Analysis of Aggregates and Binders Used for the ODOT Chip Seal Program

FINAL REPORT - FHWA-OK-10-03

ODOT SPR ITEM NUMBER 2221

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16. ABSTRACT

This project compared the results of laboratory characterization of chip seal aggregate samples for Oklahoma DOT Divisions 1,2,3,5 and 6 with performance data from the Pavement Management System (PMS) database. Binder evaluation was limited to identifying the binder sources associated with each test section and analyzing its performance based on the PMS data. No trend was found from the PMS analysis of binder sources. The laboratory testing consisted of sieve analysis, Los Angeles Abrasion Testing, Micro-Deval Testing, and the use of the Aggregate Imaging System (AIMS) to quantify chip seal aggregate characteristics from each division. The output from the laboratory testing was compared with the PMS performance data using linear regression techniques to identify those combinations that displayed a discernable trend. The project's sample size was small and therefore, the researchers were unable to reach authoritative conclusions. Nevertheless, the analysis found a potential relationship between the LA test and PMS skid number (SN) data. It also identified trends with respect to the AIMS output, particularly between gradient angularity and SN. The Performance-based Uniformity Coefficient introduced by the North Carolina DOT was also evaluated and found to be a promising metric that may warrant future inclusion in the ODOT chip seal aggregate specifications.

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SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	25.40	millimeters	mm
ft	feet	0.3048	meters	m
yd	yards	0.9144	meters	m
mi	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.0929	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac	acres	0.4047	hectacres	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallon	3.785	liters	L
ft^3	cubic feet	0.0283	cubic meters	m^3
yd^3	cubic yards	0.7645	cubic meters	m^3
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.4536	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
˚F	degrees Fahrenheit	(˚F-32)/1.8	degrees Celsius	˚C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.448	Newtons	N
lbf/in^2	poundforce per square inch	6.895	kilopascals	kPa

Approximate Conversions from SI Units

Symbol	When you know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.0394	inches	in
m	meters	3.281	feet	ft
m	meters	1.094	yards	yds
km	kilometers	0.6214	miles	mi
		AREA		
mm^2	square millimeters	0.00155	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectacres	2.471	acres	ac
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.0338	fluid ounces	fl oz
L	liters	0.2642	gallon	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.1023	short tons (2000 lb)	T
		TEMPERATURE (exact)		
˚C	degrees Fahrenheit	9/5(˚C)+32	degrees Celsius	˚F
		FORCE and PRESSURE or STRESS		
N	Newtons	0.2248	poundforce	lbf
kPa	kilopascals	0.1450	poundforce per square inch	lbf/in^2

Performance Analysis of Aggregate/Binder Combinations Used for the ODOT Chip Seal Program

FINAL REPORT - FHWA-OK-10-PS01

ODOT SPR ITEM NUMBER 2221

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EXECUTIVE SUMMARY

Purpose of the Research:

This study has three objectives:

1. Analyze the performance of different aggregate/binder combinations, the sources of each and their use for ODOT chip seals to identify both successful and unsuccessful chip seal designs.
2. Characterize the salient aggregate properties from those successful designs to furnish detailed information for revising the ODOT chip seal aggregate specifications.
3. Identify those chip seal aggregate/binder combinations and their sources that are consistently successful and those that are relatively unsuccessful to furnish input to revising ODOT chip seal specifications.

Deliverables:

- Oklahoma Chip Seal Best Practices Report – No best practices were determined beyond those found in the literature.
- Recommended revisions to ODOT chip seal aggregate/binder combination specifications and division chip seal design procedures cannot be made as the research findings, while indicating a potentially significant trend between chip seal performance and certain aggregate characteristics, are not statistically significant.
- Chip Seal Best Practices Seminar – To be delivered in December
- Final research report
- 2 to 4 page color article
- Monthly progress reports – Submitted as required

Scope of Work:

The work performed in this project consisted of the following major tasks:

1. Literature review
2. Development of division chip seal case study sections
3. Identification of material sources
4. Collection of chip seal aggregate samples from the divisions that had chip seal project in the 2010 program.
5. Characterization of the samples using a suite of tests including the Aggregate Imaging System (AIMS), Micro-Deval, LA Abrasion, and gradations.
6. Collection of PMS data from the case study sections
7. Synthesis of Tasks 1-6 to determine if recommendations for changes to ODOT specifications and procedures were applicable.
8. Development of a seminar for ODOT maintenance engineers
9. Documenting the research in this final report.

Methodology:

The methodology to reach research the project's findings are based on utility theory to correlate with the utility theory-based methodology used to reduce ODOT Pavement Management System data. It essentially involves correlating two sets of loosely related data to seek trends between the quantitative laboratory test data and the ODOT PMS performance data for the divisions from which the samples were collected. The research plan recognized the impossibility of obtaining aggregate samples from the specific test sections from which the PMS performance data was drawn. However, since chip seal aggregate in a given geographic area will typically come from the nearest pit, the team was able to replicate the utility theory-based analytical approach used in previous research in Texas (Senadheera et al 2001) to combine the PMS data with the laboratory data and identify trends worthy of further investigation.

Conclusions:

The following conclusions are made.

1. No positive or negative trends were discovered with respect to ODOT aggregate-binder combinations. Chip seal binder selection appears to yield satisfactory performance in the divisions studied.
2. The Los Angeles abrasion results show that all the aggregate samples meet ODOT specifications. The Antlers Division aggregate is more resistant than the other division aggregates. In addition, in Micro-Deval Test aggregates in Antler and Buffalo division found to be more resistant.
3. According to Micro-Deval and LA abrasion test results, it seems that the LA test may be more appropriate for measuring the quality of chip seal aggregates. However, since the sample size was not statistically significant, no authoritative conclusion can be reached.
4. Skid resistance is an important pavement characteristic purely from a safety standpoint. The study found that SN is related to aggregate gradient angularity. In AIMS analysis, it is found that increasing aggregate gradient angularity tracked with increasing SN, which was not the case for radius angularity.
5. The analysis confirmed that a relationship exists between aggregate abrasion test results and SN. SN decreases as the amount of loss measured in the aggregate abrasion test increases.
6. The Performance-based Uniformity Coefficient (PUC) is a promising metric for measuring chip seal susceptibility to failure due to flushing/bleeding. Trends between the PUC and the radius angularity index and sphericity index found using the AIMS test were observed.
7. A trend was also observed between the PUC and the PMS International Roughness Index (IRI).
8. The cost index analysis showed that the Clinton and Muskogee division maintenance programs are the most cost effective. The result is explained by the relative quality of its aggregate.

INTRODUCTION

PROBLEM

Chip seals are widely used for preventative maintenance of pavements. While there has been extensive research on the various parts of the surface treatment, there is little research on how the various materials and methods are brought together. Hence, chip sealing continues to be considered an art rather than a rationally engineered composite system. While some systematic methodology exists to design and install for chip seals, the methods are quite dated (Kearby 1953; McLeod 1969; TTI 1981). In most cases, the Oklahoma Department of Transportation (ODOT) maintenance engineers use empirical design based on trial and error. Additional technical information is needed that defines binder selection based on locally available aggregate properties and thereby permit ODOT engineers to calculate appropriate emulsion/binder and aggregate application rates during chip seal placement based on local conditions. This information may be used to revise ODOT chip seal specifications and update ODOT chip design methods.

BACKGROUND

Chip seals are one of the major pavement preservation tools used to extend the service lives of pavements across the nation. Successful application is extremely dependent on the methods employed in the field during construction. Additionally, compatibility between aggregates and binders is important to ensure that adequate adhesion is achieved. Most of the research in this field has focused on material science aspects of either the asphalt binders or the aggregates, but little has been written about combinations of binder and aggregate. A Texas DOT (TxDOT) study found that electrostatic incompatibility of aggregates and binders (i.e. using an anionic binder with an aggregate that is also anionic) was a major cause of early failure in emulsion chip seals (Gransberg et al. 1998). Additionally, the study found that lack of adequate angularity and hardness caused Texas chip seals to fail to achieve their design lives. The results were used to revise TxDOT chip seal specifications (Gransberg et al. 2000) and develop a manual for statewide implementation (Senadheera et al. 2001). Thus, these issues should be investigated in the Oklahoma context to address the potential early chip seal failure and costly corrective maintenance for ODOT.

Much of the previous materials research relies on assumption that the material will be properly installed in the field (Abdul et al. 1993). Additionally, the research that has looked at actual project performance is focused on the forensic evaluation of failures (Eltahan et al. 1990; Epps et al. 1980). Thus, ODOT and its paving contractors have a body of reference knowledge that details what they should not do when installing chip seals with very little guidance on the subject of what they should do to successfully apply an emulsion chip seal. This fact was confirmed at the national level in an NCHRP study of chip seal best practices (Gransberg and James 2005). This project seeks to extend the previous research and add to the body-of-knowledge in this area specifically for Oklahoma climate, traffic conditions, and locally available materials. Thus, *the focus will be on how to replicate success* with Oklahoma materials, means, and methods *rather than how to avoid failure.*

OBJECTIVES

This study has three objectives:

1. It will analyze the performance of different aggregate/binder combinations and the sources of each, used for ODOT chip seals to identify both successful and unsuccessful chip seal designs.
2. It will characterize the salient aggregate properties from those successful designs to furnish detailed information for revising the ODOT chip seal aggregate specifications.
3. It will identify those chip seal aggregate/binder combinations and their sources that are consistently successful and those that are relatively unsuccessful to furnish input to revising ODOT chip seal binder specifications.

SCOPE

The work performed in this project consisted of the following major tasks:

1. Literature review
2. Development of division chip seal case study sections
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9. Documenting the research in this final report.

LITERATURE REVIEW

CHIP SEALS FOR PAVEMENT MAINTENANCE

Chip seals are applied to existing pavement surfaces to seal the cracked surface against air and water intrusion. They furnish other benefits including, enhance skid values of the pavement, providing a uniform looking surface and improving the visibility of traffic lane striping. Chip seals have no structural capacity since they are effectively one rock thick. However, they do affect the performance of the pavement by increasing the life of the pavement surface as a pavement preservation or preventive maintenance application. They protect the underlying pavement structure against weathering effects. Chip seals cannot be used to improve the pavement ride quality. Therefore, chip seal applications should not be applied to correct badly cracked or weathered pavement surfaces where a rehabilitation or overlay activity is needed. In some cases, chip seals may be used on such poor surfaces as a stopgap measure until the corrective action can be taken.

Chip seals are generally effective in sealing the cracks existing on roadway surface, unless there are the indicators of heavy base distresses. Chip seal applications are appropriate in low to mid volume roads where there is no significant structural distress. Flushed or bleeding surfaces that are considered for chip seal applications should be treated carefully because flushing is generally reflected to the new seal if the aggregate and binder rates are not designed accordingly. On such surfaces, binder rates must be decreased and coarser aggregate should be selected. One of the major difficulties in chip seal design is the non-uniformity of the pavement. Most chip seal candidate sections will have patching as well as local flushing and the raveling sections observed at different locations of the pavement. All of these conditions require binder application rate to be varied as the surface conditions change. This is typically performed by an experienced field crew changing the rates as needed in the field.

CHIP SEAL DESIGN

The early practitioners of surface treatments like chip seals appear to have used a purely empirical approach to their design. Sealing a pavement was considered then, as it is now in many circles, an art. Chip seal design involves the calculation of correct amounts of a bituminous binder and a cover aggregate to be applied over a unit area of the pavement. The two major components of chip seal design process are the types and amounts of binder and aggregate. Aggregates used in chip seal are expected to transfer the load to the underlying surface as well as protect the new seal from traffic abrasion. They also enhance the skid resistant surface by providing enhanced surface drainage, which in turn reduces the probability of hydroplaning. Chip seal are also used on low volume roads to correct the effects of weathering and raveling.

Selection of cover aggregates is directly related to the local availability of aggregates. Whatever the selected aggregate is, caution should be exercised with the aggregate size distribution. Gradation of the aggregate is desired to be as uniform as possible. The rule of thumb for a single-size chip seal cover aggregate gradation correlates roughly to 85% by weight passing the desired sieve size. Single size cover stone is thought to furnish a better interlocking of particles and better aggregate retention on the surface. Also, the embedment depth will be more uniform across the road’s surface. The shape of cover aggregate is also crucial to obtain a good interlocking pattern of aggregates. Angular aggregate shapes such as cubical or pyramidal surfaces have demonstrated satisfactory service. Rounded, elongated and flat gravels should be avoided. Flakiness index defined as the ratio of smallest size of aggregate to the average aggregate size can indicate the suitability of the aggregate. In practice such undesired particle shapes are avoided by specifying a maximum percentage of aggregates having a 0.6 flakiness index (Epps et al, 1980).

Hanson Method (New Zealand)

The first recorded effort at developing a design procedure for chip seals appear to be made by Hanson (1934). His design method was developed primarily for liquid asphalt, particularly cutback asphalt, and was based on the average least dimension (ALD) of the cover aggregate spread on the pavement. Hanson calculated ALD by manually calipering a representative aggregate sample to obtain the smallest value for ALD that represents the rolled cover aggregate layer. He observed that when cover aggregate is dropped from a chip spreader on to a bituminous binder, the voids between aggregate particles is approximately 50 percent. He theorized that when it is rolled, this value is reduced to 30 percent and it further reduces to 20 percent when the cover aggregate is compacted by traffic. Hanson's design method involved the calculation of bituminous binder and aggregate spread rates to be applied to fill a certain percentage of the voids between aggregate particles. Hanson specified the percentage of the void space to be filled by residual binder to be between 60 and 75 percent depending on the type of aggregate and traffic level.

Kearby Method (Texas)

One of the first efforts at designing chip seal material application rates in the United States was made by Jerome P. Kearby, then Senior Resident Engineer at Texas Highway Department (Kearby, 1953). He developed a method to determine the amounts and types of asphalt and aggregate rates for one-course surface treatments and chip seals. He developed the nomograph shown in Figure 1 that provided an asphalt cement application rate in gallons per square yard for the input data of average mat thickness, percent aggregate embedded and percent voids in aggregate. The percent voids in aggregate used correspond to the percent voids in a bulk loose volume of aggregate and not to the aggregate spread on a pavement. If liquid asphalt were to be used, he recommended that the rate of bituminous material application should be increased such that the residual asphalt content is equal to the asphalt content given by the design nomograph. In order to determine the aggregate spread rate for aggregates containing flat and elongated particles, Kearby recommended the laboratory board test. In this test, the aggregate is manually spread over a one square-yard area and then weighed to determine the weight per unit area design spread rate.

In addition to the nomograph, Kearby recommended the use of a uniformly graded aggregate by outlining eight grades of aggregate based on gradation and associated average spread ratios. Each gradation was based on three sieve sizes. He also recommended that combined flat and elongated particle content should not exceed ten percent of any aggregate gradation requirement. Flat particles are defined as those with a thickness less than half the average width of particle, and elongated particles were defined as those with length greater than twice the other minimum dimension.

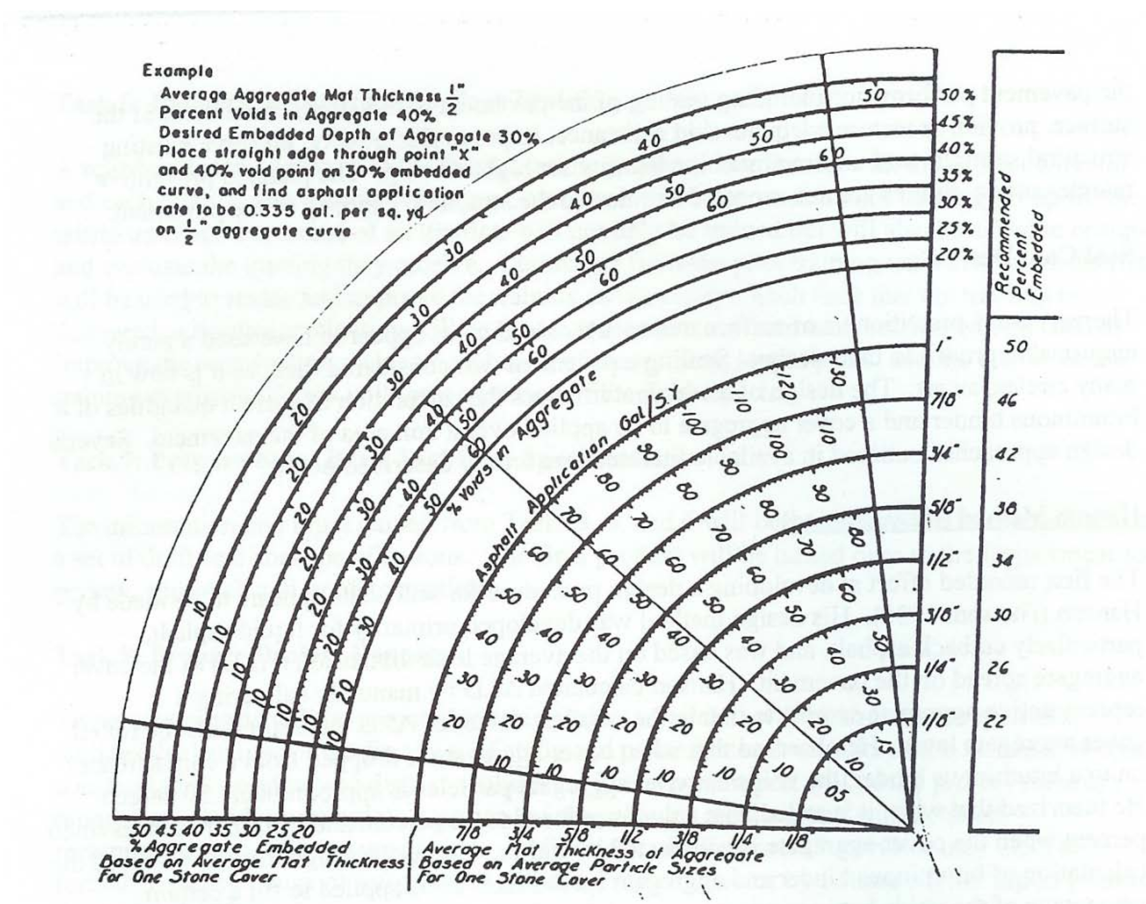

Figure 1: Nomograph to determine asphalt cement application rate in seal coats and one course surface treatments (Kearby 1953).

Kearby was quick to point out that “computations alone cannot produce satisfactory results and that certain existing field conditions require visual inspection and the use of judgment in the choice of quantities of asphalt and aggregate.” He suggested that when surface treatments are applied over existing hard-paved surfaces or tightly bonded hard base courses, the percentage of embedment should be increased for hard aggregates and reduced for soft aggregates. He also mentioned that some allowance should be made for highway traffic. It was suggested that for highways with high counts of heavy traffic, the percent embedment should be reduced along with using larger-sized aggregates and for those with low traffic volumes, the embedment should be increased with the use of medium-sized aggregates. However, Kearby did not recommend any specific numerical corrections.

Kearby also elaborated on the following construction aspects of surface treatments and chip seals based on his experience at the Texas Highway Department:

- Chip seals had been used satisfactorily on both heavy-traffic primary highways and low-traffic farm roads, with the degree of success largely depending on the structural strength of the pavement rather than the surface treatment itself.
- Thickness of the surface treatment range from ¼ in. to 1 in. with the higher thickness being preferred. However, lighter treatments have, in general, proven satisfactory when the pavement has adequate structural capacity and drainage.
- In general, most specification requirements for aggregate gradation are very broad, resulting in considerable variations in particle shape and size as well as percent voids taken together.
- It is better to err on the side of a slight deficiency of asphalt to avoid a fat, slick surface.
- Considerable excess of aggregate is often more detrimental than a slight shortage.
- Aggregate particles passing the #10 sieve acts as filler, thereby raising the level of asphalt appreciably and cannot be counted on as cover material for the riding surface.
- Suitable conditions for applying surface treatments are controlled by factors such as ambient, aggregate, and surface temperatures as well as general weather and surface conditions.
- Rolling with both flat wheel and pneumatic rollers is virtually essential.

During the same period, two researchers from the Texas Highway Department (Benson and Galloway, 1953) published a paper on their aggregate retention studies on chip seals. They conducted tests to determine the aggregate retention under a variety of conditions including source of asphalt cement, penetration grade of asphalt, number of roller passes, binder type (AC vs. cutback), aggregate gradation and binder application temperature. All their tests were conducted under the same conditions with only the test parameter being variable. The authors concluded that aggregate retention was not significantly different in asphalt cements picked from five different sources commonly used by the Texas Highway Department at the time. A commentary made in the early 1950's by the authors on the subject of asphalt quality strikes a familiar theme commonly used by practitioners even today.

> "There has long been a perhaps natural but unjustified tendency to attribute a large variety of job failures to the *quality* or source of the asphalt without adequate investigation of the other factors involved. Ironically, this was as true back in the days of almost universal use of Trinidad natural asphalt ... now often referred to as standards of *quality* in demonstrating the inferiority of some *modern* product, as it is today" (Benson and Galloway,1953).

This study also highlighted the inter-relationship between the binder type, binder grade and the temperature of the pavement during the asphalt shot and during rolling. In one set of laboratory experiments, the aggregate loss from an OA-230 penetration grade asphalt cement (close to an AC-2.5) reduced from 44 percent to 11 percent when the number of roller passes increased from one to three. In the same study, the effect of aggregate gradation on the performance of chip seals was investigated. An OA-135 asphalt cement (close to an AC-5) applied at a rate of 0.32 gallons per square yard was used under different aggregate treatments and the corresponding aggregate loss values are reproduced in Table 1 below. These results highlight the authors' contention that increased #10-sized aggregate content pose aggregate retention problems in chip seals. In addition, these researchers showed that a smaller portion of aggregate smaller than ¼ in. size will result in better performance of the chip seal.

Table 1. Effect of Aggregate Gradation and Aggregate Treatment on Retention (Benson and Galloway,1953)

Test Condition for Aggregate	**Aggregate Loss as a % of Original**
12.6% passing #10 sieve	72.0
6.7% passing #10 sieve	57.4
0% passing #10 sieve	30.5
12.6% passing #10 sieve & rock pre-heated to 250°F	17.7
12.6% passing #10 sieve & rock precoated with MC-1	33.6

In 1953, more research findings on aggregate retention were published by Benson and Galloway of Texas Engineering Experiment Station (Benson and Galloway, 1953). The intent of this research was to study the effects of field factors that usually affect the surface treatments as an extension of the Kearby design method. A comprehensive laboratory test program was conducted to study a number of factors including the material application rates, aggregate gradation, moisture and dust in the aggregate as well as the elapsed time between the application of binder and aggregate for different binder types. Some of the notable conclusions made by Benson and Galloway are listed below.

- A ten percent upward correction is needed to the aggregate quantity calculated from the Board Test recommended by Kearby (1953) to account for spreading inaccuracy.
- For average mat thickness less than 0.5 in., a higher percentage embedment is needed to hold the smaller aggregate particles together. As a result, the authors proposed an alteration to the curve proposed by Kearby.
- When asphalt cement is used as the binder, aggregate should be spread as soon as possible after the asphalt is sprayed.
- Harder asphalt cements hold cover stone more tightly, but initial retention is more difficult to obtain.
- Cover stone with a limited variation in grading will give the highest retention.
- Wet aggregates give poor retention with asphalt cement.
- Dust in aggregate result in poor retention. However, wetting the dry aggregate before application and by allowing it to dry before rolling reduced the negative effect from dust.

- Aggregate retention increased with increased quantity of asphalt.
- When a 24-hour curing period was allowed, the retention of wet stone by RS-2 emulsion was slightly greater than that for dry stone.
- The retention of wet dusty stone was slightly less than for dry stone.

During the 1940's and 1950's, research work indicated that sufficient curing time is needed for chip seals constructed using liquid asphalt. The recommendation from researchers was that at least 24 hours of curing is required before opening the road for traffic. J. R. Harris (Harris, J.R. 1955) of the Texas Highway Department proposed, based on his experience, that precoated aggregate should be used to increase the performance of the chip seal as well as to expedite the construction process. Harris' contention was that precoated aggregates considerably shorten the required curing time by eliminating the problems associated with aggregate dust and moisture, and that traffic can be allowed to use the roadway within one hour after a chip seal is placed with precoated aggregate. Also, the report said that this would allow using chip seals on high traffic roadways where shorter lane closure times due to the use of precoated aggregates would make the traffic control problem a lot more manageable.

Modified Kearby Method (Texas)

In 1974, Epps et al. proposed a further change to the design curve developed by Kearby for use in chip seals using synthetic aggregates (Epps, J.A, 1974). Due to high porosity in synthetic aggregates, a curve showing approximately 30 percent more embedment than the Benson-Gallaway curve was proposed. The rationale for this increase was that high friction lightweight aggregate may overturn and subsequently ravel under the action of traffic.

In a separate research effort, Epps et al. (Epps, 1974) continued the work done in Texas by Kearby (Kearby, 1953) and Gallaway and Benson (Galloway and Harper, 1966) by undertaking a research program to conduct a field validation of Kearby's design method. Actual pre-construction and post-construction data of 80 different projects were gathered and analyzed for this purpose. It was observed that Kearby design method predict less asphalt rates than what is used in Texas practice and the study proposed two changes to the design procedures. First one is a correction to the asphalt application rates based on level of traffic and existing pavement condition. Second is the justification of the shift of the original design curve proposed by the Kearby and Benson-Gallaway methods, as suggested for lightweight aggregates.

The following equation was used to calculate the asphalt application rate (in gallons per square yard), which included two correction factors determined for traffic level and existing surface condition.

$$A = 5.61\frac{E}{d}\left(1 - \frac{W}{62.6G}\right)T + V \qquad \text{Equation 1}$$

Where W and G are the dry unit-weight and dry bulk specific gravity of the aggregate, respectively, and d is the mat thickness that can be measured in the laboratory. Also, E is the depth of embedment and T and V are traffic correction factor and surface correction factor, respectively, for the asphalt application rate (A).

The proposed correction factors were projected from the actual mat thickness-embedment combinations that were proven to be working well in the field. Tables 2 and 3 show the asphalt application rate correction factors corresponding to traffic level and existing surface condition, respectively. Epps et al. (Epps et al, 1980) also suggested that consideration should be given to varying the asphalt rate both longitudinally and transversely as reflected by the pavement surface condition. Since then, practitioners and researchers have labeled this design approach as the "Modified Kearby Method."

Table 2. Asphalt Application Rate Correction Factor for Traffic (Epps et al, 1980).

	Traffic Level – Vehicles Per Day Per Lane				
	Over 1000	500 to 1000	250 to 500	100 to 250	Under 100
Traffic Factor (T)	1.00	1.05	1.10	1.15	1.20

Table 3. Asphalt Application Rate Existing Surface Correction Factors (Epps et al, 1980).

Description of Existing Surface	Asphalt Application Rate Correction (Gallons per Square Yard)
Flushed asphalt surface	-0.06
Smooth, nonporous surface	-0.03
Slightly porous, slightly oxidized surface	0.00
Slightly pocked, porous, oxidized surface	+0.03
Badly pocked, porous, oxidized surface	+0.06

AGGREGATE GRADATION PROPERTIES

A significant US development in chip seal research was proposed by Lee and Kim (2009) in a paper that came from a project funded by the North Carolina DOT. Essentially, the research reached back in time to the research conducted in 1962 by Norman McLeod that developed failure criteria for chip seals. McLeod postulated that "the largest size for a chip seal aggregate should be no more than twice the smallest size." Thus, the ideal chip seal aggregate gradation would continue only particles of a single size. This is not economically feasible. Therefore, Lee and Kim advocate a pragmatic tolerance be allowed. They also advocate developing the tolerance in a fashion that enhances chip seal performance, based on the principles of pavement preservation where it is better to pay an incrementally higher first cost to reduce long-term life cycle cost (Galehouse et al 2003).

Figure 2 is a schematic of the McLeod failure criteria. The aggregate particle that is the same size as the embedment depth represents failure due to flushing/bleeding. Whereas, the particle that is 1.4 times the median aggregate size represents failure due to aggregate loss because of inadequate embedment. Lee and Kim posit that to maximize chip seal performance that the aggregate should fall within the range shown in Figure 2. "M" is the median particle size.

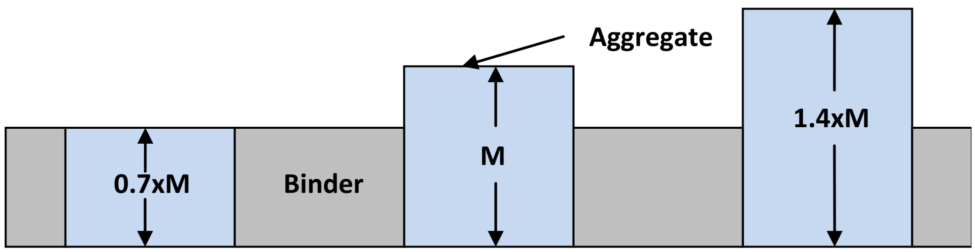

Figure 2: Schematic of McLeod's Failure Criteria (after Lee and Kim 2009).

Therefore, a coefficient of uniformity is proposed and called the "performance-based uniformity coefficient" (PUC). The paper by Lee and Kim describes the process used to compute the PUC for a given chip seal aggregate sample. Figure 3 is an example of the process used to develop input to the PUC and Equation 2 is the formula to calculate the coefficient. The PUC can then be used in a chip seal aggregate specification to quantify the allowable tolerance for particle sizes outside the bounds fixed by the McLeod failure criteria for bleeding and aggregate loss.

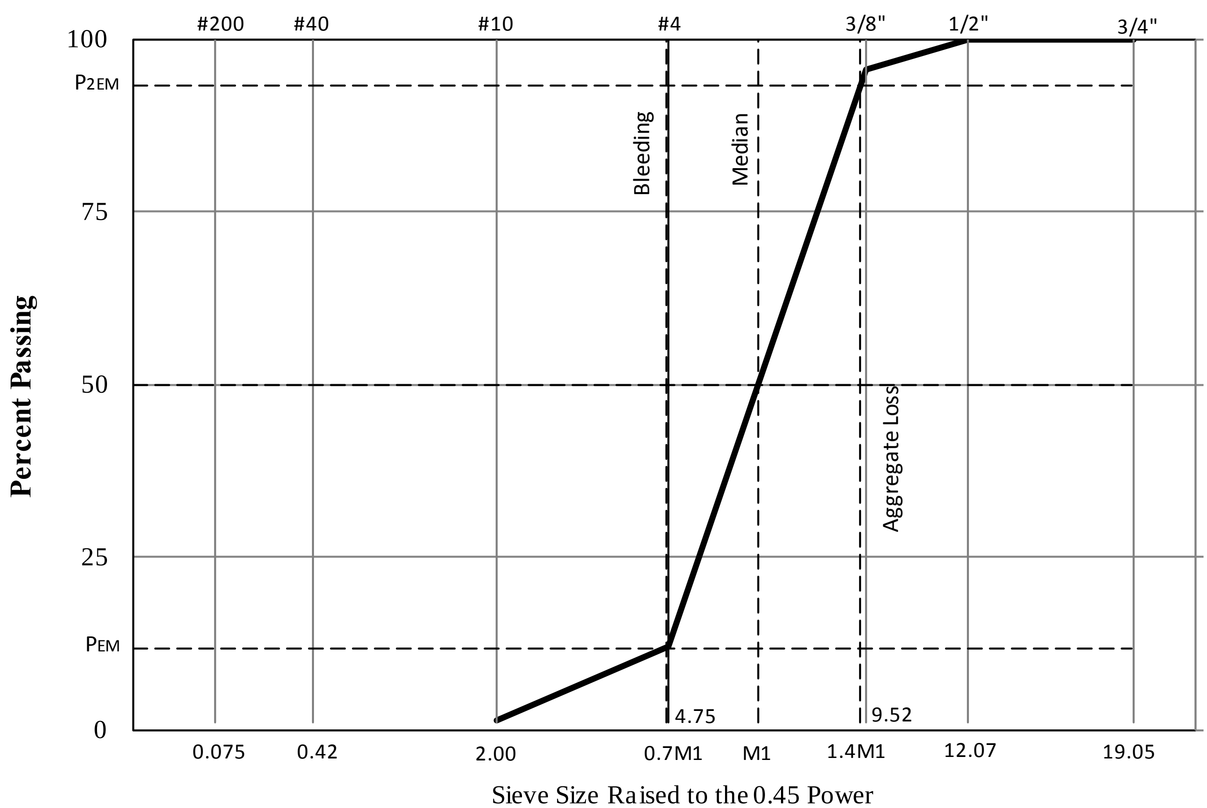

Figure 3: Gradation Range to Maximize Performance (after Lee and Kim 2009)

$$PUC = \frac{P_{EM}}{P_{2EM}}$$ Equation 2

Where: P_{EM} = Percent passing at a given embedment depth

P_{2EM} = Percent passing at twice the given embedment depth

AGGREGATE ABRASION TESTS

NCHRP Synthesis 342 (2005) found that one of the major aggregate-associated failure causes was excessive fines. The fine content in chip seal aggregate is typically measured in the pit. This creates a false reading if the aggregate must be handled multiple times before it finally gets on the road. Each time the aggregate is moved, its gradation changes and the fines content increases. The amount of degradation is a function of the aggregate's abrasion resistance. As a result, the researchers tested the chip seal aggregate samples for abrasion resistance using both the Los Angeles (LA) abrasion test and the Micro-Deval test. It is worth noting that ODOT only specifies the LA abrasion, not Micro-Deval, for cover aggregates.

Los Angeles Abrasion Test

The LA abrasion test allows for the assessment of an aggregate resistance to degradation during transport, mixing, and compaction. In this test, 5000 ± 5 g of an aggregate mix are placed into a steel cylinder with six to twelve 46.8 mm steel spheres, depending on the gradation used for the mix. The aggregates and steel spheres are then rotated at 30 to 33 rpm until the total rotations reach 500. The weight loss is measured as passing the #12 sieve, and the percent weight loss is calculated using Equation 2. The LA abrasion Test differs from the Micro-Deval because the steel spheres used are much larger and it is a dry method. The LA abrasion is therefore more of an assessment of aggregate breakage than abrasion due to wear.

$$\text{Percent Loss} = \frac{\text{(Weight Before-Weight After)}}{\text{Weight Before}}$$ Equation 3

The Los Angeles (L.A.) Abrasion and Impact Test (AASHTO T 96) is the most widely used method for measuring aggregate resistance for abrasion and aggregate toughness (Kandhal and Parker 1998). In this test aggregates are mixed with steel balls of specific size and weight in a steel drum. Drum rotation promotes interaction between aggregates and steel, which introduces different mechanisms of abrasion, impact, and grinding. The lifting and dropping action of aggregates introduces very high impact forces, which makes the test a measure of impact resistance rather than abrasion resistance. Originally, the test name was the L.A. Abrasion Test, but the addition of 'impact' to its name was to recognize that this test measures aggregate resistance to impact rather than abrasion (Rogers 1998). According to the AASHTO T 96, this test is a measure of aggregate degradation due to abrasion, impact, and grinding. However, Rogers (1998) indicated that studies revealed that this test measures mostly aggregate resistance to mechanical breakdown.

Micro-Deval Test

The Micro-Deval test allows for the assessment of aggregate resistance to abrasion and weathering. The aggregate blend with a total weight of 1500 ± 5 g, summarized, is soaked in 2000 ± 50 mL of water for a minimum of one hour. This mixture is then placed in a steel cylinder with 5000 ± 5 g of steel ball bearings. This mixture of water, aggregate, and ball bearings are rotated for 105 minutes at 100 ± 5 rpm. After abrasion, the aggregates are washed, and the weight loss is considered to be that passing the #16 sieve. In Equation 3 it can be calculate the percent of weight loss.

$$\text{Percent Loss} = \frac{(\text{Weight Before-Weight After})}{\text{Weight Before}} \qquad \text{Equation 4}$$

This test measures the durability and abrasion resistance of aggregates through abrasion between aggregate particles and between aggregate particles and steel balls in the presence of water (Cooley and James 2003).It is the second test that has been used for measuring abrasion resistance. This test was developed in the 1870s in France to evaluate aggregate to be used for roads, and it was initially adopted by ASTM in 1908 (Amirkhanian et al., 1991). The Micro-Deval test is standardized in AASHTO T 327 "Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus,"

Research has shown that there is no correlation between Micro-Deval and the LA abrasion test. This maybe because the LA abrasion test really measures impact resistance of aggregates rather than abrasion resistance (Lane et al. 2000). The wet conditions in the Micro-Deval test are thought to better simulate the field condition of aggregates than the dry state in the LA abrasion test (Rogers 1998). Two National Center for Asphalt Technology (NCAT) studies (Cooley and James, 2003; Kandhal and Parker, 1998) reported that Micro-Deval did not correlate with other abrasion tests including the LA abrasion test. Another study that tested a population of 40 different aggregates of a variety of mineralogical types found no correlation between the Micro-Deval and the British aggregate abrasion value (Latham et al., 1998). The same study also found there was a significant difference between values observed when Micro-Deval was completed in wet and dry conditions.

AGGREGATE SHAPE TESTS

The shape and texture of the chip seal aggregate furnishes two important physical characteristics related to chip seal performance. First, the angularity and sphericity of each particle impact the quality of the bond formed between the aggregate and the binder. A very angular stone has more surface area over which to develop the bond than a smooth stone. The sphericity relates to the ease with which the stone can be seated during construction. During rolling, the individual particles are reoriented to their least dimension and embedded in the binder (Benson and Gallaway 1953). If proper embedment is achieved, the probability of premature loss of aggregate is minimized. As the orientation of the embedded chip is important, cubical aggregate shapes are preferred because traffic does not have a significant effect on the final orientation of aggregate (Janisch and Galliard 1998). Cubical materials tend to lock together and provide better long-term retention and stability.

Aggregate Imaging System

Aggregate Imaging System (AIMS) determines shape characteristics of aggregate through image processing and analysis techniques. The test equipment shown in Figure 4 captures aggregate characteristics in terms of shape, angularity, and surface texture. The test is limited to aggregates whose size ranges from 37.5 mm to 150 mm (Masad 2004).

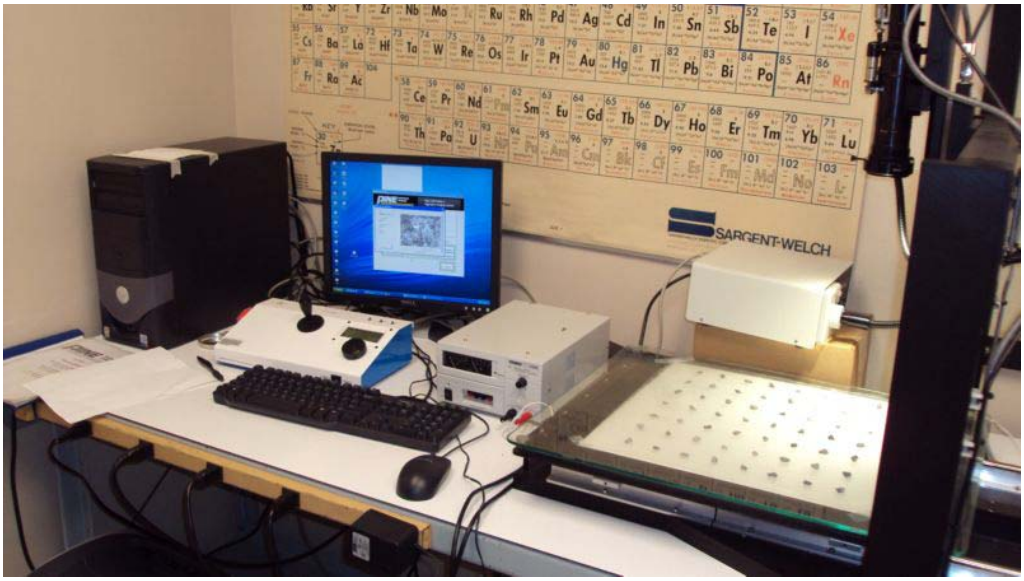

Figure 4: Aggregate Imaging System in OU Lab

AIMS equipment consists of a computer automated unit which includes an aggregate measurement tray with marked grid points at specified distances along x and y axes. Coarse aggregate samples (56 particles) are placed on the specified grid points, while fine aggregate sample is spread uniformly on the entire tray. The camera unit consists of an optem zoom 160 video microscope, equipped with bottom and top lightning to capture images in black and white format as well as gray format. The camera moves along specified grid locations in x, y, and z directions. The travel distance in the x and y directions are 37.5 cm and 10 cm in the z direction. The x, y and z-axes movement is controlled by a closed loop direct current (DC) servo and highly repeatable focus is achieved by GTS-1500. The first step in measurement is the calibration of the instrument for the type of analysis to be performed. The user has a real-time image window for selecting the type of analysis and size of aggregates to be analyzed.

The system is also equipped with top lighting, back lighting and a camera unit. The AIMS software analyzes the aggregate images and produces measurements of their shape, angularity, and surface texture. Aggregate texture is quantified using wavelet analysis method (Texture index); aggregate angularity is described by measuring the irregularity of a particle surface using the gradient and radius methods (Angularity index); and shape is described by 2D form and 3D form (Sphericity) (Al-Rousan 2004).

Radius Method (Angularity)

The analysis of angularity by the radius method was developed by Masad et al. (2001) using black and white images. In the radius method, the angularity index is measured as the difference between the particle radii in a given direction to that of an equivalent ellipse.

$$\text{Angularity Index (Radius Method)} = \sum_{\Theta=0}^{n} (|R_{\Theta} - R_{EE\Theta}|)/R_{EE\Theta} \qquad \text{Equation 5}$$

Where R_{Θ} is the radius of the particle at an angle of Θ; and $R_{EE\Theta}$ is the radius of the equivalent ellipse at an angle of Θ (Masad et al. 2001).

Gradient Method (Angularity)

The gradient method is based on the principle that at sharp corners of the image the direction of the gradient vector changes rapidly whereas it changes slowly along the outline of rounded articles. The angularity is calculated based on the values of angle of orientation of the edge points (Θ) and the magnitude of difference of these values ($\Delta\Theta$). The sum of angularity values for all the boundary points are accumulated around the edge to get the angularity index. The angularity index is calculated by the sum of angularity values for all the boundary points accumulated around the edge of the aggregate particle. The angularity is mathematically represented as.

$$\text{Angularity Index (Gradient Method)} = \sum_{\Theta=0}^{n-3} |\Theta_i - \Theta_{i+3}| \qquad \text{Equation 6}$$

Where *n is* the total number of points on the edge of the particle with the subscript *i* denoting the i_{th} point on the edge of the particle (Masad 2003).

Sphericity

Sphericity quantifies the stone's form is in three dimensions. A sphericity index of 1.0 denotes that a particle is a perfect sphere or cube while sphericity decreases as a particle becomes more flat and/or elongated. The three dimensions of the particle the longest dimension (d_L), the intermediate dimension (d_I), and the shortest dimension (d_s) are used in the following equations for sphericity and shape factor.

$$\text{Sphericity} = (d_s d_I / d_L^2)^{1/3} \qquad \text{Equation 7}$$

$$\text{Shape Factor} = d_s / (d_L d_I)^{1/2} \qquad \text{Equation 8}$$

Form Index

Form analysis using the form index was proposed by Masad et al. (2001), and is used to quantify the form in two dimensions. The form index uses incremental change in the particle radius and is expressed by the following equation:

$$\text{Form Index} = \sum_{\Theta = 0}^{\Theta = 360-\Delta\Theta} (|R_{\Theta+\Delta\Theta} - R_{\Theta}|) / R_{\Theta} \qquad \text{Equation 9}$$

Where R_{Θ} is the radius of the particle at an angle of Θ; and $\Delta\Theta$ is the incremental difference in the angle.

Texture Analysis

The AIM apparatus offers a method to analyze the surface texture of aggregate particles as well as the polishing coupons. The texture index is determined by taking a grayscale image of the surface of the aggregate particle. Wavelet method is used to determine surface texture. The wavelet method is described in detail in NCHRP Report 4-30 (Masad et al. 2005). The wavelet analysis uses short high-frequency basis functions and long low-frequency basis functions to isolate fine and coarse variations in texture. The texture contents in all directions are given equal weight and the texture index is computed as the simple sum of squares of the detail coefficients at that particular resolution. The texture index is given by the equation.

$$\text{Texture Index (Wavelet Method)} = \sum_{i=1}^{3} \sum_{j=1}^{N} (D_{i,j}(x,y))^2 \qquad \text{Equation 10}$$

Where N is the total number of coefficients in a detailed image of texture; i takes values 1, 2, or 3 for the three detailed images of texture; j is the wavelet coefficient index; and (x, y) is the location of the coefficients in the transformed domain (Masad 2004).

RESEARCH METHODOLOGY AND PROTOCOLS

The researchers approached the study by collecting aggregate samples and performance data in from the following ODOT divisions:

1. Muskogee (Division 1),
2. Antlers (Division 2),
3. Ada (Division 3),
4. Clinton (Division 5), and
5. Buffalo (Division 6).

The aggregate samples were first characterized using a sieve analysis, and then Los Angeles abrasion test, Micro-Deval abrasion test and AIMS tests were completed. Additionally each division was asked to identify three good and three poor chip seal control sections that were at least three years old and provide PMS performance data for each control section. Antlers Division reported that they did not have any suitable control sections of the required age and as a result no PMS data was collected for that division. The remaining ODOT divisions are not included in the study. They could not furnish aggregate samples because they had no chip sealing scheduled in current their pavement maintenance programs.

Table 4 is a summary of the test sections designated by the divisions that provided information and aggregate samples. It shows that there were only two different binder sources used by the four divisions that designated test sections. If that trend is state-wide, then ODOT only has to deal with a small group of binder vendors to influence the variables associated with chip seal binders. A similar inference is found among the aggregate suppliers with only two different corporations furnishing the aggregate from three different pits. “A limited number of suppliers is a distinct advantage when the constructability is evaluated” (Anderson and Fisher 1997) because it allows the owner to more easily isolate the source of material with quality issues as well as simplifies the process of initiating corrective action (Gransberg et al 1998). The other notable fact in Table 4 is the consistency of binder types and cover aggregate sizes. Again, this promotes constructability by creating a solid base of institutional knowledge and experience that can easily be transferred from one division to another.

Table 4: Test Section Information.

Division	Highway	Control	County	From	To	Binder Source (P/S)	Aggregate Source (P/S)
Div1	0108 0000	40186	Adair County	0	13.8	CRS-2 Coastal Energy-Missouri (m00305)	No. 2 APAC-Oklahoma (m001237203)
Div1	1110 0000	40492	Cherokee County	0	10		
Div1	3120 0000	31-20	Haskell County	0	5.71		
Div1	4610 1775	46-10	McIntosh County	12.75	22.8		
Div1	5128 1185	51-28	Muskogee County	11.85	21.9		
Div1	6826 0000	68-26	Sequoyah County	0	5.25		
Div1	7318 0915	73-18	Wagoner County	9.15	13.2		
Div 2	Declined to submit test sections					NA	No. 2 Dolese – Coleman (m002710302)
Div3	1514 0000	15-14	Coal County	0	7.11	CRS-2 Coastal Energy-Missouri (m00305)	No. 1 Sample from state-wide contract – could not identify source
Div3	1516 0000	15-16	Coal County	0	13.8		
Div3	4137 0000	41-37	Lincoln County	0	6.91		
Div3	6210 1078	62-10	Pontotoc County	10.78	15.3		
Div3	6310 0530	63-10	Pottawatomie County	5.3	10.8		
Div3	6736 0000	67-36	Seminole County	0	9.74		
Div5	2220 1542	22-20	Dewey County	15.42	24.1	CRS-2 Ergon-Lawton (m00326)	No. 1 Dolese-Cooperton (m002723801)
Div5	2807 0085	28-07	Greer County	0.85	4.84		
Div5	3322 0058	33-22	Jackson County	0.58	9.35		
Div5	3816 0734	38-16	Kiowa County	7.34	14.4		
Div5	3838 0002	38-38	Kiowa County	0.02	8.63		
Div6	0408 0000	40276	Beaver County	0	26	CRS-2 Ergon-Lawton (m00326)	No. 2 Dolese-Cooperton (m002723801)
Div6	2314 0000	23-14	Ellis County	0	10.9		
Div6	3016 0005	30-16	Harper County	0.05	13.09		

QUALITATIVE ANALYSIS OF FIELD EXPERIENCE

Structured interviews were conducted with knowledgeable members of each division in the study. The details and contact information are contained in the appendix. Each interviewee was asked to discuss the perceived strengths and weaknesses of the division chip seal program. Additionally, an overall rating of each test section was collected to compare with subsequent data. No trends were found in any of the material collected during the interview.

PAVEMENT MANAGEMENT SYSYTEM DATA ANALYSIS

The researchers reduced the data and conducted the statistical analysis of project performance. The following data points collected for each control section as available from the ODOT:

- Binder source
- Aggregate source
- Cost per square yard
- Length of miles
- Ride Index
- Rut Index
- Functional Index
- Structural Index
- International Roughness Index (IRI)
- Average Rut Depth
- Skid Number
- Pavement Quality Index

Project Performance Metrics

The research team sought to develop a set of numerical performance measures for the given data. Three types of metrics were created. The first are standard averages for each category of PMS performance ratings. The second category uses weighted averages based on total measures of area. These were used to develop a better idea of how the performance measures were actually distributed. Area weighted averages capture the salient physical aspect of a chip seal as it is by nature a technology based on area of coverage design. The third category consisted of cost indices that seek to combine measured performance with cost to measure the cost effectiveness of various alternatives.

Discrete Metrics

Discreet metrics are developed directly from the data and in this study; they basically consist of mathematical averages of the PMS information for each project. The study computed seven discreet metrics from the data sample. Examples of these are Average Ride Index, Average Rut Index, Average Functional Index, Average Structural Index, Average International Roughness Index (IRI), Average Rut Depth, and Average Skid Number. The ODOT PMS manual describes the calculation of the Pavement Quality Index as shown in Equation 11

$$PQI = 0.4RI + 0.3RUTI + 0.15FI + 0.15STI \qquad \text{Equation 11}$$

Where:

PQI = Pavement Quality Index (ODOT 1999)

Weighted Average Metrics

The appropriate physical parameter on which to base a comparative analysis is the unit of length. The following formulae (Equations 12 through 18) were used to compute the weighted averages.

$$WtRI = \frac{\sum_{i=1}^{n} RI_i * L_i}{\sum_{i=1}^{n} L} \qquad \text{Equation 12}$$

Where:

Wt RI = Length weighted average of the pavement ride index score

RI_i = Ride Index score of project 'i'

L_i = Length of project 'i'

$$WtRUTI = \frac{\sum_{i=1}^{n} RUTI_i * L_i}{\sum_{i=1}^{n} L} \qquad \text{Equation 13}$$

Where:

Wt RUT I = Length weighted average of the pavement rut index score

$RUTI_i$ = Rut Index score of project 'i'

L_i = Length of project 'i'

$$WtFI = \frac{\sum_{i=1}^{n} FI_i * L_i}{\sum_{i=1}^{n} L} \qquad \text{Equation 14}$$

Where:

Wt FI = Length weighted average of the pavement functional index score

FI_i = Functional Index score of project 'i'

L_i = Length of project 'i'

$$Wt\ STI = \frac{\sum_{i=1}^{n} STI_i * L_i}{\sum_{i=1}^{n} L} \qquad \text{Equation 15}$$

Where:

Wt ST I = Length weighted average of the structural ride index score

STI_i = Structural Index score of project 'i'

L_i = Length of project 'i'

$$Wt\ IRI = \frac{\sum_{i=1}^{n} IRI_i * L_i}{\sum_{i=1}^{n} L} \qquad \text{Equation 16}$$

Where:

Wt IRI = Length weighted average of the international roughness index score

IRI_i = International Roughness Index score of project 'i'

L_i = Length of project 'i'

$$Wt\ RDI = \frac{\sum_{i=1}^{n} RD_i * L_i}{\sum_{i=1}^{n} L} \qquad \text{Equation 17}$$

Where:

Wt RDI = Length weighted average of the rut depth index score

RD_i = Rut depth score of project 'i'

L_i = Length of project 'i'

$$WtSN = \frac{\sum_{i=1}^{n} SN_i * L_i}{\sum_{i=1}^{n} L} \quad \text{Equation 18}$$

Where:

Wt SN = Length weighted average of the skid number score

SN_i = Skid number score of project 'i'

L_i = Length of project 'i'

Cost Index Number Metrics

The final category of metrics comes from a variant of Utility Theory called Cost Index Number Theory (West and Riggs 1986). Since PMS is based on Utility Theory (ODOT 1999), using Cost Index Number Theory is a logical choice for this type of analysis. The method seeks to combine cost and engineering measurements into a single index that can permit the direct comparison of two or more alternatives. This theory allows the researcher to compare a more expensive technology with a less expensive technology to determine if the incremental cost difference between the two alternatives is offset by enhanced engineering performance. In layman's terms, these metrics measure the "bang for the buck."

Four Cost Index Number (CIN) Metrics were developed for this analysis. Their formulae are shown in Equations 19 through 22.

$PQCI = (PQI/TC)L^{-1}$ Equation 19

Where:

PQCI = Pavement Quality Cost Index

TC = Total Cost

L = Length of Section

$FCI = (FI/TC)^{L-1}$ Equation 20

Where:

FCI = Functional Cost Index

$$IRCI = (IRI/TC)L^{-1} \quad \text{Equation 21}$$

Where:

IRCI = International Roughness Cost Index

$$SNCI = (SN/TC)L^{-1} \quad \text{Equation 22}$$

Where:

SNCI = Skid Number Cost Index

PMS RESULTS

This section presents a comparative analysis of PMS data for chip seals in four divisions. It is worth noting that Antlers division could not designate control sections that met the project's criteria. Since each control section was a different length, the analysis is based on length weighted average data of the each control section pavement and the results are compared between divisions.

Weighted Ride Index Results

While a chip seal can do virtually nothing to improve ride quality, the PMS data allows the analyst to put other data in the perspective of the level of underlying distress and hence the expectations for chip seal performance. In other words, installing a perfect chip seal on a rough road merely creates an illusion of enhancement. Figure 19 shows the weighted average ride index of each division. As it seen in this figure Clinton division has highest ride index which is 81.9. Muskogee, Ada and Buffalo have average ride index 72.2, 78.0 and 72.1 respectively.

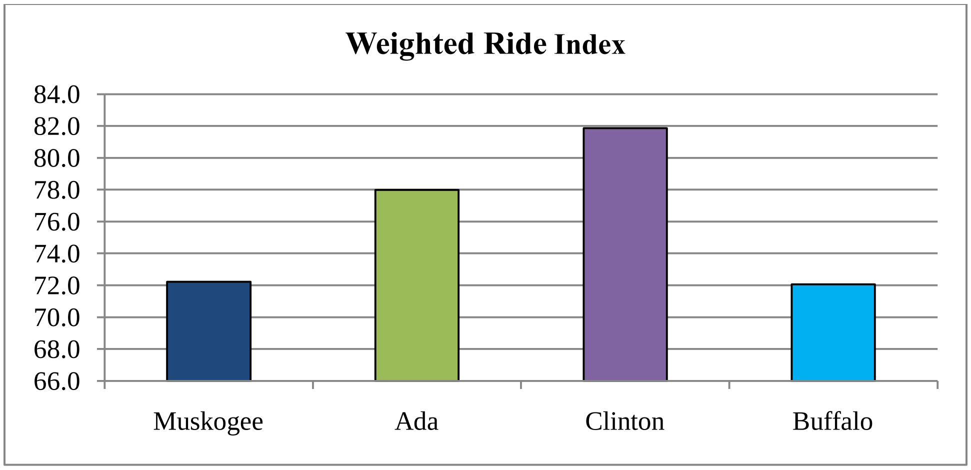

Figure 5. Weighted Ride Index

Weighted International Roughness Index

IRI is another measure of ride quality and often used as the metric attached to incentive/disincentive specifications based on constructed quality. Average weighted IRI results are illustrated in Figure 20. All divisions have almost same IRI results. The IRI results are Muskogee 129.4 in/mi, Ada 114.6 in/mi, Clinton 105.0 in/mi, and Buffalo 130.7 in/mi.

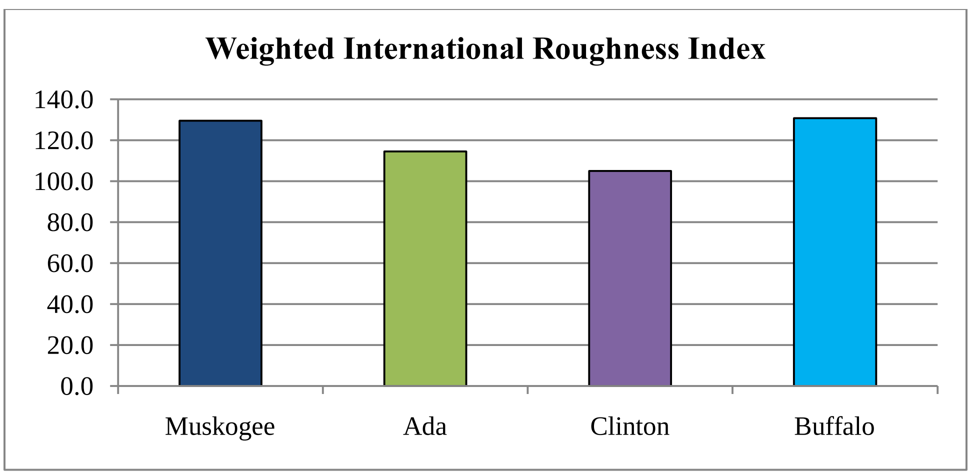

Figure 6. Weighted International Roughness Index

Weighted Rut Index and Average Rut Depth

The rut index is another measure of the structural integrity of the substrate. Additionally, the ruts tend to get flooded with binder during chip seal installation, which promotes premature flushing or bleeding in the wheel paths (Waters and Pidwerbesky 2006). This results in a reduction in skid numbers. Thus, looking at rutting in conjunction with chip seal design is important. The weighted rut index results are illustrated in Figure 21. Muskogee and Buffalo nearly same rut index these are 90.3 and 91.6 respectively. The lowest rut index is found in Ada division which is 78.5. Thus, Ada has the poorest roads in the study from a rutting perspective.

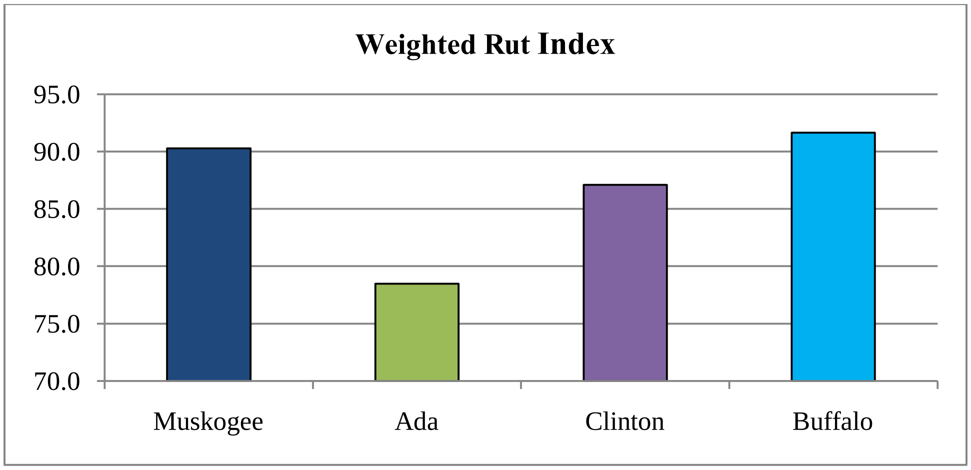

Figure 7. Weighted Rut Index

Weighted average rut depth results are shown in Figure 22. Among the divisions, Ada has highest average rut depth which is 0.22 inch, which confirms the rut index analysis. Muskogee, Clinton and Buffalo have 0.15 in, 0.17 in and 0.14 in average rut depth respectively.

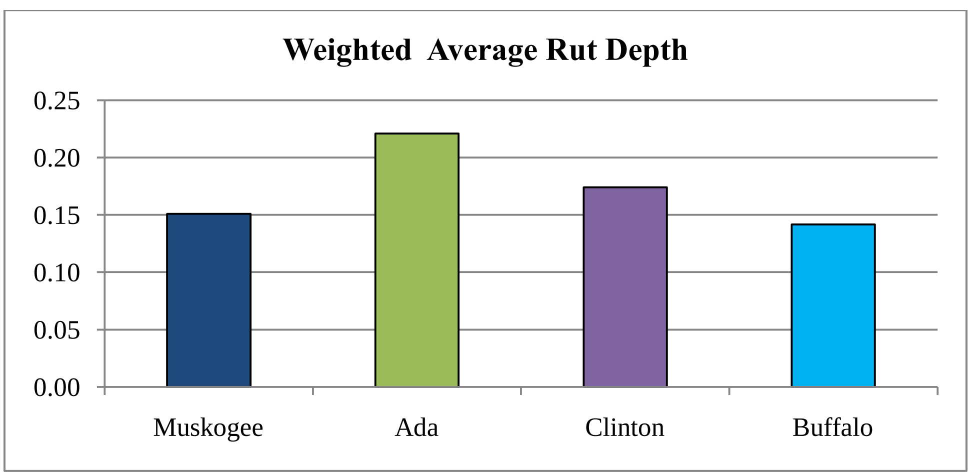

Figure 8. Weighted Average Rut Depth

Weighted Functional Index

The Functional Index is found by empirical means with the evaluator deducting points from 100 for transverse and non-wheel path cracking. Weighted functional index results are shown in Figure 23. Buffalo division has the lowest functional index at 68. Muskogee, Ada and Clinton have 85.3, 86.9 and 92.5 functional index respectively.

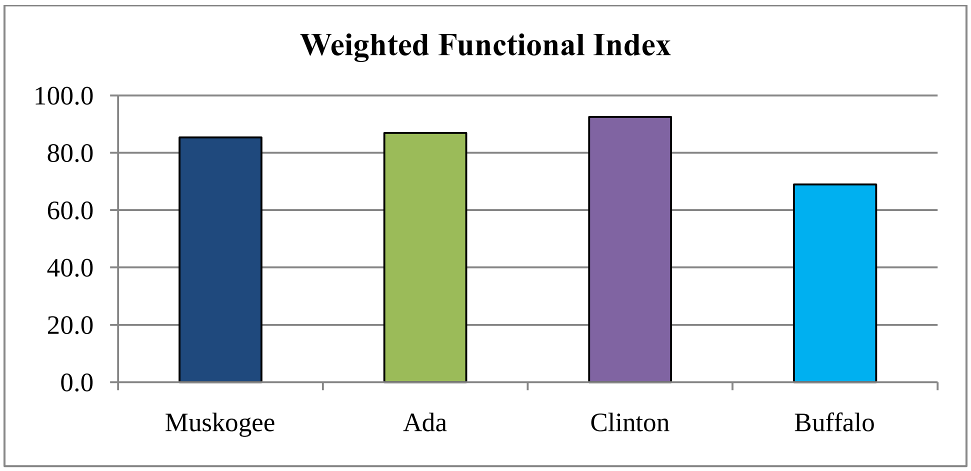

Figure 9. Weighted Functional Index

Weighted Structural Index

The Structural Index measures fatigue cracking and patching. Chip seals cannot correct fatigue cracking and research has found that a high level of patching often correlates to a high level of flushing/bleeding and low skid numbers (Gransberg and James 2006). Additionally, when chip seals are used for pavement preservation, this index can assist the maintenance engineer in identifying those roads that will benefit from preservation activities (i.e. keep a good road good) by selecting roads with a high PMS Structural Index. The results of this calculation are shown in Figure 24. It is clear to understand in this figure Clinton has best structural index with 97.9 structural index. The lowest result, which is 85.5, belongs to Buffalo division. Muskogee and Ada have 90.8 and 88.1 structural index respectively.

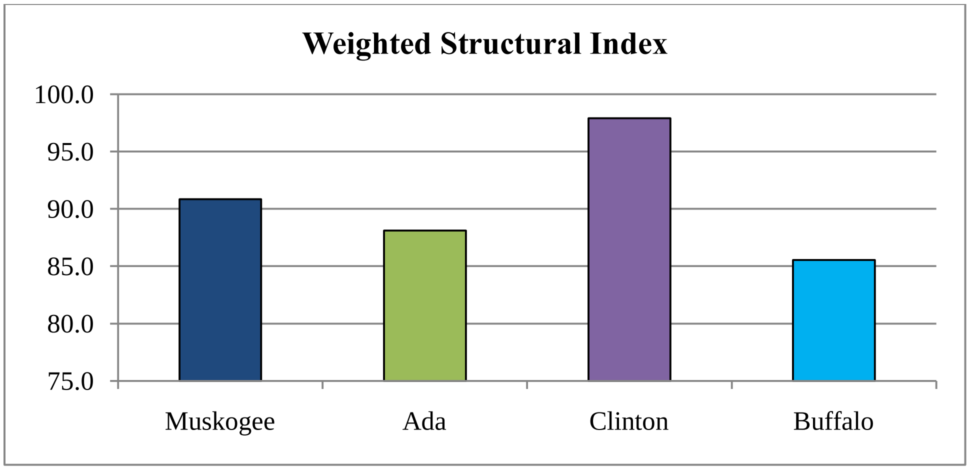

Figure 10. Weighted Structural Index

Weighted Skid Number

The skid number is one of the few PMS indicators that is directly measured rather than rated. ODOT does not have a published standard for a satisfactory skid number. An analysis of the literature confirmed by discussions with the Division 3 maintenance engineer indicates that a trigger value of 25 to 30 is used to identify pavements that need corrective action to regain their skid resistance. Skid number is also an important metric for pavement preservation project selection. A structurally sound pavement could require corrective action if it loses its skid resistance due to polishing. Additionally, it will also identify flushing/bleeding in the wheel paths for roads with chip sealed surfaces. The Weighted Skid Number results for each division are shown in Figure 25. Muskogee, Ada, Clinton and Buffalo have 51.5, 41.6, 47.8 and 46 average weighted skid numbers respectively.

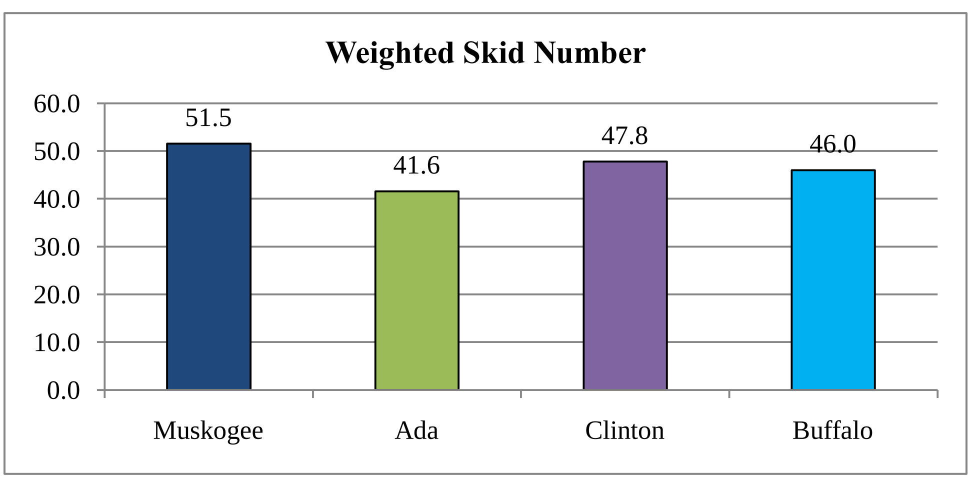

Figure 11. Weighted Skid Number

AGGREGATE/ BINDER COMBINATION ANALYSIS

No binder testing was completed in this study. Therefore, per the proposal, this analysis is limited to an evaluation of PMS data as related to the aggregate/binder combination source and type put in the context supplied by the structured interviews of division personnel. All interviewed divisions indicated that they selected the aggregate/binder combinations based on past success. It was also noted that short-term chip seal failures are rare and normally attributed to either unexpected weather events or improper construction means and methods. Based on Table 4, there are only two aggregate/binder combinations that were used for the division designated test sections and the difference is merely in the cover aggregate gradation. Thus, the only differences between the test sections are *the sources of the binder and aggregate*. Given this fact, no changes can be recommended for the material selection portion of the chip seal design methodology in use in each division.

Table 5 is a summary of the PMS data for each division. The various metrics have been developed based on the length-weighted average algorithms previously described by equations 12 through 18. This was done to arrive at a division-level set of metrics. The analysis assumes that each division procured cover aggregate from the same source. The assumption is confirmed for Divisions 1, 5 and 6. It is probably also for Division 3 who reported not knowing exactly the source of its cover aggregate since minimizing transportation cost is the norm, which would make a nearby source the mostly likely for that division.

Table 5. PMS Summary for Division Binder/Aggregate Combination

		Wt Ride Index	Wt Rut Index	Wt Functional Index	Wt Structural Index	Wt International Roughness Index	Wt Average Rut Depth	Wt Skid Number
Div1	**Muskogee**	72.2	90.3	85.3	90.8	129.4	0.15	51.5
Div3	**Ada**	78.0	78.5	86.9	88.1	114.6	0.22	41.6
Div5	**Clinton**	81.9	87.1	92.5	97.9	105.0	0.17	47.8
Div6	**Buffalo**	72.1	91.6	68.9	85.5	130.7	0.14	46.0

The purpose for including the rut index, structural index, and average rut depth relates to the ultimate purpose of a chip seal: to seal the road against water intrusion. Therefore, while the researchers recognize that a chip seal adds no structural capacity to the pavement upon which it is applied, the level of cracking and rutting will furnish two possible points of information. The first is the condition of the road prior to sealing. A road that shows structural distress will eventually see its cracks reflected through the new chip seal. Additionally, rutting causes the emulsion to flood the wheel paths and creates an uneven distribution of binder across the lane. The extra binder left in the wheel paths will contribute to early flushing and be measurable by a loss of skid numbers.

Table 5 shows that Division 3 has the highest average rut depth, the lowest weighted rut index and the lowest weighted skid numbers. This confirms the relationship between rutting and skid numbers discussed above. However, checking the reported values finds all of them within the satisfactory range. While no specific recommendations can be made, this does point to future research to authoritatively determine the relationship and potentially develop guidance with regard to chip sealing rutted roads. Such research would seek to quantify a maximum weighted average rut depth above which chip sealing would be avoided. The benefit from that research would be found in enhanced safety by not creating conditions in the wheel paths that promote flushing and loss of skid resistance. The research might also be able to furnish guidance regarding the gradation of cover aggregate based on rut depth. The New Zealand Transport Agency specifies a large size cover aggregate for its chip seals when minor rutting is present and believes that this reduces the potential for flushing in the wheel paths (Pidwerbesky et al 2004).

The weighted ride index and the weighted IRI are also related. Again chip sealing can do nothing to correct or improve these indices. However, like the previous discussion on rutting, the two indices and the weighted structural index provide a measure of the amount and severity of cracking. While no trend can be discerned from Table 5, it would seem logical that in keeping with the mantra of the pavement preservation movement, “the right treatment on the right road at the right time” (Galehouse et al 2003) that there would be a level below which chip sealing should be discouraged. Such an analysis could also be done in conjunction with the future research regarding rutting/skid.

Because of the consistency of aggregate and binder combinations supplied by the divisions (i.e. the same grade of binder and two grades of aggregate in all divisions) no discernable trend with regard to aggregate/binder combinations was found. Therefore, the remainder of the report will be devoted to reporting the trends found in the aggregate testing.

ANALYSIS OF AGREGATE ABRASION TESTS AND AIMS

This section reports the results of the laboratory testing conducted on the chip seal aggregate samples. The major characteristics of interest were abrasion resistance and angularity. Ideally, chip seal aggregate will be resistant to the abrasion that results as it is handled between the pit and the road. High angularity increases surface area, which promotes adhesion between the binder and the aggregate. Finally, aggregate microtexture enhances skid resistance.

SIEVE ANALYSIS

First, the gradation of the aggregate samples from each division was characterized by sieve analysis. The gradation curves are shown in Figure 5. It shows that gradation of Muskogee, Antlers and Buffalo are nearly identical. The aggregate dimensions from these three divisions generally range between #4 and 3/8”. Clinton and Ada division aggregates are more uniformly graded than the other divisions and gradation sizes close to each other. Table 6 shows that these two divisions also have the highest PUCs which means their samples were the least uniform of the five. Both have a high percentage of particles that are less than the embedment depth and hence would appear to promote flushing/bleeding. This can be checked with the PMS skid number data where one would infer that the skid numbers in these districts will be lower than the others.

Table 6. Performance-based Uniformity Coefficients

PUC Coefficients					
Division	D1 Muskogee	D2 Antlers	D3 Ada	D5 Clinton	D6 Buffalo
P_{EM}, %	15.3	10.4	20.5	23.4	11.8
P_{2EM}, %	90	94.6	85.7	84.8	93.4
PUC	0.17	0.11	0.24	0.28	0.13

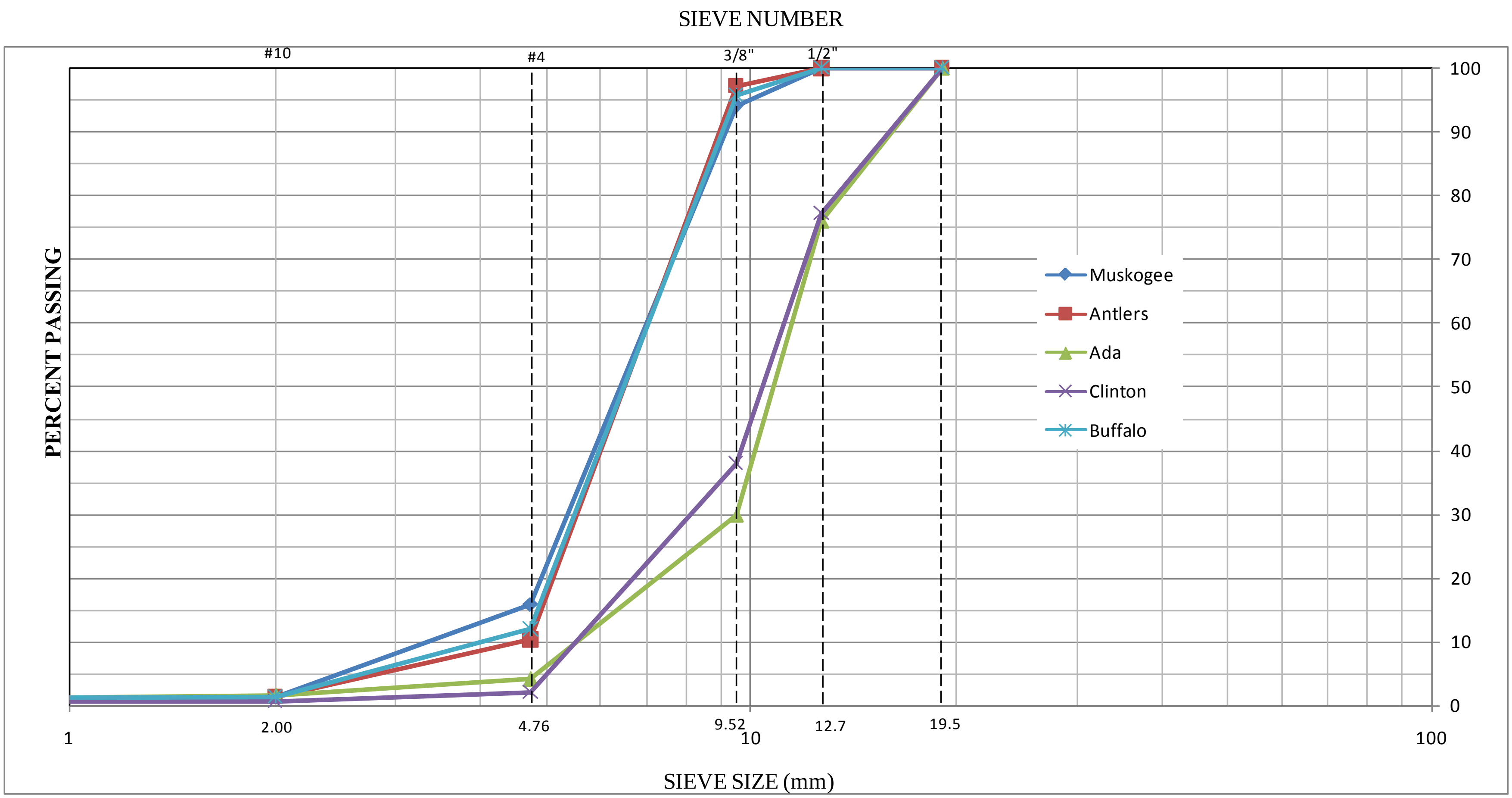

Figure 12 Gradation Curves of Division Aggregates

ABRASION TEST RESULTS

The purpose of having two tests of the same property is the fact that the Micro-Deval is conducted using water and research has shown that some aggregates are weaker when saturated (CAPA 2003). In fact, one study states: “The Micro-Deval Test is a better indicator of aggregate quality than is the LA Abrasion Test.” Therefore, since the quality of the aggregate is a key factor in chip seal performance, having both tests on the same samples allows the team to evaluate potential differences in dry abrasion resistance and wet abrasion resistance.

Los Angeles Abrasion Test Results

Los Angeles (LA) abrasion test measures aggregate resistance to crushing, degradation and disintegration in chip seals during operation. A low LA abrasion test value is desired because it indicates an aggregate with high abrasion resistance. The LA abrasion test results are shown in Figure 6. The figure shows that the Antlers sample is more abrasion resistant and the Ada sample was the least resistant. The ODOT specifies a % loss less than or equal to 40% on this test. Hence, one can see that the aggregates shown in Figure 6 are well within the specification.

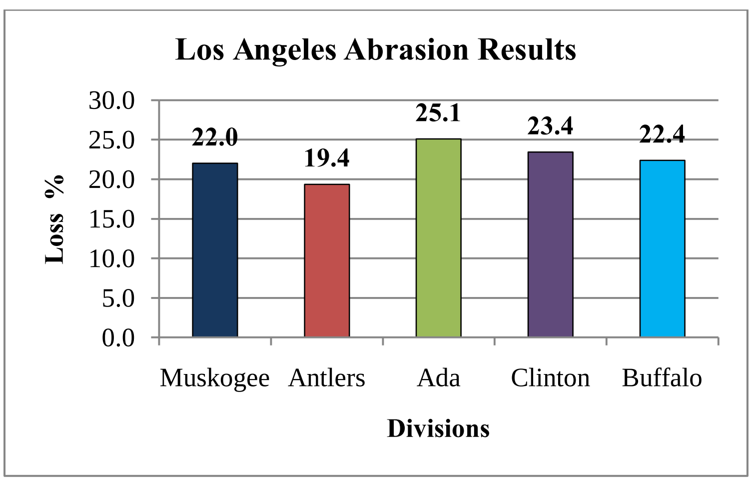

Figure 13. LA Abrasion Test Results

Micro-Deval Results

Micro-Deval is the second test to measure the abrasion resistance. While ODOT does not specify this test for chip seal cover aggregate, it does use a standard of less than or equal to 25% allowable percentage loss for other purposes (Superpave, stone matrix asphalt, permeable friction course, and open-graded friction course). The corresponding LA abrasion test specification in these applications is either less than or equal to 30% or 40% depending on the aggregate's use. The test results are shown in Figure 7. One can see that the loss observed would permit the aggregate samples to be used for other paving applications than chip seals. Looking at the relative ranking between the divisions, the Buffalo division was the most abrasion resistant sample and the Ada division sample was the least.

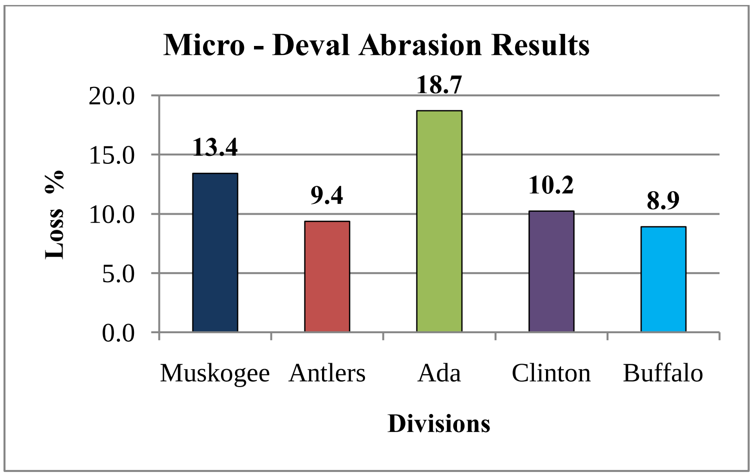

Figure 14. Micro-Deval Abrasion Test Results

Analysis

Table 7 shows a comparison of the two tests and the variation of each sample from the lowest value found in the testing. This essentially quantifies aggregate quality in terms of a variation in percentage loss from the "best" (most abrasion resistant) sample. The striking aspect of Table 6 is the variation in the Micro-Deval test results versus the LA abrasion tests. Ada was found to be the lowest quality in both tests but it was only 29% worse in the LA abrasion test but 110% worse in Micro-Deval. Ada also had the lowest percent deviation between the tests. While the sample size in this project is too low to permit a statistical inference to be made, this test protocol does establish that a relationship between aggregate qualities measured by the two different tests may carry forward to chip seal performance.

Table 7. Comparative Abrasion Test Output.

Division	Test Results			Percent Change from Lowest Value	
	Los Angeles Abrasion Results	Micro - Deval Abrasion Results	Percent Deviation Between Tests	Los Angeles Abrasion	Micro - Deval Abrasion
Muskogee	22.0	13.4	64%	13%	51%
Antlers	19.4	9.4	106%	Low value	5%
Ada	25.1	18.7	34%	29%	110%
Clinton	23.4	10.2	129%	21%	15%
Buffalo	22.4	8.9	151%	15%	Low value

The Colorado Asphalt Pavement Association (CAPA 2003) concluded that the Micro-Deval test was a better predictor of aggregate quality than the LA abrasion test. The conclusion was based on a lower observed variation between tests. The opposite was observed with the samples shown in Table 7. That may indicate that the CAPA conclusion may not be applicable to chip seals since the LA abrasion test produced less relative variation between samples. However, the focus of the study was on hot-mix pavement requirements. Chip seals are not expected to be permanent surfaces and are used to extend the service life of the underlying pavement. Therefore, it is logical to frame the value of the Micro-Deval test in the context of the specific application.

Chip seals are used for pavement preservation and maintenance. As such, their primary purpose is to seal pavement cracking and prevent water intrusion into the subgrade and the purpose of the cover aggregate is to protect the bituminous seal from traffic abrasion (Epps et al 1980). Chip seals also provide increased macrotexture which enhances pavement drainage and reduces hydroplaning. Depending on the properties of the cover aggregate, a chip seal will also enhance skid resistance (Pidwerbesky et al 2006). It is not uncommon for a maintenance engineer to apply a chip seal on a stretch of road whose skid number has fallen below minimum acceptable limits as a means to immediately correct the safety defect (Riemer et al 2010).

Given these reasons for using chip seals, it is logical to include both the Micro-Deval and the LA abrasion tests to quantify the quality of chip seal cover aggregate for three reasons:

1. Pavement surfaces are dry more than they are wet in Oklahoma (NWS 2010). Dry aggregate and dry tires will impact the polishing of the cover aggregate in a different

manner than in wet conditions. Thus, the LA abrasion test furnishes a tried and true analog for abrasion resistance and should be retained.

2. Since the LA abrasion test involves the impact resistance of the aggregate sample to crushing under load, it also gives an indication of a given cover aggregate's ability to withstand heavy wheel loads without degradation. Often the low volume rural roads where chip seals are prevalent have a high percentage of heavy loads due to the agricultural natural of the rural community. Again, these conditions argue for retaining the LA abrasion test.
3. The wet nature of the Micro-Deval test challenges the mineralogy of a given aggregate with regard to resistance to loss of solids through dissolving. Additionally, the major safety benefit accrued via chips seals is enhanced surface drainage. Therefore it seems logical that a wet abrasion test would be valuable by furnishing an indication of water's impact on the cover aggregate.

AIMS RESULTS

Seminal research by McLeod (1962) showed that aggregate shape was a key factor in chip seal performance. Since the technology to efficiently measure and characterize particle shape did not exist, McLeod developed failure criteria based on the ratio of aggregate retained weights to the median particle size (the 50% passing sieve size). Lee and Kim (2009) built on McLeod's concepts and proposed a metric called the Performance-Based Uniformity Coefficient (PUC). Their work was based on the premise that the "perfect" particle shape was a cube. As the stone shape becomes more elongated, the chance that it will not be properly embedded (defined as less than 50% by Lee and Kim) increases. Additionally, if the percent of particles less than the median particle size is greater than those that are greater than the median particle size, the potential for flushing or bleeding increases (Lee and Kim 2009). The AIMS technology now provides the ability to quantify particle shape that McLeod did not have in 1962 and hence, the researchers hope to build on the work done by Lee and Kim by adding the AIMS output to the suite of chip seal performance indicators.

The purpose for using AIMS is to characterize the surface structure of the chip seal aggregate samples. The primary factors of interest are:

- Shape – Major characteristic of adhesion and post-construction aggregate retention.
- Angularity – Major characteristic of final skid resistance
- Texture – Major characteristic of preconstruction polishing and contributing characteristic to final skid resistance.

The test requires the aggregate particles derived from the division samples to be sieved and separated to three size groups (retained on 3/8", 1/4", and #4 sieves). These were scanned with the AIMS. After that, the AIMS output uses the retained sieve analysis weights and total fractional indexes to calculate composite indexes. An example is shown in Figure 8.

									Fractional Index				
Sieve No.	Sieve Size (mm)	Cum. % Passing	% Ret.	2-D Form Index	Grad. Ang. Index	Rad. Ang. Index	Sphericity Index	Texture Index	Fractional 2-D Form Index	Fractional Grad. Ang. Index	Fractional Rad. Ang. Index	Fractional Sphericity Index	Fractional Texture Index
A	B	C	D	E	F	G	H	I	J=E*D/100	K=F*D/100	L=G*D/100	M=H*D/100	N=I*D/100
1/2 in	12.70	100.00	0.00										
3/8 in	9.52	94.00	6.00	6.56	2885.74	9.39	0.73	175.81	0.39	173.14	0.56	0.04	10.55
1/4 in	6.35	47.00	47.00	8.40	3942.86	10.64	0.63	151.34	3.95	1853.14	5.00	0.30	71.13
#4	4.75	15.00	32.00	8.63	3314.90	12.16	0.58	156.30	2.76	1060.77	3.89	0.19	50.02
#10	2.00												
#40	0.420												
#200	0.075												
		∑D	85.00					∑	7.10	3087.06	9.45	0.52	131.69

Composite 2-D Form Index =	8.36	**∑J / ∑D**
Composite Gradient Angularity Index =	3631.83	**∑K / ∑D**
Composite Radius Angularity Index =	11.12	**∑L / ∑D**
Composite Sphericity Index =	0.62	**∑M / ∑D**
Composite Texture Index =	154.93	**∑N / ∑D**

Figure 15. Example Calculation of Composite AIMS Index

Shape - 2D Form Index Results

The 2D Form Index results are shown in Figure 9. Muskogee, Antlers, Ada, Clinton and Buffalo division aggregates have 8.36, 8.59, 7.51, 7.57, and 8.00 2D indexes respectively. Figure 10 shows that aggregate circularity of the each division in the two dimensional form. It shows the distribution of aggregate circularity in each division. Figure 9 shows that the Ada and Clinton aggregates are more circular with values of 30.6% and 31.3% respectively. Conversely, Antlers and Muskogee have more elongated aggregate than other divisions at 23.0% and 16.4%. Elongated aggregates are difficult to seat during construction and when seated may promote flushing if the least particle size dimension is less than the embedment depth (Lee and Kim

2009). Thus, the results lead to an inference that Muskogee and Antlers divisions may have more post-construction aggregate retention problems and possibly a higher incidence of flushing than the other divisions.

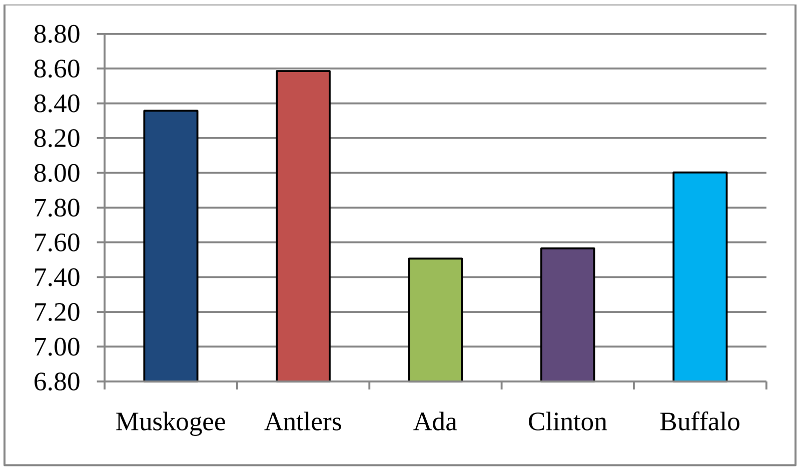

Figure 16. Composite 2-D Form Index

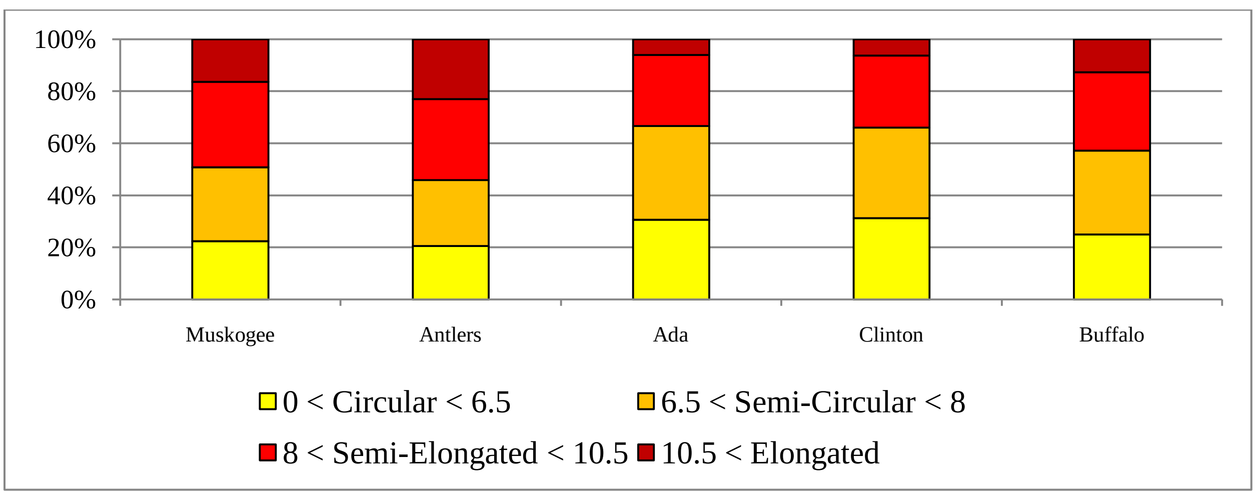

Figure 17. Details of the 2D Form Index of Division Aggregates

Shape - Sphericity Index

The composite sphericity index is a relative measure from zero to one with one denoting a cubical particle. Since the purpose of the cover aggregate is to protect the bituminous seal from traffic wear, a high sphericity index is desirable. This is based on the need for a consistent size particle (i.e. the “perfect cube”) to ensure that the majority of the cover aggregate particles have a least dimension greater than the embedment depth. The division sample results are shown in

Figure 8. Clinton and Ada division aggregates have the highest sphericity indexes of 0.69 and 0.67 respectively. Figure 11 shows the details of the sphericity index. Clinton and Ada divisions have lowest flat/elongated and low sphericity aggregate as percentage. Again, the results support the 2D Form Index results that indicate that Muskogee and Antlers divisions may have lower performing chip seals due to aggregate shape.

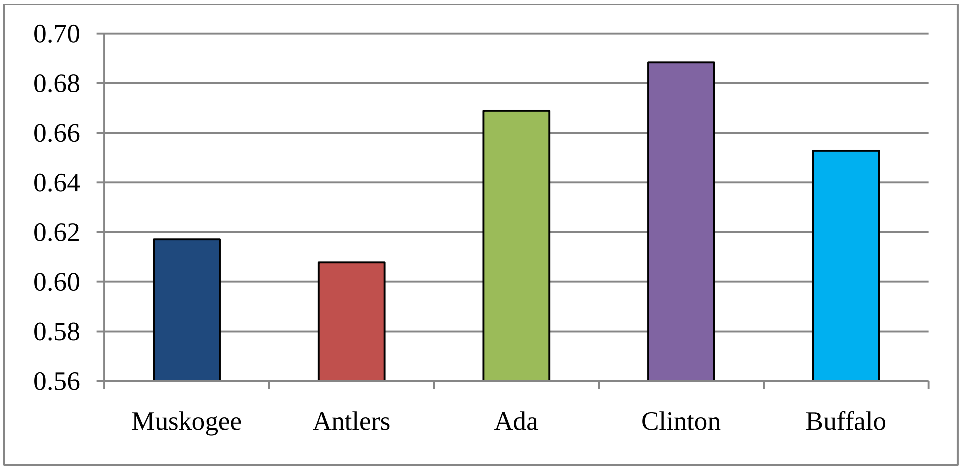

Figure 18. Composite Sphericity Index

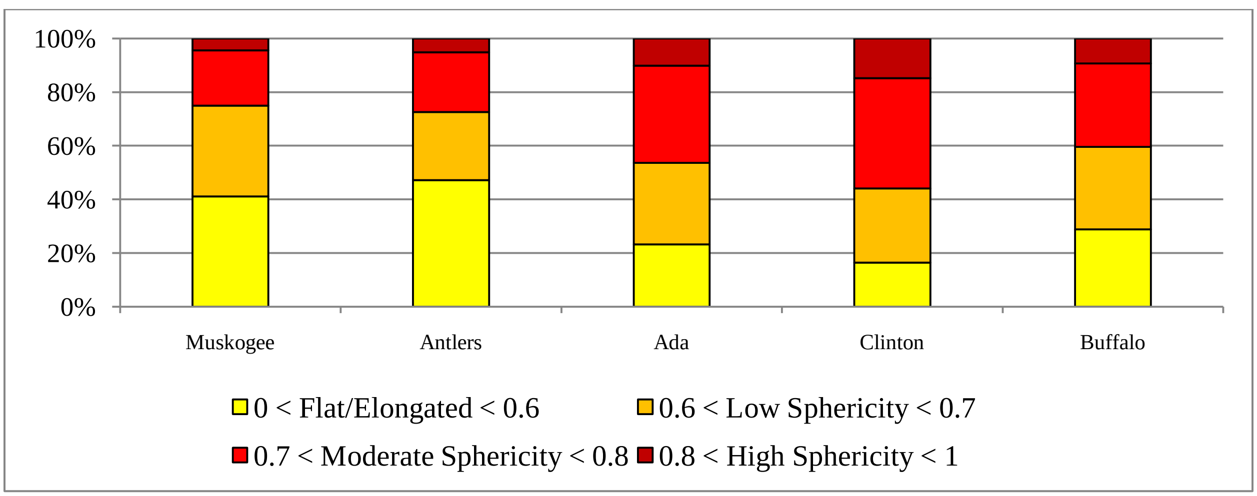

Figure 19. Details of Sphericity Index of Division Aggregates

Aggregate Angularity Results

As previously stated, angularity is promotes adhesion between the binder and aggregate and also contributes to post-construction skid resistance. Thus, this aspect of the AIMS analysis has the highest potential for ODOT implantation through future specification development based on AIMS testing.

Gradient Angularity

Aggregate angularity is important for skid resistance on pavement surfaces and binder-aggregate adhesion. The gradient angularity is expressed as a relative range of zero to 10000 with a perfect circle having a value of zero. A higher value indicates a more angular shape and high values are desired for chip seal cover aggregate. Angularities of each division sample were determined using AIMS and results are shown in Figure 13. Muskogee has the highest gradient angularity index. The other divisions are roughly equal. Figure 14 shows the details of the gradient angularity index. It shows that all division samples are composed primarily of sub-rounded aggregates.

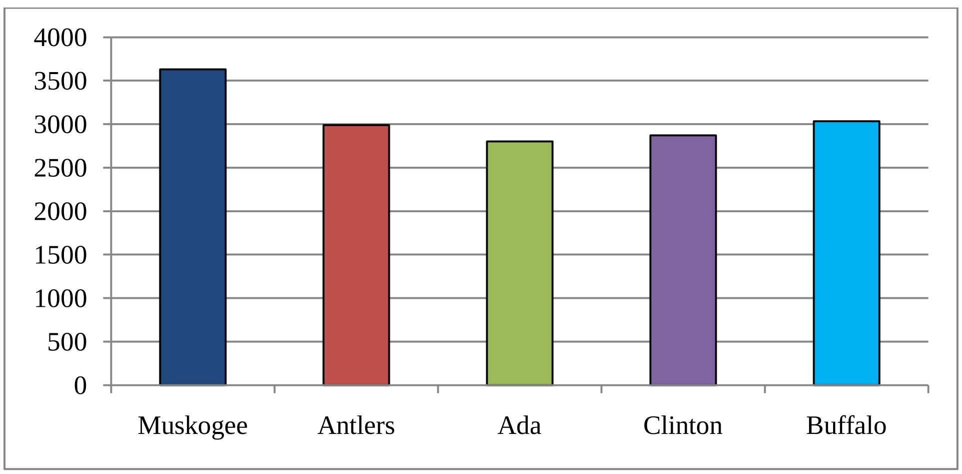

Figure 20. Composite Gradient Angularity Index

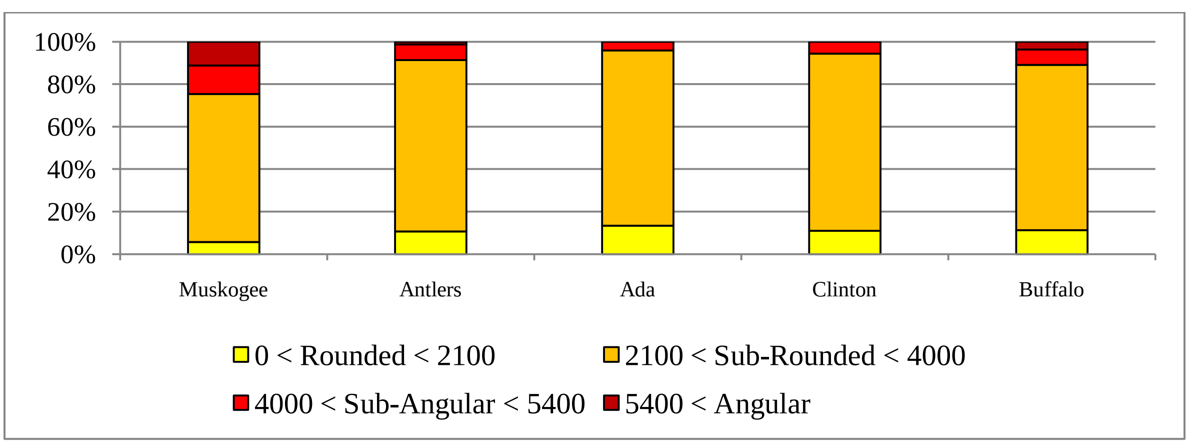

Figure 21. Details of Gradient Angularity Index of Division Aggregates

Radius Angularity Results

Radius angularity index measures the difference between the particle radius in a certain direction and that of an equivalent ellipse. It ranges from zero to 20 with zero denoting a total lack of sharp edges, i.e. no angularity. Values above 10 indicate the presence of angularity which is necessary to achieve the desired chip seal performance and lower values indicated the presence of polished particles (Masad et al 2001). Figure 15 illustrated radius angularity index of division aggregates. Antlers division has a highest value of 12.05. Second highest radius angularity index belongs to Buffalo division at 11.74. The other divisions have an angularity index that is roughly equal. The details of the radius angularity index are shown in Figure 16 and the Antlers and Buffalo divisions have less than 10% rounded and sub-rounded aggregate while other divisions have above that number. This would lead one to expect that these divisions would have fewer failures due to premature aggregate loss. It would also infer better long-term skid resistance.

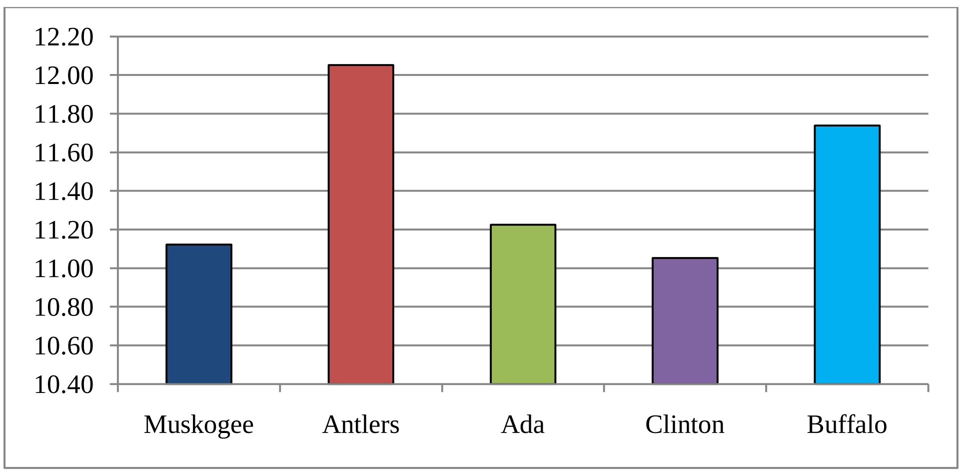

Figure 22. Composite Radius Angularity Index

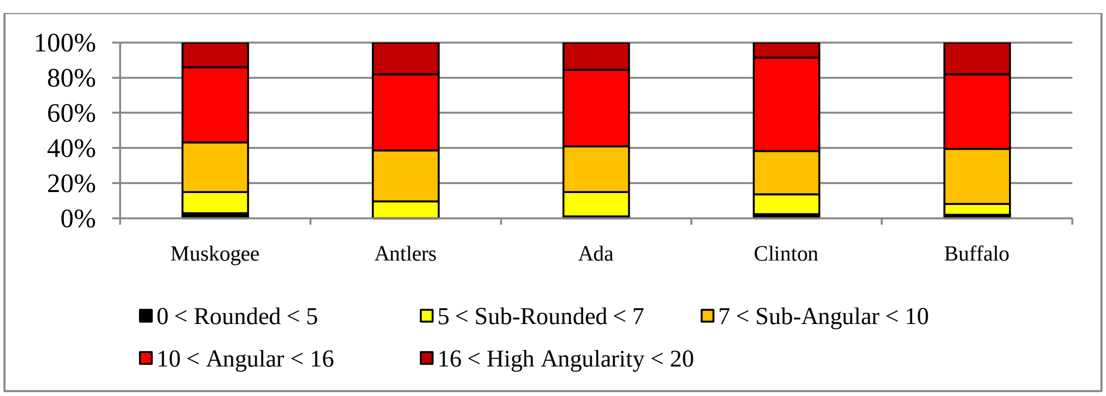

Figure 23. Details of Radius Angularity Index of Division Aggregates

Texture Index Results

The texture index is derived from wavelet analysis, “a powerful method for decomposition of the different scales of texture” (Mallat 1989). Wavelet frequencies are commonly used to differentiate between pavement surface microtexture and macrotexture (Sandberg 1998). Thus, the texture index is related to microtexture, which is usually defined as surface changes in the 0 to 0.2mm range. The texture index is expressed on a relative scale of increasing roughness from zero to 500. The texture index is highly correlated with angularity (Masad et al 2007). However, the two are measuring different interrelated components of the particle surface (e.g. roughness versus sharp corners). Therefore, it is appropriate to consider each index separately. The literature does not supply a recommended value that can be used to differentiate “good” from “bad” texture indices. However, the detailed AIMS output furnishes a breakdown of the percentage of the sample that fell below the roughness value of 165, which indicates a polished particle. Since chip seals are often applied to correct a loss of skid resistance, it is logical to infer that a sample that had a high percentage of polished particles would indicate the potential for low skids numbers and thus, this threshold could be explored as a possible standard for chip seal aggregate quality.

Figure 17 illustrates texture index results, and Ada and Clinton divisions have highest texture index among the other divisions. Their texture index results 219.25 and 210.92 respectively. The lowest texture index belongs to Muskogee division. Figure 18 shows that details of the texture index analysis. As seen in Figure 18, Muskogee division has around 60% polished aggregate. The other divisions have less than 40% polished aggregate. This would infer that Muskogee may have more skid resistance issues than the other divisions. Potentially a value less than 50% of the sample with a texture index less than 165 could be used to differentiate. However, this is an area where more research is necessary to furnish definitive guidance to ODOT specifications writers.

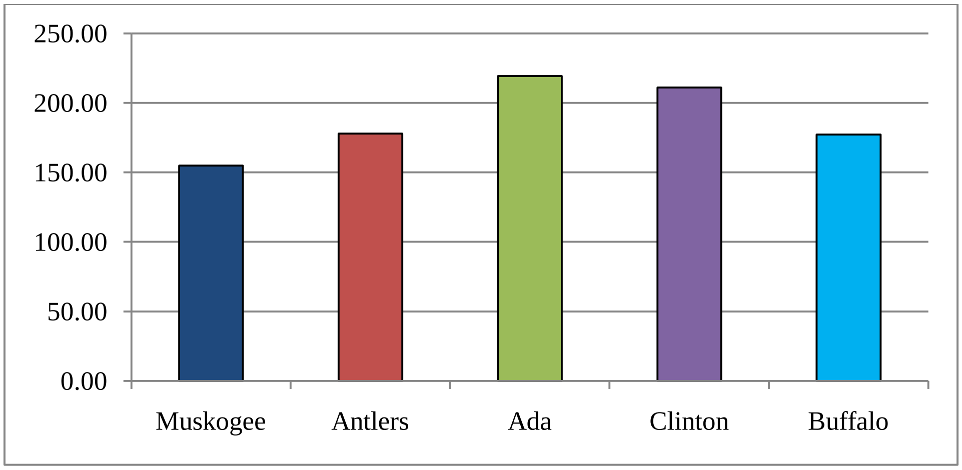

Figure 24. Composite Texture Index

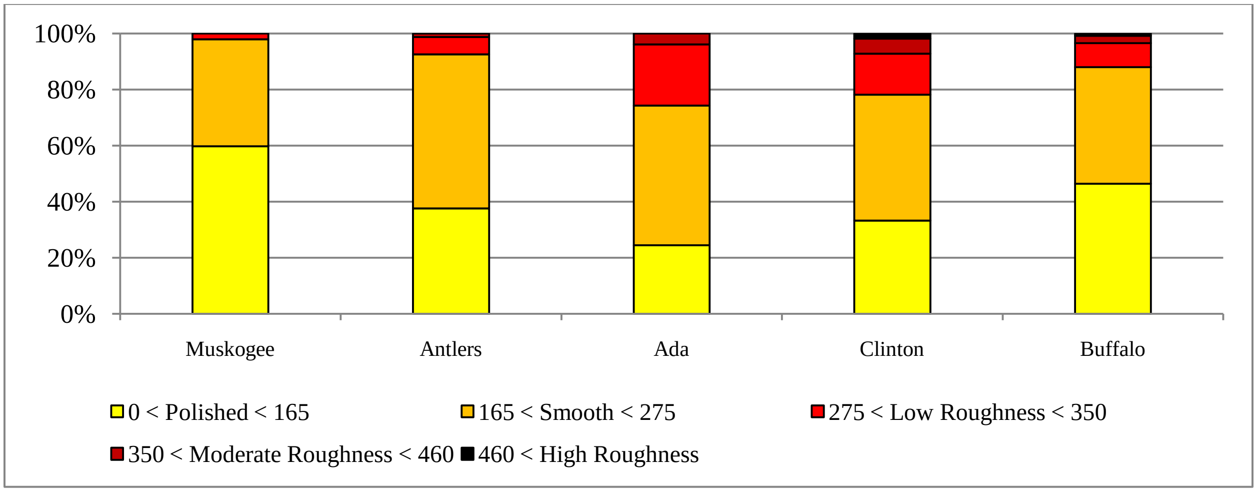

Figure 25. Details of Texture Index of Division Aggregates

Therefore, knowing the laboratory test results, allows the team to then check the above-cited inferences against the performance of typical chip seals in each divisions. If the two independent lines of information intersect, then the correlation can be turned into a recommendation to improve ODOT chip seal specifications.

TRENDS BETWEEN AGGREGATE PROPERTIES, AIMS AND PMS DATA

Given the information developed by the aggregate laboratory tests, AIMS results and PMS data, the next step is to search for trends within the data. It is appropriate to discuss the rationale behind connecting the two sets of data. The aggregate tested in this project came from the same source as the division-designated test sections. Some readers will be bothered by the fact that the aggregate samples did not come directly from the stockpiles of the PMS control sections. However, to be able to do so would require a project that lasts 3 to 5 years to be able to collect the performance data of the specific aggregate binder combinations. This is an exploratory research project that is looking for trends between the two types of data not for statistically significant correlations. Therefore, the results that follow should not be interpreted as authoritative. As will be seen, there appear to be several promising opportunities to improve ODOT specifications. These will be referred to as potential correlations and it must be understood that additional research must be completed before authoritative recommendations to change ODOT chip seal specifications can be made.

Trend Finding Methodology

Linear regression was the primary tool for identifying possible trends in the two sets of data. The regression output provides a coefficient of determination (R^2) value, which quantifies the amount of variation in the independent variable that is accounted for by the dependent variable (Draper and Smith 1998). In essence, it acts as a "goodness of fit" measure. It is used here to merely identify possible correlations and to reject those combinations that do not have promising R^2 values. *It is important to understand that while the following procedures appear to be quantitative, they are in fact the product of the largely qualitative PMS data and must be interpreted in that light.* Secondly, the sample sizes are very small and as such they cannot be considered statistically significant. However, this type of analysis is the appropriate starting point for identifying previously unknown relationships between chip seal aggregate properties and chip seal performance. Tables 8 and 9 depict the consolidated data discussed in the previous sections for the four divisions where both aggregate samples and control sections were obtained.

Table 8. Consolidated Aggregate Characteristics Data

Division		Composite 2-D Form Index	Composite Gradient Angularity Index	Composite Radius Angularity Index	Composite Sphericity Index	Composite Texture Index	Los Angeles Abrasion Results	Micro - Deval Abrasion Results
Div1	**Muskogee**	8.4	3631.8	11.1	0.8	199.1	22.0	13.4
Div3	**Ada**	7.5	2802.2	11.2	1.0	318.1	25.1	18.7
Div5	**Clinton**	7.6	2871.1	11.1	1.0	312.4	23.4	10.2
Div6	**Buffalo**	8.0	3034.9	11.7	0.9	235.5	22.4	8.9

Table 9. Consolidated PMS Metrics Data

Division		Wt Ride Index	Wt Rut Index	Wt Function Index	Wt Structural Index	Wt Pavement Quality Index	Wt IRI	Wt Average Rut Depth	Wt Skid Number
Div1	**Muskogee**	72.2	90.3	85.3	90.8	82	129.4	0.15	51.5
Div3	**Ada**	78.0	78.5	86.9	88.1	81	114.6	0.22	41.6
Div5	**Clinton**	81.9	87.1	92.5	97.9	88	105.0	0.17	47.8
Div6	**Buffalo**	72.1	91.6	68.9	85.5	78	130.7	0.14	46.0

The procedure used involved graphing an aggregate property variable from Table 8 against a PMS variable in Table 9. Linear regression analysis was applied to the resultant scatter plot and combinations with R^2 values greater than 0.5 were considered possible candidates for identifiable trends. Those combinations that did not meet this standard were rejected.

Skid Number Trends

The regression process produced two trends with regard to Skid Number (SN) and laboratory tested aggregate characteristics. The gradient angularity is based on the principle that at sharp corners of the image the direction of the gradient vector changes rapidly whereas it changes slowly along the outline of rounded articles. SN is also related to aggregate surface characteristics. Therefore, one would intuitively expect to find some level of correlation between SN and Gradient Angularity. Table 10 shows the output from the trend analysis. One can see that there is a reasonable relationship between SN and aggregate angularity as measured by the gradient method; whereas no trend was found with radius angularity. This leads to the conclusion that AIMS gradient angularity test may be used to evaluate chip seal aggregate skid resistance. Based on the discussion in the literature review, SN should increase as angularity increases.

Thus, further research is indicated to authoritatively establish the relationship between the two metrics. Assuming success in that endeavor, a ODOT chip seal aggregate specification based on gradient angularity could be developed as a mechanism to promote surface friction on sealed roads and increase the overall safety of the network.

Table 10. Regression Analysis Output for Skid Number Versus Aggregate Characteristics

Aggregate Characteristic	PMS Metric	Coefficient of Determination
Gradient Angularity	Skid Number	$R^2 = 0.69$
Radius Angularity	Skid Number	$R^2 = 0.07$
LA Abrasion Test	Skid Number	$R^2 = 0.73$
Micro-Deval Test	Skid Number	$R^2 = 0.26$

The second relationship found is the SN and aggregate abrasion resistance as measured by the LA abrasion test. Though the R^2 value is the highest in Table 10, this trend is less straightforward than the one with angularity. Essential the abrasion tests seek to quantify a given aggregate's susceptibility to polishing. Polishing is a loss of microtexture and subsequent reduction in skid resistance, resulting in lower SNs. The fact that the same trend was not evident in the Micro-Deval test probably relates to the aggregate property changes that occur when it is saturated. Again, further research is recommended to better understand the relationships. Until such time, ODOT can use this information as a reason to prefer LA abrasion testing on chip seal aggregate rather than Micro-Deval testing.

Sieve Analysis Trends

The PUC was regressed against both the aggregate characteristics and the PMS metrics. The output is shown in Table 11. Four trends were observed. First, three characteristics measured using the AIMS appear to have a relationship with the PUC. First, the radius angularity index versus the PUC rendered an R^2 value greater than 0.50. Since the PUC is a measure of the uniformity of the aggregate and radius angularity is a measure of how much the radius from a given point changes with respect to the mean radius of the stone, one would expect to find some relationship. Additionally, the sphericity index measured how close to a perfect sphere a given stone is shaped, the same intuitive relationship exists with respect to uniformity.

Table 11. Regression Analysis Output for Sieve Analysis Metric
Versus Aggregate Characteristics and PMS Metric

Sieve Analysis Metric	Aggregate Characteristic	PMS Metric	Coefficient of Determination
Performance-based Uniformity Coefficient	Composite Radius Angularity Index	-	$R^2 = 0.60$
Performance-based Uniformity Coefficient	Composite Sphericity Index	-	$R^2 = 0.70$
Performance-based Uniformity Coefficient	Composite Texture Index	-	$R^2 = 0.69$
Performance-based Uniformity Coefficient	-	Weighted IRI	$R^2 = 0.94$

The composite texture index trend is surprising and is probably a coincidence since there are no two physical parameters between it and the PUC that measured. The final trend is between the PMS IRI metric and the PUC. This makes sense in that a chip seal with very uniform gradation would have fewer macrotexture differential depths and provide a smoother and less noisy ride.

Cost Index Trends

Table 12 contains the results of the cost index number analysis. In this type of analysis, the lower number indicates a more cost effective to solution to furnishing the engineering property shown in the top row of Table 10. Thus, Clinton Division has the most cost effective program for maintaining pavement quality and pavement functional qualities. Muskogee is the most cost effective in maintaining IRI and skid. The importance of these metrics is to justify purchasing marginally higher cost materials, in this case chip seal aggregate, because of superior performance. This is in line with the approach advocated by Lee and Kim (2009) when they developed the PUC.

Table 12. Cost Index Output

Division		Pavement Quality CI	Functional CI	IRI CI	Skid CI
Div1	Muskogee	305	303	192	499
Div3	Ada	323	320	232	630
Div5	Clinton	274	260	241	512
Div6	Buffalo	373	423	214	639

When these metrics were regressed with the aggregate properties, only one trend was observed and its R2 value was very significant as seen in Figure 26. At this point, the relationship is difficult to explain in terms of the input values for each metric. However, it is a trend that is definitely worth investigating in a future project.

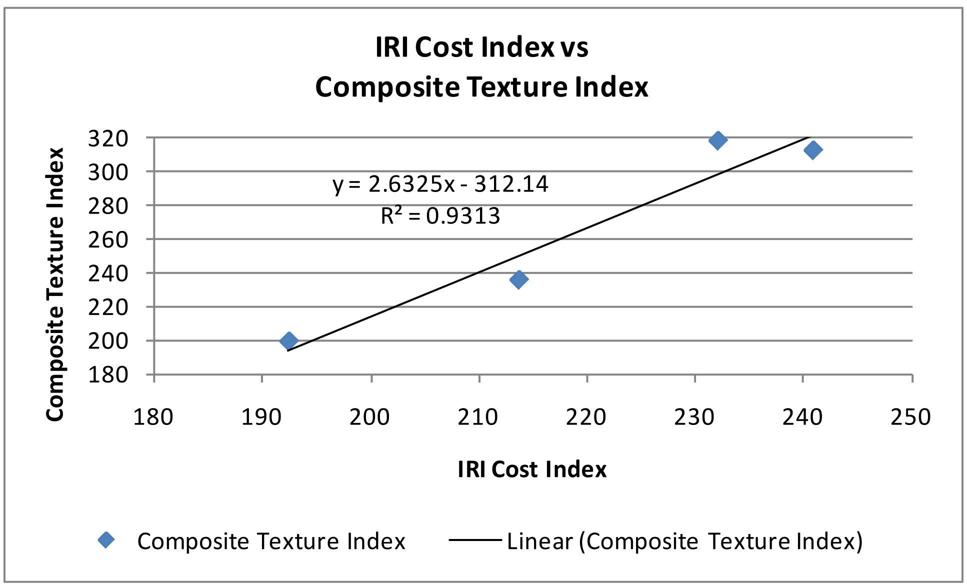

Figure 26. IRI Cost Index Regressed with Composite Texture Index.

CONCLUSIONS

The following conclusions can be drawn from the above analyses.

1. No positive or negative trends were discovered with respect to ODOT aggregate/binder combinations. Chip seal binder selection appears to yield satisfactory performance in the divisions studied.
2. The Los Angeles abrasion results show that all the aggregate samples met the ASTM, AASHTO and ODOT specification. The Antlers Division aggregate is more resistant than

the other division aggregates. In addition, in the Micro-Deval Test found the Antlers and Buffalo division to be more resistant.

3. According to Micro-Deval and LA abrasion test results, it seems that the LA test may be more appropriate for measuring the quality of chip seal aggregates. However, since the sample size was not statistically significant, no authoritative conclusion can be reached.
4. Skid resistance is an important pavement characteristic purely from a safety standpoint. The study found that SN is related to aggregate gradient angularity. In AIMS analysis, it is found that increasing aggregate gradient angularity tracked with increasing SN, which was not the case for radius angularity.
5. The analysis confirmed that a relationship exists between aggregate abrasion test results and SN. SN decreases as the amount of loss measured in the aggregate abrasion test increases.
6. The PUC is a promising metric for measuring chip seal susceptibility to failure due to flushing/bleeding. Trends between the PUC and the radius angularity index and sphericity index found using the AIMS test were observed.
7. A trend was also observed between the PUC and the PMS IRI.
8. The cost index analysis showed that the Clinton and Muskogee division maintenance programs are the most cost effective. The result is explained by the relative quality of its aggregate.

Recommendations

The sample sizes that were used in this project were too small to make authoritative recommendations based on the above conclusions. Therefore, the all the recommendations in this section are for future research.

1. Future research is needed to determine whether to add the Micro-Deval test to the LA abrasion test for measuring chip seal aggregate abrasion resistance.
2. The AIMS testing apparatus demonstrated high potential to be able to measure gradient angularity and become a predictive test for a chip seal’s ability to retain its skid resistance. A comprehensive laboratory testing protocol that included Micro-Deval, LA Abrasion, T210, OHDL-48 dust coating, and the insoluble residue test should be included

to seek statistically significant correlations between these physical test procedures and the digital imagery output provided by AIMS. If these correlations are strong, ODOT could consider using the AIMS output to replace some or the entire suite of current tests. This would save both time and cost. It would also enhance sustainability via ODOT lab energy savings.

3. The PUC showed itself to be a strong candidate for incorporation into ODOT chip seal specifications. Research targeted at quantifying how well this coefficient models chip seal performance (i.e. failure due to flushing/bleeding) is needed. Since the North Carolina DOT is using this, a pooled funded study with NCDOT would make sense. The Texas, California, and Louisiana DOTs all would have an interest in developing this to the point where it can be incorporated into state specifications.
4. Future research to authoritatively determine the relationship and potentially develop guidance with regard to chip sealing rutted roads would be useful. Such research would seek to quantify a maximum weighted average rut depth above which chip sealing would be avoided. The benefit from that research would be found in enhanced safety by not creating conditions in the wheel paths that promote flushing and loss of skid resistance. The project could also analyze the use of the structural index to determine if there is a trigger point such that chip sealing would be discouraged due to the level of structural distress.

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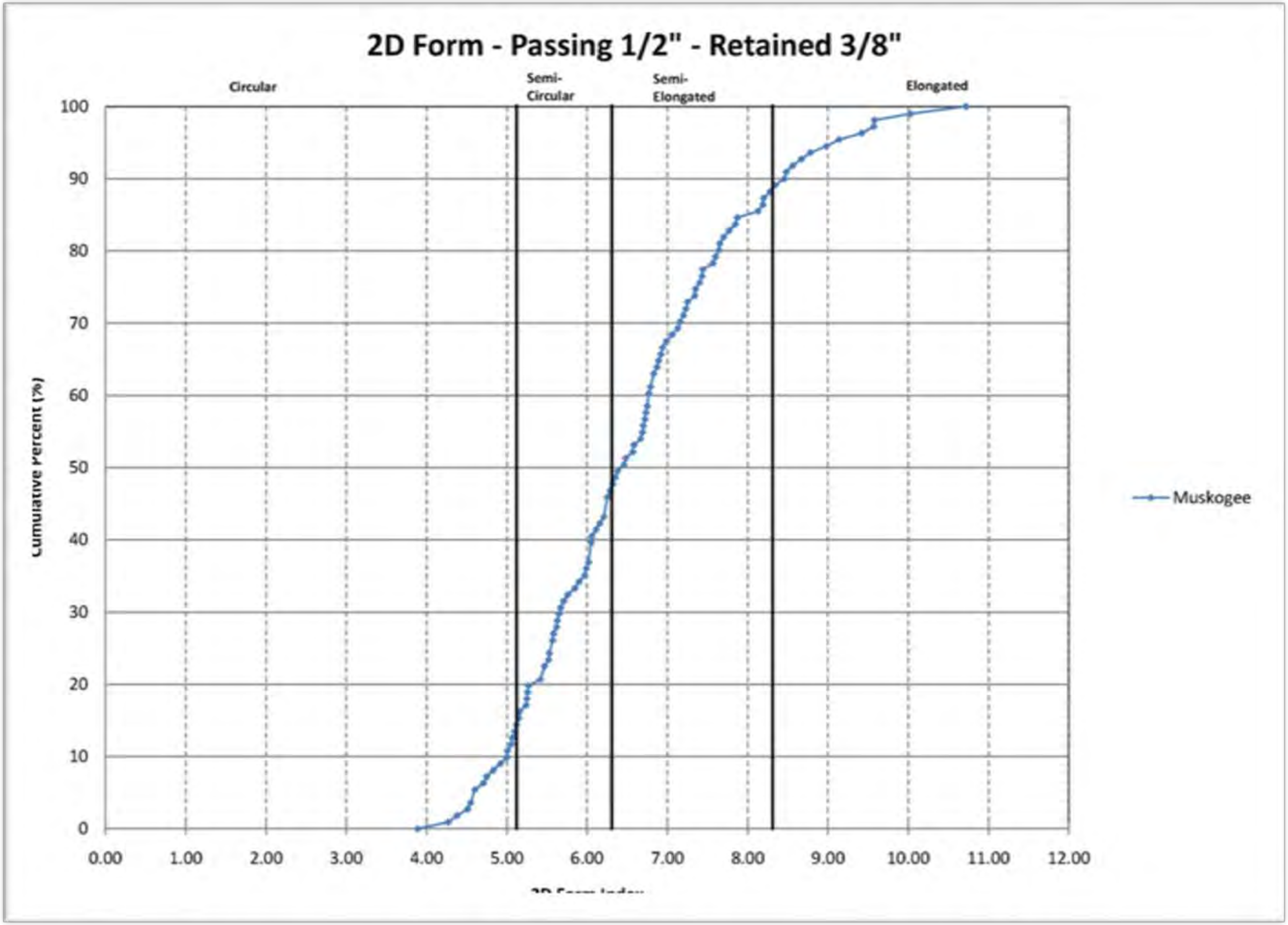
APPENDIX A

AIMS TEST RESULTS OUTPUT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Semi-
Circular
Semi-
Elongated
Elongated
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70
60
50
40
30
20
10
0
0.00
1.00
2.00
3.00
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5.00
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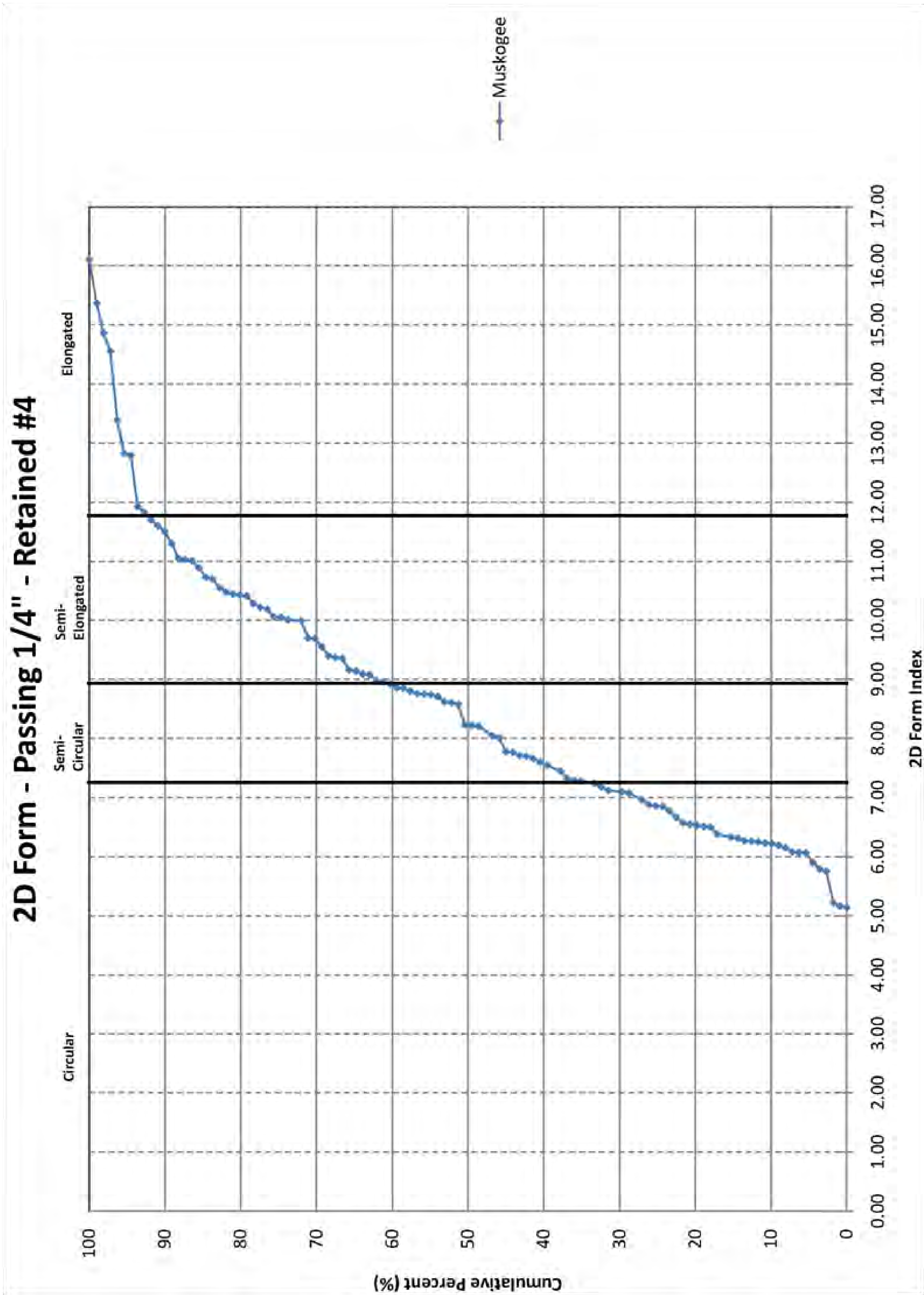
7.00
8.00
9.00
10.00
11.00
12.00
Muskogee



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Semi-Elongated
Elongated
Cumulative Percent (%)
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80
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2.00
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4.00
5.00
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7.00
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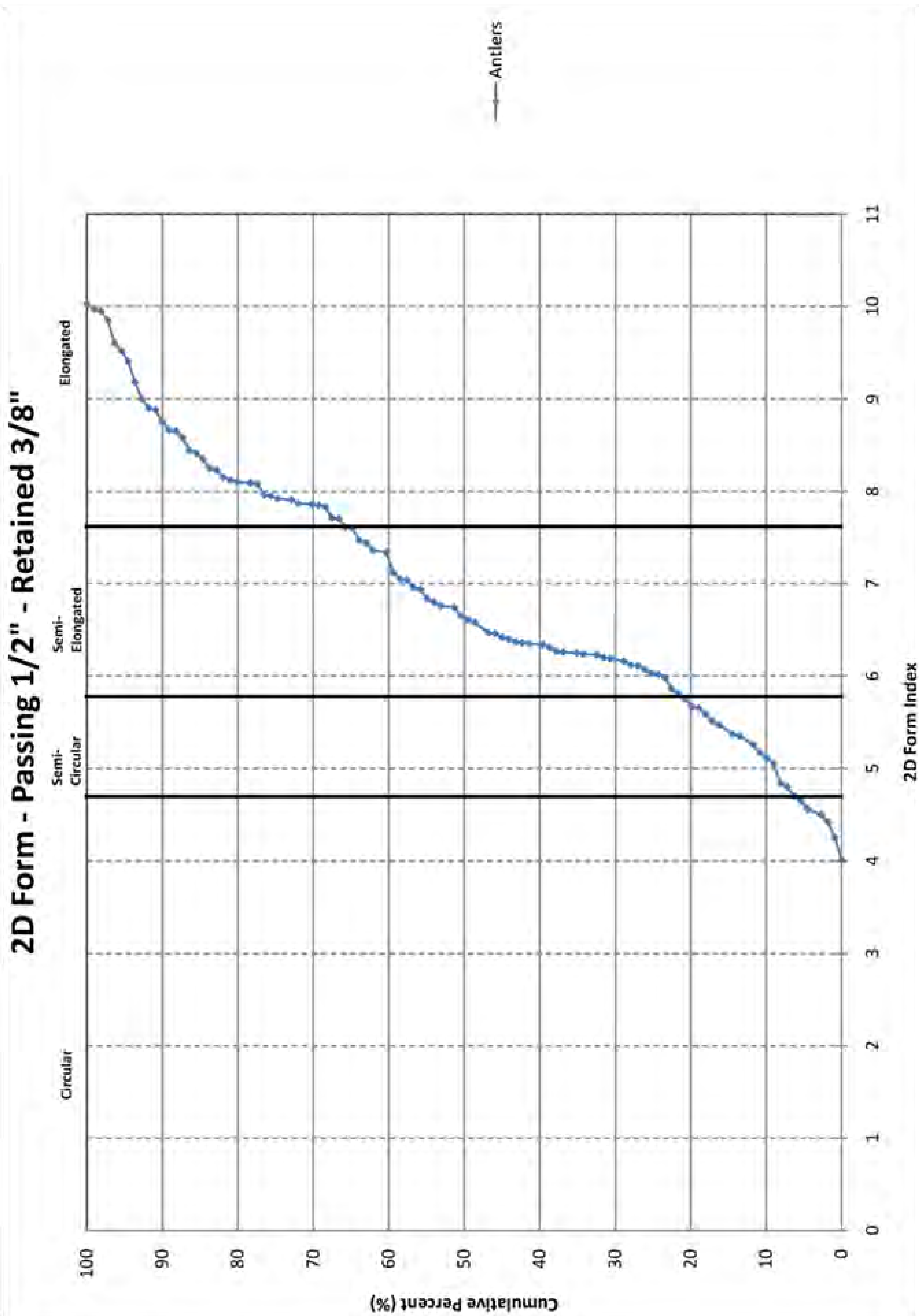
14.00
15.00
16.00
17.00
2D Form Index
Muskogee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Semi-Elongated
Elongated
Antlers
Cumulative Percent (%)
2D Form Index
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1
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80
90
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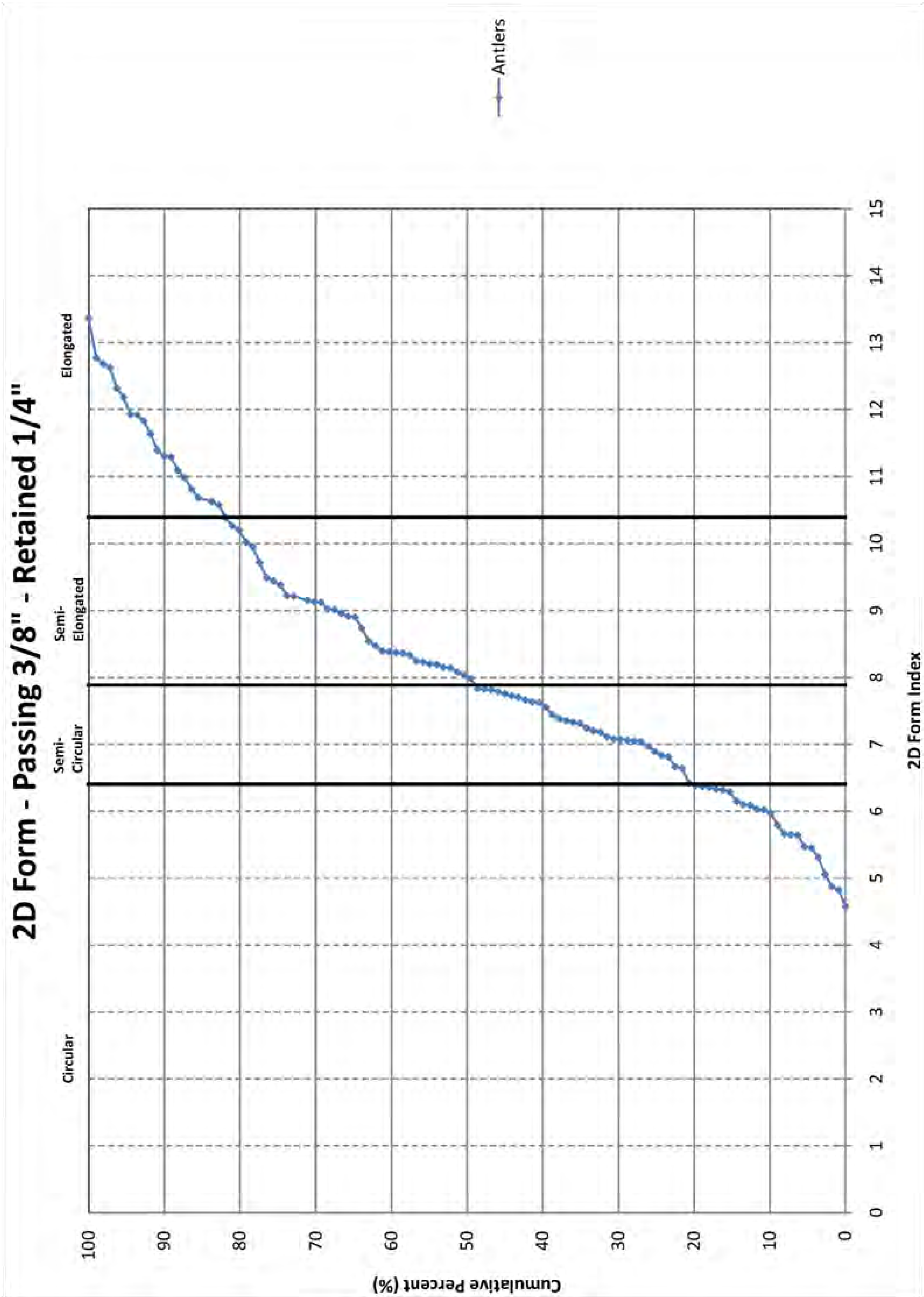

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Semi-
Circular
Semi-
Elongated
Elongated
Cumulative Percent (%)
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Antlers
0
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20
30
40
50
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3
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8
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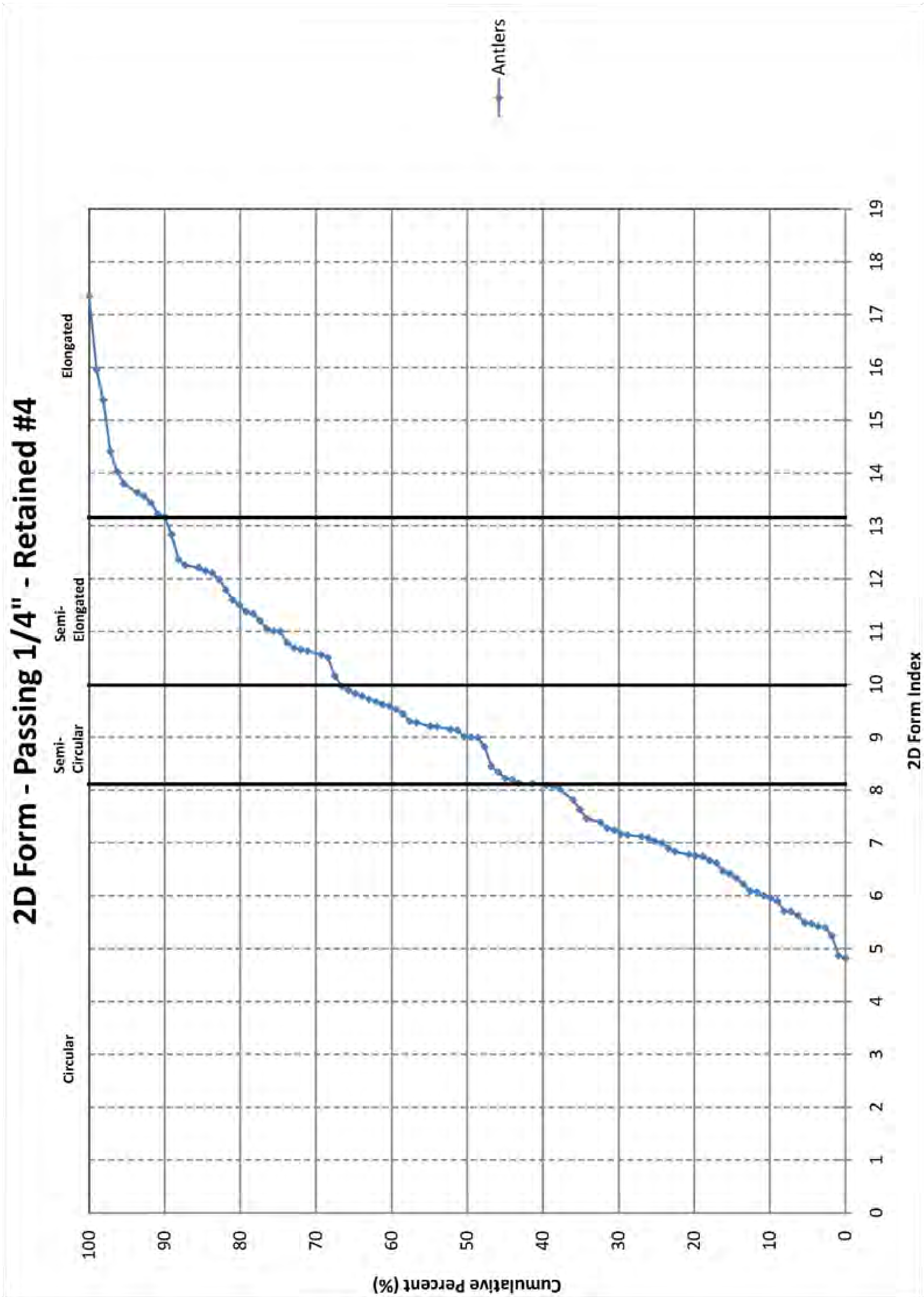
13
14
15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Semi-Elongated
Elongated
Antlers
Cumulative Percent (%)
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20
30
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50
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70
80
90
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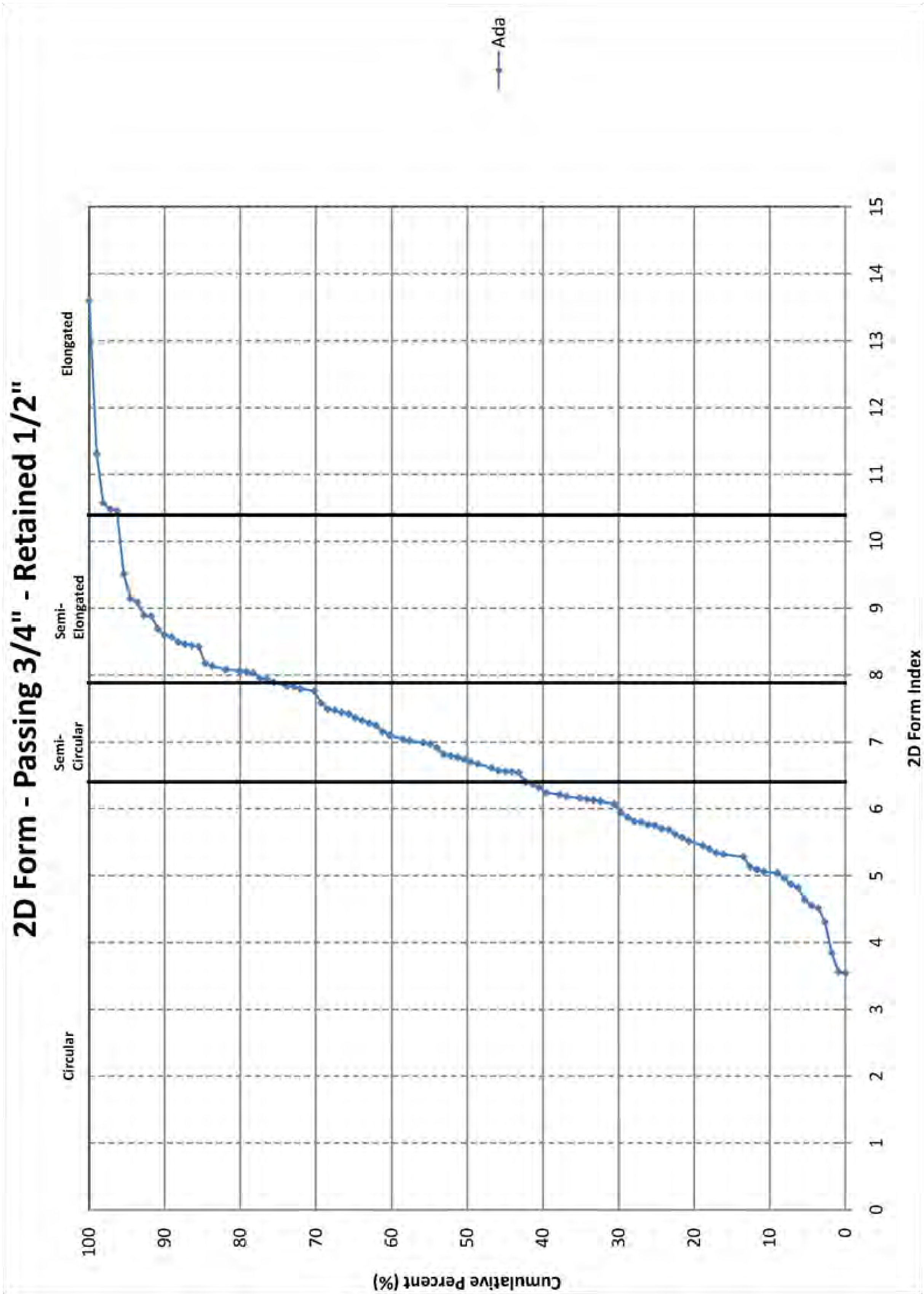
18
19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Circular
Semi-
Elongated
Elongated
Ada
Cumulative Percent (%)
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90
80
70
60
50
40
30
20
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3
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11
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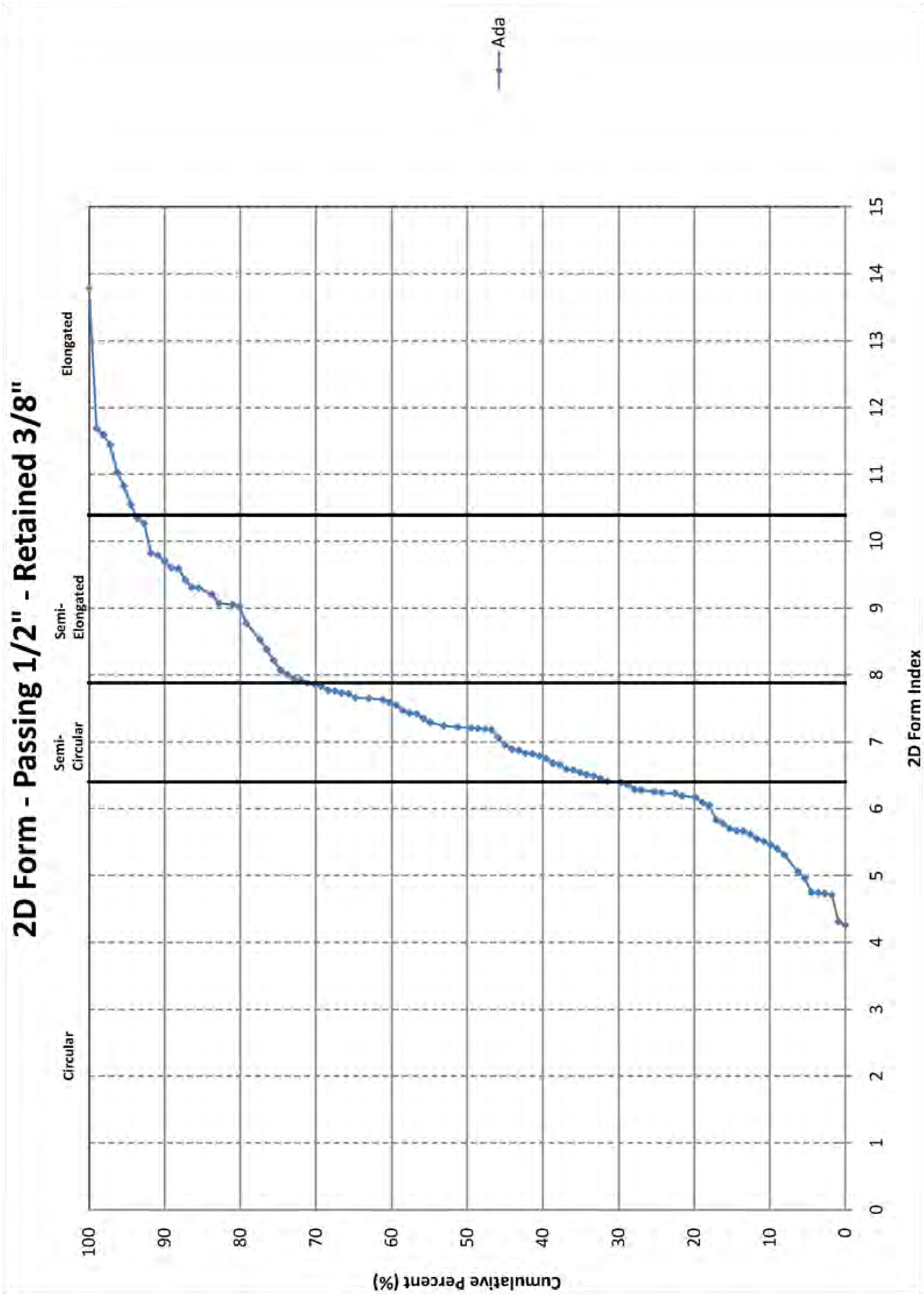
15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Semi-Circular
Semi-Elongated
Elongated
Cumulative Percent (%)
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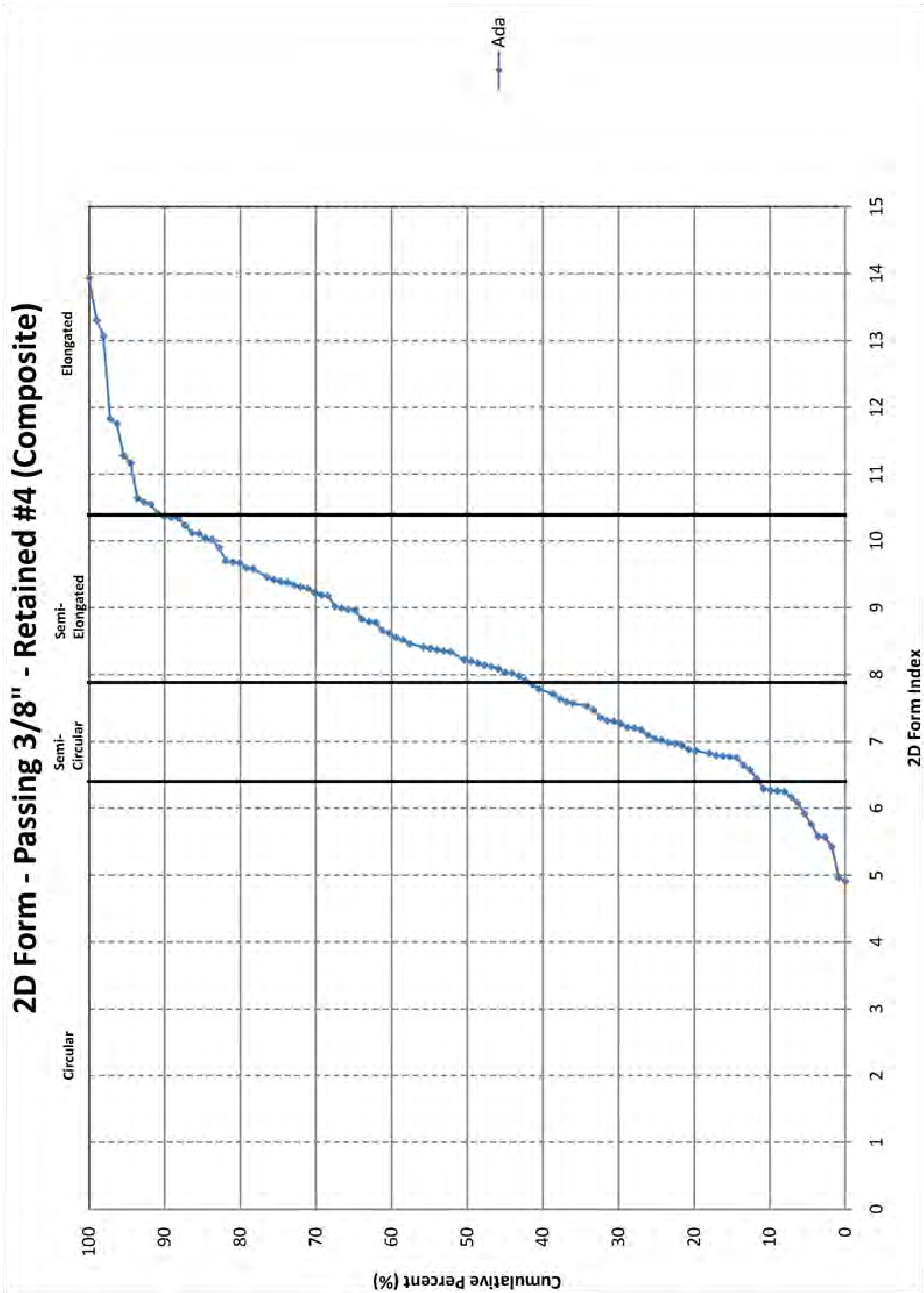
80
90
100
Ada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Semi-Elongated
Elongated
Cumulative Percent (%)
2D Form Index
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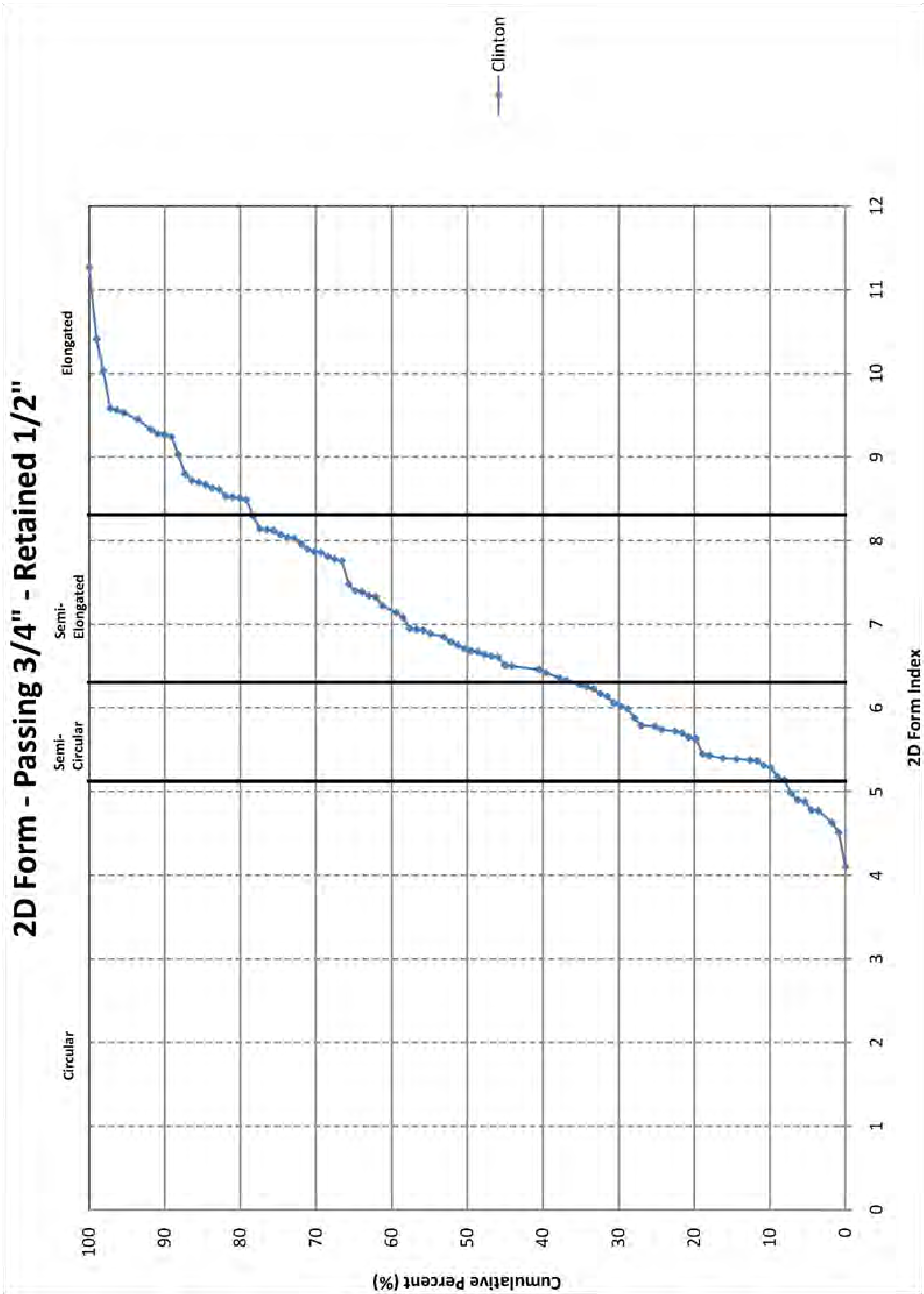

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Circular
Semi-
Elongated
Elongated
Cumulative Percent (%)
2D Form Index
Clinton
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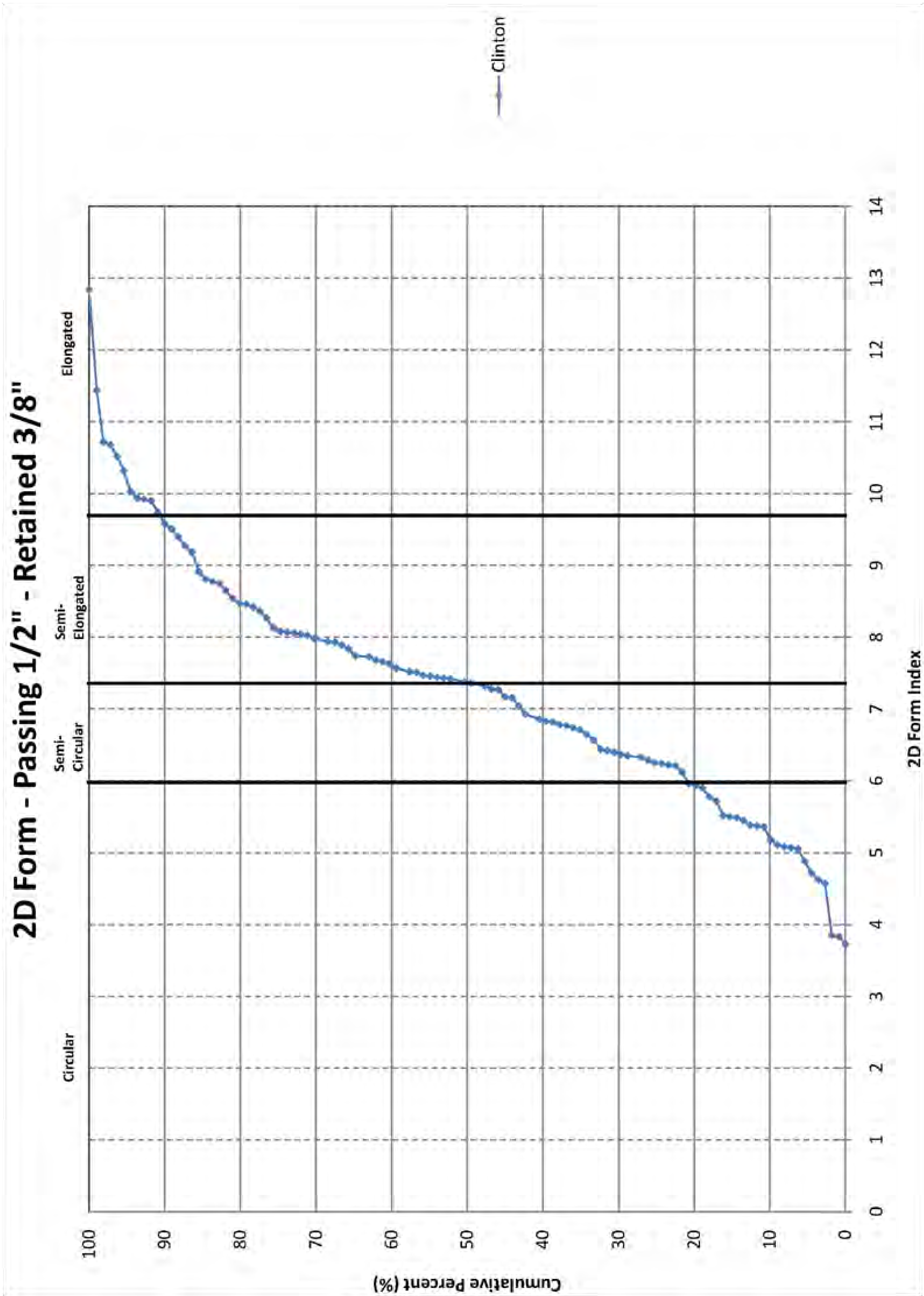

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Circular
Semi-
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Elongated
Elongated
Cumulative Percent (%)
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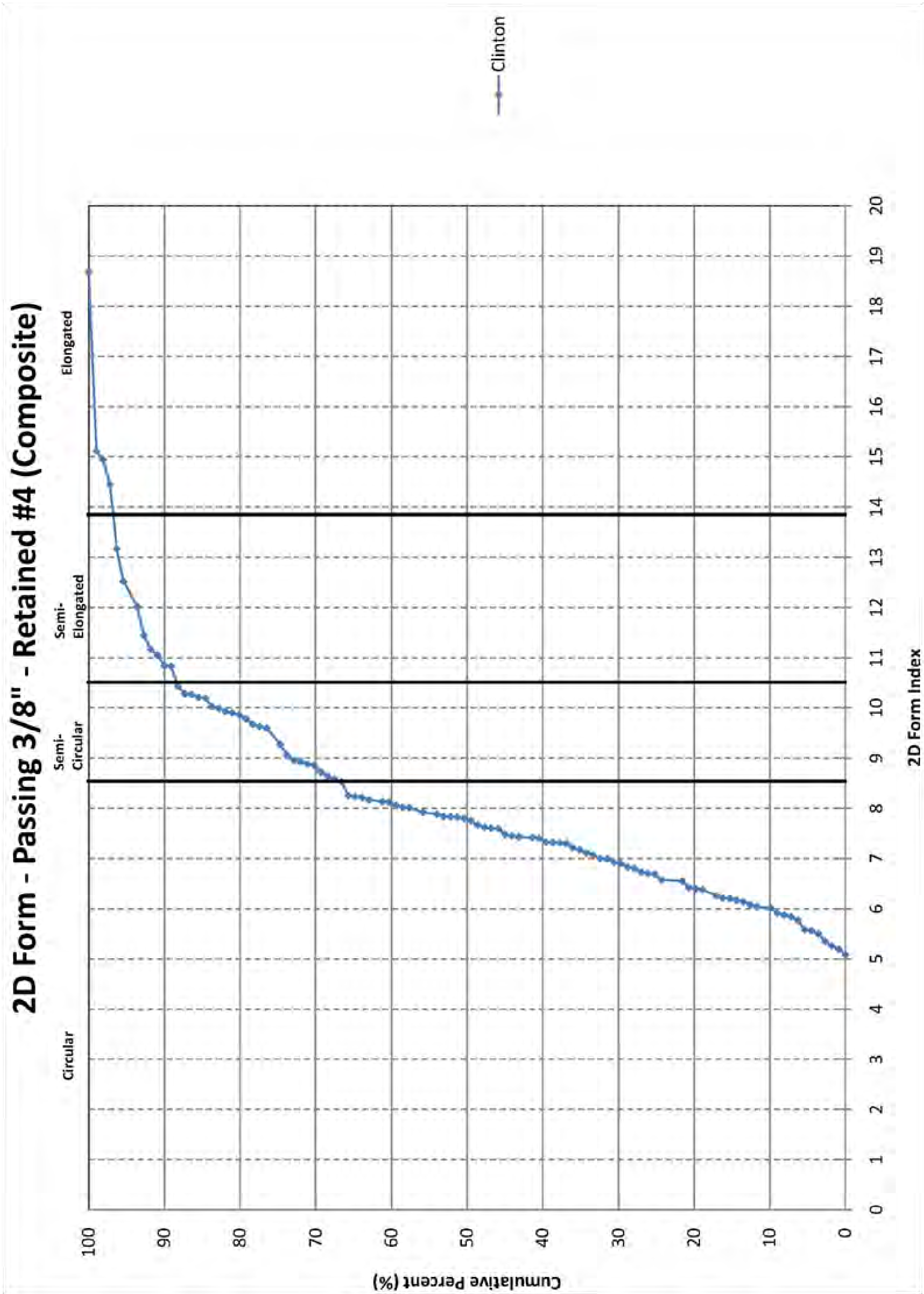
2D Form Index
Clinton


2D Form - Passing 3/8" - Retained #4 (Composite)
Circular
Semi-
Circular
Semi-
Elongated
Elongated
Cumulative Percent (%)
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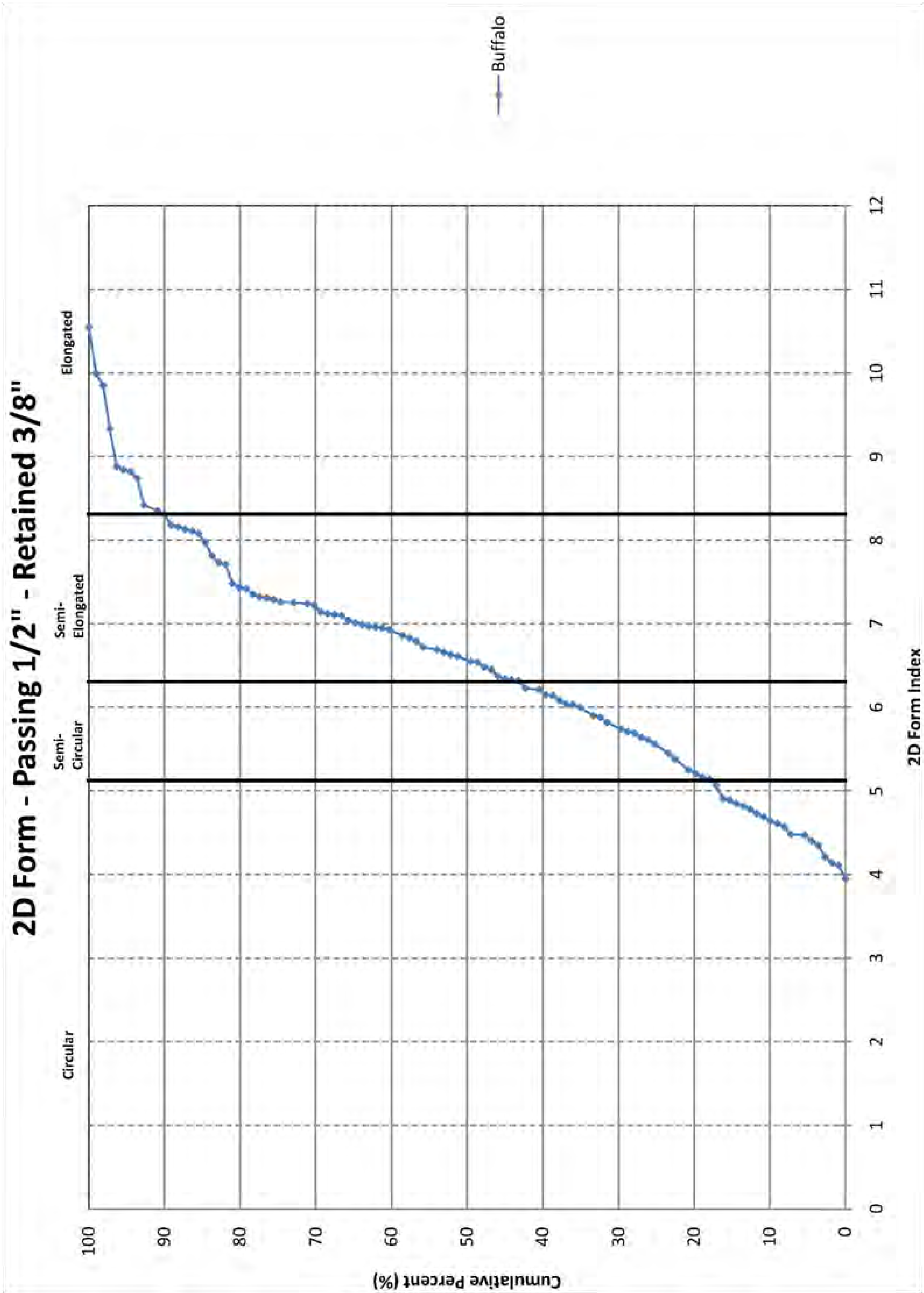
Clinton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Circular
Semi-
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Semi-
Elongated
Elongated
Cumulative Percent (%)
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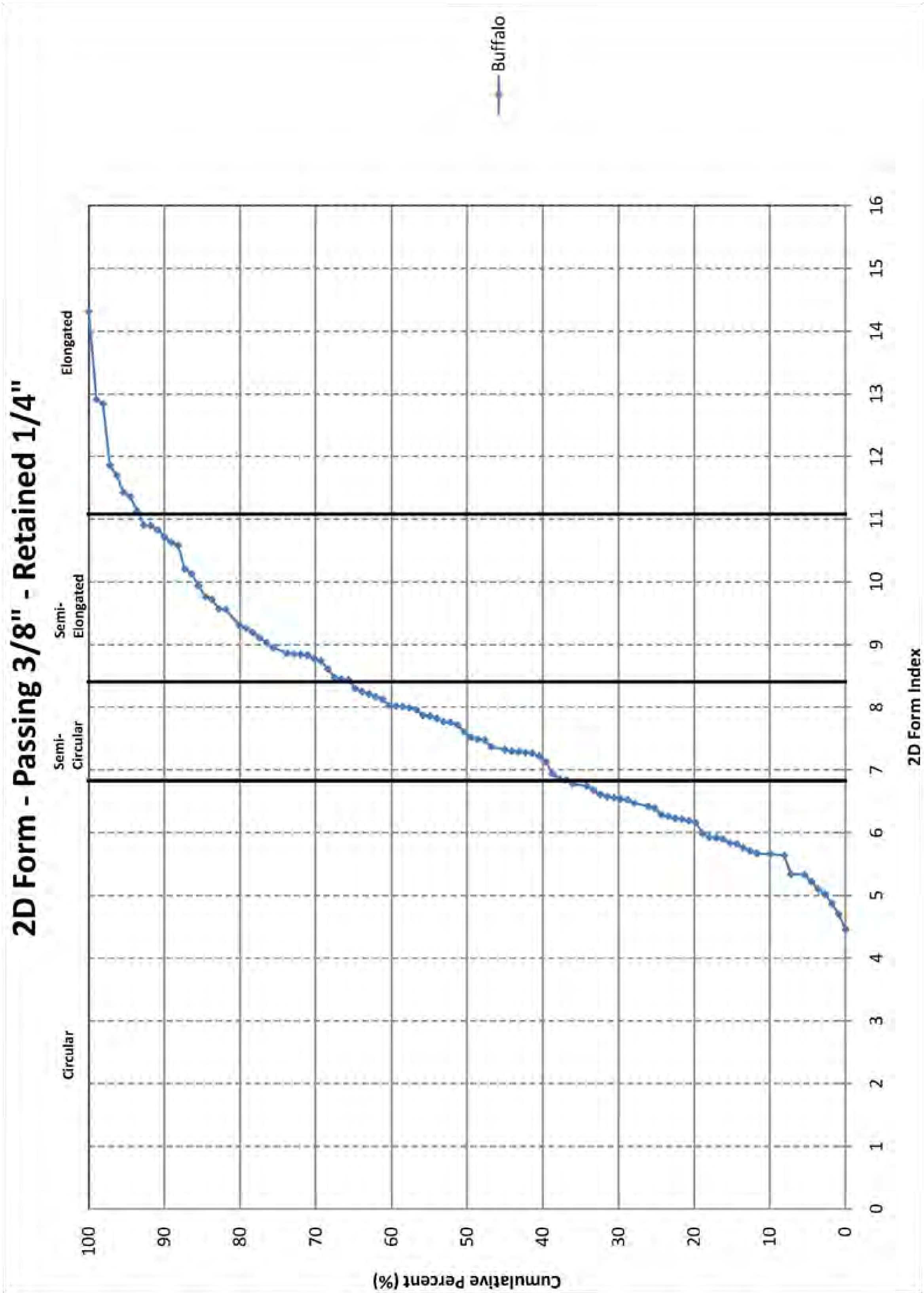
2D Form Index
Buffalo



2D Form - Passing 3/8" - Retained 1/4"
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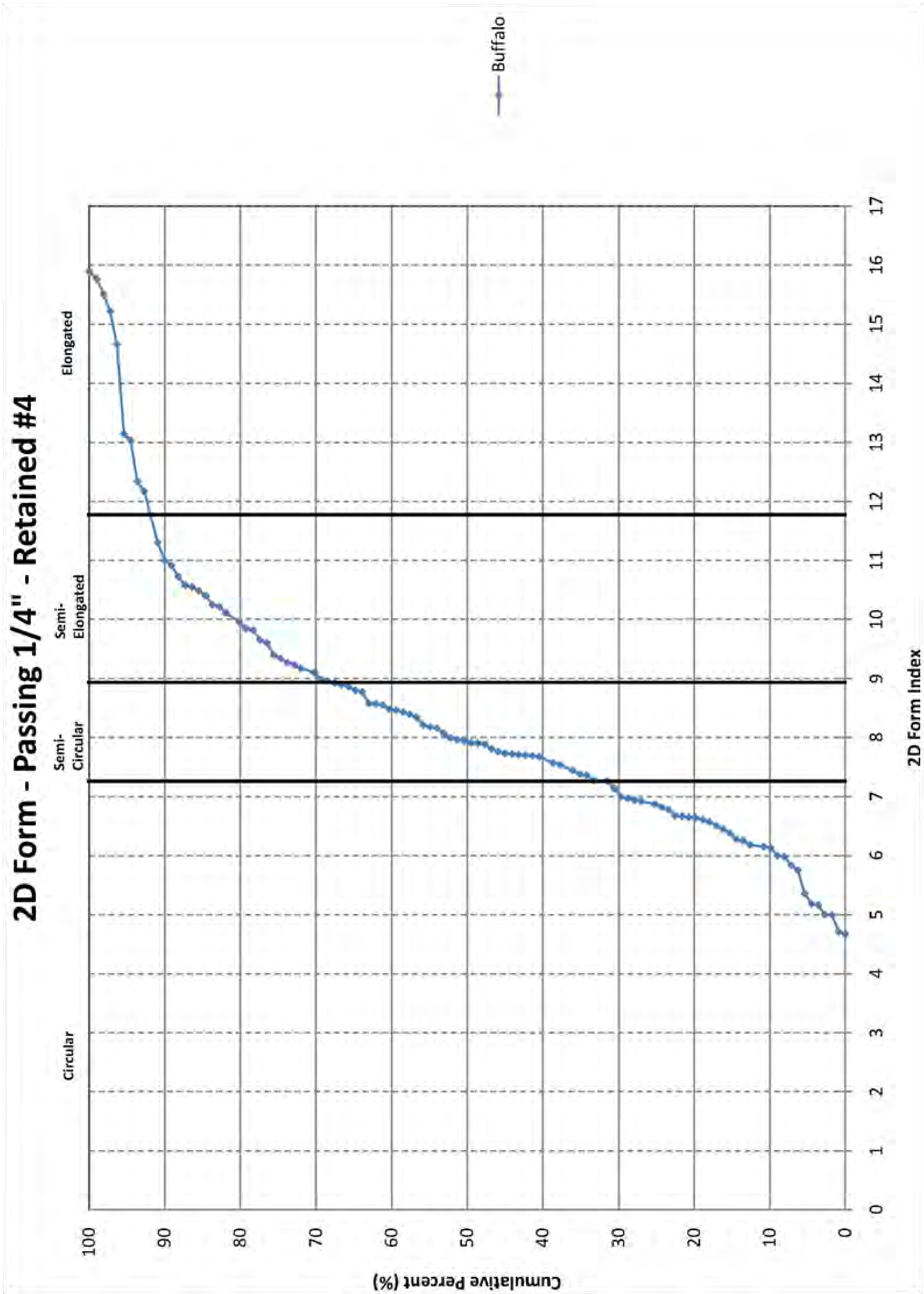
Semi-
Circular
Semi-
Elongated
Elongated
Cumulative Percent (%)
2D Form Index
Buffalo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Circular
Semi-Circular
Semi-Elongated
Elongated
Cumulative Percent (%)
2D Form Index
Buffalo
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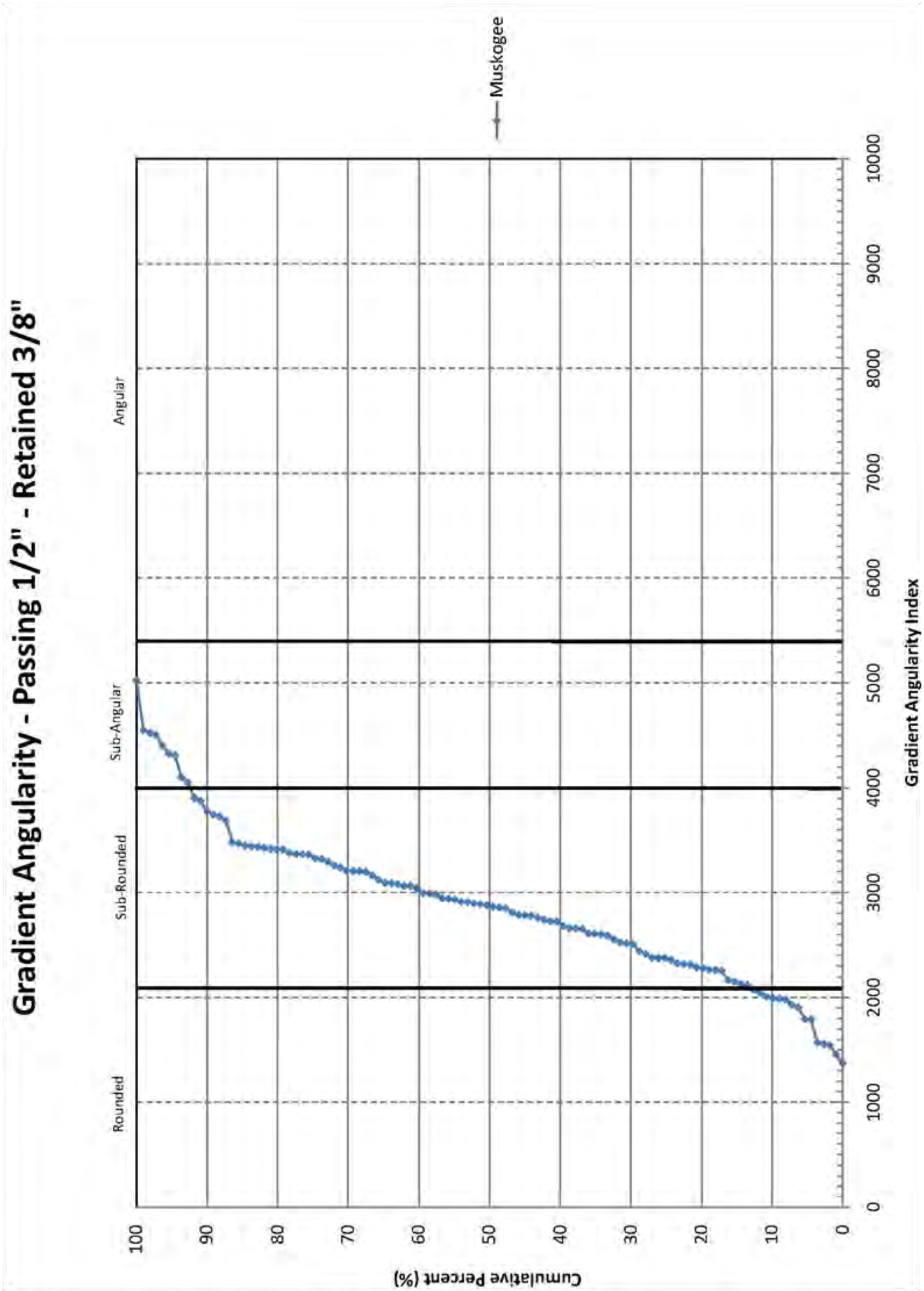
16
17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Rounded
Sub-Rounded
Sub-Angular
Angular
Muskogee
Cumulative Percent (%)
Gradient Angularity Index
0
10
20
30
40
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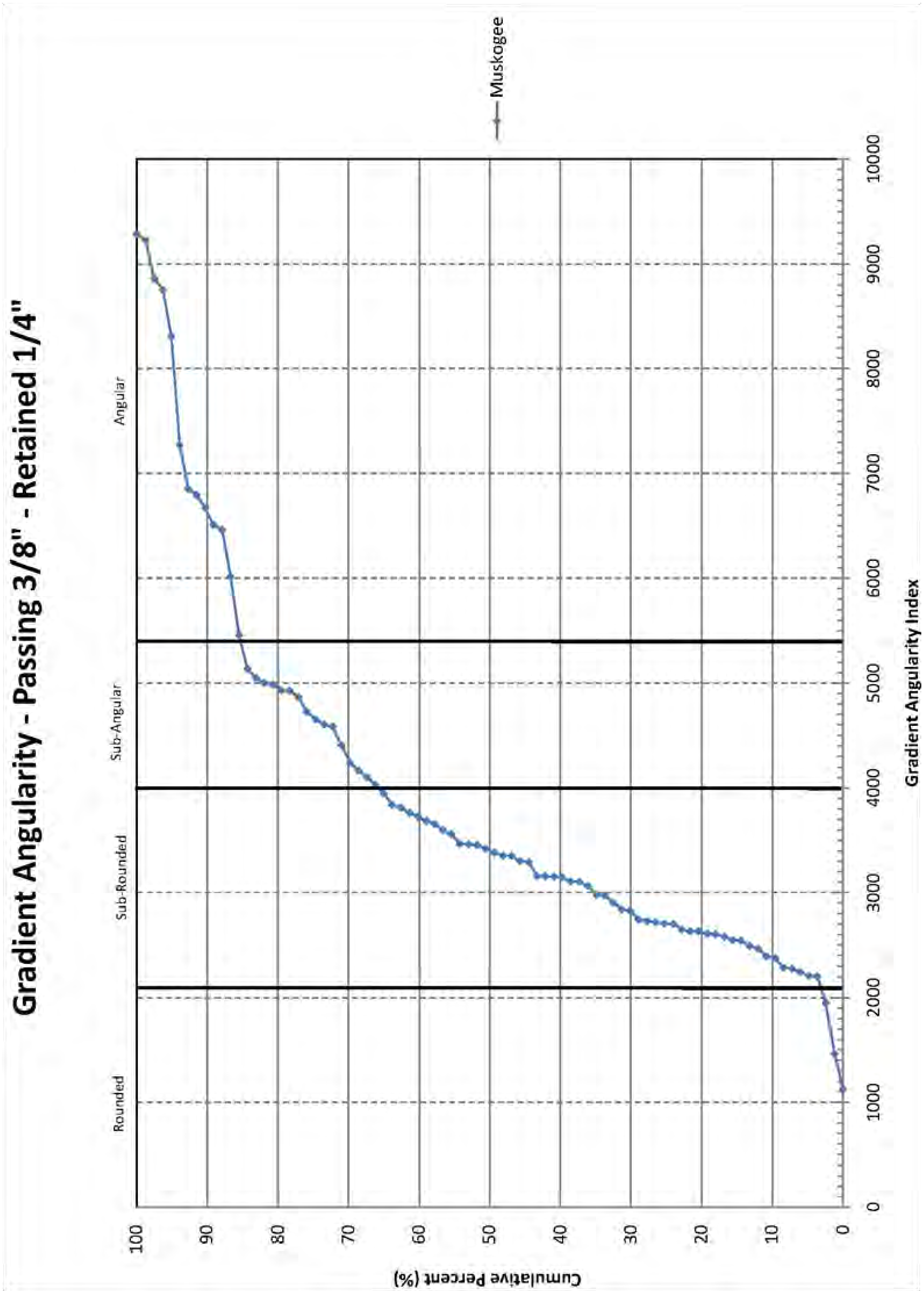
70
80
90
100
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000



Gradient Angularity - Passing 3/8" - Retained 1/4"
Rounded
Sub-Rounded
Sub-Angular
Angular
Muskogee
Cumulative Percent (%)
0
10
20
30
40
50
60
70
80
90
100
Gradient Angularity Index
0
1000
2000
3000
4000
5000
6000
7000
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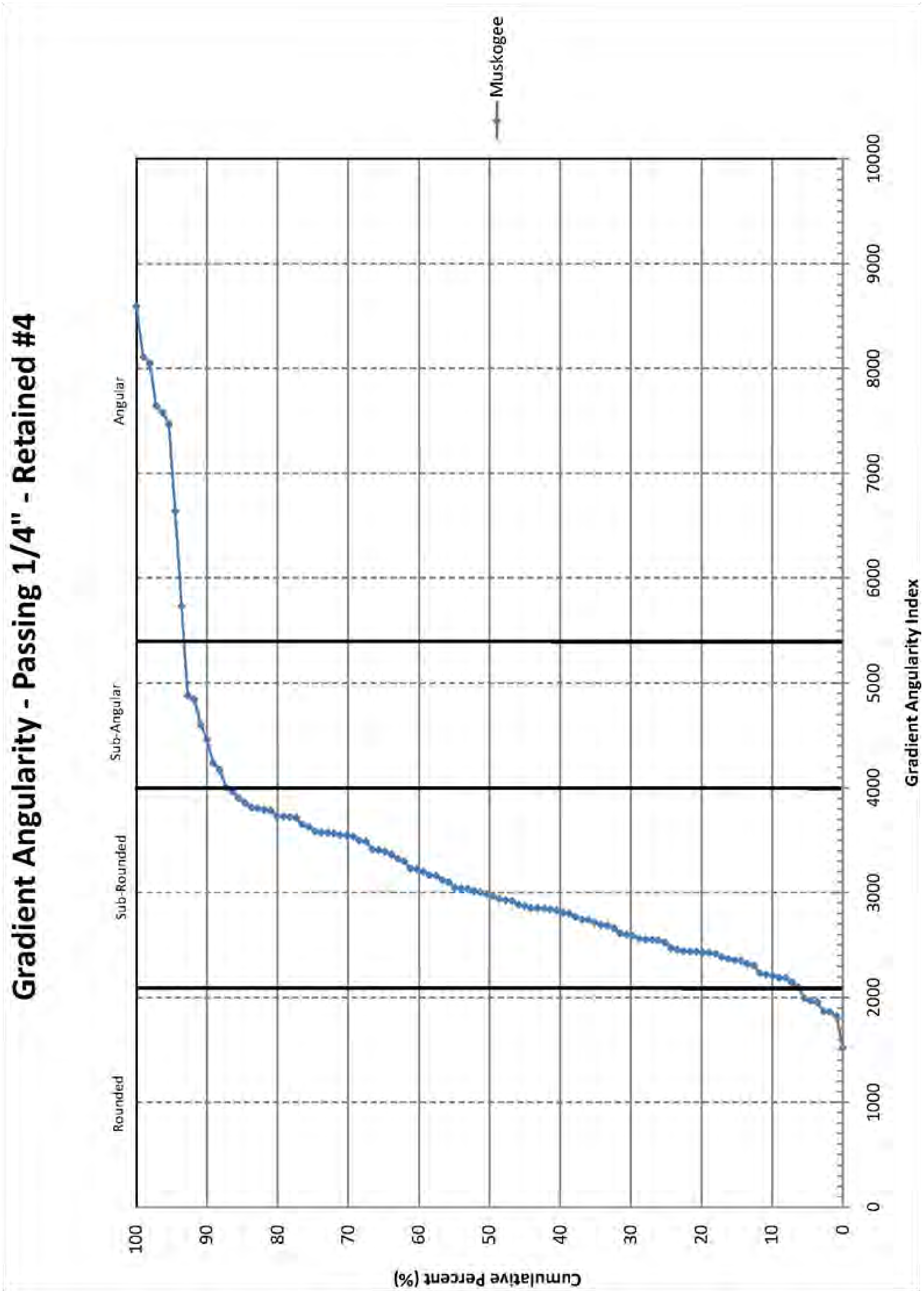
9000
10000


Gradient Angularity - Passing 1/4" - Retained #4
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
Gradient Angularity Index
Muskogee
0
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1000
2000
3000
4000
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7000
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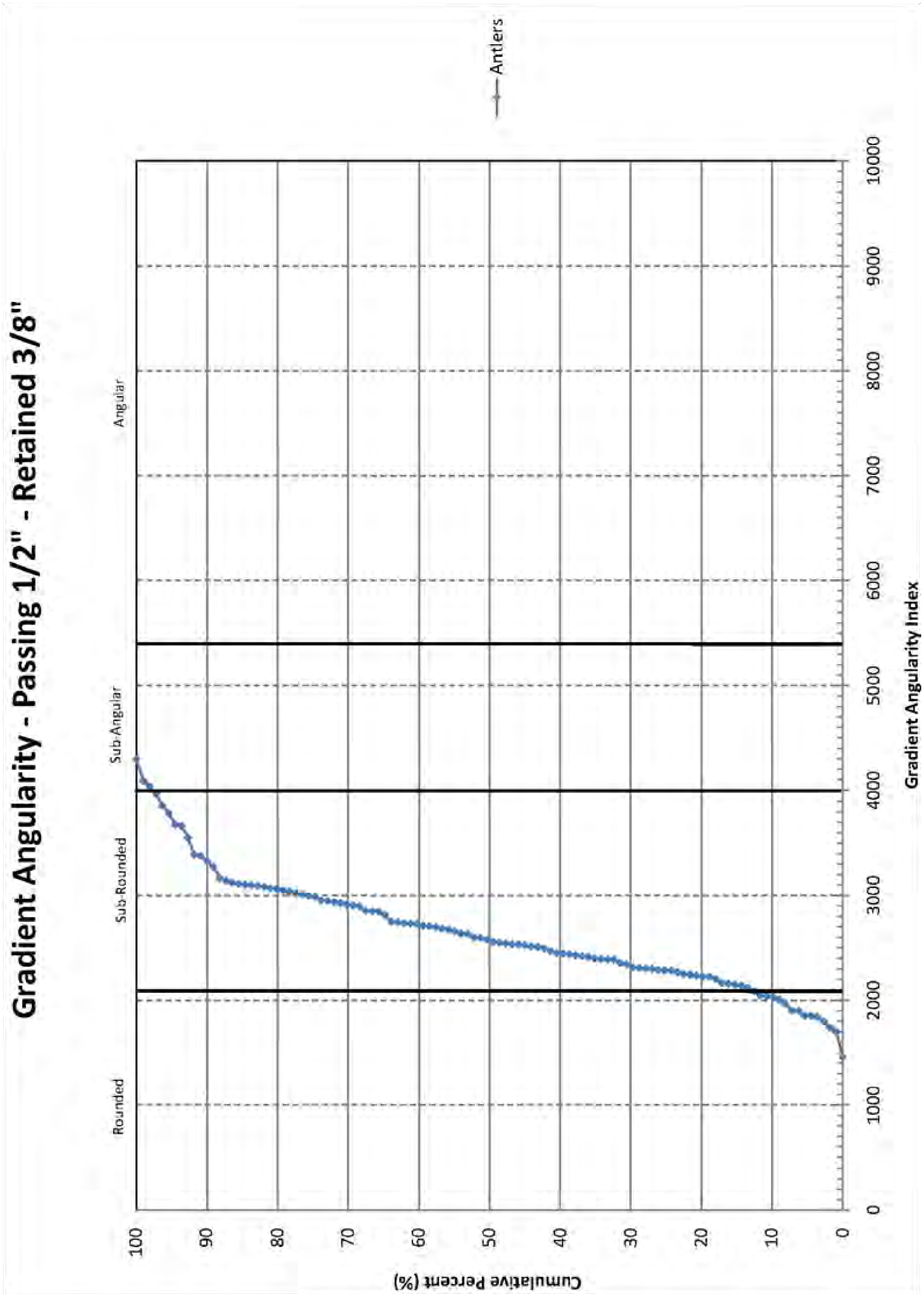
9000
10000


Gradient Angularity - Passing 1/2" - Retained 3/8"
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
100
90
80
70
60
50
40
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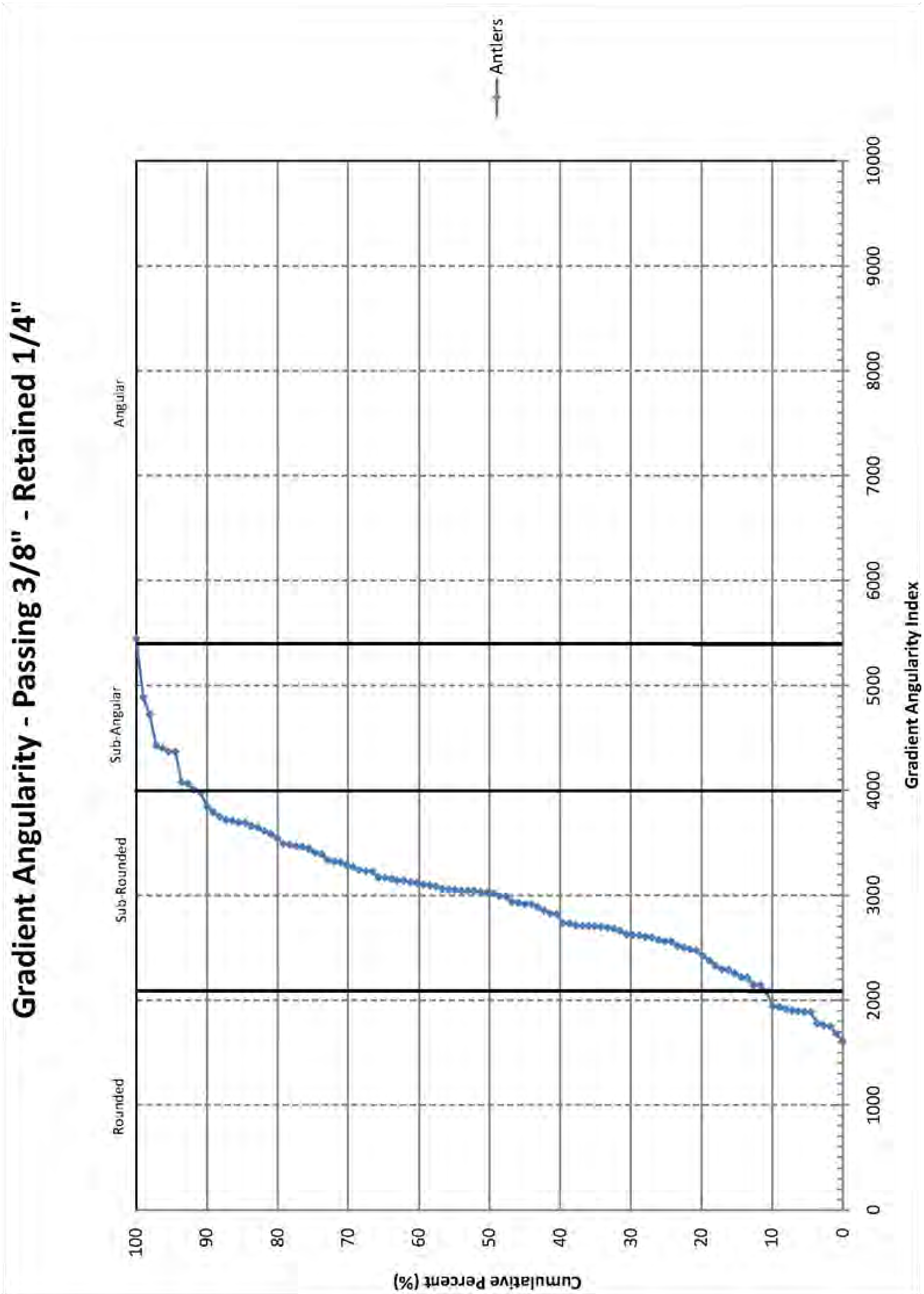
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Gradient Angularity Index
Antlers



Gradient Angularity - Passing 3/8" - Retained 1/4"
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
Gradient Angularity Index
Antlers
0
10
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3000
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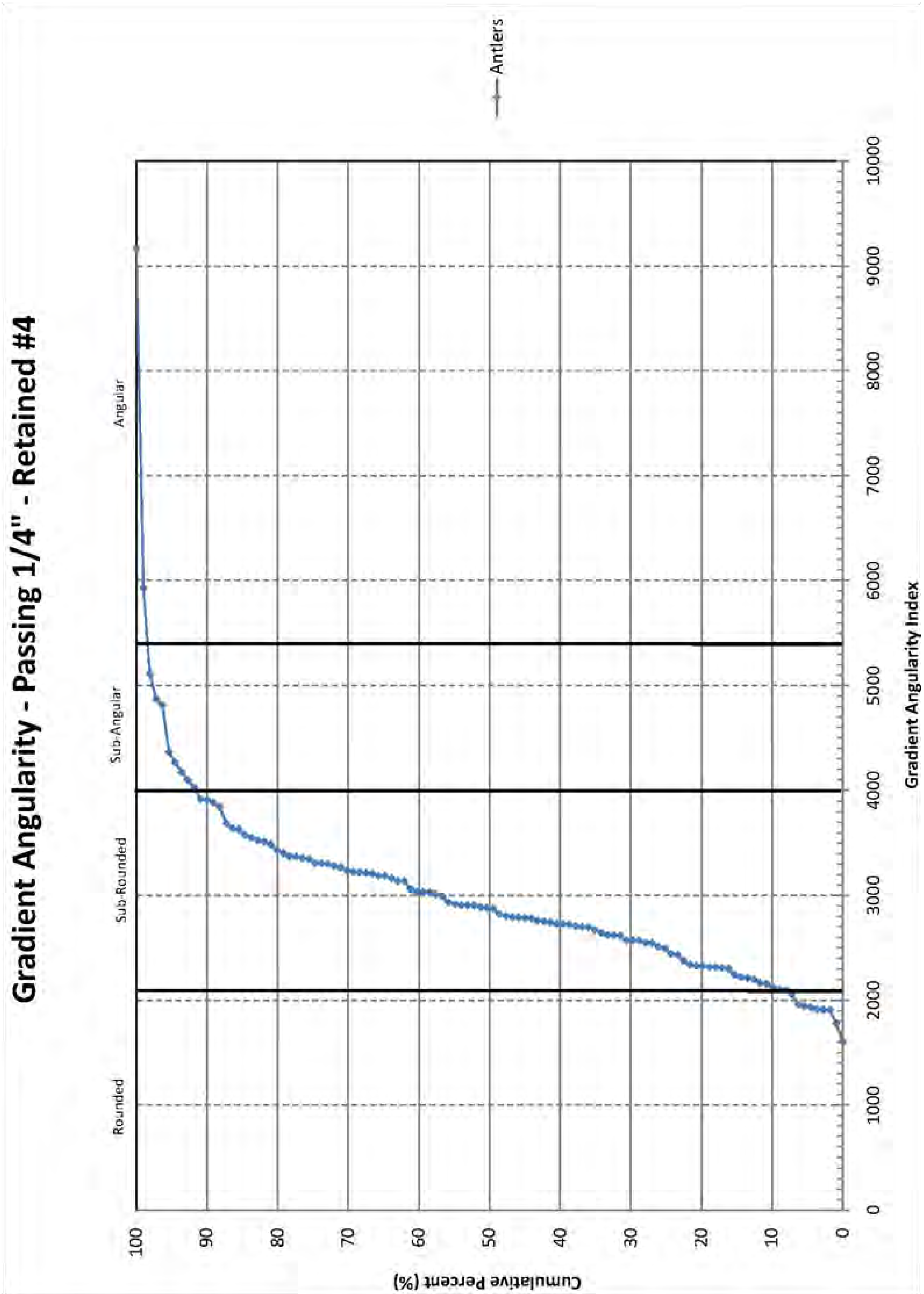
Gradient Angularity - Passing 1/4" - Retained #4
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
Gradient Angularity Index
0
10
20
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40
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80
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0
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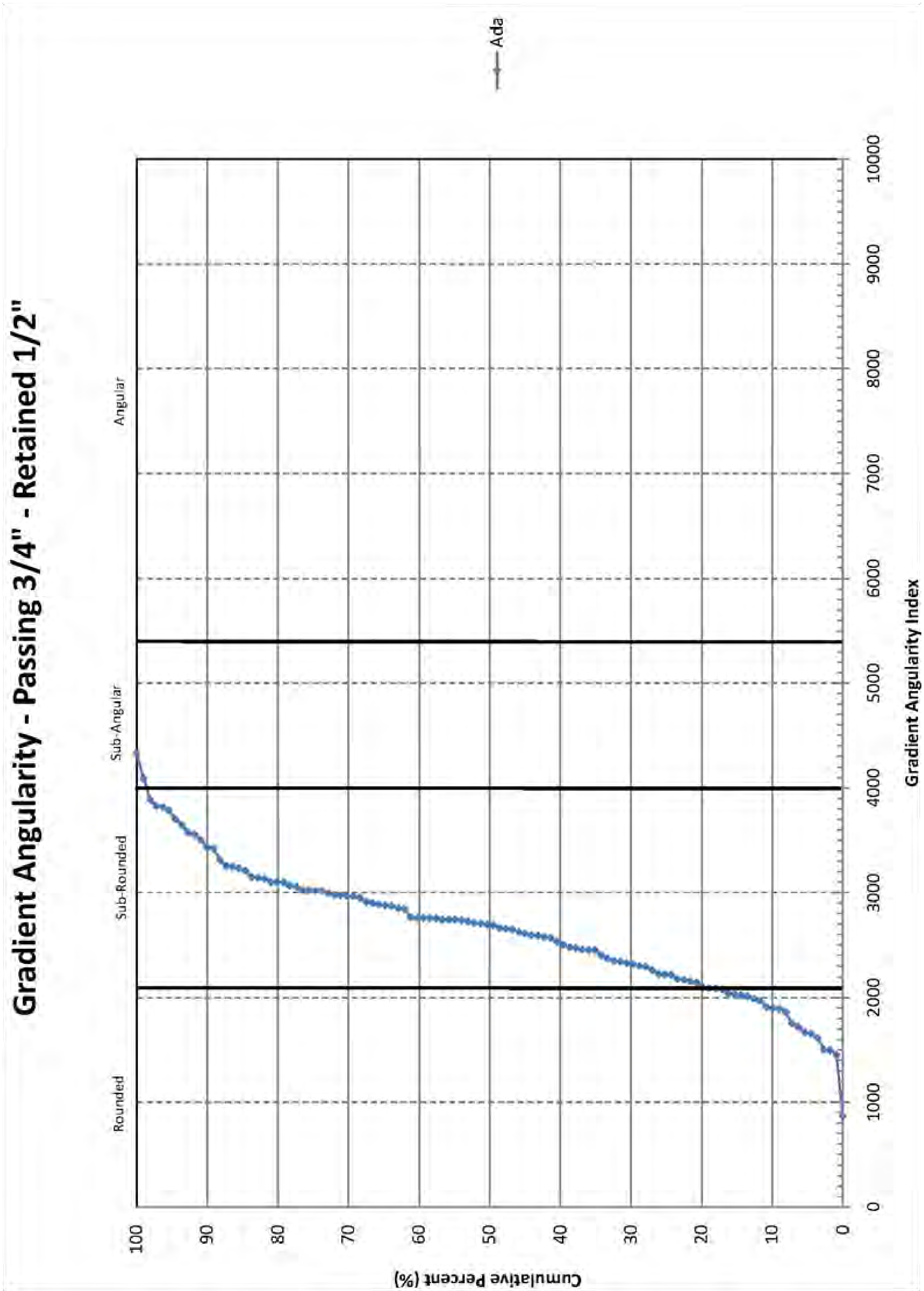
2000
3000
4000
5000
6000
7000
8000
9000
10000
Antlers



Gradient Angularity - Passing 3/4" - Retained 1/2"
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
Gradient Angularity Index
Ada
0
10
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100
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1000
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4000
5000
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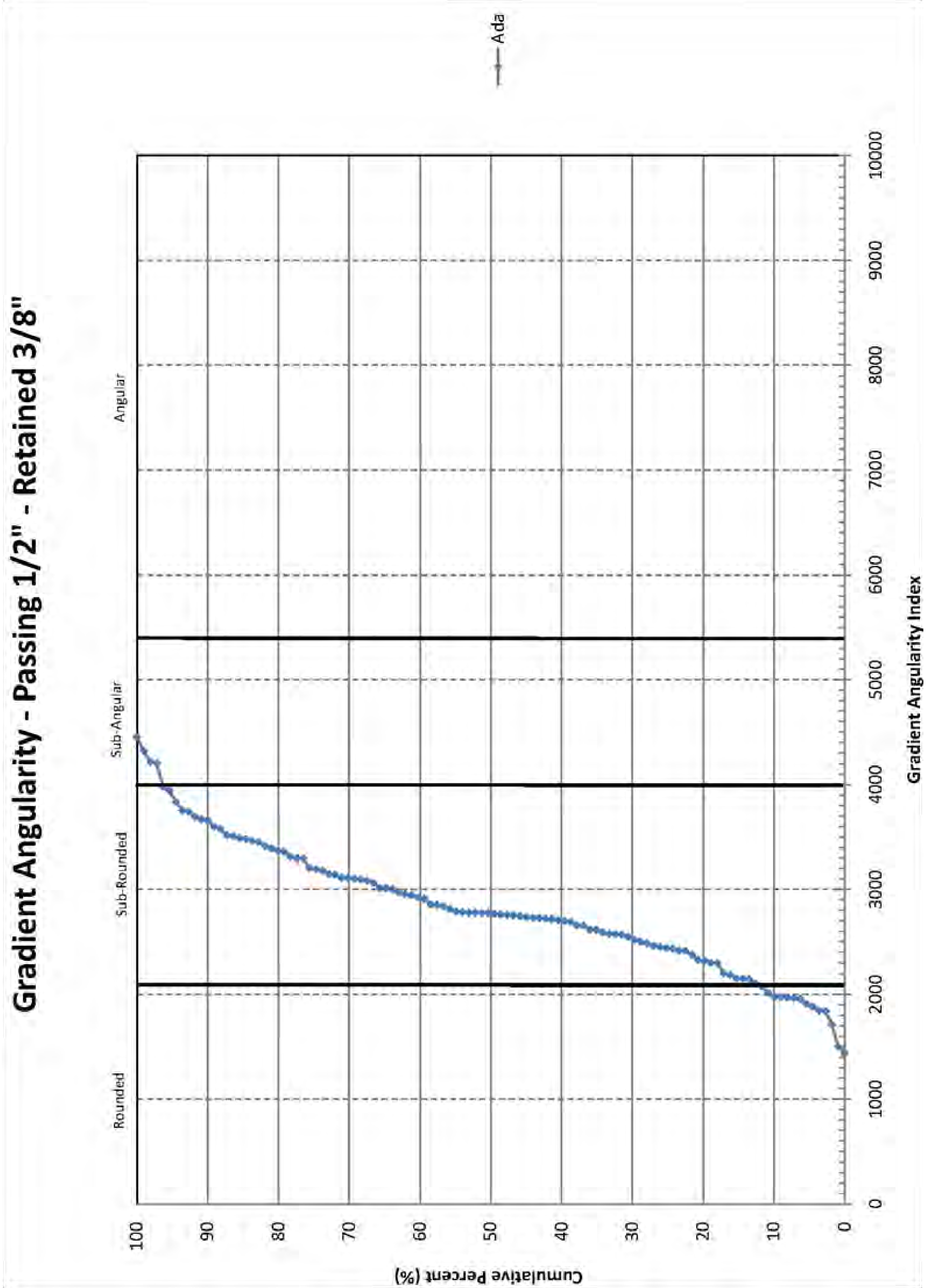
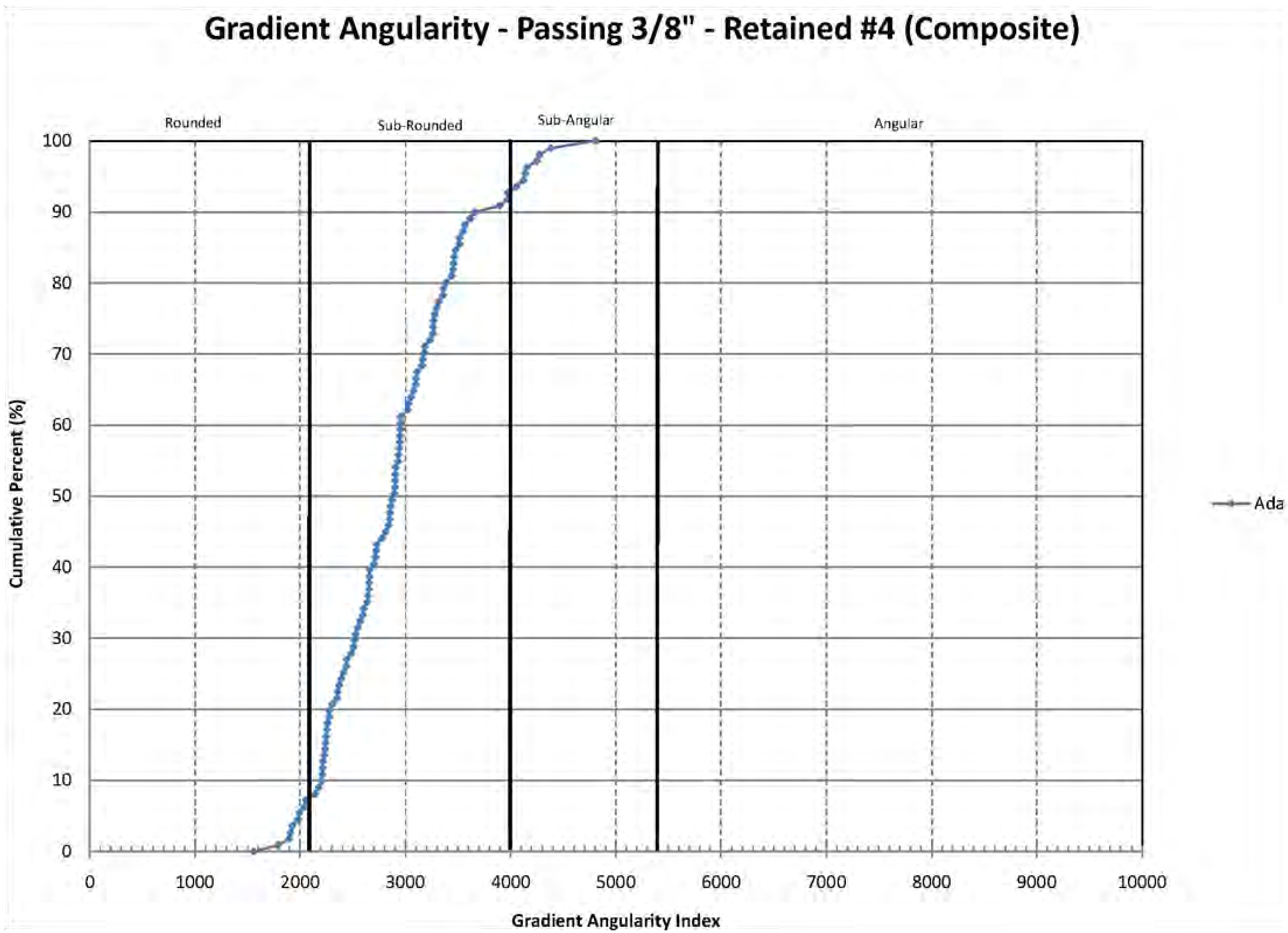
7000
8000
9000
10000



Gradient Angularity - Passing 1/2" - Retained 3/8"
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
100
90
80
70
60
50
40
30
20
10
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Gradient Angularity Index
Ada


Gradient Angularity - Passing 3/8" - Retained #4 (Composite)
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
0
10
20
30
40
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70
80
90
100
0
1000
2000
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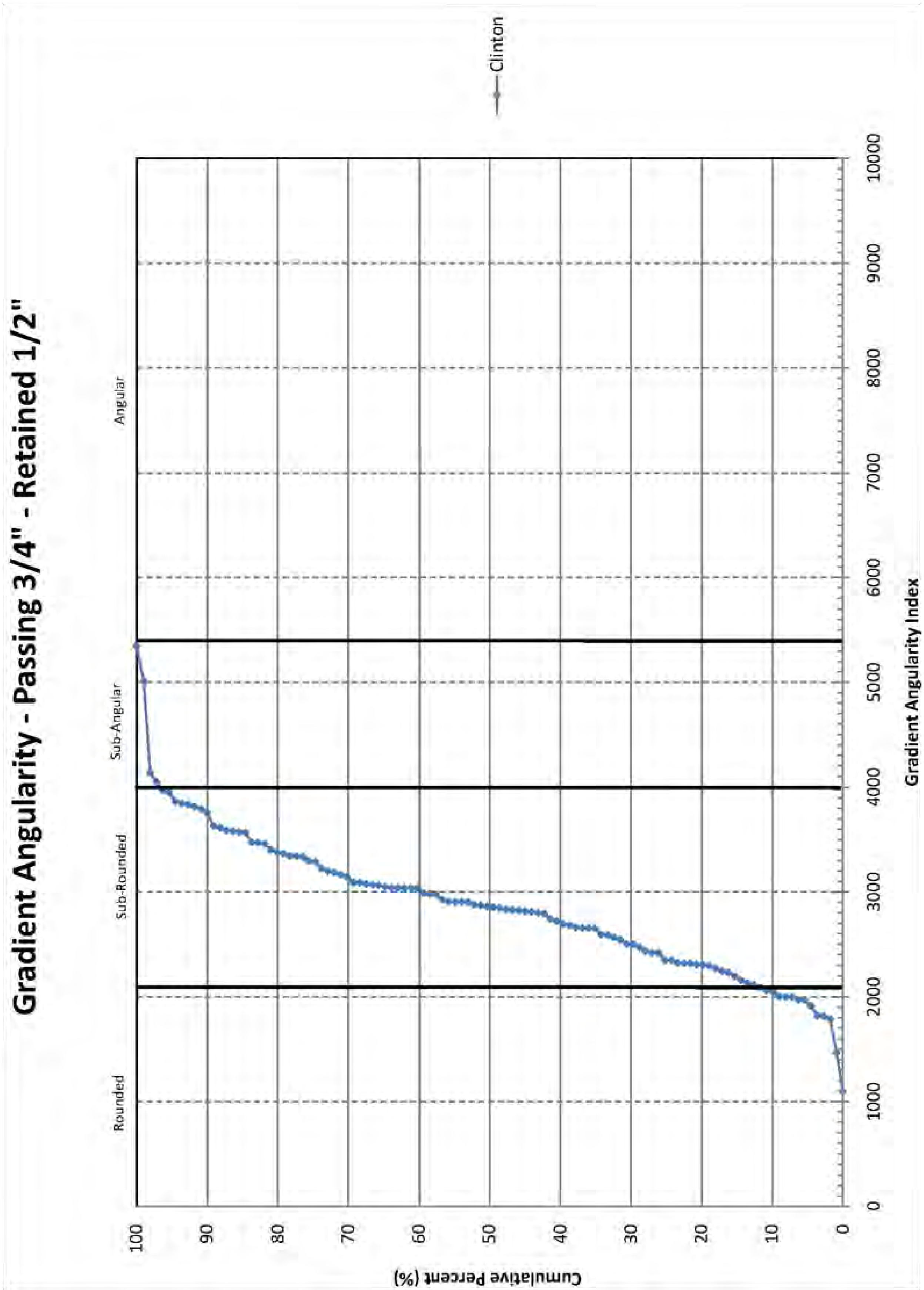
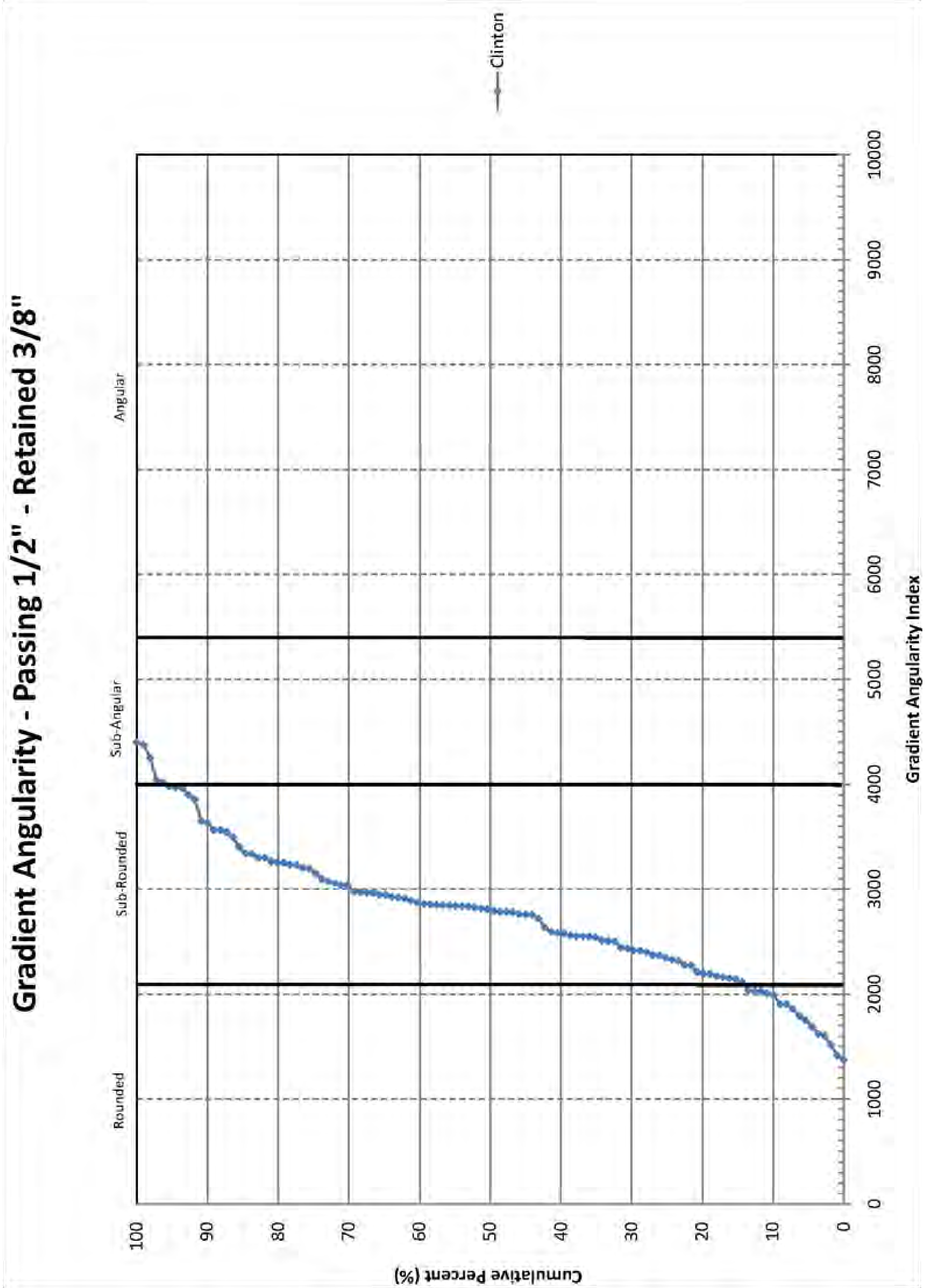
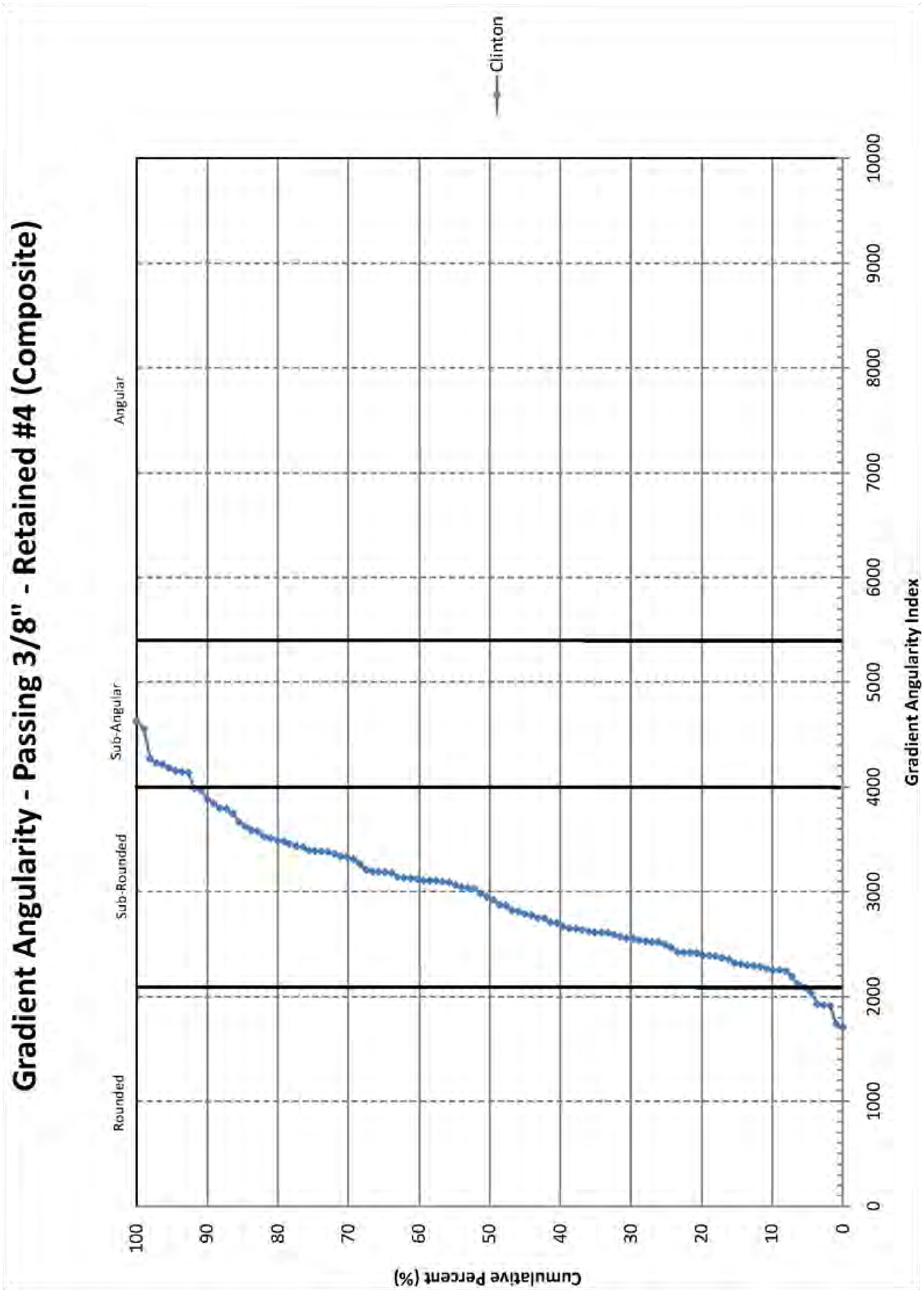
4000
5000
6000
7000
8000
9000
10000
Gradient Angularity Index
Ada



Gradient Angularity - Passing 3/4" - Retained 1/2"
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
100
90
80
70
60
50
40
30
20
10
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Gradient Angularity Index
Clinton


Gradient Angularity - Passing 1/2" - Retained 3/8"
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
Gradient Angularity Index
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
0
10
20
30
40
50
60
70
80
90
100
Clinton



Gradient Angularity - Passing 3/8" - Retained #4 (Composite)
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
100
90
80
70
60
50
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30
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3000
4000
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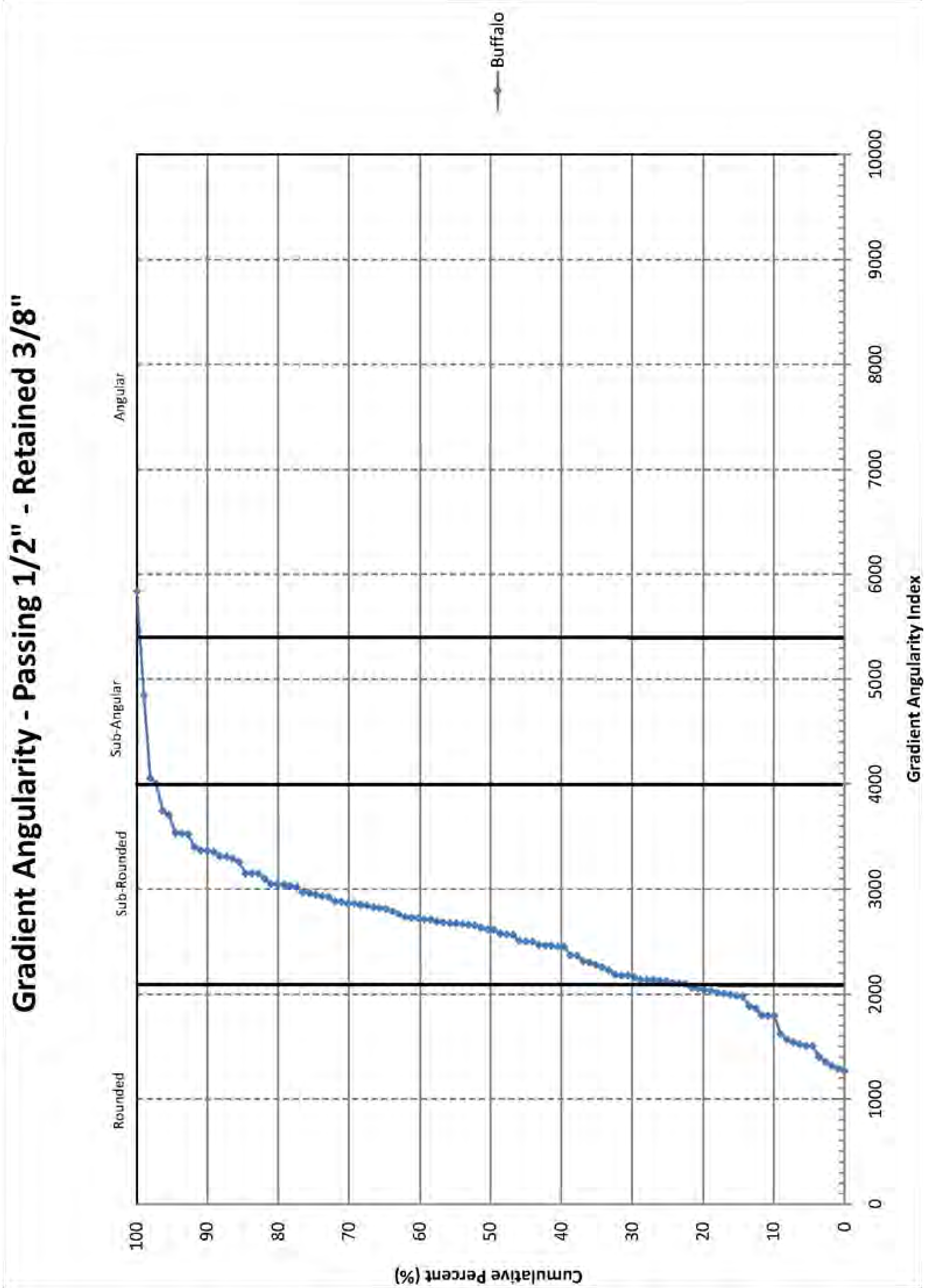
6000
7000
8000
9000
10000
Gradient Angularity Index
Clinton


Gradient Angularity - Passing 1/2" - Retained 3/8"
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
Gradient Angularity Index
Buffalo
0
10
20
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40
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70
80
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100
1000
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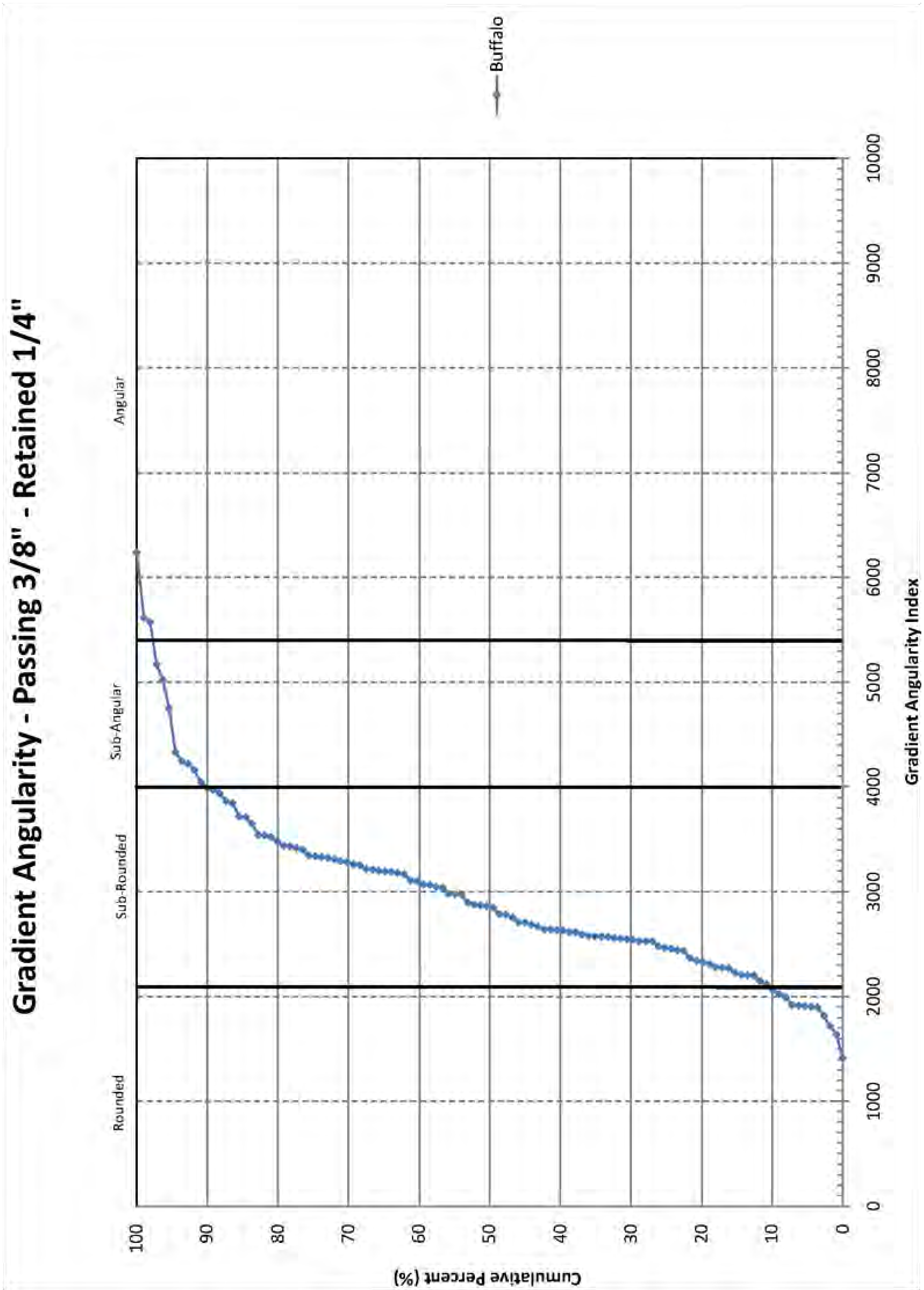
3000
4000
5000
6000
7000
8000
9000
10000


Gradient Angularity - Passing 3/8" - Retained 1/4"
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
Gradient Angularity Index
100
90
80
70
60
50
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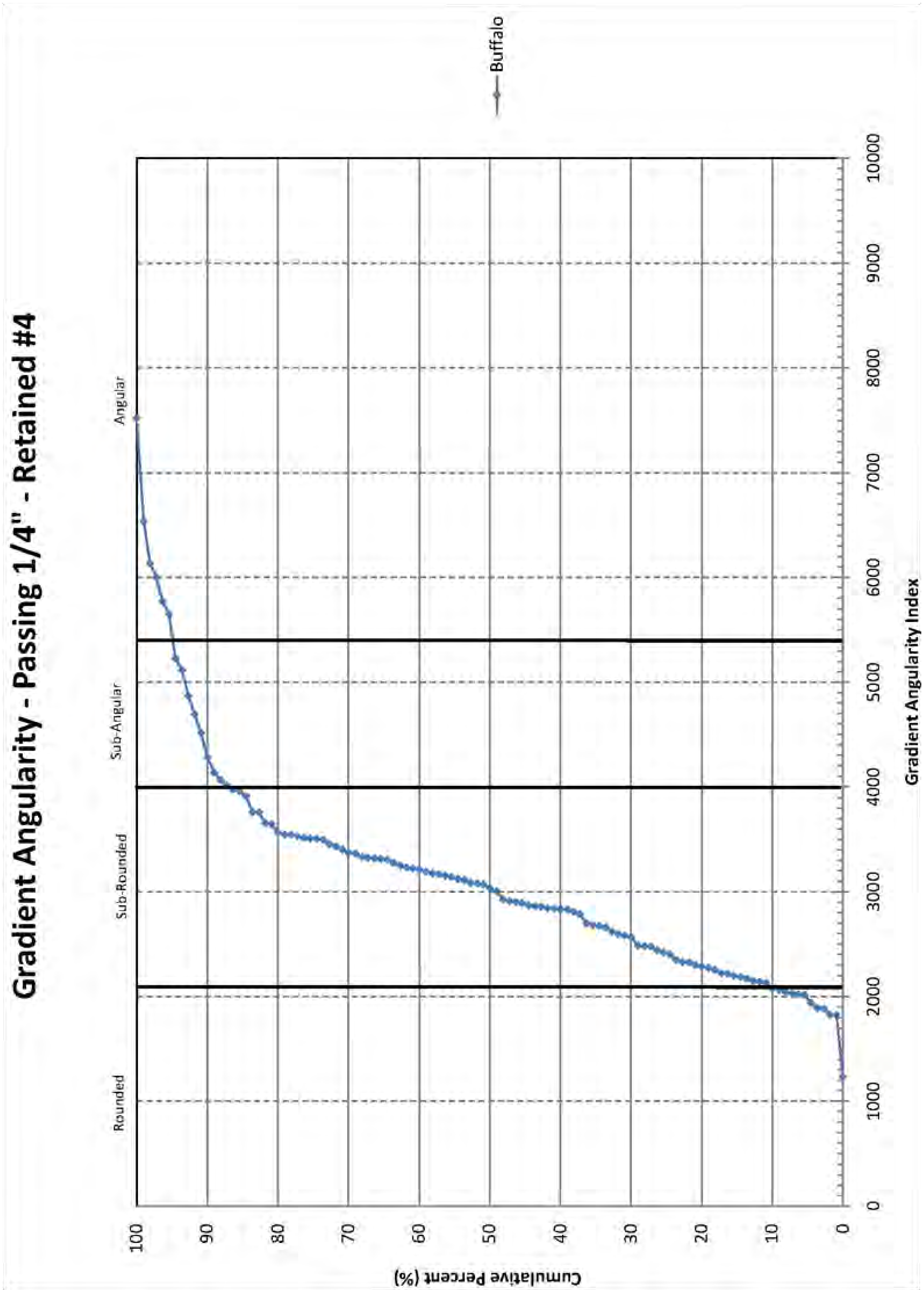
5000
6000
7000
8000
9000
10000
Buffalo



Gradient Angularity - Passing 1/4" - Retained #4
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
100
90
80
70
60
50
40
30
20
10
0
0
1000
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4000
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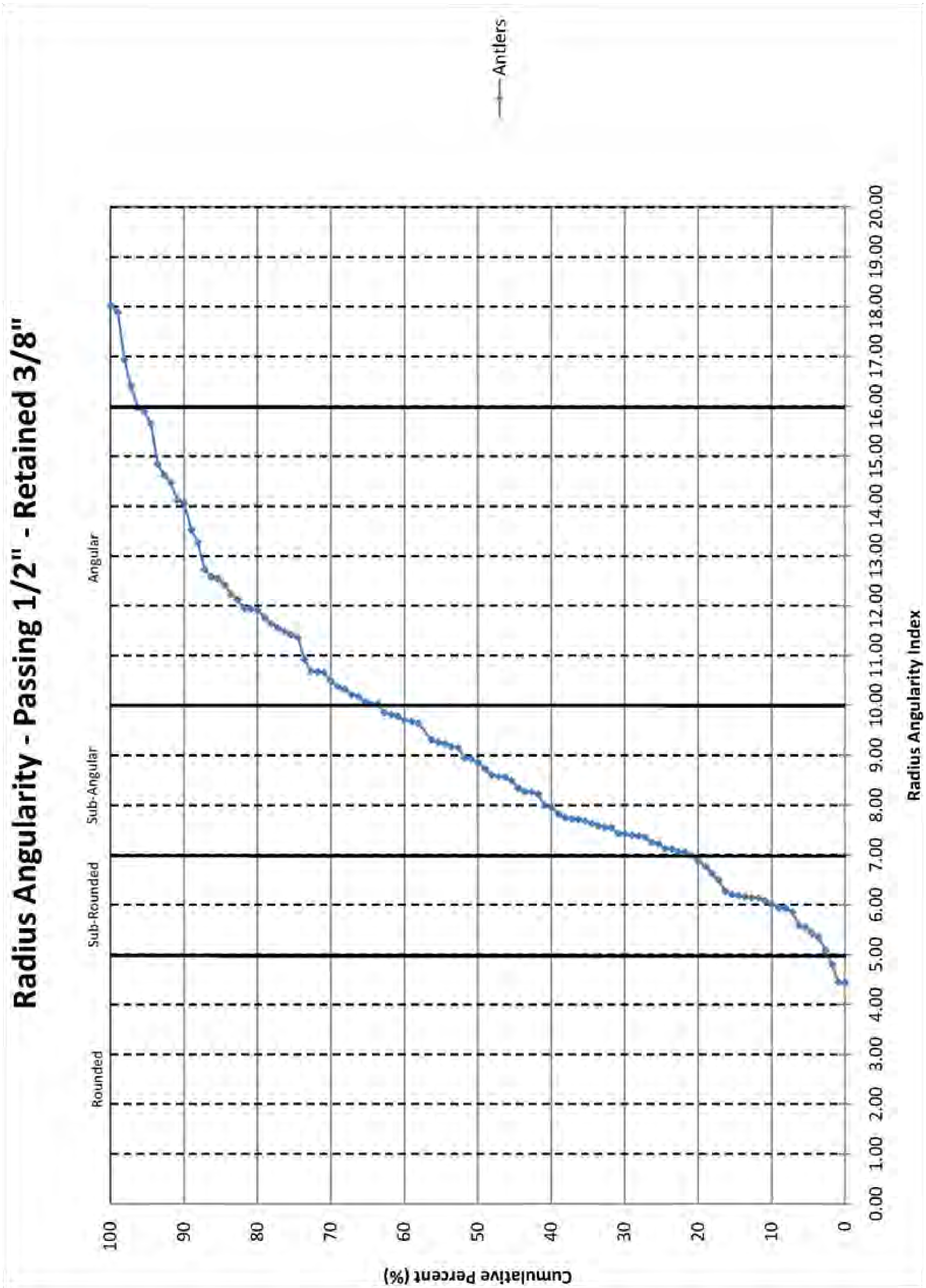
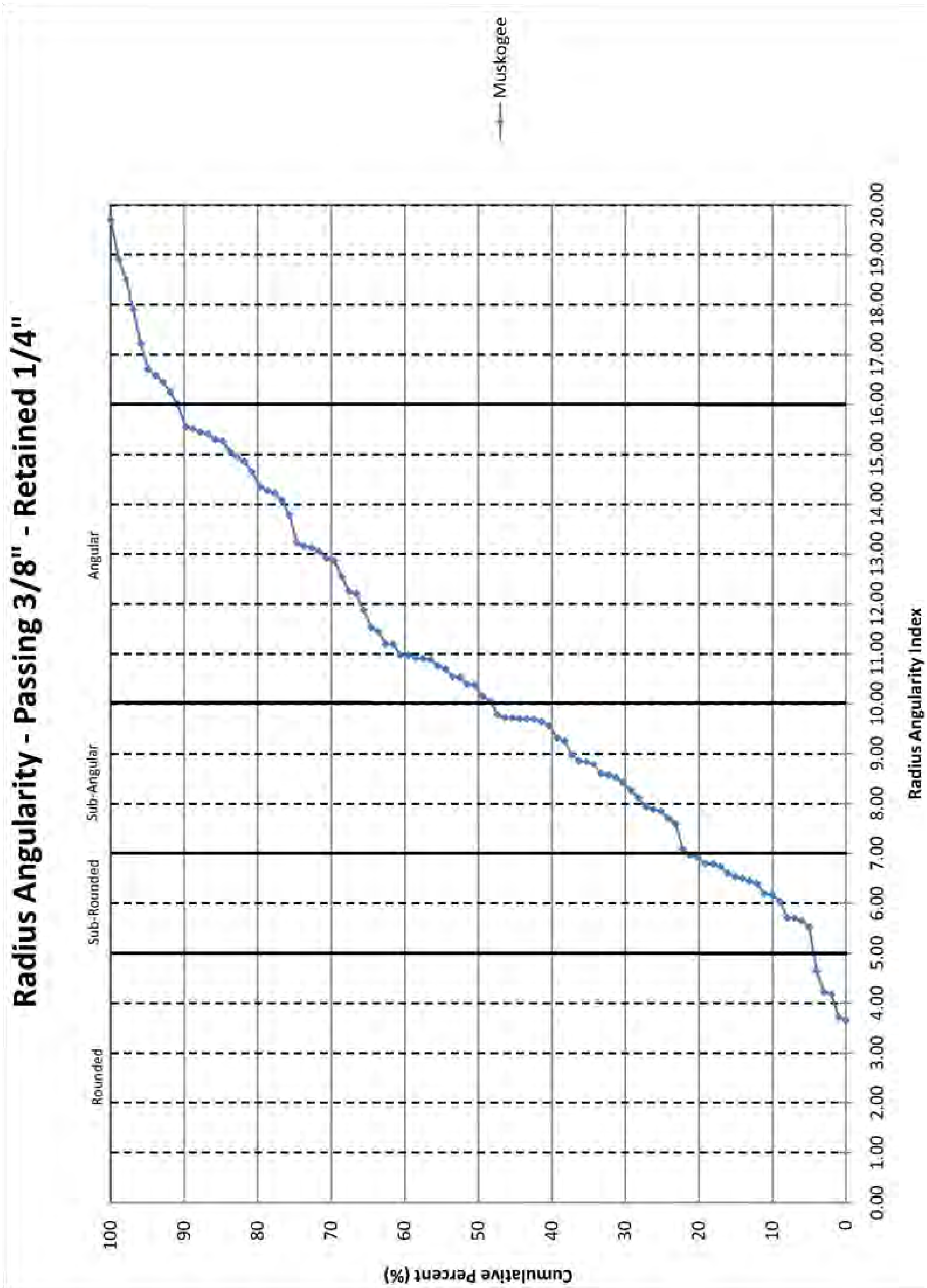
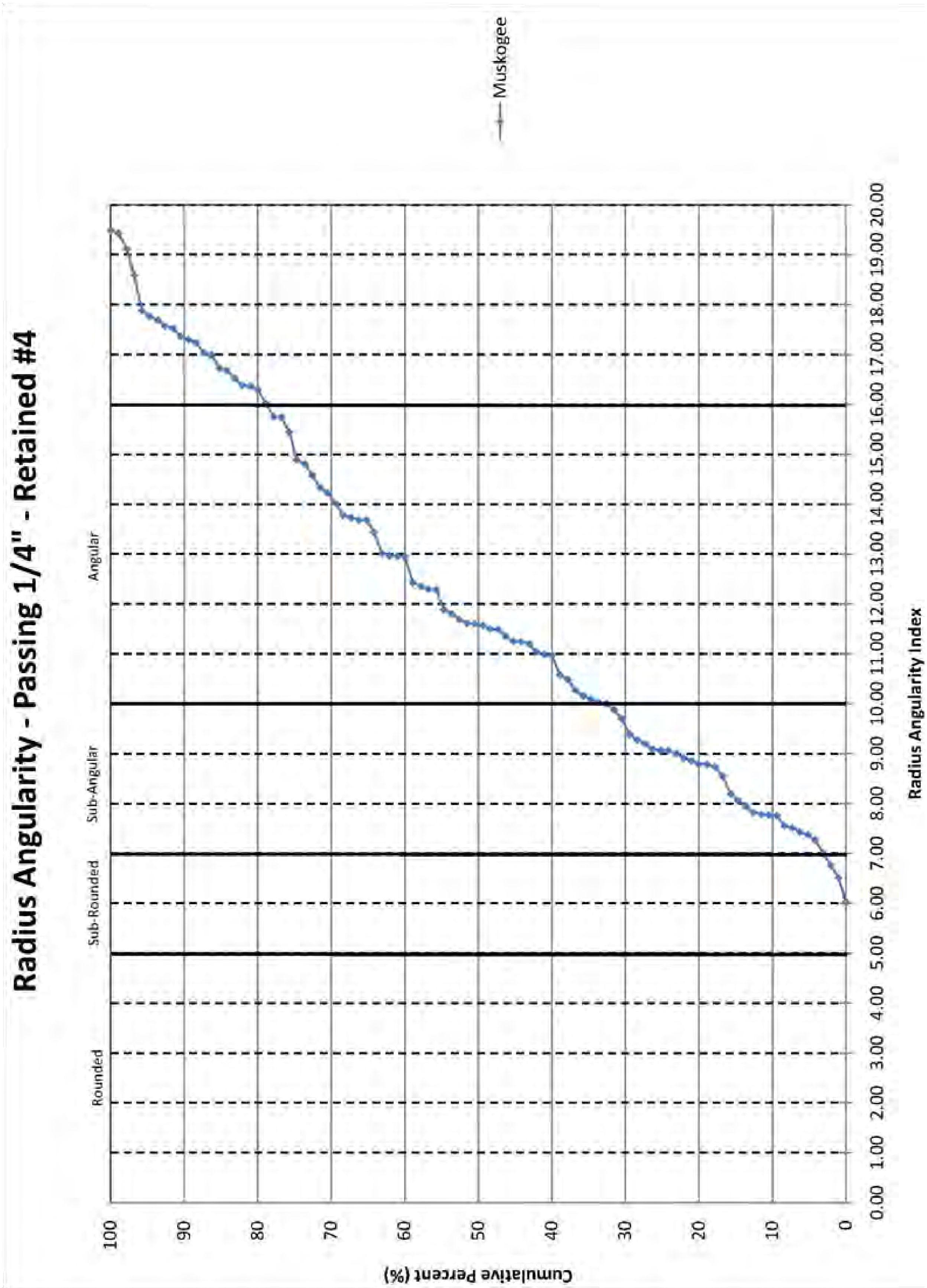
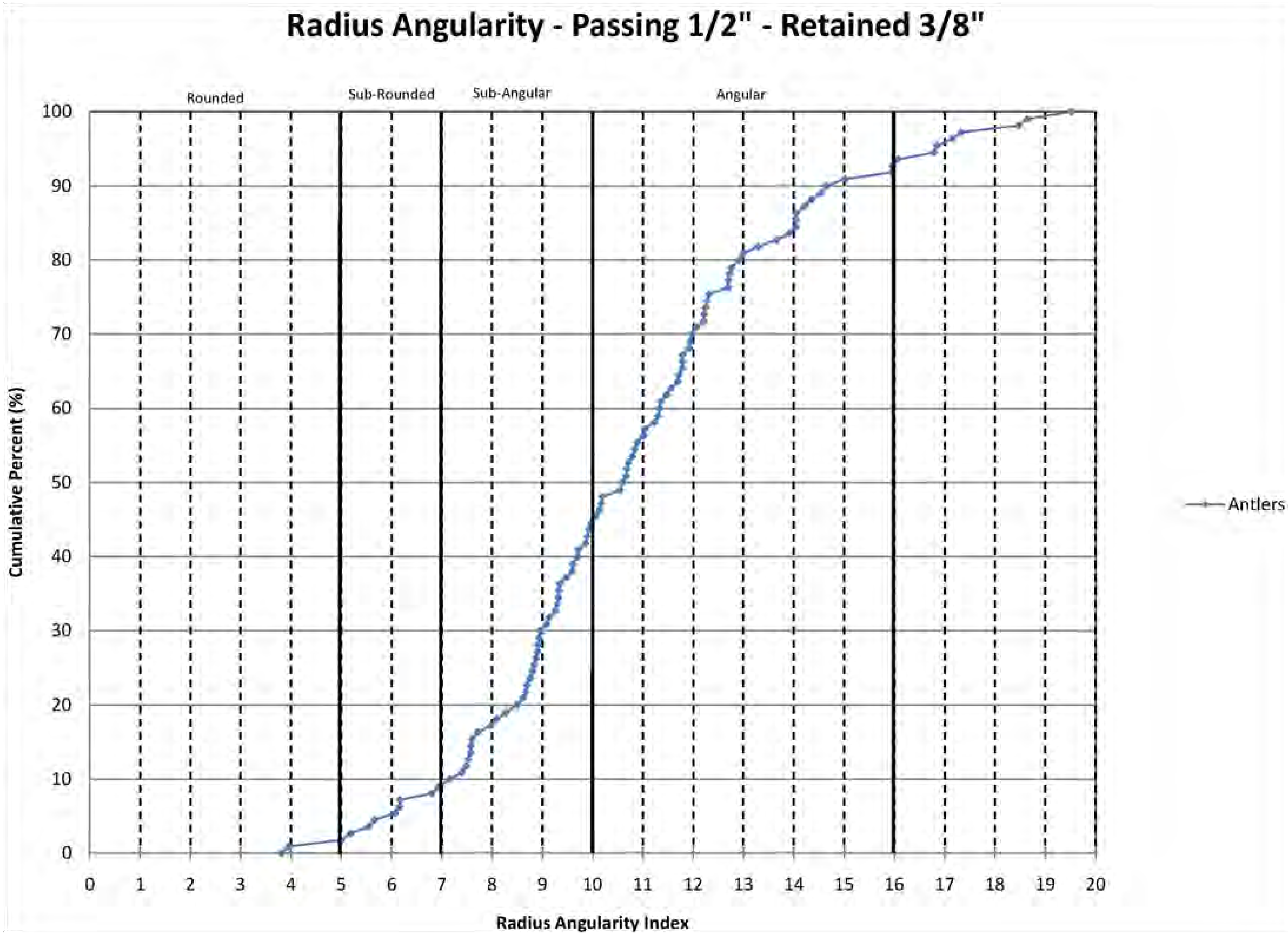
6000
7000
8000
9000
10000
Gradient Angularity Index
Buffalo


Radius Angularity - Passing 1/2" - Retained 3/8"
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
100
90
80
70
60
50
40
30
20
10
0
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00 11.00 12.00 13.00 14.00 15.00 16.00 17.00 18.00 19.00 20.00
Radius Angularity Index
Antlers


Radius Angularity - Passing 3/8" - Retained 1/4"
Rounded
Sub-Rounded
Sub-Angular
Angular
Muskogee
Cumulative Percent (%)
100
90
80
70
60
50
40
30
20
10
0
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00 11.00 12.00 13.00 14.00 15.00 16.00 17.00 18.00 19.00 20.00
Radius Angularity Index



Radius Angularity - Passing 1/4" - Retained #4
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
100
90
80
70
60
50
40
30
20
10
0
0.00 1.00 2.00 3.00 4.00 5.00 6.00 7.00 8.00 9.00 10.00 11.00 12.00 13.00 14.00 15.00 16.00 17.00 18.00 19.00 20.00
Radius Angularity Index
Muskogee



Radius Angularity - Passing 1/2" - Retained 3/8"
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
0
10
20
30
40
50
60
70
80
90
100
0
1
2
3
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8
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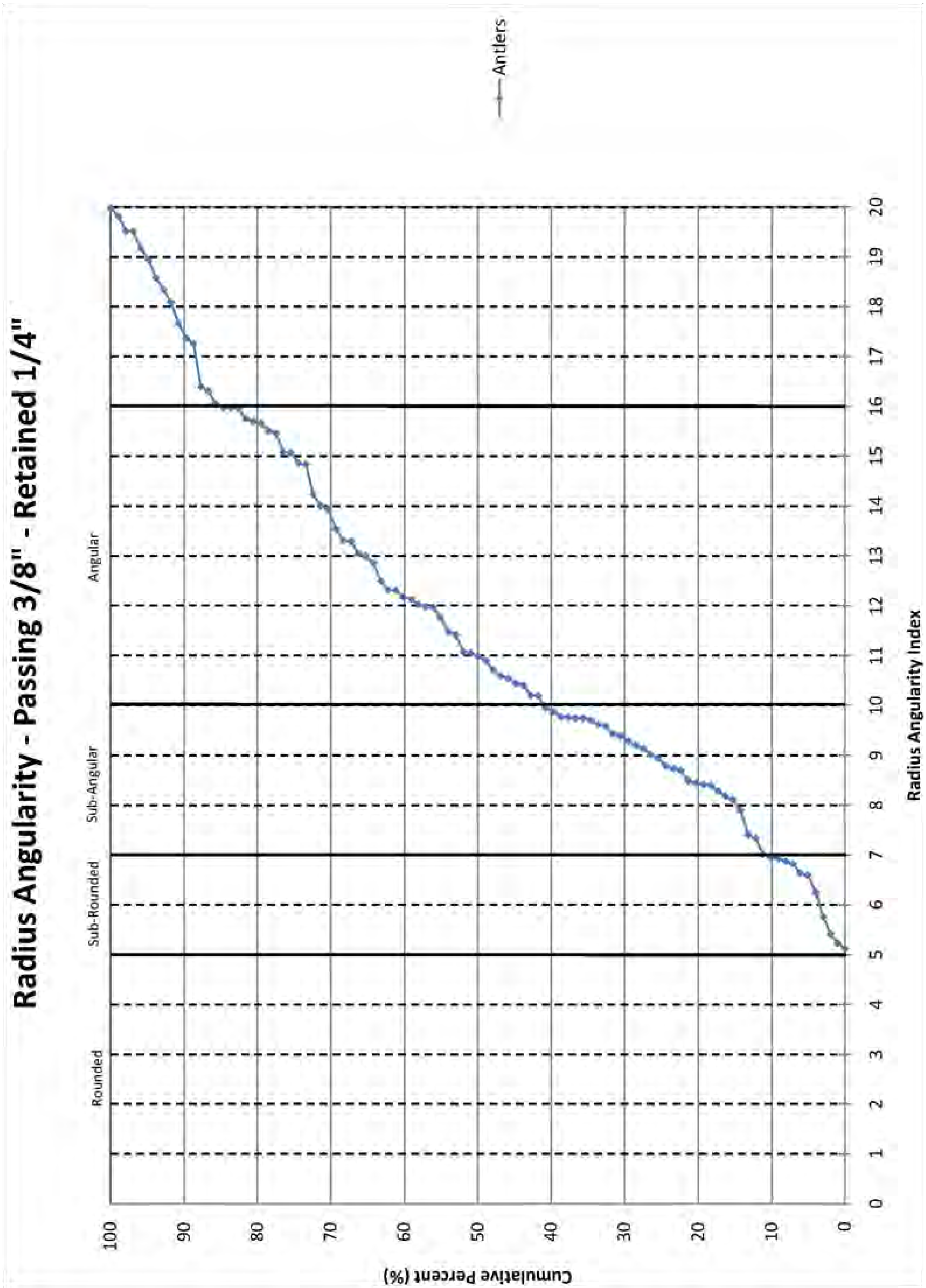
11
12
13
14
15
16
17
18
19
20
Radius Angularity Index
Antlers



Radius Angularity - Passing 3/8" - Retained 1/4"
Rounded
Sub-Rounded
Sub-Angular
Angular
Antlers
Cumulative Percent (%)
Radius Angularity Index
100
90
80
70
60
50
40
30
20
10
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0
1
2
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6
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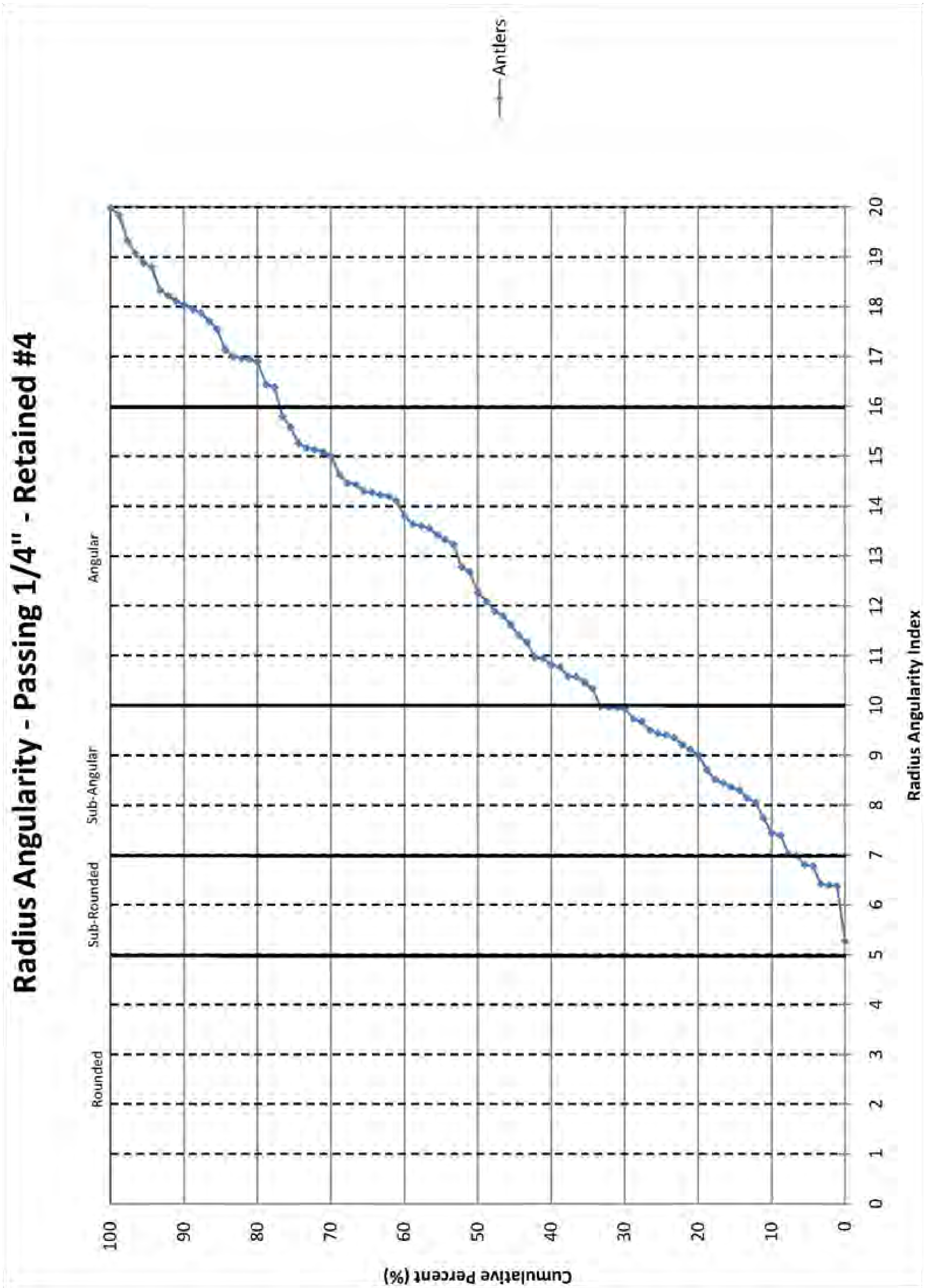
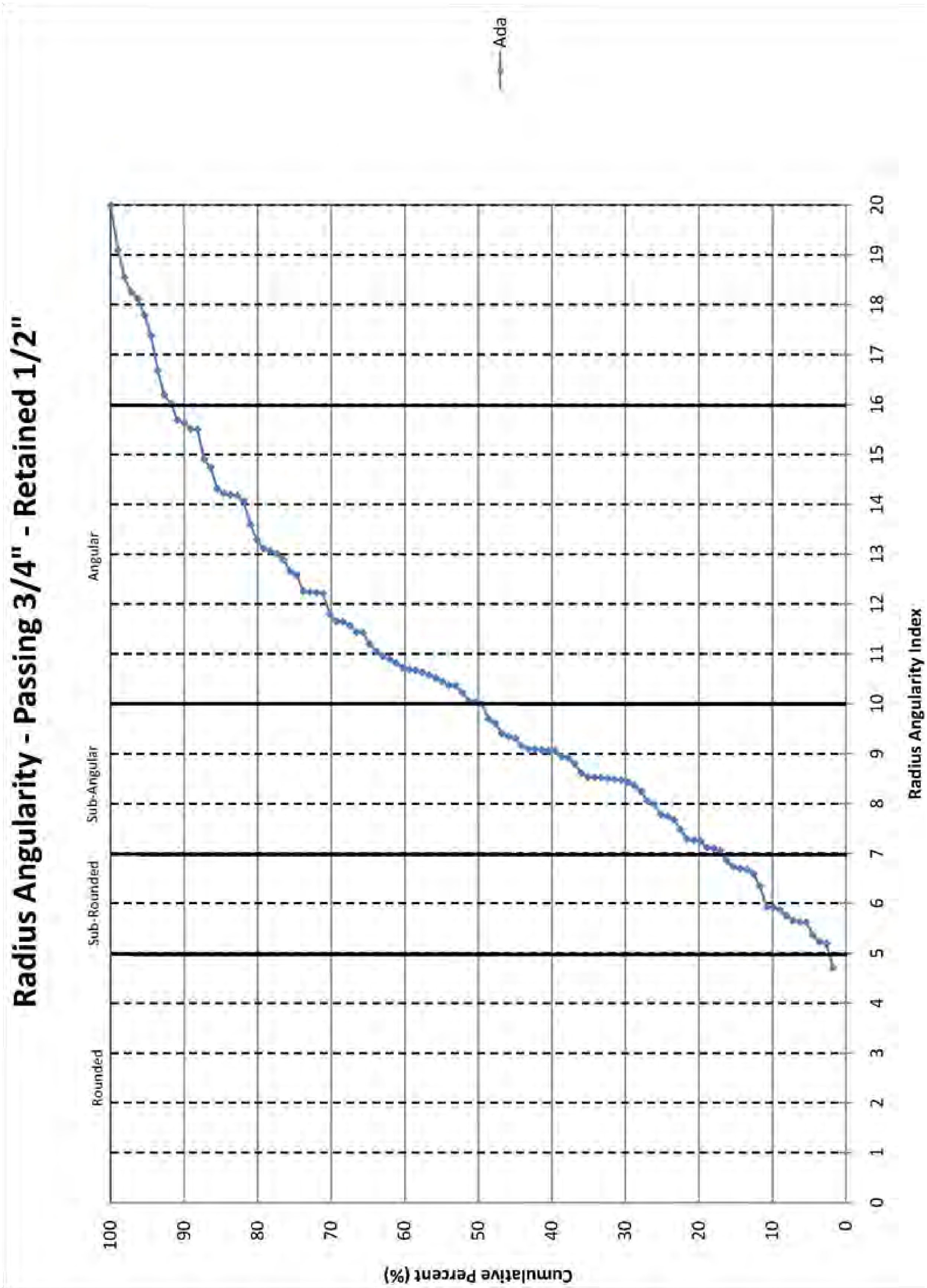


Radius Angularity - Passing 1/4" - Retained #4
Rounded
Sub-Rounded
Sub-Angular
Angular
Antlers
Radius Angularity Index
Cumulative Percent (%)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
0 10 20 30 40 50 60 70 80 90 100


Radius Angularity - Passing 3/4" - Retained 1/2"
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
Radius Angularity Index
Ada
100
90
80
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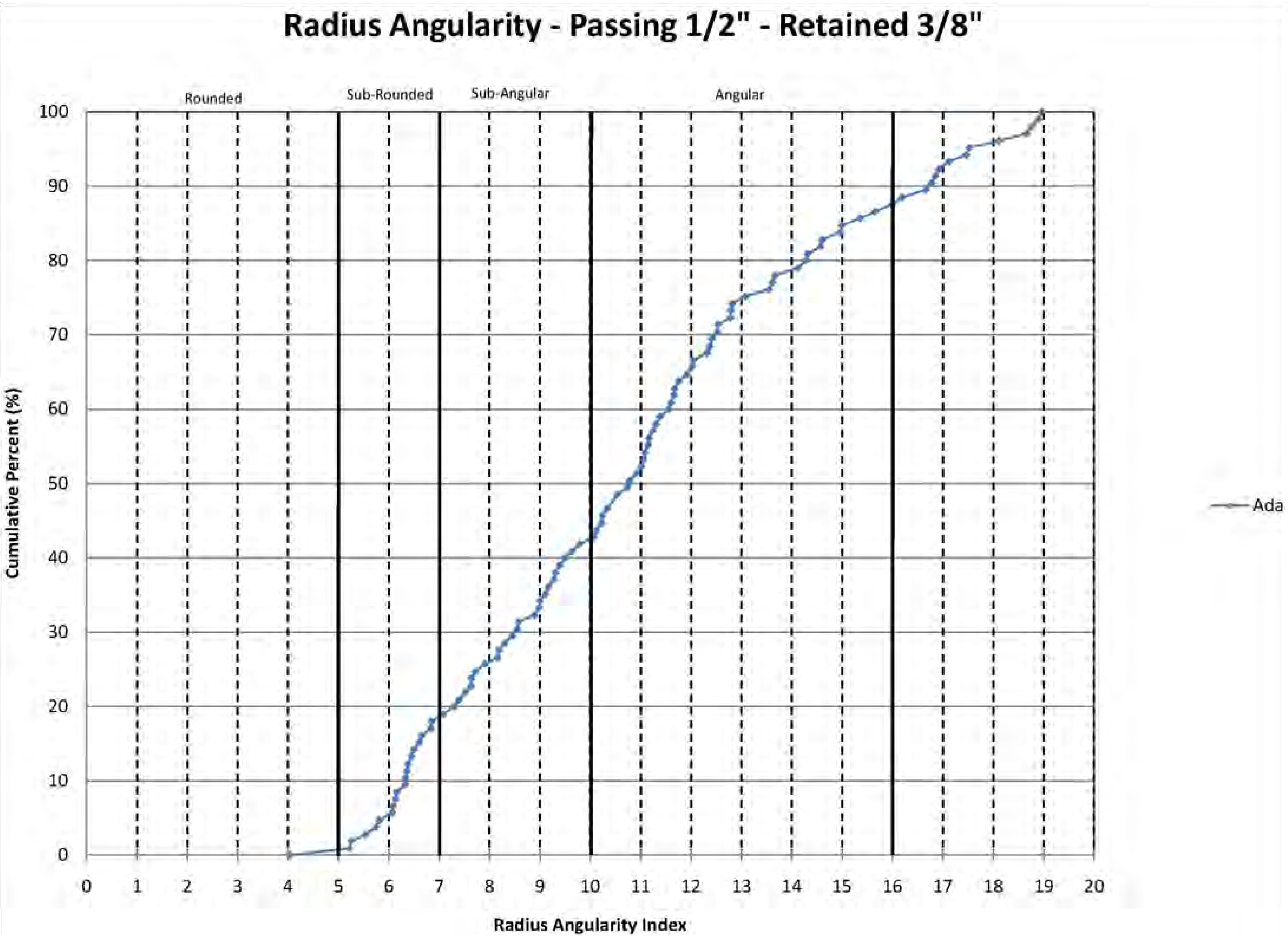
19
20


Radius Angularity - Passing 1/2" - Retained 3/8"
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
100
90
80
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60
50
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20
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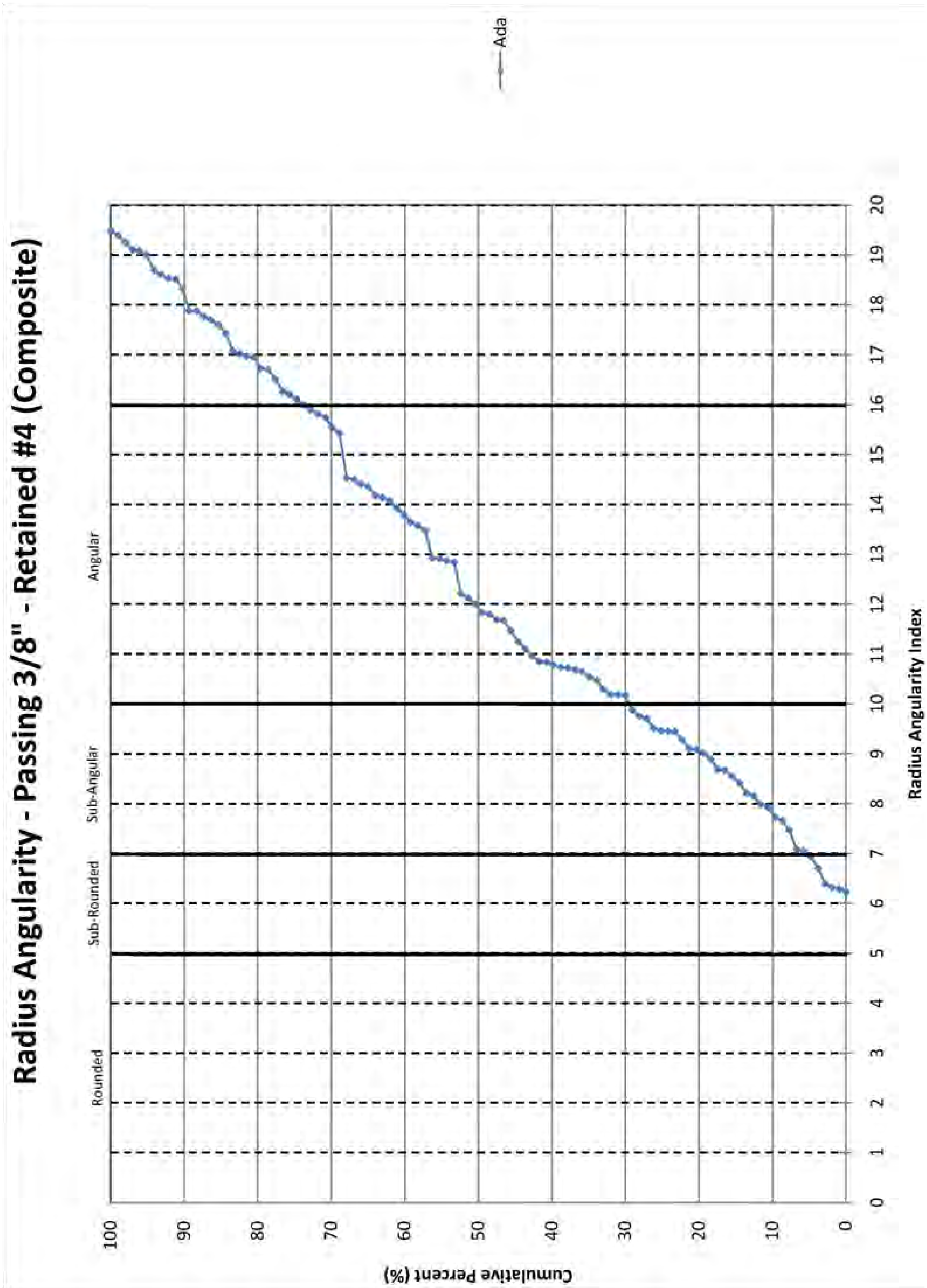
18
19
20
Radius Angularity Index
Ada


Radius Angularity - Passing 3/8" - Retained #4 (Composite)
Rounded
Sub-Rounded
Sub-Angular
Angular
Ada
Cumulative Percent (%)
Radius Angularity Index
0
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100
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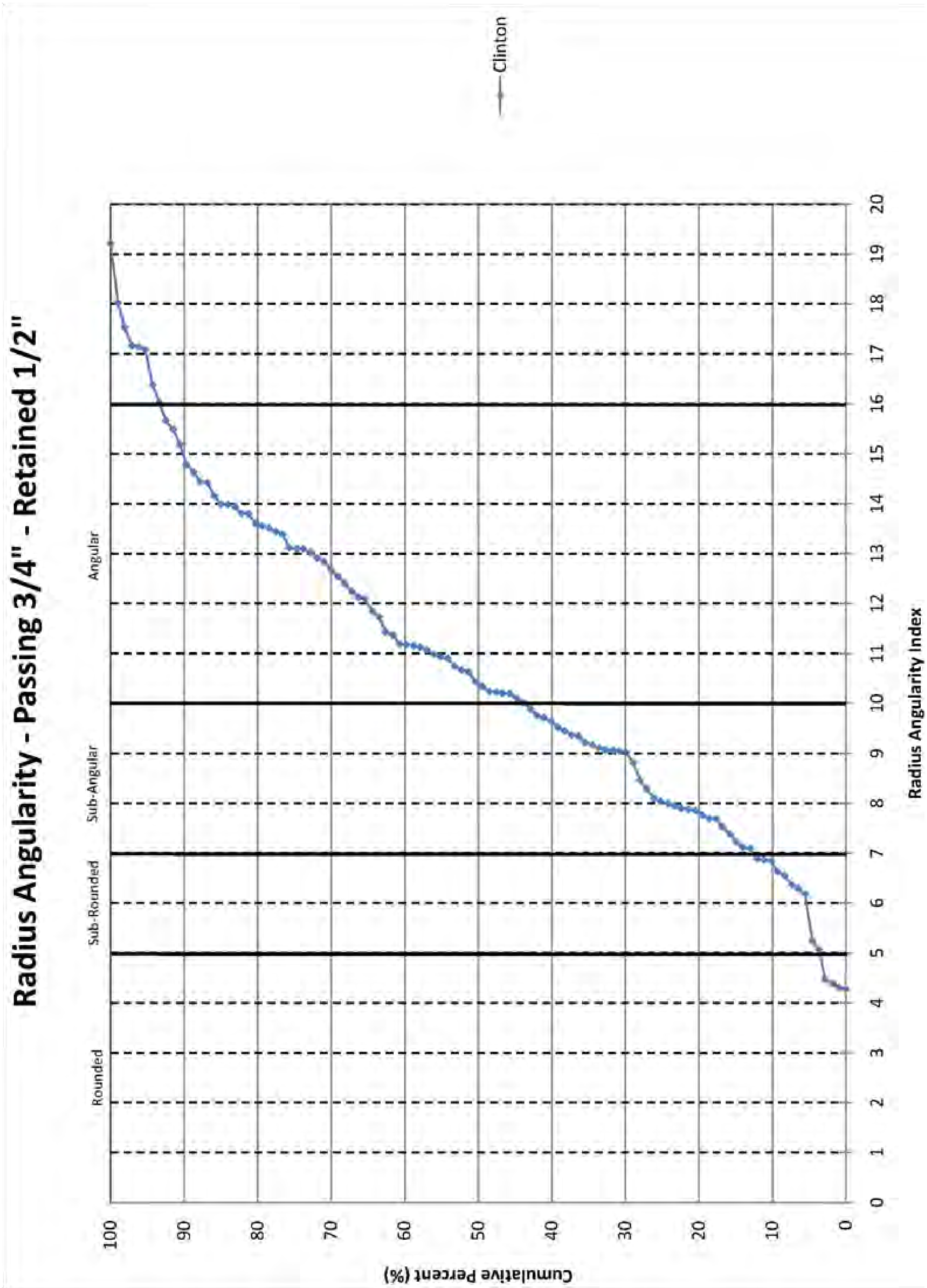

Radius Angularity - Passing 3/4" - Retained 1/2"
Rounded
Sub-Rounded
Sub-Angular
Angular
Clinton
Cumulative Percent (%)
Radius Angularity Index
0
10
20
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60
70
80
90
100
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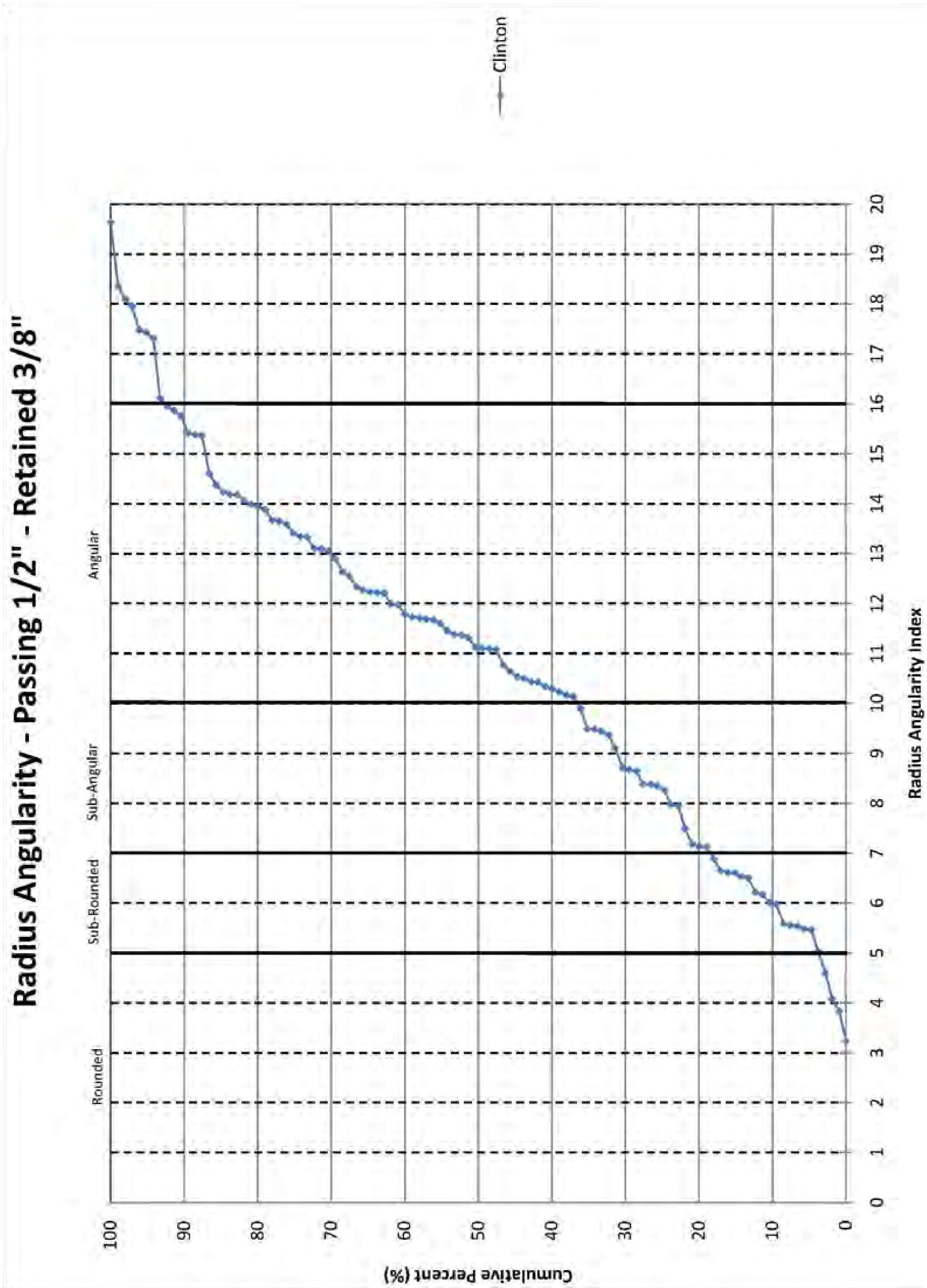
20


Radius Angularity - Passing 1/2" - Retained 3/8"
Rounded
Sub-Rounded
Sub-Angular
Angular
Clinton
Cumulative Percent (%)
Radius Angularity Index
0
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100
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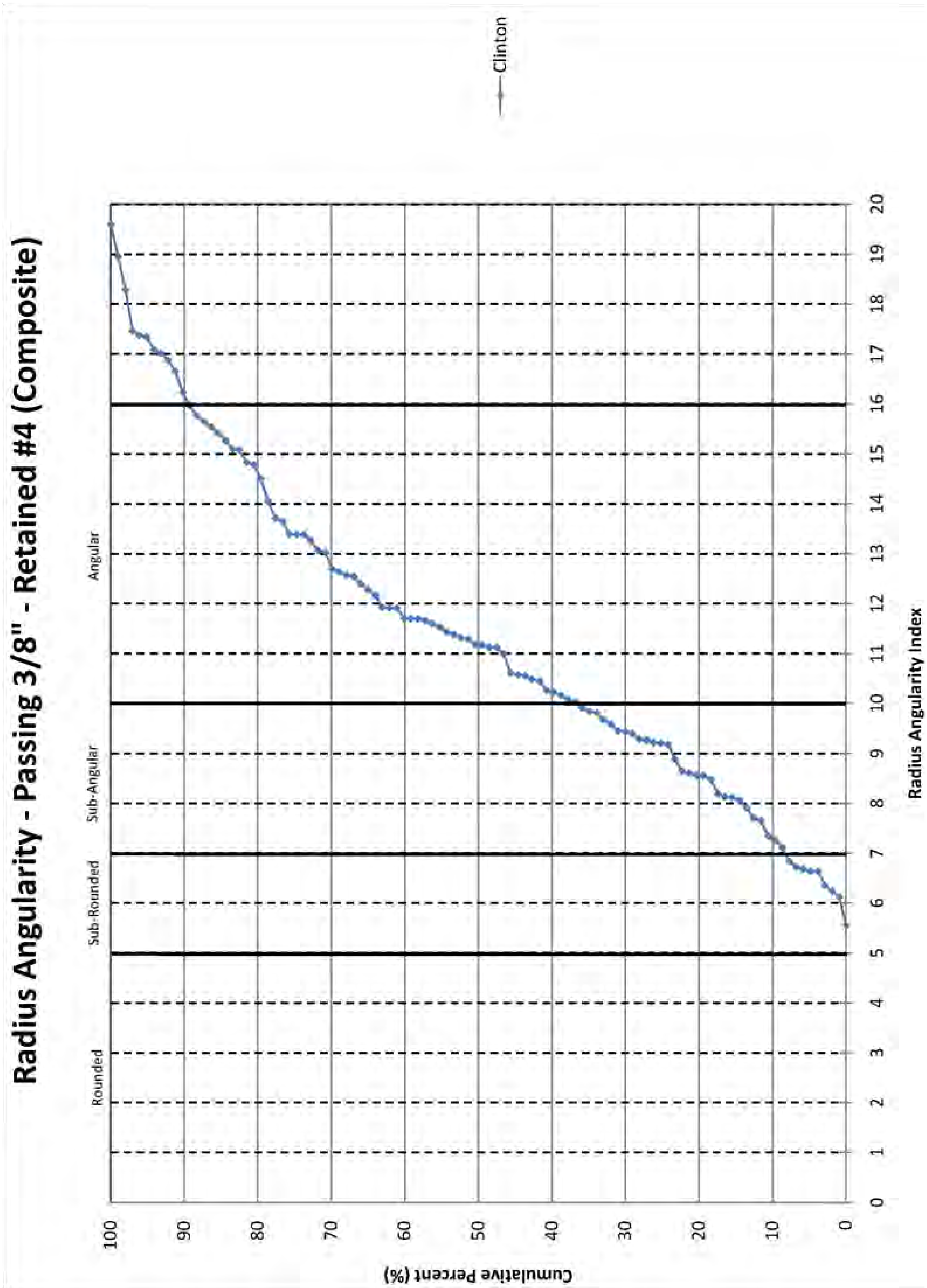
20


Radius Angularity - Passing 3/8" - Retained #4 (Composite)
Rounded
Sub-Rounded
Sub-Angular
Angular
Clinton
Cumulative Percent (%)
Radius Angularity Index
0
10
20
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100
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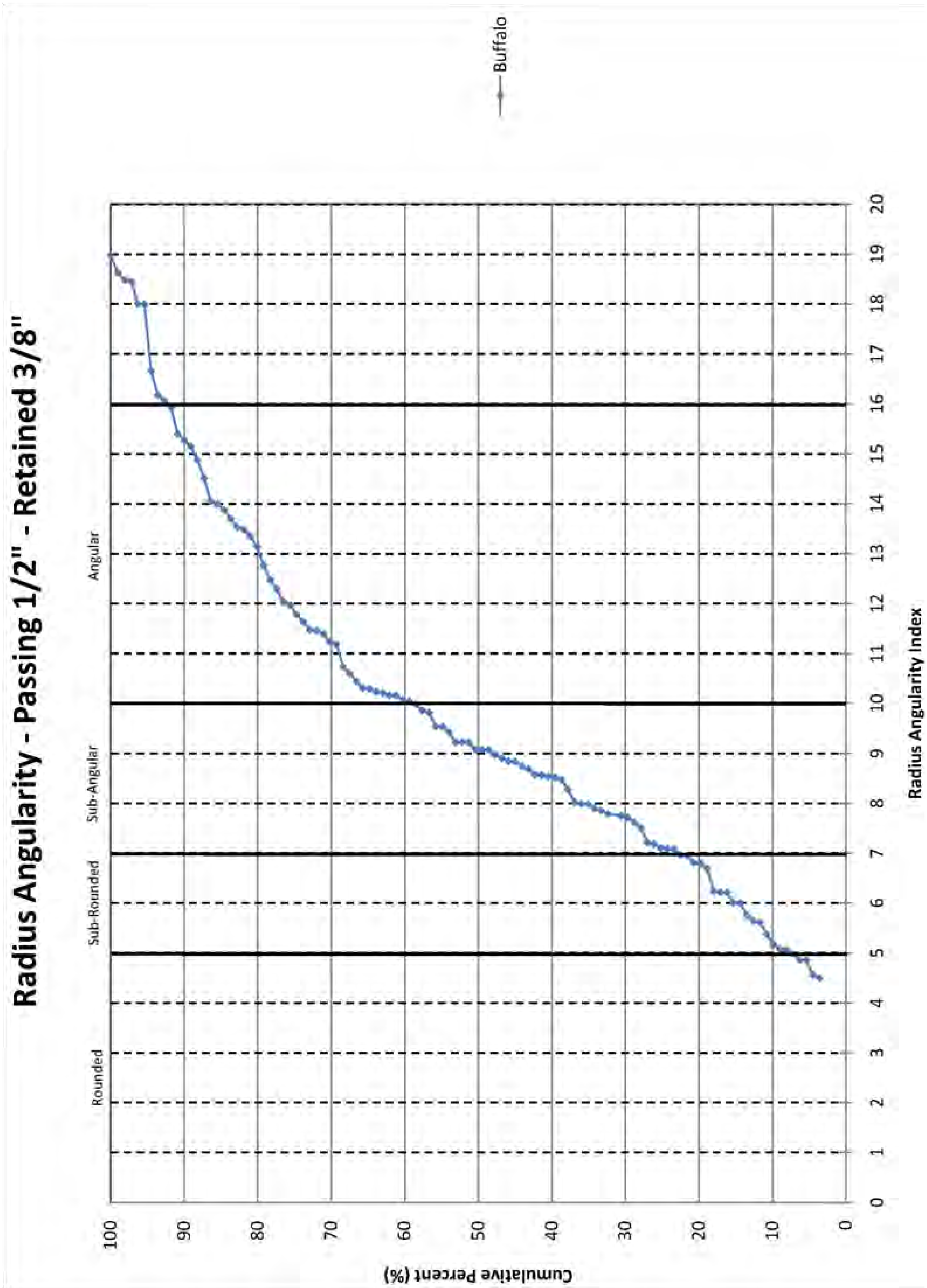
20


Radius Angularity - Passing 1/2" - Retained 3/8"
Rounded
Sub-Rounded
Sub-Angular
Angular
Buffalo
Cumulative Percent (%)
100
90
80
70
60
50
40
30
20
10
0
0
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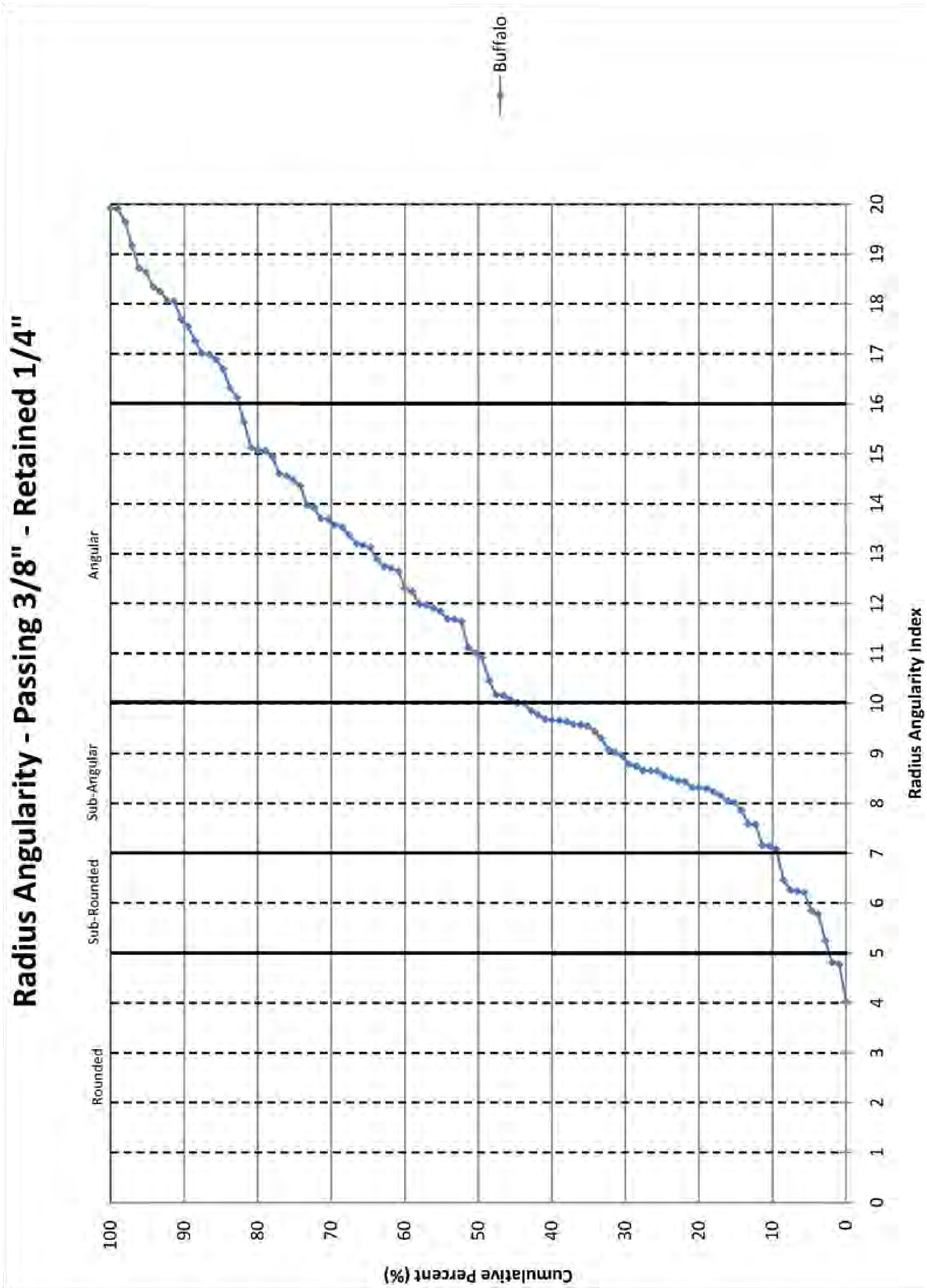
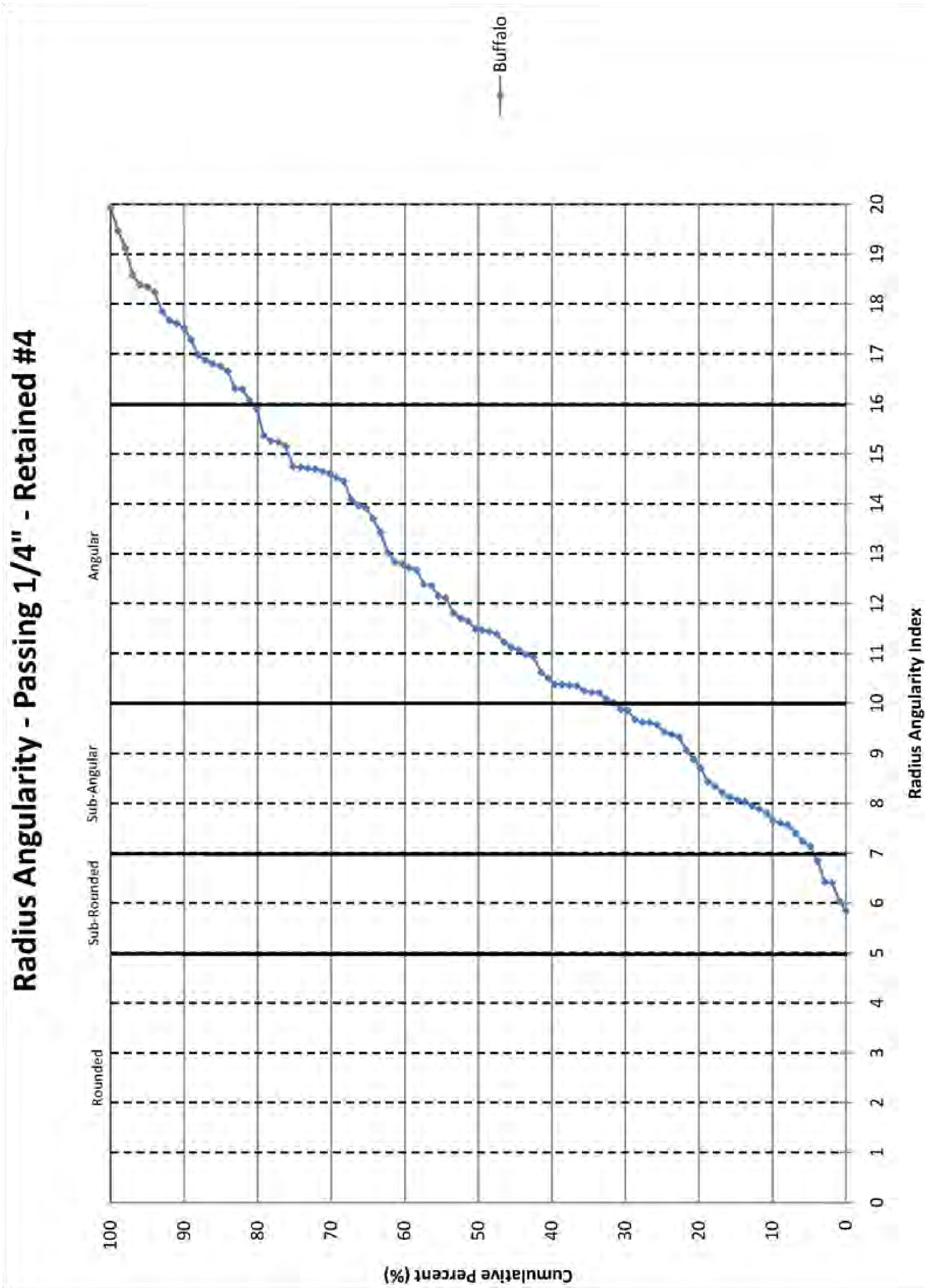
16
17
18
19
20
Radius Angularity Index


Radius Angularity - Passing 3/8" - Retained 1/4"
Rounded
Sub-Rounded
Sub-Angular
Angular
Cumulative Percent (%)
0
10
20
30
40
50
60
70
80
90
100
Radius Angularity Index
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Buffalo



Radius Angularity - Passing 1/4" - Retained #4
Rounded
Sub-Rounded
Sub-Angular
Angular
Buffalo
Cumulative Percent (%)
Radius Angularity Index
0
10
20
30
40
50
60
70
80
90
100
0
1
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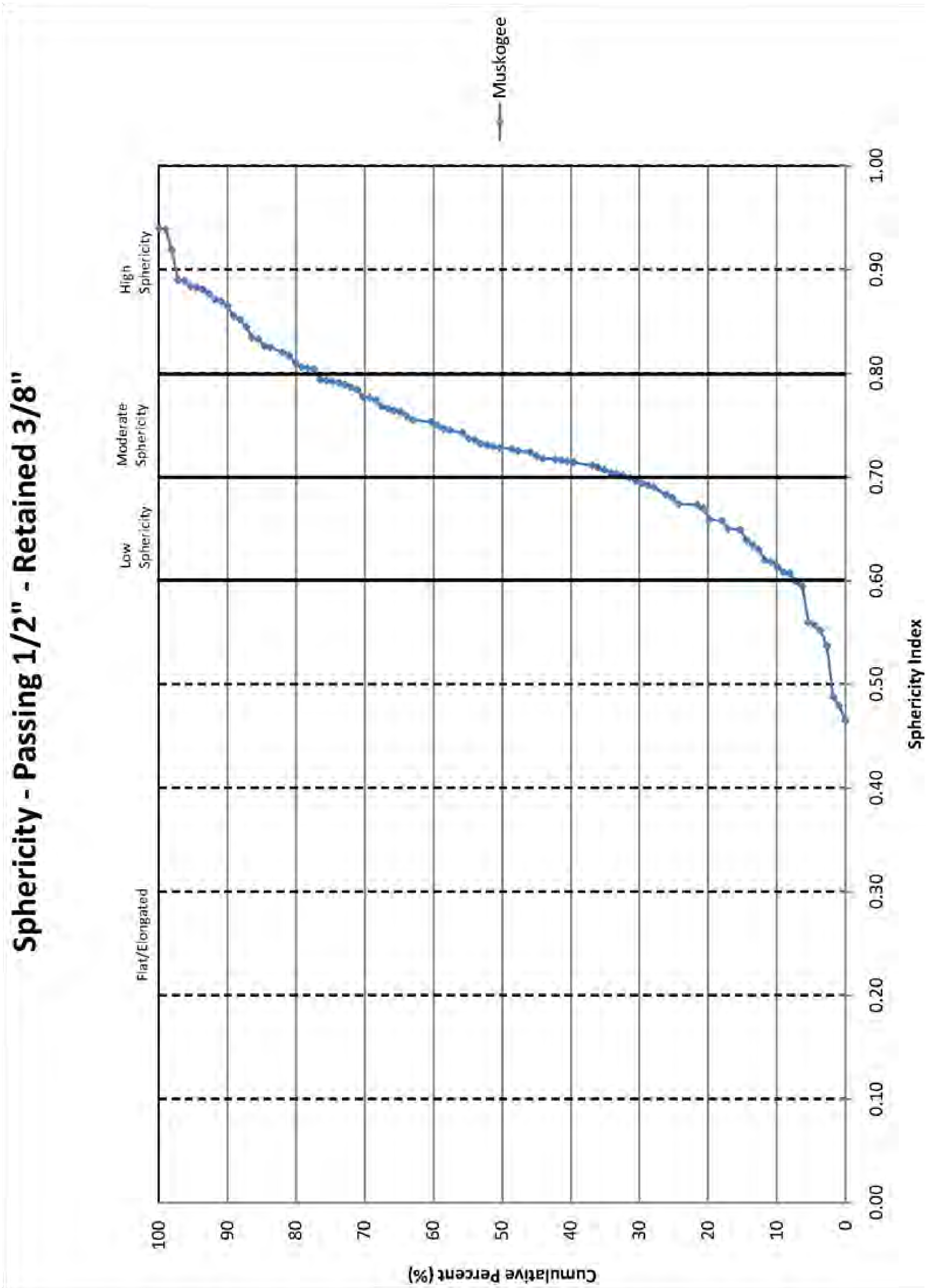
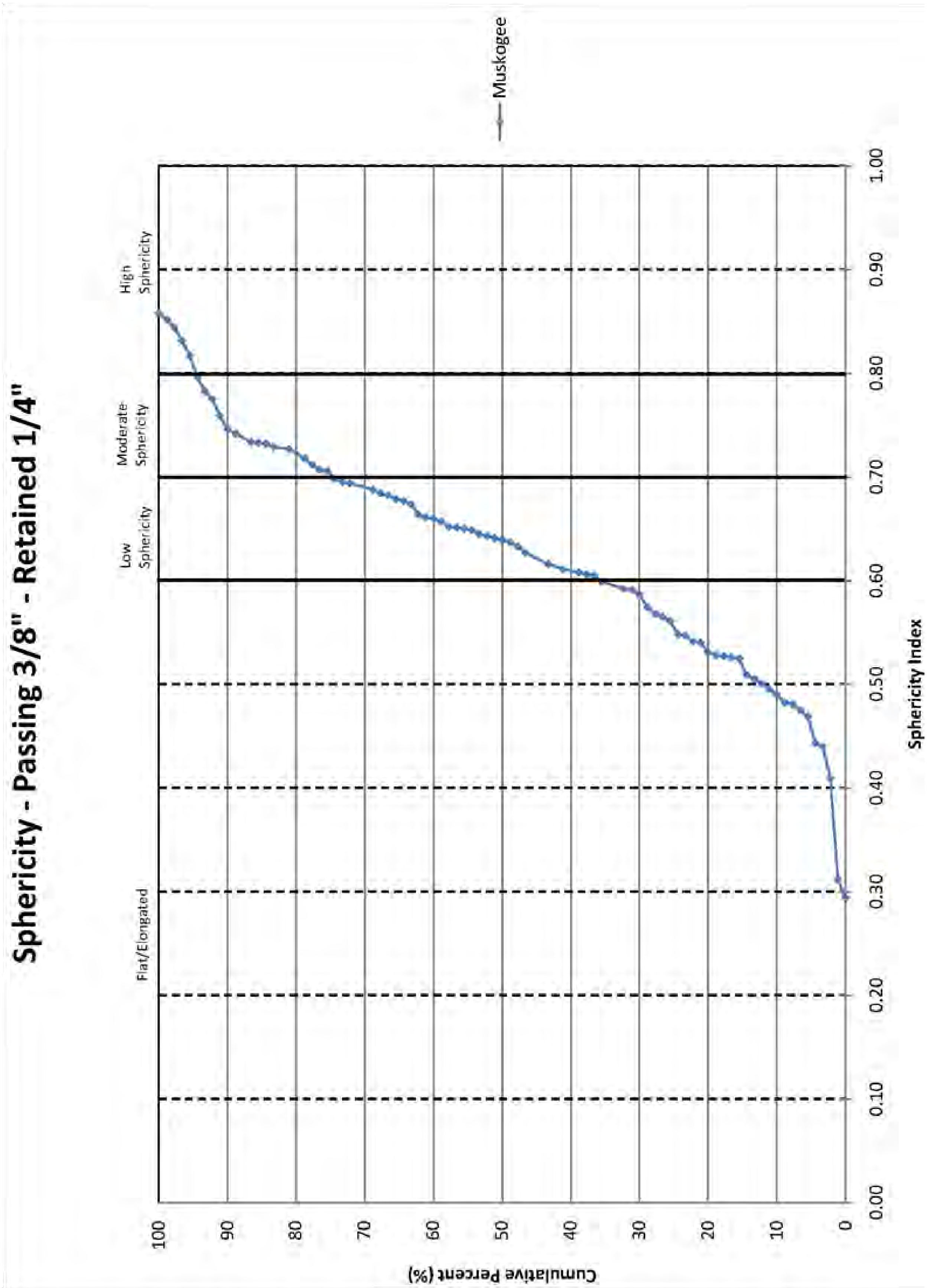
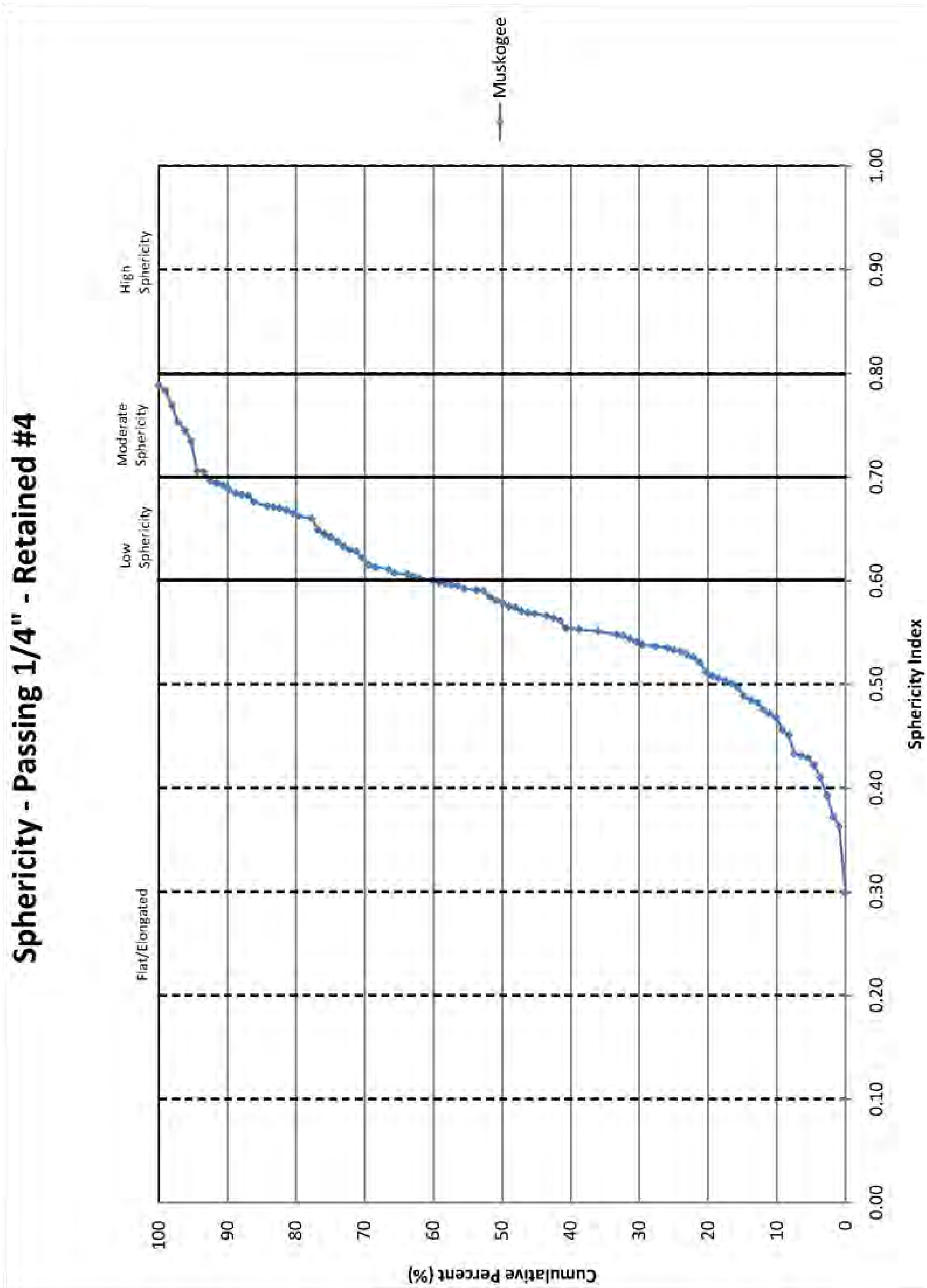
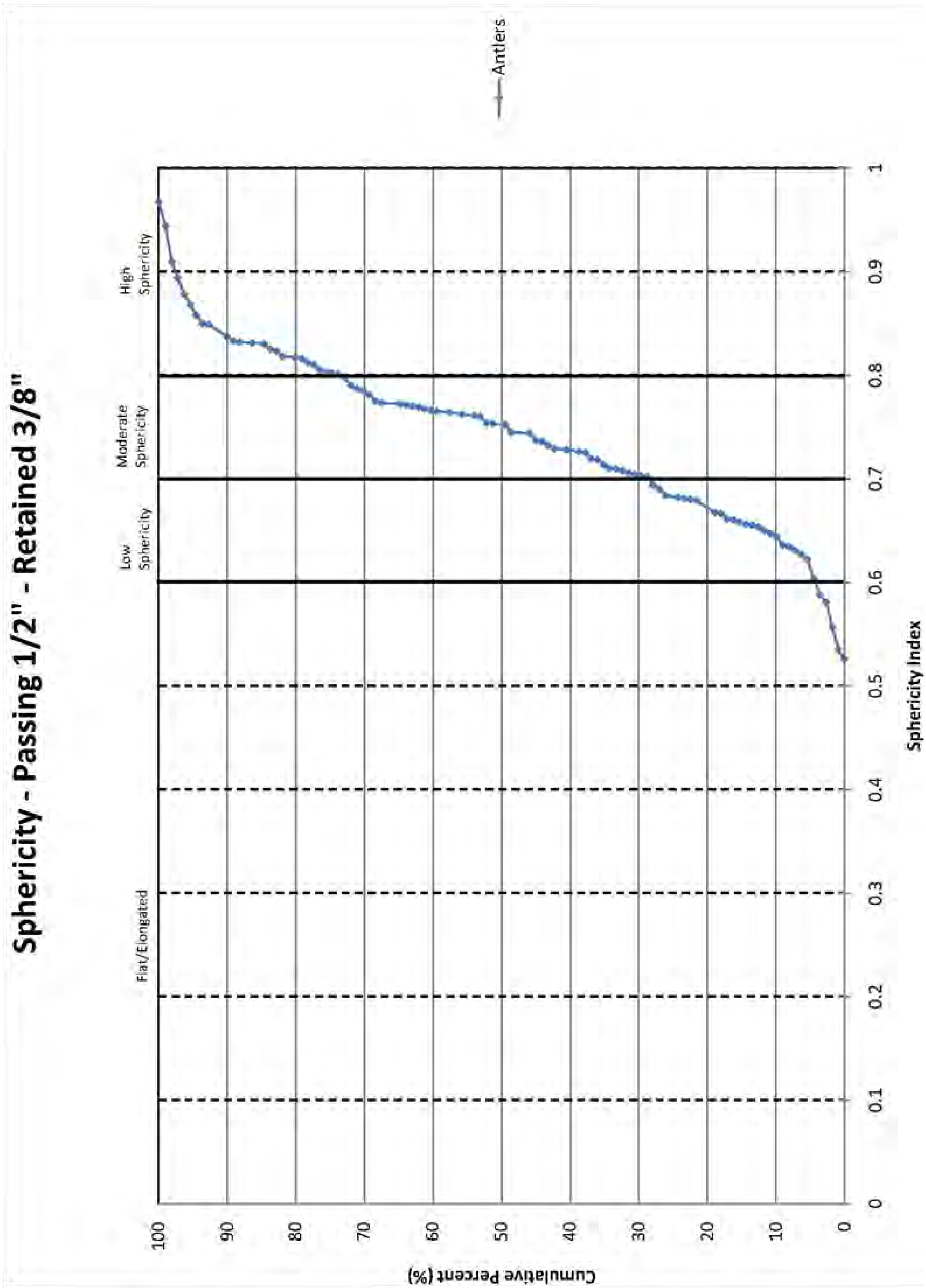
19
20


Sphericity - Passing 1/2" - Retained 3/8"
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Muskogee
Cumulative Percent (%)
100
90
80
70
60
50
40
30
20
10
0
Sphericity Index
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00

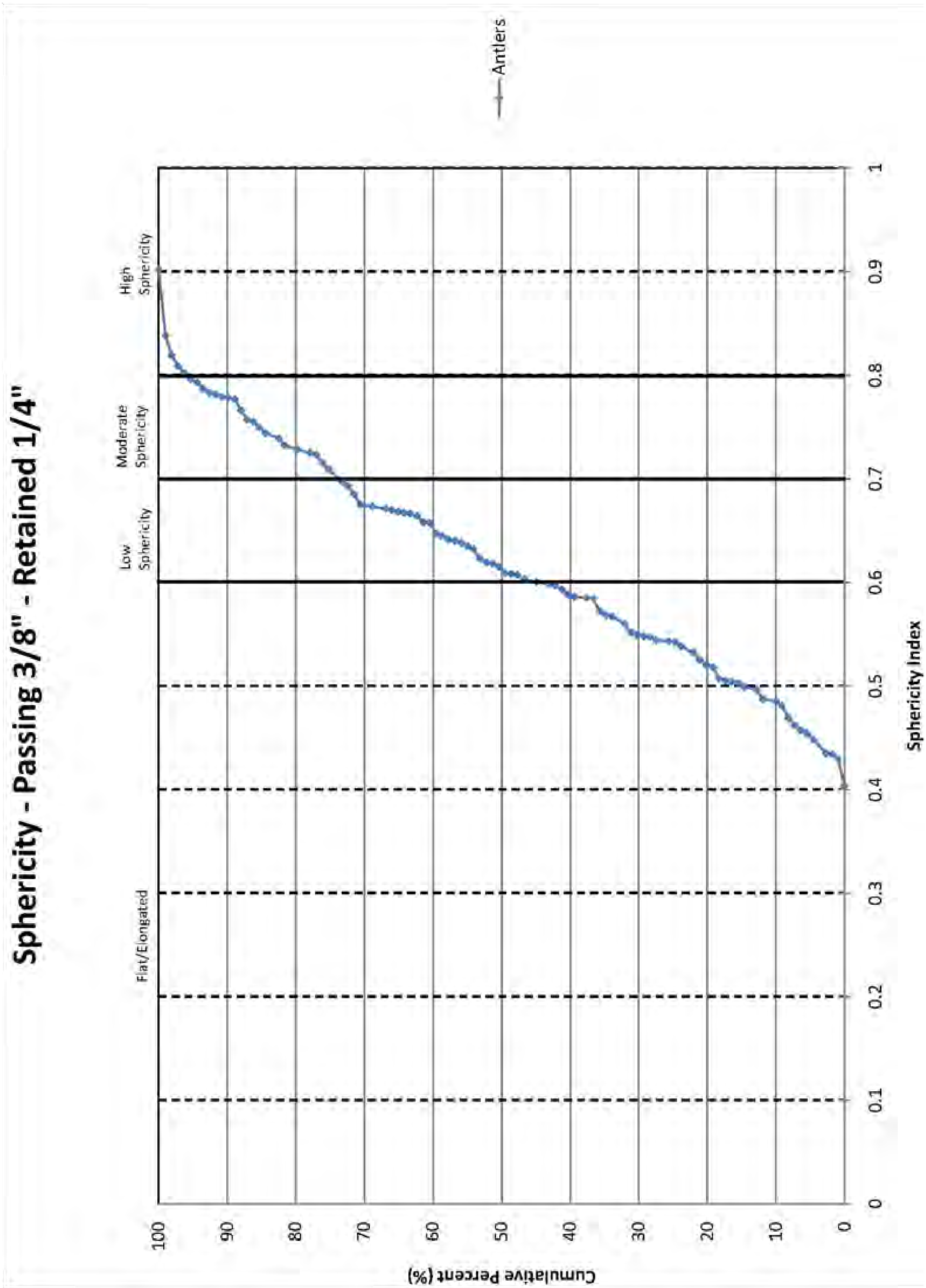

Sphericity - Passing 3/8" - Retained 1/4"
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Muskogee
Cumulative Percent (%)
Sphericity Index
0
10
20
30
40
50
60
70
80
90
100
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00

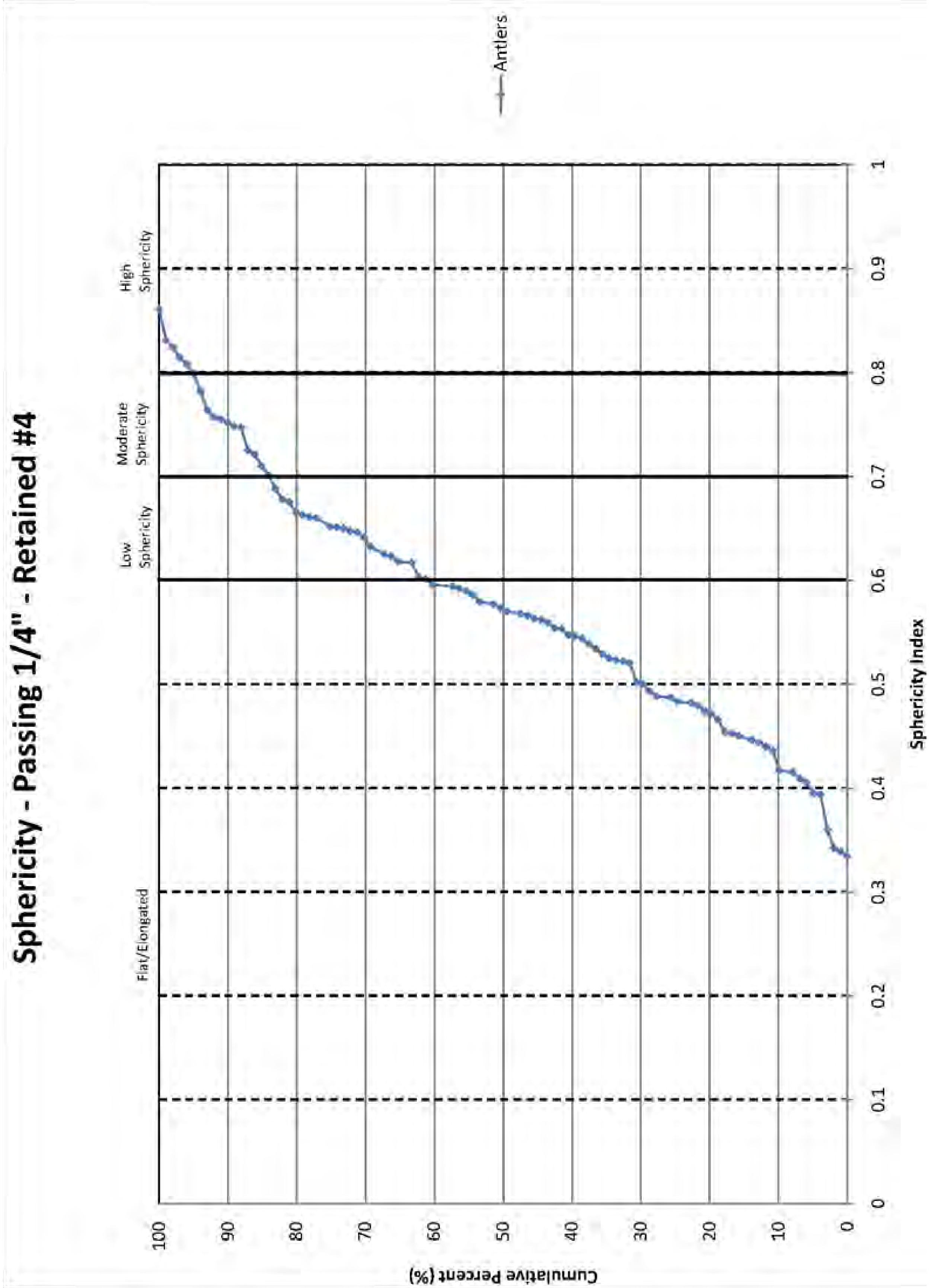


Sphericity - Passing 1/4" - Retained #4
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Muskogee
Cumulative Percent (%)
Sphericity Index
0
10
20
30
40
50
60
70
80
90
100
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00

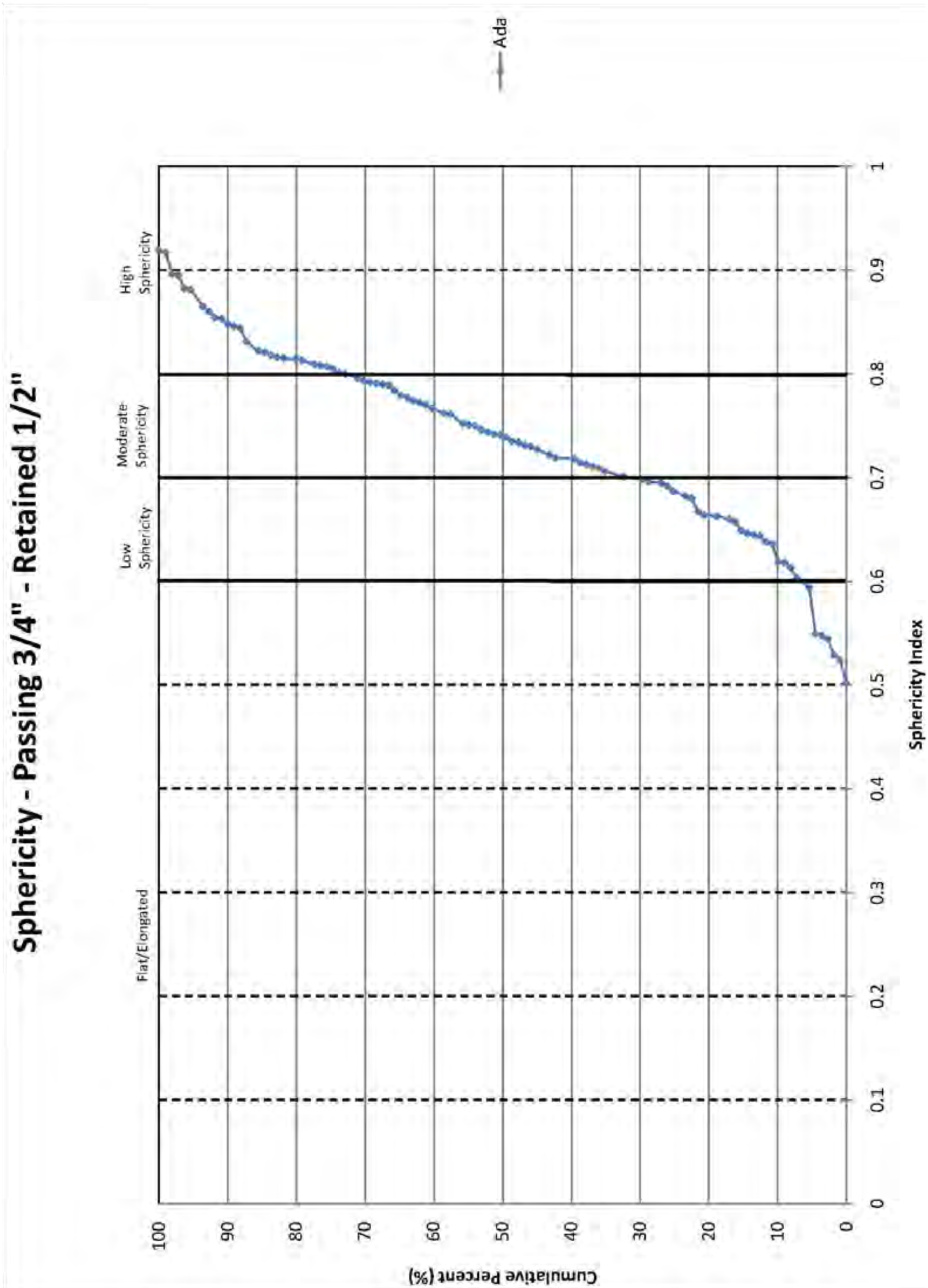


Sphericity - Passing 1/2" - Retained 3/8"
Cumulative Percent (%)
Sphericity Index
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Antlers
0
10
20
30
40
50
60
70
80
90
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

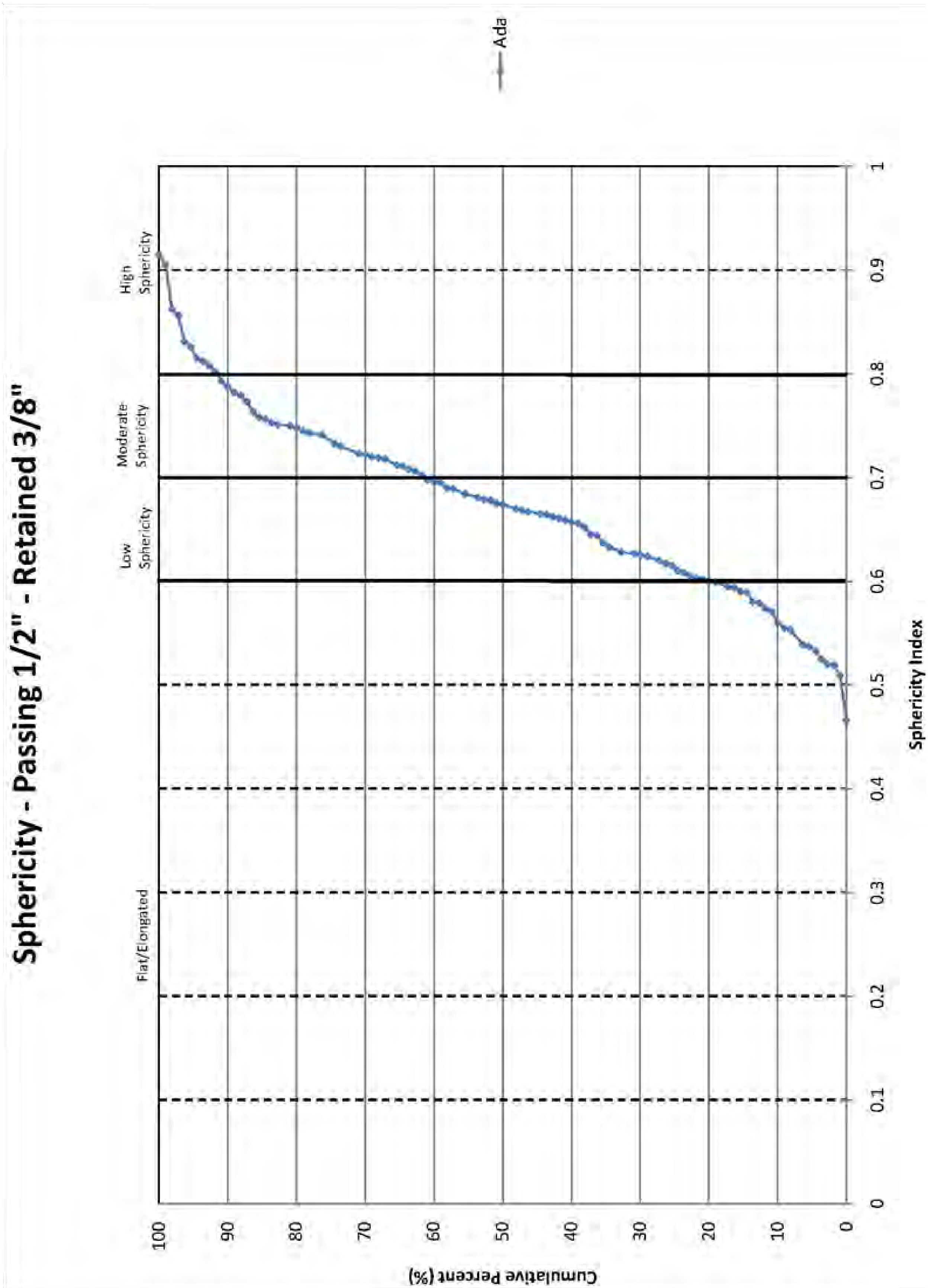

Sphericity - Passing 3/8" - Retained 1/4"
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Antlers
Cumulative Percent (%)
Sphericity Index
0
10
20
30
40
50
60
70
80
90
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

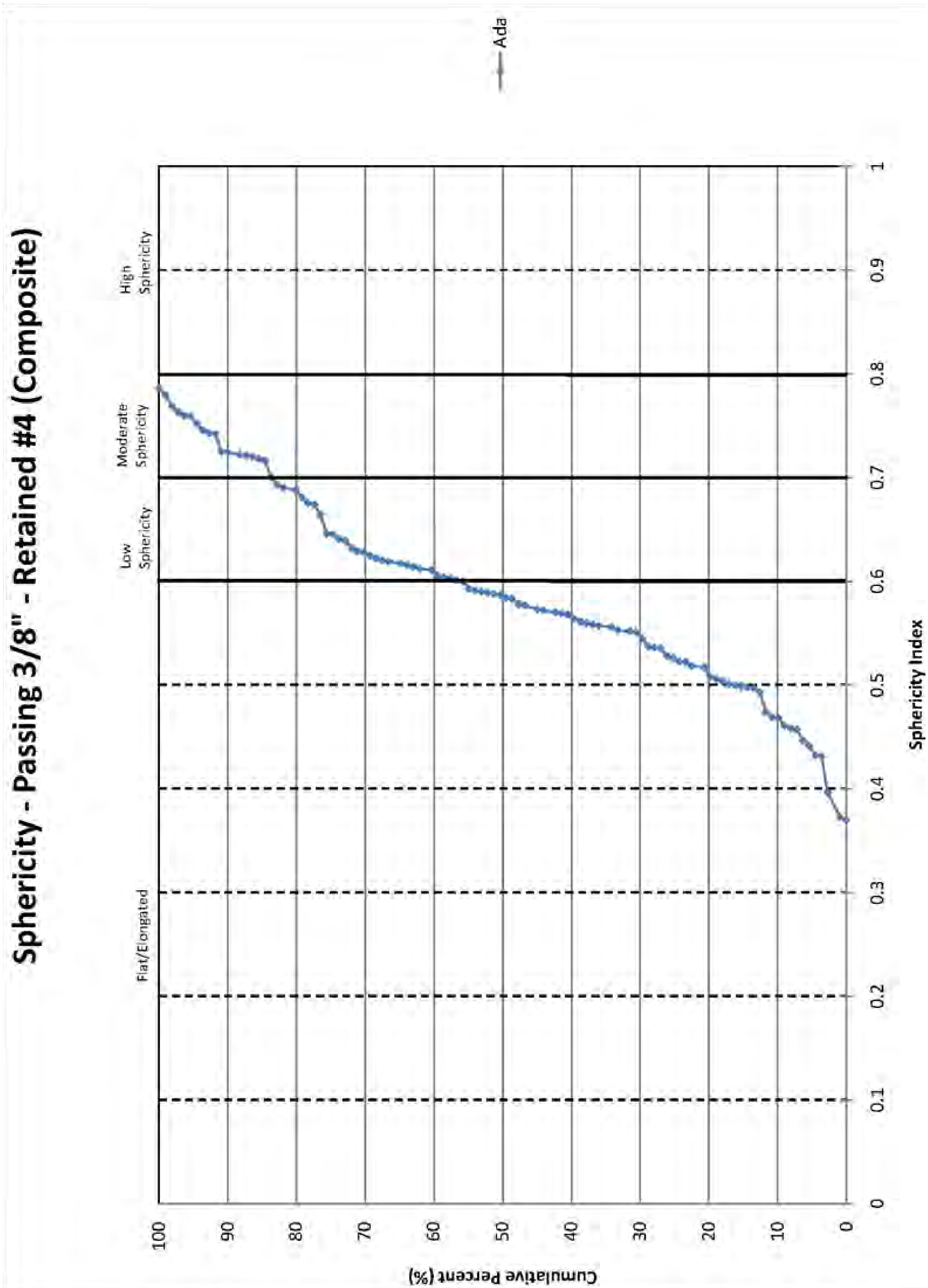


Sphericity - Passing 1/4" - Retained #4
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Cumulative Percent (%)
100
90
80
70
60
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Sphericity Index
Antlers

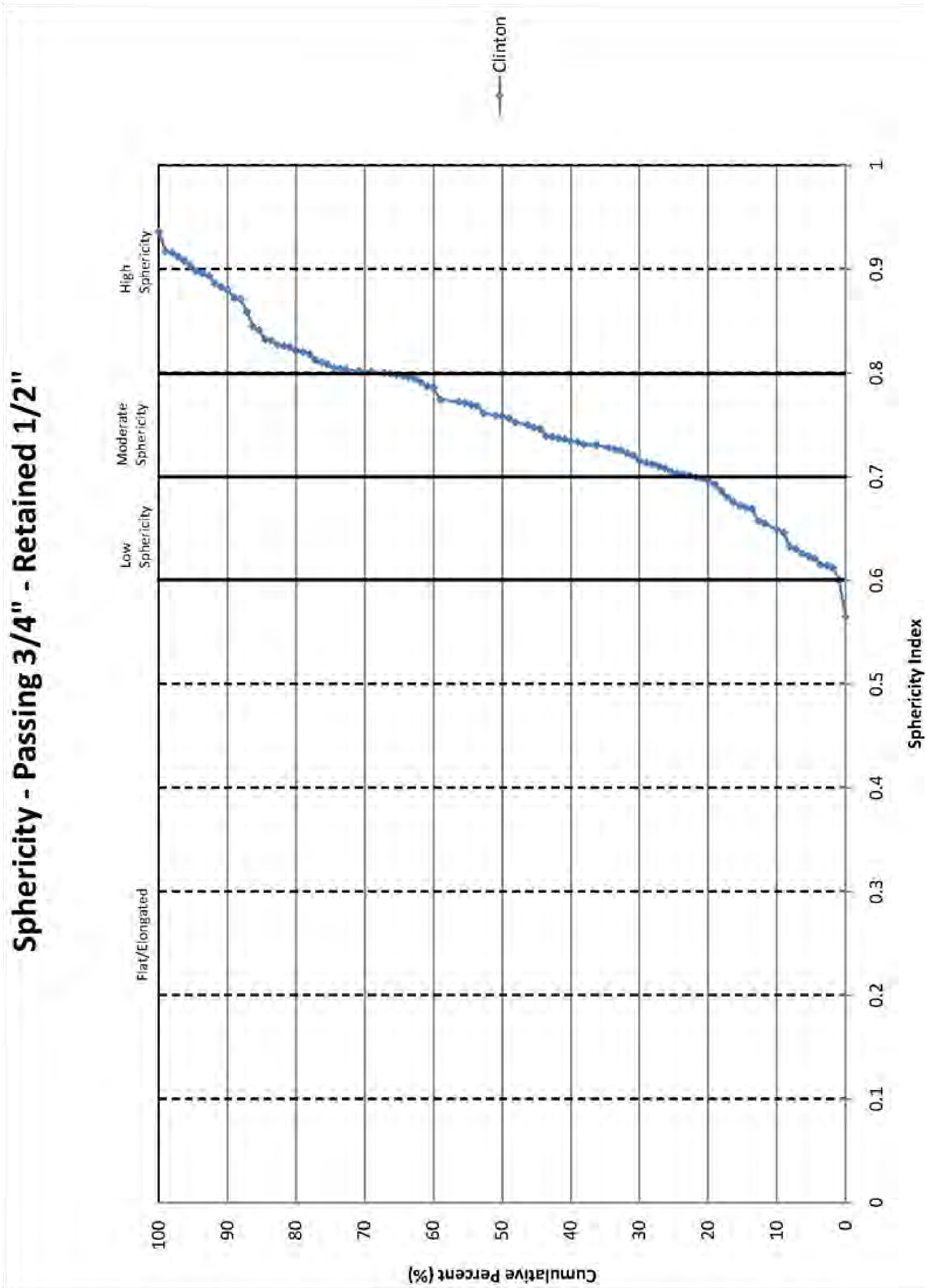


Sphericity - Passing 3/4" - Retained 1/2"
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Cumulative Percent (%)
Sphericity Index
Ada
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100

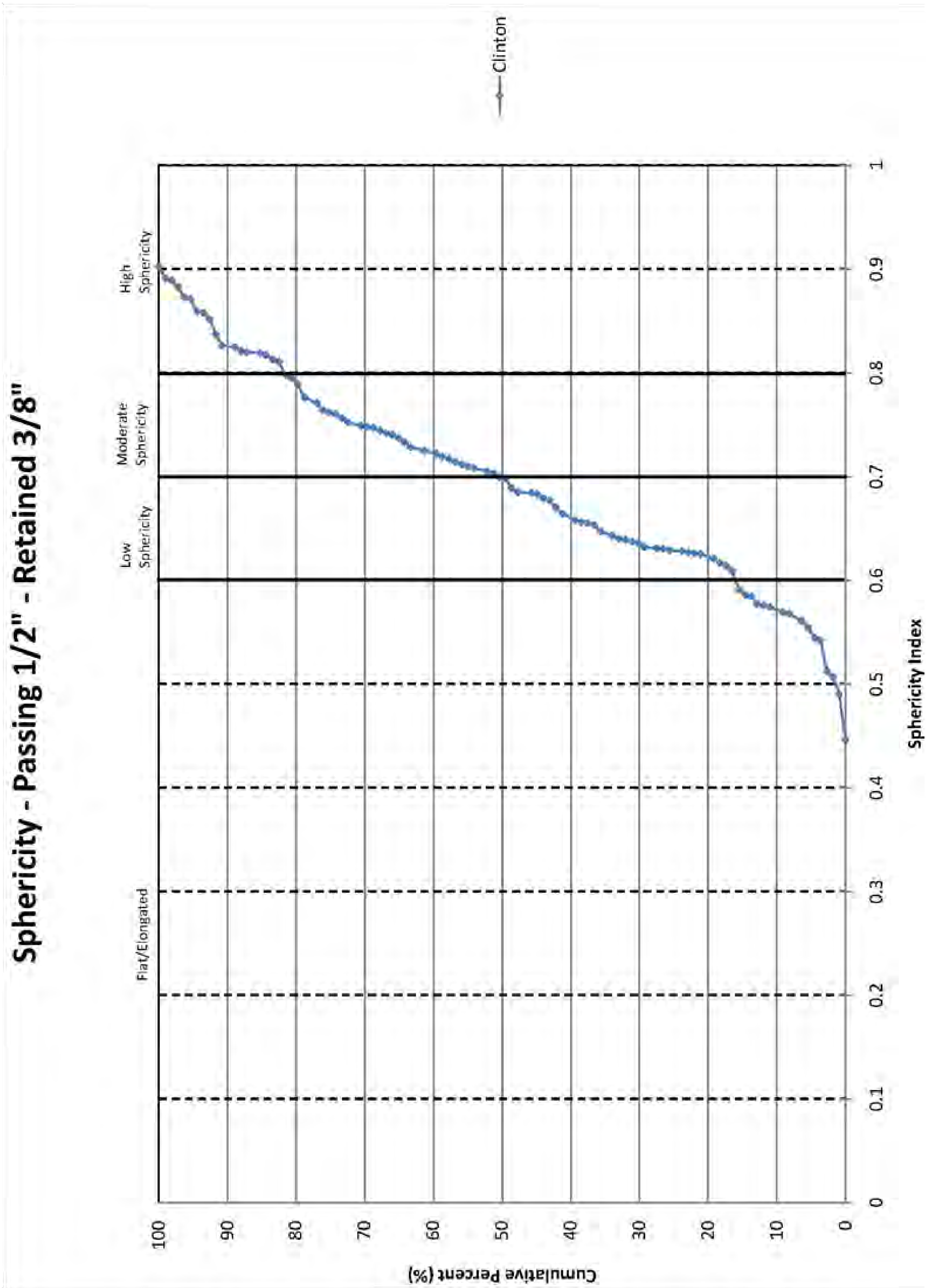

Sphericity - Passing 1/2" - Retained 3/8"
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Cumulative Percent (%)
Sphericity Index
Ada
0
10
20
30
40
50
60
70
80
90
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

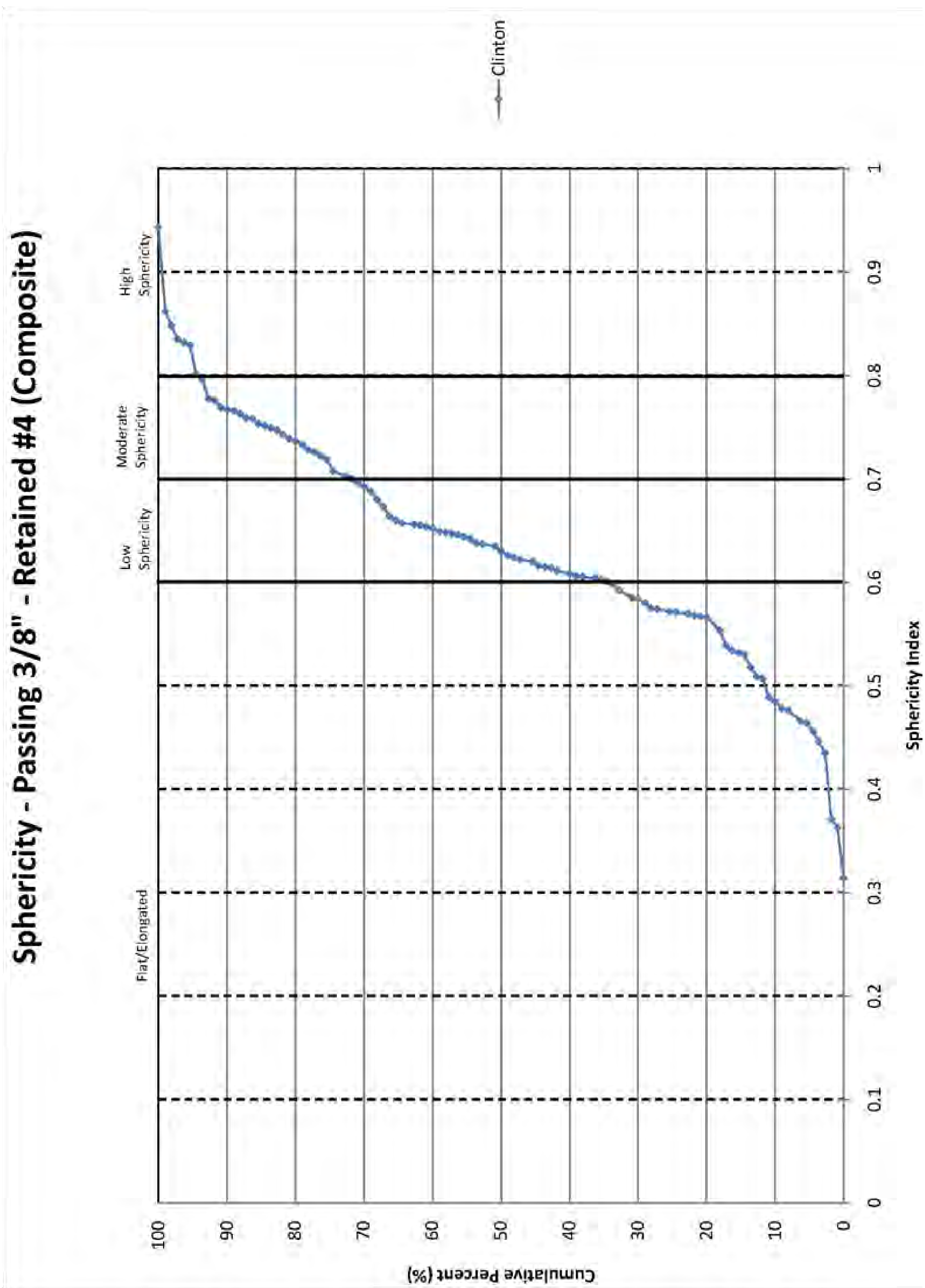


Sphericity - Passing 3/8" - Retained #4 (Composite)
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Cumulative Percent (%)
Sphericity Index
Ada
100
90
80
70
60
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

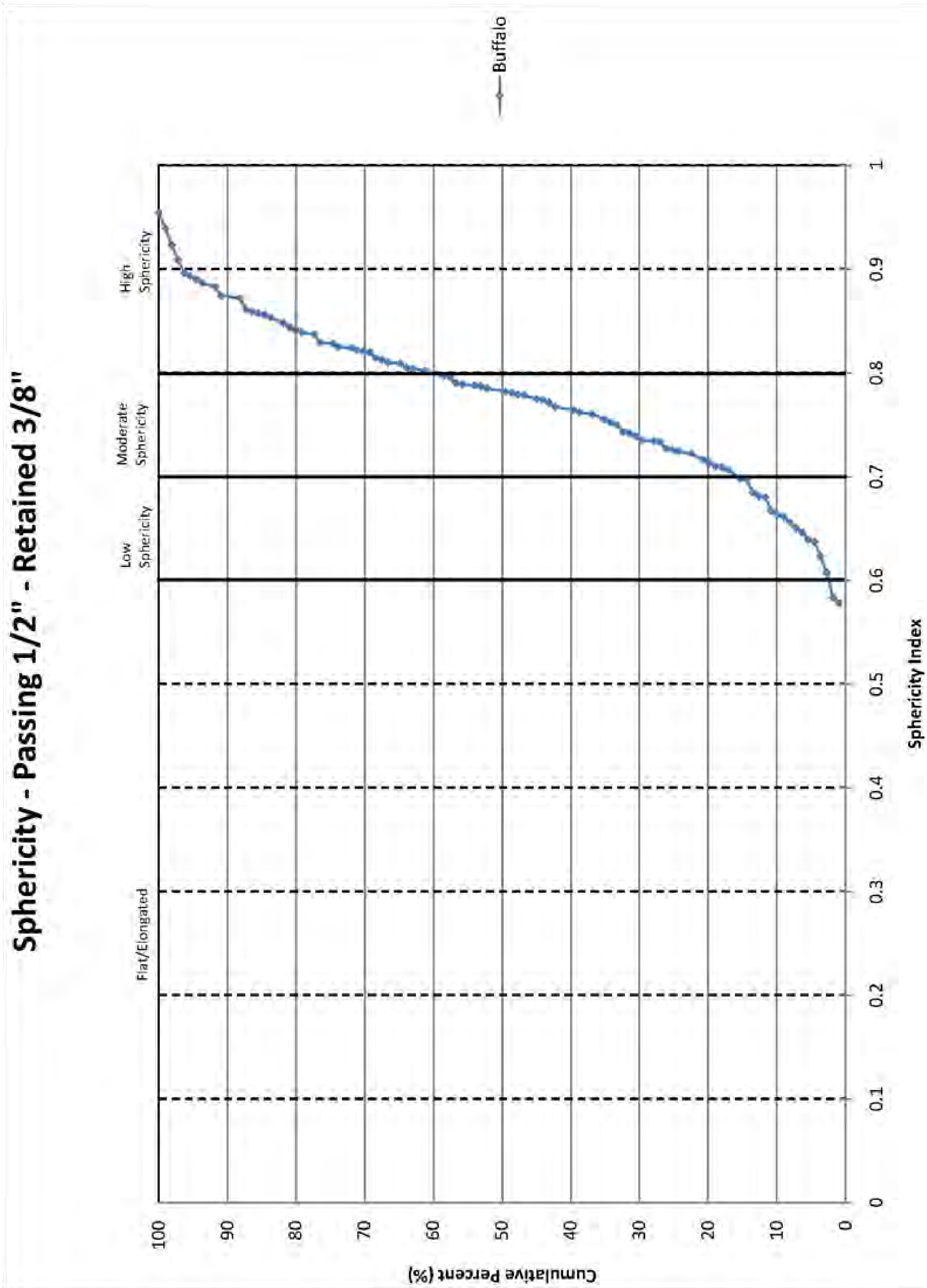


Sphericity - Passing 3/4" - Retained 1/2"
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Clinton
Cumulative Percent (%)
Sphericity Index
0
10
20
30
40
50
60
70
80
90
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

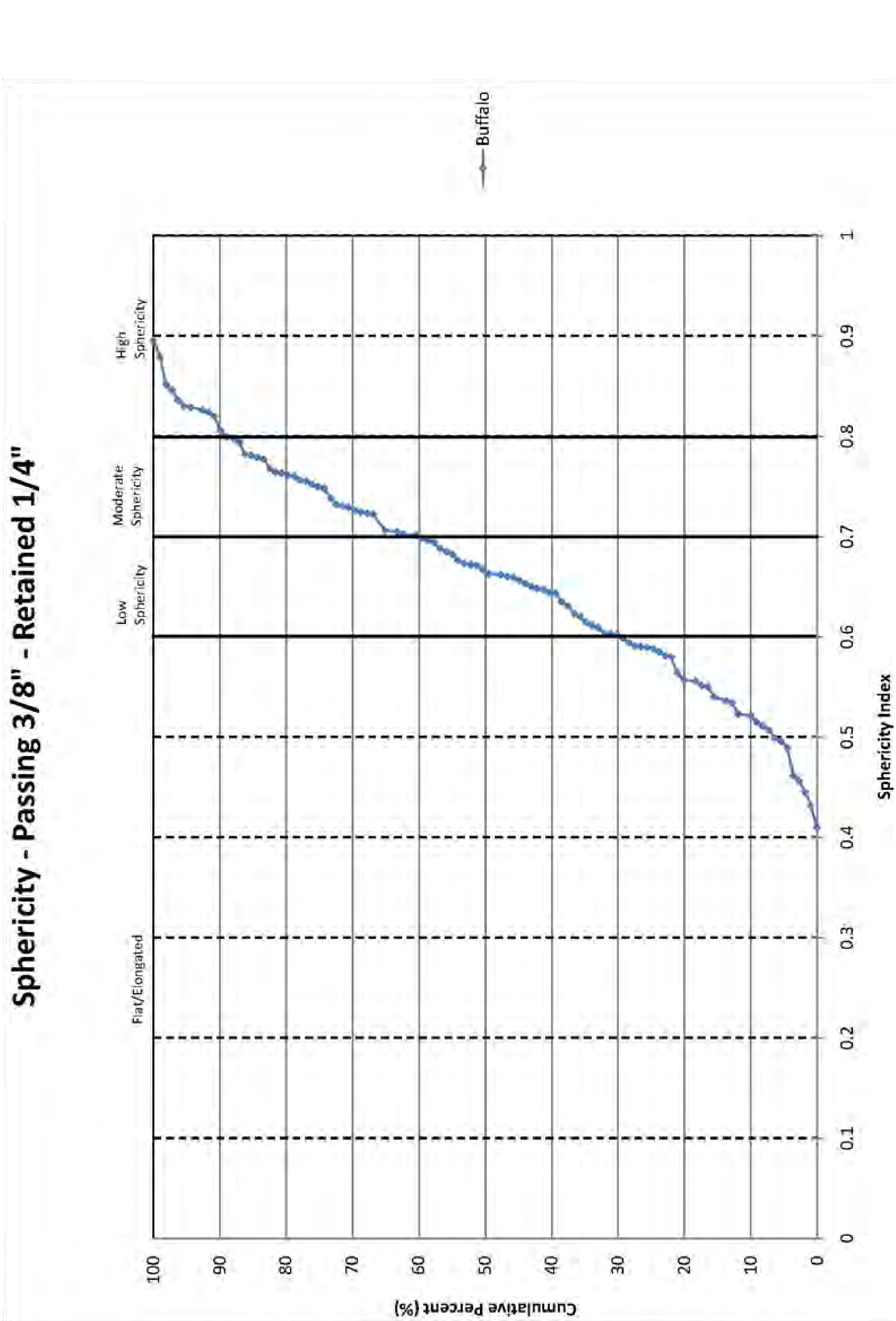

Sphericity - Passing 1/2" - Retained 3/8"
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Clinton
Cumulative Percent (%)
0
10
20
30
40
50
60
70
80
90
100
Sphericity Index
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

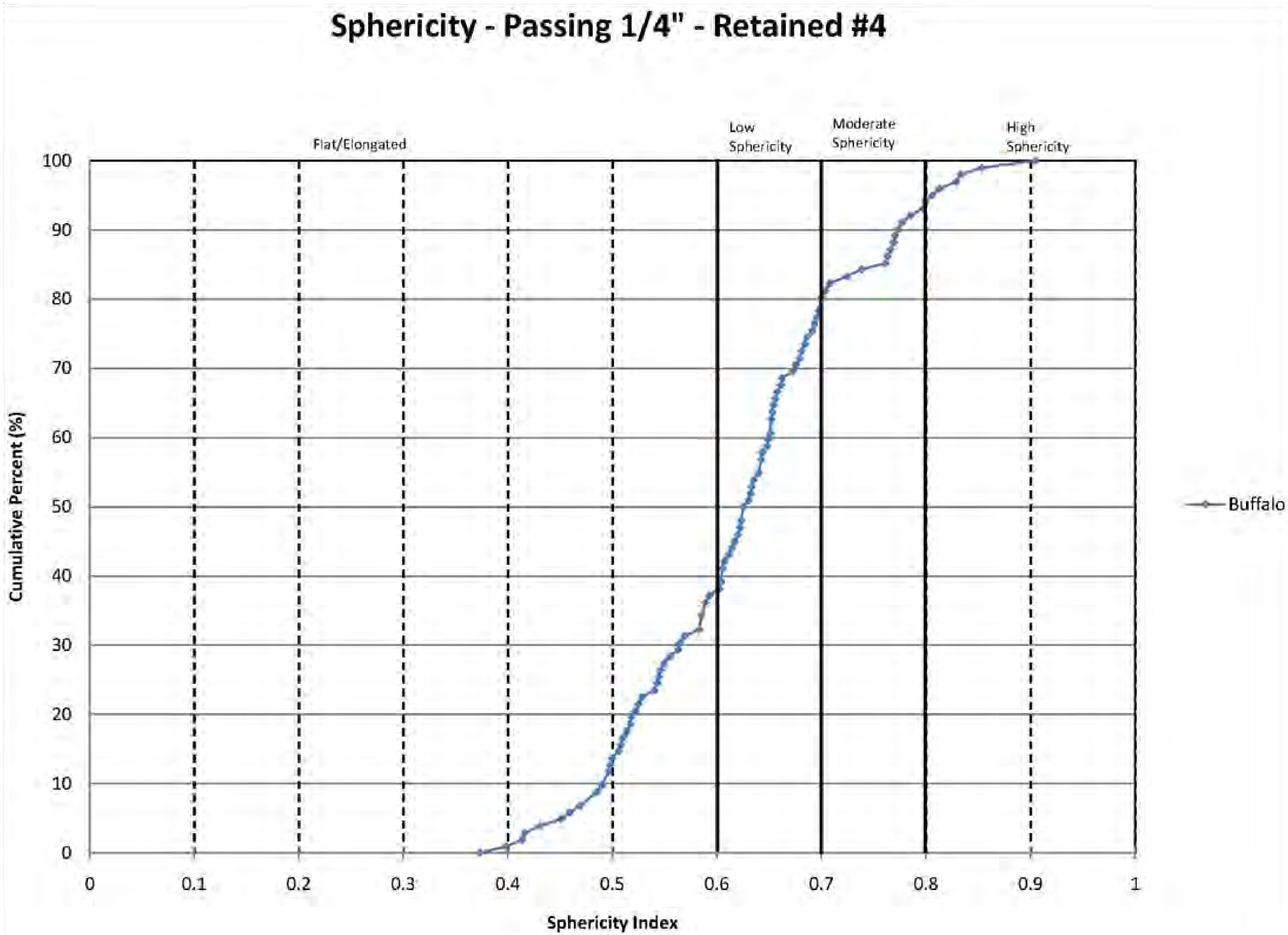


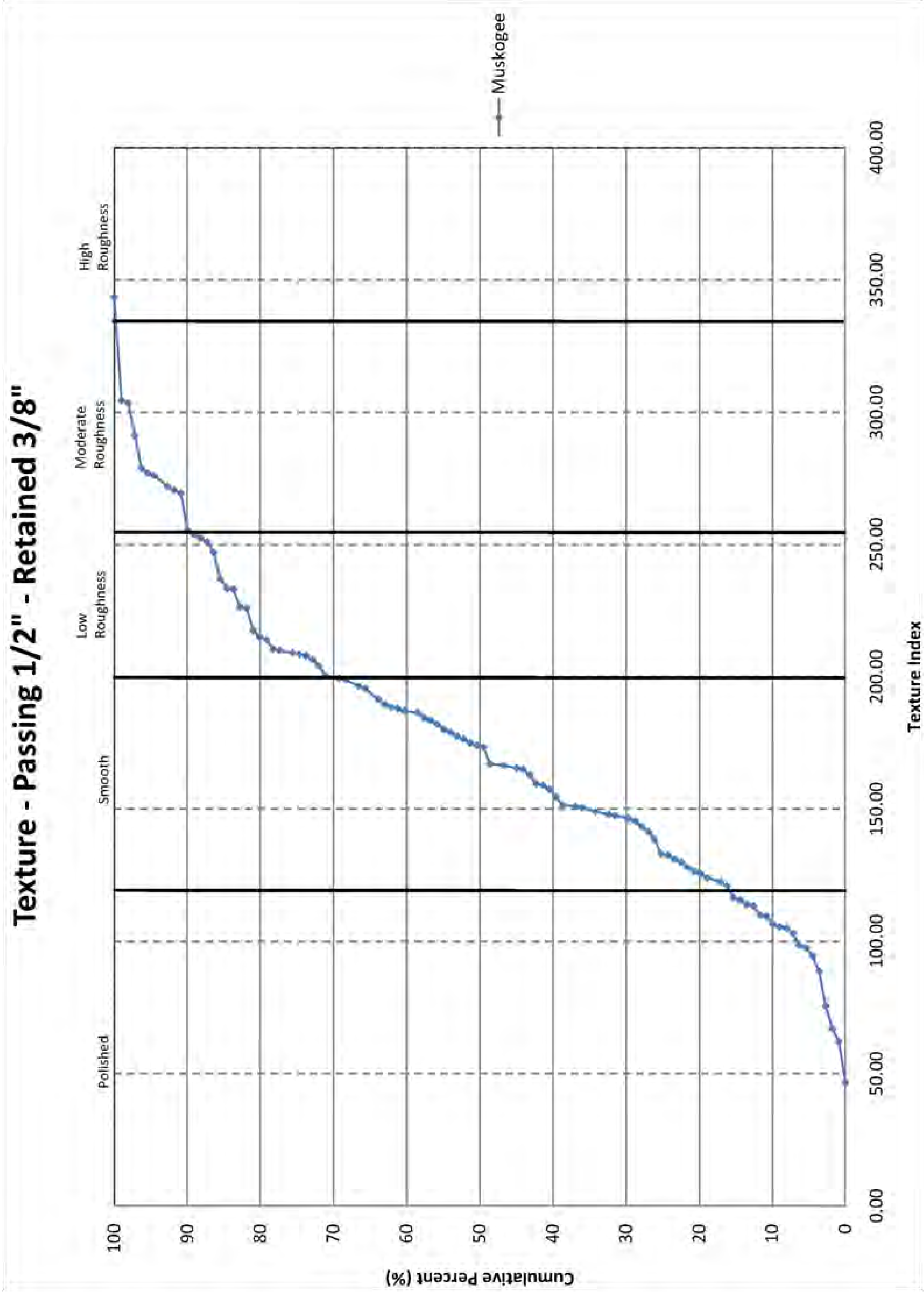
Sphericity - Passing 3/8" - Retained #4 (Composite)
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Cumulative Percent (%)
Sphericity Index
0
10
20
30
40
50
60
70
80
90
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Clinton

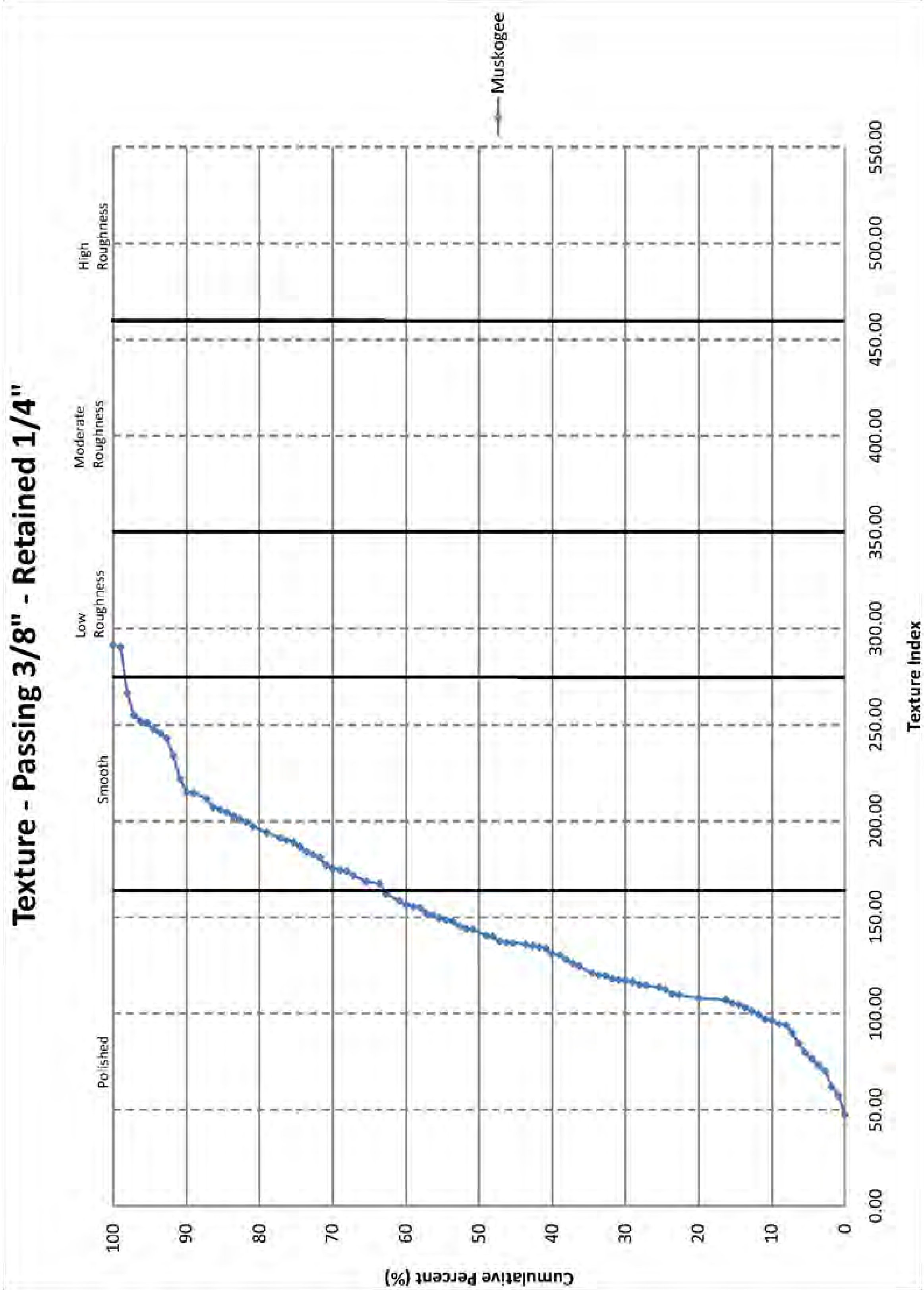


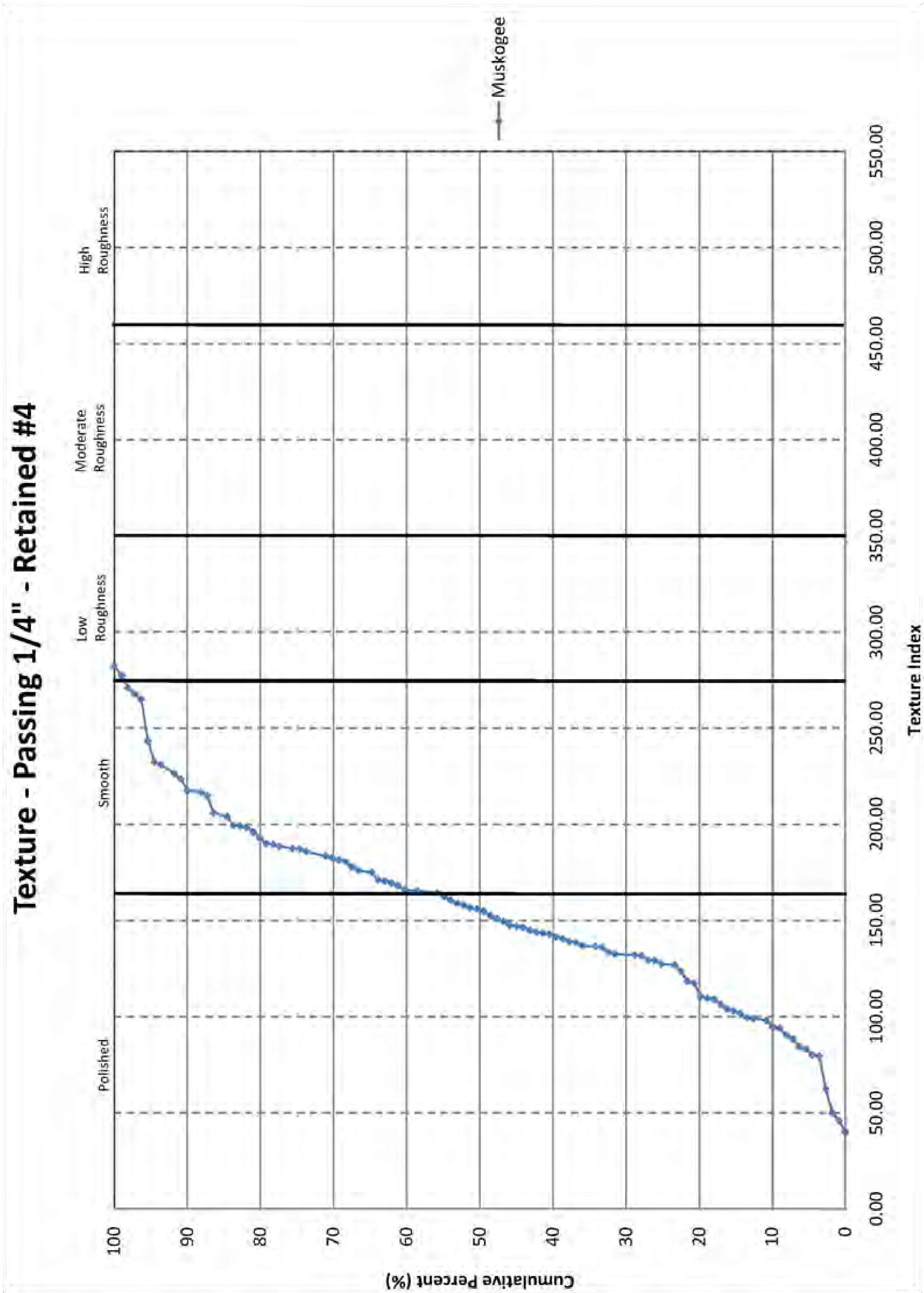
Sphericity - Passing 1/2" - Retained 3/8"
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Cumulative Percent (%)
Sphericity Index
Buffalo
0
10
20
30
40
50
60
70
80
90
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


Sphericity - Passing 3/8" - Retained 1/4"
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Buffalo
Cumulative Percent (%)
Sphericity Index
0
10
20
30
40
50
60
70
80
90
100
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

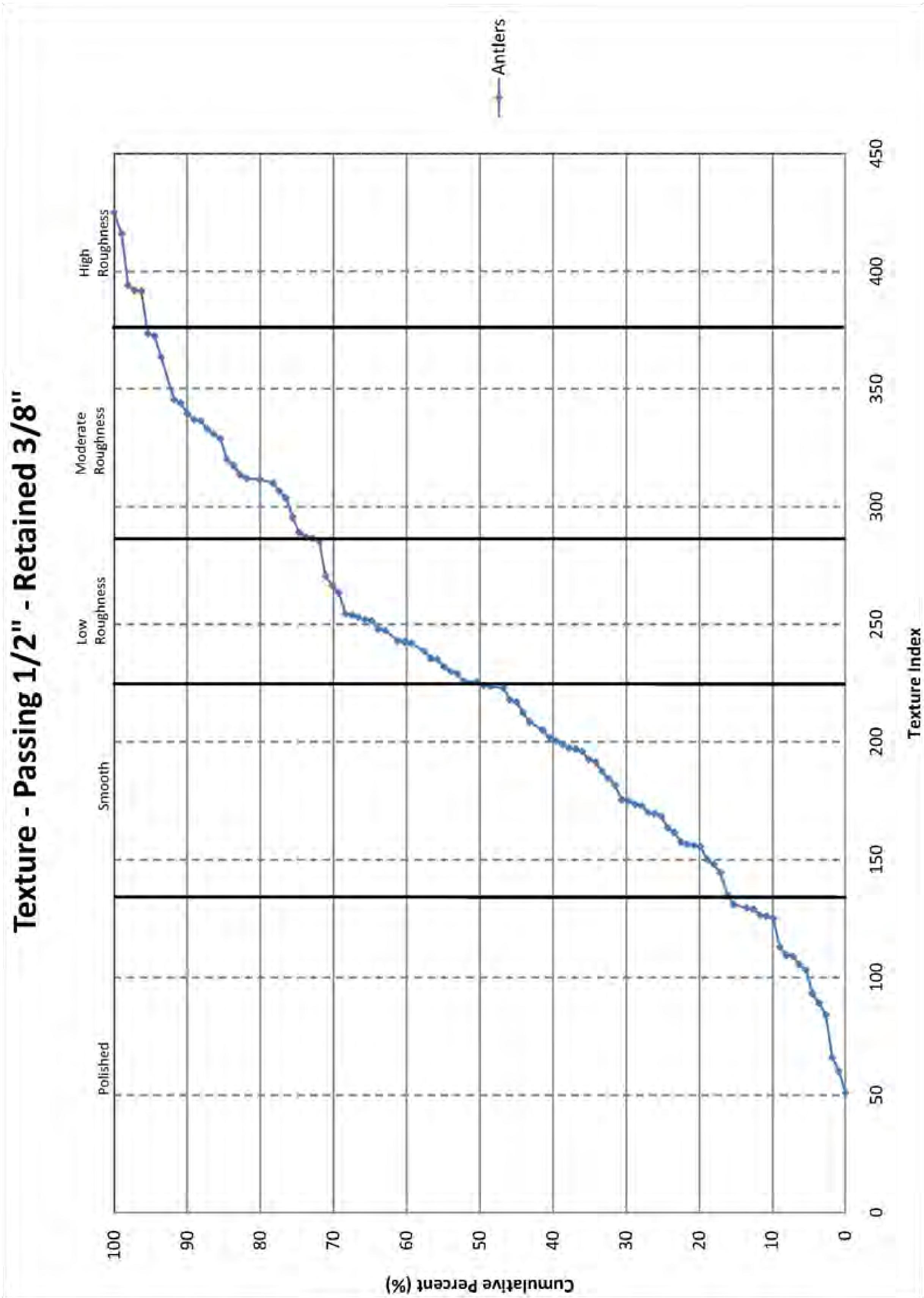

Sphericity - Passing 1/4" - Retained #4
Flat/Elongated
Low Sphericity
Moderate Sphericity
High Sphericity
Cumulative Percent (%)
100
90
80
70
60
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Sphericity Index
Buffalo

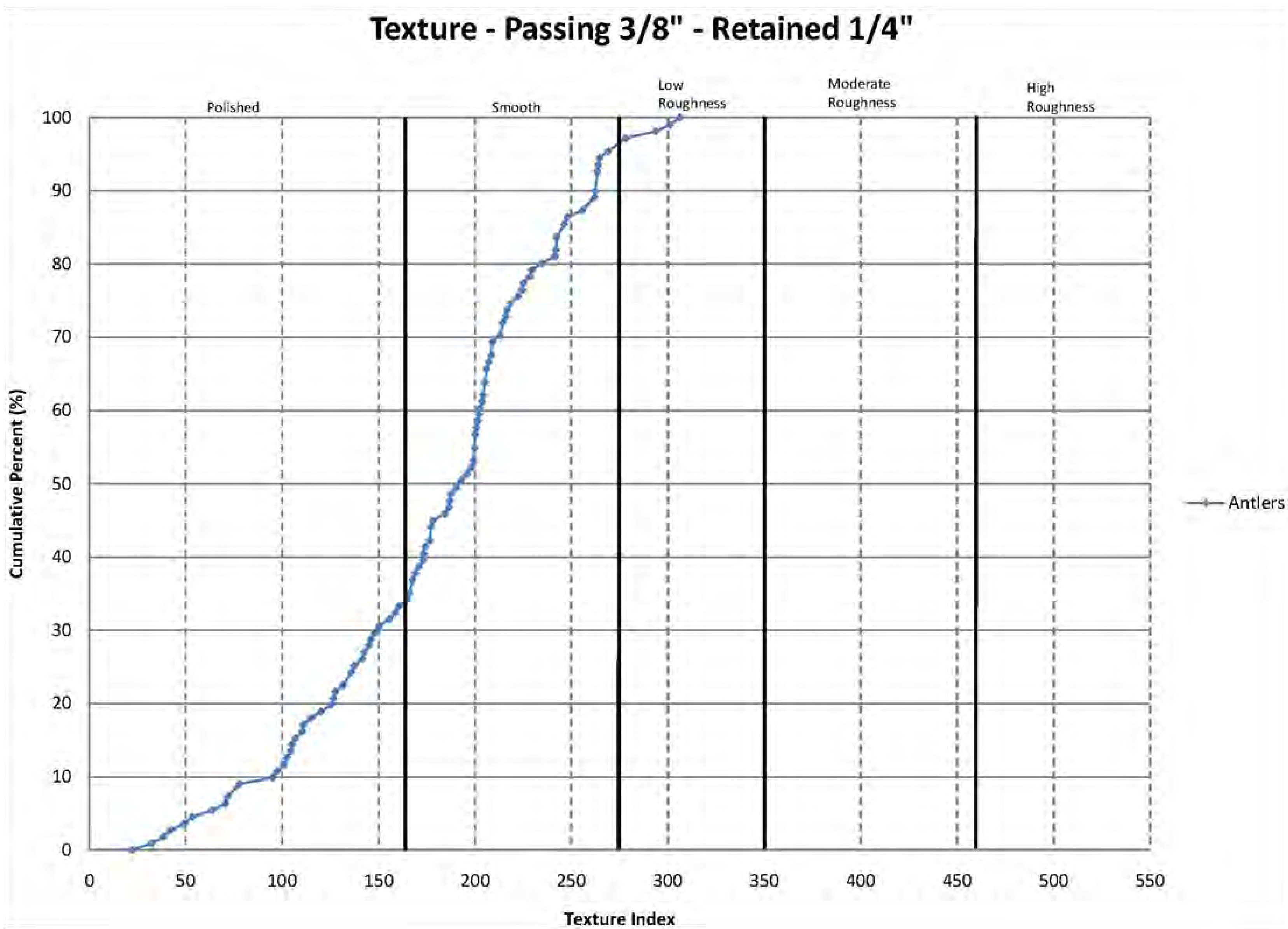

Texture - Passing 1/2" - Retained 3/8"
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
Muskogee
Cumulative Percent (%)
Texture Index
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400.00
0
10
20
30
40
50
60
70
80
90
100


Texture - Passing 3/8" - Retained 1/4"
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
Cumulative Percent (%)
Texture Index
Muskogee
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400.00
450.00
500.00
550.00
0
10
20
30
40
50
60
70
80
90
100

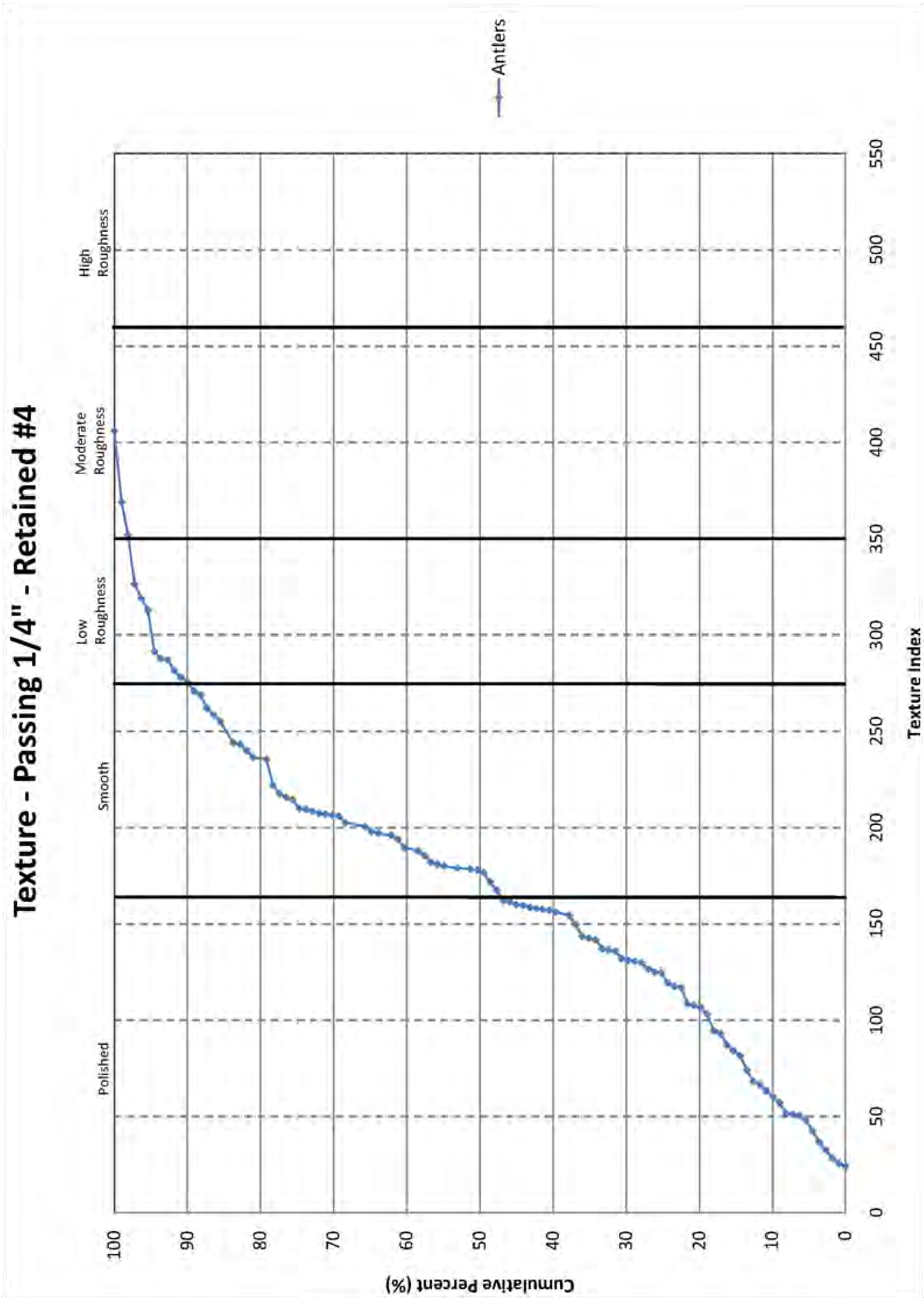


Texture - Passing 1/4" - Retained #4
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
100
90
80
70
60
50
40
30
20
10
0
Cumulative Percent (%)
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
400.00
450.00
500.00
550.00
Texture Index
Muskogee

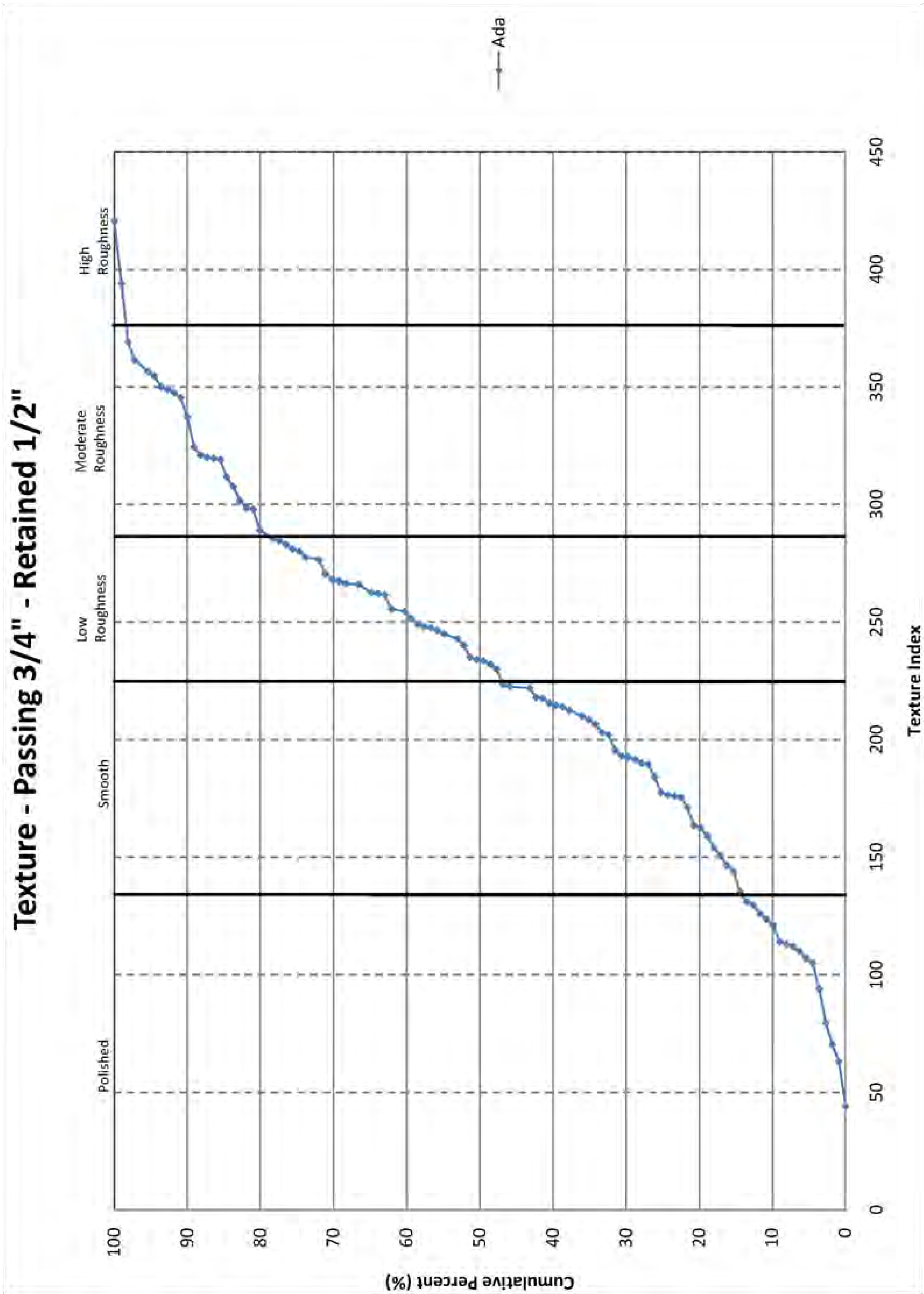

Texture - Passing 1/2" - Retained 3/8"
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
Antlers
Cumulative Percent (%)
Texture Index
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
450



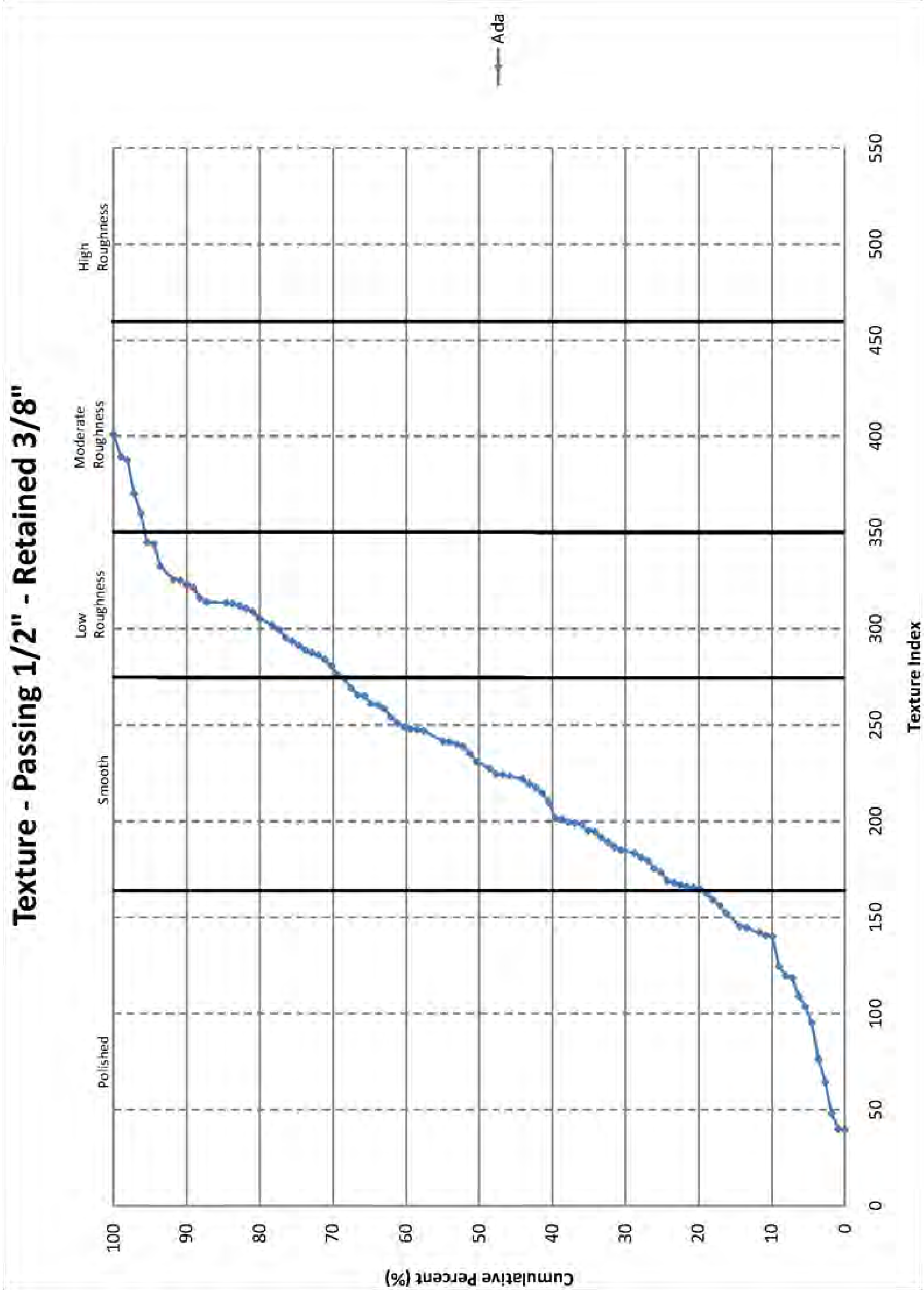
Texture - Passing 3/8" - Retained 1/4"
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
Cumulative Percent (%)
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
450
500
550
Texture Index
Antlers

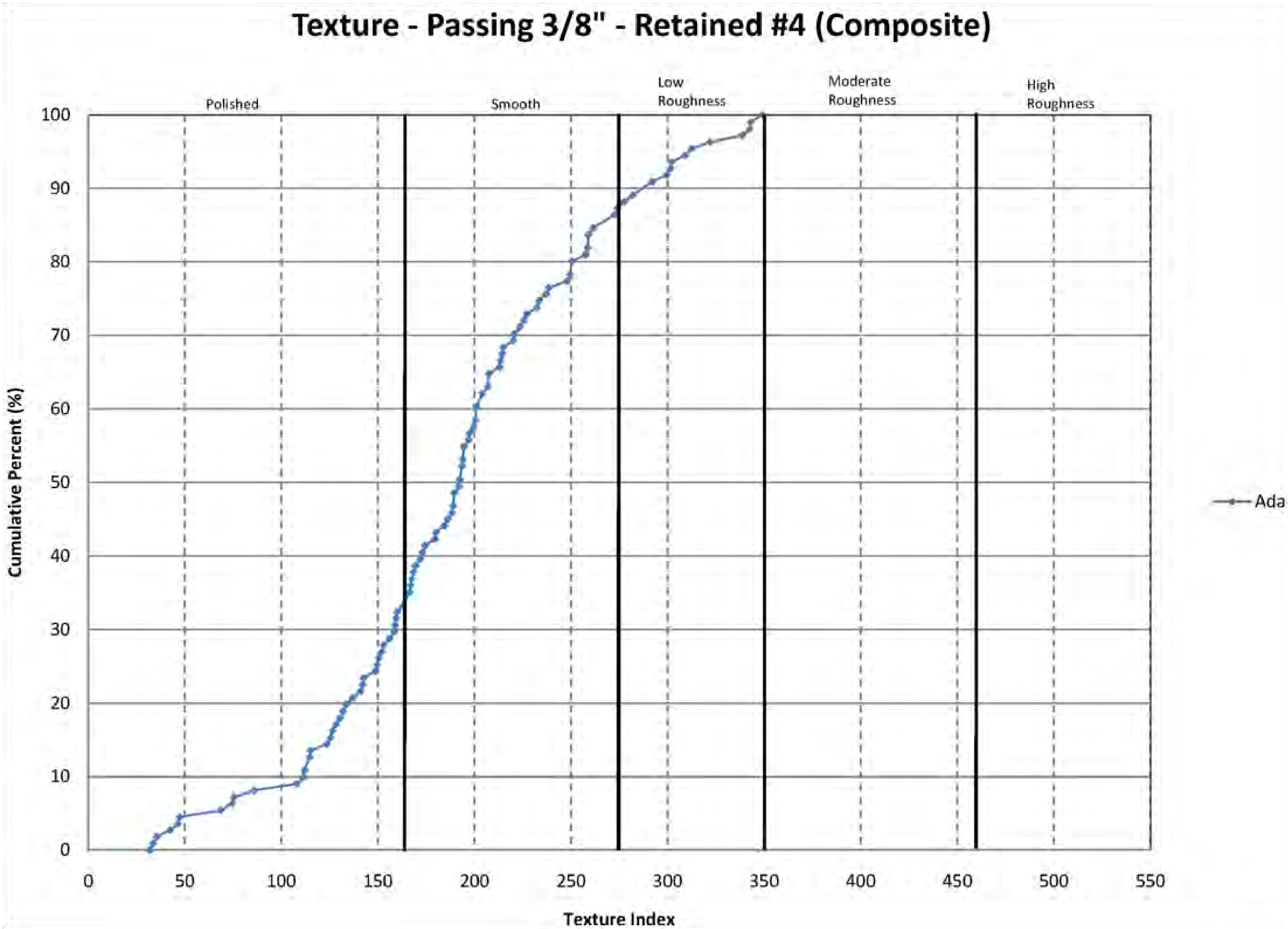


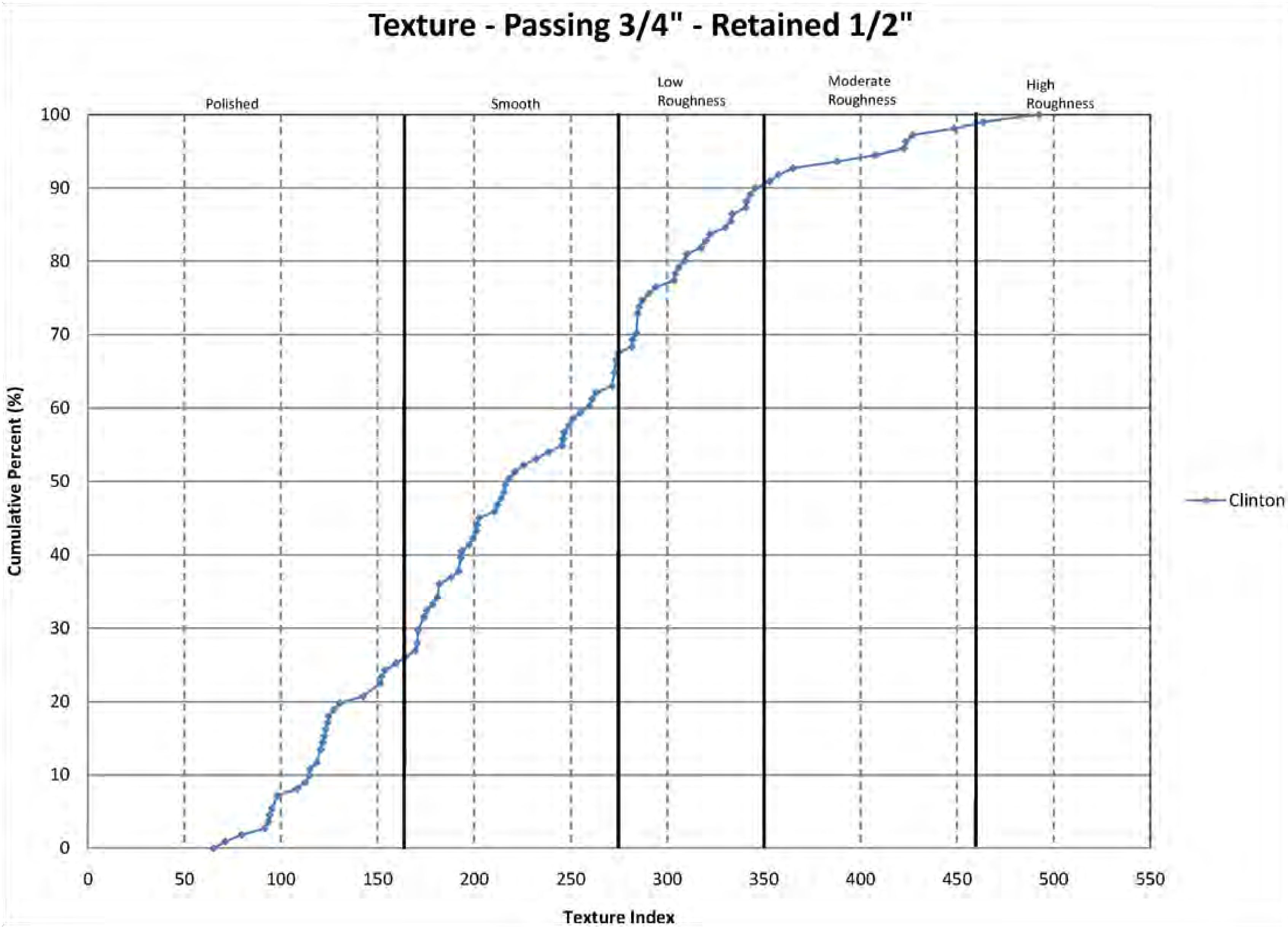
Texture - Passing 1/4" - Retained #4
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
Cumulative Percent (%)
Texture Index
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
450
500
550
Antlers

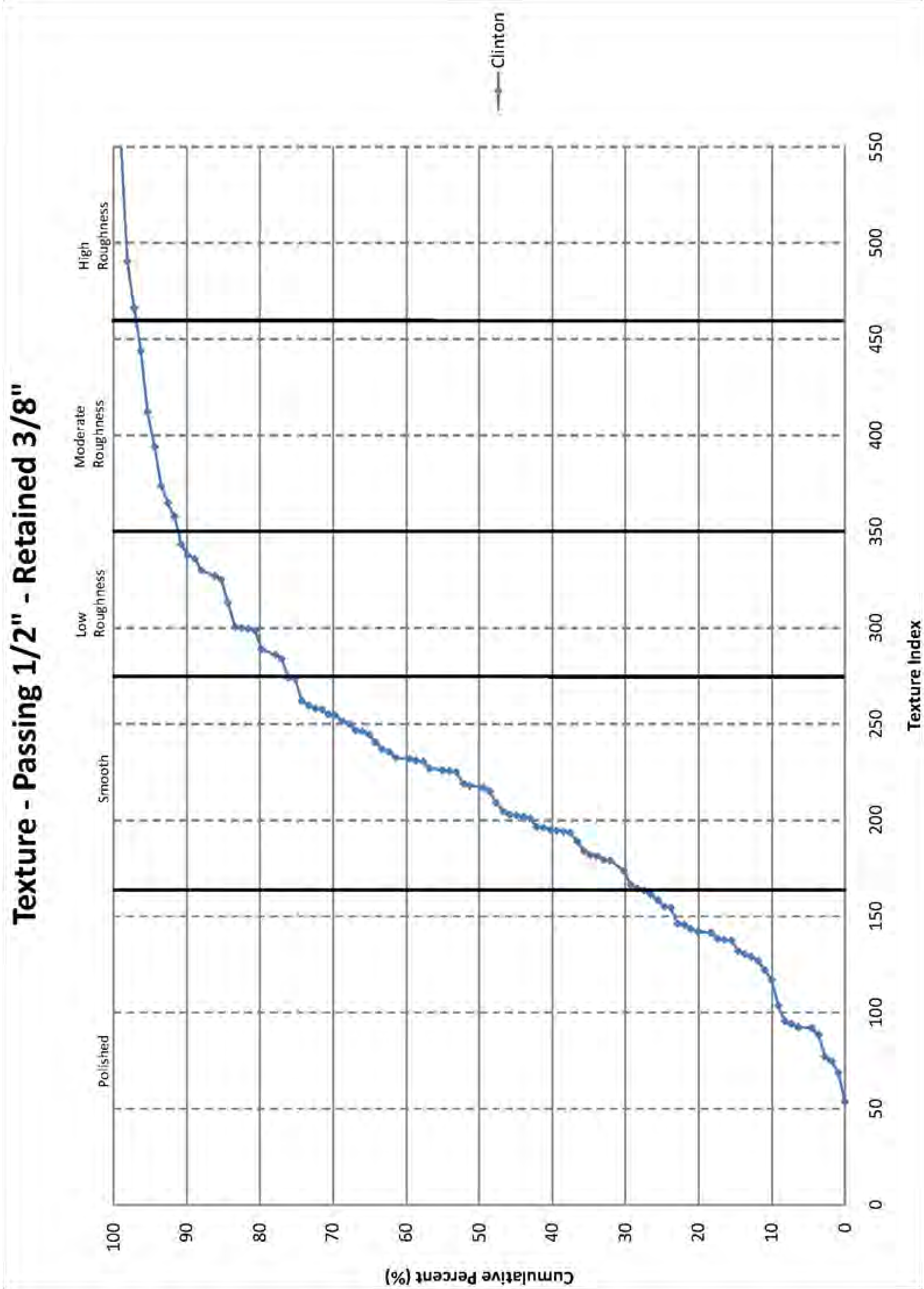


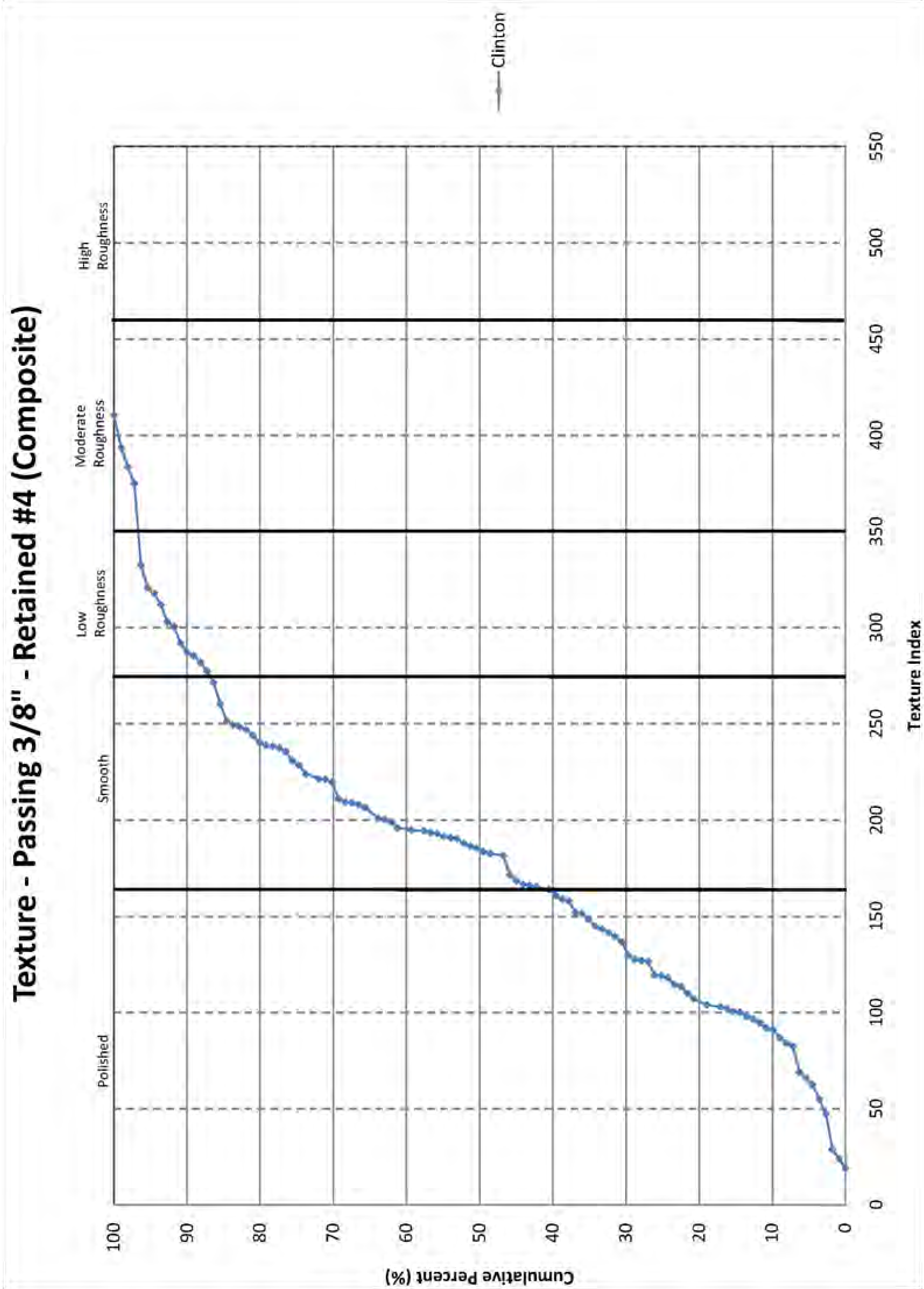
Texture - Passing 3/4" - Retained 1/2"
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
Cumulative Percent (%)
Texture Index
Ada
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
450


Texture - Passing 1/2" - Retained 3/8"
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
Cumulative Percent (%)
Texture Index
Ada
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
450
500
550

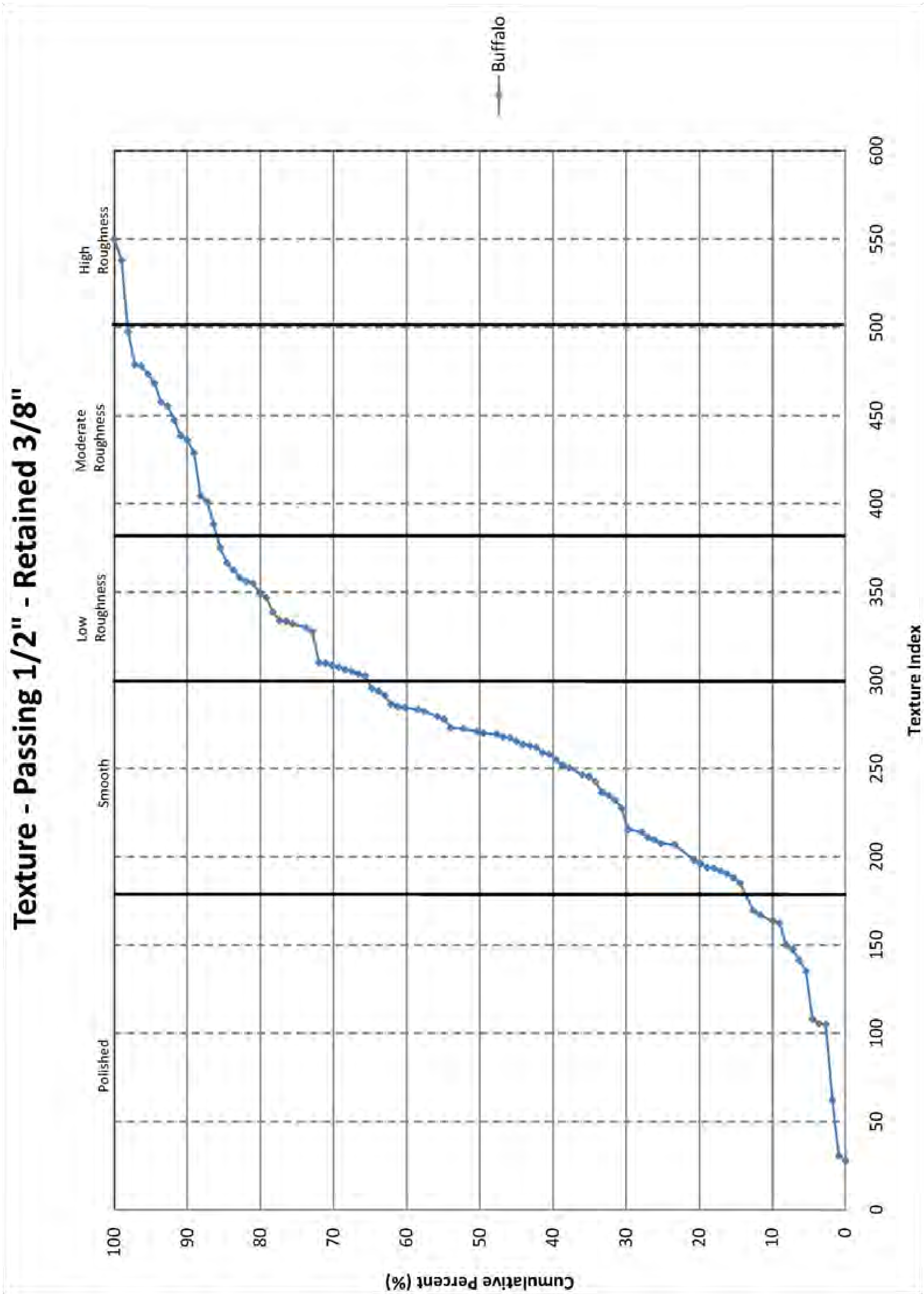

Texture - Passing 3/8" - Retained #4 (Composite)
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
Cumulative Percent (%)
Texture Index
Ada
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
450
500
550


Texture - Passing 3/4" - Retained 1/2"
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
Cumulative Percent (%)
100
90
80
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
400
450
500
550
Texture Index
Clinton

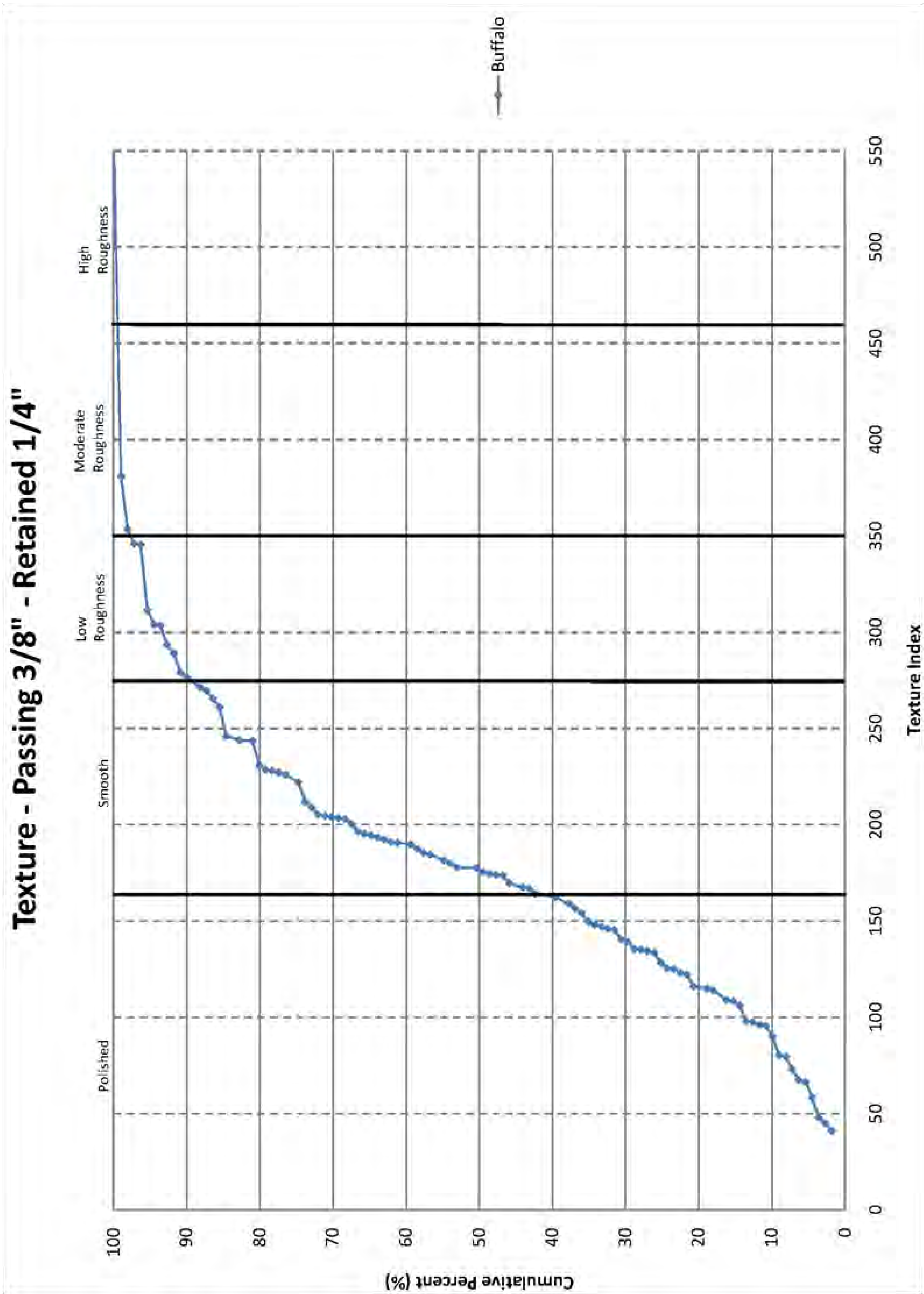

Texture - Passing 1/2" - Retained 3/8"
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
Cumulative Percent (%)
Texture Index
Clinton
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
450
500
550

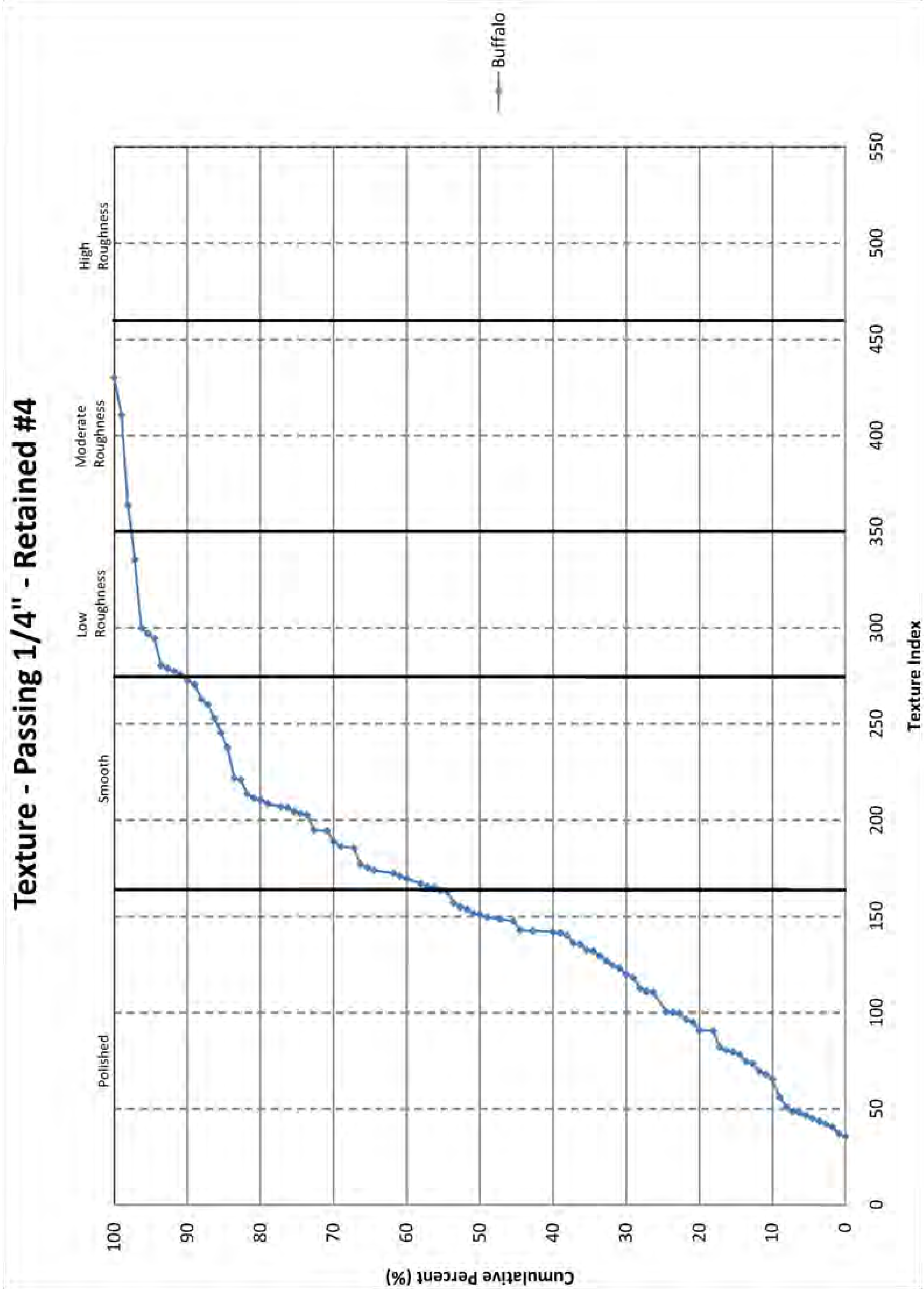


Texture - Passing 3/8" - Retained #4 (Composite)
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
Cumulative Percent (%)
Texture Index
Clinton
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
450
500
550



Texture - Passing 1/2" - Retained 3/8"
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
Cumulative Percent (%)
0
10
20
30
40
50
60
70
80
90
100
Texture Index
0
50
100
150
200
250
300
350
400
450
500
550
600
Buffalo


Texture - Passing 3/8" - Retained 1/4"
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
Cumulative Percent (%)
Texture Index
Buffalo
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
450
500
550



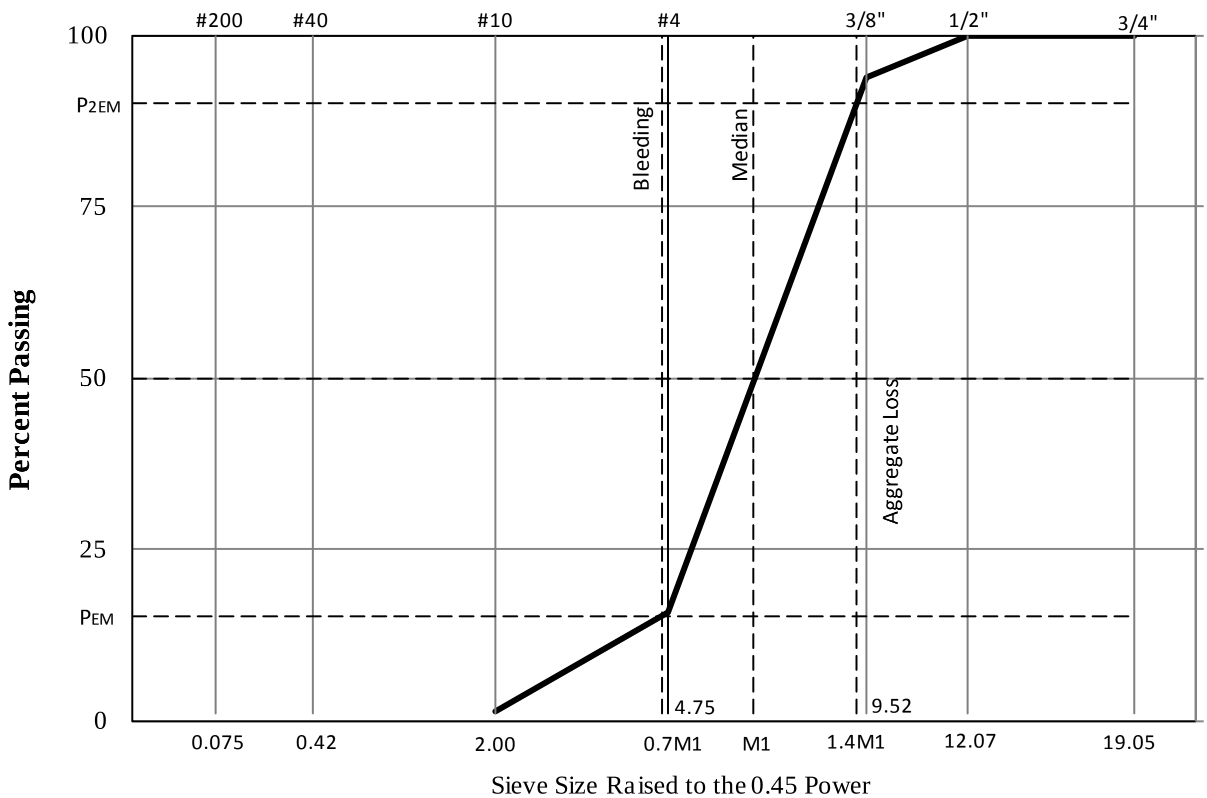
Texture - Passing 1/4" - Retained #4
Polished
Smooth
Low Roughness
Moderate Roughness
High Roughness
Buffalo
Cumulative Percent (%)
Texture Index
0
10
20
30
40
50
60
70
80
90
100
0
50
100
150
200
250
300
350
400
450
500
550

APPENDIX B

PERFORMANCE-BASED UNIFORMITY COEFICIENT OUTPUT

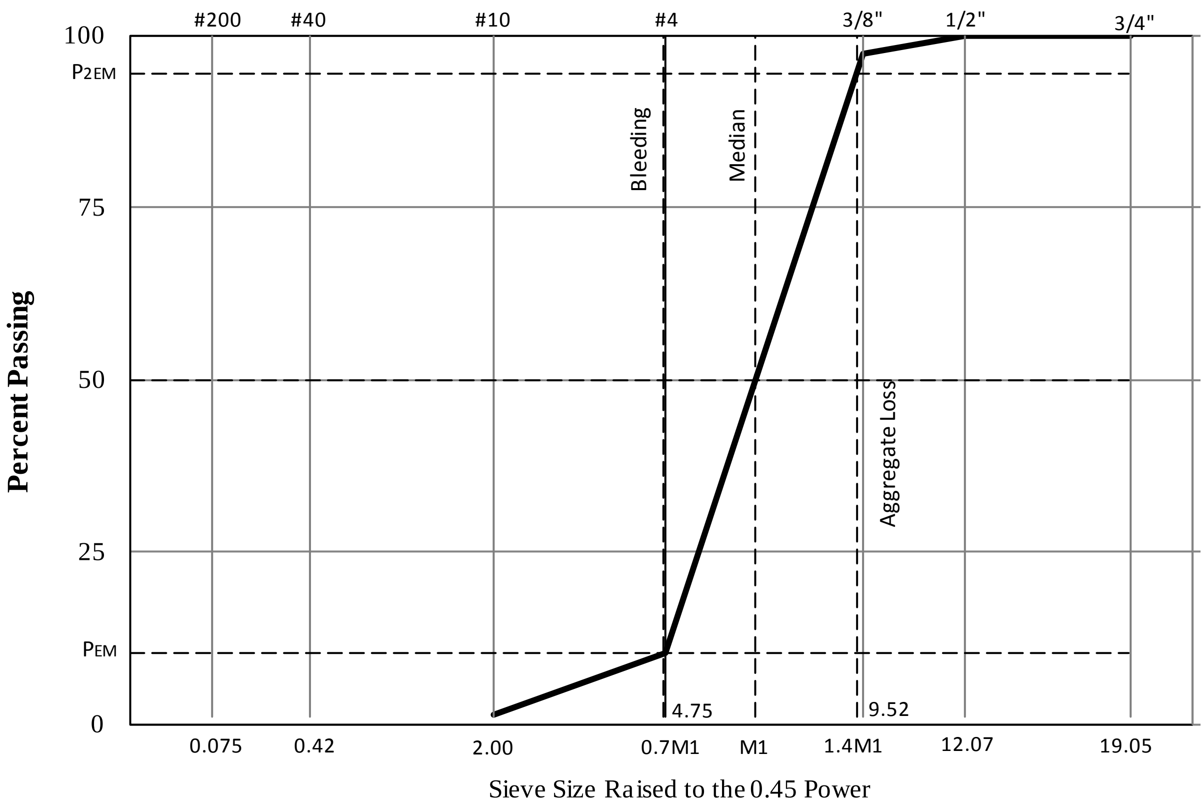
Division 1

	Sieves			Passing
	Sieve	D (mm)	D^0.45	
Muskogee	3/4 in	19.05	3.77	100.0
	1/2 in	12.7	3.14	100.0
	3/8 in	9.52	2.76	94.0
	#4	4.75	2.02	15.8
	#10	2	1.37	1.4



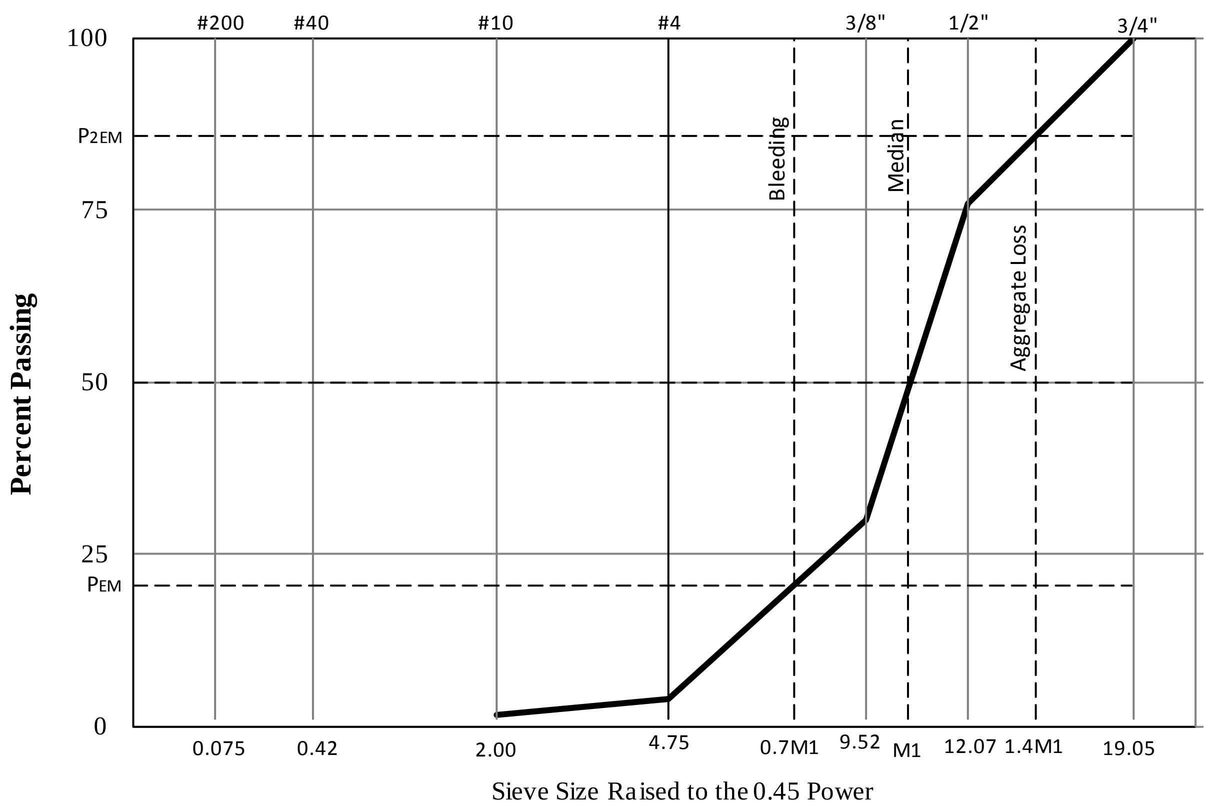
Division 2

	Sieves			Passing
	Sieve	D (mm)	D^0.45	
Antlers	3/4 in	19.05	3.77	100.0
	1/2 in	12.7	3.14	99.9
	3/8 in	9.52	2.76	97.3
	#4	4.75	2.02	10.3
	#10	2	1.37	1.4



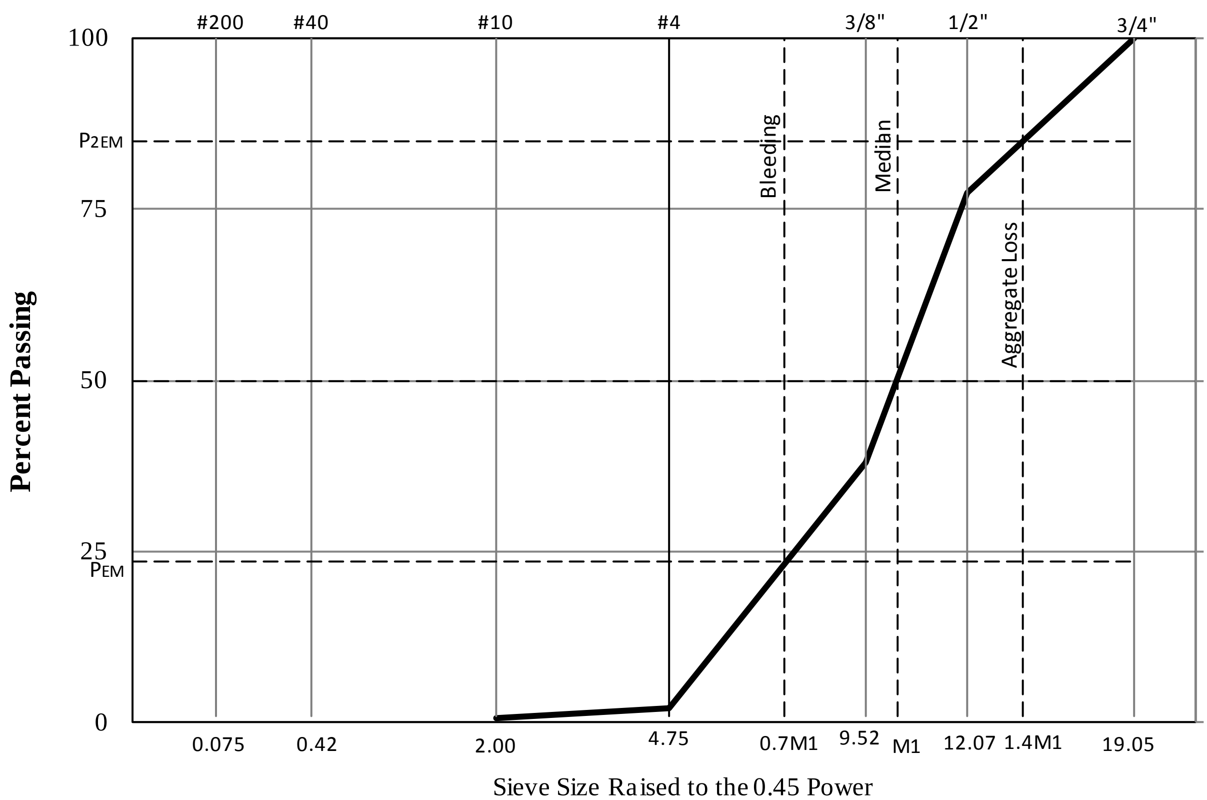
Division 3

	Sieves			Passing
	Sieve	D (mm)	D^0.45	
Ada	3/4 in	19.05	3.77	100.0
	1/2 in	12.7	3.14	76.0
	3/8 in	9.52	2.76	29.9
	#4	4.75	2.02	4.1
	#10	2	1.37	1.5



Division 5

	Sieves			Passing
	Sieve	D (mm)	D^0.45	
Ada	3/4 in	19.05	3.77	100.0
	1/2 in	12.7	3.14	77.2
	3/8 in	9.52	2.76	38.0
	#4	4.75	2.02	2.1
	#10	2	1.37	0.7



Division 6

	Sieves			Passing
	Sieve	**D (mm)**	**D^0.45**	
Buffalo	3/4 in	19.05	3.77	100.0
	1/2 in	12.7	3.14	100.0
	3/8 in	9.52	2.76	95.8
	#4	4.75	2.02	12.0
	#10	2	1.37	1.4