.5	7.1	8.7	8.5	8.4
Actual Air (%)	4.3	4.4	4.5	6.0	6.0	6.1
VMA (%)	16.9	17.3	16.3	20.0	19.5	19.5
VFA (%)	74.8	74.6	72.4	69.9	69.4	68.7
Gsb	2.551	2.551	2.551	2.500	2.500	2.500
Gse	2.665	2.658	2.658	2.647	2.647	2.647
DP	1.43	1.30	1.39	1.38	1.36	1.37
Pbe (%)	5.7	6.6	6.3	6.2	6.2	6.3
%D @ Nini	83.9	84.2	83.8	84.9	84.3	84.3
Film Thickness (microns)	7.4	8.0	7.3	8.1	7.8	7.7

Table 7. Mix design summary for limestone aggregate source

	Sandstone					
Design Air	4.5	4.5	4.5	6.0	6.0	6.0
Design VMA	16.0	16.0	16.0	18.0	18.0	18.0
Ndes	50	75	100	50	75	100
Job Mix Formula (%)						
SSsc	50		50	40	30	40
SSws		50				
SSgc	50	50	50	60	70	60
NS						
Blend Gradation						
% Passing						
½”	100.0	100.0	100.0	100.0	100.0	100.0
3/8”	100.0	100.0	100.0	100.0	100.0	100.0
No. 4	94.5	96.3	94.5	95.6	96.7	95.6
No. 8	58.9	58.5	58.9	58.7	58.6	58.7
No. 16	41.2	37.9	41.2	40.1	39.1	40.1
No. 30	32.5	28.0	32.5	30.9	29.4	30.9
No. 50	27.0	22.1	27.0	25.2	23.4	25.2
No. 100	17.7	13.4	17.7	16.2	14.7	16.2
No. 200	9.4	6.3	9.4	8.2	7.1	8.2
Binder Content (%)	8.4	8.0	7.8	8.3	8.0	7.5
Actual Air (%)	4.4	4.6	4.7	5.9	6.0	6.0
VMA (%)	17.1	16.2	16.8	19.6	18.4	18.1
VFA (%)	74.5	71.3	71.8	70.1	67.2	67.0
Gsb	2.479	2.451	2.479	2.472	2.448	2.472
Gse	2.624	2.624	2.624	2.592	2.587	2.592
DP	1.48	1.18	1.65	1.25	1.20	1.44
Pbe (%)	6.4	5.3	5.7	6.6	5.9	5.7
%D @ Nini	78.7	77.9	76.8	77.4	76.5	76.3
Film Thickness (microns)	6.8	7.4	6.1	7.6	7.5	6.6

Table 8. Mix design summary for sandstone aggregate source

	Syenite					
Design Air	4.5	4.5	4.5	6.0	6.0	6.0
Design VMA	16.0	16.0	16.0	18.0	18.0	18.0
Ndes	50	75	100	50	75	100
Job Mix Formula (%)						
SY12	20	18	18	20	16	18
SYsc	38	33	33	38	42	33
SYms	20	23	23	20	20	23
NS	22	26	26	22	22	26
Blend Gradation						
% Passing						
½”	100.0	100.0	100.0	100.0	100.0	100.0
3/8”	98.9	99.0	99.0	98.9	99.1	99.0
No. 4	89.3	90.3	90.3	89.3	90.2	90.3
No. 8	71.6	60.0	60.0	71.6	72.3	60.0
No. 16	56.7	74.2	74.2	56.7	57.2	74.2
No. 30	41.9	44.9	44.9	41.9	42.2	44.9
No. 50	23.4	25.0	25.0	23.4	23.5	25.0
No. 100	12.4	13.3	13.3	12.4	12.4	13.3
No. 200	7.3	7.9	7.9	7.3	7.3	7.9
Binder Content (%)	8.2	7.6	7.3	7.8	6.8	6.7
Actual Air (%)	4.4	4.6	4.5	5.8	6.1	6.1
VMA (%)	17.8	19.2	18.6	18.9	19.2	18.8
VFA (%)	75.5	76.1	76.0	69.4	68.0	67.3
Gsb	2.574	2.571	2.571	2.574	2.573	2.571
Gse	2.632	2.627	2.627	2.632	2.629	2.627
DP	1.07	1.16	1.22	1.13	1.15	1.32
Pbe (%)	6.8	6.8	6.5	6.5	6.4	6.0
%D @ Nini	80.8	80.2	79.6	79.5	79.9	78.2
Film Thickness (microns)	8.8	7.6	7.2	8.3	7.0	6.5

Table 9. Mix design summary for syenite aggregate source

The optimum binder contents (Pb) ranged from 6.7 to 8.7 percent. These binder contents are higher than those used in typical 12.5mm surface mixes. In general, the highest binder contents were required for the limestone mixes, and the lowest binder contents were required for the syenite mixes. Effective binder contents ranged from 5.3 to 6.8 percent and were affected by the absorptivity of the aggregate. The finer gradation of the aggregates in the 4.75mm mixes created more surface area for the binder to coat, and increased the potential for binder absorption. Film thicknesses ranged from 6.1 to 8.8 microns.

The dust proportion values ranged from 1.07 to 1.65. None of these values were near the maximum allowable for this parameter.

As is typical of the mix design process, the VMA specification was the most difficult to meet. In some cases, the VMA curves were relatively flat, making it more difficult to determine a design binder content that was not on the "wet" side of optimum. In order to create changes in VMA, adjustments were made to the aggregate proportions. To increase VMA, angular aggregates were added. To decrease VMA, natural sand was added.

For the mixes attempted, the efforts were largely successful. However, some designs were more easily obtained than others. The limestone mixes required the fewest trial blends, probably due to the larger number of available aggregate sources. The limestone aggregate gradations were slightly less dense-graded. Thus, it was a bit more straightforward to adjust these aggregate proportions in order to create a desired change in the blend gradation. In general, the mixes designed at 6.0 percent air voids had VMA percentages that were close to the maximum allowable values. The mixes designed at 4.5 percent air voids had VMA percentages in the lower to middle portion of the allowable range. Also, the two sets of mixes were made up of different constituent materials. From the volumetric properties of the two mix sets, it appeared that the LSbc, LScl, and LSms generated more VMA than the LS12, LSsc, and LSgs. Interestingly, the fine aggregate angularity values for the high VMA mixes were, on average, slightly less than that of the lower VMA mixes. Also, the higher VMA mixes contained a modest portion of natural sand. Had the natural sand not been included, the VMA levels would have likely been even higher. Thus, it was concluded that the differences in VMA for the different materials was related more to gradation and shape than angularity.

In designing the sandstone mixes, the VMA requirement was the most difficult to achieve. In many of the trial blends, VMA levels were significantly below the minimum value. To combat this problem, higher percentages of SSgc (which is a gravel, not a sandstone) were added. Originally, the coarse nature of the SSgc was such that only a small portion could be included in the mix. This prompted the adjustment of the SSgc gradation by removing all material larger than the No. 4 sieve. The use of this modified aggregate source was able to significantly improve the success of the mix design process. In order to meet mix design specifications all SS mixes contained at least 50 percent of the SSgc material.

The predominant issue in designing the syenite mixes was high VMA. This aggregate source is very dense and angular, thereby elevating VMA values. A significant portion (approximately 25 percent) of each syenite mix was composed of natural sand. In general, the rounded shape of natural sand caused a decrease in VMA. However, this decrease was still not enough to adequately limit VMA in some cases. The dust proportion for these mixes, while acceptable, was in the low end of the specified range. In order increase the dust proportion, the binder content could have been decreased or the dust content could have been increased. However, the aggregate that contained the largest percentage of dust also added VMA, and the aggregate used to limit VMA (natural sand) contained minimal dust. Also, reducing the binder content would have reduced the compactibility of the mix, thereby reducing air void content and VMA. In order to balance VMA and dust proportion more effectively in the syenite mixes, the addition of a rounded aggregate with high dust content could prove beneficial.

Overall, the mix design process was dependent on the aggregate source. Aggregate sources that were appropriate for designing 4.75mm mixes were more limited (i.e., fewer in number) than those used for larger stone mixes. Therefore, the characteristics of the individual materials were likely to have a more significant effect on the volumetric properties of the mix. Some aggregates were more suited to the design of 4.75mm mixtures than others. However, the use of additional aggregate materials or relatively simple modifications to existing aggregate sources, such as scalping the plus No. 4 material, was beneficial to the mix design process.

Performance

Rutting and stripping susceptibility were used to evaluate the relative performance of the 4.75mm mixes with respect to design air void content and level of compactive effort. A summary of average results obtained from testing in the ERSA device is given in Table 10, and the results are presented graphically in Figures 10 - 12. All ERSA sample graphs for the 4.75mm mixes are presented in Appendix A.

ERSA Rut Test Data for 4.75mm Mixtures								
Mix Design			Rutting Response					
Aggregate Source	Design Air	Ndes	Avg Rut20k	Avg Rut10k	Avg Rut5k	Avg RSlope	Avg SIP	Avg SSlope
LS	4.5	50	18.05	18.05	17.95	155	1000	72
		75	18.20	18.20	18.20	149	500	76
		100	18.25	18.25	18.25	235	1000	163
	6.0	50	17.80	17.80	17.80	190	1500	111
		75	18.00	18.00	18.00	264	1250	116
		100	18.20	18.20	18.20	440	1500	140
SS	4.5	50	10.70	10.70	7.20	1260	4050	409
		75	19.50	5.80	2.50	4549	9100	535
		100	13.60	3.95	2.45	3109	13150	966
	6.0	50	11.60	7.20	3.40	2357	8900	465
		75	11.00	4.00	3.00	5032	14900	1085
		100	11.30	4.55	3.90	4736	16800	420
SY	4.5	50	18.00	3.80	1.70	4529	12600	504
		75	16.00	13.40	10.20	1499	2900	320
		100	5.35	2.70	2.20	8679	DNS[1]	DNS[1]
	6.0	50	9.70	5.35	2.75	1977	DNS[1]	DNS[1]
		75	16.40	16.20	4.55	1527	5300	234
		100	14.55	14.55	5.75	1284	5900	314

[1]Did not strip

Table 10. Summary of Phase I results – ERSA rut test data for 4.75mm mixtures

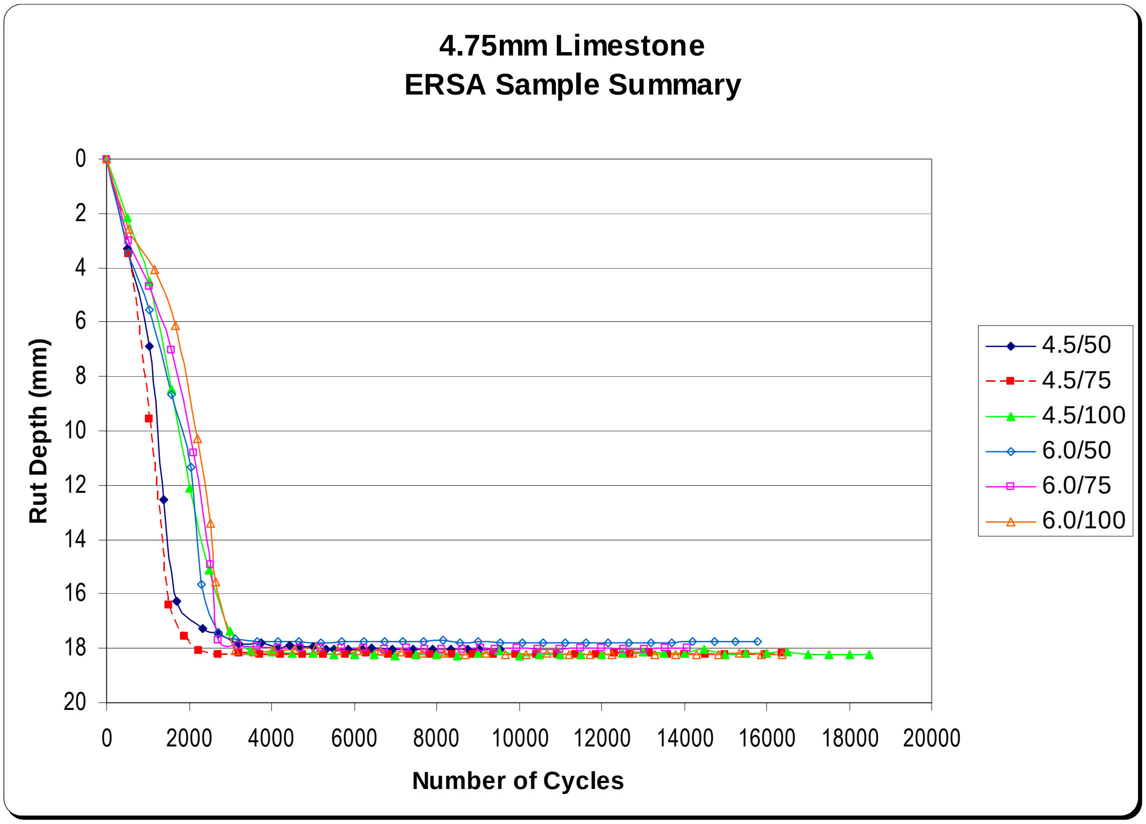

Figure 10. ERSA summary for 4.75mm limestone mixes

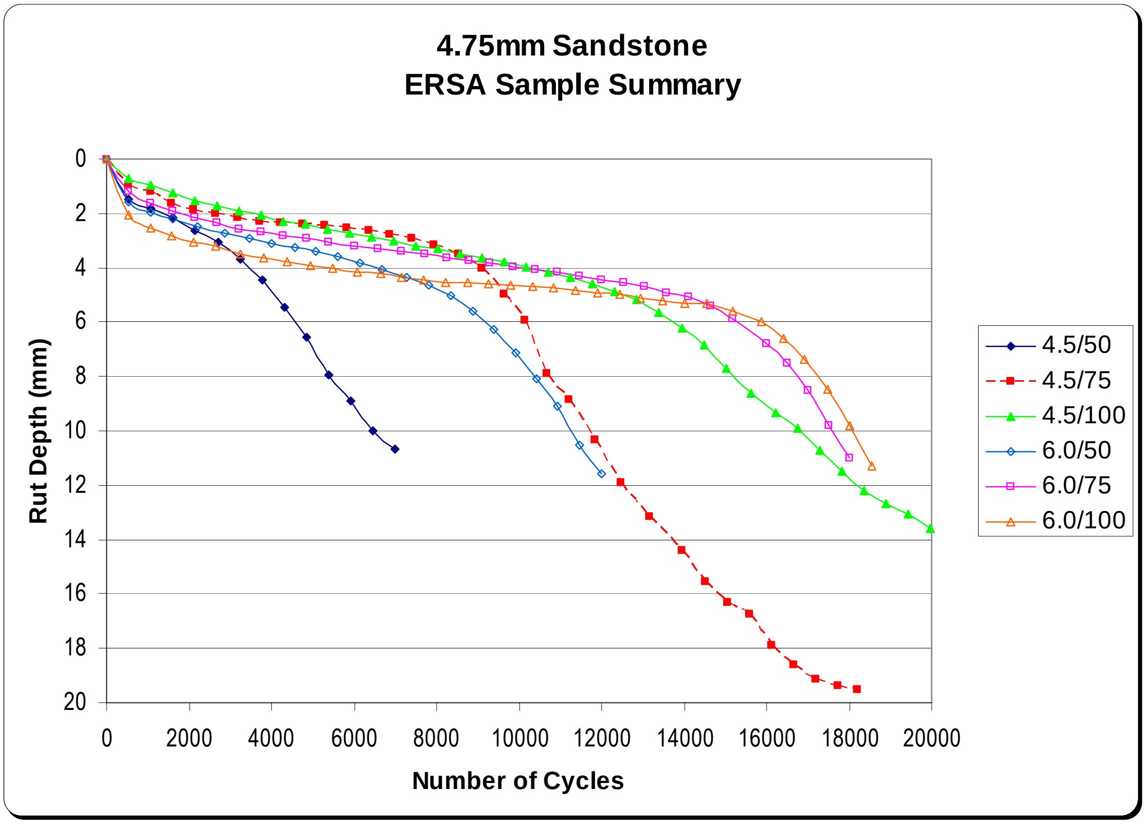

Figure 11. ERSA summary for 4.75mm sandstone mixes

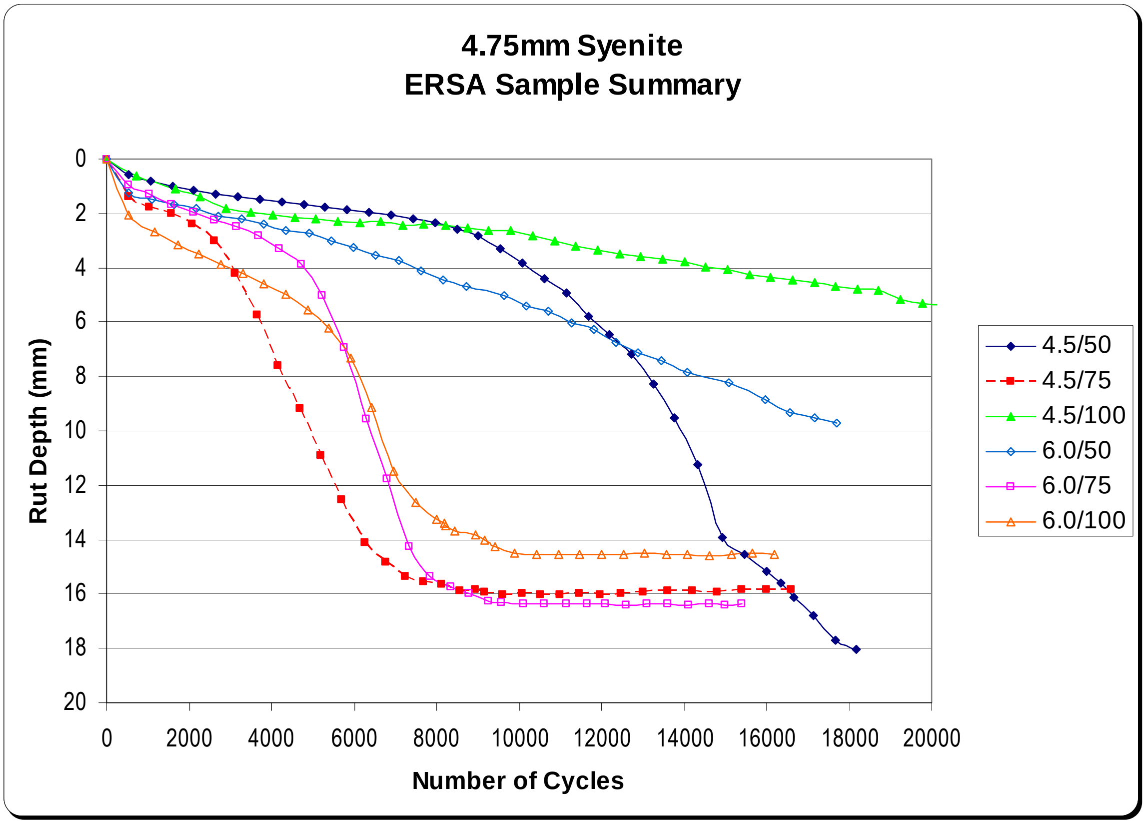

Figure 12. ERSA summary for 4.75mm syenite mixes

By initial observation, it was evident that the limestone mixes were poor performers, in all cases reaching a maximum rut depth before 5000 cycles. Since all the limestone mixes performed poorly, little can be concluded relative to the experimental design factors. Overall, the sandstone mixes appeared to be the slightly better performers than the syenite mixes. Most of the mixes stripped, but did so at various stages of testing. Thus, stripping performance provided greater discrimination with respect to the experimental design factors.

Rutting susceptibility was also measured using the RAWT. A summary of average RAWT test results is shown in Table 11, and is presented graphically in Figures 13 - 15.

RAWT Rut Test Data for 4.75mm Mixtures				
Mix Design			Rutting Response	
Aggregate Source	Design Air	Ndes	Avg Final Rut	Avg RutperCycle
LS	4.5	50	15.53	0.00337
		75	13.84	0.00303
		100	12.56	0.00187
	6.0	50	16.06	0.00372
		75	16.08	0.00268
		100	16.15	0.00282
SS	4.5	50	13.78	0.00325
		75	9.52	0.00083
		100	6.62	0.00025
	6.0	50	12.38	0.00171
		75	10.23	0.00127
		100	9.08	0.00047
SY	4.5	50	16.01	0.00132
		75	16.02	0.00105
		100	16.05	0.00224
	6.0	50	16.02	0.00112
		75	10.64	0.00069
		100	16.07	0.00386

Table 11. Summary of Phase I results – RAWT rut test data for 4.75mm mixtures

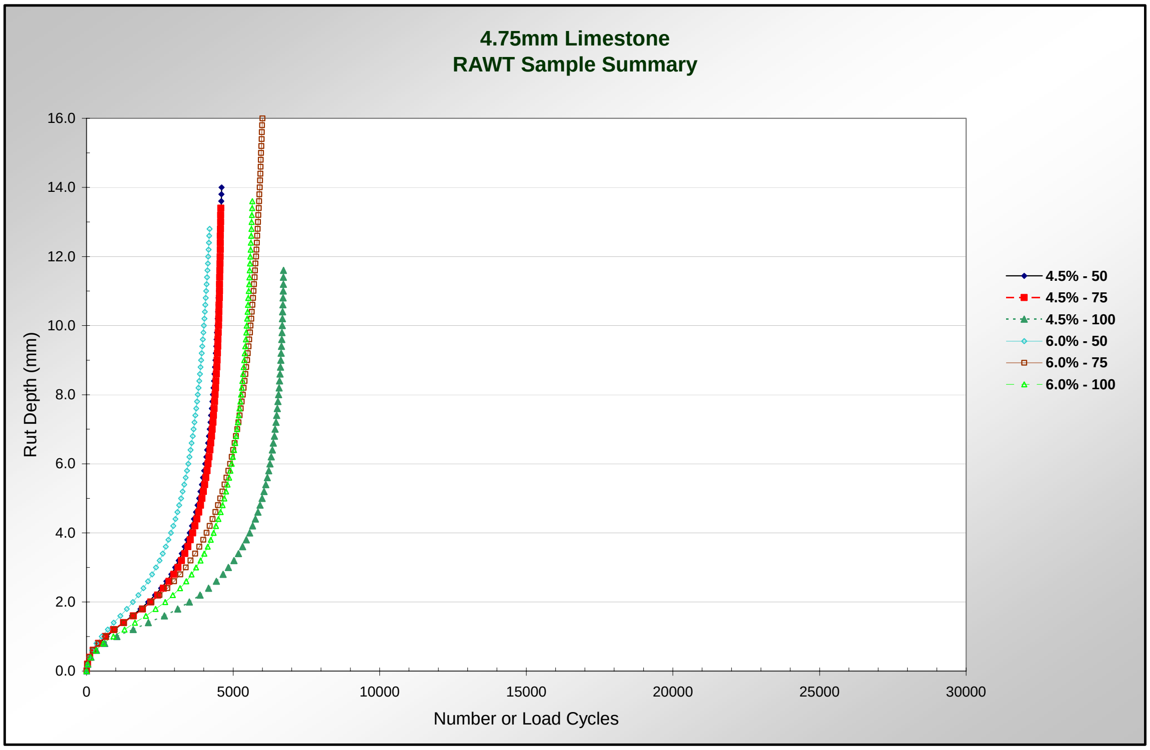

Figure 13. RAWT summary for 4.75mm limestone mixes

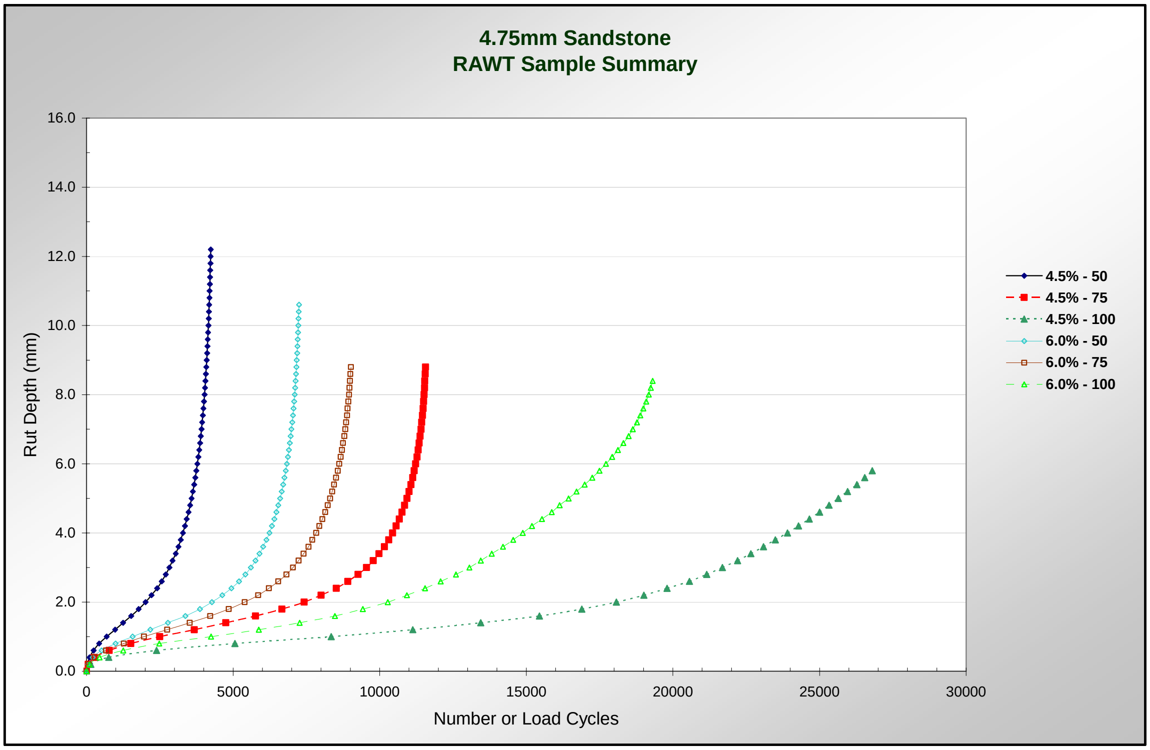

Figure 14. RAWT summary for 4.75mm sandstone mixes

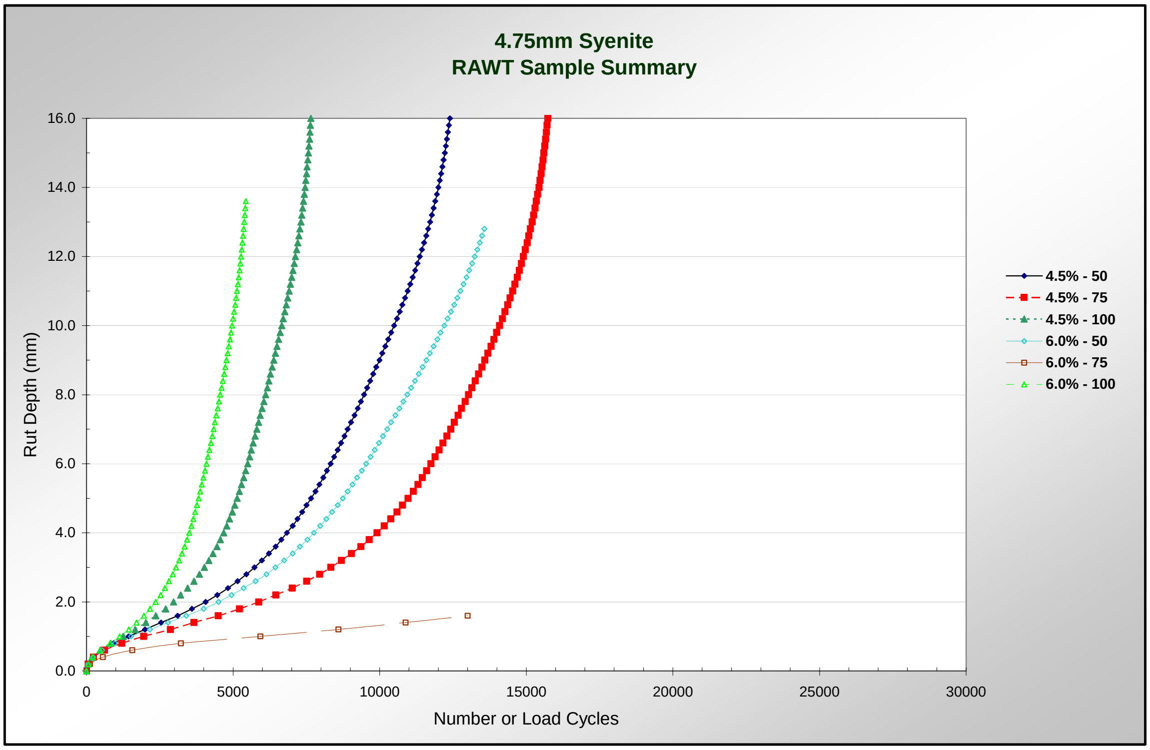

Figure 15. RAWT summary for 4.75mm syenite mixes

One way to examine the data is by visual classification so that conclusions could be drawn regarding the relative performance of each mix type. Based on visual inspection and interpretation, the mixture types from each aggregate source were ranked from best to worst in terms of rutting resistance in ERSA and RAWT. The rankings are shown in Table 12. In this table, mixtures are designated according to air void content and compaction level. In the top section, mixtures having 6.0 percent air voids are shaded. The shaded areas in this section appear scattered, indicating that rutting performance is not likely to be significantly affected by design air void content. In the middle section, the mixtures having the lowest level of compaction (Ndes = 50 gyrations) are shaded. In general, the shaded portions are nearer the bottom of the rankings, which means that mixes designed with low levels of compaction are not necessarily the best performers. It is noted, however, that in all but one case, the 50 gyration mix designed at 6.0 percent air voids exhibited better performance than the 50 gyration mix designed at 4.5 percent air voids. In the lower section of the table, the mixes having the highest level of compaction (Ndes = 100 gyrations) are shaded. In all but one case, these mixes occupy the top ranking. This suggests that mixtures designed at 100 gyrations are more likely to resist failure by rutting and stripping. This conclusion was reasonable and expected.

Although this analysis method did provide valuable information, these cursory observations were based solely on visual interpretation. Therefore, appropriate statistical analysis procedures were also used in order to draw more accurate conclusions.

ERSA			RAWT		
Limestone	Sandstone	Syenite	Limestone	Sandstone	Syenite
6.0 / 100	6.0 / 100	4.5 / 100	4.5 / 100	4.5 / 100	6.0 / 75
6.0 / 75	6.0 / 75	6.0 / 50	6.0 / 75	6.0 / 100	4.5 / 75
4.5 / 100	4.5 / 100	4.5 / 50	6.0 / 100	4.5 / 75	6.0 / 50
6.0 / 50	4.5 / 75	6.0 / 75	4.5 / 50	6.0 / 75	4.5 / 50
4.5 / 50	6.0 / 50	6.0 / 100	4.5 / 75	6.0 / 50	4.5 / 100
4.5 / 75	4.5 / 50	4.5 / 75	6.0 / 50	4.5 / 50	6.0 / 100

Mixtures with 6.0 % design air voids are shaded.

ERSA			RAWT		
Limestone	Sandstone	Syenite	Limestone	Sandstone	Syenite
6.0 / 100	6.0 / 100	4.5 / 100	4.5 / 100	4.5 / 100	6.0 / 75
6.0 / 75	6.0 / 75	6.0 / 50	6.0 / 75	6.0 / 100	4.5 / 75
4.5 / 100	4.5 / 100	4.5 / 50	6.0 / 100	4.5 / 75	6.0 / 50
6.0 / 50	4.5 / 75	6.0 / 75	4.5 / 50	6.0 / 75	4.5 / 50
4.5 / 50	6.0 / 50	6.0 / 100	4.5 / 75	6.0 / 50	4.5 / 100
4.5 / 75	4.5 / 50	4.5 / 75	6.0 / 50	4.5 / 50	6.0 / 100

Mixtures with Ndes = 50 are shaded.

ERSA			RAWT		
Limestone	Sandstone	Syenite	Limestone	Sandstone	Syenite
6.0 / 100	6.0 / 100	4.5 / 100	4.5 / 100	4.5 / 100	6.0 / 75
6.0 / 75	6.0 / 75	6.0 / 50	6.0 / 75	6.0 / 100	4.5 / 75
4.5 / 100	4.5 / 100	4.5 / 50	6.0 / 100	4.5 / 75	6.0 / 50
6.0 / 50	4.5 / 75	6.0 / 75	4.5 / 50	6.0 / 75	4.5 / 50
4.5 / 50	6.0 / 50	6.0 / 100	4.5 / 75	6.0 / 50	4.5 / 100
4.5 / 75	4.5 / 50	4.5 / 75	6.0 / 50	4.5 / 50	6.0 / 100

Mixtures with Ndes = 100 are shaded.

Table 12. Mixture rankings (visual) and factor shading

Analysis of variance (ANOVA) was used to statistically analyze the effects of design air voids and compaction level on rutting performance. A rank transformation was used as a non-parametric alternative when the underlying assumptions of the AVOVA were not met. Duplicate ERSA tests were performed on each of the 18 mixes from the three aggregate sources. A summary of the factors and levels for this analysis is contained in Table 13.

Factor	# of Levels	Levels
Source	3	Limestone (LS), Sandstone (SS), Syenite (SY)
Design Air Voids	2	4.5%, 6.0%
Gyration Level (Ndes)	3	50, 75, 100

Table 13. Summary of ANOVA factors for ERSA analysis.

The results of the analysis were expected to be affected by aggregate type, so this factor had to be considered even though it was not the variable of interest and had no practical bearing on factor interactions. Thus, a complete randomized block design was used to isolate the variability associated with aggregate source. The effects of design air voids, gyration level, and their interaction were analyzed for significance with respect to the six response variables generated from the ERSA test – rut depth at 20,000 cycles (RUT20K), rut depth at 10,000 cycles (RUT10K), rut depth at 5,000 cycles (RUT5K), 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	2	11.09	0.0004
Air	1	0.12	0.7274
Ndes	2	2.77	0.0826
Air * Ndes	2	1.6	0.2167
Error	31		

Table 14. ANOVA results for rut depth at 20,000 cycles in ERSA

Relative to rut depth at 20,000 cycles, the data presented in Table 14 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 was 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, rut depth at 10,000 cycles (RUT10K) was investigated next. By examining rut depths that occurred earlier in the test, the chances for greater discrimination between testing factor combinations was improved. Results are presented in Table 15.

RUT10K			
Factor	df	F-calc	P-value
Source	2	30.82	<0.0001
Air	1	0.45	0.5084
Ndes	2	1.79	0.1883
Air * Ndes	2	2.22	0.1303
Error	31		

Table 15. ANOVA results for rut depth at 10,000 cycles in ERSA

Again, aggregate source was a significant factor, but still no factors or interactions were significant. However, many samples exhibited poor performance. Another attempt was made at improving the discrimination between samples by evaluating the rut depth at 5,000 cycles. The results of this analysis are presented in Table 16.

RUT5K			
Factor	df	F-calc	P-value
Source	2	180.57	<0.0001
Air	1	1.16	0.2928
Ndes	2	1.26	0.3018
Air * Ndes	2	3.22	0.0575
Error	31		

Table 16. ANOVA results for rut depth at 5,000 cycles in ERSA

Rut depth at 5,000 cycles was somewhat better at detecting significant effects of the experimental factors. In this case, the interaction between design air voids and compaction level was marginal. 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 terms of rut depth at 5,000 cycles,

Figure 16 indicates that the mixes designed at 4.5 percent air voids were a bit more sensitive to changes in compaction level than those designed at 6.0 percent air voids.

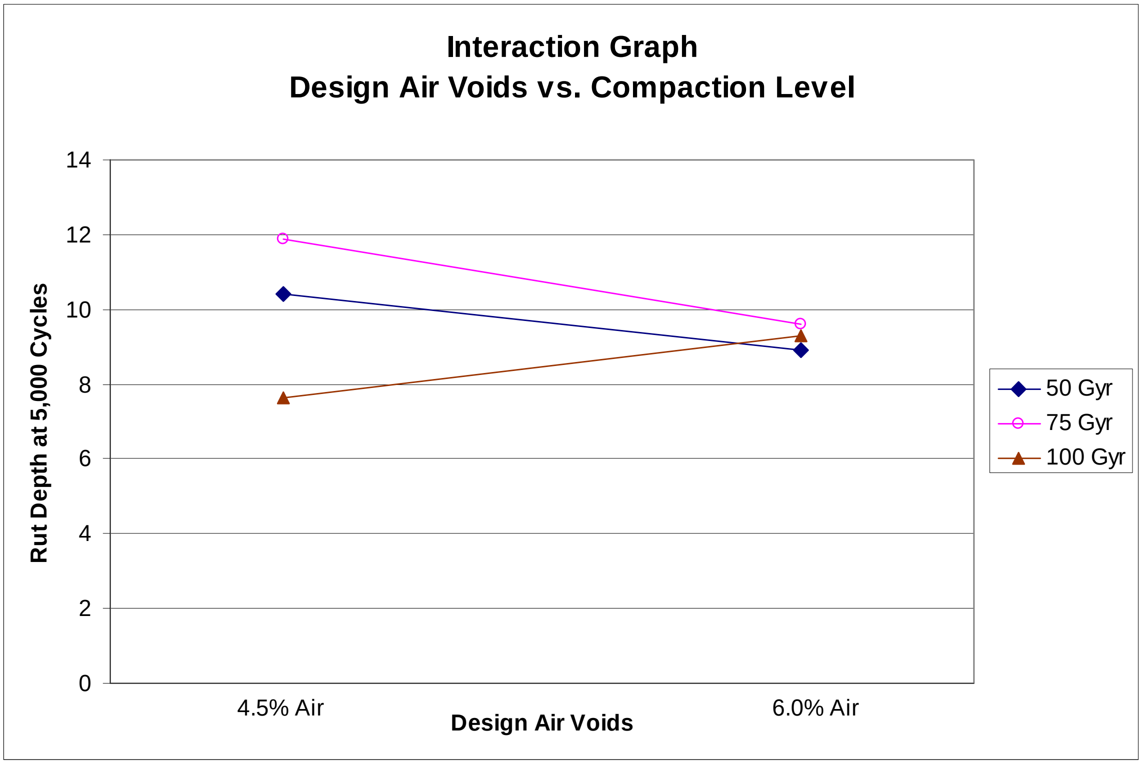

Figure 16. Interaction graph based on rut depth at 5,000 cycles in ERSA

The final response variable relating to rutting performance in ERSA was rutting slope. This variable was expected to provide greater discrimination between the various mixes because it describes the rate of rutting rather than the actual rut depth, however, none of the factors or interactions (other than aggregate source) were significant. The results of this analysis are given in Table 17.

RSLOPE			
Factor	df	F-calc	P-value
Source	2	40.21	<0.0001
Air	1	0.45	0.5098
Ndes	2	2.50	0.1029
Air * Ndes	2	0.63	0.5436
Error	31		

Table 17. ANOVA results for rutting slope in ERSA

In order to assess the stripping performance of the 4.75mm mixtures, the response variables of stripping inflection point (SIP) and stripping slope (SSLOPE) were analyzed. The results for stripping inflection point are given in Table 18.

SIP			
Factor	df	F-calc	P-value
Source	2	52.70	0.0010
Air	1	5.71	0.6272
Ndes	2	4.92	0.0939
Air * Ndes	2	2.82	0.0322
Error	31		

Table 18. ANOVA results for stripping inflection point in ERSA

The stripping inflection point is the point at which the sample deterioration begins to be dominated by moisture damage. Samples that are more resistant to stripping have a SIP that occurs late during the test, or not at all. Thus, higher values are desired for this parameter. With respect to stripping inflection point, there was a significant interaction between design air voids and compaction level. This interaction is illustrated in Figure 17.

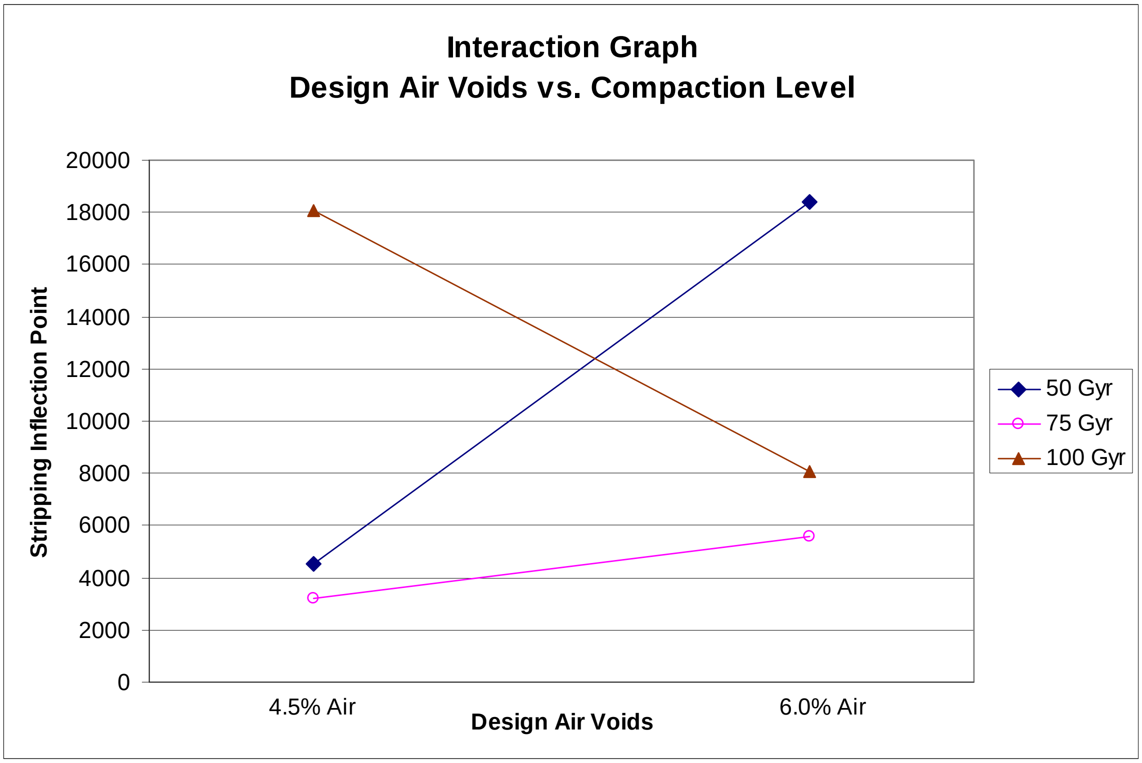

Figure 17. Interaction graph based on stripping inflection point in ERSA

According to the interaction graph, mixes designed at 100 gyrations are more resistant to stripping at 4.5 percent design air voids, and mixes designed at 50 gyrations are more resistant to stripping at 6.0 percent design air voids. Mixes designed at 75 gyrations were not as resistant to stripping as the other mixes, and were relatively unaffected by design air void content.

The other measure of stripping resistance is stripping slope, which describes the rate at which stripping occurs after the stripping inflection point. The results of this analysis are shown in Table 19.

SSLOPE			
Factor	df	F-calc	P-value
Source	2	55.88	<0.0001
Air	1	0.22	0.6415
Ndes	2	3.46	0.0477
Air * Ndes	2	7.89	0.0023
Error	31		

Table 19. ANOVA results for stripping slope in ERSA

Again, there was a significant interaction between the main factors of design air void content and level of compaction. The interaction graph for stripping slope is presented in Figure 18.

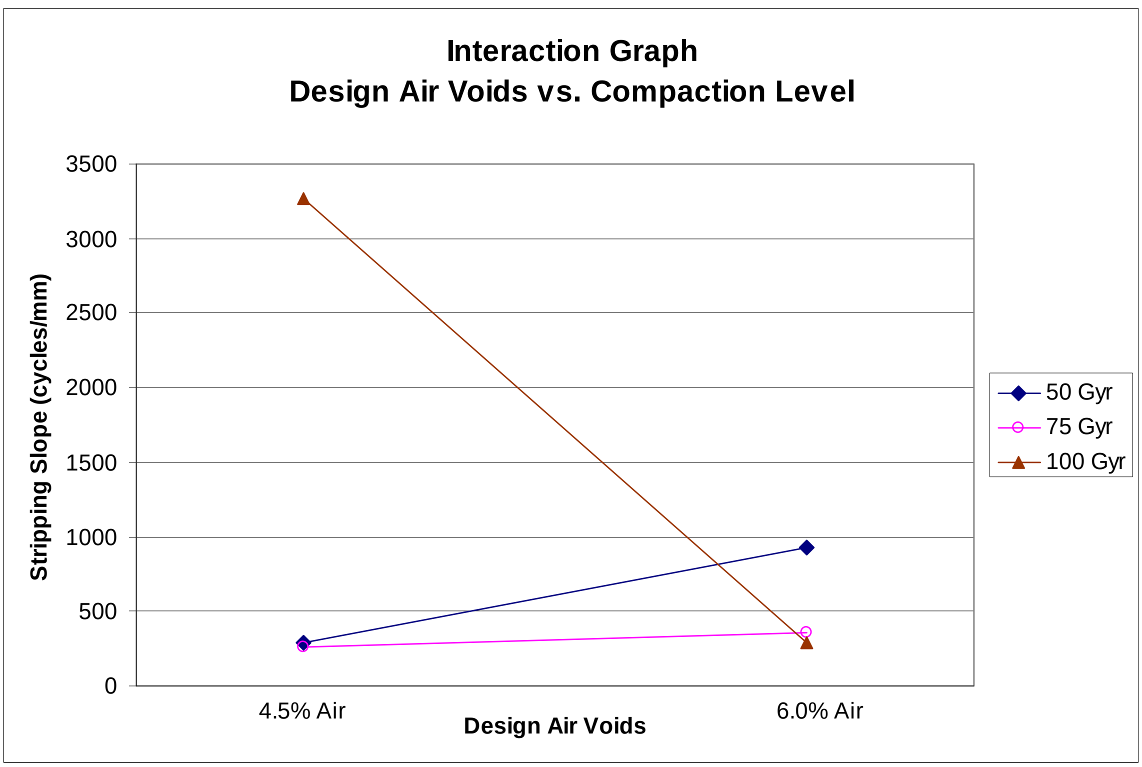

Figure 18. Interaction graph based on stripping slope in ERSA

In this interaction plot, it is apparent that the 4.5 percent design air void level is more affected by compaction level in that the mixes designed at 100 gyrations exhibited greater performance with respect to stripping. Thus, the 100 gyration mixes perform better when designed at 4.5 percent air voids.

A second measure of rutting susceptibility was measured using the RAWT. Similar analyses were performed for this dataset with respect to the response variables of final rut depth (FINALRUT) and rut per cycle (RUTPERCYCLE). The results for final rut depth are given in Table 20.

FINALRUT					
Factor	df		F-calc	P-value	
Source	2		34.74	<0.0001	
Air	1		4.85	0.0328	
Ndes	2		2.70	0.0781	
Air * Ndes	2		2.41	0.1010	
Error	31				
Duncan's Test			Duncan's Test		
Air	Mean	Rank	Ndes	Mean	Rank
4.5%	13.33	A	50	14.96	A
6.0%	13.63	B	75	12.72	B
			100	12.75	B

Table 20. ANOVA results for final rut depth in RAWT

For this response variable, the interaction of factors was not significant, so the main effects could be analyzed separately. Design air void content was significant. Normally, when a main effect is determined to be significant, Duncan's Multiple Range Test (or some other means test) is used to indicate which means caused the difference. In this case, there were only two means to compare, so Duncan's test wasn't really necessary. However, the means and ranks of the two groups are shown in the table.

Means with the same letter ranking do not have a statistically significant difference. In the practical sense, the two means are very similar. Thus, the perceived statistical significance of air void content may not have practical significance. In this case, the variability of the response was small enough to allow a greater amount of discrimination between air void levels. The other main effect, compaction level, was not significant at the 95 percent level of significance, but it was marginal. Thus, Duncan's test was performed and differences were detected among the various compaction levels. The 100 and 75 gyration mixes performed similarly, both exhibiting smaller rut depths than the 50 gyration mix.

The RAWT final rut depth is indicative of a 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 defined as the final rut depth divided by the total number of cycles applied during the test. ANOVA results are given in Table 21.

RUTPERCYCLE				
Factor	df	F-calc	P-value	
Source	2	19.91	<0.0001	
Air	1	0.04	0.8403	
Ndes	2	5.88	0.0053	
Air * Ndes	2	1.53	0.2270	
Error	31			
		Duncan's Test		
		Ndes	Mean	Rank
		50	0.0024	A
		75	0.0019	B
		100	0.0016	B

Table 21. ANOVA results for rut per cycle in RAWT

In this analysis, the interaction of terms was not significant, so the main effects were analyzed. The number of design gyrations was significant in that the medium and high (75 and 100) design gyration levels exhibited lower rates of rutting than the 50 gyration mixes.

Based on the rutting and stripping characteristics of the mixes, the following observations were made. In terms of rutting resistance in ERSA, the experimental design factors were largely insignificant. Rutting resistance as measured by the RAWT was affected by the design compaction level of the mix, such that mixes designed to higher compaction levels were more resistant to rutting. In terms of stripping, ERSA test results indicated a significant interaction of factors such that the greatest stripping resistance was provided for the 100 design gyration mixes when designed at 4.5 percent air voids. For mixes designed at 50 gyrations, the greatest stripping resistance was generated when the mixes were designed at 6.0 percent air voids.

Natural Sand

Overall, sandstone mixes were the best performers, and this was the only source from which none of the mixes contained natural sand. To evaluate the effects of natural sand on this aggregate source, two additional mixes were designed. Both were designed at 4.5 percent air voids and 100 gyrations, then compared to the corresponding mixture that did not contain natural sand. For this summary, three percentages of natural sand were used - 0 percent, 10 percent, and 15 percent. A summary of the mix designs is given in Table 22.

	Sandstone Mixes for Natural Sand Comparison		
Design Air	4.5	4.5	4.5
Design VMA	16.0	16.0	16.0
Ndes	100	100	100
Job Mix Formula (%)			
SSsc	50	40	45
SSws			
SSgc	50	50	40
NS	0	10	15
Blend Gradation			
% Passing			
½”	100.0	100.0	100.0
3/8”	100.0	100.0	100.0
No. 4	94.5	95.3	94.6
No. 8	58.9	61.8	63.5
No. 16	41.2	43.8	46.2
No. 30	32.5	33.3	35.2
No. 50	27.0	24.7	25.3
No. 100	17.7	15.3	15.6
No. 200	9.4	7.9	8.3
Binder Content (%)	7.8	7.7	7.6
Actual Air (%)	4.7	4.5	4.5
VMA (%)	16.8	17.3	17.5
VFA (%)	71.8	74.0	74.3
Gsb	2.479	2.487	2.498
Gse	2.624	2.606	2.606
DP	1.65	1.30	1.38
Pbe (%)	5.7	6.1	6.0
%D @ Nini	76.8	87.4	87.4
Film Thickness (microns)	6.1	7.0	6.8

Table 22. Mix design summary for natural sand comparison

Duplicate ERSA tests and triplicate RAWT tests were performed on each of the mixes, which provided a basis for comparing the three sand contents. The resulting data is presented in Table 23, and graphical comparisons are illustrated in Figures 19 and 20.

Rutting Test Data for Natural Sand Comparison									
Mix Design		Rutting Response							
		ERSA						RAWT	
Natural Sand %	NMAS	Avg Rut20k	Avg Rut10k	Avg Rut5k	Avg RSlope	Avg SIP	Avg SSlope	Final Rut	Rut per Cycle
0	4.75	13.60	3.95	2.45	3108.5	13150.0	965.5	6.62	0.00025
10	4.75	18.55	16.65	3.45	2113.95	5400.0	320.3	9.03	0.00056
15	4.75	18.25	18.25	12.4	710.65	3450.0	222.6	10.76	0.00080

Table 23. Summary of rutting results – natural sand comparison

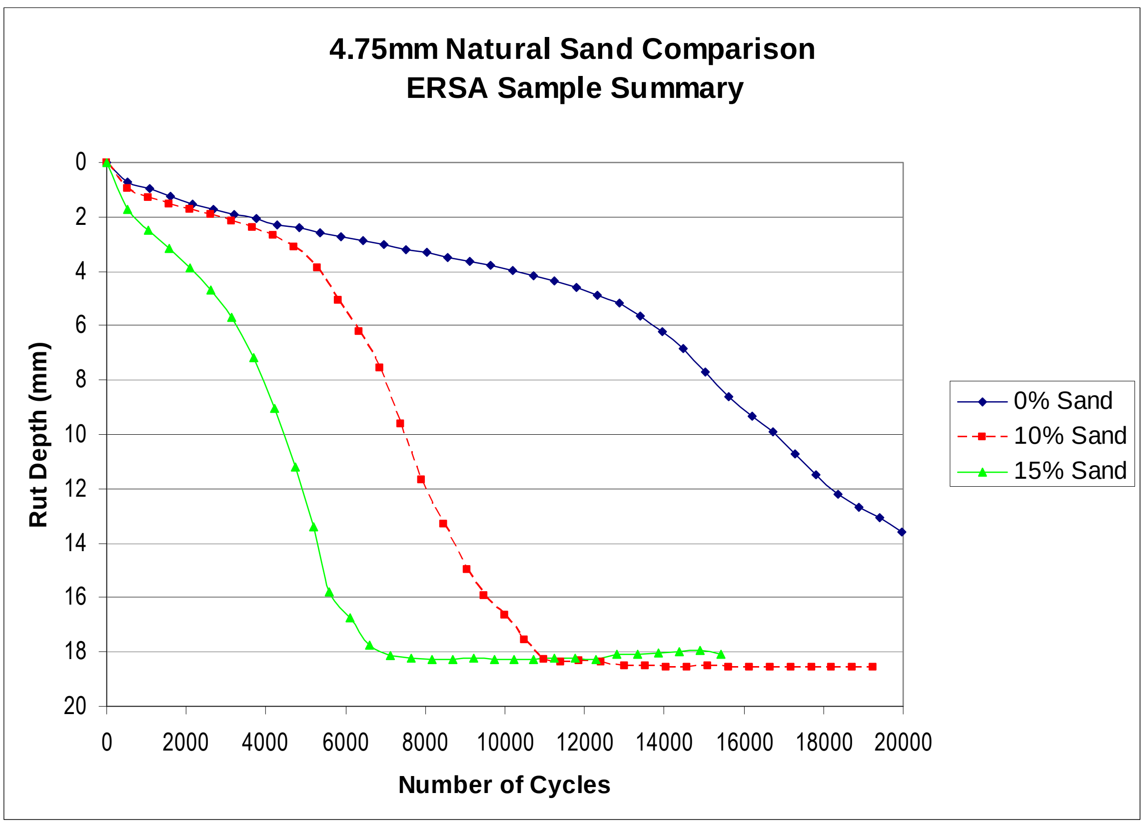

Figure 19. ERSA summary for natural sand comparison

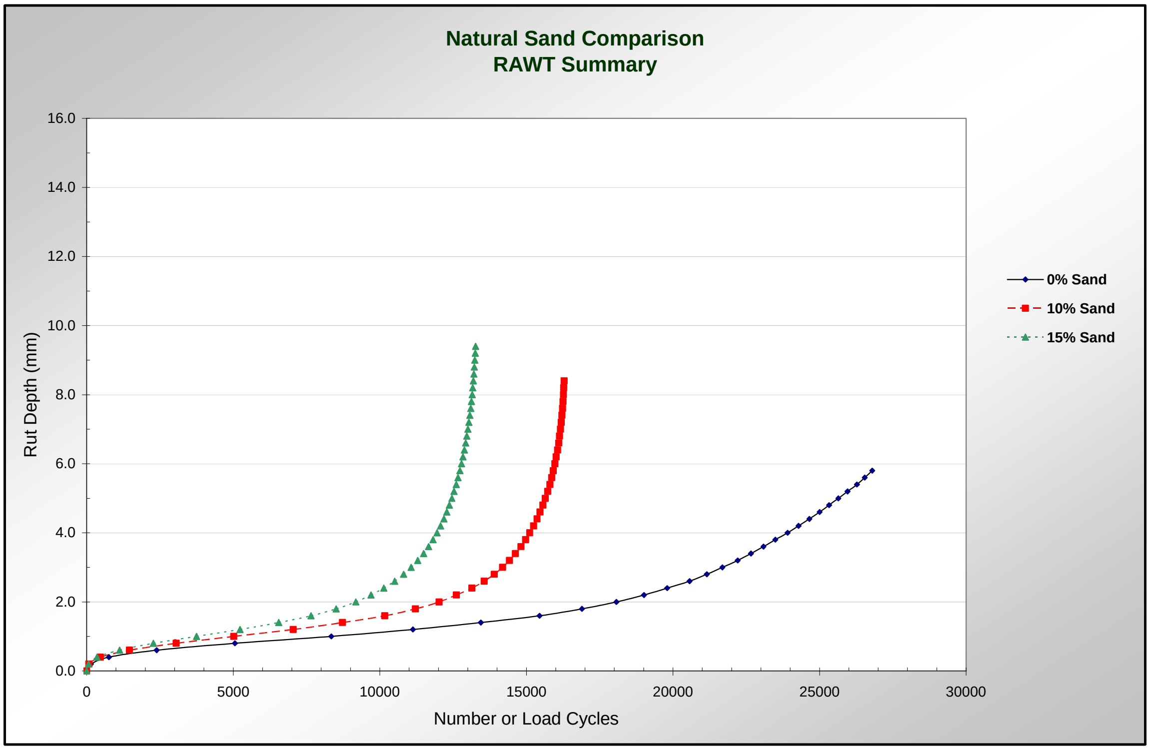

Figure 20. RAWT summary for natural sand comparison

The effects of natural sand are clearly shown in these graphs. As the percent of natural sand increases, the rutting and stripping resistance of the mixes decreases. These conclusions are supported by statistical analyses. The results of the ANOVA procedures are presented in Table 23.

	ANOVA Test Results for Natural Sand Comparison 4.5% Air Voids, 100 Gyrations		
		%Sand Significant?	%Sand P-Value
ERSA	Rut20k	No	0.1176
	Rut10k	Yes	0.0003
	Rut5k	Yes	0.0189
	RSlope	Yes	0.0010
	SIP	Yes	0.0014
	SSlope	No	0.1530
RAWT	Final Rut	Yes	0.0168
	RutperCycle	Yes	0.0003

Table 23. Summary of ANOVA results – natural sand comparison

Permeability

The permeability of 4.75mm mixes was another issue of concern. For each of the 18 mixtures, laboratory permeability was measured. Since previous research established that lift thickness affects the permeability of a mixture, two sample thicknesses were tested – 25 mm and 50 mm. *(38)* A summary of average permeability values for each mix is presented in Table 24.

Permeability Test Data for 4.75mm Mixtures				
Mix Design			Average Permeability (x 10^{-5} cm/s)	
Aggregate Source	Design Air	Ndes	25 mm Sample Thickness	50 mm Sample Thickness
LS	4.5	50	1.717	1.209
		75	2.544	0.118
		100	1.929	0.068
	6.0	50	2.248	0.188
		75	3.482	0.497
		100	0.892	0.209
SS	4.5	50	0.385	0.030
		75	0.311	0.046
		100	1.329	0.059
	6.0	50	0.812	0.030
		75	0.842	0.000
		100	1.080	0.354
SY	4.5	50	0.640	1.988
		75	0.202	0.847
		100	0.543	1.144
	6.0	50	1.093	1.375
		75	1.481	3.780
		100	1.039	2.266

Table 24. Summary of permeability results for 4.75mm mixtures

Based on 2 replicate permeability tests per mix, per thickness, an ANOVA determined that sample thickness was a significant factor ($p = 0.001$), such that the 25mm samples were slightly more permeable than the 50 mm samples. However, the magnitude of the values was very low for all mixes, regardless of thickness. In fact, the highest individual measured permeability value was 4.341 x 10^{-5} cm/s.

Since 4.75mm mixtures are typically intended for use with a maximum lift thickness of 25 mm, only the 25 mm samples were included in the final analysis. Also, since the 25 mm samples exhibited slightly higher levels of permeability, these measurements were considered to be a “worst case” estimate. Similar to the analyses for rutting, a completely randomized block design was used to isolate the variability cased by aggregate source. Four replicate permeability tests were performed on the 25 mm specimens for each of the 18 mixtures. The results of the ANOVA are presented in Table 25.

PERMEABILITY (x 10^{-5} cm/s)			
Factor	df	F-calc	P-value
Source	2	39.44	<0.0001
Air	1	10.47	0.0019
Ndes	2	0.12	0.8880
Air * Ndes	2	7.37	0.0013
Error	71		

Table 25. ANOVA results for laboratory permeability testing

The ANOVA indicates that there is a significant interaction between design air void content and compaction level. This interaction is illustrated in Figure 21.

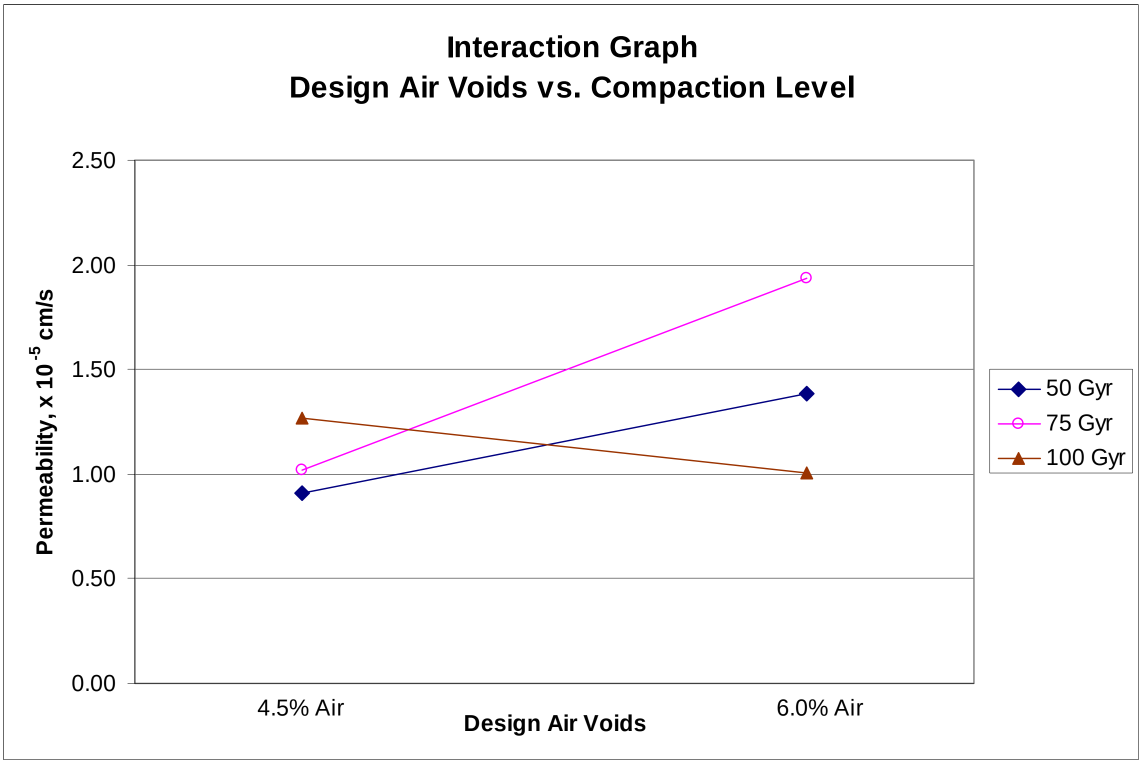

Figure 21. Interaction graph based on permeability

The interaction plot reveals that the mixes with 6.0 percent design air voids are more sensitive to changes in compaction level than those with 4.5 percent design air voids. However, since the magnitudes of the values for permeability were so low, the practical conclusion was that all 4.75mm mixes were relatively impermeable.

Nominal Maximum Aggregate Size

In the second phase of the research study, the performance of 4.75mm mixes was compared with that of typical surface mixes having a 12.5mm NMAS. For this purpose, four replicate samples were tested for two 12.5mm mixes from each of the three aggregate sources. Thus, a total of six 12.5mm mixes were tested. Mix design summaries are given in Table 26. The 12.5mm mixes were designed using 4.5 percent air voids and 100 design gyrations. They contained a PG 70-22 binder and no anti-stripping agent.

	12.5mm Mixtures					
	Limestone		Sandstone		Syenite	
Design Air	4.5	4.5	4.5	6.0	6.0	6.0
Ndes	100	100	100	100	100	100
NMAS	12.5mm	12.5mm	12.5mm	12.5mm	12.5mm	12.5mm
Blend Gradation						
% Passing						
¾"	100	100	100	100	100	100
½"	95	97	95	98	91	94
3/8"	85	90	86	95	81	87
No. 4	52	68	54	77	58	65
No. 8	37	51	28	47	39	45
No. 16	25	35	19	31	26	31
No. 30	17	23	15	24	18	23
No. 50	10	15	13	20	12	15
No. 100	6	9	9	13	7	8
No. 200	4.7	6.7	5.1	6.7	4.2	5.1
% Binder	6.3	6.6	6.3	6.7	5.8	5.7
% Air Voids	4.8	4.3	4.6	4.4	4.4	4.8
% VMA	14.8	14.5	14.3	14.4	15.7	15.5
% VFA	67.6	70.3	67.8	69.4	72.0	68.4
Gsb	2.514	2.504	2.466	2.459	2.586	2.585
Gmm	2.403	2.393	2.365	2.362	2.420	2.416
DP	1.1	1.5	1.2	1.5	0.8	0.9
Film Thickness (microns)	9.7	7.2	8.9	6.5	10.8	9.0

Table 26. Mix design summaries for 12.5mm NMAS

Because the Phase I analysis indicated significant effects and interactions of design air voids and compaction level, a fair assessment of the effect of NMAS could only be obtained by comparing the 4.75mm mixes designed with the same parameters. Therefore, only the 4.75mm NMAS mixes designed at 4.5 percent air voids and 100 design gyrations were included in the second phase of the analysis. A summary of the average sample rutting performance data is presented in Table 27, and mixture comparisons for ERSA and RAWT tests are illustrated in Figures 22 - 27. A complete set of graphical sample data for the 12.5mm mixes tested in ERSA is included in Appendix C. A complete set of graphs for the 12.5mm samples tested in the RAWT data is included in Appendix D.

Rutting Test Data for 4.75mm and 12.5mm Mixtures									
Mix Design		Rutting Response							
		ERSA						RAWT	
Aggregate Source	NMAS	Avg Rut20k	Avg Rut10k	Avg Rut5k	Avg RSlope	Avg SIP	Avg SSlope	Final Rut	Rut per Cycle
LS	4.75	18.25	18.25	18.25	235	1000	163	12.56	0.00187
	12.5	17.10	16.14	8.93	1006.6	4175.0	339.5	14.00	0.00104
SS	4.75	13.60	3.95	2.45	3108.5	13150.0	965.5	6.62	0.00025
	12.5	16.01	12.18	5.44	1964.4	5031.3	434.4	11.61	0.00051
SY	4.75	5.35	2.70	2.20	8679.0	DNS[1]	8679.0	16.05	0.00224
	12.5	13.95	8.30	3.66	2353.7	6887.5	883.4	12.03	0.00070

[1]Did not strip

Table 27. Summary of Phase II results – rutting test data for 4.75mm and 12.5mm NMAS

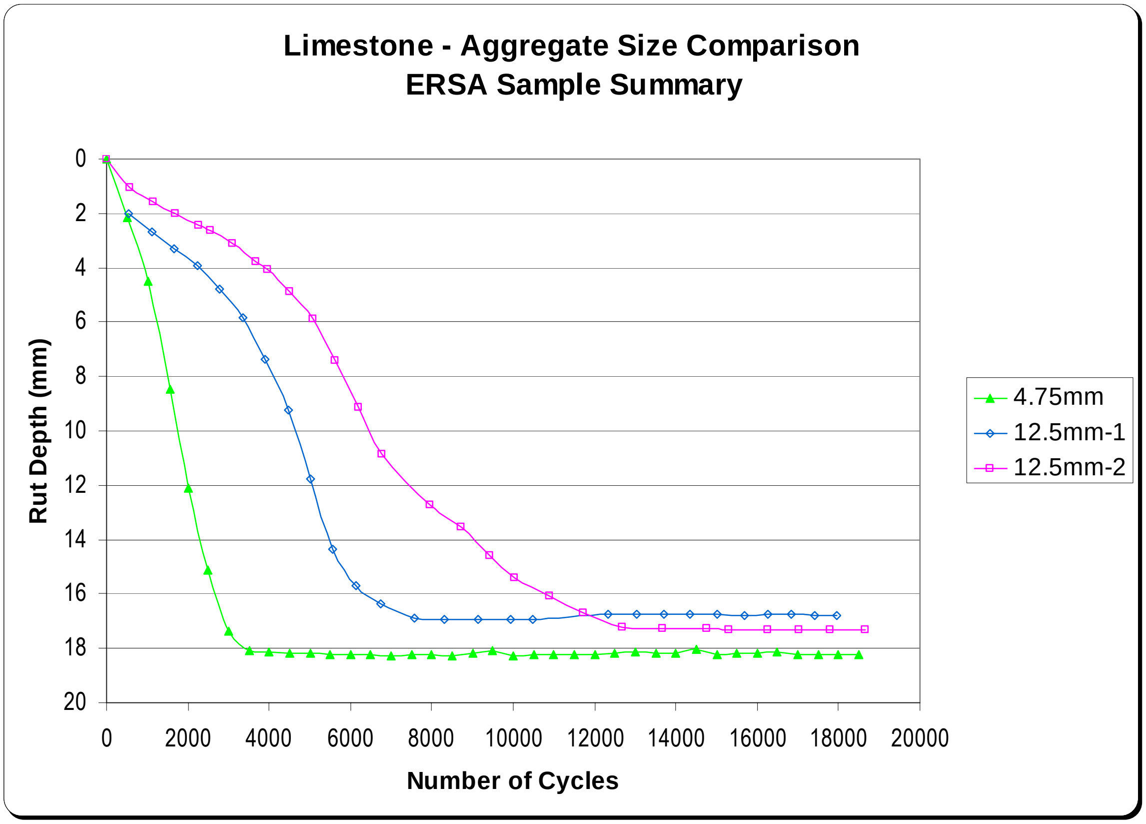

Figure 22. ERSA comparison for 4.75mm and 12.5mm limestone mixes

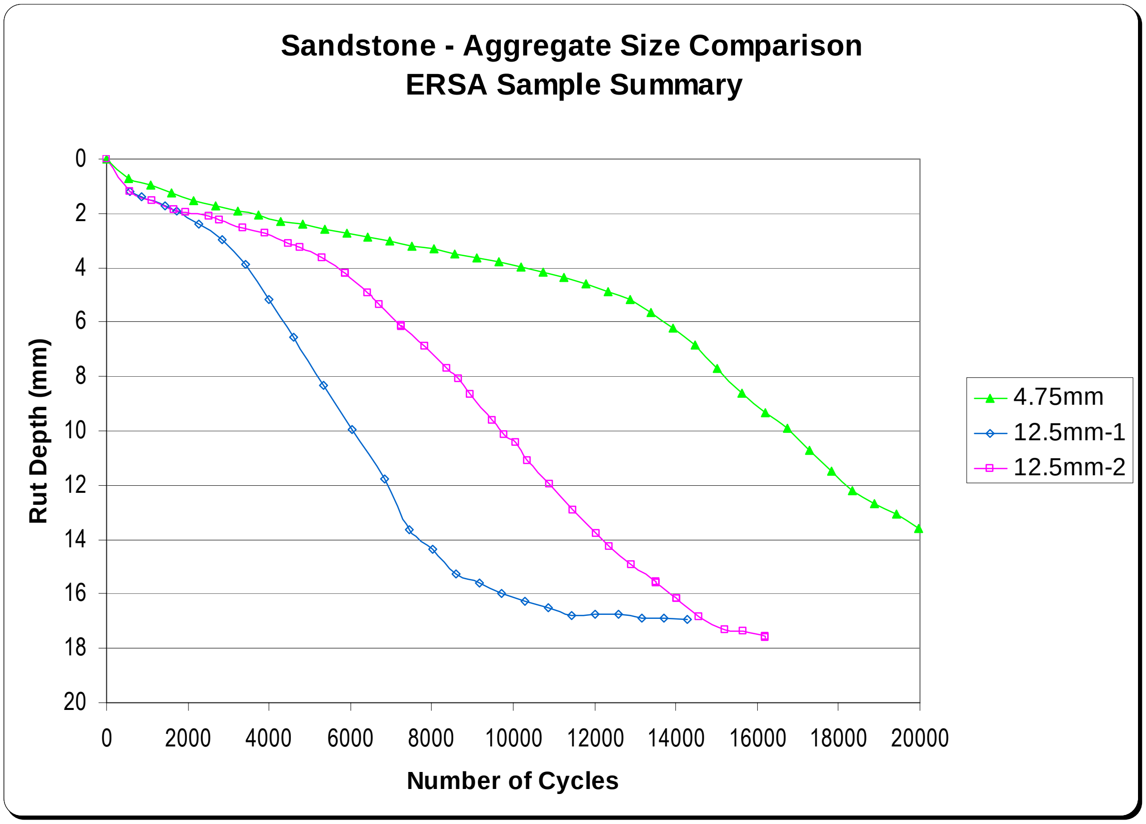

Figure 23. ERSA comparison for 4.75mm and 12.5mm sandstone mixes

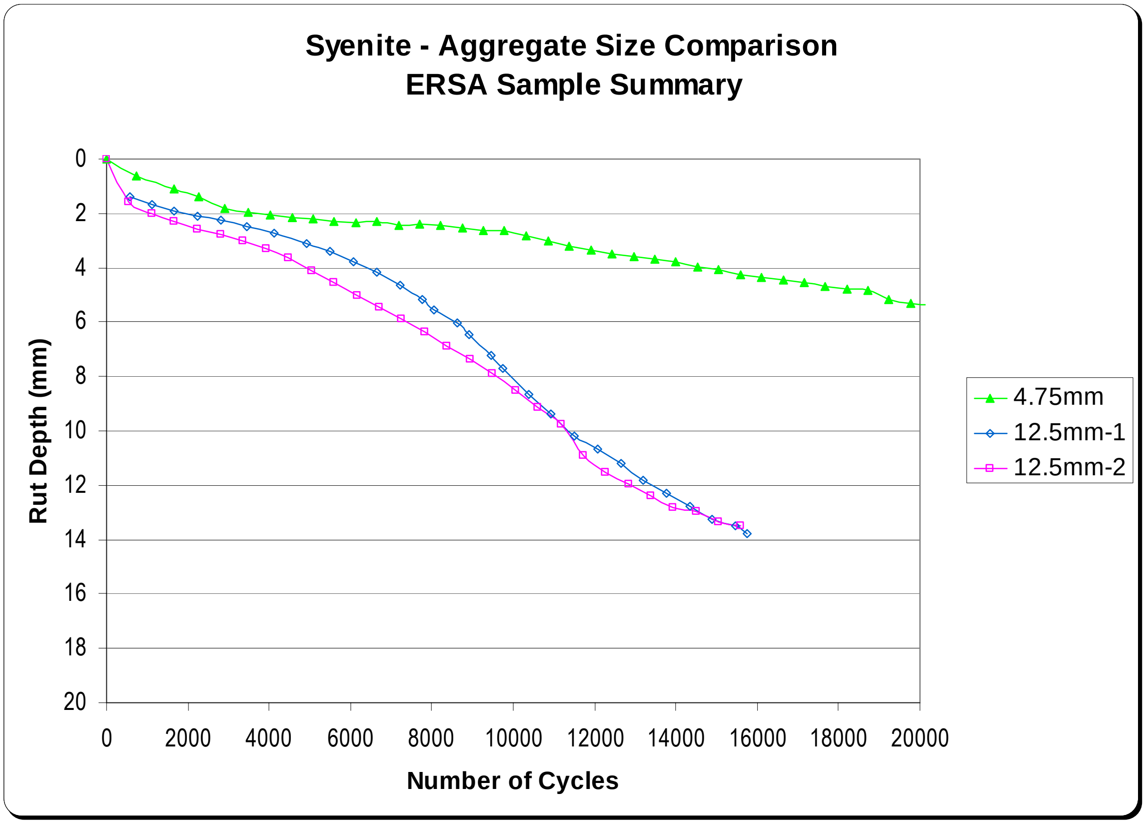

Figure 24. ERSA comparison for 4.75mm and 12.5mm syenite mixes

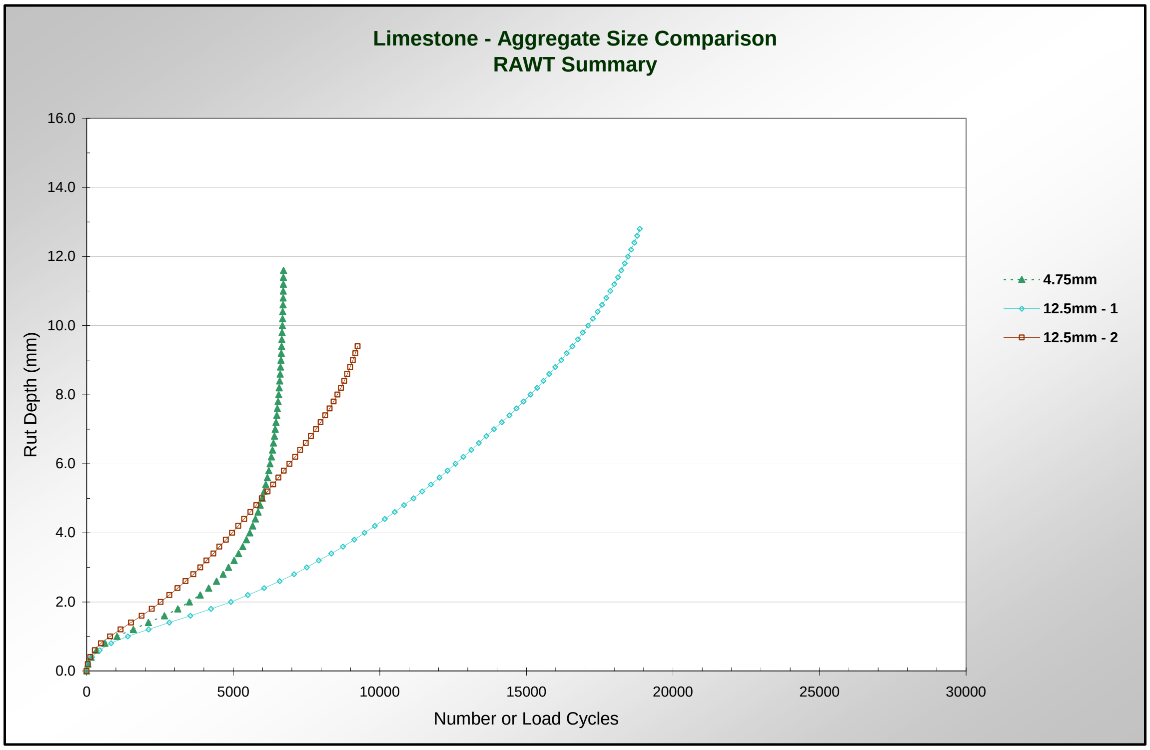

Figure 25. RAWT comparison for 4.75mm and 12.5mm limestone mixes

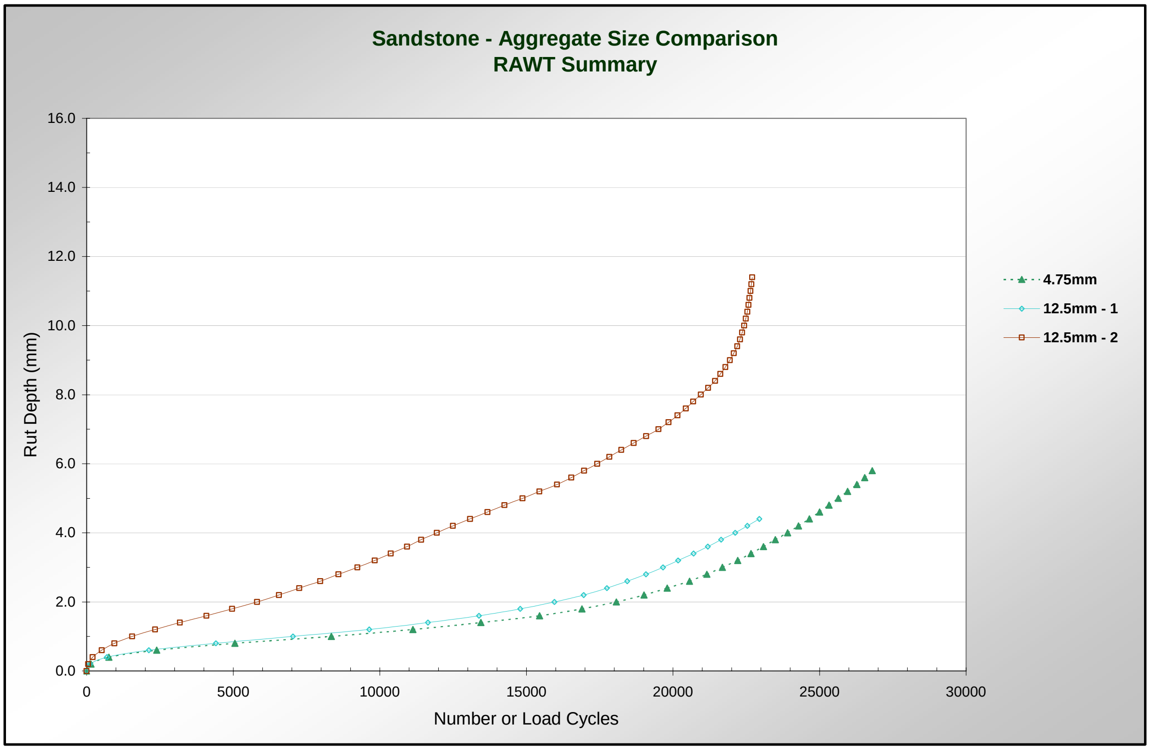

Figure 26. RAWT comparison for 4.75mm and 12.5mm sandstone mixes

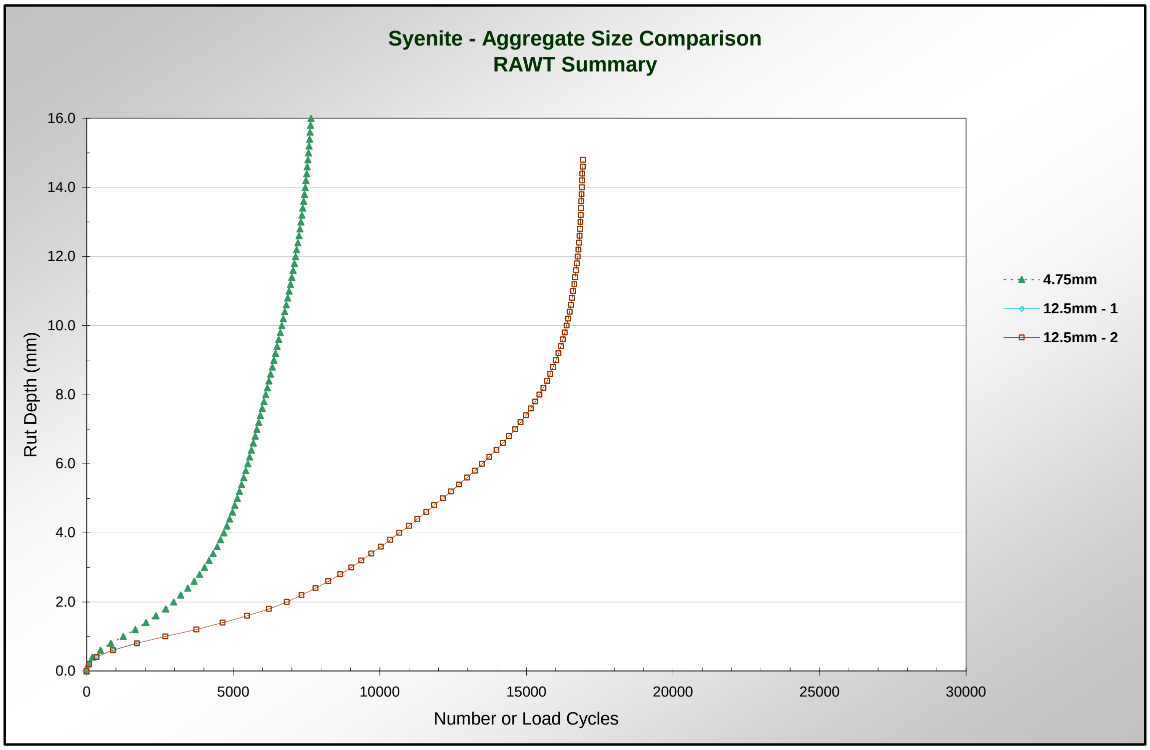

Figure 27. RAWT comparison for 4.75mm and 12.5mm syenite mixes

Upon visual inspection, the 4.75mm NMAS mixes were more rut resistant for the sandstone and syenite aggregate sources tested in ERSA, and for the sandstone source as tested in the RAWT. The 12.5mm NMAS mixes were more rut resistant for the limestone source in ERSA, and for the limestone and syenite mixes as tested in the RAWT. Results were mixed, however it appeared that mixture performance may have been more affected by aggregate source than NMAS. Also, it appeared that 4.75mm NMAS mixtures could be designed to be as rut-resistant as their 12.5mm NMAS counterparts.

Next, an ANOVA was used to validate these conclusions. Again, a complete randomized block design was used to isolate the effects of aggregate source. A summary of the ANOVA procedures for the six ERSA response variables and the two RAWT response variables is presented in Table 28.

		ANOVA Test Results for 4.75mm and 12.5mm Mixes 4.5% Air Voids, 100 Gyrations				
		4.75mm Average	12.5mm Average	NMAS Significant?	NMAS P-Value	Source significant?
ERSA	Rut20k	12.40	15.69	Yes	0.0363	Yes
	Rut10k	8.30	12.20	Yes	0.0186	Yes
	Rut5k	7.63	6.01	No	0.3109	Yes
	RSlope	4007.5	1775.0	No	0.1357	Yes
	SIP	18050	5365	No	0.1235	Yes
	SSlope	3269	552	No	0.1276	Yes
RAWT	Final Rut	11.74	12.38	No	0.6895	No
	RutperCycle	0.00145	0.00074	Yes	0.0027	Yes

Table 28. Summary of Phase II results – rutting test data for 4.75mm and 12.5mm NMAS

In these analyses, source was significant for all but one case – RAWT final rut depth. For reasons previously discussed, this response is not necessarily a good measure of relative performance. Thus, it was concluded that aggregate source was significant to the rutting and stripping performance of both the 4.75mm and 12.5mm mixtures. The NMAS of the mix was significant in some cases, specifically for rut depth at 20,000 cycles in ERSA, rut depth at 10,000 cycles in ERSA, and rut per cycle in RAWT. Thus, it was concluded that rutting performance was significantly affected by NMAS. In several cases, the 4.75mm mixes showed greater resistance to rutting than the 12.5mm mixes. Again, it appears that 4.75mm NMAS mixtures have potential for rutting resistance similar to that of 12.5mm NMAS mixtures.

CONCLUSIONS

A total of 18 4.75mm NMAS mixes were designed from three aggregate sources at two design air void levels (4.5 percent and 6.0 percent) and three levels of compaction (Ndes = 50, 75, 100). The rutting and stripping performance of each mix was determined so that the effects of the experimental factors could be obtained. In addition, the permeability of the mixes was investigated. Additional testing was performed to assess the effect of NMAS and the use of natural sand.

Mix Design

During the mix design process, the following observations were made.

- For the design of 4.75mm NMAS Superpave mixes, no single source of screenings was determined to produce an acceptable design. For those single materials meeting the gradation requirements, other volumetric properties prevented a successful design.
- The successful mix designs were composed of a blend of multiple materials, often having different mineral compositions.
- Binder contents were higher than those used for 12.5mm mixes and ranged from 6.7 to 8.7 percent.
- VMA was the most difficult mix design requirement to meet. Sandstone mixes were prone to low VMA, and the syenite mixes were prone to high VMA. Angular aggregates were used to increase VMA, and natural sand was used to decrease VMA.
- Making minor adjustments to aggregate gradations or introducing new aggregate types can improve mix design success.

Overall, 4.75mm mixes can be successfully designed using existing Arkansas aggregate sources. In some cases, success can be improved by making minor adjustments to individual aggregate gradations.

Performance

- The rutting and stripping performance of 4.75mm mixtures was assessed using the ERSA and RAWT wheel-tracking devices. The effects of variations in design air voids and compactive effort were evaluated. The following conclusions were noted.
- Relative to rutting in ERSA, the experimental design parameters were largely insignificant.
- Relative to stripping performance in ERSA, there was a significant interaction of factors. For mixes designed at 100 gyrations, those designed at 4.5 percent air voids were the better performers. For the mixes designed at 50 gyrations, those designed at 6.0 percent air voids were the better performers.
- Aggregate source was significant for all response variables.
- Relative to rutting in the RAWT, level of compaction was significant. The 75 and 100 design gyration mixes exhibited better performance than the 50 gyration mixes.
- As natural sand content increased, performance decreased.

Mixes for low and medium traffic roadways (i.e., 50 and 75 design gyrations) should be designed at 6.0 percent air voids. Mixes for high traffic applications (i.e., 100 design gyrations) should be designed at 4.5 percent air voids. The use of natural sand should be limited.

Permeability

The permeability of 4.75mm Superpave mixtures was evaluated using the Karol-Warner flexible wass permeability device. The following conclusions emerged.

- The permeability values for the samples having a 25 mm thickness were slightly higher than for the samples having a 50 mm thickness.
- A 25 mm sample thickness was determined to provide a more realistic measure of permeability since it is consistent with the recommended lift thickness for a 4.75mm mix.
- The permeability of mixes designed at 6.0 percent was more sensitive to changes in level of compaction than those designed at 4.5 percent.
- All of the 4.75mm mixtures exhibited very low levels of permeability.

4.75mm NMAS Superpave mixtures have very low permeability. Therefore, they have excellent potential for use in sealing surfaces that may be susceptible to permeability problems.

Nominal Maximum Aggregate Size

Two 12.5mm mixes were prepared for each of the three aggregate sources. The rutting and stripping performance for the 4.75mm mixes was compared to that of the 12.5mm mixes. The following observations were made.

- It is possible to design 4.75mm mixtures with rutting resistance that is equal to or greater than that of a 12.5mm mixture.
- The comparison of NMAS was significantly affected by aggregate source.

- Rutting performance was significantly affected by NMAS. In several cases, the 4.75mm mixes exhibited greater rutting resistance than the corresponding 12.5mm mixes.
- Stripping resistance was not significantly affected by NMAS.

4.75mm mixtures can be designed to resist failure by rutting and stripping in a manner similar to, and sometimes better than, 12.5mm mixtures.

Recommendations

Based on the favorable conclusions of this study, it is recommended that the use of 4.75mm HMA mixtures should be implemented in the state of Arkansas according to the following specification presented in Table 29.

Mix Design Parameter	Recommended Specification	
Sieve Size (mm)	Control Points (% Passing)	
½" (12.5)	100	
3/8"(9.5)	95-100	
No. 4 (4.75)	90-100	
No. 16 (1.18)	30-60	
No. 200 (0.075)	6-12	
Binder Content (%)	Design Value	
Air Voids (%)	Ndes	Air Voids (%)
	50, 75	6.0
	100	4.5
VMA (%)	Ndes	VMA (%)
	50, 75	18.0 – 20.0
	100	16.0 – 18.0
VFA (%)	Ndes	VFA (%)
	50, 75	66.7 – 70.0
	100	71.9 – 75.0
DP	0.9-2.0	

Table 29. Recommended 4.75mm HMA mixture specification

FUTURE RESEARCH

The effect of binder grade was not investigated in this project. It is assumed that increasing the binder grade would increase the rutting resistance of the mix. Therefore, the use of PG 76-22 binder in 4.75mm mixes should be investigated, particularly for medium and high volume applications.

In order to fully implement the use of 4.75mm mixtures in Arkansas, a specification limit should be set for the maximum allowable rut depth according to a wheel tracking test. The AHD currently requires mixes to meet criteria for rutting as measured by the Asphalt Pavement Analyzer (APA) according to AHTD method 480. Current specification limits for low volume designs (i.e., maximum allowable rut depth = 8.000 mm) would probably be most appropriate for 4.75mm mixes. However, since other wheel tracking devices were used in this research project, further testing using the APA should be performed in order to validate the criteria.

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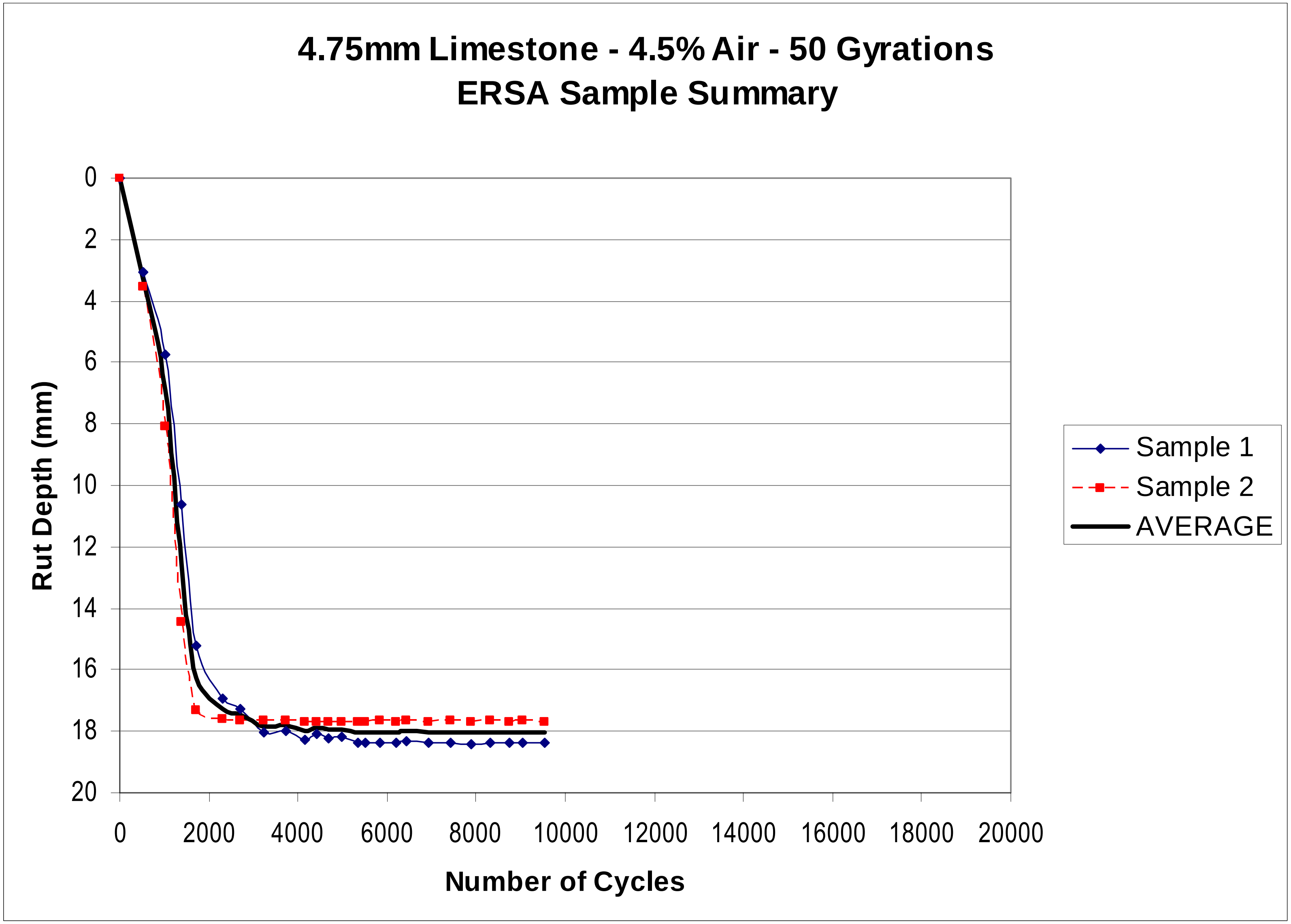
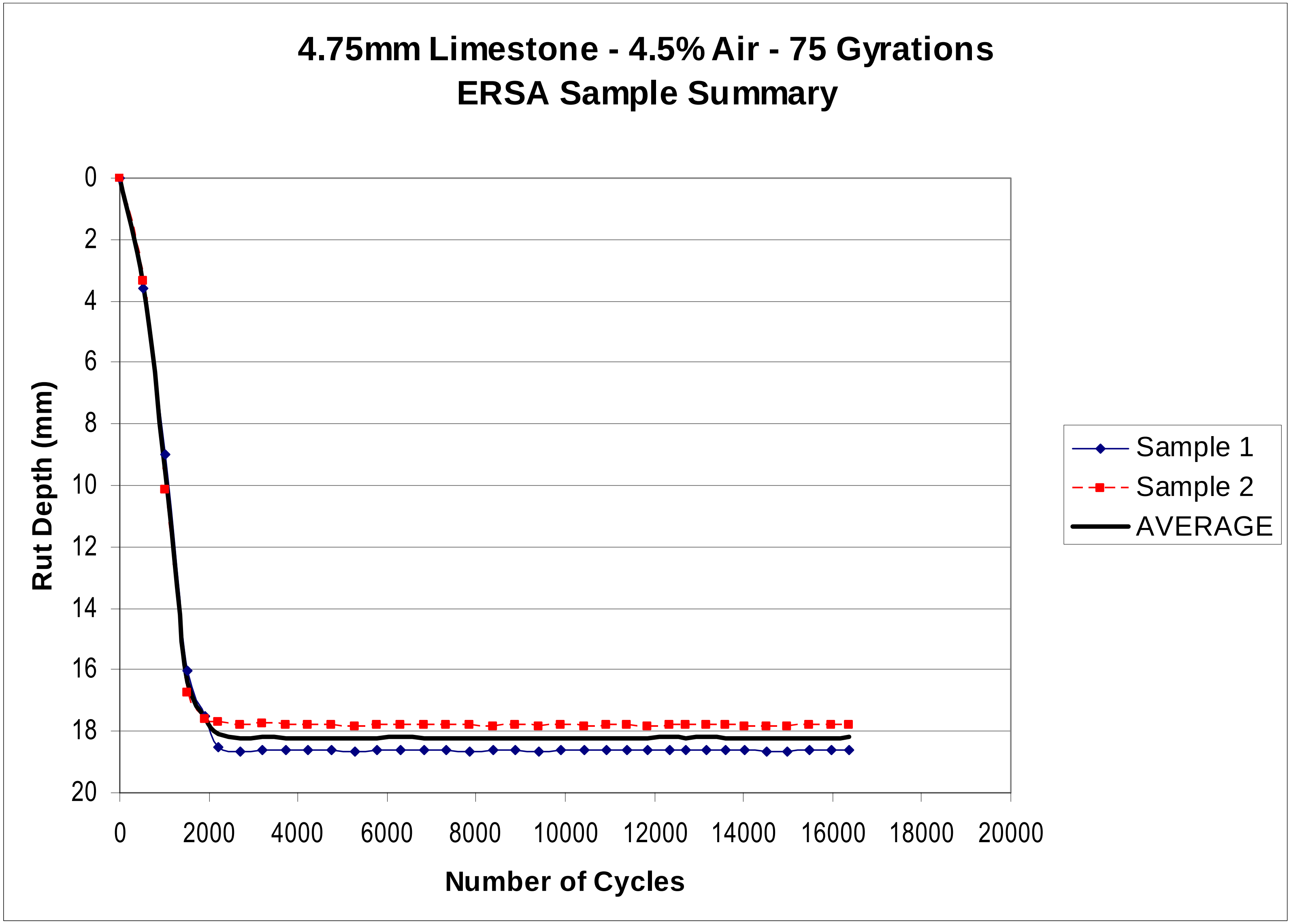
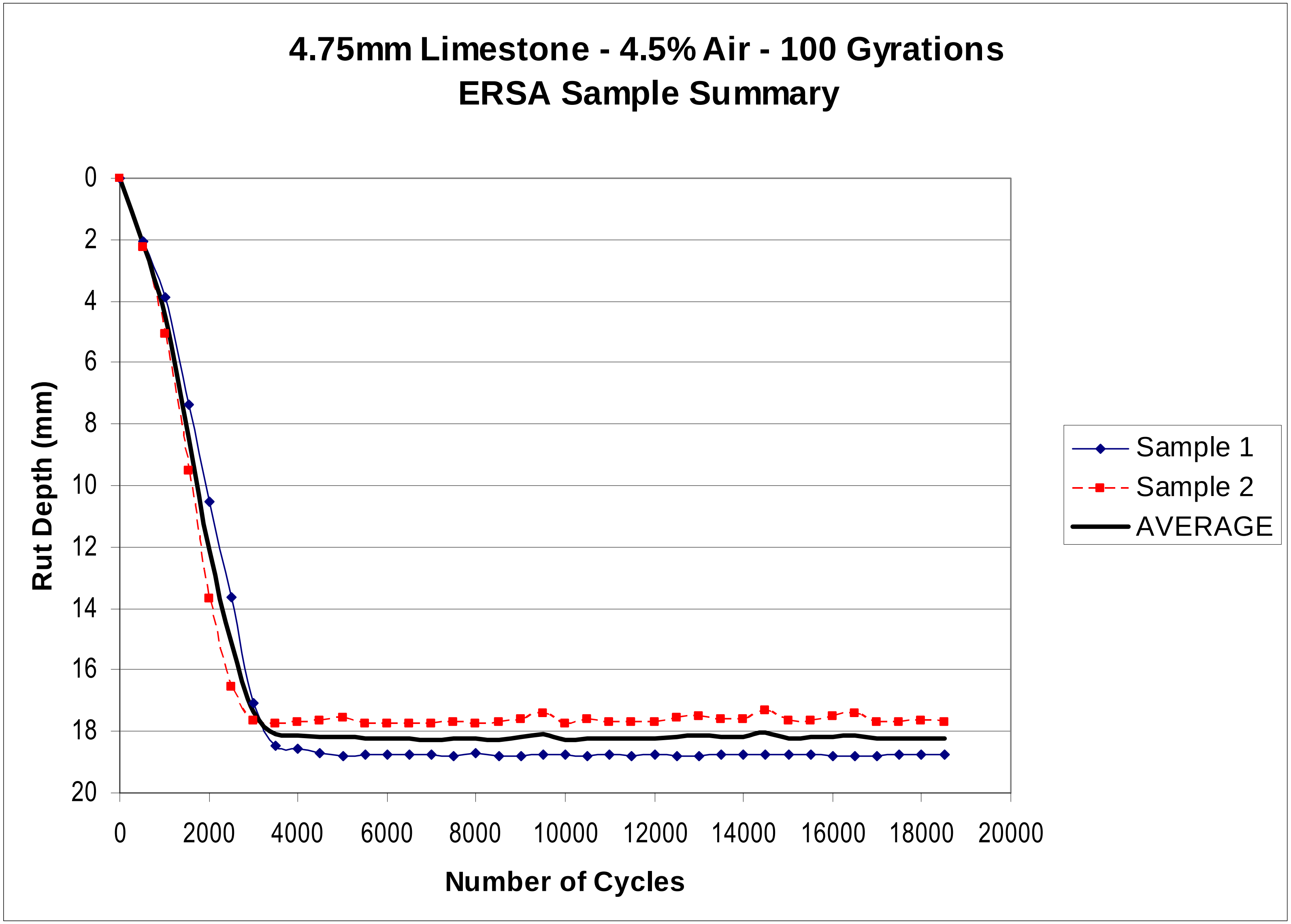
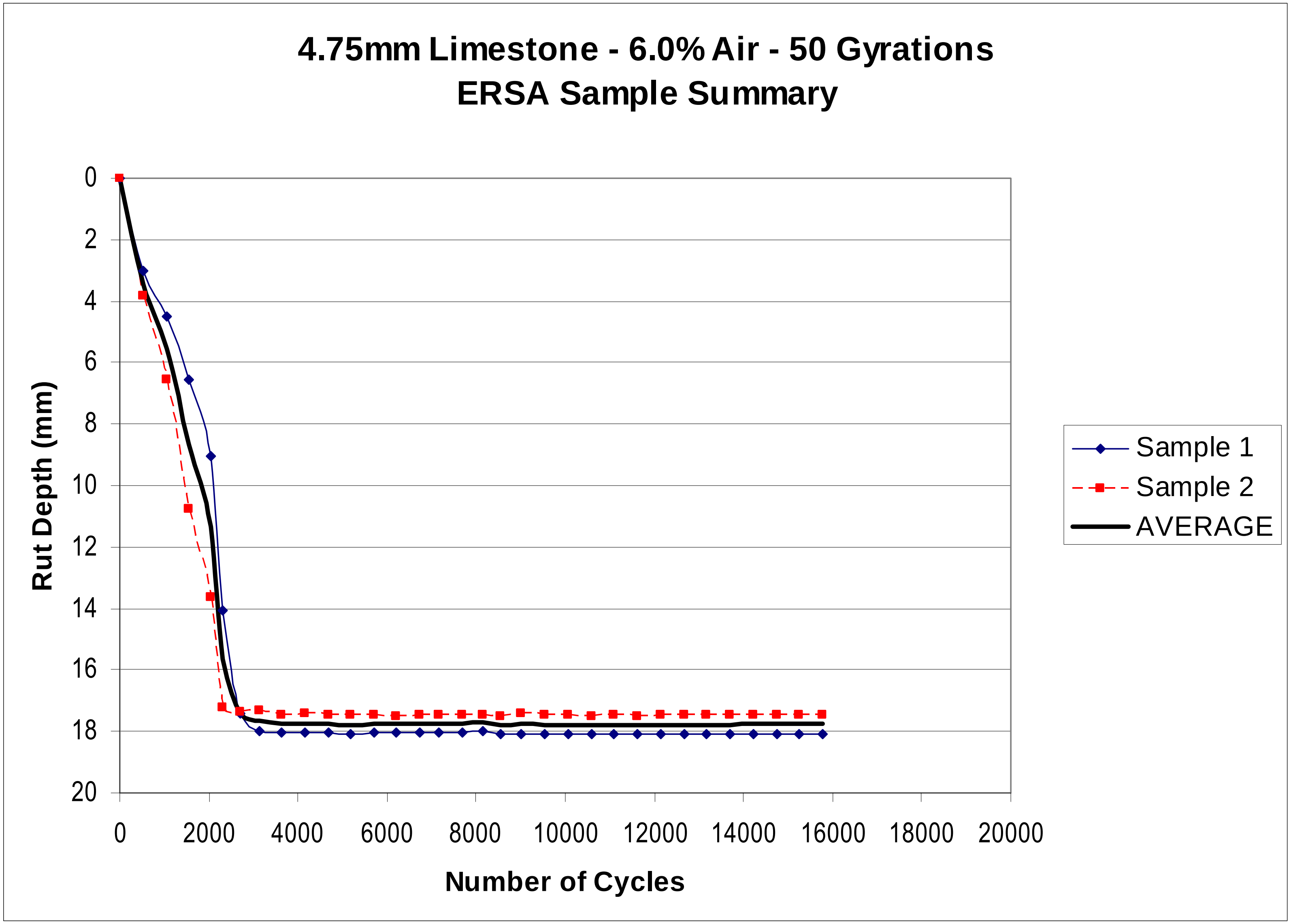
APPENDIX A

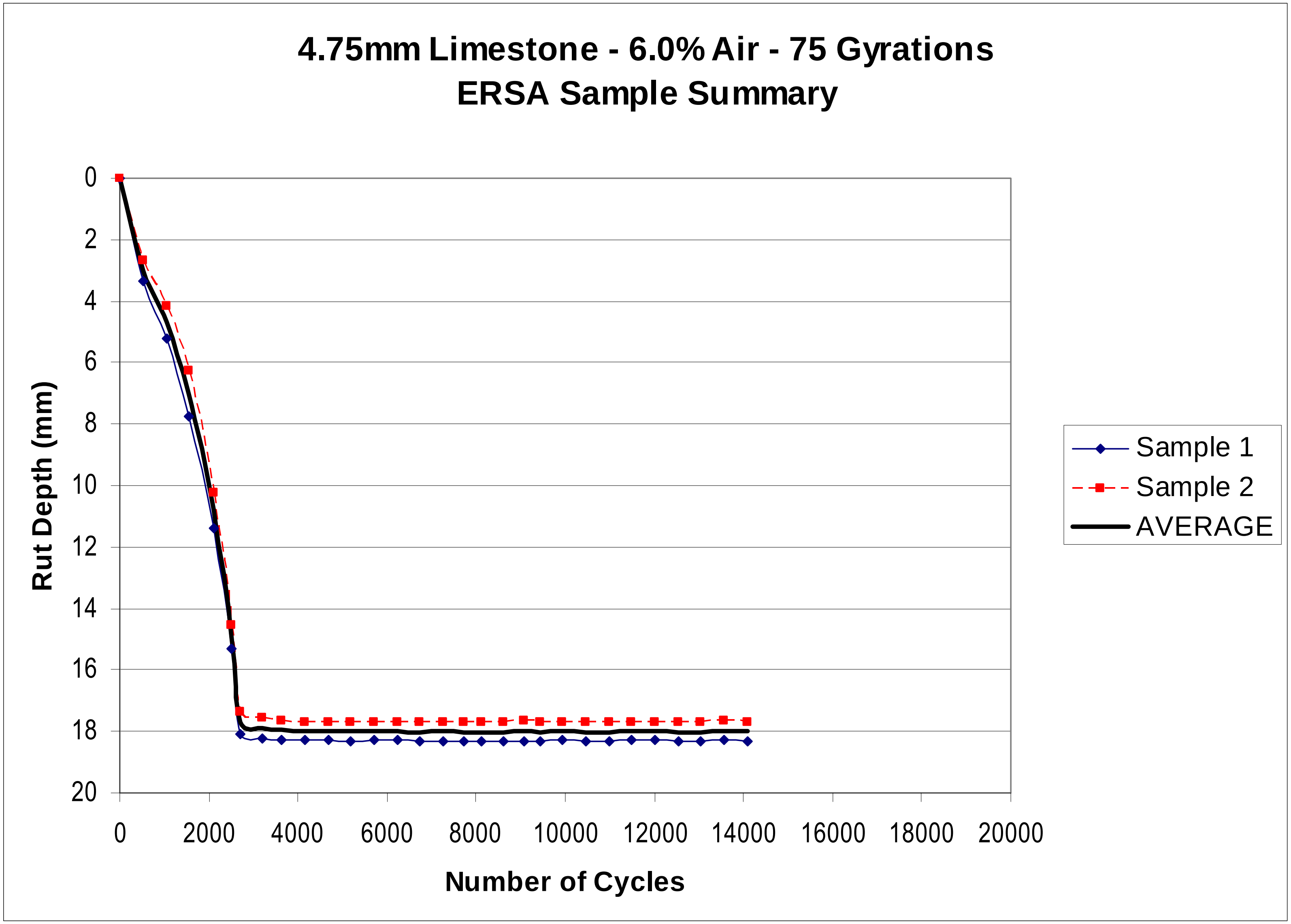
4.75mm ERSA RESULTS

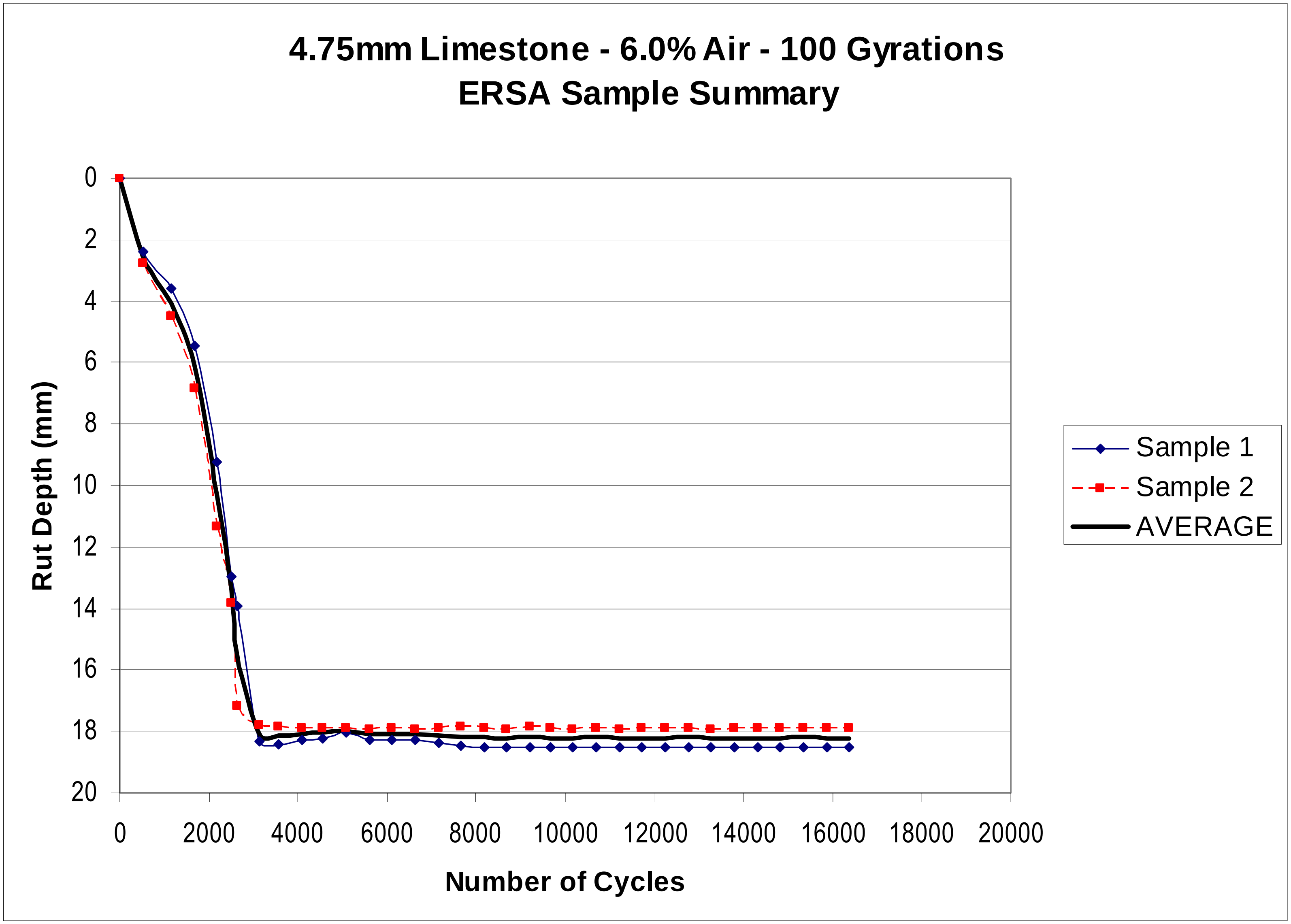

4.75mm Limestone - 4.5% Air - 50 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE

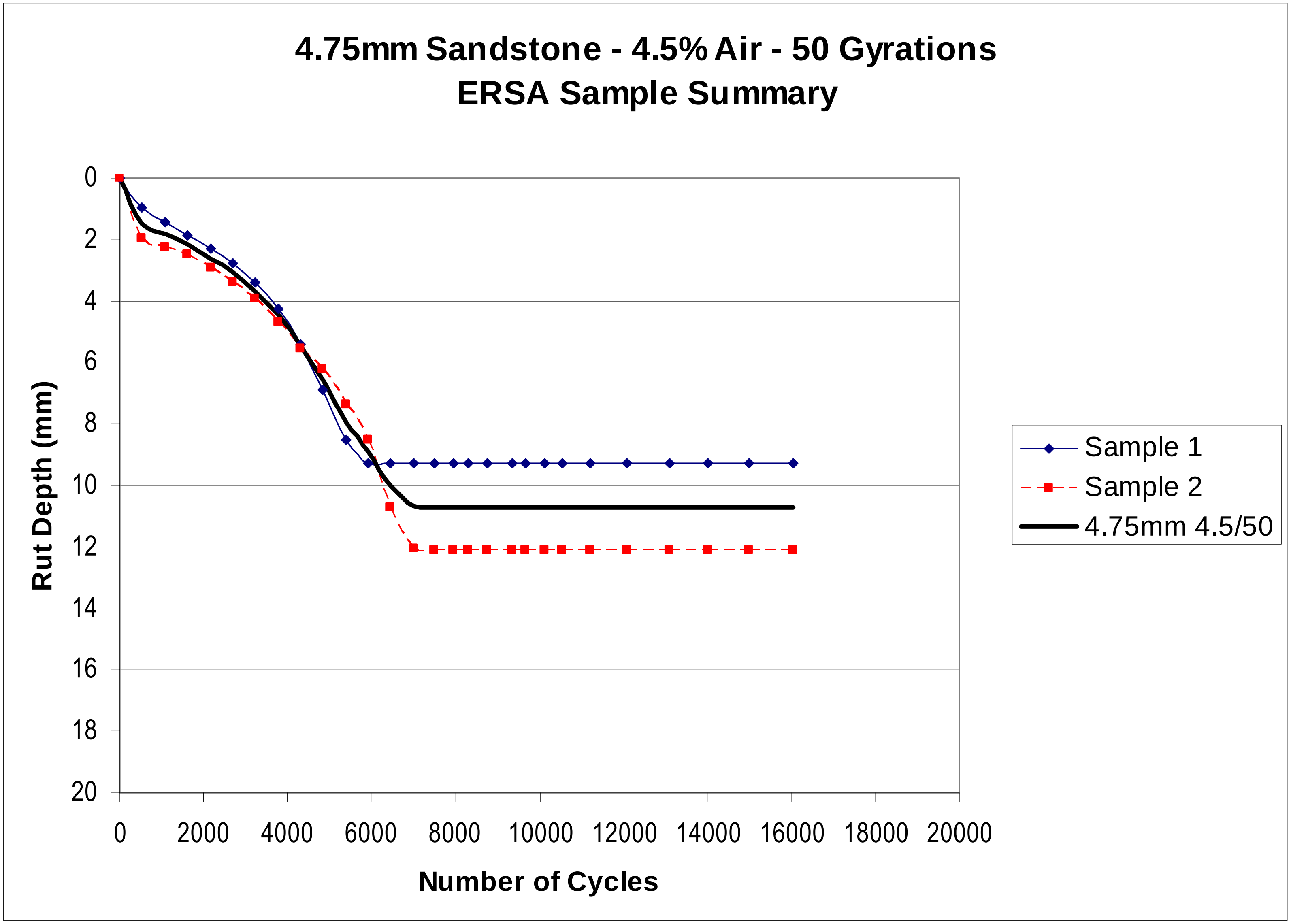

4.75mm Limestone - 4.5% Air - 75 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE

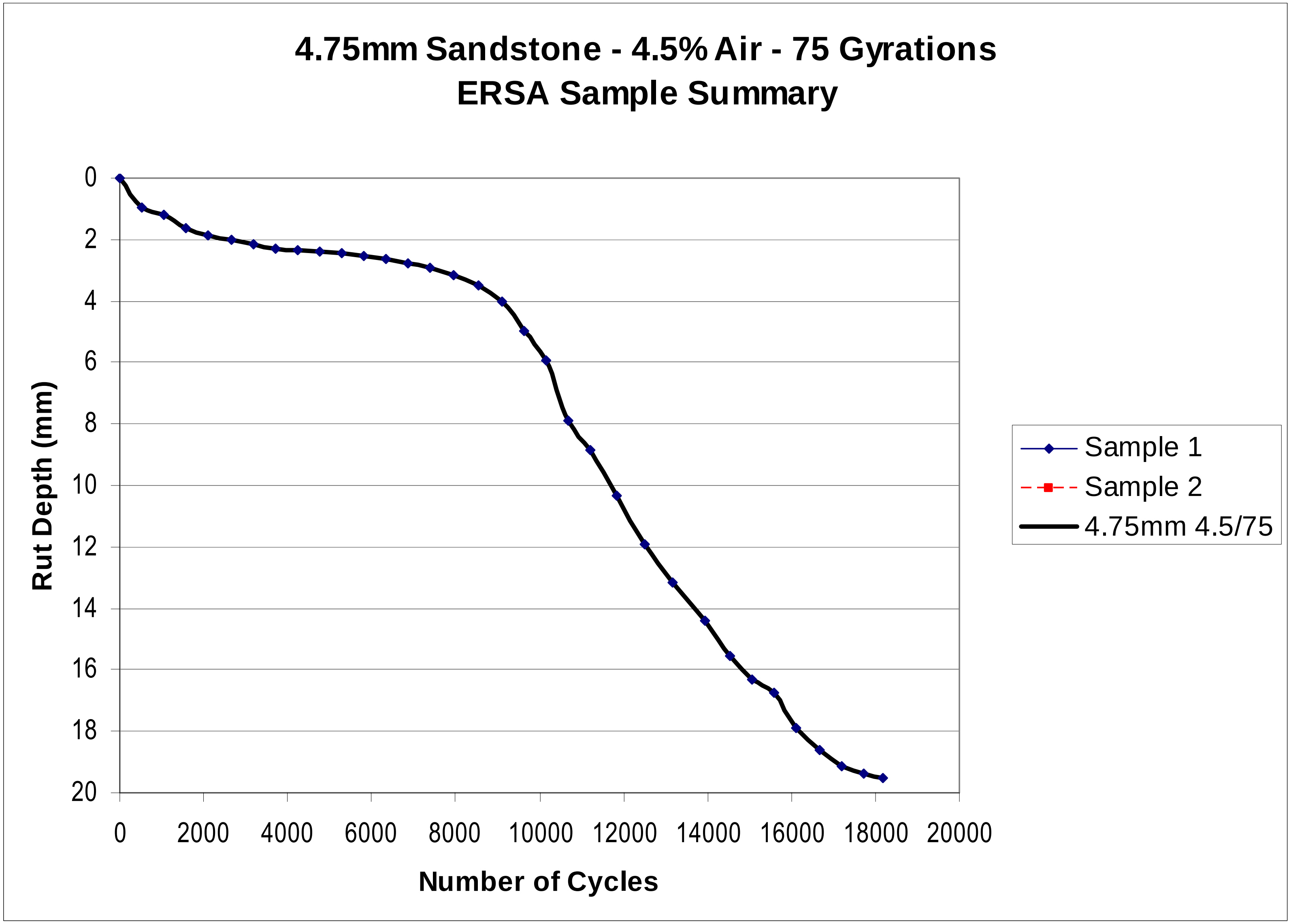

4.75mm Limestone - 4.5% Air - 100 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE

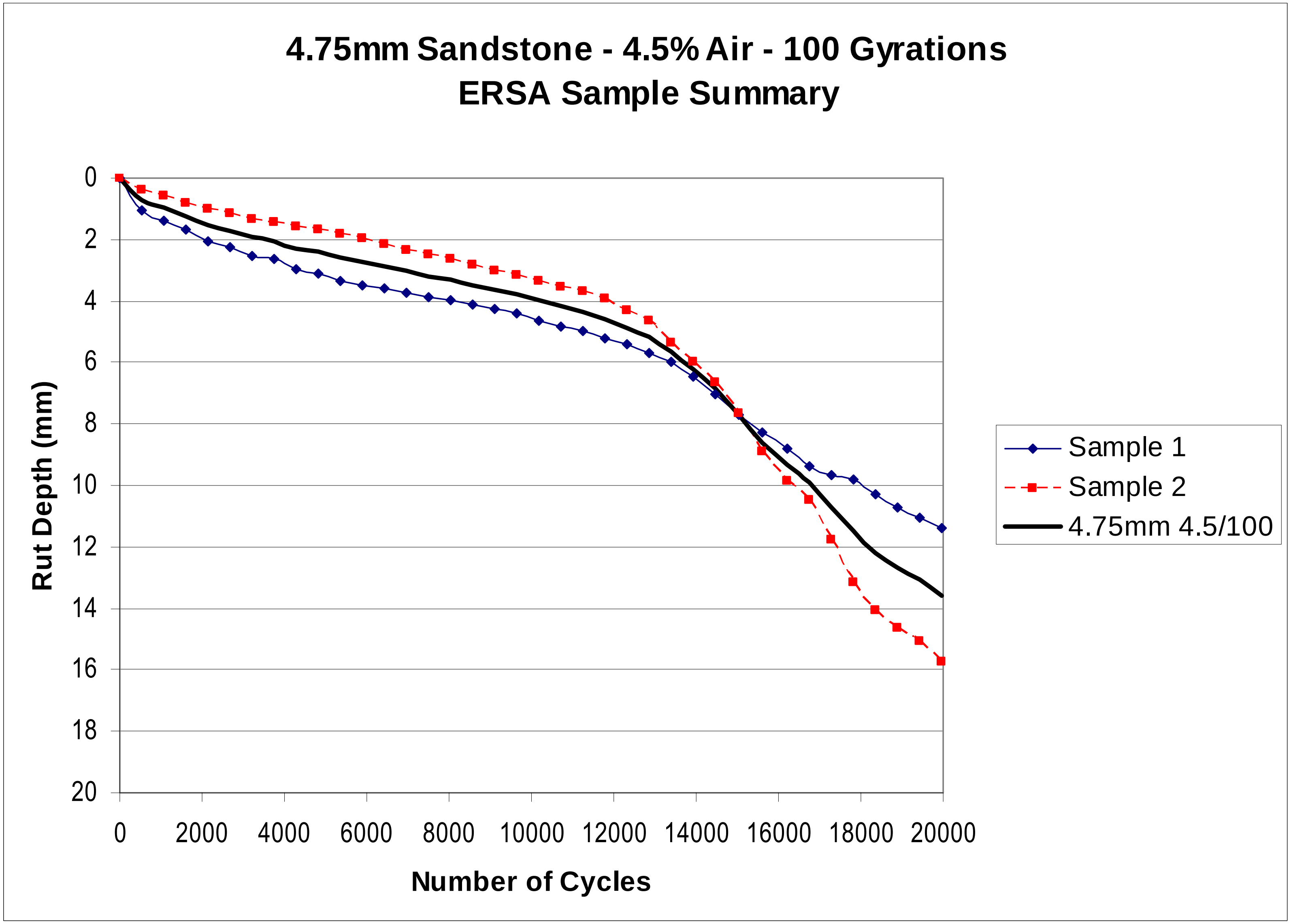

4.75mm Limestone - 6.0% Air - 50 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE

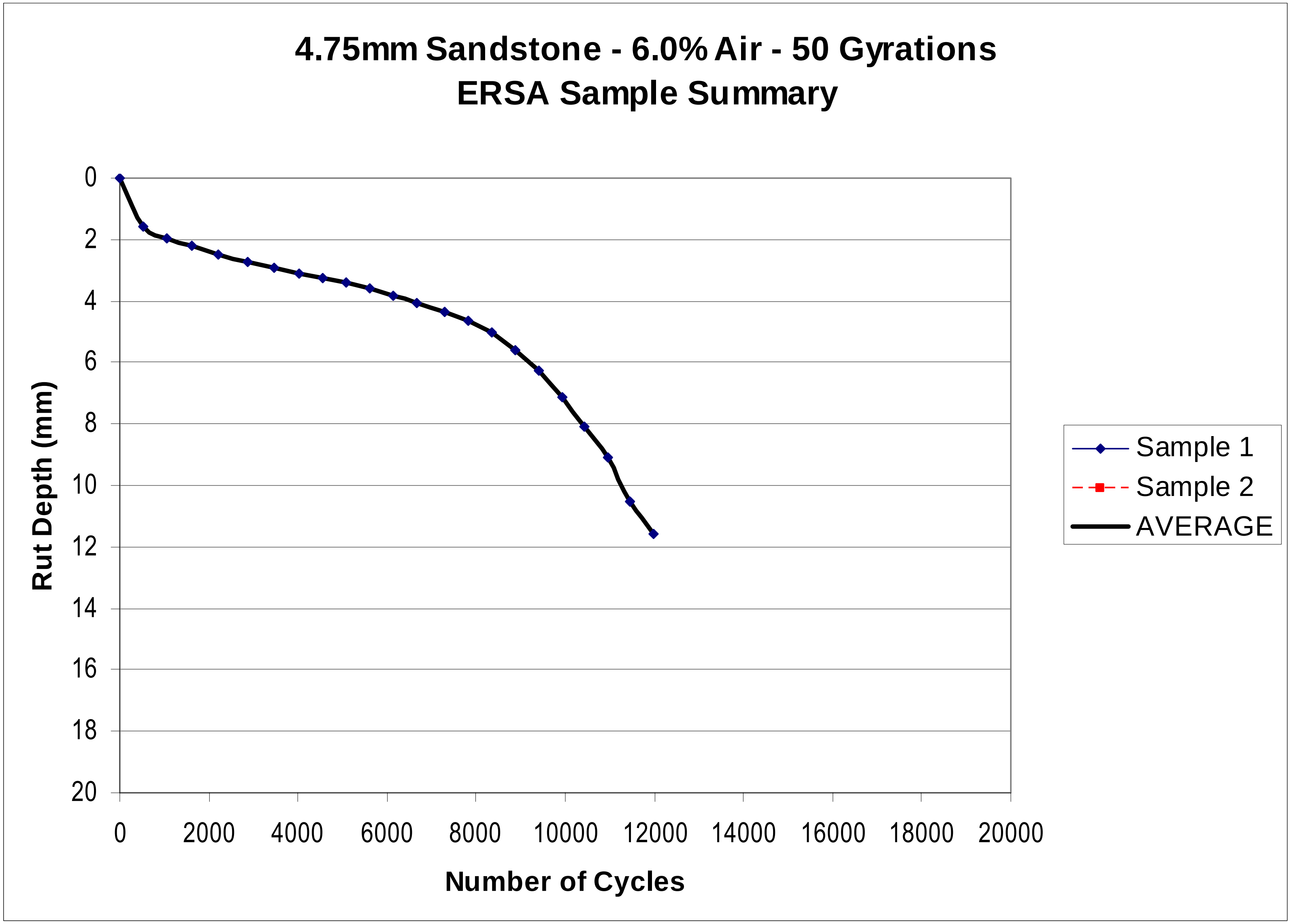

4.75mm Limestone - 6.0% Air - 75 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE

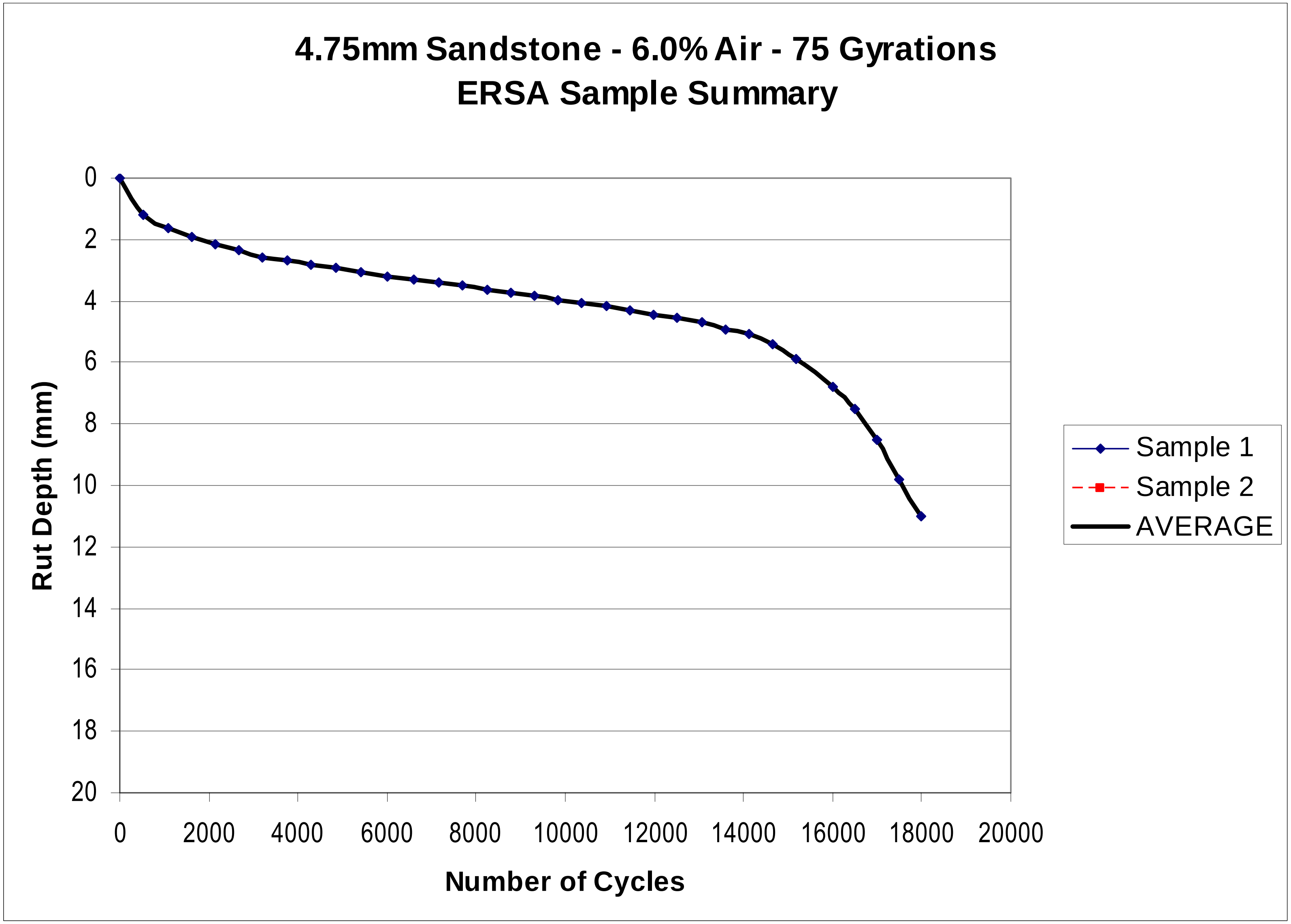

4.75mm Limestone - 6.0% Air - 100 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE


4.75mm Sandstone - 4.5% Air - 50 Gyrations
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
4.75mm 4.5/50

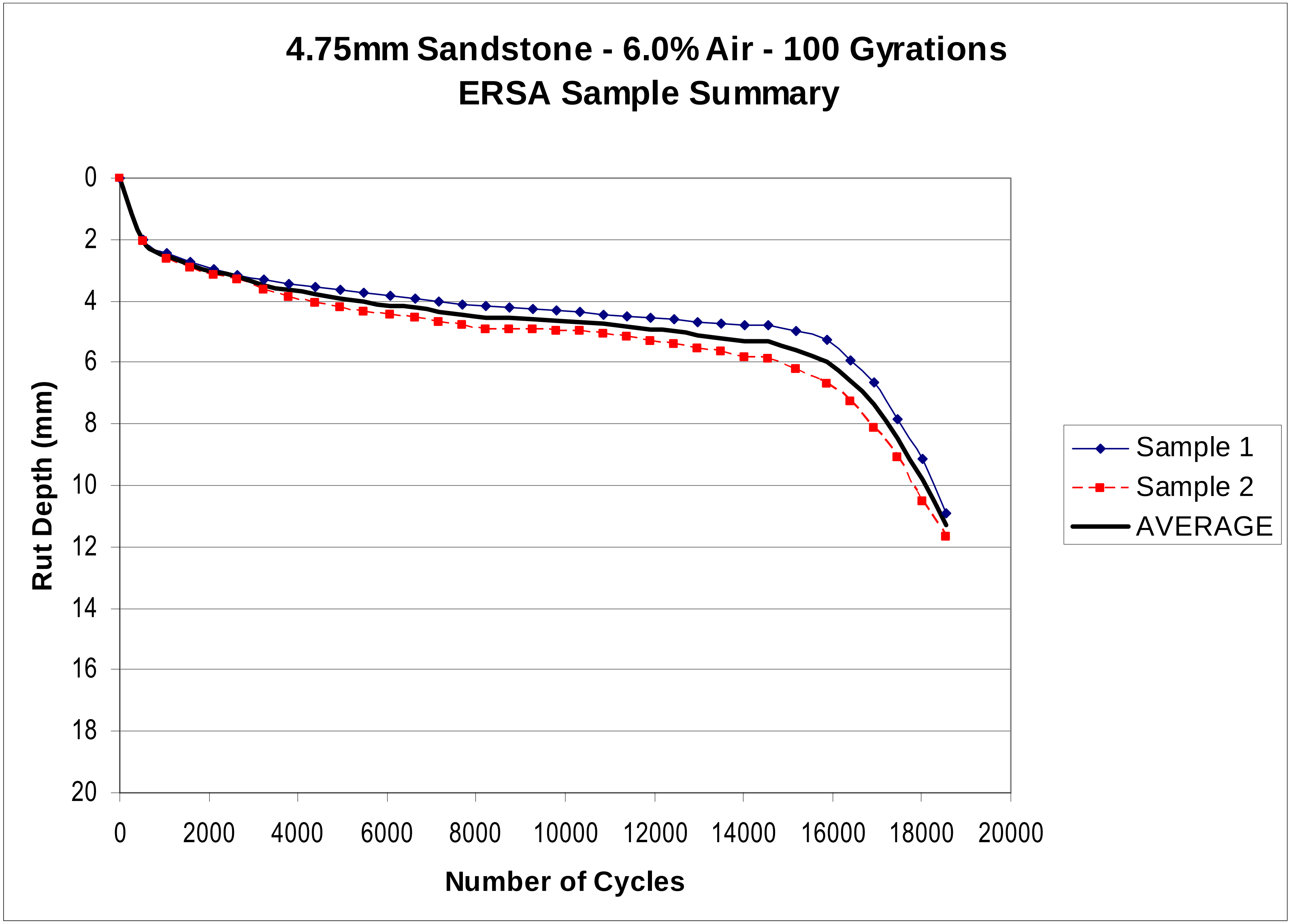

4.75mm Sandstone - 4.5% Air - 75 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
4.75mm 4.5/75

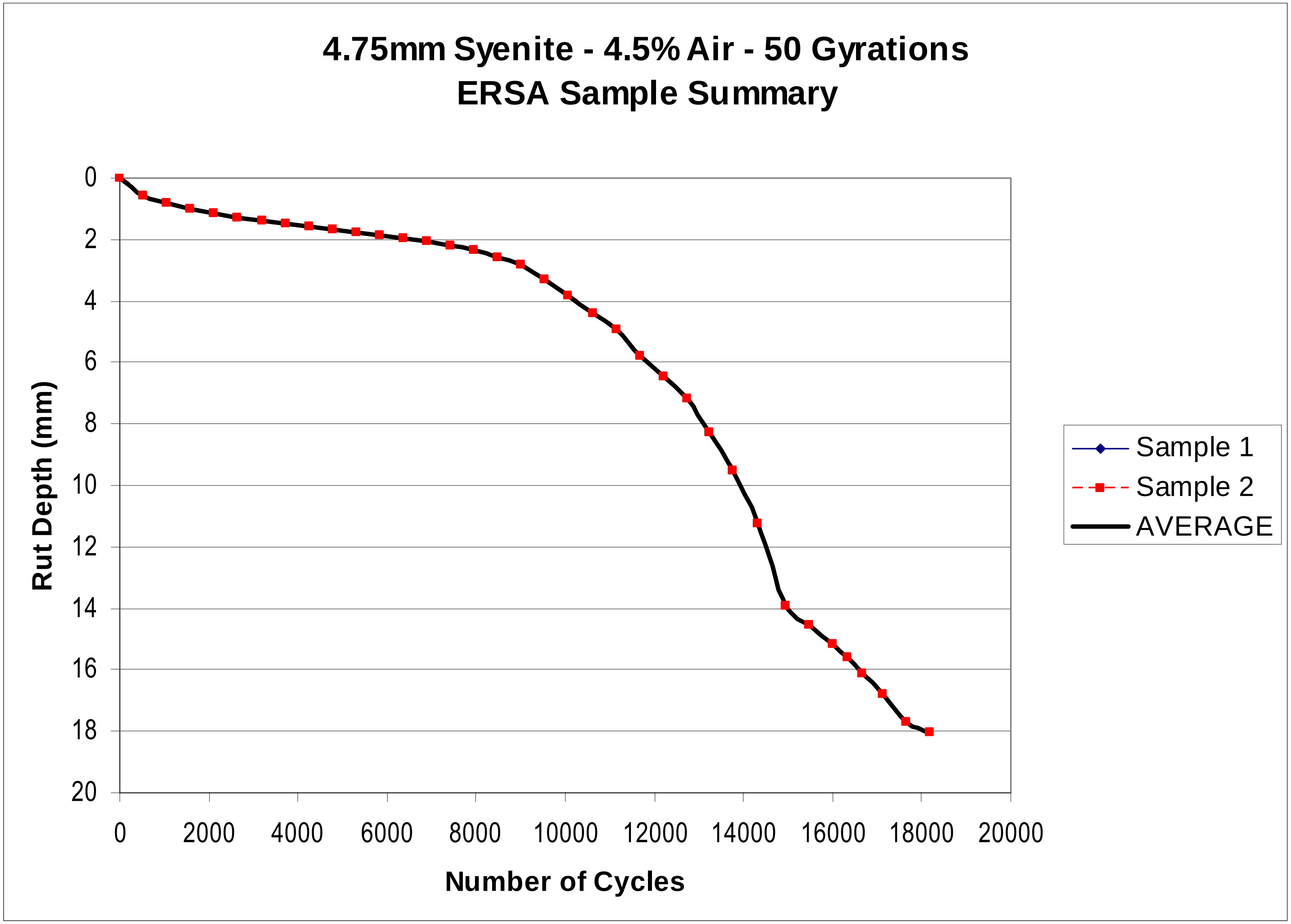

4.75mm Sandstone - 4.5% Air - 100 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
4.75mm 4.5/100

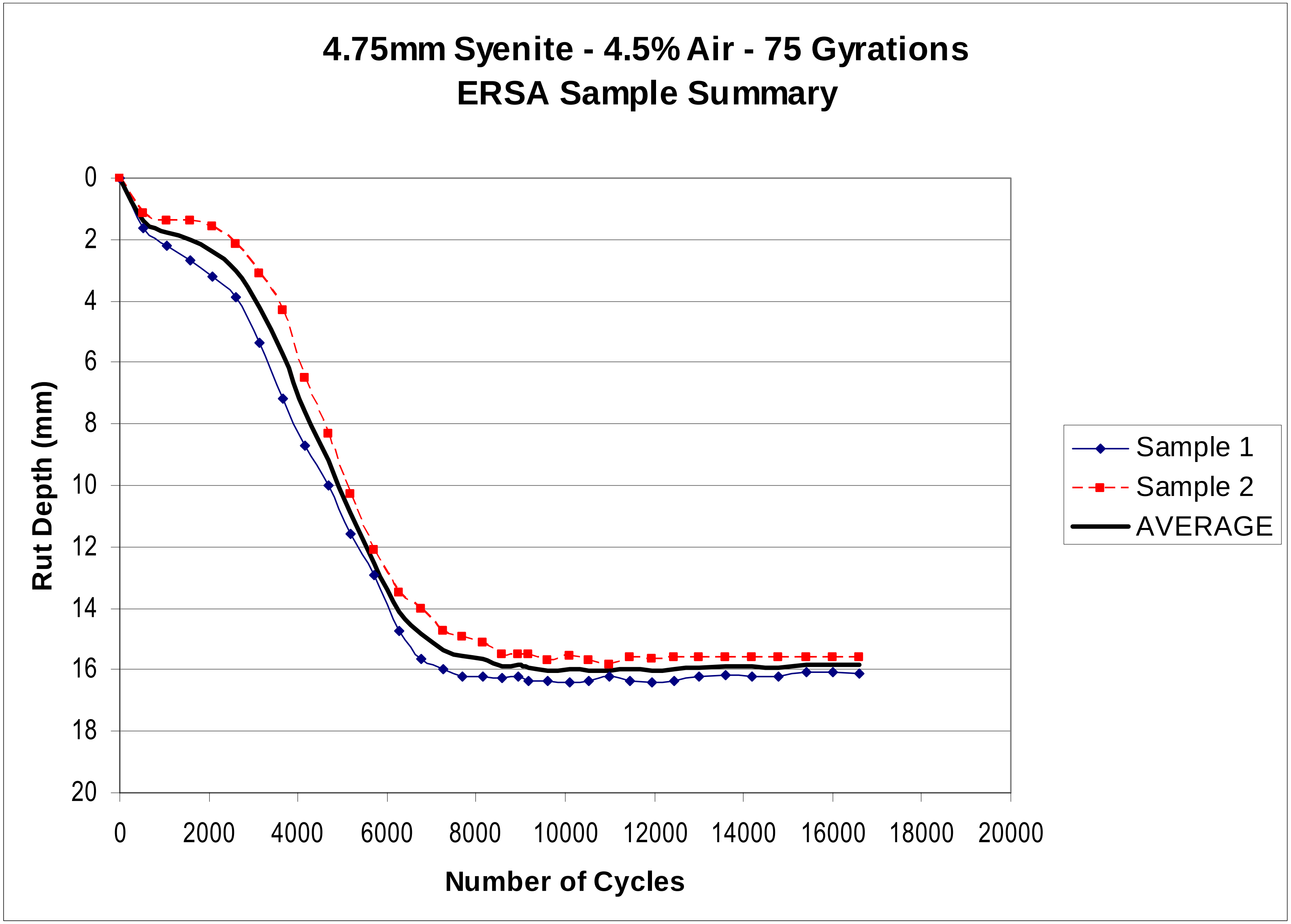

4.75mm Sandstone - 6.0% Air - 50 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE

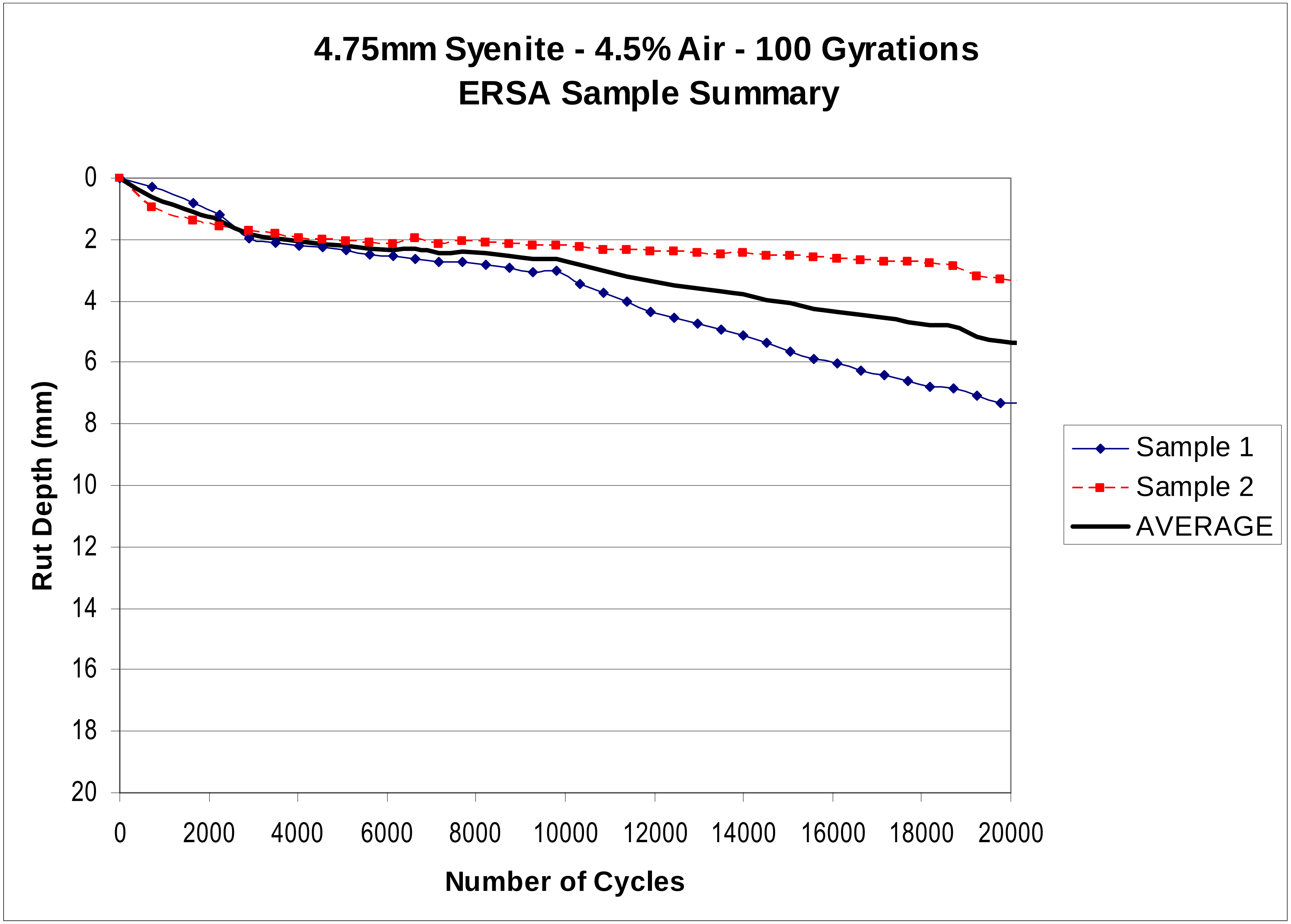


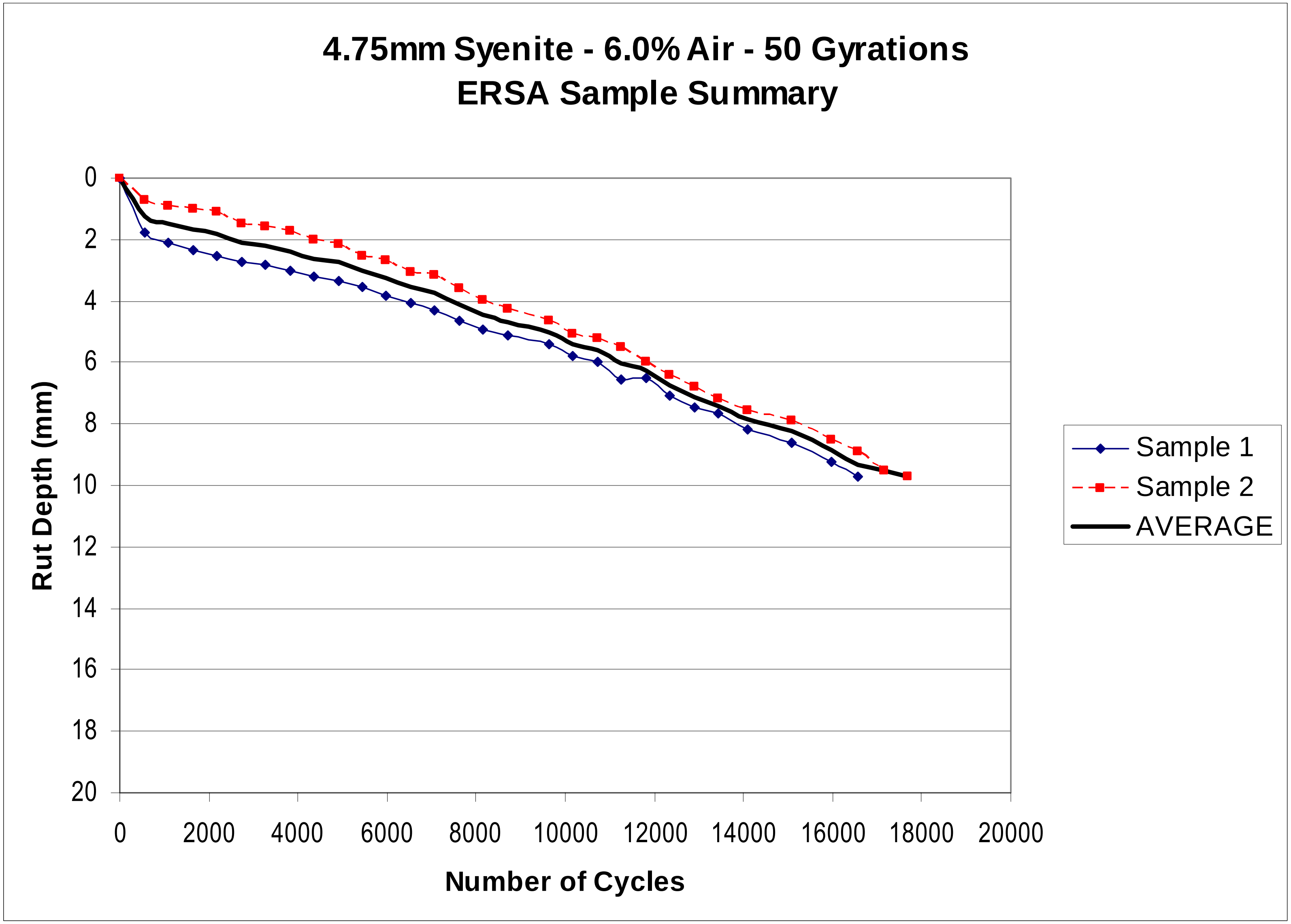
4.75mm Sandstone - 6.0% Air - 75 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE


4.75mm Sandstone - 6.0% Air - 100 Gyrations
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
AVERAGE

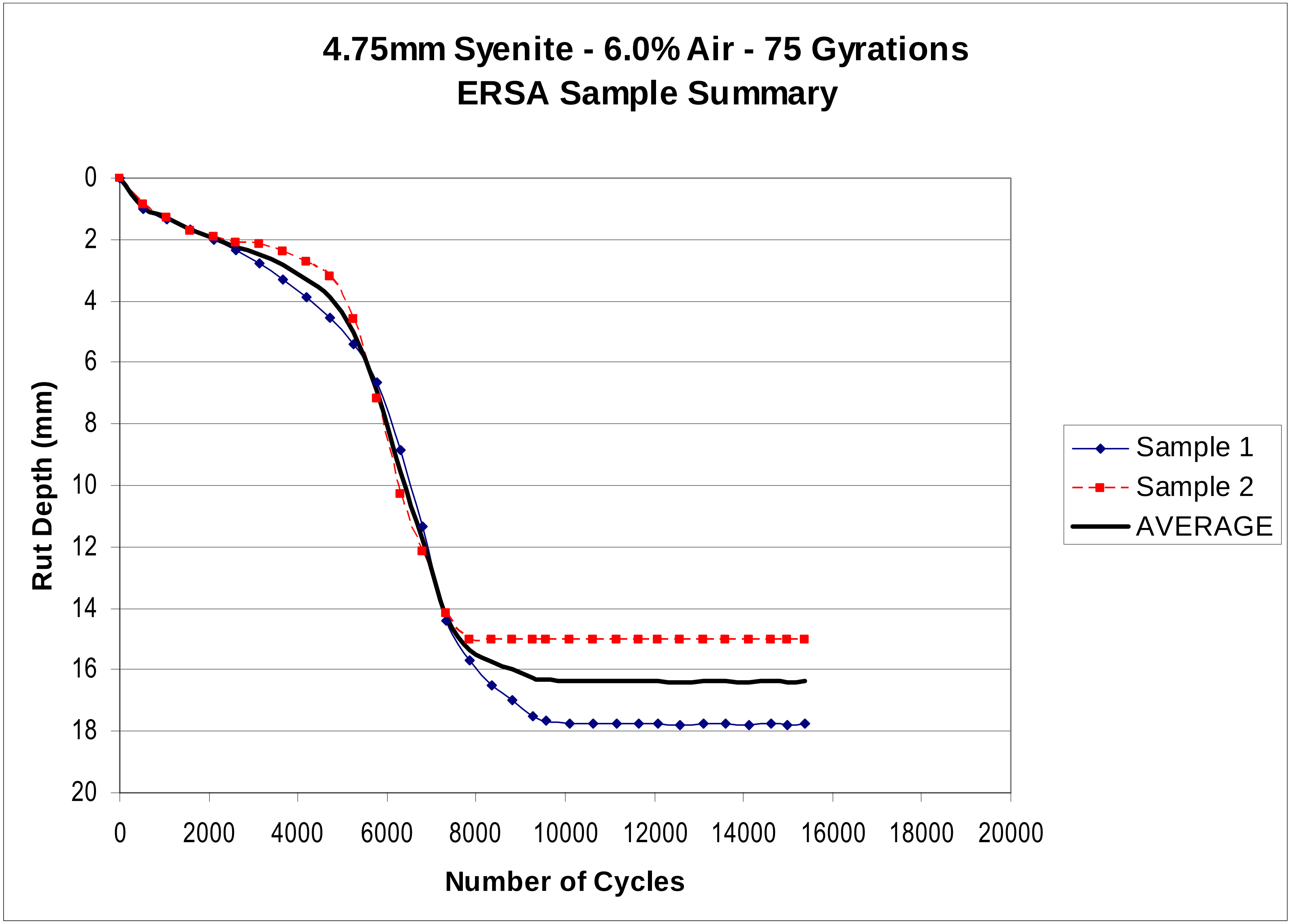

4.75mm Syenite - 4.5% Air - 50 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE

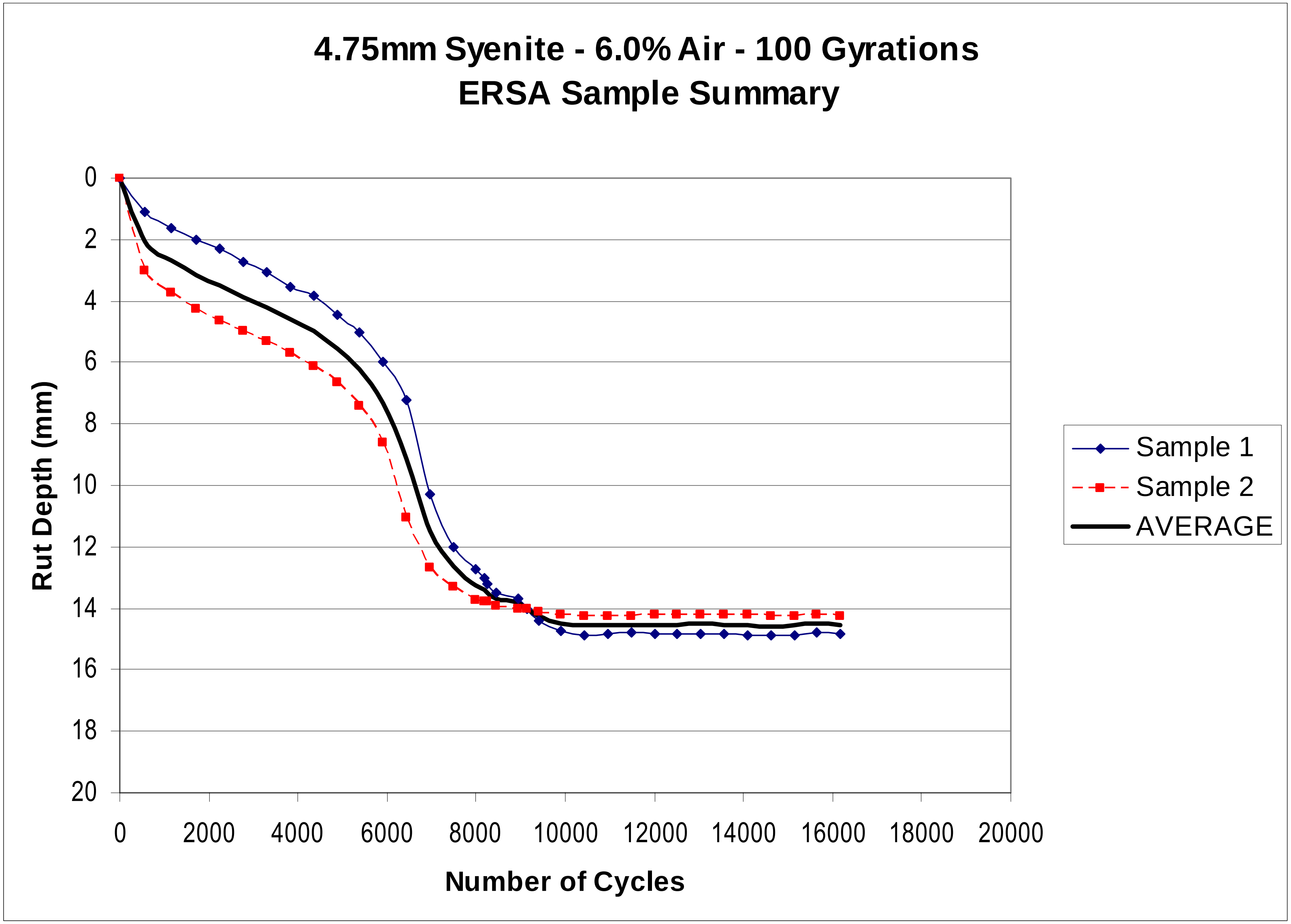

4.75mm Syenite - 4.5% Air - 75 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE

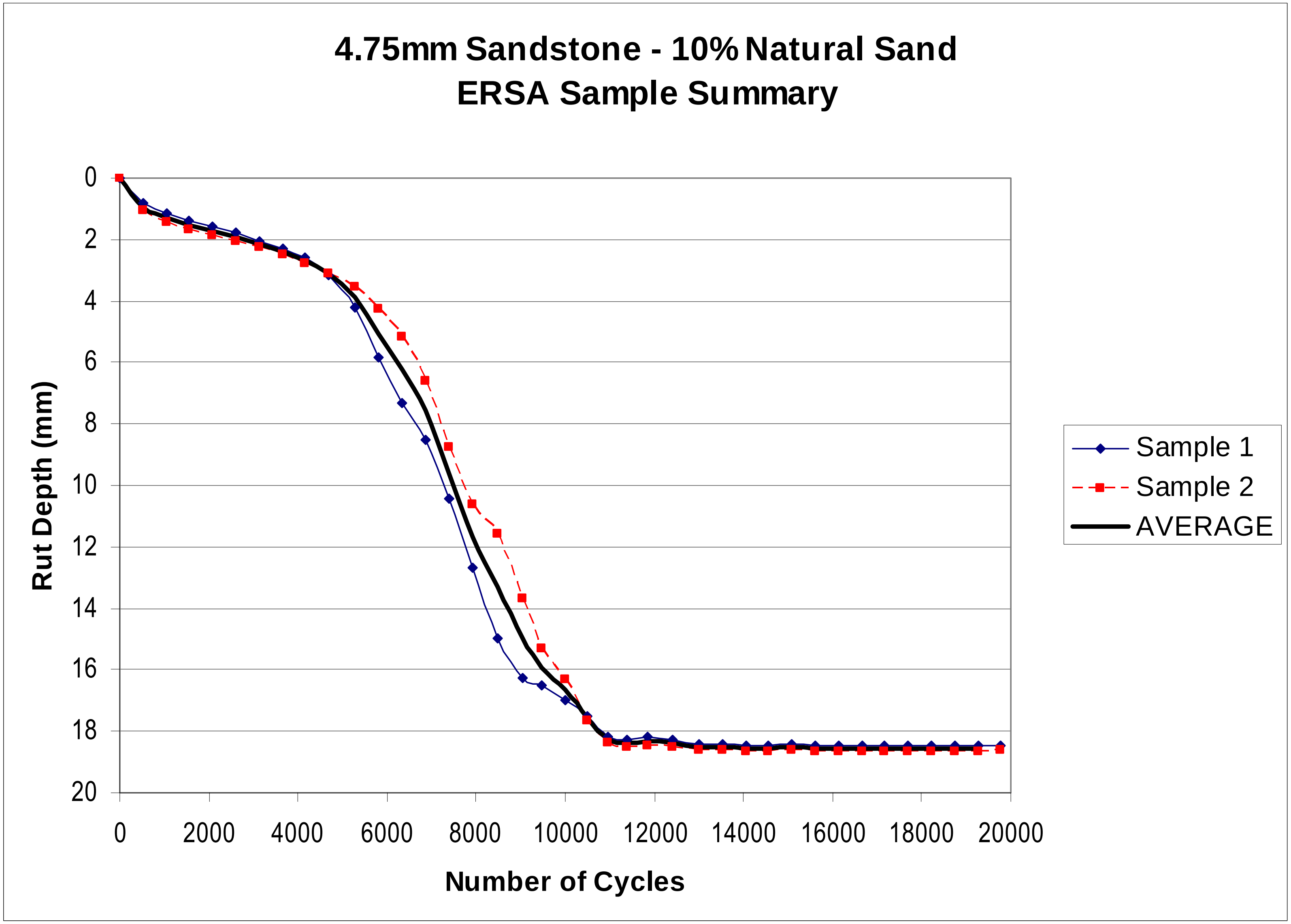

4.75mm Syenite - 4.5% Air - 100 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE

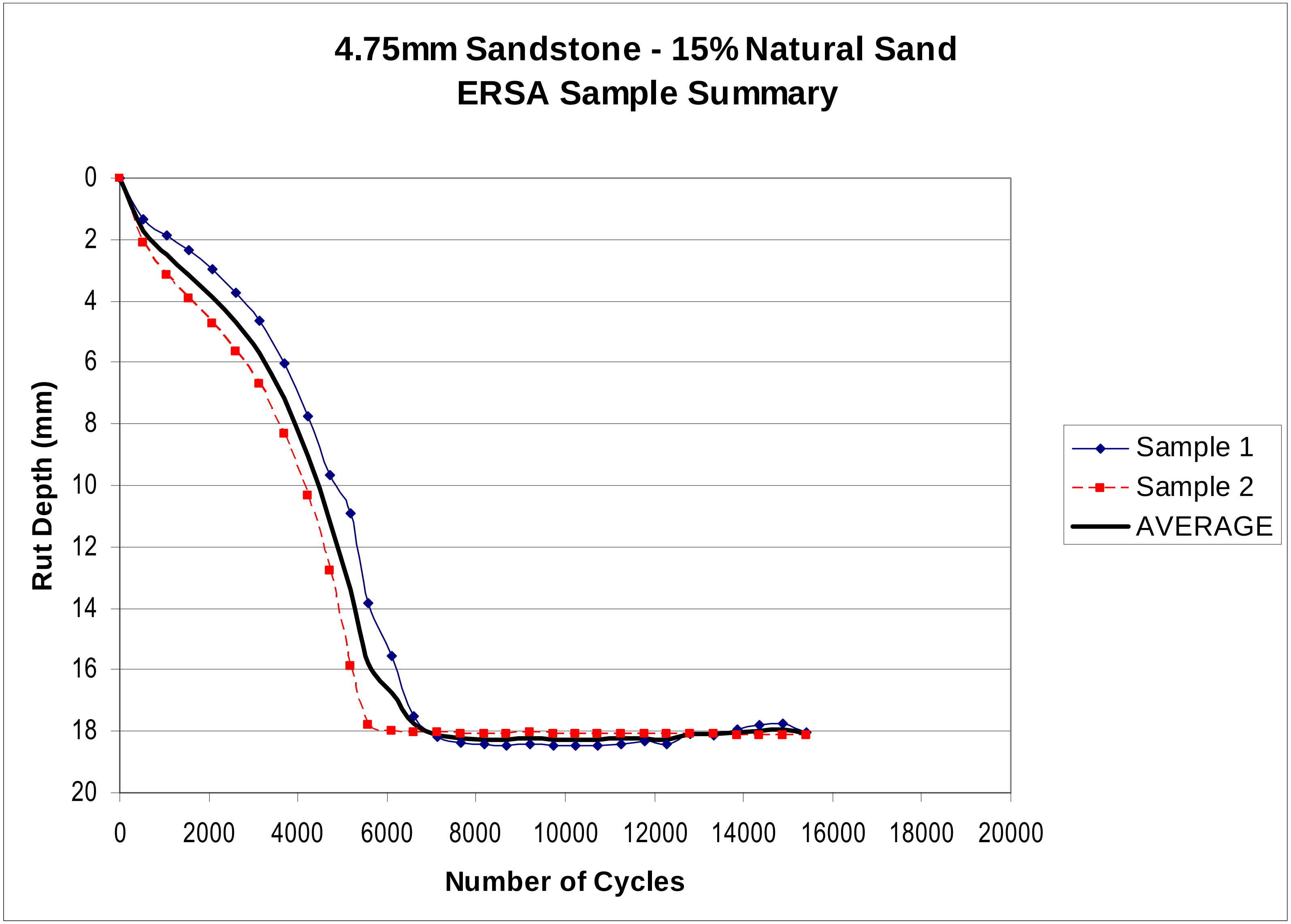


4.75mm Syenite - 6.0% Air - 50 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE


4.75mm Syenite - 6.0% Air - 75 Gyrations
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
AVERAGE

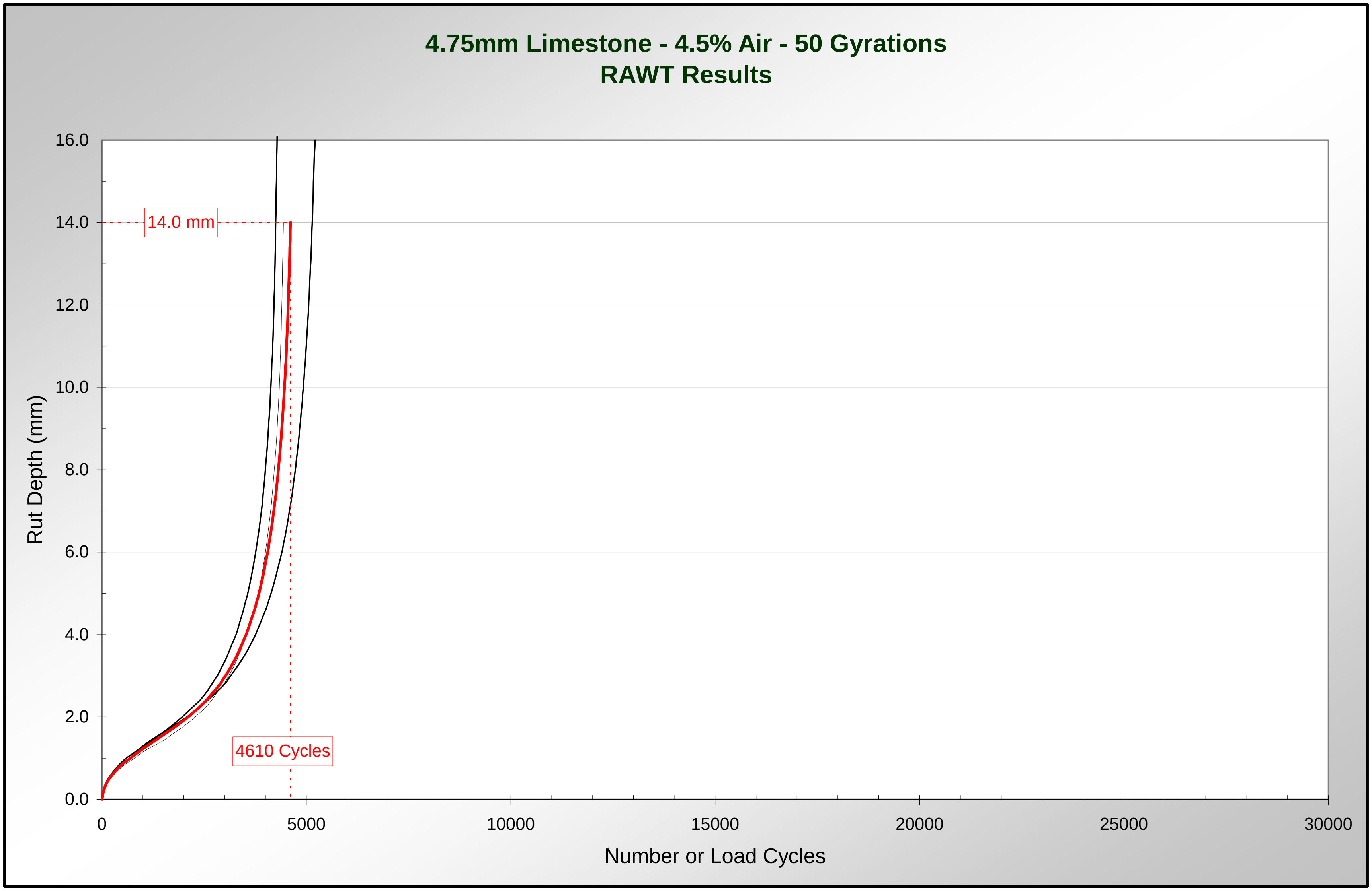

4.75mm Syenite - 6.0% Air - 100 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE

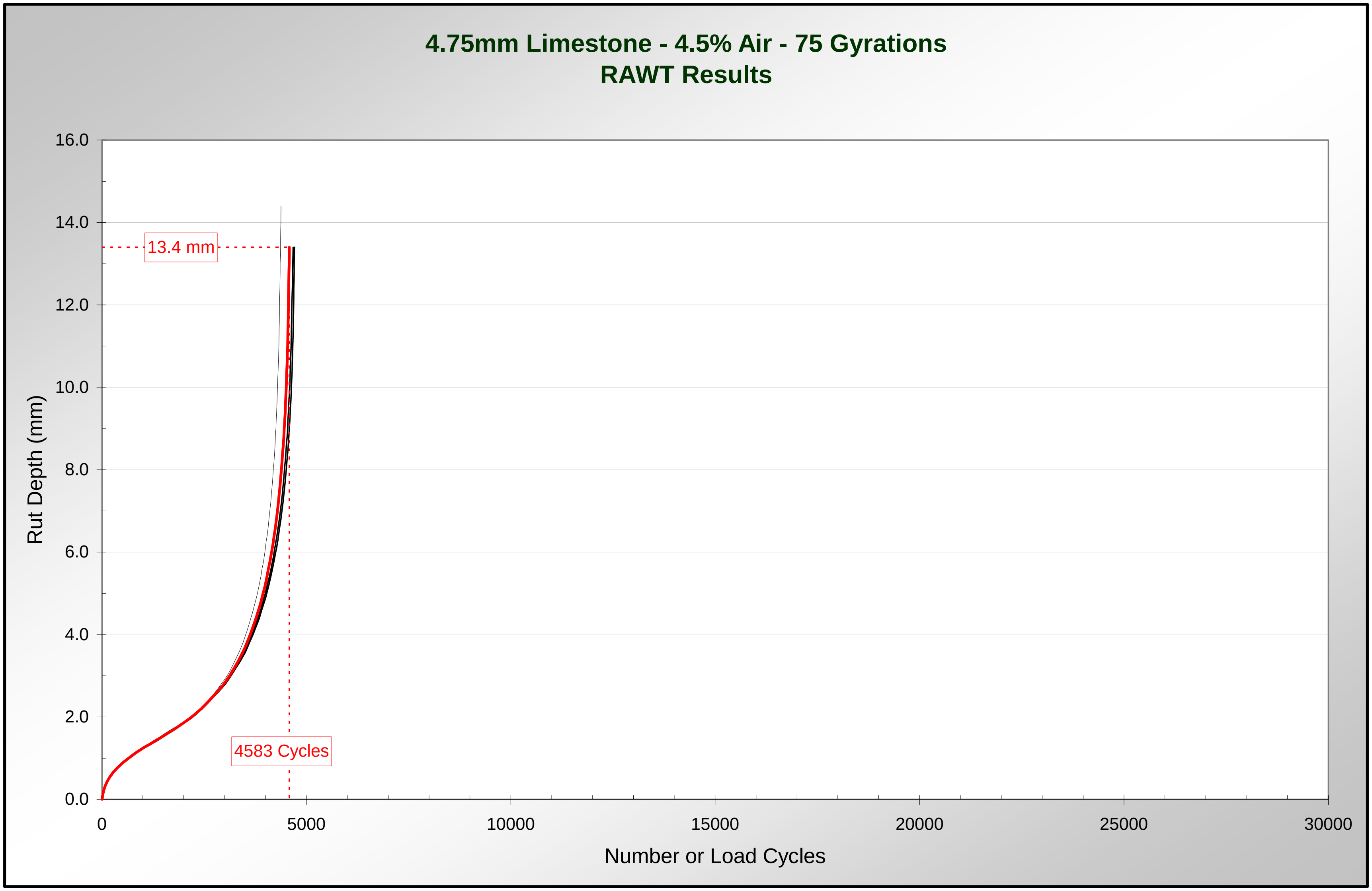

4.75mm Sandstone - 10% Natural Sand
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE

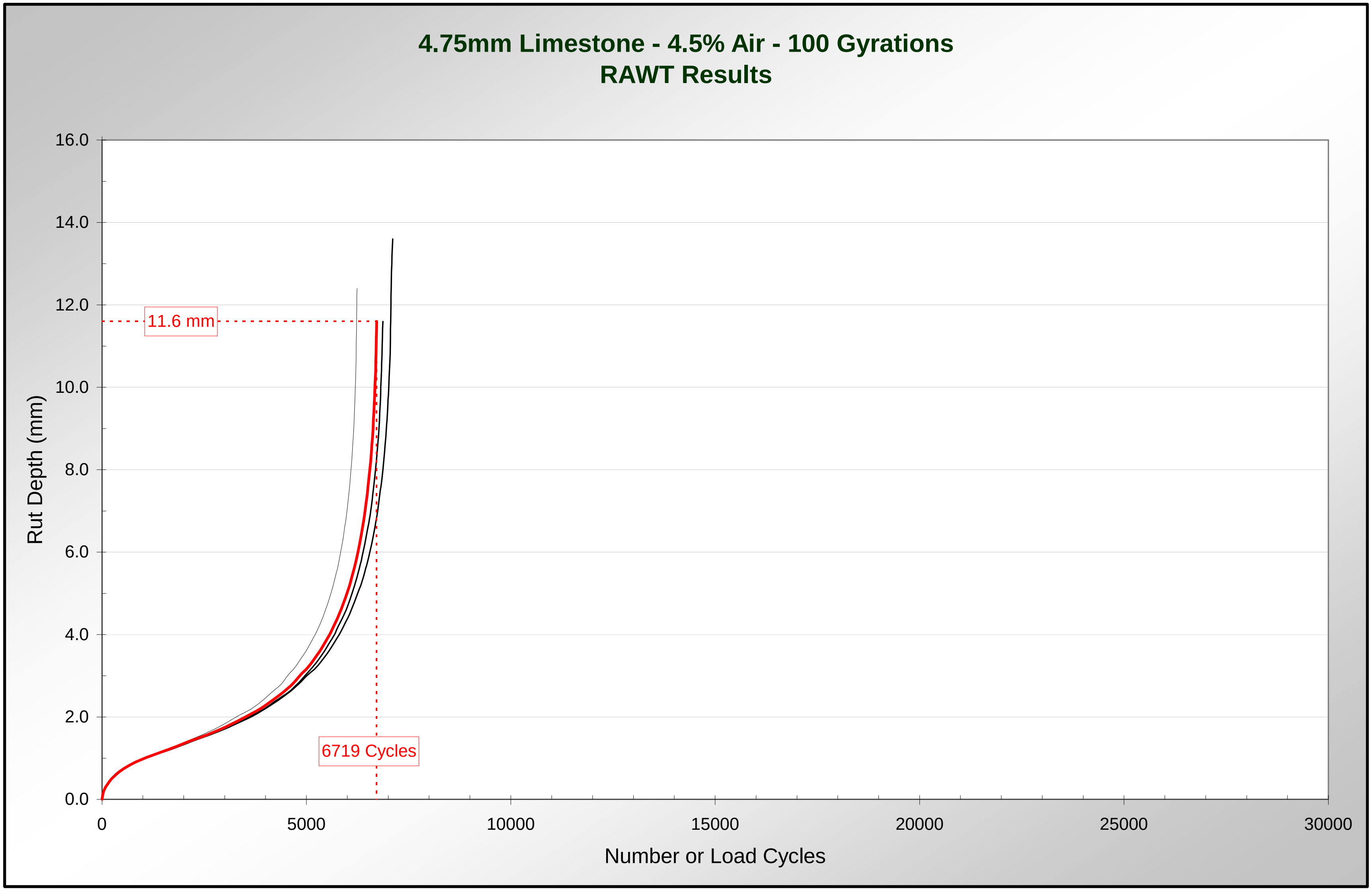

4.75mm Sandstone - 15% Natural Sand
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
AVERAGE

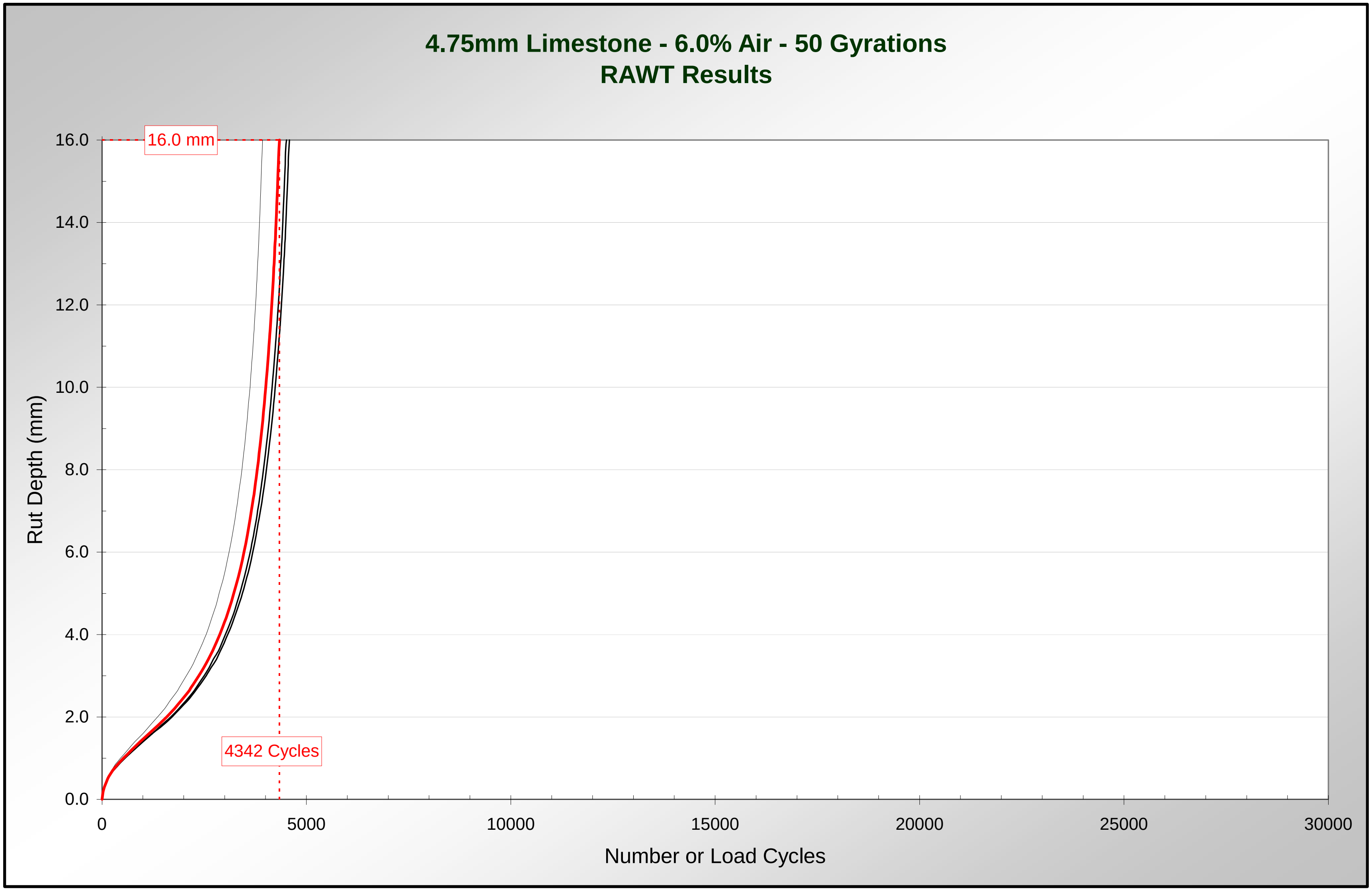
APPENDIX B

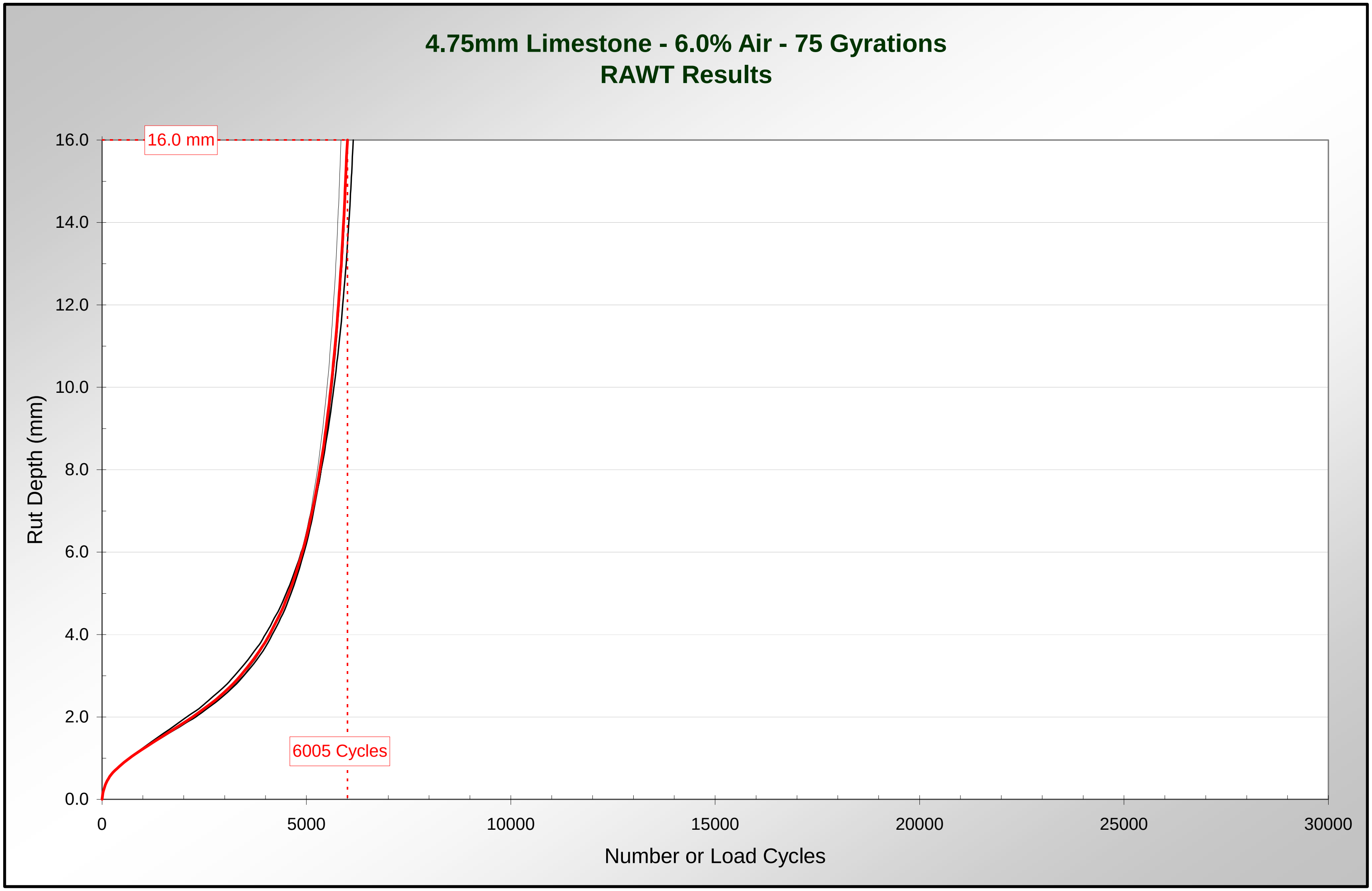
4.75mm RAWT RESULTS

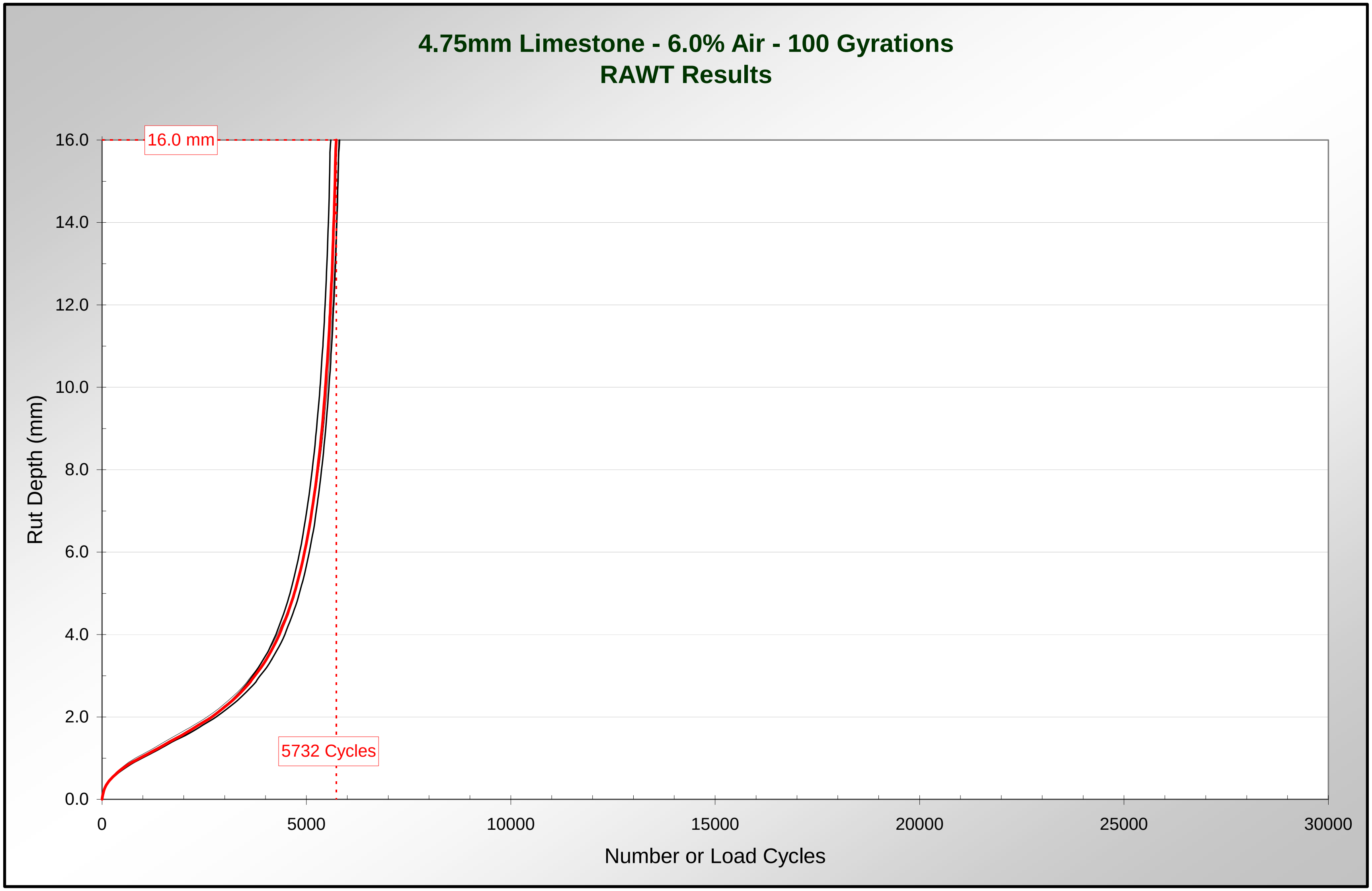

4.75mm Limestone - 4.5% Air - 50 Gyrations
RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
14.0 mm
4610 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

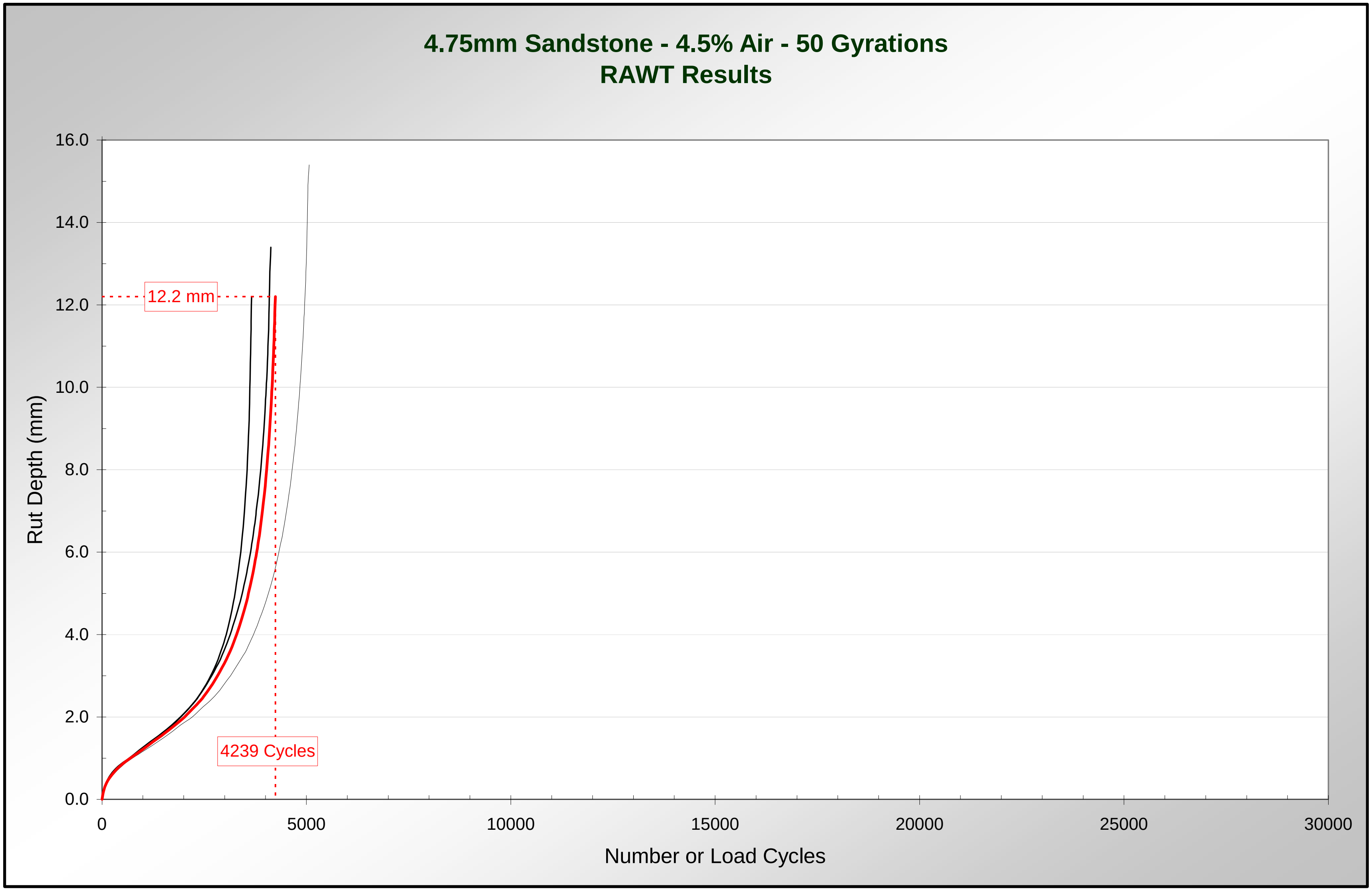

4.75mm Limestone - 4.5% Air - 75 Gyrations
RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
13.4 mm
4583 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

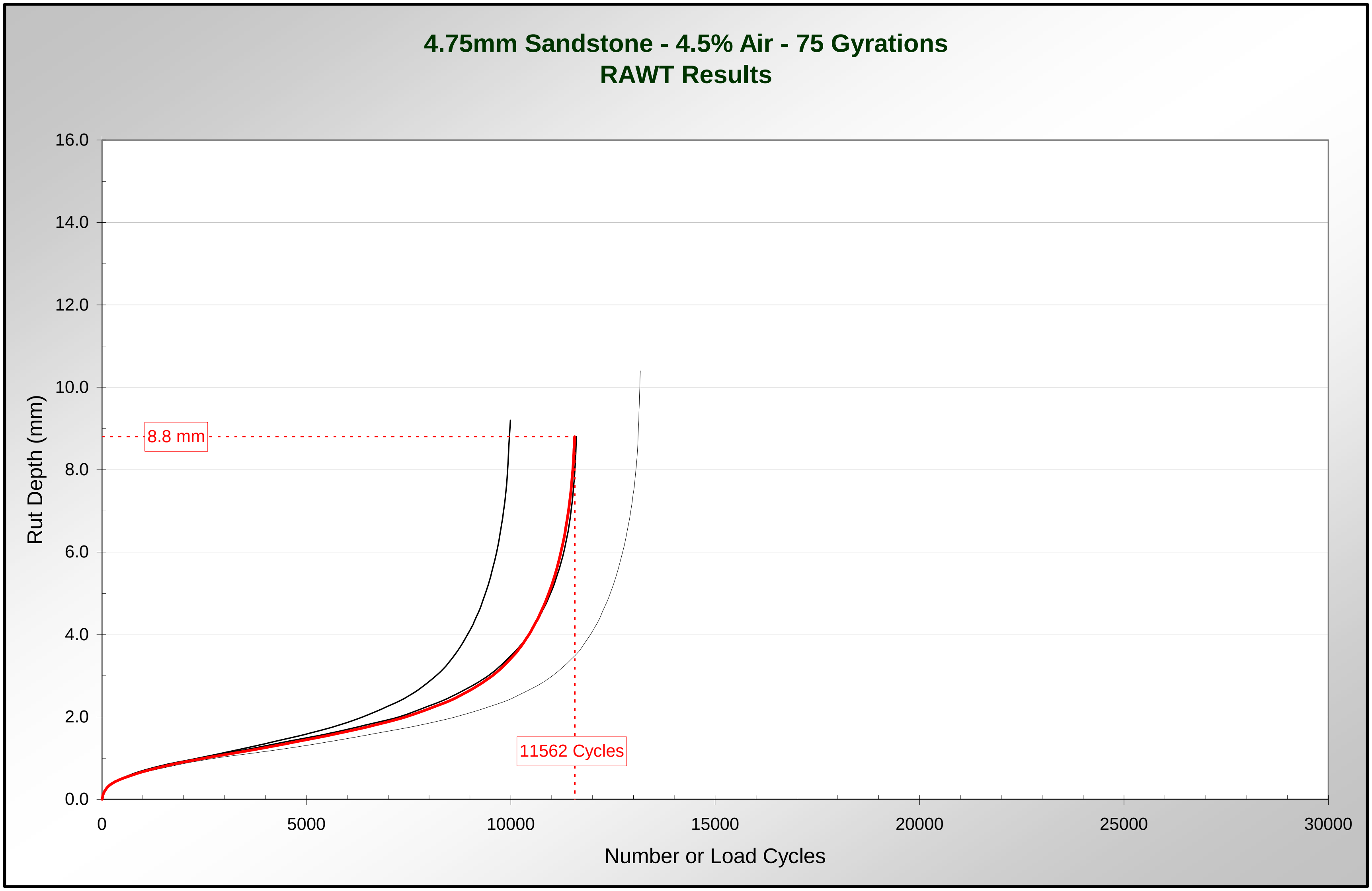

4.75mm Limestone - 4.5% Air - 100 Gyrations
RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
11.6 mm
6719 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles


4.75mm Limestone - 6.0% Air - 50 Gyrations
RAWT Results
16.0 mm
4342 Cycles
Rut Depth (mm)
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
Number or Load Cycles

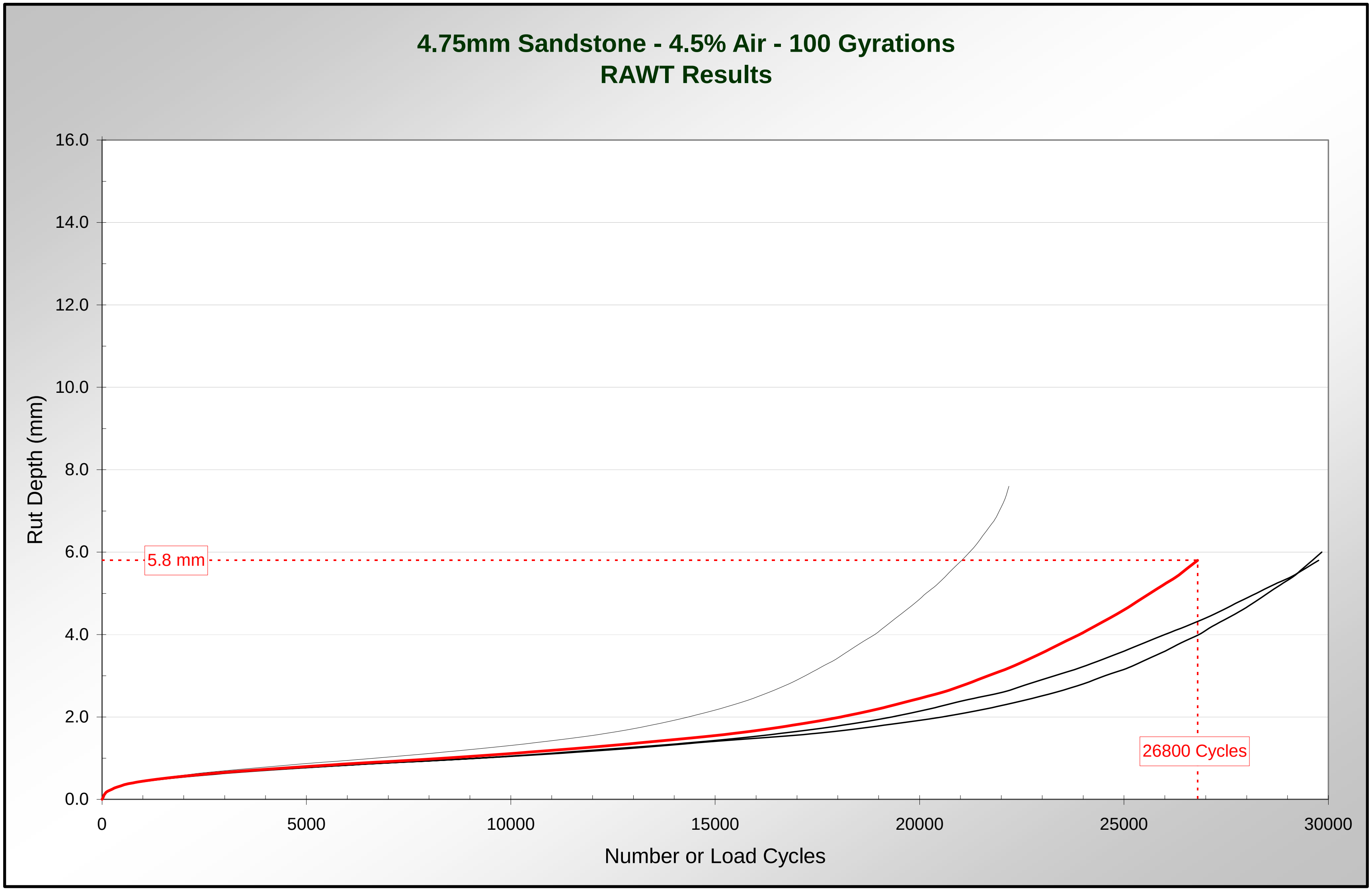

4.75mm Limestone - 6.0% Air - 75 Gyrations
RAWT Results
16.0 mm
6005 Cycles
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

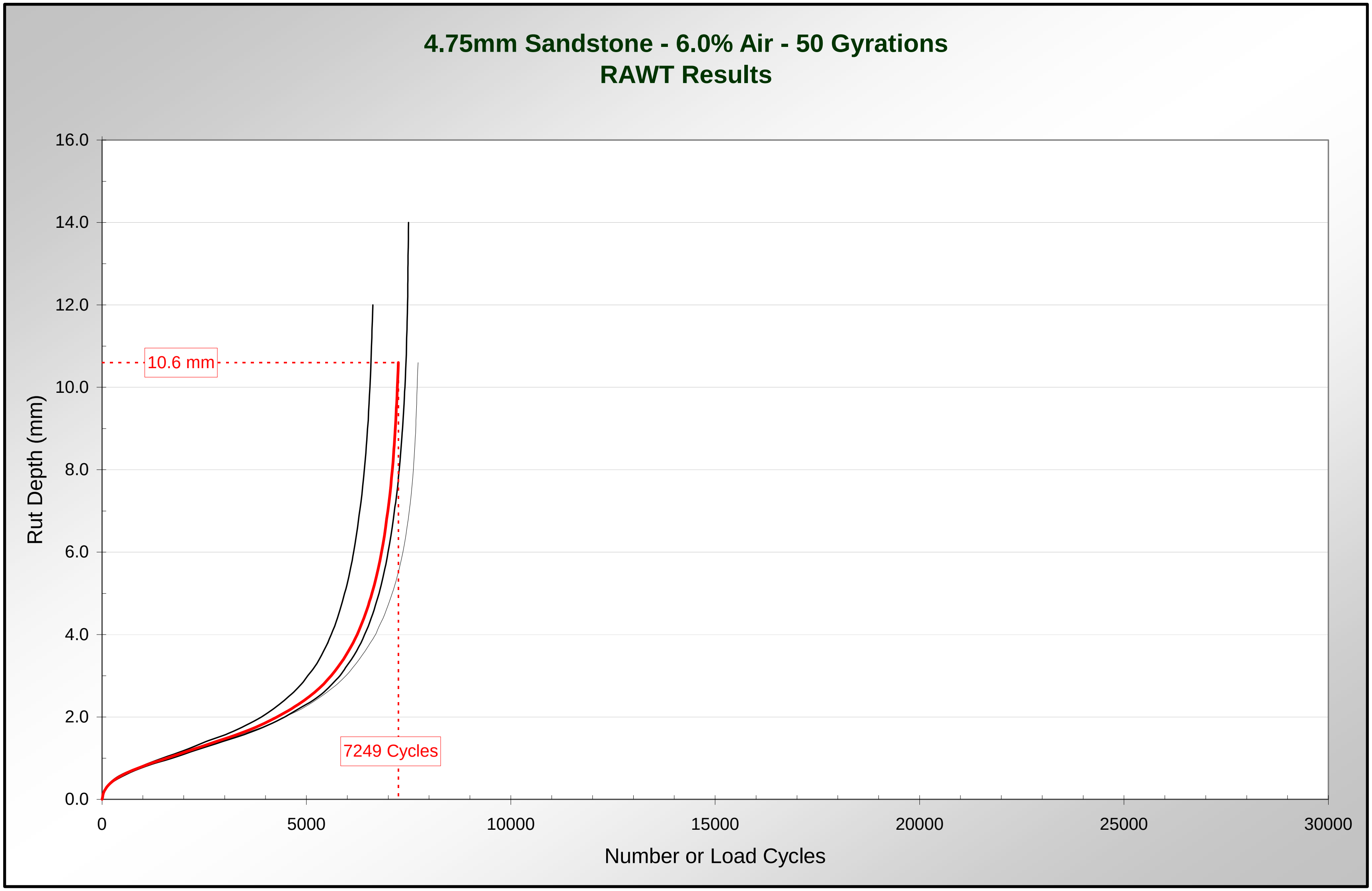

4.75mm Limestone - 6.0% Air - 100 Gyrations
RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
16.0 mm
5732 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

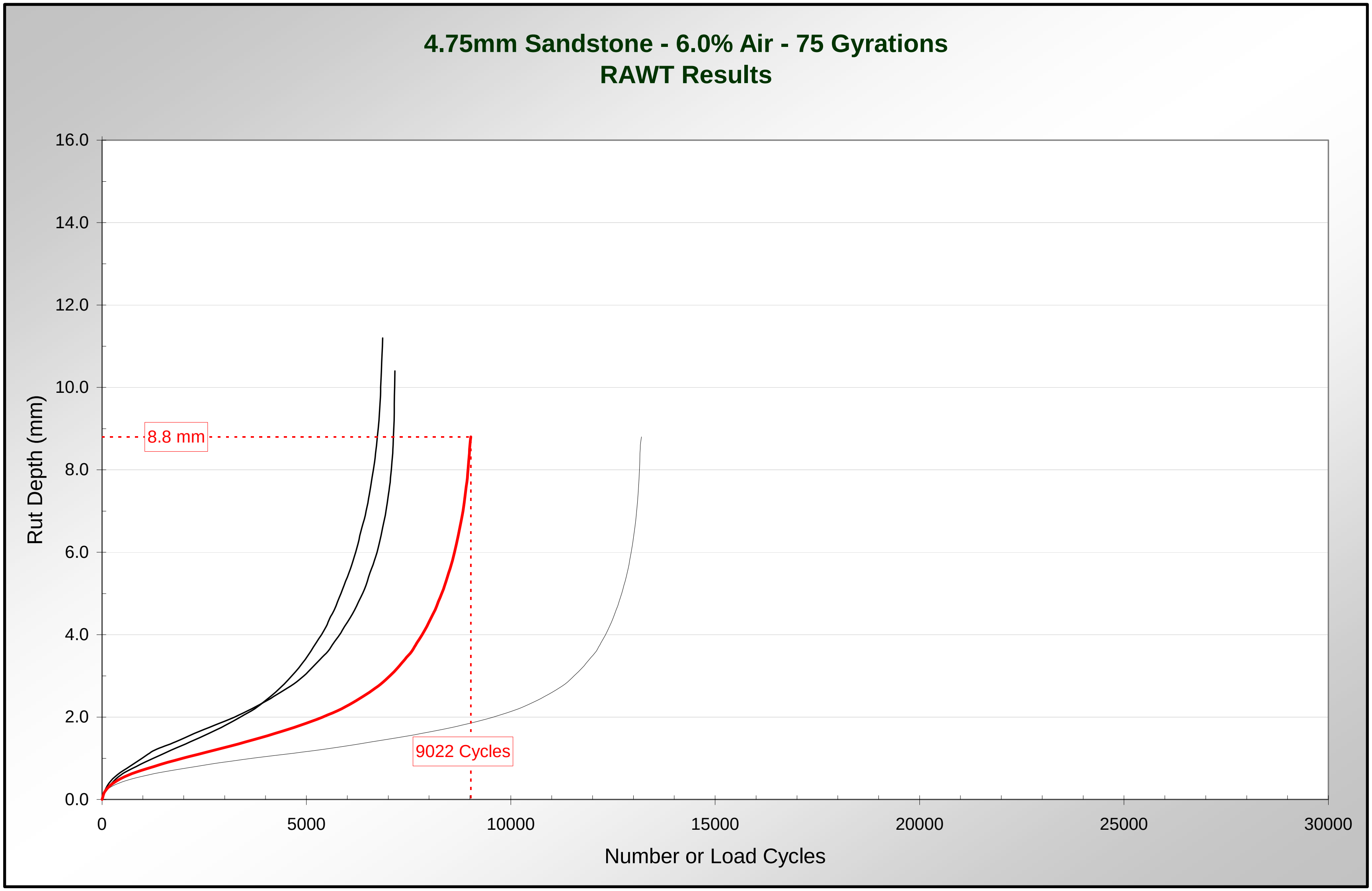

4.75mm Sandstone - 4.5% Air - 50 Gyrations
RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
12.2 mm
4239 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

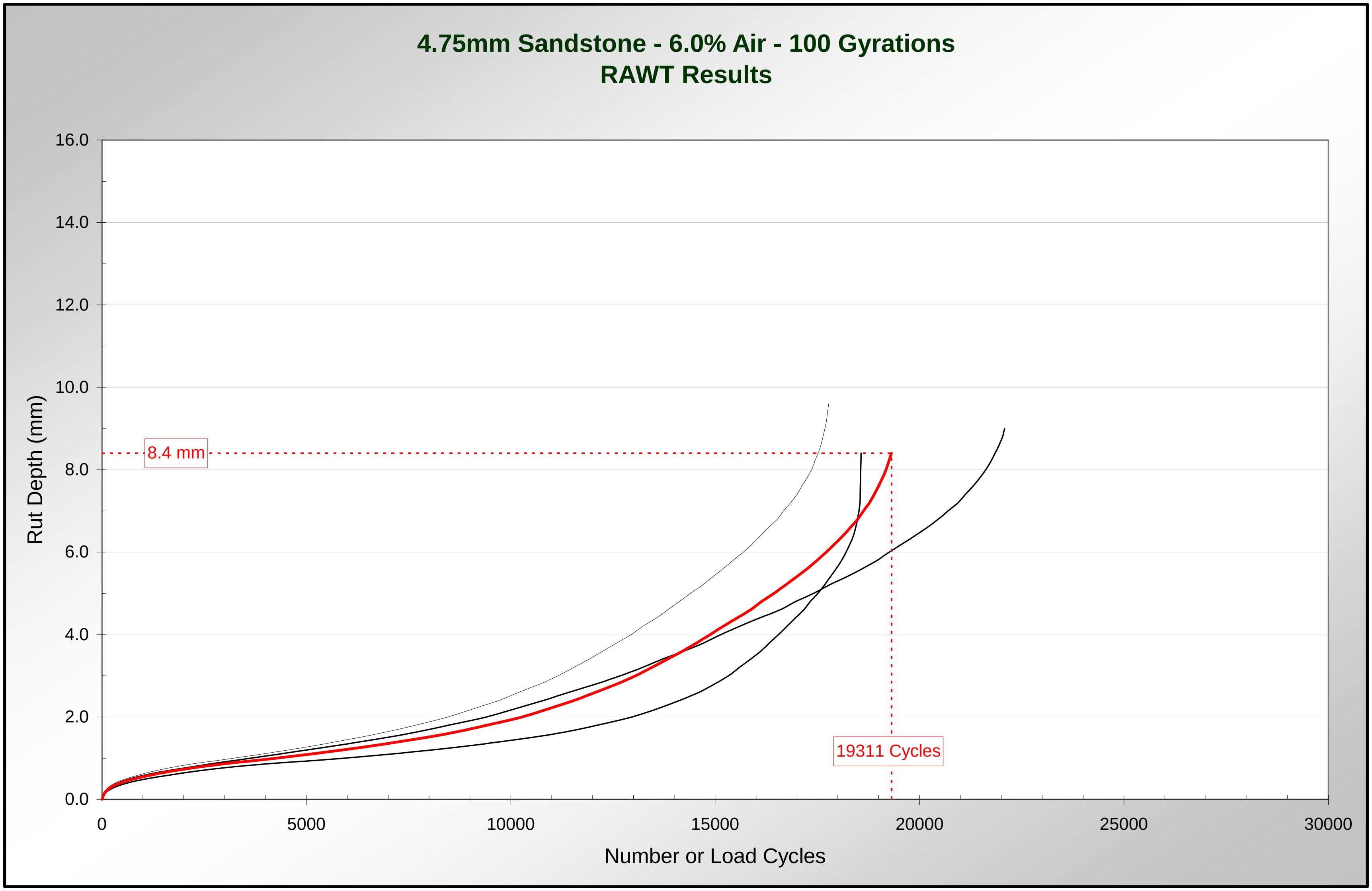


4.75mm Sandstone - 4.5% Air - 75 Gyrations
RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
8.8 mm
11562 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

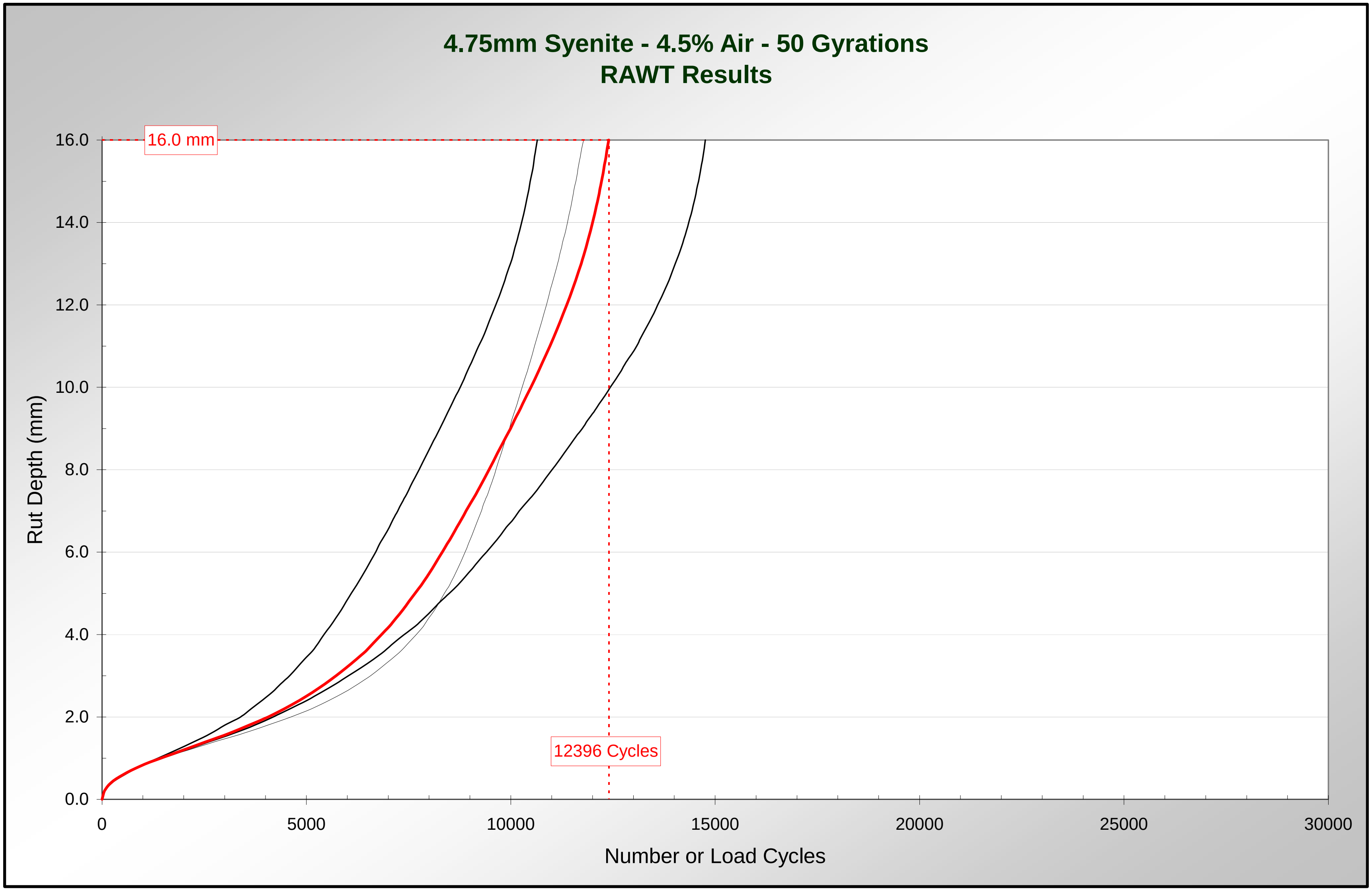

4.75mm Sandstone - 4.5% Air - 100 Gyrations
RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles
5.8 mm
26800 Cycles

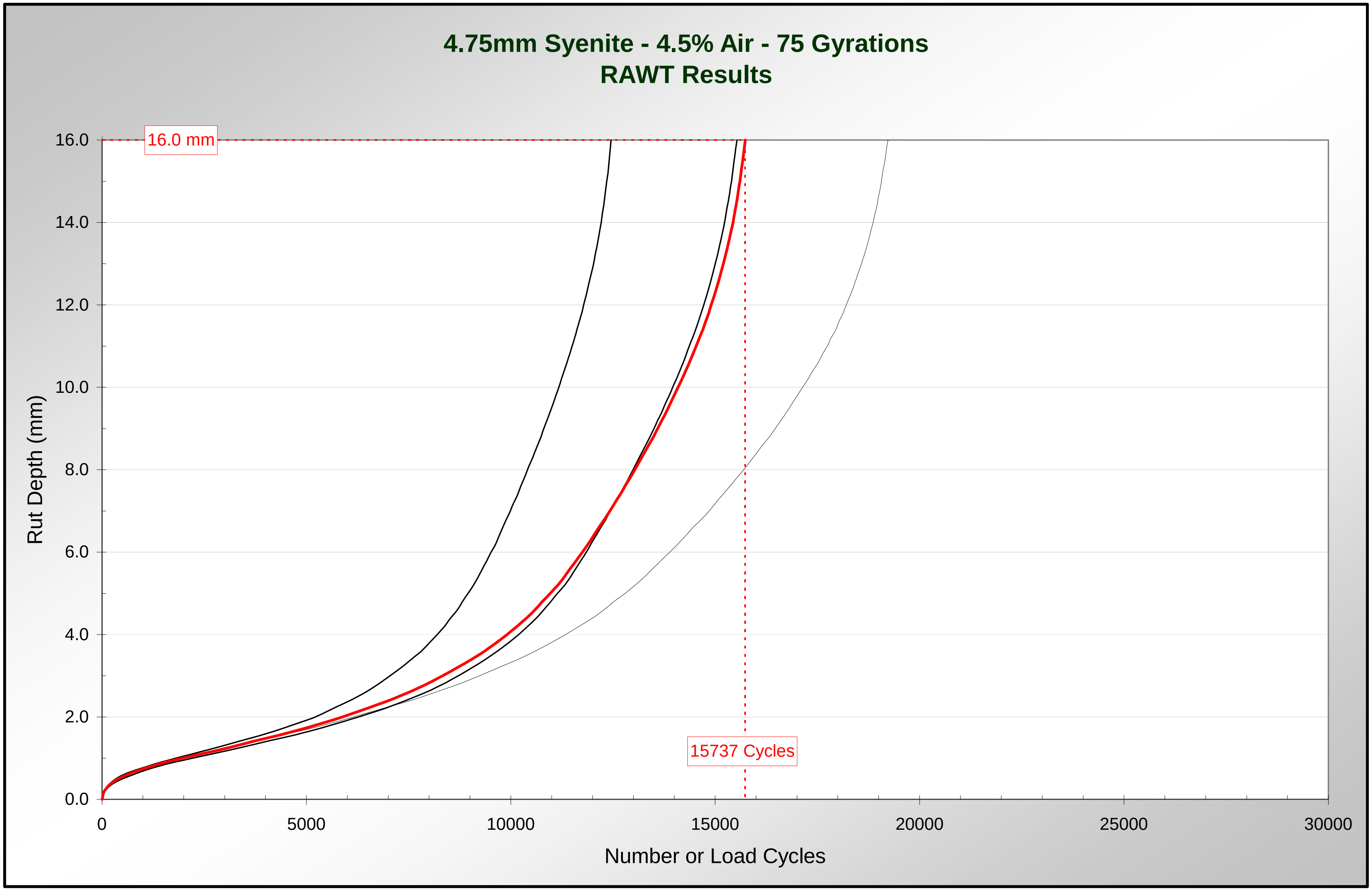

4.75mm Sandstone - 6.0% Air - 50 Gyrations
RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
10.6 mm
7249 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles


4.75mm Sandstone - 6.0% Air - 75 Gyrations
RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
8.8 mm
9022 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

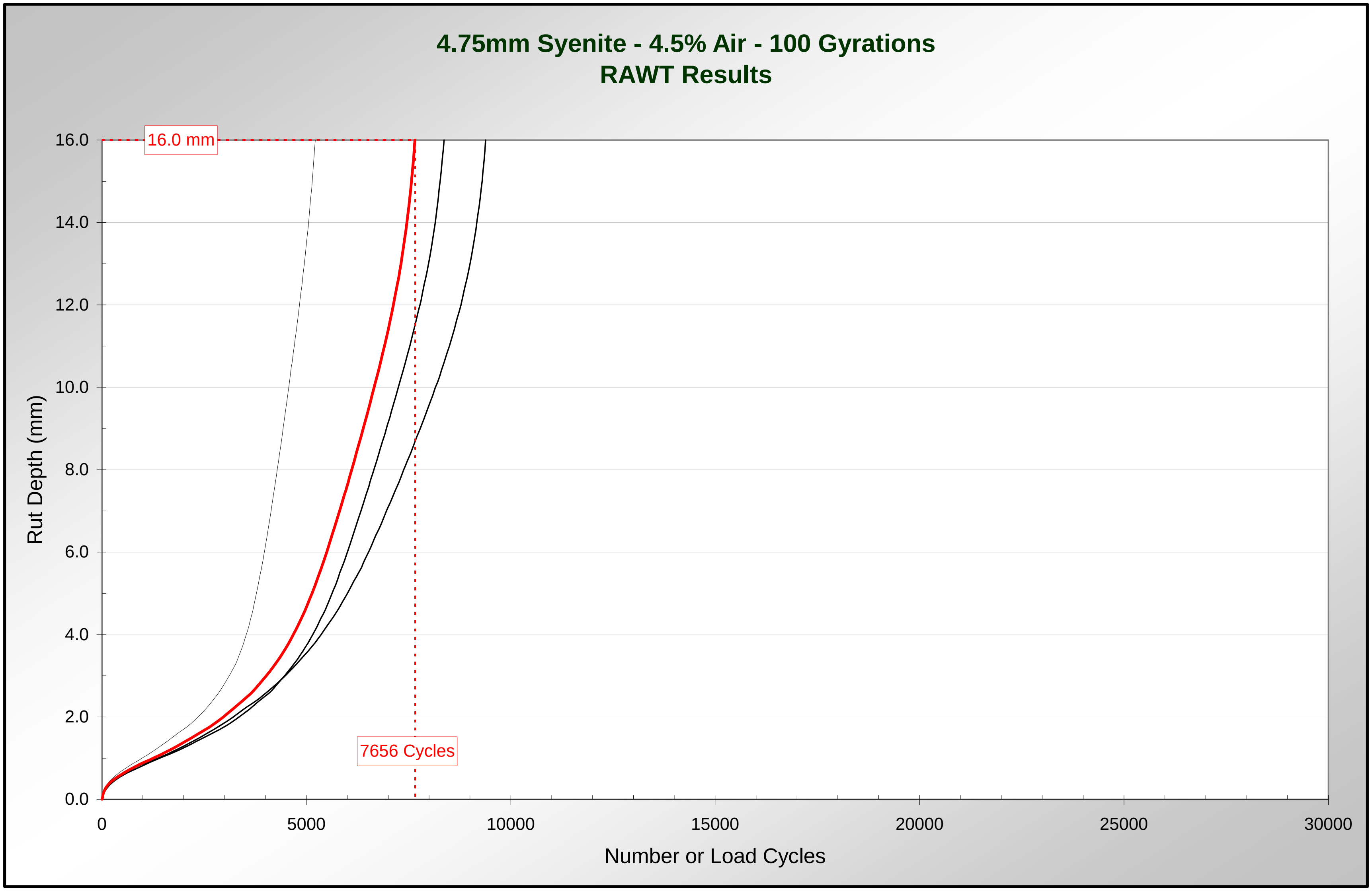


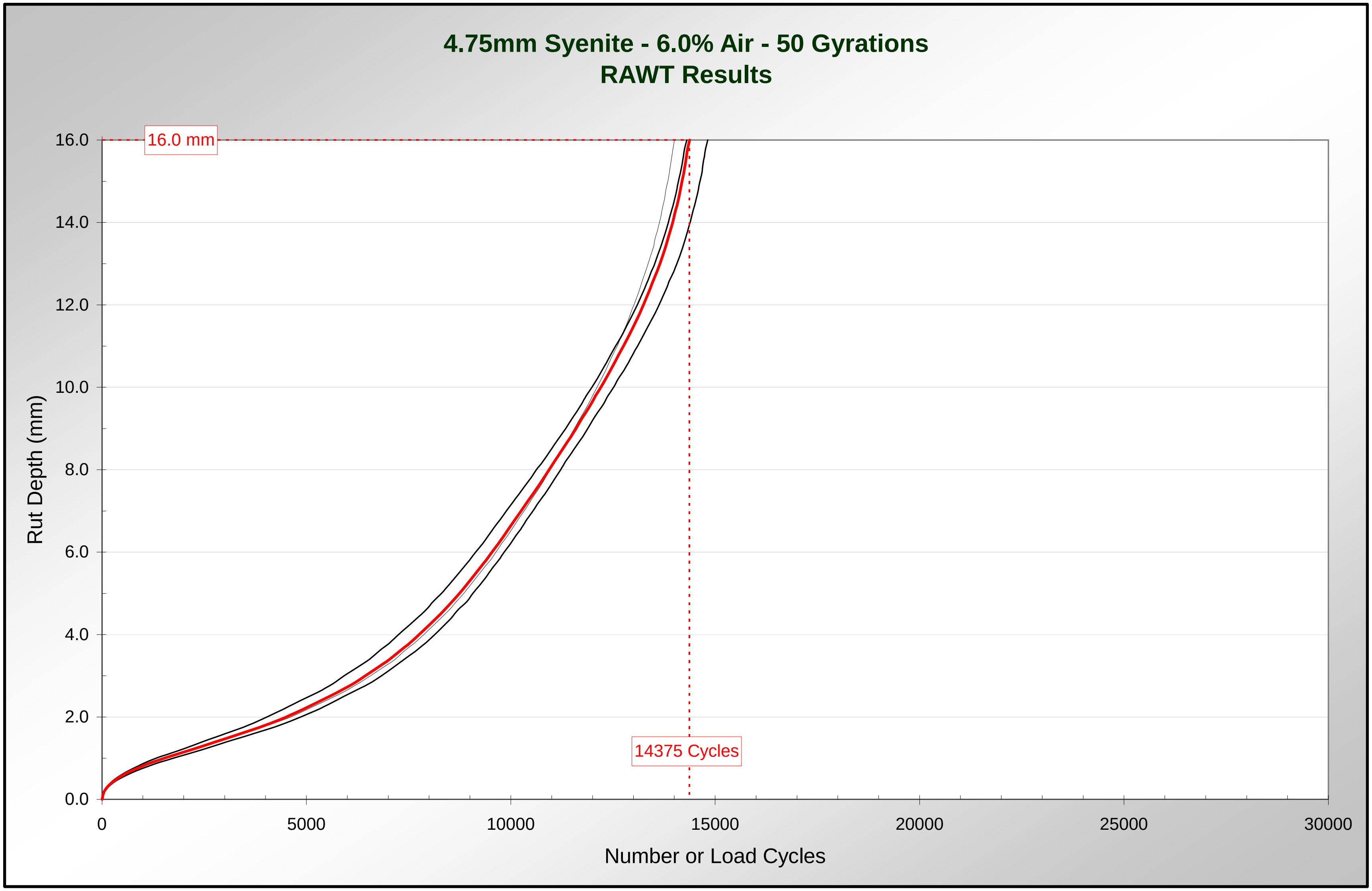
4.75mm Sandstone - 6.0% Air - 100 Gyrations
RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
8.4 mm
19311 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

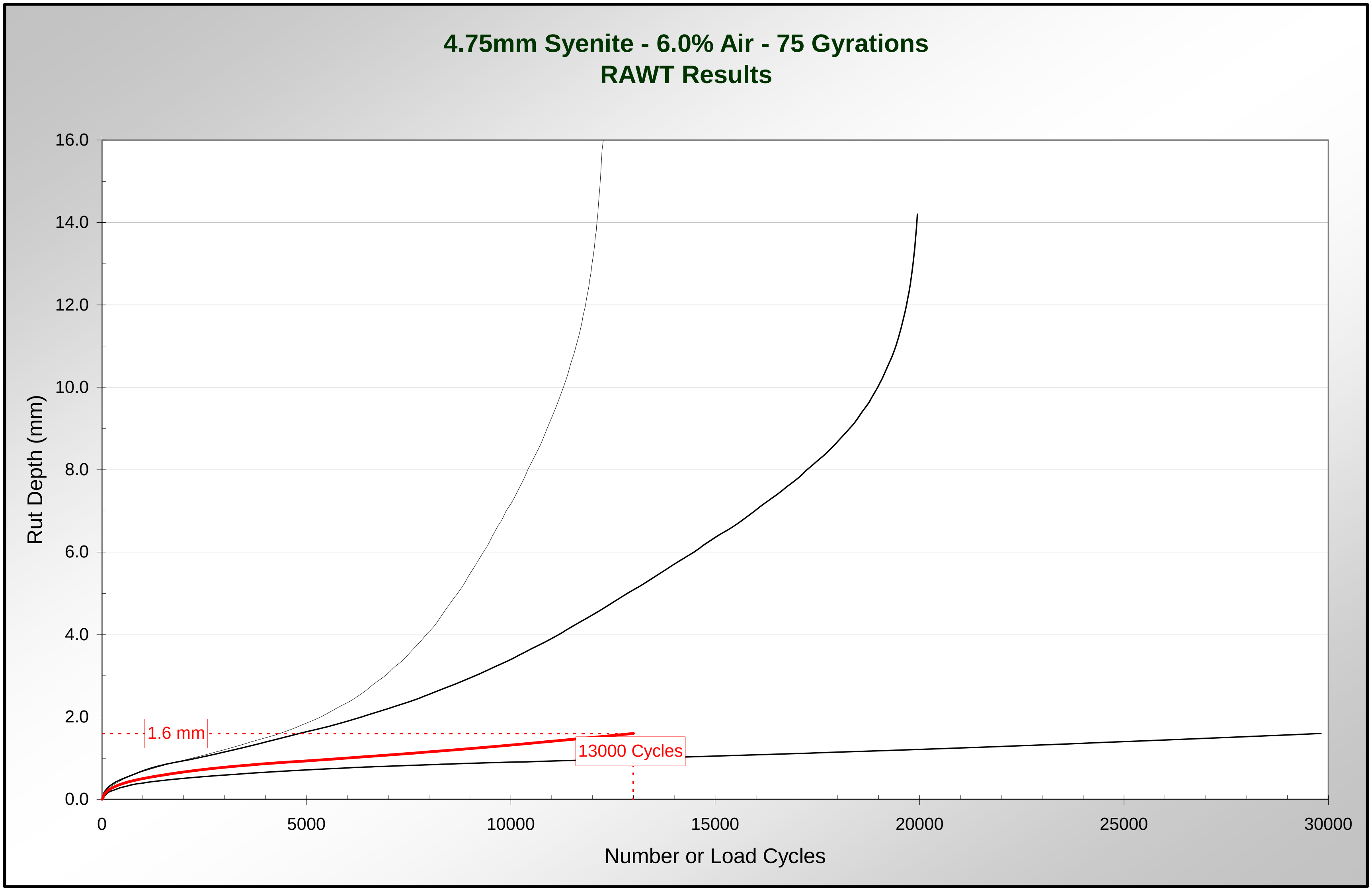

4.75mm Syenite - 4.5% Air - 50 Gyrations
RAWT Results
16.0 mm
12396 Cycles
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

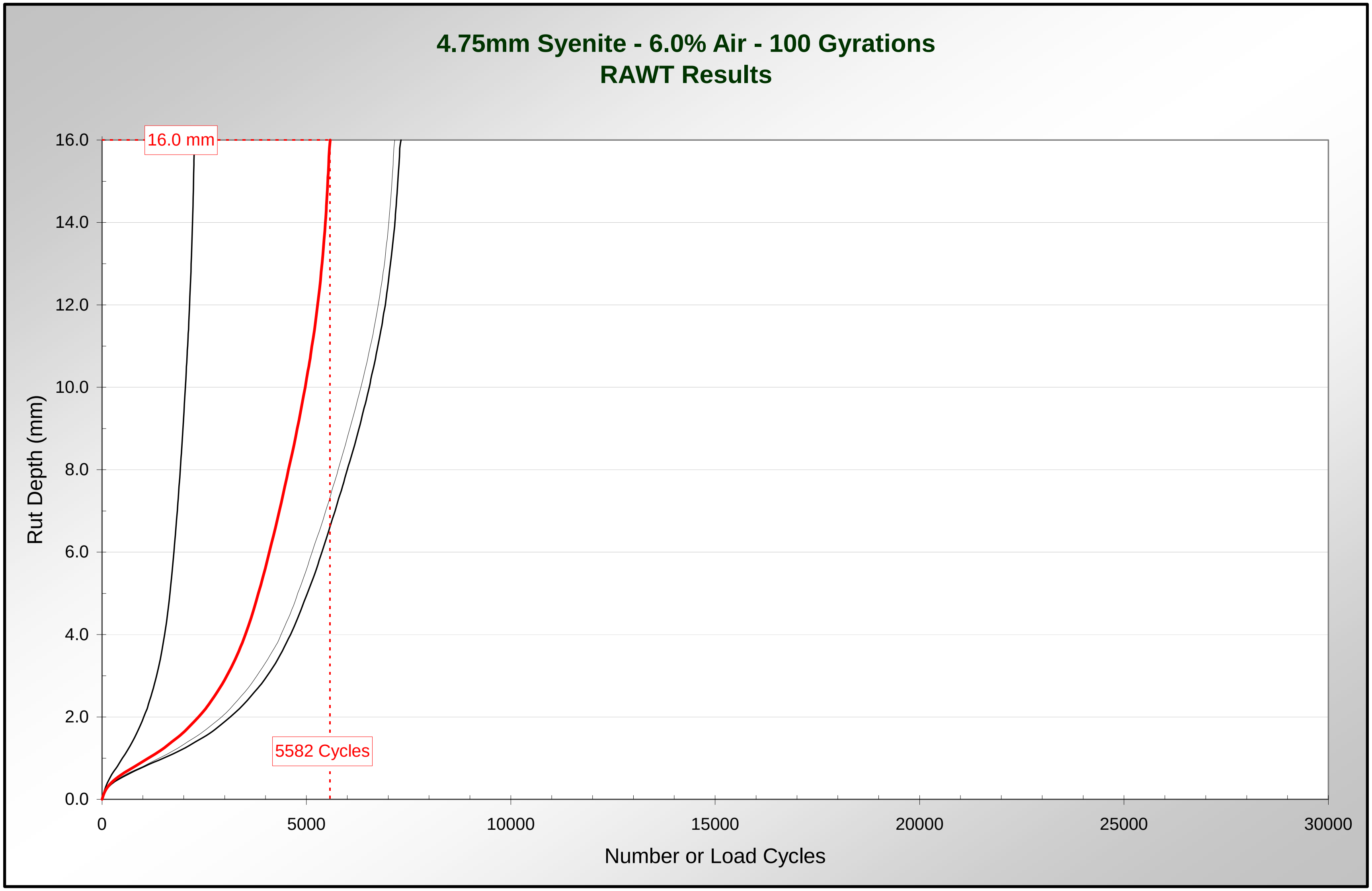


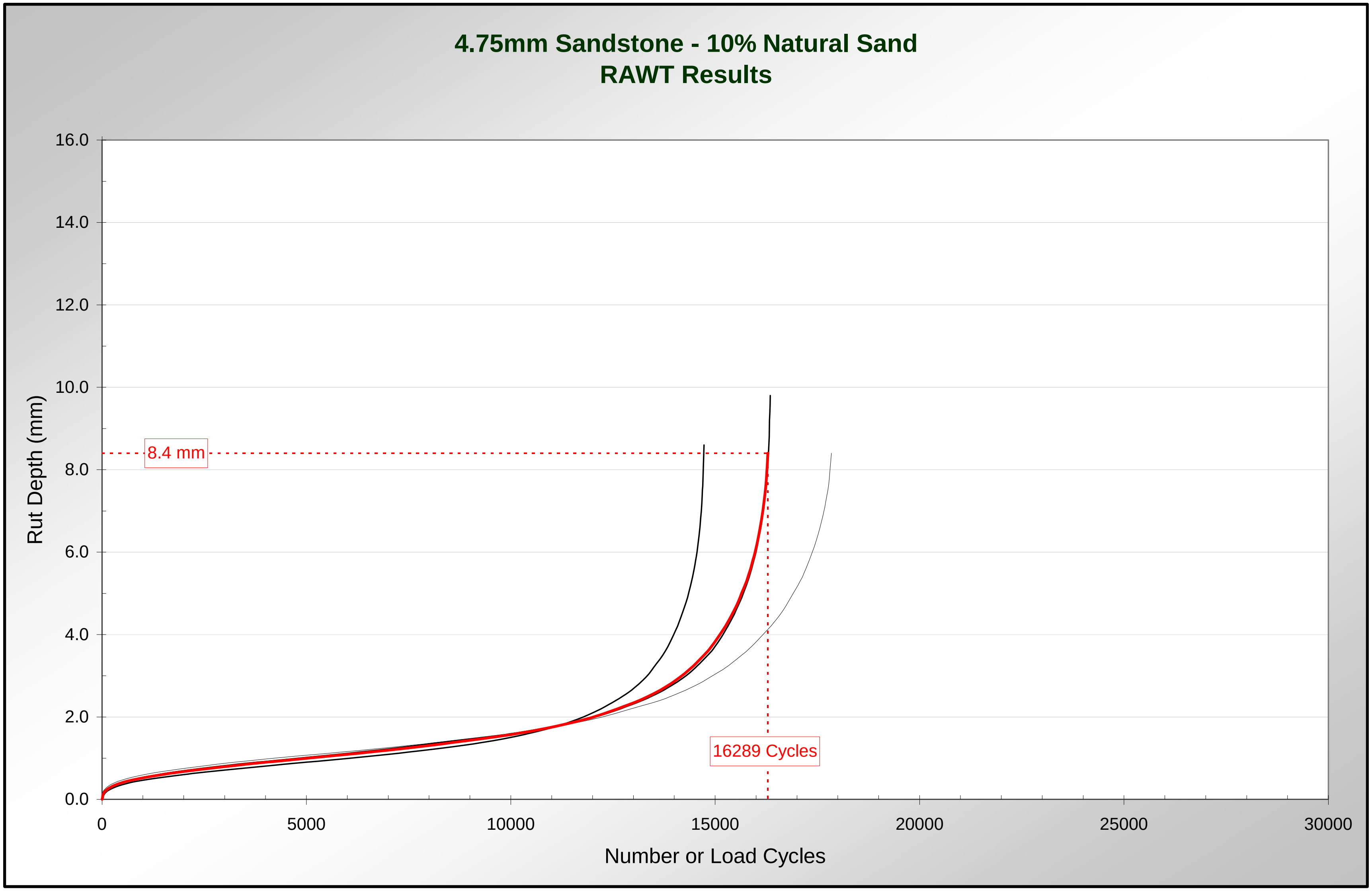
4.75mm Syenite - 4.5% Air - 75 Gyrations
RAWT Results
16.0 mm
15737 Cycles
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

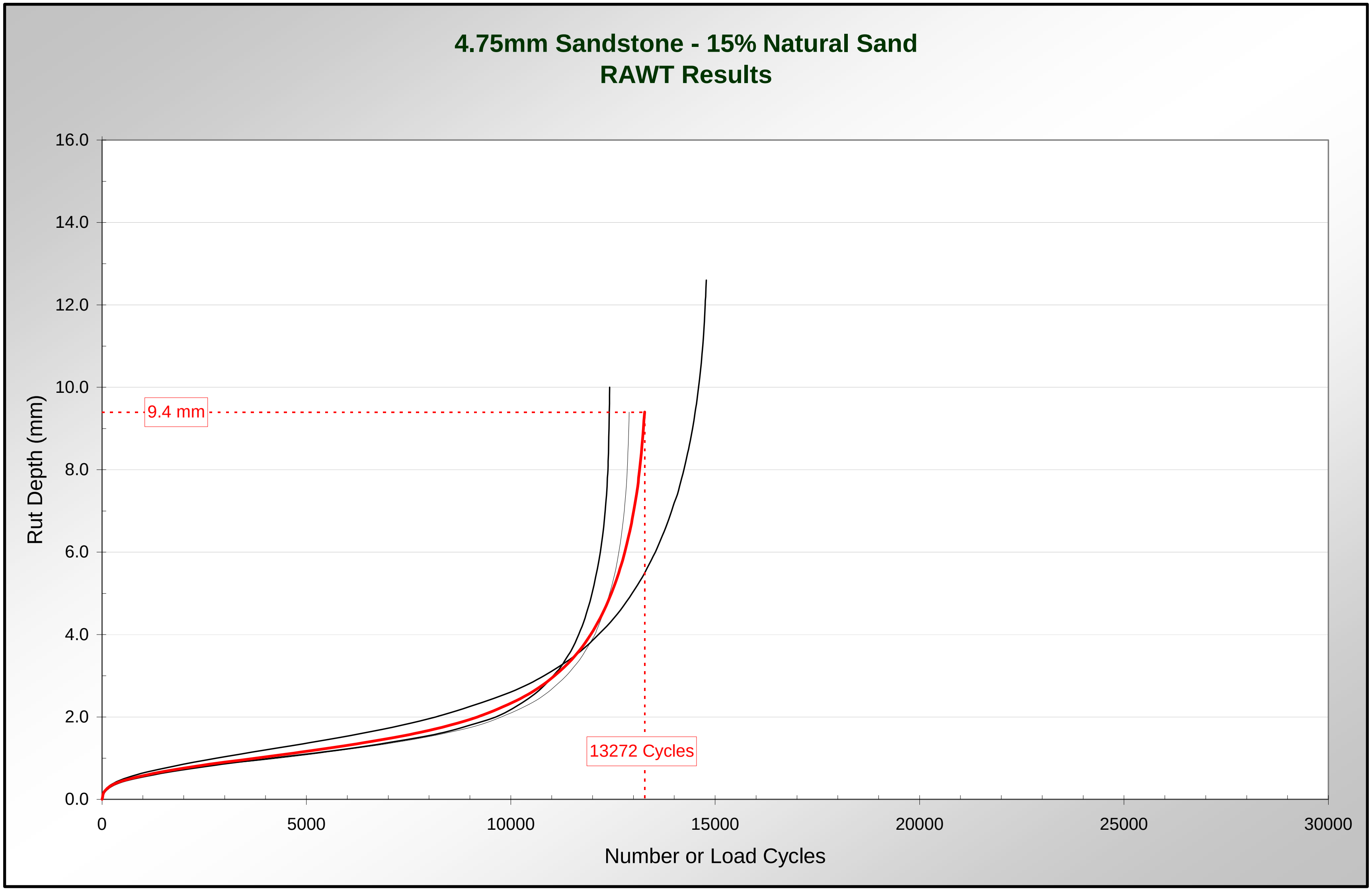

4.75mm Syenite - 4.5% Air - 100 Gyrations
RAWT Results
16.0 mm
7656 Cycles
Rut Depth (mm)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles


4.75mm Syenite - 6.0% Air - 50 Gyrations
RAWT Results
16.0 mm
14375 Cycles
Rut Depth (mm)
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
Number or Load Cycles


4.75mm Syenite - 6.0% Air - 75 Gyrations
RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1.6 mm
13000 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

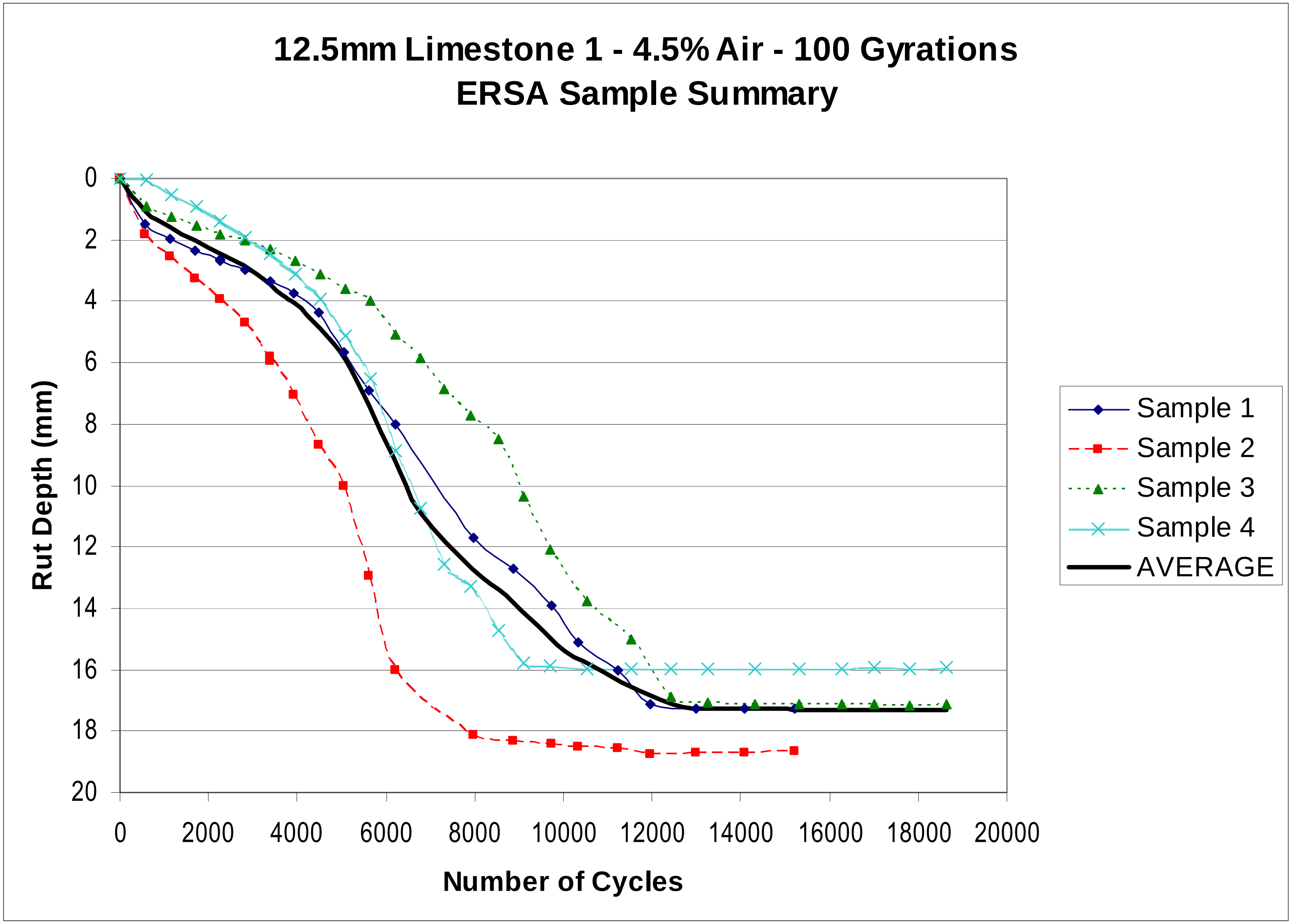

4.75mm Syenite - 6.0% Air - 100 Gyrations
RAWT Results
16.0 mm
5582 Cycles
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

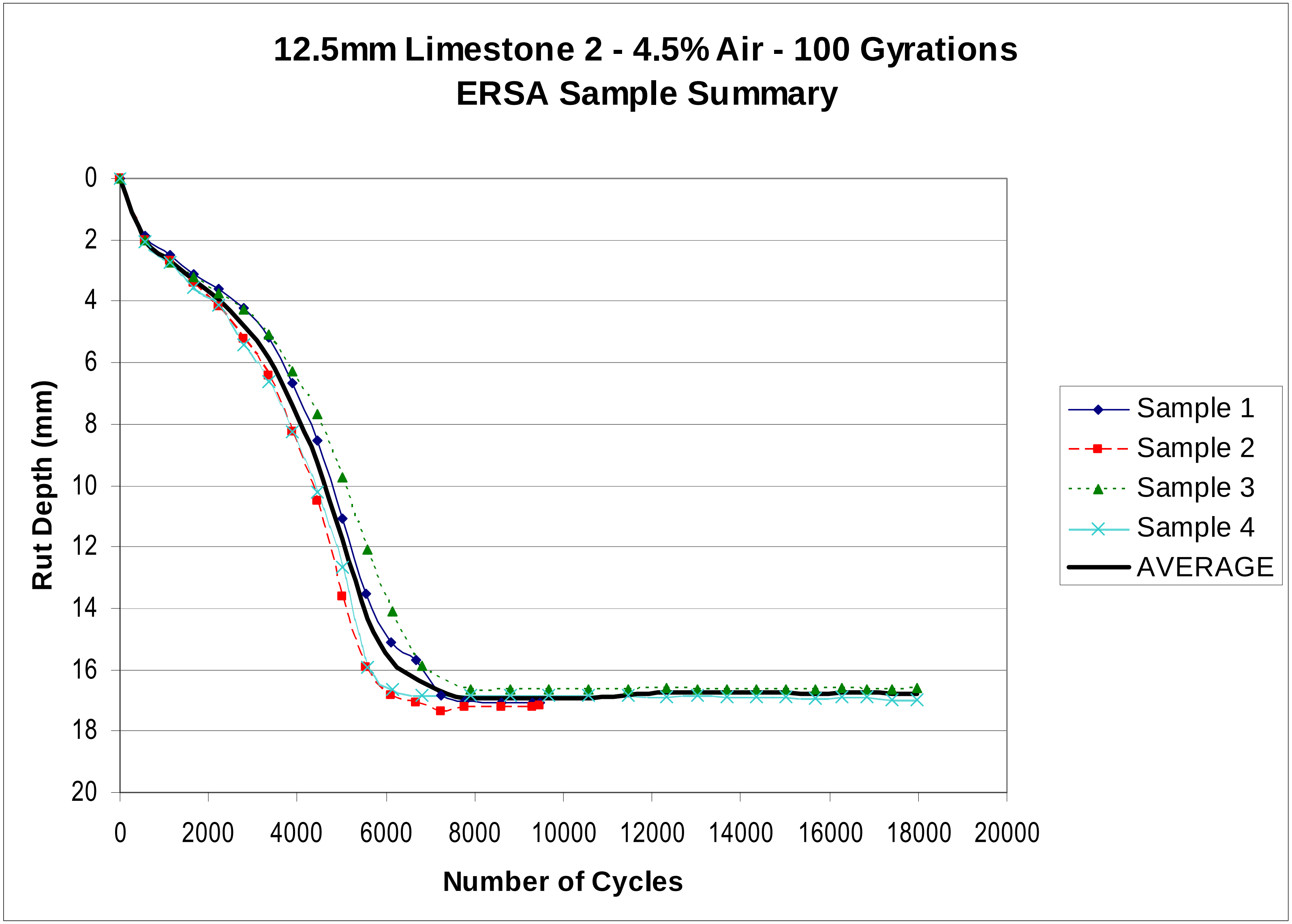

4.75mm Sandstone - 10% Natural Sand
RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
8.4 mm
16289 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles


4.75mm Sandstone - 15% Natural Sand
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
13272 Cycles
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles

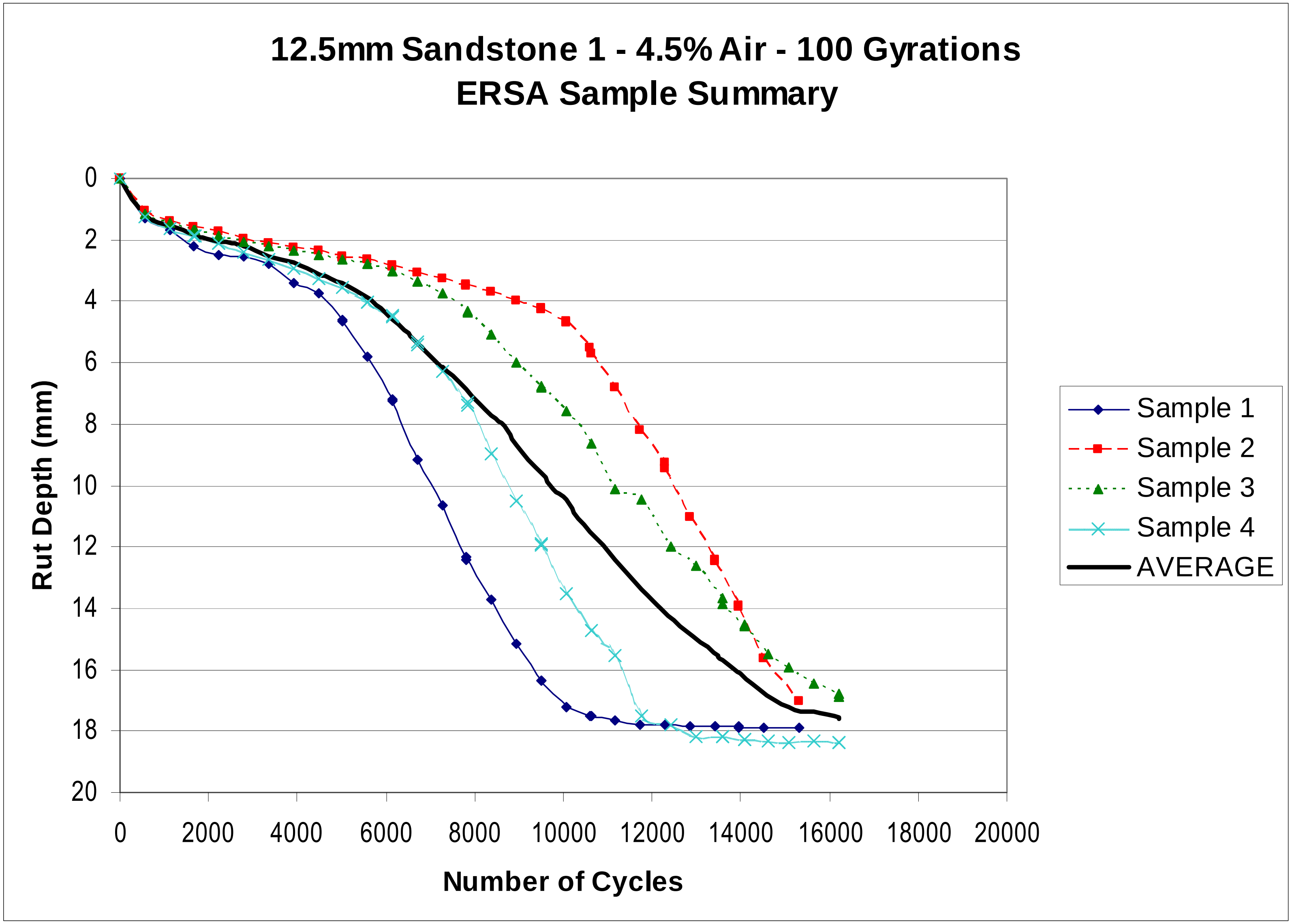
APPENDIX C

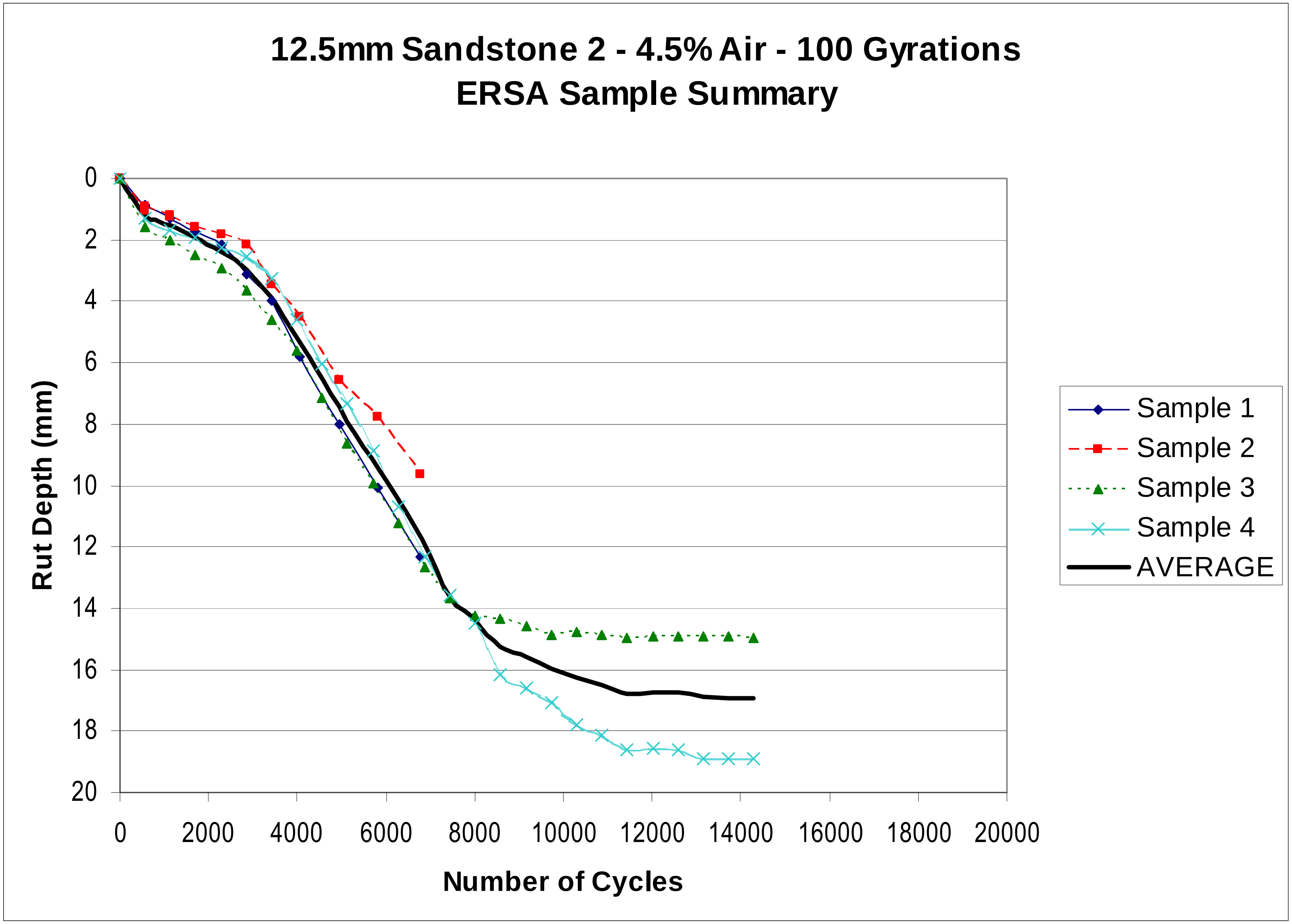
12.5mm ERSA RESULTS

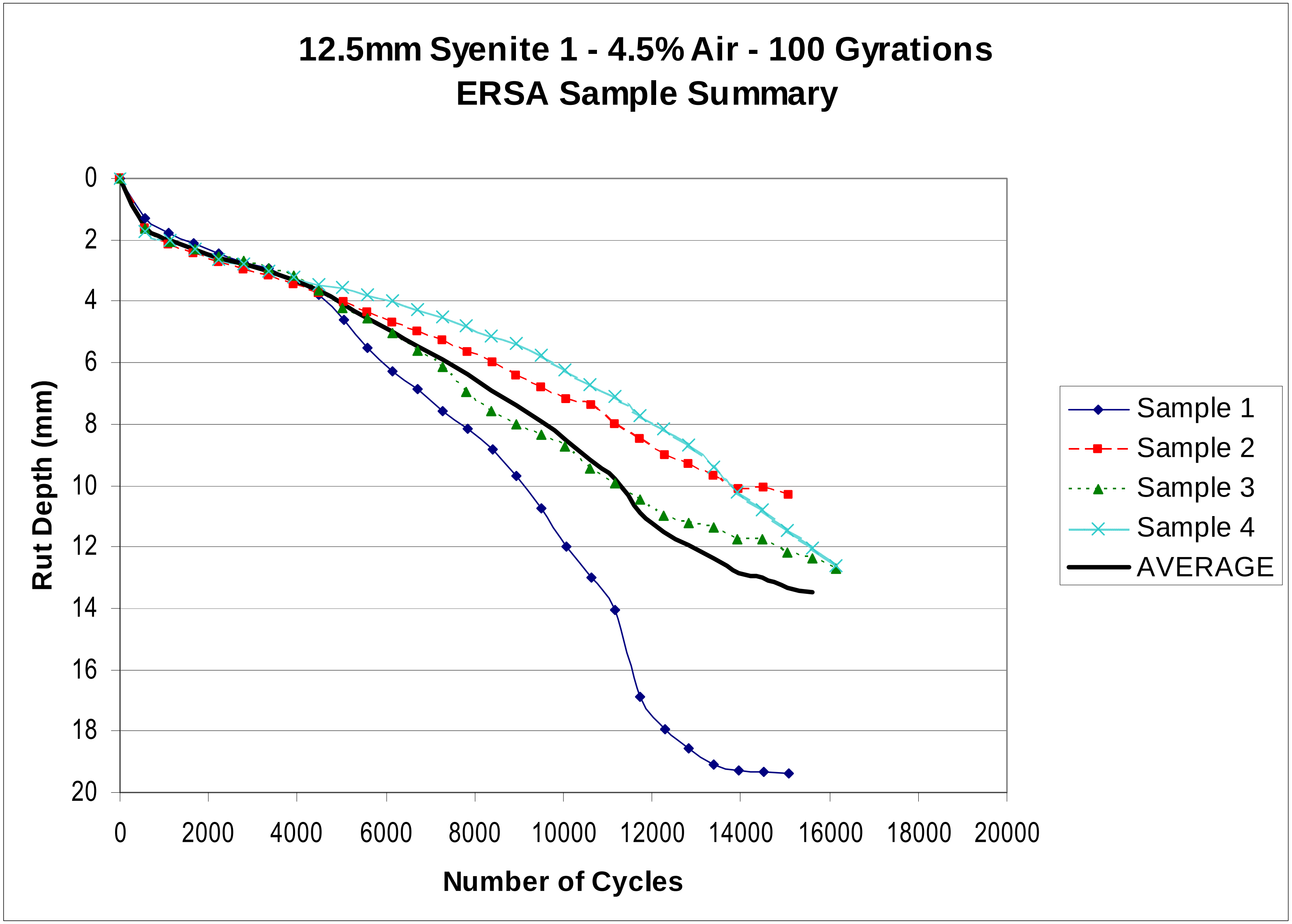

12.5mm Limestone 1 - 4.5% Air - 100 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

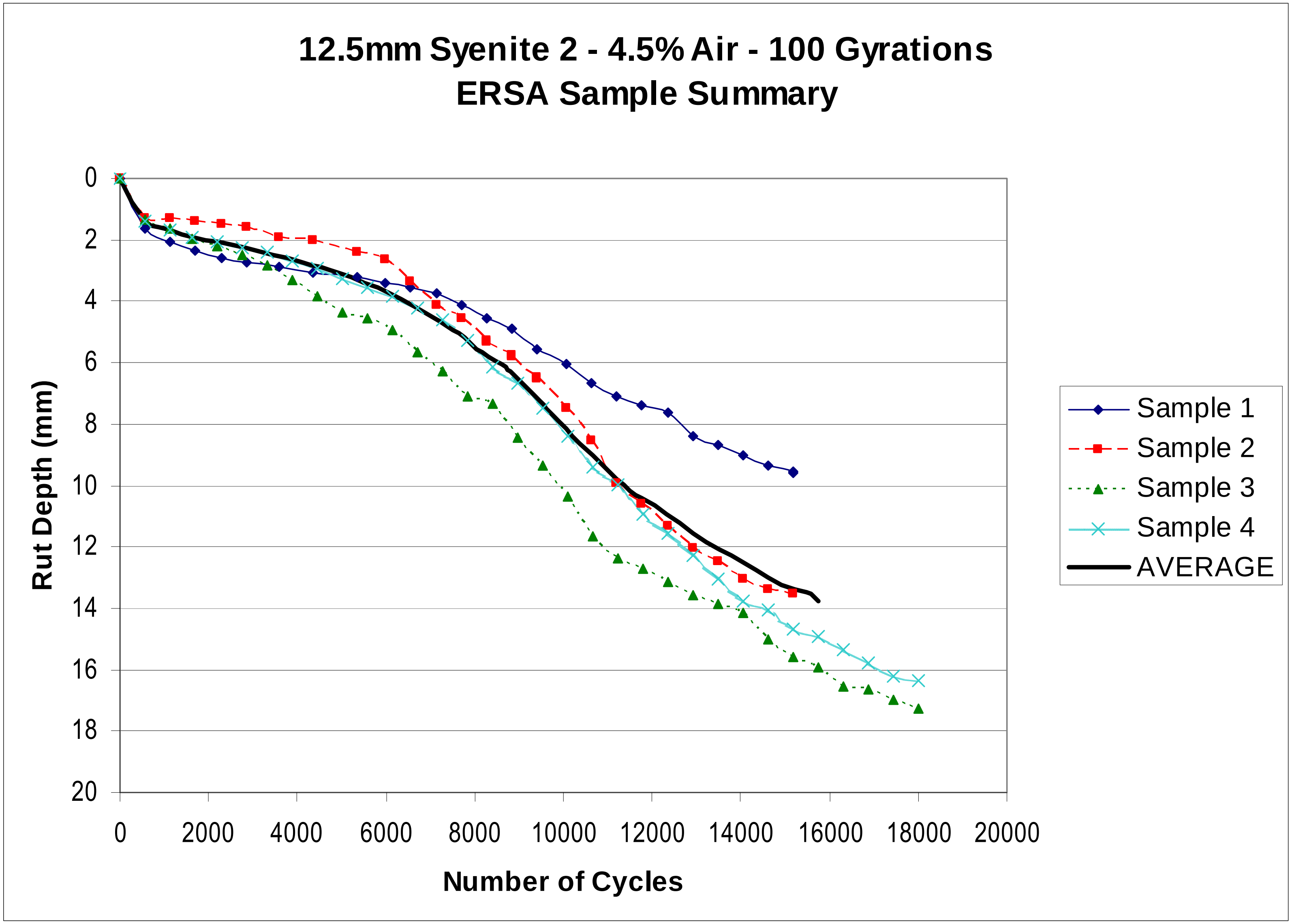


12.5mm Limestone 2 - 4.5% Air - 100 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE


12.5mm Sandstone 1 - 4.5% Air - 100 Gyrations
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

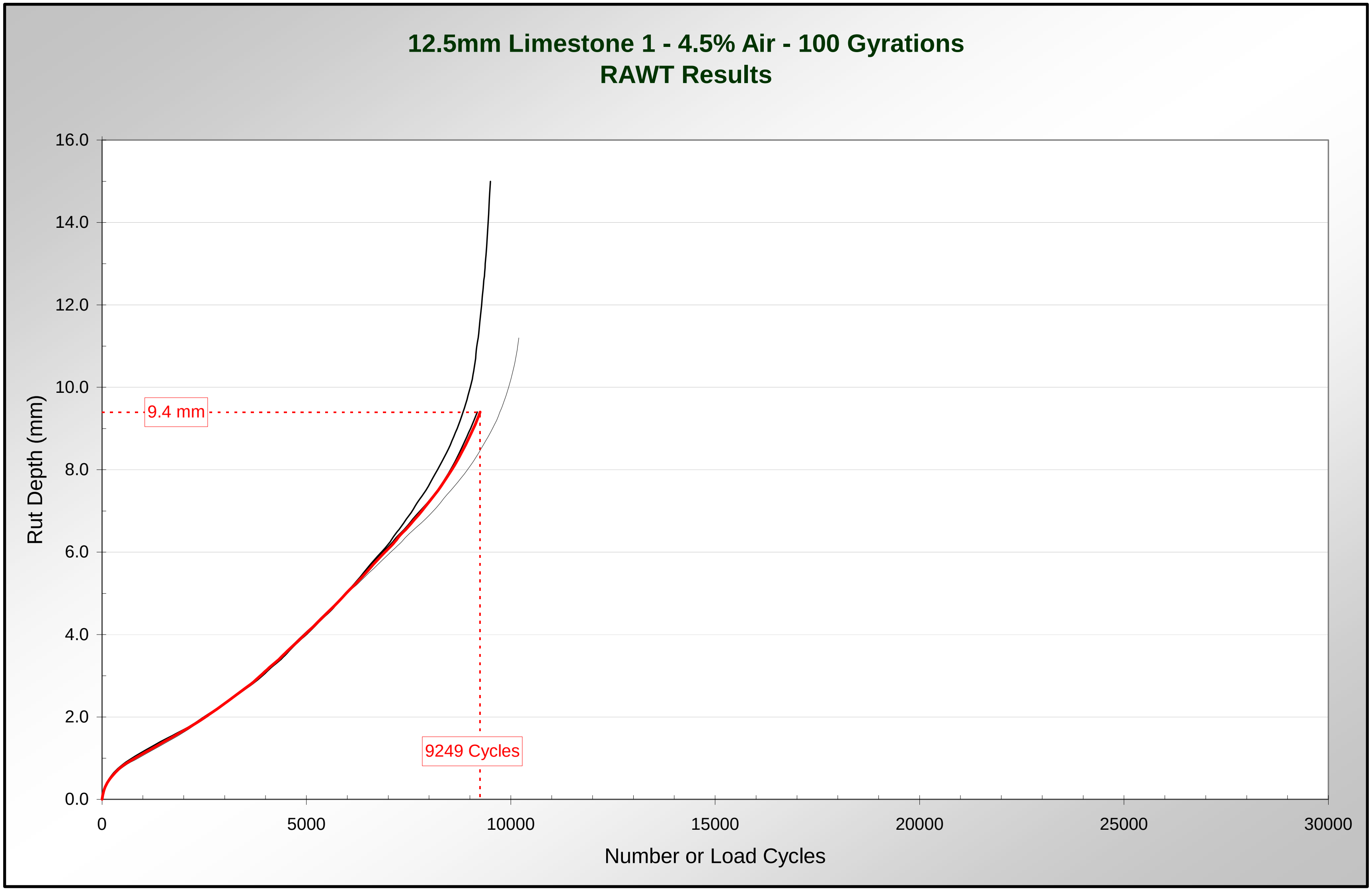

12.5mm Sandstone 2 - 4.5% Air - 100 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

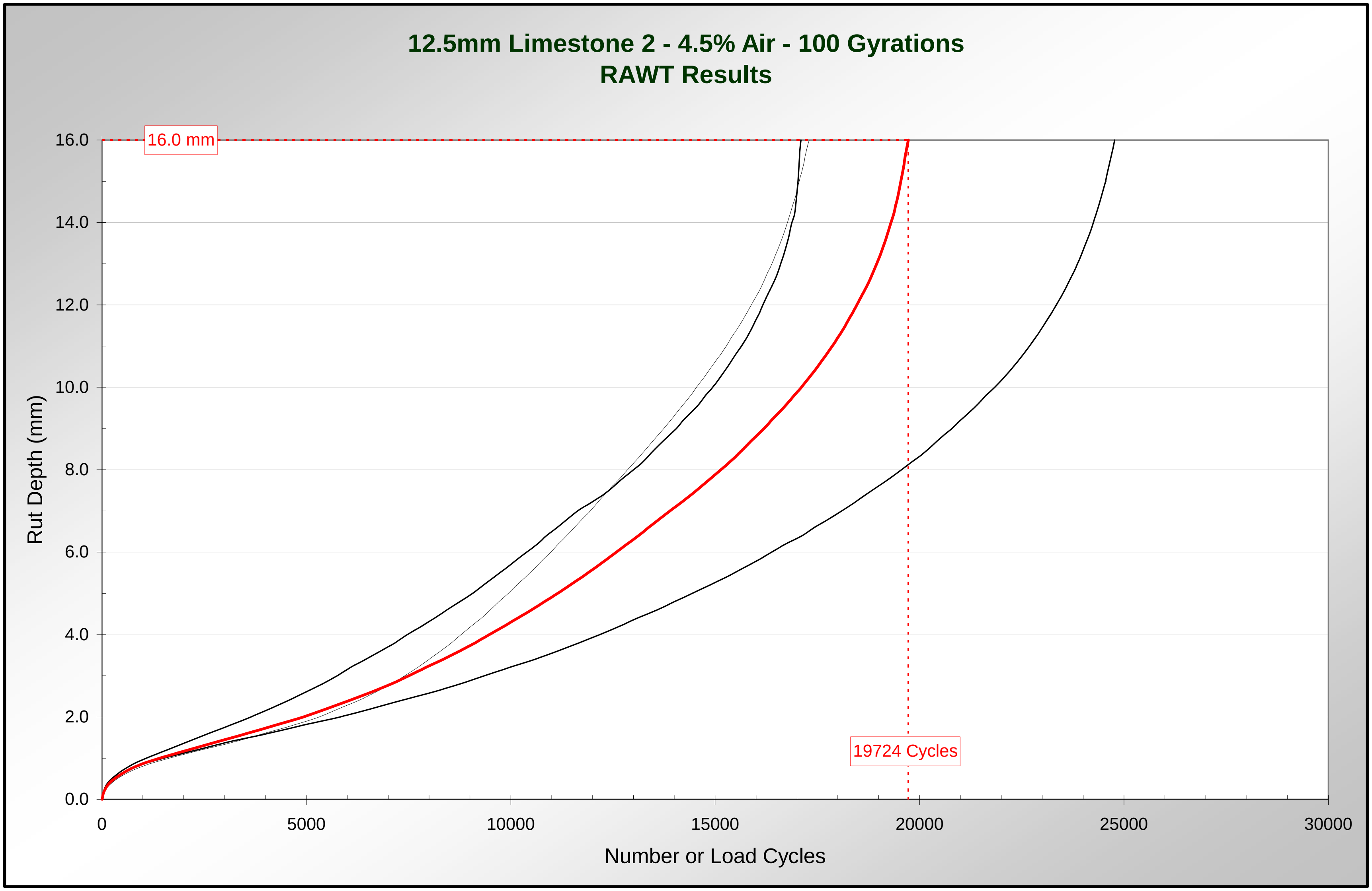

12.5mm Syenite 1 - 4.5% Air - 100 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

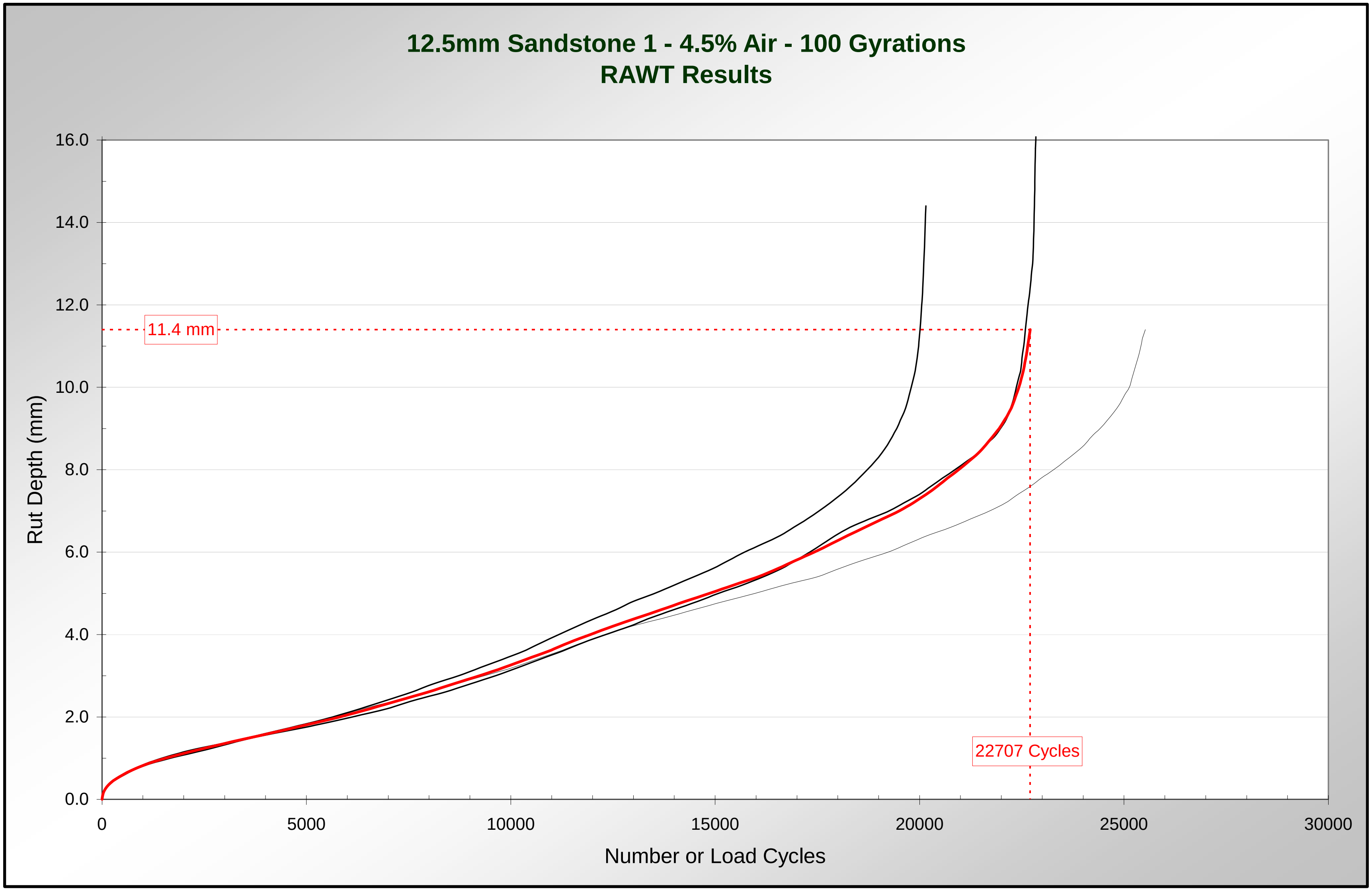

12.5mm Syenite 2 - 4.5% Air - 100 Gyrations
ERSA Sample Summary
Rut Depth (mm)
0
2
4
6
8
10
12
14
16
18
20
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Number of Cycles
Sample 1
Sample 2
Sample 3
Sample 4
AVERAGE

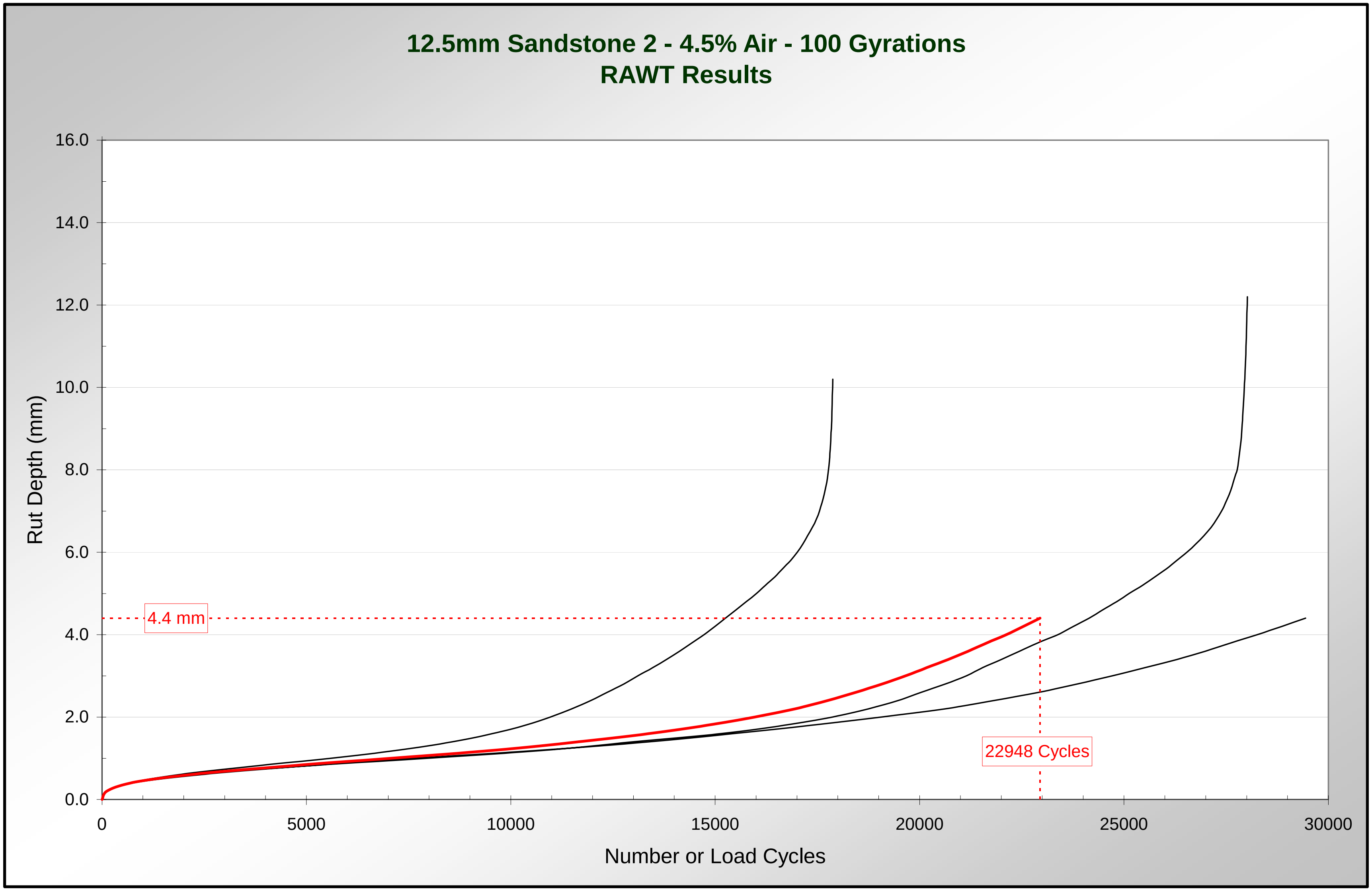
APPENDIX D

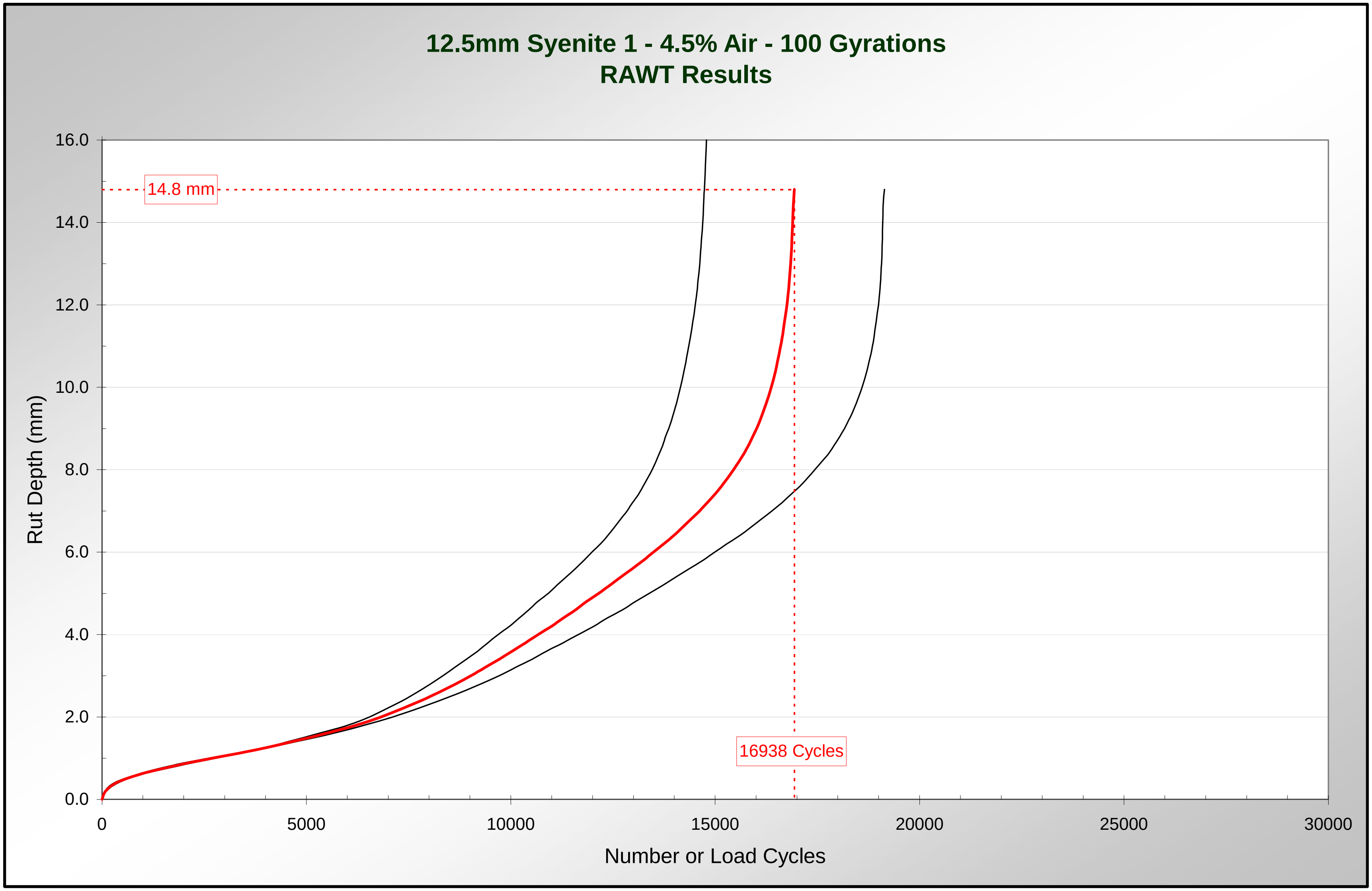
12.5mm RAWT RESULTS


12.5mm Limestone 1 - 4.5% Air - 100 Gyrations
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

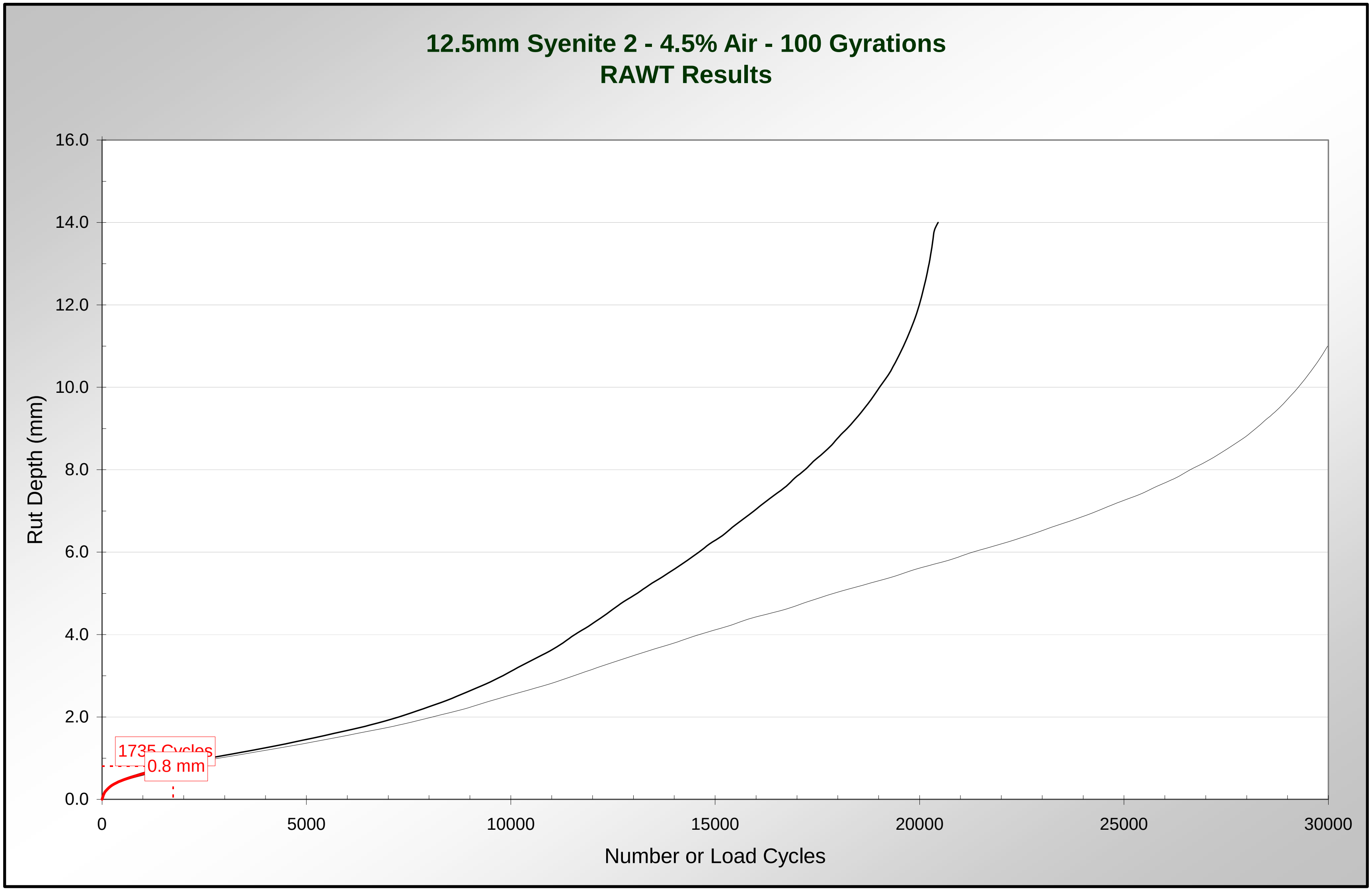

12.5mm Limestone 2 - 4.5% Air - 100 Gyrations
RAWT Results
16.0 mm
19724 Cycles
Rut Depth (mm)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles


12.5mm Sandstone 1 - 4.5% Air - 100 Gyrations
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


12.5mm Sandstone 2 - 4.5% Air - 100 Gyrations
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



12.5mm Syenite 1 - 4.5% Air - 100 Gyrations
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


12.5mm Syenite 2 - 4.5% Air - 100 Gyrations
RAWT Results
Rut Depth (mm)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
1735 Cycles
0.8 mm
0
5000
10000
15000
20000
25000
30000
Number or Load Cycles