Final Report

EVALUATION OF SUPERPAVE™ CRITERIA FOR VMA AND FINE AGGREGATE ANGULARITY

VOLUME 2 OF 2 VOLUMES
FINE AGGREGATE ANGULARITY (FAA)

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CHAPTER 1
INTRODUCTION

1.1 Background

It has been well established that the characteristics of the fine aggregate portion of asphalt paving mixtures can have a significant and sometimes dominant influence on mixture rutting resistance. Foster (1970) illustrated the dominant effect of fine aggregate on the strength of dense-graded asphalt mixtures. Benson (1970) also showed that regardless of the coarse aggregate used, the strengths of both dense- and open-graded mixtures changed substantially when the fine aggregate portion of the mixture was changed. Shklarsky and Livneh (1964) showed that the influence of the fine fraction had a decisive effect on mixture shear resistance, while the replacement of coarse material with crushed coarse aggregate entailed no such decisive effect. Therefore, it would be highly desirable to have a reliable test to identify fine aggregates that are likely to result in mixtures with poor resistance to rutting.

From 1987 to 1993, the Strategic Highway Research Program (SHRP) investigated asphalt binders and asphalt mixtures. One product of the research is the new method of mixture design called SuperPave™ (Superior Performing Asphalt Pavements). The SuperPave™ mixture design was conceptualized as a three-level, integrated system. The first level (Level 1) is a volumetric mixture design method and, as such, is built upon previous mix design methods, such as the Marshall method. Levels 2 and 3 involve performance based testing that has yet to be determined.

The SHRP program initially emphasized the asphalt binder specifications, but SHRP researchers believed that mineral aggregates played a key role in asphalt mixture performance (FHWA, 1995). Therefore, aggregate specifications for the blended aggregates and volumetric proportions of air, asphalt binder and aggregate were introduced. Two types of aggregate properties were specified in the SuperPave™ system: consensus properties and source properties. Consensus properties are those believed by engineers to be critical in achieving high performance asphalt mixtures. Source properties are those that state highway agencies often use to qualify local sources of aggregate. In principle, the design method is similar to Marshall mixture design except that a gyratory compactor replaces the Marshall hammer, and strength-related tests are not performed. There are two significant differences between Marshall and SuperPave™ besides the compactor type. Marshall mix design uses aggregate requirements set locally that vary widely throughout the country and mixture strength tests (stability and flow) that may not represent the rutting performance of pavements.

SuperPave™ volumetric mixture design recognizes the weak link between Marshall stability and rutting performance and contains no strength test or measurement of performance-based properties. Some agency and industry representatives advocate the addition of a strength test or torture test to the SuperPave™ system. It appears that other tests may need to be added to SuperPave™ after a relationship to rutting is demonstrated.

The Uncompacted Void Content of Fine Aggregate, which is commonly referred to as the Fine Aggregate Angularity (FAA), is one of the aggregate consensus properties which have generated considerable debate. It was introduced in the SuperPave™ mixture design system as a way to identify smooth and/or rounded fine aggregates that may result in mixtures with low rutting resistance (Kandhal et al. 1992). The assumption is that FAA measures the angularity of an aggregate and the more angular the aggregate, the greater the VMA and more particle interlocking. Therefore, fine aggregates with lower

FAA values have lower shear strength (internal friction) and lower resistance to rutting. Higher minimum values of FAA are specified in the SuperPave™ system as the traffic level increases or as the position of mixture is closer to the surface.

Adopting an FAA requirement for high-traffic pavements has changed the number of aggregate sources available for asphalt mixtures. This reduction of available sources, in addition to the new requirements for aggregate properties, has sparked an interest in the industry to question the basis of the FAA specification and the values specified. Experiences in Florida and elsewhere indicate that fine aggregates that have performed well in mixtures are having trouble meeting the SuperPave™ FAA requirements.

Based on an empirical study of field sections from around the country, Brown and Cross (1992) found some correlation between FAA and rutting. However, the correlation was not very strong, and, as in any other empirical field study, there were many interactive variables that may have contributed to the rutting performance of the pavements involved. Continued implementation and evaluation of the SuperPave™ system have led to numerous questions regarding the validity of the assumed relationship between FAA and shear strength, and of the use of FAA in general.

Based on tests performed using a full-scale wheel tracking device, Lee et al. 1999 concluded that FAA alone may not be adequate to evaluate the contribution of fine aggregate to mixture performance. Experiences in Florida and elsewhere indicate that fine aggregates that have performed well in mixtures are having trouble meeting FAA requirements in SuperPave™. Therefore, there was a clear need to further evaluate the validity of the FAA as a tool for eliminating unsatisfactory fine aggregates and for determining an asphalt mixture shear resistance.

This research was undertaken to evaluate the FAA test and to determine whether FAA was a reliable indicator of shear strength (internal friction) of fine aggregates and to evaluate the properties of fine aggregates used in SuperPave™ asphalt mixtures as they affect the mixture's shear resistance.

The research was divided into two phases:

- Phase I - Laboratory Evaluation of Fine Aggregate Properties
- Phase II - Evaluation of the Effects of Fine Aggregate Properties on Asphalt Mixtures.

1.2 Phase I

1.2.1 Objectives

The primary objectives of this phase may be summarized as follows:

- to evaluate the FAA test and identify the factors that influence the determination of FAA;
- to determine whether FAA is a reliable measure that is related to fine aggregate shear strength (internal friction);
- to determine whether the existing FAA test is adequate to eliminate aggregates resulting in asphalt mixtures with poor rutting resistance; and
- to investigate an alternative acceptance procedure for fine aggregates.

1.2.2 Scope

The scope of the research focused on nine materials, the sources of fine aggregates were selected to encompass as wide a range in angularity as possible. The testing included determining of shear strength as a measure of internal friction, and determining FAA as a measure of angularity and texture.

1.2.3 Research Approach

A literature review was conducted to document the history of FAA and its requirements in asphalt mixtures, as well as to obtain experimental evidence of the effects of this variable on mixture stability and durability. The current information in the literature pertaining to FAA testing, relationships, and application to the SuperPave™ mix design procedure was reviewed and is presented later in this report.

All samples of fine aggregate were obtained by FDOT personnel. The materials were washed, dried and placed in labeled containers. Sieve analyses of the washed materials were performed. The bulk specific gravity was determined for two samples from each of the nine materials.

A microscope was used to visually evaluate the angularity and texture as determined by an eight-person panel. An average rating was used for comparison with the results of FAA tests.

The uncompacted void content (FAA) testing was conducted using the three standard methods specified by ASTM and AASHTO. In addition, three standard gradations were used to evaluate the effect of gradation on FAA.

The research team, along with the FDOT, hypothesized that the direct shear test (DST) would be the most suitable way of obtaining a direct measurement of the fine aggregates' resistance to shear that could be used to evaluate the relevance of FAA test results. A semi-automated and simple-to-use direct shear device was used for this project. After extensive preliminary testing, a standard sample preparation procedure was established to achieve consistent testing results. A summary of the resulting procedure is contained later in this report.

After conducting both FAA and DST testing, the results of FAA were compared to both the visual measurements (angularity and texture) and to the DST values. Statistical analyses were performed on the FAA and DST data to assess the reproducibility of the tests and to determine whether, and to what degree, FAA was related to aggregate type, particle shape (visual rating), surface texture (visual rating), and gradation of the fine aggregate. Thus, properties affecting FAA and shear strength were determined.

1.3 Phase II

1.3.1 Objectives

The primary objectives of this study may be summarized as follows:

- to determine the effect of the fine aggregate properties, as determined in Phase I, on the shear resistance of asphalt mixtures.
- to determine whether the FAA test is an adequate parameter to predict shear resistance in an asphalt mixture.
- to investigate alternative acceptance procedures for fine aggregates as it relates to rutting characteristics of asphalt mixtures.

1.3.2 Scope

The scope of the research focused on five of the nine different fine aggregates used in Phase 1. These fine aggregates were selected to evaluate the effect of aggregate properties as determined from Phase I on mixture rut resistance. Asphalt mixtures were designed using the SuperPave™ Volumetric mix design procedure. This research was intended to investigate fine aggregate properties as they relate to mixture shear strength.

1.3.3 Research Approach

This research project was the second phase of a study funded by the Florida Department of Transportation (FDOT). Meetings were held with the FDOT to discuss key issues and achieve a consensus on the project's direction. During these meetings, decisions were made regarding the research approach and the materials to be tested as part of the investigation for this phase of the project. Typical aggregates used in Florida were selected for laboratory testing. The first phase involved the testing of fine aggregate material to determine the effectiveness of the Fine Aggregate Angularity Test in predicting the quality of the aggregates for use in SuperPave™ mixtures. This phase will incorporate some of these fine aggregates into SuperPave™ mixtures and evaluate their effect on the mixture quality.

A literature review was conducted to document the history of the FAA requirements in asphalt mixtures, mixture analysis using various gyratory compactors, and the use of loaded wheel-testing equipment in the evaluation of asphalt mixtures. Experimental evidence of the effect of fine aggregate properties on the shear strength and durability of asphalt mixtures was also obtained through this literature review. Current information in literature regarding determination of mixture quality by means of the FAA test, gyratory compactor, and loaded wheel tester results will be reviewed later in this report.

All materials obtained from the FDOT were washed, dried, and separated into individual sieve sizes. One coarse-graded and one fine-graded limestone SuperPave™ mixture, known to perform well in the field, were provided by FDOT as the reference asphalt mixtures. The fine aggregate portion of this reference mixture was replaced volumetrically by the fine aggregates of materials to be evaluated in this research. These mixtures were designed on the Pine gyratory compactor using four percent air voids at design number of revolutions as the only SuperPave™ design criteria. This resulted in a total of five different coarse-graded and fine-graded SuperPave™ asphalt mixtures.

Since the Pine gyratory compactor does not give a measure of shear strength during compaction, the Servopac gyratory compactor was used for the determination of shear resistance of the coarse and fine SuperPave™ mixtures. After compaction, all mixtures were evaluated against SuperPave™ mixture design criteria to determine the mixture properties.

The Asphalt Pavement Analyzer (APA), a version of the Georgia Loaded Wheel Tester, was used to determine the rutting resistance of the mixtures in the laboratory. Mixture specimens were compacted on the Pine gyratory compactor to approximately eight percent air voids. The samples were then cut to achieve the correct APA mold height. A summary of all testing procedures is contained later in this report.

After conducting testing on both gyratory compactors and rutting tests on the APA, the effect of FAA, LA Abrasion, and direct shear strength values of the fine aggregates on mixture performance were evaluated. Other mixture properties were also compared among the resulting mixtures. Mixture compaction data was evaluated to determine to what degree FAA, DST, and LA Abrasion related to the shear resistance of a SuperPave™ asphalt mixture. Analysis was conducted to determine the effect of aggregate properties on mixture performance and subsequently determine a tentative acceptance protocol for fine aggregates.

CHAPTER 2
LITERATURE REVIEW

2.1 Overview

This research was undertaken to investigate the effectiveness of the Uncompacted Void Content of Fine Aggregate (FAA) Test in determining the quality of fine aggregates and the effect of fine aggregate properties, (such as particle shape and texture) on the quality of SuperPave™ asphalt mixtures. In reviewing the relevant research, the following was accomplished. Firstly, as part of understanding the background of FAA, other methods available for measuring the quality of the fine aggregates based on their angularity and texture were analyzed. Secondly, the background of the FAA test was reviewed in order to understand its basis. Thirdly, methods of analyzing asphalt mixture quality based upon gyratory compaction data were studied to obtain a better understanding of the effect of fine aggregate properties on mixture performance. Finally, the effects of fine aggregate properties on SuperPave™ asphalt mixture quality were analyzed to determine the need for further research.

The literature reviewed firmly establishes that shape and texture of fine aggregate particles significantly affect the properties of the asphalt concrete mixture. In general, the rougher textured and more angular aggregate particles are believed to produce a higher rut resistant mixture.

2.2 Background of Fine Aggregate Test Methods

A summary of the various test methods for measuring shape and texture of fine aggregates was presented by Parker (1977). These test methods can be generally classified as direct or indirect, depending on the method of measurement. *Direct* methods are tests where particle shape and texture are described qualitatively and possibly quantified by direct measurement of individual particles. *Indirect* tests are those where measurements of the bulk properties of the fine aggregate are made separately or as mixed in the end product.

Direct tests have received little attention from material engineers, although an examination of the physical characteristics of aggregate particles is a part of the petrographic examination of aggregate sources. An example of a direct test would be the Corps of Engineers Method, CRD-C 120-55 (Method of Test for Flat and Elongated Particles in Fine Aggregate), in which particle shape is evaluated by observing the sample with a microscope. With direct tests, the results are generally qualitative rather than quantitative. For fine aggregates, the shape and texture are difficult to quantify, and no convenient or standard composite index has been developed. In the literature reviewed, no studies were encountered where a direct test had been used and correlated well with properties of the end product. The real advantage of a direct test is that it would provide a way of measuring the basic parameters in question (i.e., particle shape and texture), which would be independent of other properties (such as gradation and size).

This advantage of a direct test would diminish, however, with the formulation of a composite index, if the index varied with size. In addition, direct tests, such as microscopic examinations, are too time-consuming for routine analysis, and the results are obtained by visual (subjective) observations only.

There are two types of indirect tests. One type measures the properties of the end product (or portions of the end product) containing the fine aggregate. This type of test is actually performed quite routinely. For example, when a mix design for bituminous mixtures is performed, an indirect assessment of the shape and texture of the aggregate is made by virtue of the results obtained. Materials proportions are selected which give workable mixtures with desired end properties. The fine aggregate is not separately evaluated and compared with other materials, but if ingredient proportions deviate from the design, the designer has the option of changing sources of fine aggregate. Thus, an indirect and inconspicuous evaluation of the fine aggregate is accomplished and this includes particle shape and texture as well as other aggregate characteristics.

The other type of indirect test measures the specific gravity of the fine aggregates and includes flow tests, flow tests combined with density or void content tests, and permeability tests. Flow tests, such as the Corps of Engineers Method of Test for Flow of Grout Mixtures (CRD-C 79-58), measure the time for a standard amount of grout to flow through a cone. The time of flow gives an indication of the fluidity of the grout and could be used to assess the fine aggregate particle shape and texture. The more angular, rougher-textured particles will have a slower rate of flow.

In addition to measuring the rate of flow, the material may be permitted to flow into a container and the density or void content measured. The New Zealand Method is an example of this type of test. These tests are based on the principle that more angular, rougher-textured particles will not pack as much as more rounded, smoother-textured particles and will therefore have smaller densities and higher void contents.

Permeability tests have received limited application for the measurement of particle shape and texture. The principle of the permeability tests is that more angular, rougher-textured particles will produce smaller flows because their tendency to pack better creates less interconnected voids. Assessing particle shape and texture using this method is questionable.

In any of the indirect tests, it is impossible to separate the effects of particle shape and texture. The literature reviewed emphasized particle shape over texture. However, the tests assess the combined effects of particle shape and texture.

Some other test methods require that the sample of material be broken down into various size groups, the test being performed separately on each size group, and the results from each size group combined to form a composite result for the material as a whole. The composite result for a material will then be influenced by gradation (when combined), if the different size groups have different particle shape and texture. However, if the different size groups have the same shape and texture of particles, then the composite result should represent a true measure of particle shape and texture. The same reasoning would also apply to an indirect test performed on the sample as a whole.

When Parker evaluated these test methods in 1977, he faced two major problems: first, that the test methods were based primarily on workability requirements for Portland Cement Concrete and, second, that the limited number of studies of bituminous mixtures dealt primarily with the influence of fine aggregate particle shape and texture on binder requirement.

Recently, Wang and Lai (1998) evaluated a new method for quantifying specific surface area of aggregates using an imaging technique. The approximate specific surface areas were based on the average specific surface areas of the spheres having the diameters equal to the corresponding passing and retaining sieve-opening sizes. However, the specific surface areas of crushed sand determined by Wang and Lai's method are higher, particularly for the aggregates passing #16, #30 and #50 sieve sizes, than that determined from an approximate method commonly used by the aggregate industry. Although the authors claimed that their method was more accurate than the method commonly used at the time, quantifying the surface area of an aggregate blend, or even a single aggregate particle, is difficult due to the irregular shapes and the roughness of the surface texture. Their test did measure surface area, which may have the potential to measure roundness and other relevant properties, but a more practical test is needed that would be easier to perform and would accurately measure angularity and texture.

However, the FAA test does not take into account the strength of the aggregate in determining the quality of the material, and even though FAA is supposed to be a measure of shear strength, no data was available to validate the hypothesis.

2.3 FAA Test

In this test, a specified amount of one-size sand was allowed to flow freely through an orifice, and the rate, in terms of seconds per cubic centimeters, was determined. This rate of flow was compared with that of Ottawa Sand of the same size, and this was considered a measure of the relative angularity and surface roughness of the sand.

In addition to measuring the rate of flow, the Uncompacted Void Content was calculated by allowing the material to flow into a 1,000 mL container. Having measured the void content and the rate of flow, the results were plotted on a graph (which was developed from individually separated samples totaling nearly 200 tests) from which the fineness modulus and the relative angularity were determined.

Several other variations were also developed along the way, until finally ASTM subcommittee C09.03.05 considered several alternative methods in order to develop one standardized test for measuring particle shape and texture of fine aggregates. The five methods employed fine aggregate void content as an index of shape and texture to minimize the effect of gradation.

The method currently employed for FAA falls into the category of indirect tests, one of the flow tests combined with density and void content. The test is based on the principle that smooth-textured, rounded sand particles offer less resistance to free flow than do rough-textured, angular particles. As sand becomes more rounded, smooth aggregate particles pack more closely, resulting in lower void content percentages. Conversely, as sand becomes more angular, void content increases which indicates a better quality of material.

The National Sand and Gravel Association and the National Ready-Mix Concrete Association used a sample size of 190 grams. The National Crush Stone Association used three individual size fractions of the material (a distinction of Method B). The New Zealand procedure used the as-received grading of the materials (a distinction of Method C). These characteristics are now incorporated into the current FAA test, known as ASTM C1252 or AASHTO TP33.

2.4 Asphalt Concrete Mixture Test Methods

In general, there are three types of test methods in asphalt concrete mixture:

- test methods to determine fundamental material properties like dynamic complex modulus and creep compliance;

- tests to determine surrogate material properties or index, e.g., gyratory shear from compactors such as Servopac and GTM, and the rate of accumulated plastic deformation from repeated shear constant height test; and
- empirical testing procedures that include a rut tester, such as the Asphalt Pavement Analyzer.

2.4.1 Test Methods to Determine Fundamental Material Properties

There are several test methods to determine the fundamental material property and are recommended for characterization of materials. The common fundamental properties to address high temperature performance are the shear complex modulus and the phase angle. These properties could be used in existing models to predict rutting. But these may be difficult and expensive to conduct and are often substituted by test methods to determine surrogate material property or empirical test methods. In this study, tests were not conducted to determine the fundamental material property of the mixture and will not be discussed in detail.

2.4.1.1 Test Methods to Determine Surrogate Material Properties

Surrogate material properties are not fundamental material properties, but can be substituted for a fundamental material property. These properties are developed because fundamental material properties may be difficult to measure. These surrogate material properties are usually conducted with simple and quick tests in which mechanical responses are measured. These responses may be equipment dependent, but they can be an extremely useful tool in relative ranking of mixture in the laboratory.

A Repeated Shear at Constant Height test was developed during the SHRP program to evaluate rutting resistance of mixtures. The test was performed in accordance with AASHTO TP7 on samples that had been compacted in a SuperPave™ gyratory compactor to 7 percent air voids. This test is commonly used to compare the laboratory performance of mixtures at high temperatures (Anderson and Bahia, 1997). The permanent shear strain at 5000 cycles and the slope of permanent shear strain versus cycles are commonly used to evaluate the performance of mixtures.

The SuperPave™ gyratory compactor (SGC) was designed to knead aggregate particles similar to the compaction that occurs in the field under rollers and traffic. Because of this kneading action, the bridging effect often observed in the Marshall compacted specimens should be reduced. However, the SGC was originally developed only to densify mixtures. No attempts were made to measure resistance to compaction or gyratory shear strength during compaction, or to use the device to gauge mixture stability or sensitivity.

Since the advent of the SGC, many new gyratory compactors have been developed that measure various mixture parameters during the compaction process that relate to mixture shear strength. These compactors have the ability to measure the change in height during compaction as well as the resistance to compaction through a parameter known as the "gyratory shear strength." However, there are questions as to the true meaning of the gyratory shear as it relates to mixture strength and stability.

The Servopac gyratory compactor, developed in Australia, is a compatible SuperPave™ gyratory compactor and has the ability to vary compaction parameters such as vertical pressure, angle of gyration, and rate of rotation for each individual compaction performed. It also has the ability to measure height, density, and gyratory shear during the compaction process. Butcher (1998) investigated the sensitivity of these compaction parameters to determine the effect on the compacted asphalt specimen. It was determined that compaction is highly sensitive to the gyratory angle below one degree and to a lesser extent between one and two degrees. A setting of two degrees or above was recommended to obtain the most consistent results. Although a less critical parameter, a vertical stress in the region of 400 kPa to 600 kPa seemed to produce the most desirable results. To reduce influence of this parameter on precision, a vertical stress of 600 kPa is recommended. The rate of rotation seemed to have little effect on the compaction characteristics.

Butcher also investigated the void relationship as it relates to shear strength and its ability to differentiate between asphalt mixtures. The maximum shear resistance may be equal for different mixtures but occurs at different air void levels. Butcher analyzed the slope of the air voids at the maximum shear stress in order to evaluate mixture stiffness. Butcher found that stiffer, more desirable mixtures have a lower slope than softer mixtures. However, this approach neglects some material properties that may influence the evolution of the gyratory shear parameter and the volumetric properties of the final compacted sample.

Several researchers have attempted to relate the slope of the density versus revolutions plot or the energy used during compaction to mixture stability. It is widely assumed that the slope of the density cycle plot relates to mixture quality. Again, the use of mixture density is interchangeable with air voids as Butcher used. The energy parameter is used to distinguish between the energy used to densify the asphalt sample and the energy used in distortion seems to be a viable alternative. However, at this time there is no research to support this approach.

2.4.1.2 Empirical Test Methods

Empirical tests, such as rut testers, have also been linked to rutting susceptibility. A rut tester is an empirical laboratory-scale device designed to simulate the action of a wheel rolling on a compacted mixture sample. There are many variations of this testing device including the Hamburg Rut Tester, Georgia loaded wheel tester, and the Asphalt Pavement Analyzer (APA).

The APA, which is a variation of the Georgia loaded wheel tester, measures the amount of permanent deformation under a pressurized hose. APA tests are generally conducted for 8,000 cycles with a wheel load of 445 N (100 lb) and a hose pressure of 690 kPa (100 psi) to simulate actual loading conditions that a pavement may experience in the field. The tests are usually performed at average temperatures for a specific region. Kandhal et al. (1999) performed rutting tests with the APA and correlated the results with actual in-place rut depths in pavements. Test samples were compacted in a gyratory compactor to 4 percent air voids. In most cases, the APA rut depths had the potential to predict the relative rutting potential of the asphalt mixtures tested. However, it was noted that there were some discrepancies in test results due to such factors as aging and number of ESAL's applied to each pavement evaluated. Therefore, they suggested that more field sections should be tested to confirm rutting criteria for the APA. The data showed that rut depth in APA was sensitive to aggregate gradation.

2.5 The Need for Further Research

Huber et al. (1998) evaluated the role of fine aggregate angularity and particle shape on asphalt mixture properties using a SuperPave™ mixture design for high Equivalent Single Axle Loads (ESAL). One of their experiments substituted various fine aggregates into a SuperPave™ mixture design to measure the effect. In this experiment, they created a reference mixture using a fine aggregate with an FAA of 48%. Later, the fine aggregate was replaced with other fine aggregates having lower FAA values and tested.

The reference mixture consisted of a 12.5 mm nominal SuperPave™ mixture design containing all quarried Georgia granite aggregates. Four fine aggregate sources were investigated and are listed with their Fine Aggregate Angularity values as follows: Quarried Georgia granite (reference aggregate) with an FAA of 48, Quarried Alabama limestone with an FAA of 46, Indiana crushed sand with an FAA of 42, Indiana natural sand with an FAA of 38.

The fine aggregate angularity was then determined using the measured bulk specific gravity values. The fine aggregate angularity values were 48 for the Georgia granite, 46 for the Alabama limestone, 42 for Indiana crusher sand and 38 for the Indiana natural sand.

Each fine aggregate was combined with coarse aggregate and mixed with the optimum percentage of asphalt cement from the reference mixture design. Specimens were compacted and tested on the SuperPave™ Shear Tester (SST), the Couch Wheel Tracker (CWT), a variant of the Hamburg Rut Tester, and the Asphalt Pavement Analyzer (APA) to isolate the effects of Fine Aggregate Angularity.

For the mixtures investigated, the FAA did not correlate well to the average rut rate as determined by the CWT or the APA. Even more surprising, the mixture with the lowest FAA also gave the lowest rut depth at 8,000 cycles. Because this experiment was performed on such a limited range of materials, there is a clear need to extend that range to improve the accuracy of the findings.

The fact that the material with the lowest FAA caused the mixture to perform the best does not mean that the FAA was the determining factor in the mix, since other variables were also involved. Since the FAA test is performed on the fine aggregate itself, a more direct correlation between the fine aggregate and its own quality needs to be obtained. Although shear strength was never directly addressed in any of the literature reviewed, it is known that a high quality material is one with high shear strength. Similarly, the rougher textured and more angular the particles, the better the quality of the pavement. Therefore, a comparison needs to be made between the FAA of the material and its own shear strength outside of the resulting pavement mixture. Since asphalt mixture quality involves the interaction of many other aspects, a comparison needs to be made between quality of fine aggregates and their affect on the resulting pavement mixture.

CHAPTER 3
MATERIALS AND METHODS

3.1 Overview

Sources of fine aggregates were selected for laboratory testing to encompass as wide a range of aggregates typically used in Florida. All materials used were sampled in accordance with ASTM C-702 and washed according to ASTM C-117. The amount of material finer than a No. 200 sieve was determined. The washed materials were placed in labeled containers, and washed sieve analyses were performed according to ASTM C-136 to determine the as-received gradation of each material.

For each material, the bulk specific gravity was determined in accordance with ASTM C-128 and visual angularity and texture measurements were obtained. The FAA values were calculated using the Uncompacted Void Content of Fine Aggregate Test (ASTM C-1252 and AASHTO TP33), and the Direct Shear Test (DST, ASTM Standard Method D 3080) was used to determine the shear strength of each aggregate. Both FAA and DST were performed using three standard gradations typically used in SuperPave™ representing the range of the materials used.

Although the uncompacted void content is commonly referred to as the Fine Aggregate Angularity (FAA), this latter term is not mentioned in either the ASTM or the AASHTO standards. Nevertheless, the term FAA is used in this study because of its common usage, and because it is used in the SuperPave™ system.

Coarse and fine limestone SuperPave™ asphalt mixtures were provided by FDOT for use as the reference mixtures in this research project. The nominal maximum aggregate size for these mixtures is 12.5 mm (1/2”). These SuperPave™ mixtures were selected because they are commonly used Florida aggregates and they are known to perform well in the field. The fine aggregate portions of these mixtures were volumetrically replaced by five other fine aggregates used in this study. This would eliminate the effect of gradation on the shear resistance of the mixture.

The asphalt mixtures were prepared according to SuperPave™ Volumetric Mix design procedure. The mixtures were compacted on the Pine Gyratory compactor to determine design asphalt content for each mixture at 4 % air voids. This was the only SuperPave™ criterion used for acceptance of the asphalt mixtures. Asphalt specimens were compacted to an N_{max} value of 174 revolutions. The mixture properties were then determined by back calculating to an N_{des} value of 109 revolutions.

Each fine and coarse SuperPave™ mixture was compacted using the Servopac Gyratory Compactor to determine the shear strength of each mixture. The Servopac, which maintains a constant angle of gyration during compaction, was used to compact each mixture at a 1.25- and 2.5-degree angle of compaction.

A determination of an asphalt mixture's shear strength may depend upon many factors and the interaction of different mixture components. Therefore, to determine the actual rutting potential of a mixture, it is suggested to perform a type of rutting test. The Asphalt Pavement Analyzer (APA), a variation of the Georgia Loaded Wheel Tester, was used for the purposes of this research.

3.2 Types of Material

The following nine fine aggregates were carefully selected by the FDOT to encompass a broad range of angularity, texture, gradation, toughness, and historical performance:

- Limestone
  - Rinker (L1)
  - Anderson (L2)
  - White Rock (L3)
  - Cabbage Grove (L4)
  - Brooksville (L5)
  - Calera (L6)
- Granite
  - Ruby (G1)
  - Nova Scotia (G2)
- Gravel
  - Chattahoochee FC-3 (G3)

Table 3-1 shows the source and the mines of the aggregates used in the study.

Table 3-1 Source of Fine Aggregates

Material	**Type**	**LA Loss[a]** **%**	**Modified LA Loss[b]** **%**	**Mine**	**Producer**
Rinker	Limestone	33	9.8	87090	Rinker Materials
Anderson	Limestone	NA	16.7	29361	Anderson
White Rock	Limestone	34	9.6	87339	White Rock Ind.
Calera	Limestone	25	9.4	AL149	Vulcan Materials
Brooksville	Limestone	34	16.2	08012	Florida Crushed Stone
Cabbage Grove	Limestone	41	22.6	38036	Limerock Ind.
Ruby	Granite	20	10.7	GA185	Martin Marietta, GA
Nova Scotia	Granite	18	5.9	NS315	Martin Marietta, Canada
Chattahoochee FC-3	Gravel	42	8.6	50-120	Martin Marietta, FL

[a]Los Angeles Abrasion Test performed on the parent rock. Values provided by the DOT.
[b]Modified LA Abrasion Test performed on percent passing no. 8 sieve. Values provided by the DOT.

3.2.1 Bulk Specific Gravity

Bulk specific gravity is the characteristic generally used for calculating the volume occupied by the aggregate in various bituminous concrete mixtures that are proportioned or analyzed on an absolute volume basis. Bulk specific gravity is also used in the computation of voids and the determination of moisture in aggregates.

The bulk specific gravity was determined for two samples from each of the nine materials in accordance with ASTM C-128. This procedure was repeated twice for each material. If the values obtained were within 1% of each other, then the average of both values was used as the bulk specific gravity (G_{sb}). If the difference was equal to or greater than 1%, the test was performed a third time, and the two results with a difference of less than 1% were averaged and reported. The bulk specific gravity was calculated using two samples of each of the nine materials. The average of these values for each material was the measurement used throughout the study (Table 3-2).

Table 3-2 Bulk Specific Gravity (G_{sb})

Material Name	**Material Type**	**Sample A G_{sb}**	**Sample B G_{sb}**	**Average G_{sb}**
Rinker (L1)	Limestone	2.496	2.470	**2.483**
Anderson (L2)	Limestone	2.275	2.269	**2.272**
White Rock (L3)	Limestone	2.507	2.444	**2.476**
Calera (L4)	Limestone	2.562	2.551	**2.556**
Brooksville (L5)	Limestone	2.355	2.380	**2.368**
Cabbage Grove (L6)	Limestone	2.563	2.552	**2.558**
Ruby (G1)	Granite	2.715	2.643	**2.679**
Nova Scotia (G2)	Granite	2.662	2.654	**2.658**
Chattahoochee3 (G3)	Gravel	2.593	2.603	**2.598**

3.2.2 Gradations

To evaluate the effect of gradation on FAA and shear strength, three gradations were tested. Gradation A (G-A) corresponds to the standard gradation stipulated for the determination of FAA Method A, which is the gradation used to determine FAA for evaluation in the SuperPave™ system. Gradations A, 1, and 3 in Figure 3-1 were selected to produce the samples that were tested using the direct shear test (DST). These gradations were typical coarse and fine blends for a SuperPave™ mixture using gradations 1, 3, and A. Gradation 1 (G-1) and Gradation 3 (G-3) were found to be typical of those used in asphalt mixtures. When all nine materials were plotted in one graph, they tended to group into three well-defined gradations. The gradations from a stockpile were within the range of gradations 1 and 3. Multiple samples of all nine fine aggregates were blended according to each of the three gradations.

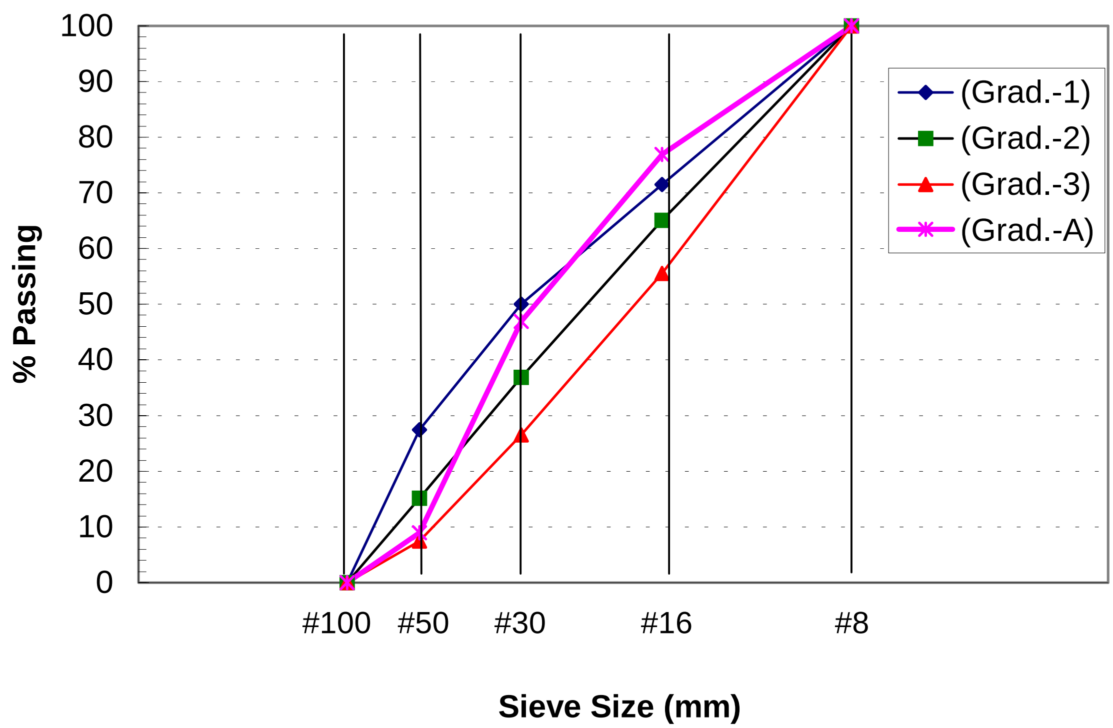


Figure 3-1 Gradations For Evaluation of Fine Aggregates

3.2.3 Visual Angularity and Texture Measurements

By and large, non-clay particles may be treated as relatively inert materials whose interactions are predominately physical in nature. The physical characteristics of cohesionless, non-clay soils are determined mainly by particle size, shape, surface texture, and size distribution (gradation). The shape can be measured in terms of roundness or angularity and the texture in terms of roughness or smoothness.

In order to measure angularity (shape), a scale ranging from 1 to 5 was decided upon, with 1 being very rounded to 5 being very angular, as shown in Figure 3-2. A similar scale was chosen for texture (roughness), with 1 being very smooth to 5 being very rough. These two scales provided a relative measurement for angularity and roughness.

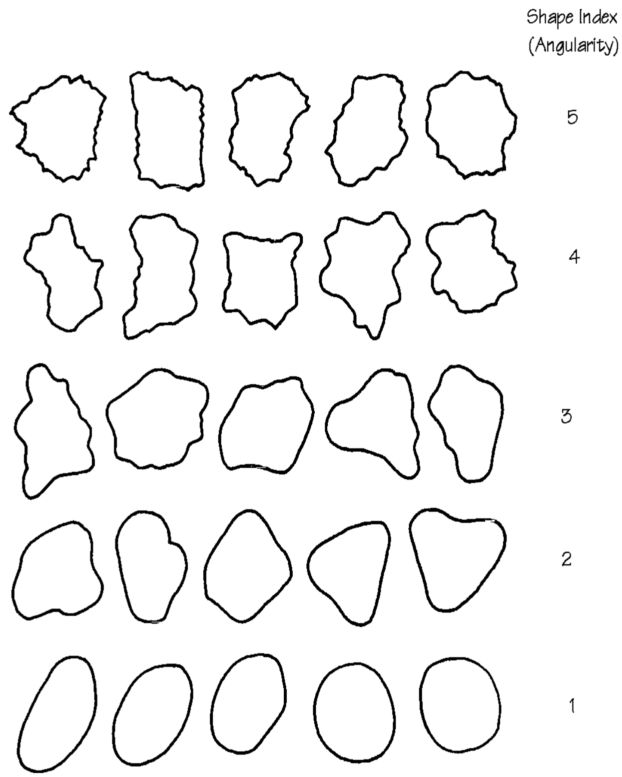


Figure 3-2 Angularity (Shape) Index

Since visual measurements tend to be subjective, it was best to average the values assigned by a panel of raters for both angularity and roughness. Eight raters participated in this portion of the study. To minimize the effect introduced by size variation, the material used for examination was randomly selected from particles passing a #8 sieve and retained on a #16 sieve. This size appeared to be the easiest to examine when using a Tasco microscope with magnifications of 100X and 200X. In addition, the background upon which the samples were placed was changed from a flat black to a flat white to provide the best contrast for the specific soil under examination.

3.2.4 Fine Aggregate Angularity (FAA) Test

The Uncompacted Void Content of Fine Aggregate Test (ASTM C-1252 and AASHTO TP33 Standard Methods) determines the loose, uncompacted void content of a sample of fine aggregate. This test is best known in SuperPave™ as FAA. The higher FAA value indicates a higher uncompacted void content, which is believed to be the measure of angularity. The higher the uncompacted voids content, the higher the FAA and, therefore, the greater is the angularity of the aggregates. The Federal Highway Administration (FHWA) has adopted a minimum FAA value of 45% for the selected blend of aggregates contained in the asphalt mixture used for high-volume pavement.

Three standard methods can be used to determine FAA (Method A, B, or C), and each will yield a different result for the same aggregate. Method A specifies that the test be performed using Gradation A, while Method C specifies that the test be performed using the gradation of the fine aggregate. Method B specifies that FAA be determined for three individual aggregate size ranges, and then the final value of FAA is reported as an average of the three. The SuperPave™ system stipulates use of Method A. The test methods are described more specifically below.

3.2.4.1 Test Method A (*Standard Graded Sample*)

This test method uses a standard fine aggregate grading that is obtained by combining individual sieve fractions from a typical fine aggregate sieve analysis. The standard gradation consists of 44 g of the material retained in #16 (passing #8), 57 g retained in #30 (passing #16), 72 g retained in #50 (passing #30), and 17 g retained in #100 (passing #50), totaling 190 g.

3.2.4.2 Test Method B (*Individual Size Fractions*)

This test method uses each of three fine aggregate size fractions:

(a) 190 g of material between 2.36 mm (No. 8) to 1.18 mm (No. 16);

(b) 190 g of material between 1.18 mm (No. 16) to 600 μm (No. 30); and

(c) 190 g of material between 600 μm (No. 30) to 300 μm (No. 50).

For Test Method B, each size is tested separately, and the average of the three results is calculated.

3.2.4.3 Test Method C (*As-Received Grading*)

This test method uses 190 g of that portion of the fine aggregate finer than the 4.75 mm (No. 4) sieve.

In addition to these three test methods, Gradations 1 and 3 were used to test the materials. Method C was also used with washed material passing the #4 sieve. All three ASTM methods, Gradations 1 and 3, and Method C with washed material, were performed in duplicate to determine the FAA for all nine aggregates investigated.

3.2.4.4 Sample Preparation for Performing the FAA Test

The samples were prepared as required by the specification. Each material was washed, oven-dried, and sieved. Each material was stored in a labeled container according to its size. The sizes stored were the materials passing the #8 sieve (retained on the #16 sieve), passing the #16 sieve (retained on the #30 sieve), passing the #30 sieve (retained on the #50 sieve), and passing the #50 sieve (retained on the #100 sieve). One specimen of each material was prepared for the determination of the FAA values. The test was performed twice on the same sample. If the difference between the two results was less than 1%, the average of those two results was reported. If the difference was equal to or greater than 1%, the test was performed a third time, and the two results with a difference of less than 1% were averaged and reported. Only in a few cases did the test have to be performed a third time.

3.2.4.5 Calibration of Cylindrical Measure for Performing the FAA Test

A nominal 100 mL cylindrical measure was used to perform the FAA test. A light coat of grease was applied to the top edge of the dry, empty cylindrical measure. The weight of measure, grease, and glass plate was 225.7 g. The measure was filled with freshly boiled, deionized water at a temperature of 24^{o} C. The glass plate was placed on the measure, making sure that no air bubbles remained. The outer surfaces of the measure were dried and the combined mass of measure, glass plate, grease, and water was 325.0g. The net mass of water was determined by subtracting 225.7 g from 325.0 g. The volume of the measure was calculated as follows:

$$V = 1000\frac{M}{D} = 1000\frac{99.3}{993.0} = 100 \qquad (3\text{-}1)$$

where *V* = volume of cylinder, mL
M = net mass of water = 99.3 g
D = density of water @ 24^{o} C = 993.0 Kg/m^3

3.2.4.6 FAA Test Procedure

Before proceeding with the test, the cylindrical measure was weighed and the scale was set to read zero while the measure was on the scale. Each test sample was mixed with a spatula until it appeared to be homogeneous. The jar and funnel section was positioned in the stand and the cylindrical measure was centered underneath the funnel. Using a finger to block the opening of the funnel, the test sample was poured into the funnel. The material was leveled in the funnel with the spatula. The finger was removed and the sample was allowed to fall freely into the cylindrical measure.

After the funnel was emptied, the excess fine aggregate from the cylindrical measure was stricken off by a single pass of the glass plate with the width of the edge of the plate almost vertical, using the flat part in light contact with the top of the measure. While this operation was taking place, extreme care was exercised to avoid vibration or any disturbance that could cause compaction of the fine aggregate in the cylindrical measure. After strike-off, the cylindrical measure was tapped lightly to compact the sample to make it easier to transfer the container to the scale or balance without spilling any of the sample. Any adhering grains were brushed from the outside of the container. The mass of the contents was determined to the nearest 0.1 g directly by reading the scale. All fine aggregate particles were kept for a second test run.

The sample from the retaining pan and cylindrical measure were recombined and the procedure was repeated. The results of the two runs were averaged. For a graded sample (Test Method A or Test Method C), the percent void content was determined directly, and the average value from the two runs was reported. For the individual size fractions (Test Method B), the mean percent void content was calculated using the results from tests of each of the three individual size fractions.

3.2.4.7 Calculation of the FAA

The uncompacted void content (FAA) was calculated as the difference between the volume of the cylindrical measure and the absolute volume of the fine aggregate collected in the measure. The FAA was calculated using the bulk specific gravity of the fine aggregate as follows:

$$FAA = \frac{V - \left(F/G\right)}{V} * 100 \tag{3-2}$$

where FAA = uncompacted voids in the material, %
V = volume of cylindrical measure, mL
F = net mass of fine aggregate in measure, g (gross mass minus the mass of the empty measure)
G = bulk dry specific gravity of fine aggregate

For the standard graded sample (Test Method A), the average FAA for the two determinations was calculated and used in this investigation.

For the individual size fractions (Test Method B), the average FAA for the determinations made on each of the three-size fraction samples was calculated, yielding FAA_1, FAA_2, and FAA_3. The mean (FAA) of the three averages was calculated and used in this investigation [$FAA = (FAA_1 + FAA_2 + FAA_3) / 3$]. For the as-received grading (Test Method C), the average FAA for the two determinations was calculated and used in this investigation.

3.2.5. Direct Shear Test (DST)

The Direct Shear Test (DST, ASTM Standard Method D 3080) is probably the most straightforward way to determine the stress-dependent shear strength of fine aggregates. The test consists of placing and compacting the test sample in the direct shear device, applying a predetermined normal stress (confining pressure) and displacing one frame horizontally with respect to the other at a constant rate of shearing deformation. The shearing force is measured along with the horizontal and vertical displacements as the sample is sheared. Shear stress is determined by dividing the applied force by the corrected cross-sectional area of the sample. Horizontal and vertical strains are determined using the measured displacement and the sample dimensions.

A significant amount of preliminary work was done to identify appropriate placement and compaction procedures for the aggregates, as well as the most appropriate confining stresses for consistent determination of shear strength parameters c (cohesion intercept) and φ (angle of internal friction). Preliminary work indicated that compaction procedures could significantly affect shear strength results. Important factors included compaction or tamping procedures, number and thickness of lifts used to prepare the sample, and the proximity of the interface between lifts to the shear plane.

3.2.5.1 DST Testing Procedure

Based on preliminary work done to investigate the factors mentioned before, a standard sample preparation procedure was established that yielded consistent results. A brief description of the resulting procedure (Fernandes et al. 2000) is as follows:

- Each sample was prepared with the appropriate gradation and consisted of approximately 190 g of material. This amount of material was ideal to fill the mold. The sample was divided into three pre-measured parts, and each part was placed into a separate marked container indicating the exact volume to fill 1/3 of the volume of the mold after compaction. The first two containers held the same volume of material. The third one had a variable amount depending on the specific gravity of the material. The purpose of this was to allow for the compaction of the sample in three lifts such that the middle of the second (center) lift coincided with the shear plane of the sample. This assured that interfaces between lifts would not influence the DST results.

- The lower half of the mold was placed into the Direct Shear Tester and secured with the horizontal holding screws.
- The bottom (grooved) platen was placed at the bottom of the mold.
- The upper half of the mold was then placed directly on top of the lower half.
- Both halves of the mold were secured together by means of vertical screws called shear pins. This step allowed the sample to be placed inside the mold and compacted without affecting the integrity and position of both halves of the mold.
- Once both halves of the mold were secured to each other, and the mold was secured to the tester, the sample was placed inside the mold in three different lifts, compacting each lift after its placement with an aluminum tamper of 1-inch diameter.
- The thickness of the lifts had to be determined and verified for each aggregate type because of variation in specific gravity between the materials. The amount of material in each lift and the position of the center of the second lift in relation to the shear plane were verified by measuring the distance from the top of the mold to the top of each lift.
- Great care was taken to avoid segregation between and within lifts. The sample was separated into three containers (one for each lift), and each lift was carefully placed by rotating the container and placing material at different locations (i.e., not just dropping all the material in the center of the mold).
- Each lift was carefully tamped to assure the greatest level of compaction possible. It should be noted that it was not possible to accurately determine a specific density level in the DST because of grooves in the mold. Therefore, it was decided that

achieving the maximum density possible for all aggregates was the best way to standardize the test.

- Once the sample was fully compacted, a top grooved platen (or load transfer plate) was placed on top of the sample, and a metal ball bearing was placed above the top platen.
- The loading bar was then placed horizontally above the ball bearing, making sure it was level and that its recess sat on top of the ball bearing without touching it.
- The loading bar was secured to the pulling screws connected to the pneumatic pump.
- A small normal load was applied to make the loading bar, the ball and the load transfer plate sit snugly against each other.
- Then, the desired load was applied and the shear pins were removed.
- The dial gauge for horizontal movement was placed against the shear bowl. The gauge for vertical movement was placed on a pin that went across the loading bar and rested on the ball bearing. Both gauges were reset at this point.
- With a selected shear rate of 0.05 inches per minute and the desired confining load being applied, the lower part of the mold began to move with respect to the top part. As one part slid across the other, with the sample being trapped in the middle, a shear force was produced.
- For every 100th of an inch of horizontal movement, the force being applied in the shear plane was recorded. This force could be read directly from a digital load cell readout.
- The vertical expansion or contraction of the sample, which was being measured by the vertical dial gauge, was also recorded.

- At the end of 0.3 in. of total displacement, the process was stopped, the sample removed, and the device cleaned.

3.2.5.2 Typical Data of DST Test

Based on preliminary data, it was determined that confining stresses of about 200 kPa (29 psi) or greater were required to obtain a linear relationship between shear strength and confining pressure. The confining stresses must generally be in this range to obtain the strength parameters c (cohesion intercept) and φ (angle of internal friction) consistently. Furthermore, strengths determined within this range of confinement are definitely appropriate for asphalt mixtures, since rutting occurs near the surface of pavement where there are high levels of confinement.

Figures 3-3 and 3-4 show results of a typical strength test performed on White Rock (L3) at a confining stress of 382 kPa (55.6 psi). These results show the typical behavior of a well-compacted fine aggregate. The material clearly dilated (increased in volume or vertical strain) as the sample approached peak strength. The stress then dropped below the peak strength as constant volume conditions were reached. An example of the strength envelope for Rinker is presented in Figure 3-5, which illustrates the determination of the shear strength parameters. Duplicate tests were performed at the highest confining stress, and duplicate values of shear strength parameters were also obtained.

Shear strength parameters were obtained in this manner for each of the nine fine aggregates. These parameters define the Mohr-Coulomb failure criterion, which describes the relationship between peak shear strength and normal stress on the failure plane:

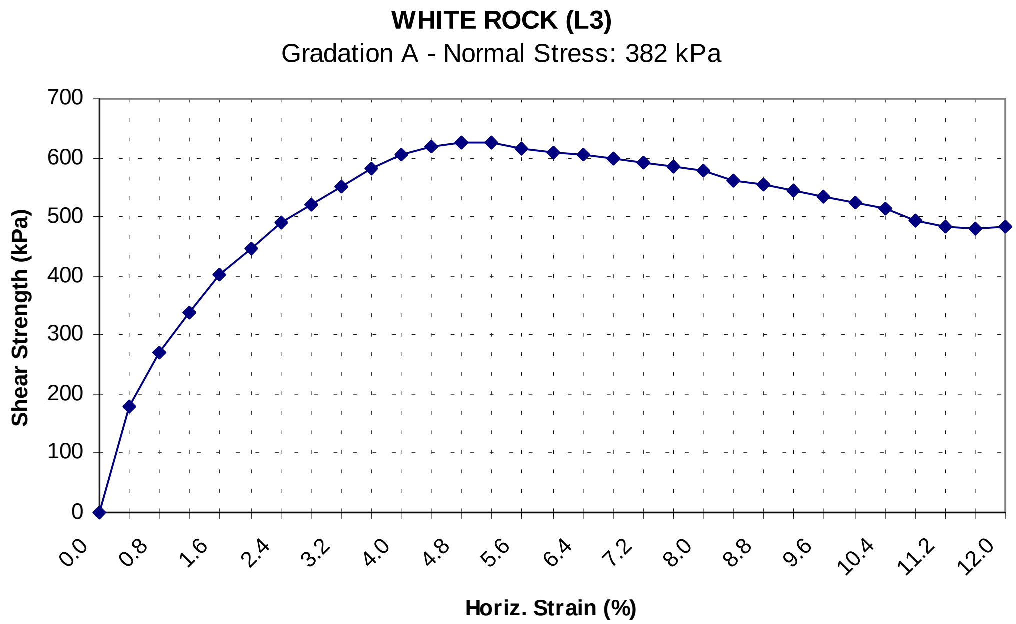


Figure 3-3 Typical Shear Stress versus Horizontal Strain from DST

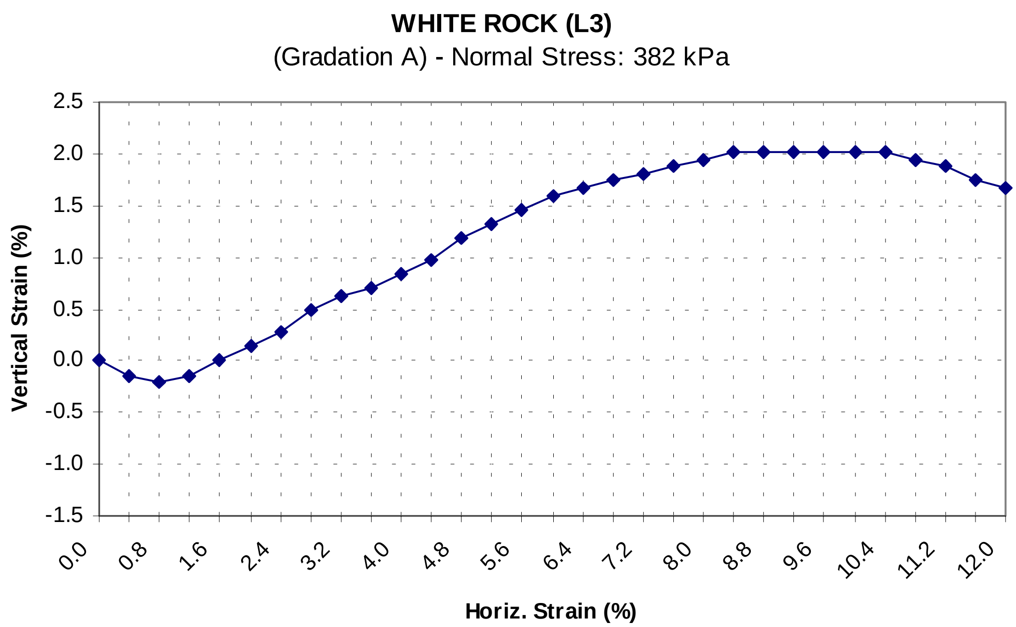


Figure 3-4 Typical Vertical Strain versus Horizontal Strain from DST

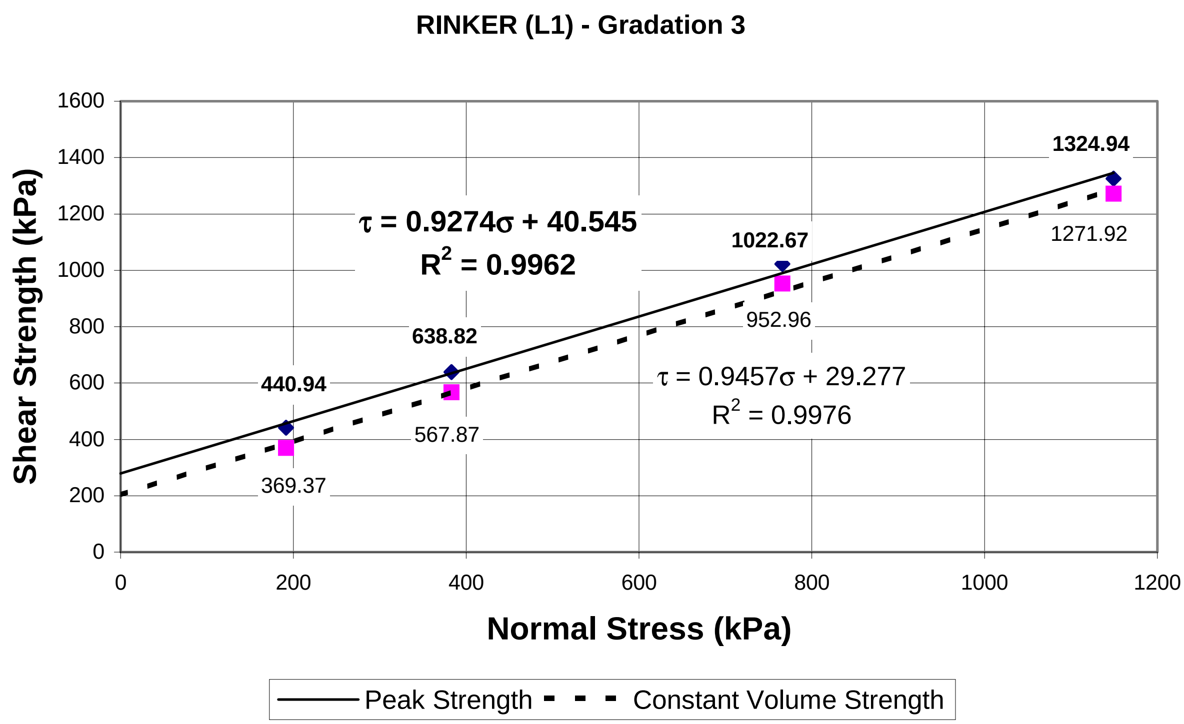


Figure 3-5 Typical Strength Envelope from Direct Shear Test (DST) Results

$$\tau_f = c + \sigma_n \tan\varphi \qquad (3\text{-}3)$$

where τ_f = shear strength
c = cohesion intercept
φ = angle of internal friction
σ_n = normal stress on the failure plane

A confinement level of 689 kPa (100 psi) was selected for comparison of shear strength between fine aggregates for two reasons: it was approximately in the middle of the range of confining stresses used; and, 689 kPa (100 psi) was typical of the compressive normal stress experienced at the surface of a pavement subjected to a design wheel load. It should be noted that the selection of this confining stress for evaluation was not critical, as the aggregate strengths ranked in the same way at all levels of confinement tested.

3.3 Mixture Design

A coarse and fine SuperPave™ asphalt mixture, nominal maximum aggregate size of 12.5 mm, was produced using each of the five different fine aggregates. The Florida DOT provided the gradation for a coarse and fine limestone SuperPave™ mixture for use as the White Rock (reference) mixture. These mixtures will be referred to as Coarse 1 and Fine 1 for the remainder of this paper. These SuperPave™ mixtures were selected as the reference mixtures for three reasons: 1) they have performed well in the field; 2) it is a commonly used Florida aggregate; and 3) extensive testing was being conducted at the university using these particular mixtures. To isolate the effect of the five fine aggregates on mixture shear resistance, the effect of gradation and fines (material passing the #200 sieve) had to be minimized. Figures 3-6 and 3-7 are gradation plots of the coarse and fine mixtures, respectively.

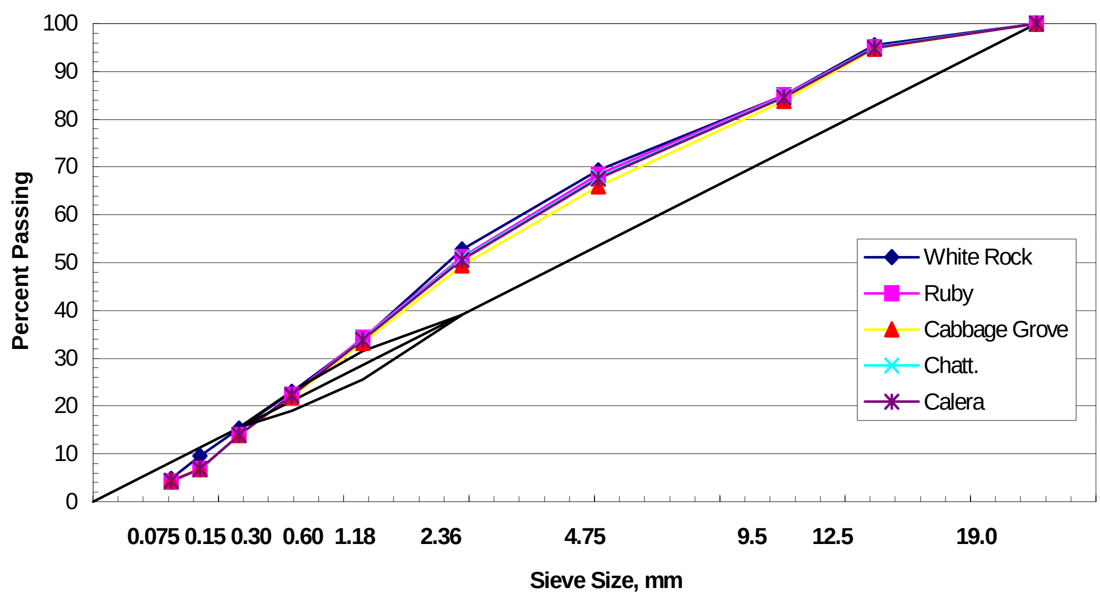


Figure 3-6 Fine Graded Mixtures

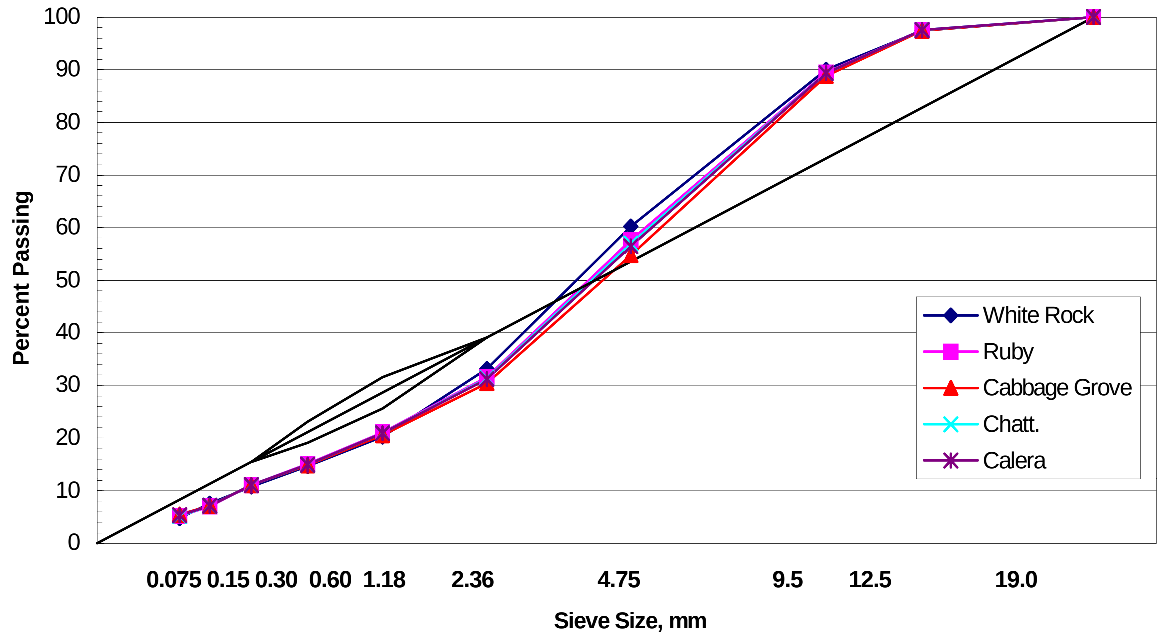


Figure 3-7 Coarse Graded Mixtures

The effect of gradation was eliminated by volumetrically replacing the fine aggregate portion of Coarse 1 and Fine 1 with the other four fine aggregates. The fine aggregate portion of the asphalt mixtures is any aggregate passing the #4 sieve. Using the known weight of the aggregate that was retained on the #8 sieve through the #200 sieve for the reference Coarse 1 and Fine 1, the weight could be volumetrically converted for another fine aggregate using that fine aggregates specific gravity.

To determine the amount of fines in the reference, Coarse 1 and Fine 1 gradations needed to be determined. A washed sieve analysis of the Coarse 1 and Fine 1 gradations was performed and the amount of material passing the #200 sieve was determined. Since the fine portion of the reference mixtures, Coarse 1 and Fine 1, would only be replaced by new fine aggregates, the amount of fines contained on the aggregates of the coarse portion of the mixture would need to be determined. This determination was made on a percentage basis. For example, if fifty percent of the gradation was coarse and fifty percent was fine, then fifty percent of the material passing the #200 sieve would remain in the new mixture after replacing the existing fine aggregate portion with a new washed fine aggregate. The fifty percent of fine lost due to adding a washed material would be replaced with mineral filler. By using this procedure, each test mixture contained the same amount of material passing the #200 sieve.

3.3.1 Mixture Preparation Procedure

The following procedure was used for all of the coarse and fine mixtures tested in this research. Steps include volumetric replacement of fine aggregate through mixture design on the Pine gyratory compactor.

- A washed sieve analysis of the reference C1 and F1 was performed in accordance with ASTM C-117 to determine the amount of material finer than the #200 sieve.
- The amount of material finer than the #200 sieve to be replaced by mineral filler was determined. This was done by determining the percentage of coarse aggregate in the reference mixtures and assuming that the same percentage of fines would also remain in the new asphalt mixture to be tested. The remaining percentage of fines is assumed to be lost through the addition of a new washed fine aggregate and would be replaced by granite mineral filler in all mixtures.
- Each new fine aggregate was washed, oven-dried, and then sieved to remove the material passing the #200 sieve. Each separate sieve size was stored in individual containers for ease of mixture preparation.
- The fine aggregate portion of the reference Coarse 1 and Fine 1 mixtures was volumetrically replaced by a new fine aggregate. This was done by using the specific

gravity of the new fine aggregate to determine an equivalent volume based on the volume occupied by the fine portion of the reference mixture. The following formula was used to determine the new weight of each sieve size by volumetric replacement:

$$W = \frac{G_{ref} * W_{ref}}{G_{sb}} \tag{3-3}$$

where: G_{ref} = bulk specific gravity of the reference aggregate
W_{ref} = weight of the reference aggregate for a particular sieve size
G_{sb} = bulk specific gravity of the new fine aggregate.

- An estimate of the design asphalt content to obtain 4 % air voids at N_{des} was determined based on prior experience.
- Three asphalt specimens were prepared in accordance with SuperPave™ Volumetric Mix Design procedure. Short-term oven aging of two hours was used prior to sample compaction to remain consistent with Florida DOT procedures. After one hour of short-term aging, each sample was thoroughly stirred.
- After the short-term oven aging, samples were then compacted on the Pine gyratory compactor to 174 revolutions, which corresponds with N_{max}. This value is used for mixture design at Traffic Level 5.
- Compacted samples were allowed to cool for a minimum of 24 hours at room temperature before determining the Bulk Specific Gravity of each compacted sample.
- The bulk specific gravity of the compacted samples was then determined in accordance with ASTM D1189 and D2726.
- The theoretical maximum specific gravity (Rice specific gravity) was determined using ASTM D2041. Two samples of approximately 800 grams were prepared for each specific mixture. Rice specific gravity tests were performed on both samples.

The value for the Rice specific gravity for each sample should not vary by more than 0.011. If the two Rice specific gravity samples did not meet this tolerance specification, then the test was performed again.

- The percentage of air voids was determined for each of the three samples at N_{max}.
- A back-calculation formula was used to determine the % of air voids at N_{des}. If the compacted samples did not meet the SuperPave™ criteria of 4% ± 0.5% air voids, then a new optimum asphalt content was determined based upon the previous compaction results. The mixture design process would continue from this point and follow the steps described above until the SuperPave™ criteria of 4% air voids is obtained.
- The design asphalt content was determined to obtain air-voids of 4 % at design gyrations. The remaining SuperPave™ volumetric parameters such as VMA, VFA, and bulk specific gravity at N_{int}, N_{des}, and N_{max} were calculated.

3.3.2 Servopac Gyratory Compactor Testing Procedure

After the design asphalt content was determined for each specific mixture by use of the Pine gyratory compactor, then each individual coarse and fine mixture was compacted in the Servopac gyratory compactor. The Servopac is a specific type of SuperPave™ gyratory compactor. Shear resistance measurements during compaction and the ability to easily vary the angle of compaction are two advantages of the Servopac that aided this research.

In most cases, three specimens of each individual coarse and fine graded mixture were compacted in the Servopac. For some mixtures, only two specimens were compacted because of material availability. Each mixture was prepared and compacted in accordance with SuperPave™ Volumetric Mix Design procedures with the exception of the short-term oven aging process. The suggested SuperPave™ short-term oven aging of four hours was replaced with two hours in accordance with FDOT. All mixtures were compacted to an N_{max} of 174 gyrations, which corresponds to FDOT Traffic Level 5.

Each coarse and fine testing mixture was compacted at two different angles: 1.25 and 2.5 degrees. The standard angle of compaction used in SuperPave™ Volumetric Mix Design procedures is 1.25 degrees. This is the basis for the selection of this angle of compaction for testing purposes. However, some of the fine aggregate effects on the asphalt mixtures seem to be more pronounced at 2.5 degrees. Also, there is less variation in compaction results between specimens of the same asphalt mixture at 2.5 degrees (Butcher, 1998).

After compaction, each asphalt specimen was allowed to cool at room temperature for a minimum of 24 hours. The Bulk Specific Gravity of each specimen was then determined in accordance with ASTM D1189 and D2726. Compacted specimens were then evaluated to determine SuperPave™ mixture properties such as VMA, VFA, air voids, etc. Specimens were also evaluated for shear resistance using the compaction data obtained from the Servopac.

3.3.3 Asphalt Pavement Analyzer Testing Procedure

The Asphalt Pavement Analyzer (APA) is a variation of the Georgia Loaded Wheel Tester. It is possible to test beam samples or SuperPave™ gyratory compactor samples with the APA. In APA testing, asphalt concrete specimens are subjected to an elevated temperature in a loaded wheel system under repetitive loading conditions, and the permanent deformation induced under the wheel path is measured. This approach to access rutting susceptibility is thought to be a more representative means of assessing rutting susceptibility of asphalt concrete under actual field conditions.

It was decided to test SuperPave™ Gyratory Compactor (SGC) samples in the APA. Two specimens of each coarse and fine mixture to be tested were rutted in the APA. The procedure for sample preparation and APA testing is as follows:

- The sample height needed to produce 8% air voids using the Pine gyratory compactor was determined for each mixture to be tested.
- The asphalt mixtures to be tested were prepared in the Pine gyratory compactor to the predetermined height.
- Each specimen was allowed to cool at room temperature for a minimum of 24 hours. The Bulk Specific Gravity of each specimen was then determined in accordance with ASTM D1189 and D2726.
- Since the sample height used for testing in the APA is 75 mm, the specimens fabricated in the Pine gyratory compactor would need to be trimmed. All samples were trimmed to the specified height using a saw, and then allowed to dry for 48 hours.
- After each sample was completely dry, the bulk specific gravity of each specimen was then determined in accordance with ASTM D1189 and D2726.
- Six to eight percent is the range for percentage of air voids of an asphalt sample to be tested in the APA. A calculation of the percentage of air voids for each saw-cut specimen was performed to determine if the samples met this criterion.
- One week after compaction of each specimen, rut testing was performed using the APA. The samples were tested under dry conditions at a temperature of 60 ° C.

- Approximately 12 hours prior to testing, the samples to be tested were placed in the APA for preheating while in the APA molds.
- The hose pressure was set to 100 ± 5 psi.
- The load cylinder pressure reading was set for each wheel to achieve a load of 100 ± 5 lb. For the purposes of this research, only the center position was used during testing to minimize variation in results due to position in the APA.
- The horizontal and vertical movement of the APA was calibrated.
- The preheated, molded specimens were secured in the APA, the chamber doors closed and 10 minutes was allowed for the temperature to stabilize.
- 25 cycles were applied to seat the specimens before initial measurements.
- After the initial 25 cycles, an initial reading of the rut depth at each location on the specimen under testing was manually taken.
- The preheated, molded specimens were secured in the APA, the chamber doors closed and 10 minutes was allowed for the temperature to stabilize.
- Then the APA was restarted and rut testing continued for 8000 cycles.
- Once testing was complete, an end-of-test reading of the rut depth at each location on the specimen was manually taken.
- In addition to the manual rut depth taken prior to and at the end of testing, the APA takes automatic rut depth readings. Some users have reported significant differences in rut depths between the automatic measurements and manual measurements.
- The difference between the beginning and ending rut depth was calculated manually for each location. The average of these rut depths was considered to be the reported rut depth for that particular mixture after testing.

3.3.4 Asphalt Content And Sieve Analysis

Aggregate degradation may have a significant effect on the mixture properties of a compacted asphalt specimen. To determine the degree of aggregate breakdown in the SuperPave™ asphalt mixtures tested in this research, extraction and recovery procedures had to be employed on the compacted specimens. Extraction and recovery methods were performed on the fine asphalt mixtures compacted at 2.5 and 1.25 degrees. Due to the nature of the different fine aggregates, two different test methods were used to extract the aggregate from the compacted asphalt specimens.

The Ignition Method (AASHTO TP – 53) was the first procedure used to extract the aggregate from the compacted specimens. This particular procedure was used on all compacted asphalt samples except those containing the Cabbage Grove limestone. The extremely high temperatures used in the testing procedure tend to burn off part of the Cabbage Grove aggregate leading to erroneous results. The aggregate of the Cabbage Grove Fine asphalt mixtures was extracted in accordance with ASTM 3-D5404, the Florida Method for Recovery of Asphalt from Solution Using the Rotavapor Apparatus.

After extraction, a washed sieve analysis of the aggregate was performed in accordance with ASTM C-136. The new aggregate gradation after compaction at 2.5 and 1.25 degrees was compared with the original gradation to determine the amount of aggregate breakdown. Since the researchers were interested only in the aggregate breakdown, a determination of asphalt content was not made using these procedures.

CHAPTER 4
RESULTS AND ANALYSIS

4.1 Introduction

During the Phase I of the study, the visual evaluation of the nine materials was used to compare the angularity and texture to the Fine Aggregate Angularity (FAA) results. The FAA tests from all three methods (Methods A, B, and C) were performed in duplicate for all aggregates investigated to ensure the accuracy of the test. The results of the direct shear test (DST) were used as a measure of shear resistance of aggregates and, therefore, were compared to the FAA values to determine whether there was agreement in quality of the materials between FAA and DST. A statistical analysis of the data presented in the following sections was used to identify relationships between different aggregate properties and shear strength. Based on the results and analysis of Phase I, mixtures were tested to evaluate the effect of various properties of aggregates on rutting resistance of mixture.

4.2 Phase I: Evaluation of Fine Aggregates

4.2.1 Visual Evaluation of Fine Aggregate Angularity and Texture

Surface texture and particle shape values reported in Table 4-1 were determined through microscopic analysis. Standard soil classification charts were used to rank angularity on a scale of 1 to 5 as follows: 1 = well-rounded, 2 = rounded, 3 = sub-rounded, 4 = sub-angular, and 5 = angular. Surface texture was also ranked on a scale of 1 to 5, with 1 being very smooth and 5, very rough. The values shown in Table 4-1 are the averages of eight independent evaluators who were asked to rank the nine aggregates according to angularity and texture. The range of average particle shape values was 2.4 to 4.3, and the range of average surface texture values was 1.7 to 4.6.

Table 4-1 Angularity and Texture (Visual Measurements)

Fine Aggregate Classification based on Shape and Texture (Performed on Material passing #8 sieve and retained in #16 sieve)																			
		SHAPE (Angularity) Angular = 5 <----> Rounded = 1									TEXTURE (Roughness) Rough = 5---------> Smooth = 1								
		[<--------- Rater --------->]									[<--------- Rater --------->]								
Material Name	**Type**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**Avg.**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**Avg.**
Rinker (L1)	Limestone	4	4	3	3	4	--	4	4	**3.7**	3	3	--	3	3	3	2	3	**2.9**
Anderson (L2)	Limestone	3	2	5	2	5	3	5	2	**3.4**	3	3	3	2	3	3	4	3	**3.0**
White Rock (L3)	Limestone	3	3	3	--	3	3	3	3	**3.0**	2	--	4	4	3	3	4	3	**3.3**
Calera (L4)	Limestone	2	5	4	5	4	3	2	3	**3.5**	3	--	2	2	1	1	1	2	**1.7**
Brooksville (L5)	Limestone	2	3	3	--	3	4	4	3	**3.1**	3	2	3	--	2	2	3	2	**2.4**
Cabbage Grove (L6)	Limestone	1	1	3	3	3	3	0	3	**2.4**	4	5	5	5	4	4	5	--	**4.6**
Ruby (G1)	Granite	4	5	4	4	5	4	4	--	**4.3**	3	2	--	3	3	3	2	3	**2.7**
Nova Scotia (G2)	Granite	4	--	3	4	4	3	3	3	**3.4**	--	3	3	3	2	2	2	2	**2.4**
Chattahoochee3 (G3)	Gravel	2	4	3	4	5	3	3	4	**3.5**	2	1	2	4	4	2	1	2	**2.3**

4.2.2 Fine Aggregate Angularity (FAA)

The FAA test was extremely simple to perform and the results were highly reproducible. Table 4-2 shows the individual and the average FAA results for all materials, methods and gradations. The uncompacted air voids are a function of gradation, angularity and texture. In fact, the test description in the standards recognizes that uncompacted void content is affected by factors other than aggregate angularity, including surface texture and gradation.

Table 4-2 Results of Uncompacted Void Content Test (FAA)

Material Name and Type	Gradation 1			Gradation A			Gradation 3		
	Sample		Avg.	Sample		Avg.	Sample		Avg.
	A	B		A	B		A	B	
Rinker (L1)	44.7	44.5	**44.6**	46.3	46.0	**46.2**	47.4	47.1	**47.2**
Anderson (L2)	44.8	44.5	**44.7**	45.9	46.2	**46.1**	46.4	46.2	**46.3**
White Rock (L3)	42.1	42.1	**42.1**	44.0	44.2	**44.1**	43.9	44.1	**44.0**
Calera (L4)	41.8	41.9	**41.9**	43.1	43.5	**43.3**	42.9	42.9	**42.9**
Brooksville (L5)	41.1	40.6	**40.8**	41.9	41.8	**41.8**	41.4	40.8	**41.1**
Cabbage Grove (L6)	50.0	50.0	**50.0**	54.0	54.1	**54.0**	53.2	53.2	**53.2**
Ruby (G1)	45.3	45.7	**45.5**	47.0	46.9	**47.0**	46.5	46.2	**46.3**
Nova Scotia (G2)	41.6	41.7	**41.7**	43.7	43.5	**43.6**	42.5	42.5	**42.5**
Chattahoochee 3 (G3)	44.4	44.7	**44.5**	44.5	44.3	**44.4**	43.1	43.1	**43.1**

The SuperPave™ recommends conducting the FAA test on method A, which is a standard gradation and it eliminates the effect of gradation on FAA values. Method B is conducted on individual sieve sizes and it does not represent a specific gradation. Method C is run on as-received material and the values should be interpreted with caution since the gradation can influence the uncompacted air voids.

Methods A, B, and C resulted in different values for FAA, as shown in Figure 4-1. In all cases, Method B resulted in the highest FAA values, followed by Method A and Method C, respectively. The gradation of Method A (Gradation A) was more uniformly graded than the gradation of the natural fine aggregates of Method C, so it resulted in higher FAA values than Method C. This makes sense, since the voids between particles should increase as the aggregate gradation becomes more uniform (i.e., uniformly-graded aggregates pack less densely than well-graded aggregates). Method B was performed on single-sized aggregates, and thus resulted in the highest FAA values.

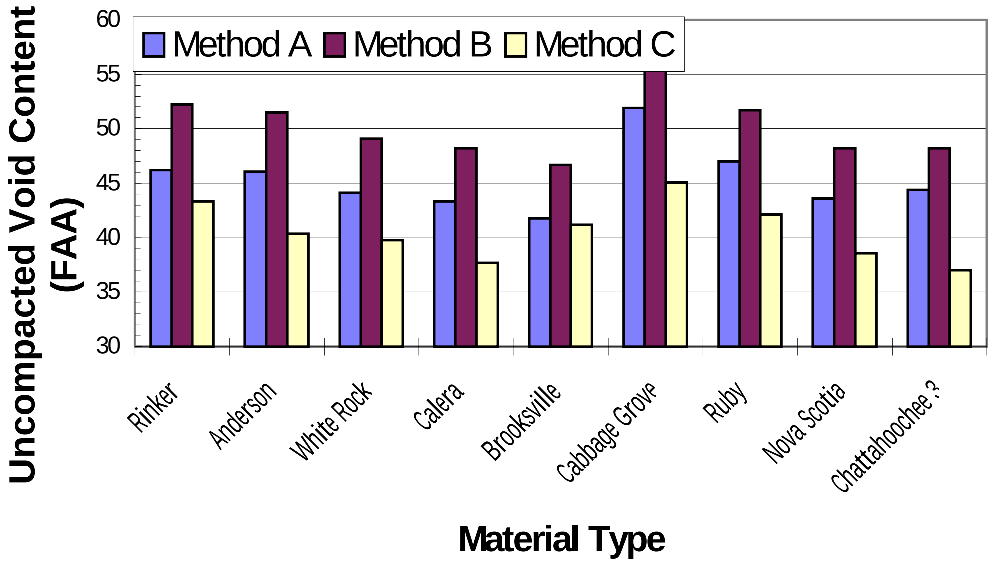


Figure 4-1 Variation of Uncompacted Void Content (FAA) versus Test Method

Figure 4-2 shows FAA for the three gradations. The FAA test was conducted on gradations 1 and 3 using Method C to evaluate the effect of gradation on FAA and shear strength. Figure 4-2 shows that the effect of gradation was minimum on FAA and was not as significant as the test method or the material type. In general, Gradation A resulted in the highest values for FAA and Gradation 1 resulted in the lowest value.

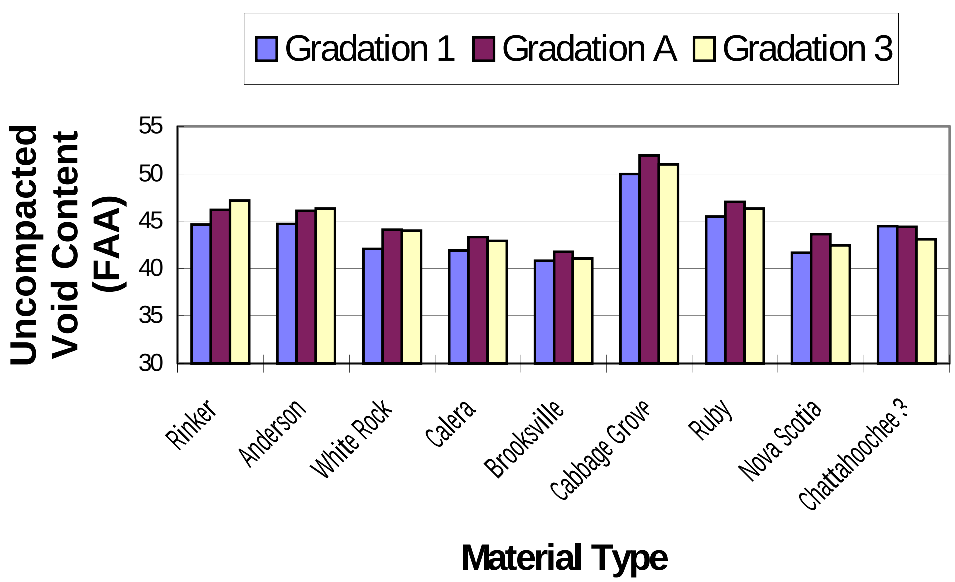


Figure 4-2 Variation of Uncompacted Void Content (FAA) as a Function of Aggregate Type and Gradation

4.2.3 Direct Shear Test (DST)

The results of peak shear strength at 689 kPa (100 psi) confining stress are presented in Table 4-3 for the nine aggregates and three gradations tested. Equation 3.1 was used to determine the shear strength.

Table 4-3 Results of Direct Shear Test (DST)[a]

Shear Strength, kPa			
Material Name & Type	**Gradation 1**	**Gradation A**	**Gradation 3**
Rinker (L1)	921	805	914
Anderson (L2)	915	862	882
White Rock (L3)	940	928	912
Calera (L4)	978	941	993
Brooksville (L5)	918	820	874
Cabbage Grove(L6)	738	727	742
Ruby (G1)	831	818	843
Nova Scotia (G2)	949	913	1,000
Chattahoochee FC-3 (G3)	728	724	760

[a]Average of two tests, performed in accordance with ASTM D-3080.
The numerical values are the peak shear strength (kPa) at a normal stress of 689 kPa.

As shown in Table 4-3, shear strength ranged from 724 (105 psi) to 1,000 kPa (145 psi). In general, Gradations 1 and 3 (more well-graded) exhibited higher shear strength than Gradation A (more uniformly-graded).

FAA results did not show a good correlation with either shear strength at 689 kPa (100 psi) confining pressure or angle of internal friction, as demonstrated in Figures 4-3 and 4-4, respectively. It should be noted that although Cabbage Grove had the lowest shear strength, the FAA value was well above the 45 mark specified by SuperPave™. Furthermore, the FAA values of the three materials with the highest shear strength, (Calera, Nova Scotia, and White Rock) fell below 45. In addition, Figures 4-3 and 4-4 seem to indicate that as shear strength and angle of internal friction decrease, the quality of the material (as indicated by FAA) increases. On the other hand, the toughness appears to correlate better with DST than FAA.

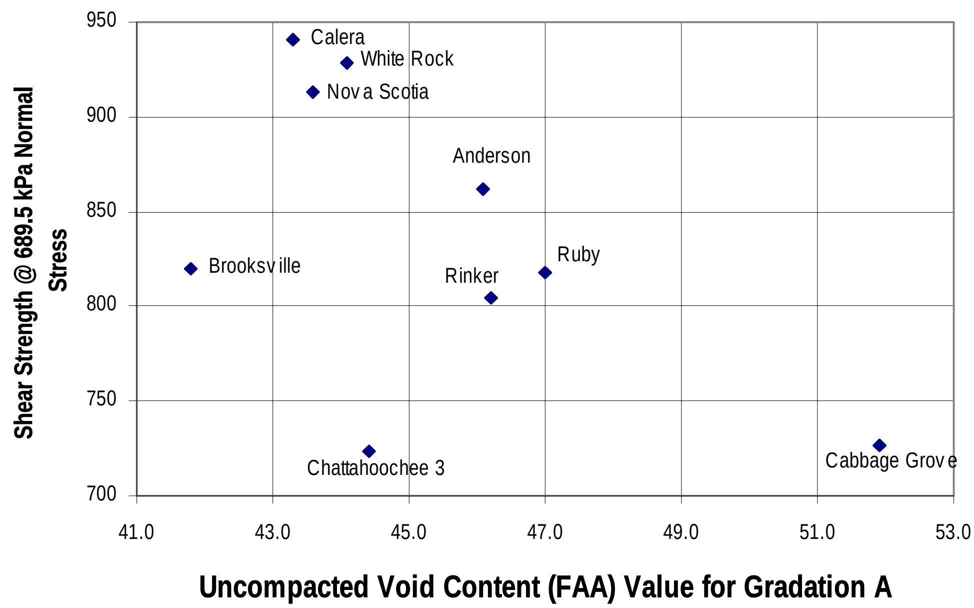


FIGURE 4-3 Correlation Between Shear Strength and Uncompacted Void Content

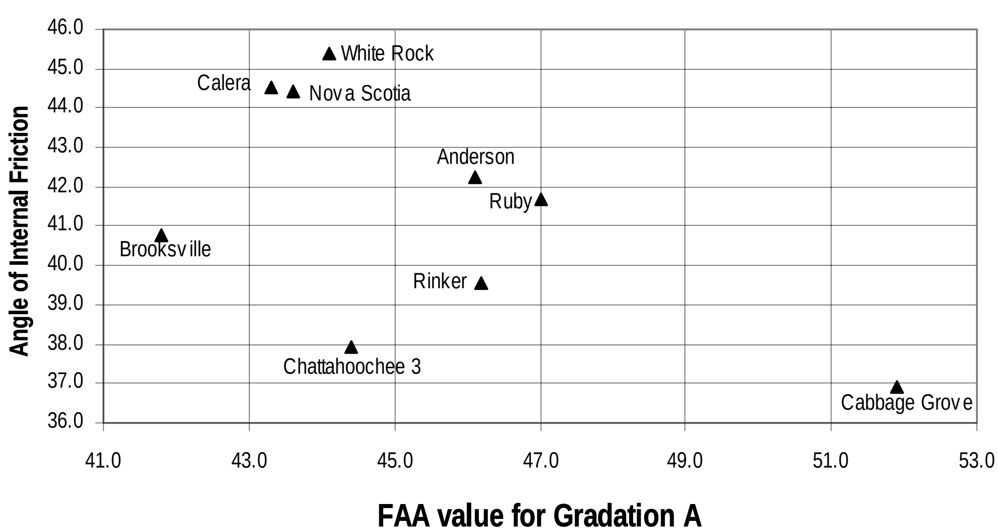


Figure 4-4 Correlation Between Angle of Internal Friction and Uncompacted Void Content

4.2.4 Analysis And Discussion

A statistical analysis was performed on the FAA and DST data to:

1. determine the reproducibility of the results;
2. evaluate whether FAA was related to aggregate type, particle shape (visual rating), surface texture (visual rating), and gradation of the fine aggregate; and
3. evaluate whether the shear strength was related to toughness (based on L.A. Abrasion), particle shape (visual rating), surface texture (visual rating), FAA, and gradation of the fine aggregate.

Three gradations, nine material types, and two replicates were used to evaluate the FAA and DST results, using Analysis of Variance (ANOVA). Table 4-4 shows the DST individual results, their totals, and averages for the nine materials tested. The DST results shown in Table 4-4 reflect peak shear strength (kPa) at a normal confining pressure of 689 kPa (100 psi). When evaluating whether particular factors had a significant effect on fine aggregate properties (FAA and DST), groups of fine aggregates exhibiting extreme values of those factors were compared. The factors evaluated include material type, toughness, surface texture and particle shape. There were not always an equal number of measurements within the groups being compared. To compensate for this a multiplier was used to properly weigh the measurements within each group. For example, when two groups were compared for texture, one with a high texture value to one with a low texture value, only one material was used within the high texture group while two materials were used within the low roughness group. Therefore, a multiplier of +2 was assigned to the value in the high roughness group and a multiplier of -1 was assigned to the two values in the low roughness group. Also a multiplier of zero was

Table 4-4 Individual Values, Totals and Averages from DST Tests @ 689 kPa Confining Pressure

Fine Aggregate Type	[----------- (Gradation) -----------]				*Aggregate Type Average*
	G-1	G-A	G-3	Row Total	
Rinker (L1)	929.8	800.9	919.0		
	934.4	810.7	911.0		
Total	1,864.2	1,611.6	1,830.1	5,305.9	
Average	*932.1*	*805.8*	*915.0*		***884.3***
Anderson (L2)	929.3	865.0	884.1		
	902.4	860.9	881.5		
Total	1,831.7	1,725.9	1,765.7	5,323.3	
Average	*915.9*	*862.9*	*882.8*		***887.2***
White Rock (L3)	950.9	938.2	978.3		
	930.0	920.3	936.8		
Total	1,880.9	1,858.5	1,915.0	5,654.4	
Average	*940.4*	*929.2*	*957.5*		***942.4***
Calera (L4)	990.3	950.5	992.6		
	966.7	932.5	995.2		
Total	1,957.1	1,883.0	1,987.8	5,827.9	
Average	*978.5*	*941.5*	*993.9*		***971.3***
Brooksville (L5)	937.5	821.7	888.9		
	899.5	820.3	860.1		
Total	1,837.0	1,642.0	1,749.0	5,228.1	
Average	*918.5*	*821.0*	*874.5*		***871.3***
Cabbage Grove (L6)	750.3	735.2	745.9		
	727.5	720.6	739.9		
Total	1,477.8	1,455.8	1,485.8	4,419.4	
Average	*738.9*	*727.9*	*742.9*		***736.6***
Ruby (G1)	839.3	832.0	845.3		
	824.4	805.1	842.1		
Total	1,663.8	1,637.1	1,687.3	4,988.2	
Average	*831.9*	*818.5*	*843.7*		***831.4***
Nova Scotia (G2)	957.3	915.0	1,011.8		
	942.5	913.1	988.9		
Total	1,899.8	1,828.1	2,000.8	5,728.6	
Average	*949.9*	*914.0*	*1,000.4*		***954.8***
Chattahoochee 3 (G3)	734.5	727.8	767.3		
	721.7	720.5	754.0		
Total	1,456.2	1,448.3	1,521.2	4,425.8	
Average	*728.1*	*724.1*	*760.6*		***737.6***

assigned to those materials for which the factor was neither within the extreme low or the extreme high range. These multipliers, as shown in Table 4-5, were then used in conjunction with the individual values of FAA and DST to determine whether each factor had a significant effect on the FAA and DST test results.

Table 4-5 Material Properties and Their Multipliers

Material Name and Type	Los Angeles Abrasion[a]		Surface Texture[b]		Particle Shape[c]	
	Value, %	Multiplier	Value	Multiplier	Value	Multiplier
Rinker (L1)	33	**0**	2.9	**0**	3.7	**+1**
Anderson (L2)	16	**+1**	3.0	**0**	3.4	**0**
White Rock (L3)	34	**0**	3.3	**0**	3.0	**-1**
Calera (L4)	25	**+1**	1.7	**-1**	3.5	**0**
Brooksville (L5)	34	**0**	2.4	**0**	3.1	**0**
Cabbage Grove (L6)	41	**-1**	4.6	**+2**	2.4	**-1**
Ruby (G1)	20	**+1**	2.7	**0**	4.3	**+1**
Nova Scotia (G2)	18	**+1**	2.4	**0**	3.4	**0**
Chattahoochee 3 (G-3)	42	**-1**	2.3	**-1**	3.5	**0**

[a]Los Angeles Abrasion Test performed on the parent rock, as a measure of toughness. Values provided by the Florida DOT Materials Office.
[b]Average of 8 evaluations, where 1 = smooth and 5 = rough.
[c]Average of 8 evaluations, where 1 = rounded and 5 = angular.

The ANOVA was used to evaluate the significance of fine aggregate (as defined by toughness, surface texture, particle shape, and material type), gradation, and the interaction between the two on FAA and shear strength. All analyses were conducted at a 99% level of confidence, which is slightly tighter than the commonly used 95% for engineering applications.

4.2.4.1 Fine Aggregate Angularity (FAA)

Results of the statistical analysis presented in Table 4-6 show that fine aggregate, gradation, and the interaction between the two, all had a significant effect on FAA according to the ANOVA results. The results of this statistical analysis illustrate the significance of specific properties (material type, texture, and particle shape) on FAA. As shown in Table 4-6, surface texture appeared to have a more significant effect on FAA than particle shape or material type. Ironically, particle shape, which is more commonly referred to as angularity, appeared to have a smaller effect on FAA.

Table 4-6 Analysis of Variance (ANOVA) of FAA Results

Source of Variation	Sum of squares	Degrees of Freedom	Mean Square	F
Gradation	**9.06**	**2** 2	**453**	**11.0**[a]
Fine Aggregate	**200.11**	**8**	**25.1**	**60.9**[a]
Material Type (G1&G2 vs. G3)	0.41	1	0.41	0.4
Surface Texture (L4&G3 vs. L6)	116.03	1	116.03	309.0[a]
Particle Shape (L1&G1 vs. L3&L6)	3.10	1	3.10	22.0a
Experimental Errors	**6.58**	**16**	**0.41**	
Material Type (G1&G2 vs. G3)	2.20	2	1.10	
Surface Texture (L4&G3 vs. L6)	0.75	2	0.38	
Particle Shape (L1&G1 vs. L3&L6)	0.28	2	0.14	
Total	**215.75** 131.82	**26**		

[a]Significant at an α level of 1%

4.2.4.2 Direct Shear Strength

Results of the statistical analysis presented in Table 4-7 show that fine aggregate type, gradation, and their interaction all had a significant effect on DST according to the ANOVA. As shown in Table 4-7, toughness appeared to have a more significant effect than surface texture, while the effect of particle shape (angularity) was not significant.

Table 4-7 Analysis of Variance (ANOVA) of DST Results

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Gradation	**14,345**	**2** 2	**7,173**	**9.1**[a]
Fine Aggregate	**182,662**	**8**	**22,833**	**29.0**[a]
Toughness (L2,L6,G3 vs. L4,G1,G2)	79,295	1	79,295	216.0[a]
Surface Texture (L4&G3 vs. L6)	27,238	1	27,238	168.6[a]
Particle Shape (L1&G1 vs. L3&L6)	380	1	380	0.5
FAA (L1,L2&G1 vs. L4, L5&G2)	21,418	1	21,418	118.9[a]
Experimental Errors	**12,598**	**16**	**787**	
Toughness (L2,L6,G3 vs. L4,G1,G2)	734	2	367	
Surface Texture (L4&G3 vs. L6)	323	2	162	
Particle Shape (L1&G1 vs. L3&L6)	1,585	2	792	
FAA (L1,L2&G1 vs. L4, L5&G2)	360	2	180	
Total	**209,606** 123,900	**26**		

[a]Significant at an α level of 1%.

As previously shown in Table 4-6, surface texture had a much greater effect on FAA than particle shape. Consequently, one would expect FAA to have a similar effect on shear strength as surface texture had. In addition, aggregates with high FAA such as Rinker (L1), Anderson (L2) and Ruby (G1) were compared to aggregates with low FAA values such as, Calera (L4), Brooksville (L5) and Nova Scotia (G2) to illustrate the effect of FAA on DST.

Although FAA had some influence on shear strength, aggregate toughness and gradation appeared to overwhelm its affects, confirming that FAA alone was not a good predictor of fine-aggregate shear strength.

4.2.5 Overall Rankings of Fine Aggregates

Table 4-8 shows the relative rankings of the nine fine aggregates according to FAA, shear strength, and historical performance. The relative value of FAA or shear strength is also provided next to the ranking. The results clearly indicate that both the rankings and the relative values of FAA are significantly different from those determined by the shear strength. For example, Cabbage Grove (L6) exhibited the highest FAA but had the lowest shear strength of all the aggregates. As indicated by the qualitative rating of the aggregates based on historical performance, this aggregate has long been considered

Table 4-8 Overall Rankings of Fine Aggregates

Fine Aggregate	**FAA**[a]	**Shear Strength**[b]	**Quality**[c]
Rinker (L1)	3rd (high)	5th (high)	Good
Anderson (L2)	4th (high)	4th (high)	Good
White Rock (L3)	6th (medium)	3rd (very high)	Good
Calera (L4)	7th (low)	1st (very high)	Good
Brooksville (L5)	9th (very low)	6th (high)	Medium
Cabbage Grove (L6)	1st (very high)	9th (low)	Poor
Ruby (G1)	2nd (high)	7th (medium)	Medium
Nova Scotia (G2)	8th (low)	2nd (very high)	Good
Chattahoochee 3 (G3)	5th (medium)	8th (low)	Poor

[a]Based on Tukey Test of Significance. Definition of FAA ranges:
Very High: > 47; High: 45 - 47; Medium: 43 - 45; Low: 41- 43; Very Low: < 41
[b]Based on Tukey Test of Significance. Definition of Shear Strength ranges:
Very High: > 950; High: 850 - 950; Medium: 750 - 850; Low: 650- 750; Very Low: < 650
[c]Based on information obtained from bituminous materials engineers.

a problem material, probably because of its low toughness. Conversely, Calera (L4) had a low FAA, yet exhibited the highest shear strength of all fine aggregates tested, including the granites. Calera (L4) has long been considered an excellent limestone fine aggregate. Therefore, FAA would reject a material considered to be excellent according to both shear strength and historical performance, and accept a material considered to be poor according to both shear strength and historical performance.

4.2.6 Summary of Findings

Based on the analysis, it was concluded that FAA and toughness were the two properties of fine aggregates that could affect the rutting resistance of mixtures. The toughness, DST and FAA was categorized according to Table 4-9. Based on the categories in Table 4-9, all nine aggregates were categorized according to Table 4-10. Four fine aggregates were selected in addition to White Rock for mixture testing. The fine aggregates were selected so as to evaluate the effects of toughness and FAA on rutting resistance of mixtures. The testing matrix is shown in Table 4-11.

Table 4-9 Criteria for Categorizing Factors Affecting Fine Aggregate Properties

Factor	Category	Criteria
Toughness	High	LA Loss > 35%
	Low	LA Loss<35%
DST	High	DST > 800 kPa
	Low	DST < 800 kPa
FAA	High	FAA > 45
	Low	FAA < 45

Table 4-10 Summary of Fine Aggregate Properties

Material Type	LA Loss		DST		Particle Shape Value	Particle Texture Value	FAA	
	Value, %	Rank	Value, kPa	Rank	1=rounded 5=angular	1=smooth 5=rough	Value	Rank
Rinker	33	L	884	H	3.7	2.9	46.0	H
Anderson	16	L	887	H	3.4	3.0	45.7	H
White Rock	34	L	842	H	3.0	3.3	43.4	L
Calera	25	L	971	H	3.5	1.7	42.7	L
Brooksville	34	L	871	H	3.1	2.4	41.3	L
Cabbage Grove	41	H	737	L	2.4	4.6	51.0	H
Ruby	20	L	831	H	4.3	2.7	46.3	H
Nova Scotia	18	L	955	H	3.4	2.4	42.6	L
Chattachoochee3	42	H	738	L	3.5	2.3	44.0	L

Table 4-11 Fine Aggregates Selected for Mixture Testing

Test Matrix		Toughness	
		HIGH	LOW
FAA	**HIGH**	Ruby	Cabbage Grove
	LOW	Calera and White rock-(reference mix)	Chattahoochee

4.3 Phase II: Evaluation of Effects of Fine Aggregate Properties on Asphalt Mixtures

Five different fine aggregates were evaluated to determine the effect of material properties on the quality of asphalt mixtures within the constraints of the SuperPave™ Volumetric Mix Design method. The reference fine and coarse gradations were F1 and C1 commonly used by FDOT. The White Rock was used as a reference material. To create a coarse gradation of a different material, the material retained passing no. 8 sieve of C1 was volumetrically replaced by the gradation of a different material. On the other hand, the fine gradation of other materials was created by volumetrically replacing the material passing no. 8 sieve of F1 mixture. Figures 3-6 and 3-7 in the previous section show the coarse and fine graded asphalt mixtures that were produced with each of the different fine aggregates.

All mixtures were designed using the Pine gyratory compactor to obtain the design asphalt content to meet the SuperPave™ criteria of 4 percent air voids at N_{des}. The Servopac gyratory compactor, which gives a measure of mixture shear resistance through the gyratory shear parameter, was used to compact each mixture at 1.25 degree.

The shear resistance of the mixture was evaluated by compacting the mixture at a 2.5-degree angle of gyration in the Servopac and then analyzing the compaction data to evaluate the effects of fine aggregate properties on mixture shear resistance. The Asphalt Pavement Analyzer (APA) was used to perform rutting tests on each mixture to determine if mixture performance in the APA could be predicted by fine aggregate properties and trends observed in the gyratory compaction data.

4.3.1 Aggregate Degradation

After compaction of the test samples, an extraction and recovery procedure was performed to determine if there were any changes in the aggregate gradation of the mixtures due to compaction using the Servopac gyratory compactor. Since the role of the fine aggregate portion of a mixture is more prevalent in fine-graded asphalt mixtures, only the five fine mixtures compacted at 1.25 and 2.5 degrees were evaluated.

As can be seen in Tables 4-12 and 4-13, the fine portion of the gradation changed significantly from gradation prior to compaction for the mixtures containing Chattahoochee and Cabbage Grove fine aggregates. The coarse portion of the gradation, aggregate retained on the #4 sieve and larger, showed little change in the percent passing each particular sieve size. This trend was consistent at a compaction angle of 1.25 and

2.5 degrees, although the breakdown was less but still significant for a compaction angle of 1.25 degrees. As can be seen, both fine aggregate mixtures fail to meet SuperPave™ requirements after compaction due to the gradation being outside of the control points for the #200 (.075 mm) sieve. This is due to excessive breakdown in the fine aggregate portion of the mixtures.

Table 4-12 Fine Chattahoochee Mixture Gradations

Sieve Size	% Passing, Original	% Passing, Servo 2.5	% Passing Difference	% Passing, Servo 1.25	% Passing Difference
19	100	100.0	0	100	0.0
12.5 (1/2)	95	96.4	1.4	96.1	1.1
9.5 (3/8)	84.7	87.6	2.9	87.9	3.2
4.75 (#4)	67.9	71.1	3.2	71.7	3.8
2.36 (#8)	50.8	55.4	4.6	53.7	2.9
1.18 (#16)	34.04	40.7	6.7	38.3	4.3
600 (#30)	22.2	29.3	7.1	28.1	5.9
300 (#50)	14	21.0	7.0	20	6.0
150 (#100)	6.9	14.3	7.4	12.6	5.7
75 (#200)	4.3	11.0	6.7	9.4	5.1

Table 4-13 Fine Cabbage Grove Mixture Gradations

Sieve Size	% Passing, Original	% Passing, Servo 2.5	% Passing Difference	% Passing, Servo 1.25	% Passing Difference
19	100	100.0	0	100	0
12.5 (1/2)	94.7	95.9	1.2	95.5	0.8
9.5 (3/8)	83.8	86.4	2.6	85.8	2.0
4.75 (#4)	66	68.2	2.2	67.9	1.9
2.36 (#8)	49.4	53.9	4.5	53.0	3.6
1.18 (#16)	33.3	40.9	7.6	39.8	6.5
600 (#30)	21.9	31.6	9.7	29.1	7.2
300 (#50)	13.9	24.4	10.5	21.3	7.4
150 (#100)	7.03	18.9	11.9	17.4	10.4
75 (#200)	4.5	12.7	8.2	10.9	6.4

Cabbage Grove seems to exhibit an aggregate breakdown process that leads to an excessive amount of material that is finer than the #200 (.075 mm) sieve. The breakdown of the Chattahoochee material seems to be a more uniform process of aggregate degradation for #8 (2.36 mm) through the #200 (.075 mm) sieve sizes, although there is an excessive amount of material finer than the #200 (.075 mm) sieve as well.

For the fine mixtures containing Calera, White Rock (reference mixture), and Ruby fine aggregates, there was little change in the gradation before and after compaction. Appendix A shows the complete set of aggregate degradation results for all materials. This trend seems to be consistent with toughness values as Calera, White Rock, and Ruby exhibit low L.A. abrasion loss values. Conversely, Chattahoochee and Cabbage Grove experienced high L.A. abrasion loss values. The modified LA loss in fine aggregates for the Chattachoochee was very low contrary to the breakdown observed during compaction. This could indicate that this test may not be appropriately reflecting breakdown during compaction. The LA loss on the parent rock was considered for further analysis instead of the modified LA loss values.

Aggregate breakdown is very important when trying to assess the quality of a fine aggregate as it pertains to shear resistance of an asphalt mixture. It is thought by many researchers that an excessive amount of fines contributes to the lack of rutting resistance of an asphalt mixture. Therefore, an aggregate that experiences breakdown during compaction may tend to produce a mixture with less rut resistance regardless of the FAA of the material incorporated in the mixture. That is why it is important to address the breakdown of Cabbage Grove, a high FAA fine aggregate, compared to Calera, a low FAA fine aggregate, that does not experience breakdown during compaction.

4.3.2 Evaluation of Mixture Properties

After the design and compaction of the five coarse-graded and five fine-graded asphalt mixtures on the Pine gyratory compactor, the volumetric mixture properties were compared against SuperPave™ design criteria. The mixture volumetrics properties are shown in Table 4-14. The values are an average of a minimum of three replicates for each mixture tested.

Table 4-14 Mixture Properties

	Criteria	White Rock		Ruby		Cabbage Grove		Chattahoochee		Calera	
		Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine
G_{mm} at N_{max}	**<= 98%**	97.7	97.5	97.8	99.0	98.1	97.7	97.1	97.2	97.7	97.5
G_{mm} at N_{des}	**96%**	96.0	96.0	96.4	96.0	96.3	96.1	95.7	96.0	95.9	96.9
G_{mm} at N_{int}	**<= 89%**	84.3	86.5	85.7	87.1	83.6	85.9	86.7	89.0	83.8	86.6
% Air Voids	**4%**	4.0	4.0	3.9	3.7	3.8	3.9	4.4	3.7%	4.1	3.8
% Air Voids at N_{int}	**> 8%**	15.7	13.5	14.3	12.7	16.6	14.0	14.2	11.1	16.2	13.4
% VMA	**14%**	15.4	15.5	16.1	16.0	**11.2**	**11.2**	14.8	14.1	**12.6**	**10.5**
% VFA	**65-75%**	74.0	74.0	**77.3**	**76.8**	66.5	65.2	70.6	73.7	67.4	63.8
Dust/Asphalt Ratio	**0.6- 1.2**	1.0	0.8	0.9%	0.7	1.7	1.4	1.1	0.9	1.4	1.3
Eff. AC %	**N/A**	5.3	5.3	5.6	5.7	3.3	3.2	4.7	4.8	3.7	3.4
Pass/Fail		**Pass**	**Pass**	**Fail**	**Fail**	**Fail**	**Fail**	**Pass**	**Pass**	**Fail**	**Fail**

In theory, aggregate particles that are round and smooth (lower FAA) will result in mixtures that have a lower void content at a given compactive effort than particles that are more angular and rough. Aggregates that exhibit low toughness resulting in break-down during compaction may also produce a low void content. Cabbage Grove and Calera fine aggregates resulted in low VMA mixtures. Cabbage Grove exhibits a high

FAA but a low toughness. Conversely, Calera is tough fine aggregate with a low FAA. The mixtures containing the Ruby fine aggregate, a tough material with a high FAA, resulted in high VMA mixtures. Even though Chattahoochee is a low toughness fine aggregate exhibiting low FAA, the resulting mixtures met the 14 percent VMA requirement. This may be due to the nature of the breakdown that occurs during compaction of the Chattahoochee asphalt mixtures.

The only mixtures to meet all SuperPave™ design criteria (% VMA, % VFA, dust to asphalt ratio, and Specific Gravity requirements) were the coarse-graded and fine-graded mixtures containing the Chattahoochee fine aggregate and the reference mixture containing the White Rock fine aggregate. Although the coarse-graded and fine-graded mixtures containing the Ruby fine aggregate failed to meet the VFA requirement, an adjustment in the asphalt content may be warranted to reduce the percentage of VFA in these mixtures and still allow the mixtures to meet the 4 percent air voids requirement.

In general, when examining the mixtures containing fine aggregates that were tough and did not experience breakdown, the FAA did appear to identify substandard VMA mixtures. Calera has an extremely low FAA (42.7) and resulted in a low VMA mixture. But this could be corrected by adding appropriate amount of asphalt content. Ruby had an adequate FAA (46.3) and resulted in a high VMA mixture. Of note is the extremely high FAA (53.1) fine aggregate Cabbage Grove that resulted in an extremely low VMA (11.1) mixture. The low VMA for the Cabbage Grove mixtures appears to be the result of breakdown of the fine aggregate.

Film thickness of asphalt mixtures especially in fine mixtures is generally associated with mixture durability. Table 4-15 contains the results of mixture theoretical film thickness calculations for fine-graded mixtures. The Calera and Cabbage Grove mixtures having film thickness values of 5.4 and 6.1 microns respectively. Generally, a value of at least 8 microns is considered acceptable for film thickness of fine-graded mixtures. Such a low film thickness is a problem for fine-graded mixtures and can lead to potential durability problems. The low film thickness for the mixtures containing these two aggregates was predicted by the low VMA of these mixtures as previously stated. All other fine mixtures exhibited adequate film thickness values.

Table 4-15 Film Thickness for Fine-Graded Mixtures

Sieve Size, mm	**Percentage Passing Each Sieve Size**				
	White Rock	**Ruby**	**Cabbage Grove**	**Chatt.**	**Calera**
25	100.0	100.0	100.0	100.0	100.0
19	100.0	100.0	100.0	100.0	100.0
12.5	95.5	95.1	94.7	95.0	94.9
9.5	85.1	85.0	83.8	84.7	84.6
4.75	69.3	68.5	66.0	67.9	67.6
2.36	52.7	51.2	49.4	50.8	50.6
1.18	34.0	34.3	33.3	34.0	33.9
6.00E-01	22.9	22.4	21.9	22.2	22.2
3.00E-01	15.3	14.0	13.9	14.0	14.0
1.50E-01	9.6	6.8	7.0	6.9	6.9
7.50E-02	4.8	4.2	4.5	4.3	4.3
Surface Area	29.45	26.30	26.60	26.44	26.42
%AC	0.063	0.059	0.067	0.055	0.053
G_{mb}	2249	2334	2308	2355	2417
G_b	1.035	1.035	1.035	1.035	1.035
Volume Asphalt (cm^3)	136.9	133.0	149.4	125.1	123.8
% Asphalt Absorbed	1.077	0.574	3.72	0.9186	2.54
Weight Asphalt (g)	22.7	12.6	80.1	20.4	58.1
Effective Vol. Asphalt (cm^3)	115.0	120.9	72.0	105.4	67.6
Film Thickness	**9.0**	**10.2**	**6.1**	**8.7**	**5.4**

4.3.3 Servopac Gyratory Compactor Testing

All coarse and fine mixtures were compacted on the Servopac Gyratory Compactor at 1.25 and 2.5 degrees. The mixes were compacted to an N_{max} value of 174 gyrations, which corresponds to an N_{des} value of 109. The compaction curves for the two gyratory angles exhibited similar behavior up to the maximum gyratory shear stress. However, past the peak, the results differed drastically. The samples compacted at the 1.25-degree gyratory angle do not show a significant post-peak drop in gyratory shear strength, whereas the samples compacted at 2.5 degrees show a drastic post-peak drop. For this reason, the characteristics of the fine aggregate are more discernable, and therefore, the results presented are from the compaction data for a 2.5-degree angle of gyration. In all cases, similar trends were observed for a gyratory angle of 1.25 degrees, but to a lesser extent.

As expected, the effect of the fine aggregates is more prevalent in the fine asphalt mixtures than the coarse mixtures. For this reason, the results presented are from the compaction data of the fine asphalt mixtures, and, as stated above, a gyratory angle of 2.5 degrees. In most cases, similar trends were observed for the coarse mixtures. For some mixture parameters, no differentiation could be made between the course mixtures containing the different fine aggregates. This indicates that the coarse portion of the mixture overwhelms the effect of the fine aggregate.

Since the gyratory compaction characteristics of a mixture are dependent upon the material properties of the aggregates used in the mixtures, it is important to try to determine a relationship between these properties and the shear resistance of the mixture. These material properties may also give some insight as to how gyratory shear evolves during the compaction process. Toughness, as determined by L.A. abrasion and FAA, are the properties most associated with shear resistance of an asphalt mixture.

The Cabbage Grove and Chattahoochee fine aggregates are of interest when examining compaction. Because of breakdown encountered by these two fine aggregates during compaction, the aggregate gradation has changed and influenced the gyratory shear values. Since gradation was to be volumetrically the same for all fine-graded and coarse-graded mixtures, it is not possible to accurately examine the effects of these fine aggregates, and therefore, it is not acceptable to compare these mixtures to the other fine aggregate mixtures (Calera, White Rock, and Ruby) used in the Servopac testing.

Although the true meaning of the gyratory shear parameter is still unclear, it is generally used to evaluate asphalt mixtures. Figure 4-5 depicts the gyratory shear plot for the five fine aggregates tested. FAA of a fine aggregate is generally assumed to be a strong contributor to mixture shear strength. With the exception of Cabbage Grove and Chattahoochee due to breakdown, the gyratory shear strength of the other fine aggregate

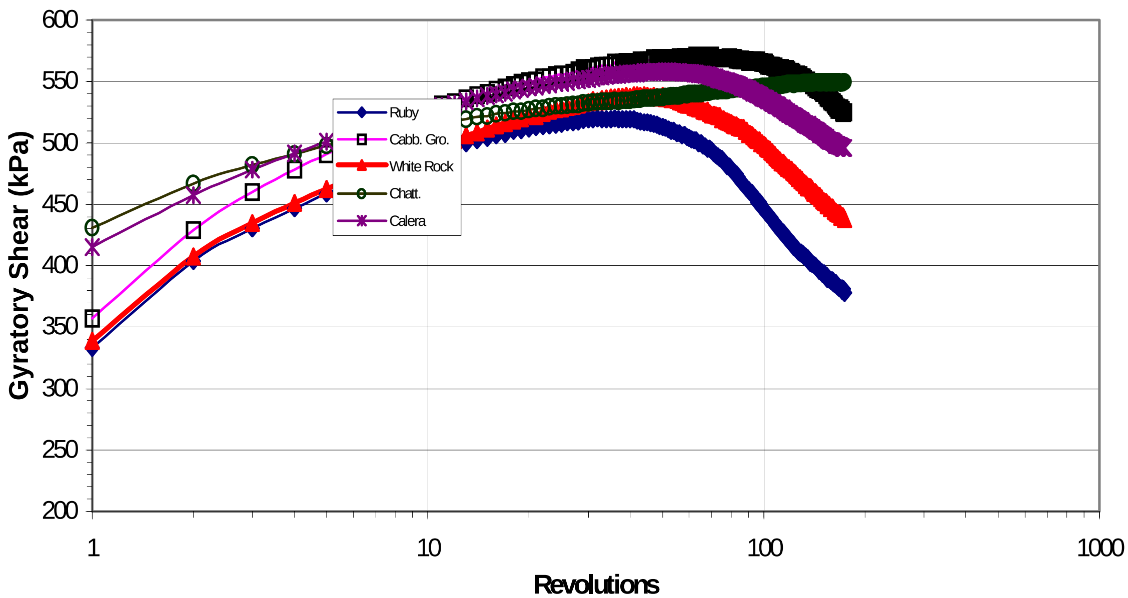


Figure 4-5 Gyratory Shear versus Revolutions for Fine Mixtures Compacted at 2.5 Degrees

mixtures was predicted by the direct shear strength and toughness of the fine aggregate and not the FAA. Therefore, the use of the FAA as a screening tool for the acceptance of fine aggregates must be seriously questioned.

Another compaction parameter examined was the gyratory shear at a specific level of VMA. A value of 14 percent was used to evaluate the mixtures in Figure 4-6. This value corresponds to the minimum percentage of VMA allowed for a 12.5-millimeter nominal mixture at N_{des} such as the mixtures presented in this study. Again, with the exception of Cabbage Grove and Chattahoochee, the mixture gyratory shear strength at 14 percent VMA was predicted by direct shear strength and toughness of the fine aggregate and not the FAA.

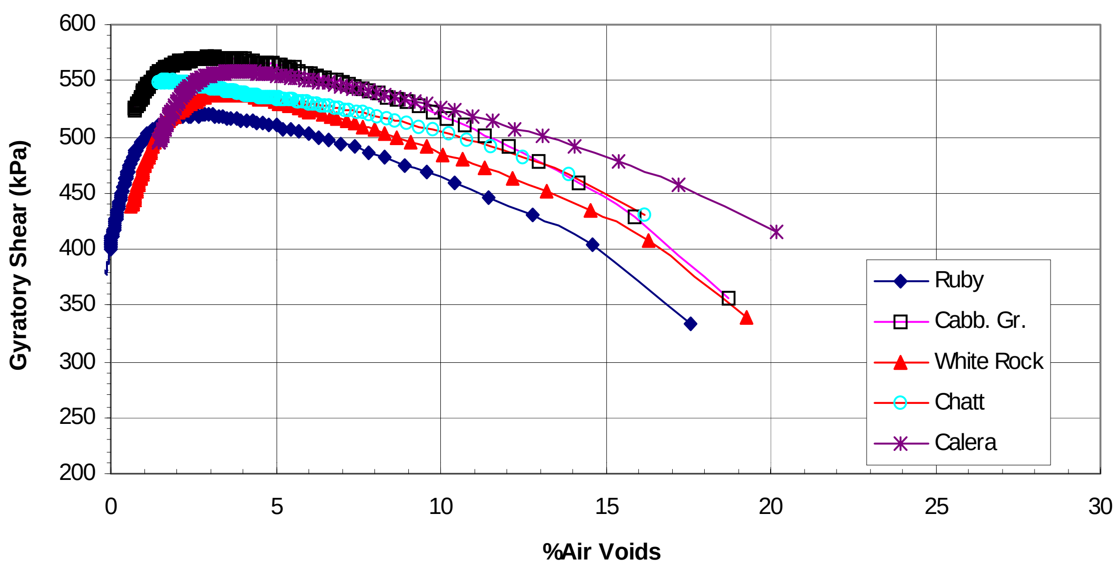


Figure 4-6 Gyratory Shear versus Air Voids for Fine Mixtures Compacted at 2.5 Degrees

It is still possible to evaluate compaction parameters, such as density during compaction, using all five fine aggregates tested. Some researchers have suggested that the slope of the density versus log revolutions plot can be used to assess mixture quality.

When analyzing Figure 4-6, the slope of the density curve for Cabbage Grove and Chattahoochee continue to increase throughout the compaction process while the slopes of Calera, White Rock, and Ruby seem to be leveling off and approaching zero.

This would suggest that Cabbage Grove and Chattahoochee are still undergoing densification at the end of the compaction cycle. This could be due to aggregate breakdown experienced by these two fine aggregates.

In summary, FAA did not relate to shear resistance of mixtures containing tough fine aggregates. Direct shear strength and toughness of the fine aggregates did measure the shear resistance of the mixture. Aggregate structure appears to be more important than surface texture of the fine aggregates incorporated in the asphalt mixtures.

4.3.3.1 Volumetric Strain

Since the compaction mold has a fixed diameter, volumetric strain is directly proportional to the height reduction of a mixture during the shear driven compaction process. Volumetric strain should be influenced by material properties such as FAA and direct shear strength. By analyzing the volumetric strain of a mixture during compaction, it may be possible to better assess mixture quality and stability.

In the first stage, the compaction is mostly volumetric in nature, where the particles are being pushed together into a closer arrangement until a point is reached where the particles are in full contact with each other (initial breakpoint). From this initial breakpoint forward (stage two), the primary compaction process is primarily shear driven and the reorientation of the particles is occurring. Stage two continues up to a point close to peak gyratory shear where the particles are in a preferred orientation. The increase in gyratory shear strength stabilizes, and the compaction curve starts to become increasingly nonlinear, due to the greatly increased aggregate effects. Beyond peak gyratory shear is stage three where a decrease in gyratory shear is usually observed. This decrease in gyratory shear is usually associated with instability.

The state of Illinois currently uses the locking point concept (Vavrick et al., 1999) to prevent over-compaction in the SuperPave™ gyratory compactor. The "locking point" is defined as the first gyration in which three gyrations are at the same height preceded by two sets of two gyrations at the same height. The locking point is the first of those three consecutive height gyrations. Gyrations beyond this point exhibit the deviation from linearity in the densification curve. The locking point is a preferred orientation of the aggregate due to compaction and it is assumed that further compaction beyond this point will result in aggregate breakdown or shear failure of the mixture. All mixtures lock up, but at different void and gyration levels.

The use of the locking point concept may make it possible to analyze the volumetric strain of a mixture in a different manner. Volumetric strain after the locking point could be analyzed to determine a mixtures ability to resist shear. Another approach is to determine the amount of area under the volumetric strain curve. The area under this curve is related the amount of energy required to compact a particular mixture. By determining the amount of area before and after the locking point, the energy used in compaction could be separated from the energy used in distortion of the mixture, which is a measure of shear resistance.

The area under the strain curve may give an indication as to the amount of energy required to compact a mixture using the gyratory compactor. In this analysis, the locking point was used as the point in compaction where a "critical condition" exists. Any additional load beyond the critical condition could result in shear failure of the mixture.

Mixtures with a higher strain tolerance, and therefore, more area under the volumetric strain curve are able to redistribute this additional load and avoid failure.

The area under the strain curve (Figure 4-6) for each mixture tested was determined. Table 4-16 shows the calculated areas (energy) for each mixture. Figure 4-7 shows the area after the locking point versus the LA loss. As the LA loss increases the area decreases. This appears to indicate that the tougher material undergoes more energy

Table 4-16 Areas Under Volumetric Strain Curve for Fine Mixtures

Mixture	Area Before Locking Point	Area After Locking Point
Chattahoochee	620	1590
Cabbage Grove	1012	1717
Ruby	790	1986
White Rock	882	2017
Calera	1029	1905

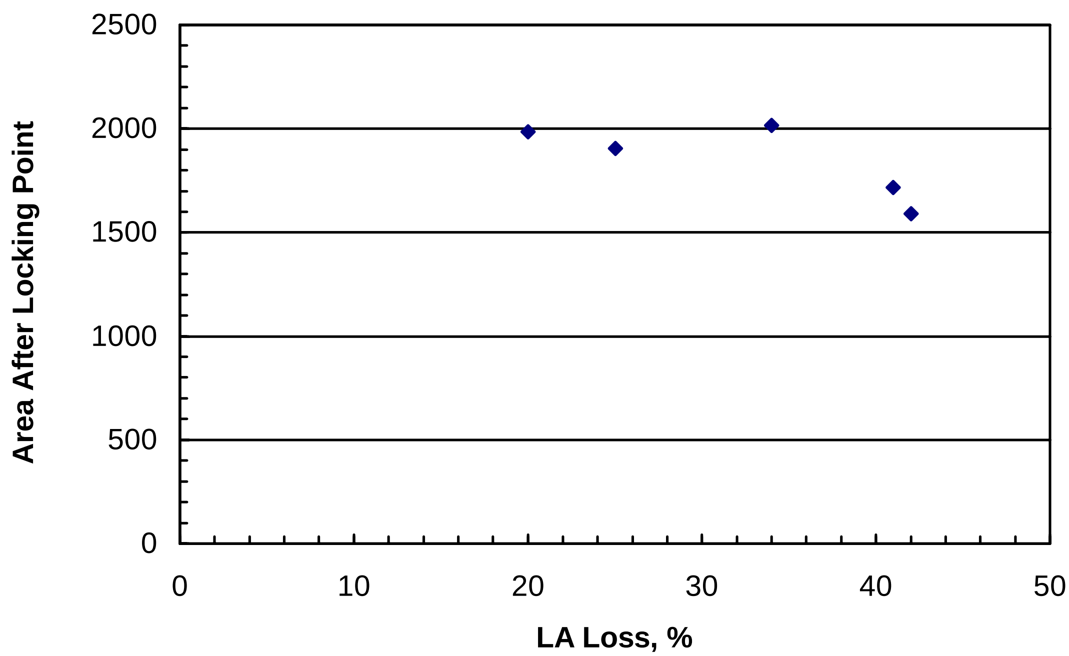


Figure 4-7 Area Under the Volumetric Strain After Locking Point versus LA Loss

to peak shear strength. Based on this data, it could be that area under the curve at 2.5 degrees appears to reflect on the degree of aggregate breakdown during compaction in the Servopac.

4.3.4 Asphalt Pavement Analyzer (APA) Test

Rutting tests were performed on the APA for each coarse-graded and fine-graded aggregate containing the five different fine aggregates. Two replicates of each mixture were tested in the APA. Figure 4-8 shows the results of the APA testing for the fine asphalt mixtures only.

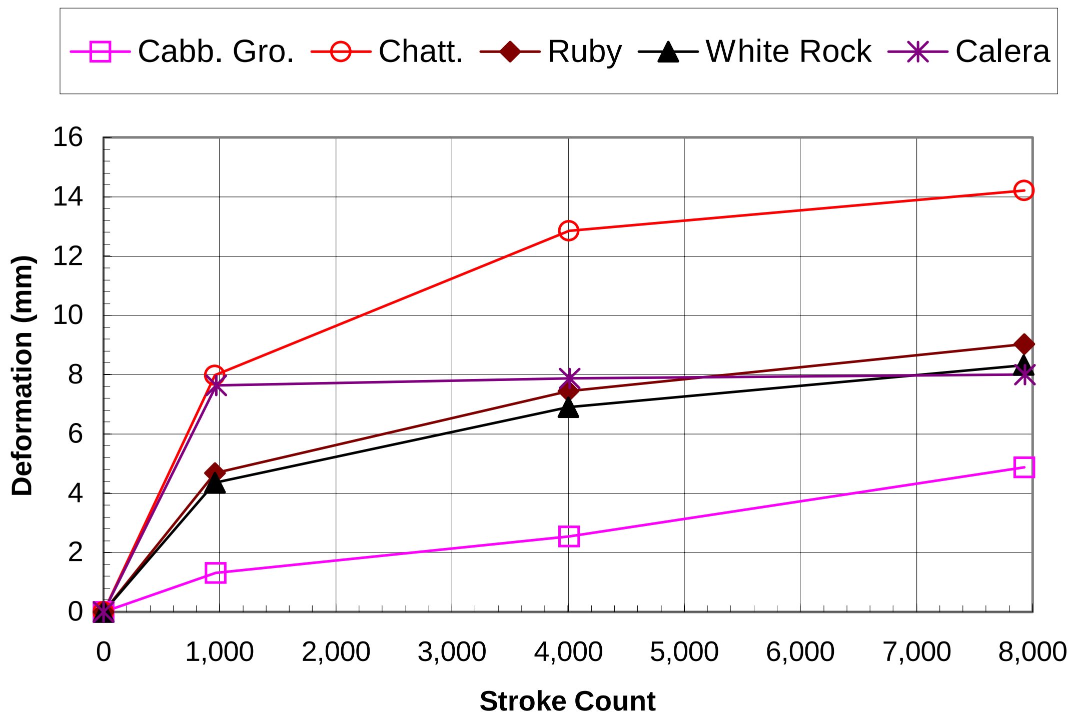


Figure 4-8 Rutting Results from the Asphalt Pavement Analyzer for Fine Mixtures Compacted at 1.25 Degrees

The fine mixture containing the Chattahoochee fine aggregate rutted excessively. The fine asphalt mixtures rutted slightly more than the coarse mixtures, but the effect of fine aggregate type on rutting was the same. Therefore, only the results for the fine graded mixtures are presented since these mixtures more clearly represent the effect of the different fine aggregates. These results agree with DST results, toughness, and known field performance. A possible explanation for the low rutting of the Cabbage Grove mixture may be high FAA. Aggregate degradation could lead to a lower effective asphalt content resulting in a stiffer mixture, and thus, lower rutting potential. Fine-graded Cabbage Grove mixtures also exhibited low VMA, which may also contribute to low rutting.

The rutting in APA versus FAA (Figure 4-9) shows that White Rock and Calera, which have low FAA have performed adequately even though FAA less than 45. This could be because of high toughness (LA loss<35%). But, Chattahoochee has performed

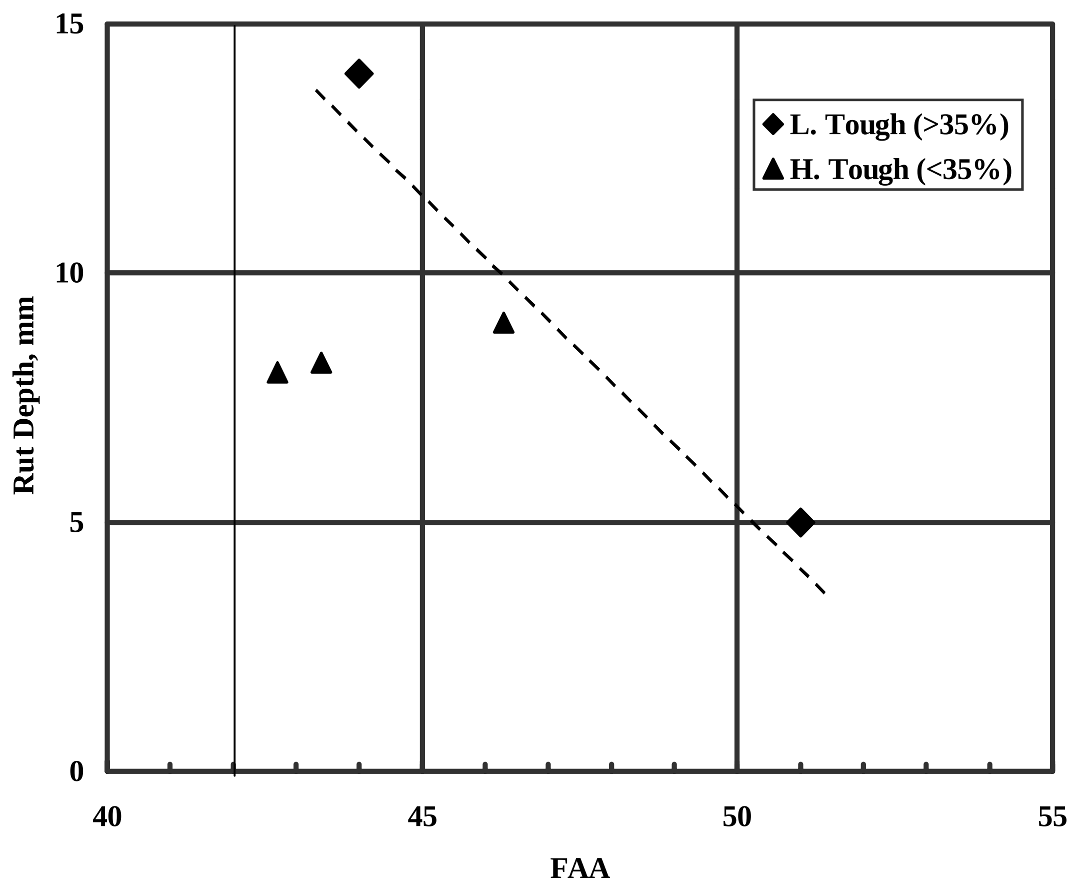


Figure 4-9 Rut Depth versus FAA

poorly in the APA and this could be because of low FAA (<45) and low toughness (LA loss>35%). Cabbage Grove on the other hand has a very low toughness, but a high FAA (51) and has performed well in the APA. Therefore, based on the limited testing conducted, toughness and FAA, both should be part of the acceptance criteria of fine aggregates**.**

4.4 Summary of Findings

Based on the testing conducted, the following are the findings:

1. For aggregates with rough texture (FAA greater than 50), the mixture rutting performance may be adequate.
2. For aggregates with intermediate texture (for FAA greater than 42 and less than 50), the toughness of the aggregate should be part of the acceptance criteria:
    a. for LA Loss > 35%, the mixture rutting performance may be adequate;
    b. for LA Loss < 35%, the mixture rutting performance may not be adequate.
3. For aggregates with smooth texture (FAA less than 42), the fine aggregate may not be adequate.

CHAPTER 5
CLOSURE

5.1 Overview

Nine fine aggregates that encompassed a fairly broad range of material type, angularity, texture, gradation, and toughness, were used in this investigation to evaluate the FAA test and its relationship to fine aggregate direct shear strength (DST) and past performance. Out of these nine fine aggregates, five were selected to evaluate the effect of aggregate properties on rutting resistance of mixture.

5.2 Summary of Findings

Based on the test conducted on fine aggregates the findings are summarized below:

1. FAA as measured from Method A generally yielded lower FAA results than Method B; Method C was lower than both the methods. All methods resulted in the same relative ranking of FAA among the nine aggregates tested.
2. For the range of fine aggregate gradations typical of those used in SuperPave™ asphalt mixtures, gradation appeared to have a relatively small effect on FAA. Furthermore, all three gradations appeared to result in the same relative FAA rankings for the fine aggregates tested. In general, but not in all cases, the more uniform gradations (Gradations A and 3) resulted in slightly greater FAA values.
3. FAA was most strongly related to the surface texture of the fine aggregates tested. Particle shape (angularity), gradation, and aggregate type also affected FAA but to a much lesser degree. FAA did not correlate well with fine aggregate shear strength. Although FAA, as well as visual ratings of particle shape and texture was found to

have some influence on shear strength, aggregate toughness and gradation had a dominant effect on shear strength that overwhelmed the effect of FAA.

4. The aggregate breakdown observed in the Servopac correlated well with the LA loss of the parent rock rather than that of the modified LA loss values on the fine aggregate portion. For example, Chattachoochee that showed breakdown in the Servopac had high LA loss in the parent rock but lower LA loss on the modified LA abrasion test in on the fine aggregate (percent passing no. 8 sieve) portion of the stockpile. The LA loss values on the parent rock were used for further analysis.
5. Direct Shear Tests (DST) appeared to correlate well with toughness as measured by LA loss on the parent rock. But the strength results appeared to be more variable than FAA results. It was determined that very careful specimen preparation procedures are required to achieve consistent DST results. The specimen preparation procedures presented in the ASTM standard for this test do not include sufficient detail to assure consistent results with fine granular materials similar to those used in asphalt mixtures. The specimen preparation procedure identified in this study appeared to provide consistent DST results.
6. The Asphalt Pavement Analyzer test results show that the mixtures that have low FAA (FAA < 45) and high toughness (LA loss<35%) have performed reasonably well. This could be because even though material has poor interlocking, it derives its shear strength from the toughness of the material. On the other hand the mixture with high FAA and very low toughness performed well in the APA. The low toughness aggregates breakdown easily, but if they can have a good interlock and the break down is accounted for in the design, the mixture may perform well. Finally, the

mixtures containing aggregates with low FAA and high LA loss (low toughness) have performed poorly in the APA. This was expected because they over-compacted due to breakdown and had poor interlocking.

7. The area under the volumetric strain curve after aggregate lock was also examined. This area is related to the amount of energy required to compact a mixture; the more area indicates the greater the energy required. A calculation of the areas revealed that the low toughness aggregates had less area under the volumetric strain curve. These results also suggest that mixtures with more area exhibit a greater strain tolerance, which may allow the mixture to redistribute a loading under "critical conditions" and avoid shear failure. The analysis involving these volumetric strain parameters appear to give some insight as to the role of fine aggregate properties on mixture performance, but further research is needed.

5.3 Conclusions

Based on the above findings, the following conclusions were made:

1. FAA appears to correlate with particle texture rather than particle shape.
2. The gradation appears have a slight effects on FAA as compared to method and material type.
3. Toughness or direct shear strength in addition to FAA appears to be a better indicator of accepting fine aggregates to evaluate shear resistance of mixtures.
4. A performance test is needed to evaluate mixtures.

5.4 Recommendations

Based on the findings and conclusions the following recommendations were made:

1. Relax the current FAA criteria from 45 to 42. Between 42 and 50, require a toughness requirement of LA loss less than 35 percent. Waive the toughness requirement if FAA is greater than 50.
2. Reject the blend consisting of different source aggregates, if:
   a. the FAA of the blend is less than 45; and
   b. the LA loss of any of the individual component is greater than 35 percent.
3. Develop a performance test to evaluate rutting resistance of mixtures.

A recent study conducted at TTI (Chowdhury et al. 2001) showed that the FAA test method does not consistently identify angular, cubical aggregates as high quality-materials. FAA values of some cubical crushed limestones fell below 45. Some high-quality fine aggregates with good field performance history did not meet the SuperPave™ criteria for the FAA for using in surface course for heavy traffic. A fair correlation was observed between the compacted aggregate resistance value and the angle of internal friction from the direct shear tests. No correlation was found between FAA and CAR stability or between FAA and AIF. Some cubical, crushed, calcareous aggregates with FAA values from 42.6 to 44.6 gave high values of CAR stability, AIF, and K-index. The APA sub-study indicated that FAA was not sensitive to rut resistance of HMA mixtures. Further, certain fine aggregates with a FAA value lower than 45 or even lower than 43, but with relatively high particle surface texture, would produce mixtures with relatively good rut resistance.

The three-year research effort has complimented and supplemented the findings from studies conducted by ICAR that the FAA is a measure of texture rather than angularity and FAA criterion alone is not sufficient to evaluate aggregates with poor rut resistance. This study shows that toughness measure coupled with FAA may be required for intermediate FAA values.

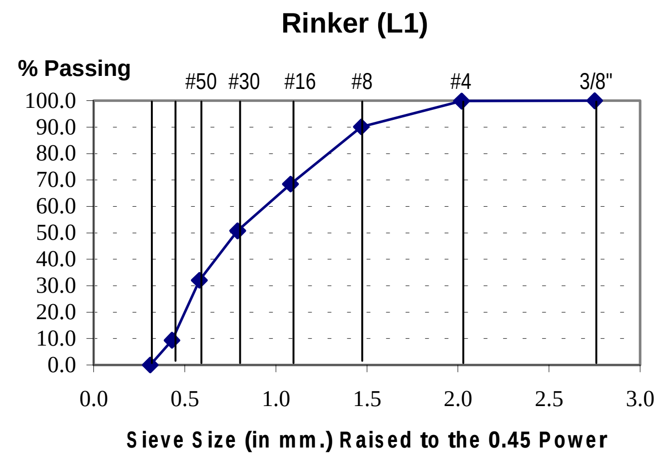
APPENDIX A
AS-RECEIVED GRADATION OF MATERIALS TESTED

Rinker (L1)

(87090)

Sample #	Oven-dry Weight [gr.]	Washed Oven-dry Weight [gr.]	Percent finer than # 200 [%]
A	602.4	581.3	3.5027
B	595.2	577	3.0578
		Avg. =	**3.2802**

Sieve #	Sieve Size [mm]	Sieve Size in mm raised to .45 power	Sample A Retained Weight [gr.]	Sample B Retained Weight [gr.]	A+B Retained Weight [gr.]	Passing Weight [gr.]	% Passing [%]
3/8"	9.500	2.8	0.0	0.0	0.0	1154.5	100.0
4	4.750	2.0	0.6	0.8	1.4	1153.1	99.9
8	2.360	1.5	42.9	70.1	113.0	1040.1	90.1
16	1.180	1.1	102.3	148.0	250.3	789.8	68.4
30	0.600	0.8	98.8	104.3	203.1	586.7	50.8
50	0.300	0.6	117.5	98.7	216.2	370.5	32.1
100	0.150	0.4	154.5	108.3	262.8	107.7	9.3
200	0.075	0.3	62.2	45.5	107.7	0.0	0.0
		Total	578.8	575.7	1154.5		
<200			2.3	1.2			
		TOTAL	581.1	576.9			



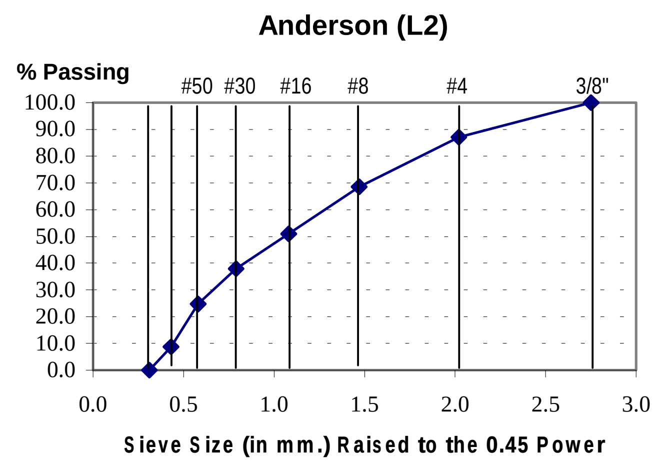
"As-received" Gradation of Rinker (L1)

Anderson (L2)

(29361)

Sample #	Oven-dry Weight [gr.]	Washed Oven-dry Weight [gr.]	Percent finer than # 200 [%]
A	566.7	541.5	4.4468
B	585.3	559.9	4.3397
		Avg. =	**4.3932**

Sieve #	Sieve Size [mm]	Sieve Size in mm raised to .45 power	Sample A Retained Weight [gr.]	Sample B Retained Weight [gr.]	A+B Retained Weight [gr.]	Passing Weight [gr.]	% Passing [%]
3/8"	9.500	2.8	0.0	0.0	0.0	1095.3	100.0
4	4.750	2.0	70.3	71.4	141.7	953.6	87.1
8	2.360	1.5	103.1	99.6	202.7	750.9	68.6
16	1.180	1.1	96.1	97.1	193.2	557.7	50.9
30	0.600	0.8	69.6	73.0	142.6	415.1	37.9
50	0.300	0.6	69.5	75.0	144.5	270.6	24.7
100	0.150	0.4	83.5	91.1	174.6	96.0	8.8
200	0.075	0.3	46.7	49.3	96.0	0.0	0.0
		Total	538.8	556.5	1095.3		
<200			2.7	3.5			
		TOTAL	541.5	560.0			



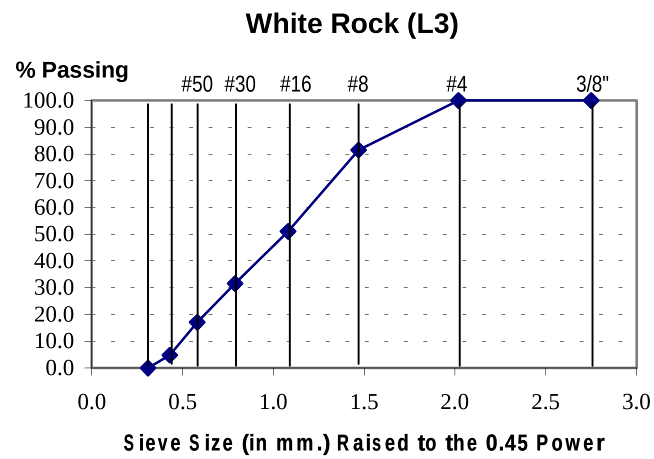
"As-received" Gradation of Anderson (L2)

White Rock (L3)

(87339)

Sample #	Oven-dry Weight [gr.]	Washed Oven-dry Weight [gr.]	Percent finer than # 200 [%]
A	505.2	491.7	2.6722
B	565.5	547.7	3.1477
		Avg. =	**2.9099**

Sieve #	Sieve Size [mm]	Sieve Size in mm raised to .45 power	Sample A Retained Weight [gr.]	Sample B Retained Weight [gr.]	A+B Retained Weight [gr.]	Passing Weight [gr.]	% Passing [%]
3/8"	9.500	2.8	0.0	0.0	0.0	1036.2	100.0
4	4.750	2.0	0.0	0.0	0.0	1036.2	100.0
8	2.360	1.5	111.1	80.6	191.7	844.5	81.5
16	1.180	1.1	164.8	150.2	315.0	529.5	51.1
30	0.600	0.8	90.7	111.8	202.5	327.0	31.6
50	0.300	0.6	59.0	90.9	149.9	177.1	17.1
100	0.150	0.4	45.7	81.1	126.8	50.3	4.9
200	0.075	0.3	18.8	31.5	50.3	0.0	0.0
		Total	490.1	546.1	1036.2		
<200			1.4	1.7			
		TOTAL	491.5	547.8			



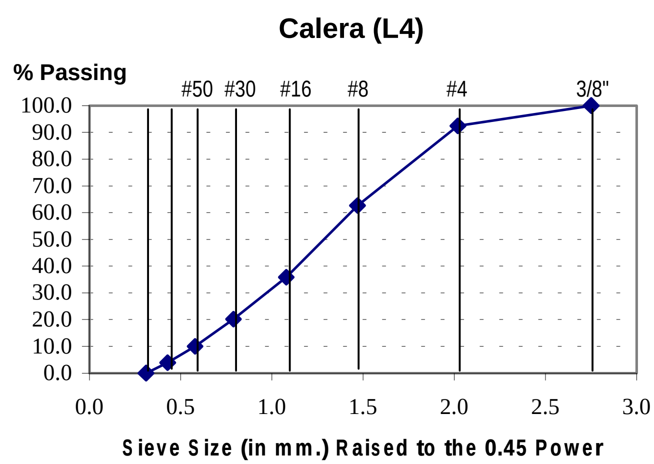
"As-received" Gradation of White Rock (L3)

Calera (L4)

(AL149)

Sample #	Oven-dry Weight [gr.]	Washed Oven-dry Weight [gr.]	Percent finer than # 200 [%]
A	544.8	484.5	11.068
B	525.4	469.4	10.659
		Avg. =	**10.863**

Sieve #	Sieve Size [mm]	Sieve Size in mm raised to .45 power	Sample A Retained Weight [gr.]	Sample B Retained Weight [gr.]	A+B Retained Weight [gr.]	Passing Weight [gr.]	% Passing [%]
3/8"	9.500	2.8	0.0	0.0	0.0	947.6	100.0
4	4.750	2.0	36.6	35.9	72.5	875.1	92.3
8	2.360	1.5	139.9	142.1	282.0	593.1	62.6
16	1.180	1.1	127.9	125.1	253.0	340.1	35.9
30	0.600	0.8	77.6	72.1	149.7	190.4	20.1
50	0.300	0.6	50.2	45.6	95.8	94.6	10.0
100	0.150	0.4	30.3	27.3	57.6	37.0	3.9
200	0.075	0.3	19.3	17.7	37.0	0.0	0.0
		Total	481.8	465.8	947.6		
<200			2.3	3.3			
		TOTAL	484.1	469.1			



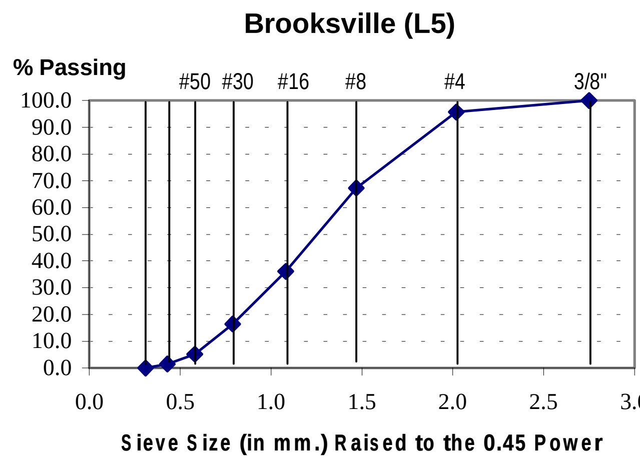
"As-received" Gradation of Calaera (L4)

Brooksville (L5)

(08012)

Sample #	Oven-dry Weight [gr.]	Washed Oven-dry Weight [gr.]	Percent finer than # 200 [%]
A	543	509.1	6.2431
B	579.2	538	7.1133
		Avg. =	**6.6782**

Sieve #	Sieve Size [mm]	Sieve Size in mm raised to .45 power	Sample A Retained Weight [gr.]	Sample B Retained Weight [gr.]	A+B Retained Weight [gr.]	Passing Weight [gr.]	% Passing [%]
3/8"	9.500	2.8	0.0	0.0	0.0	1044.8	100.0
4	4.750	2.0	24.3	21.0	45.3	999.5	95.7
8	2.360	1.5	147.5	149.4	296.9	702.6	67.2
16	1.180	1.1	169.5	155.2	324.7	377.9	36.2
30	0.600	0.8	99.8	105.9	205.7	172.2	16.5
50	0.300	0.6	47.3	70.1	117.4	54.8	5.2
100	0.150	0.4	13.6	25.8	39.4	15.4	1.5
200	0.075	0.3	6.3	9.1	15.4	0.0	0.0
		Total	508.3	536.5	1044.8		
<200			0.8	1.3			
		TOTAL	509.1	537.8			



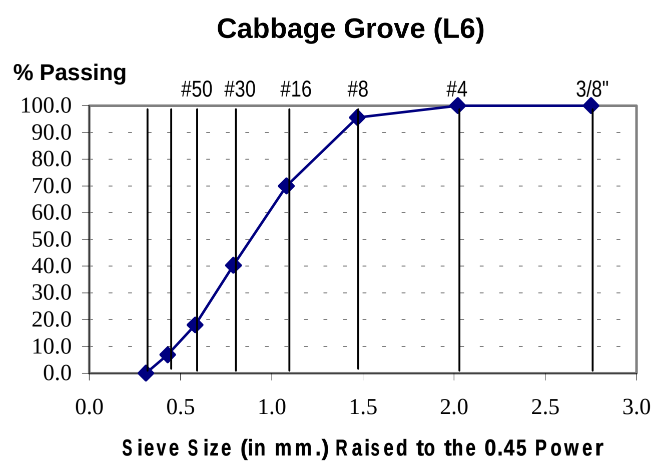
"As-received" Gradation of Brooksville (L5)

Cabbage Grove (L6)

(38036)

Sample #	Oven-dry Weight [gr.]	Washed Oven-dry Weight [gr.]	Percent finer than # 200 [%]
A	546.8	533.3	2.4689
B	548.2	536.2	2.1890
		Avg. =	**2.3289**

Sieve #	Sieve Size [mm]	Sieve Size in mm raised to .45 power	Sample A Retained Weight [gr.]	Sample B Retained Weight [gr.]	A+B Retained Weight [gr.]	Passing Weight [gr.]	% Passing [%]
3/8"	9.500	2.8	0.0	0.0	0.0	1049.2	100.0
4	4.750	2.0	0.3	0.1	0.4	1048.8	100.0
8	2.360	1.5	23.3	23.2	46.5	1002.3	95.5
16	1.180	1.1	137.7	130.1	267.8	734.5	70.0
30	0.600	0.8	153.9	158.3	312.2	422.3	40.2
50	0.300	0.6	111.8	121.2	233.0	189.3	18.0
100	0.150	0.4	58.4	59.5	117.9	71.4	6.8
200	0.075	0.3	37.3	34.1	71.4	0.0	0.0
		Total	522.7	526.5	1049.2		
<200			10.4	9.5			
		TOTAL	533.1	536.0			



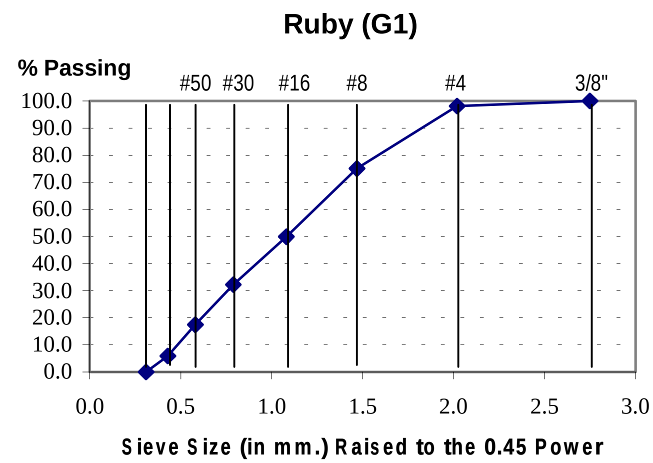
"As-received" Gradation of Cabbage Grove (L6)

Ruby (G1)

(GA185)

Sample #	Oven-dry Weight [gr.]	Washed Oven-dry Weight [gr.]	Percent finer than # 200 [%]
A	534.0	511.7	4.1760
B	519.6	500.6	3.6567
		Avg. =	**3.9163**

Sieve #	Sieve Size [mm]	Sieve Size in mm raised to .45 power	Sample A Retained Weight [gr.]	Sample B Retained Weight [gr.]	A+B Retained Weight [gr.]	Passing Weight [gr.]	% Passing [%]
3/8"	9.500	2.8	0.0	0.0	0.0	1004.1	100.0
4	4.750	2.0	10.0	9.1	19.1	985.0	98.1
8	2.360	1.5	119.0	112.0	231.0	754.0	75.1
16	1.180	1.1	126.2	126.9	253.1	500.9	49.9
30	0.600	0.8	88.3	89.5	177.8	323.1	32.2
50	0.300	0.6	74.5	74.0	148.5	174.6	17.4
100	0.150	0.4	59.1	56.6	115.7	58.9	5.9
200	0.075	0.3	30.9	28.0	58.9	0.0	0.0
		Total	508	496.1	1004.1		
<200			3.9	4.7			
		TOTAL	511.9	500.8			



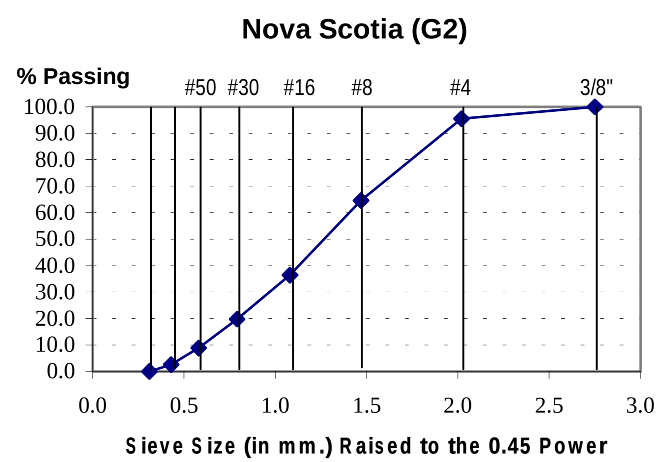
"As-received" Gradation of Ruby (G1)

Nova Scotia (G2)

(NS315)

Sample #	Oven-dry Weight [gr.]	Washed Oven-dry Weight [gr.]	Percent finer than # 200 [%]
A	560	537.8	3.9643
B	579	557.5	3.7133
		Avg. =	**3.8388**

Sieve #	Sieve Size [mm]	Sieve Size in mm raised to .45 power	Sample A Retained Weight [gr.]	Sample B Retained Weight [gr.]	A+B Retained Weight [gr.]	Passing Weight [gr.]	% Passing [%]
3/8"	9.500	2.8	0.0	0.0	0.0	1092.5	100.0
4	4.750	2.0	23.6	26.0	49.6	1042.9	95.5
8	2.360	1.5	151.8	185.6	337.4	705.5	64.6
16	1.180	1.1	155.3	152.9	308.2	397.3	36.4
30	0.600	0.8	95.0	86.4	181.4	215.9	19.8
50	0.300	0.6	61.6	57.8	119.4	96.5	8.8
100	0.150	0.4	34.8	33.2	68.0	28.5	2.6
200	0.075	0.3	14.5	14.0	28.5	0.0	0.0
		Total	536.6	555.9	1092.5		
<200			1.4	1.8			
		TOTAL	538.0	557.7			

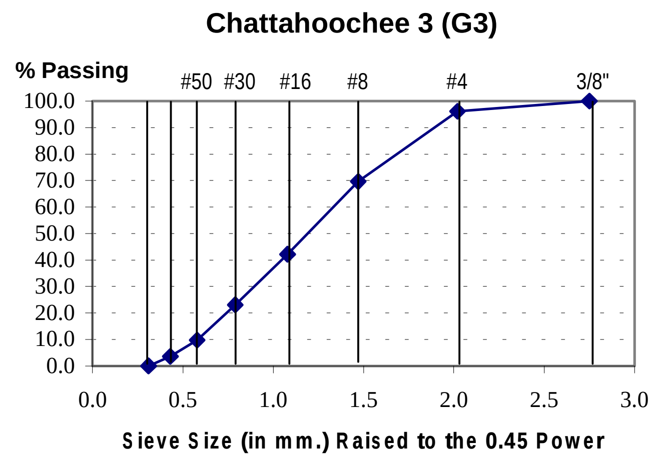


"As-received" Gradation of Nova Scotia (G2)

Chattahoochee 3 (G3)

Sample #	Oven-dry Weight [gr.]	Washed Oven-dry Weight [gr.]	Percent finer than # 200 [%]
A	588.7	570.9	3.0236
B	662.3	636.9	3.8351
		Avg. =	**3.4294**

Sieve #	Sieve Size [mm]	Sieve Size in mm raised to .45 power	Sample A Retained Weight [gr.]	Sample B Retained Weight [gr.]	A+B Retained Weight [gr.]	Passing Weight [gr.]	% Passing [%]
3/8"	9.500	2.8	0.0	0.0	0.0	1200.7	100.0
4	4.750	2.0	29.2	17.3	46.5	1154.2	96.1
8	2.360	1.5	179.0	139.1	318.1	836.1	69.6
16	1.180	1.1	168.2	162.0	330.2	505.9	42.1
30	0.600	0.8	99.8	129.1	228.9	277.0	23.1
50	0.300	0.6	56.5	103.4	159.9	117.1	9.8
100	0.150	0.4	22.1	52.6	74.7	42.4	3.5
200	0.075	0.3	13.8	28.6	42.4	0.0	0.0
		Total	568.6	632.1	1200.7		
<200			2.5	5			
		TOTAL	571.1	637.1			



"As-received" Gradation of Chattahoochee 3 (G3)

APPENDIX B
UNCOMPACTED VOID CONTENTS OF FINE AGGREGATES (FAA) TESTED USING ALL METHODS AND GRADATIONS

	Gradation	Sample A Weight [g.]	Sample B Weight [g.]	Relative Error [%]	Avg. [g.]	[---Uncompacted Voids (FAA)---] Sample A [%]	Sample B [%]	**Avg. [%]**
Gradation 1	G-1	137.1	137.7	0.4	137.4	44.7	44.5	**44.6**
Method A:	G-A	133.2	133.8	0.5	133.5	46.3	46.0	**46.2**
Gradation 3:	G-3	130.5	131.3	0.6	130.9	47.4	47.1	**47.2**
	Ret.in #16	119.8	119.7	0.1	119.8	51.7	51.7	51.7
	Ret.in #30	115.5	115.2	0.3	115.4	53.4	53.5	53.5
	Ret.in #50	120.6	120.8	0.2	120.7	51.4	51.3	51.3
Method B:				Avg.=	118.6			**52.2**
Method C:	as-received	140.1	141.0	0.6	140.6	43.5	43.1	**43.3**
Method C(W):	washed	142.7	143.4	0.5	143.1	42.5	42.2	**42.3**

Rinker (L1)

	Gradation	Sample A Weight [g.]	Sample B Weight [g.]	Relative Error [%]	Avg. [g.]	[---Uncompacted Voids (FAA)---] Sample A [%]	Sample B [%]	**Avg. [%]**
Gradation 1	G-1	125.2	125.9	0.6	125.6	44.8	44.5	**44.7**
Method A:	G-A	122.7	122.1	0.5	122.4	45.9	46.2	**46.1**
Gradation 3:	G-3	121.6	122.2	0.5	121.9	46.4	46.2	**46.3**
	Ret.in #16	107.3	108.2	0.8	107.8	52.7	52.3	52.5
	Ret.in #30	109.8	110.3	0.5	110.1	51.6	51.4	51.5
	Ret.in #50	113.2	112.2	0.9	112.7	50.1	50.6	50.4
Method B:				Avg.=	110.167			**51.5**
Method C:	as-received	134.9	135.5	0.4	135.2	40.6	40.3	**40.4**
Method C(W):	washed	139.1	139.0	0.1	139.1	38.7	38.8	**38.7**

Anderson (L2)

	Gradation	Sample A Weight [g.]	Sample B Weight [g.]	Relative Error [%]	Avg. [g.]	[---Uncompacted Voids (FAA)---] Sample A [%]	Sample B [%]	**Avg. [%]**
Gradation 1	G-1	143.6	143.6	0.0	143.6	42.1	42.1	**42.1**
Method A:	G-A	139.0	138.5	0.4	138.8	44.0	44.2	**44.1**
Gradation 3:	G-3	139.1	138.7	0.3	138.9	43.9	44.1	**44.0**
	Ret.in #16	127.3	128.5	0.9	127.9	48.7	48.2	48.4
	Ret.in #30	123.9	124.4	0.4	124.2	50.0	49.8	49.9
	Ret.in #50	127.2	126.2	0.8	126.7	48.7	49.1	48.9
Method B:				Avg.=	126.25			**49.1**
Method C:	as-received	149.0	149.4	0.3	149.2	39.9	39.8	**39.8**
Method C(W):	washed	149.0	149.9	0.6	149.5	39.9	39.6	**39.7**

White Rock (L3)

						Uncompacted Voids (FAA)		
	Gradation	Sample A Weight [g.]	Sample B Weight [g.]	Relative Error [%]	Avg. [g.]	Sample A [%]	Sample B [%]	**Avg. [%]**
Gradation 1	G-1	148.9	148.8	0.1	148.9	41.8	41.9	**41.9**
Method A:	G-A	145.6	144.6	0.7	145.1	43.1	43.5	**43.3**
Gradation 3:	G-3	146.3	146.3	0.0	146.3	42.9	42.9	**42.9**
	Ret.in #16	137.5	138.5	0.7	138.0	46.3	45.9	46.1
	Ret.in #30	132.7	131.8	0.7	132.3	48.2	48.5	48.3
	Ret.in #50	127.6	127.9	0.2	127.8	50.2	50.0	50.1
Method B:				Avg.=	132.667			**48.2**
Method C:	as-received	159.2	159.9	0.4	159.6	37.8	37.5	**37.7**
Method C(W):	washed	157.9	157.3	0.4	157.6	38.3	38.6	**38.4**

Calera (L4)

						Uncompacted Voids (FAA)		
	Gradation	Sample A Weight [g.]	Sample B Weight [g.]	Relative Error [%]	Avg. [g.]	Sample A [%]	Sample B [%]	**Avg. [%]**
Gradation 1	G-1	139.6	140.8	0.9	140.2	41.1	40.6	**40.8**
Method A:	G-A	137.8	137.9	0.1	137.9	41.9	41.8	**41.8**
Gradation 3:	G-3	139	140.2	0.9	139.6	41.4	40.8	**41.1**
	Ret.in #16	127.9	128.5	0.5	128.2	46.0	45.8	45.9
	Ret.in #30	126.1	126.2	0.1	126.2	46.8	46.8	46.8
	Ret.in #50	124.7	125.2	0.4	125.0	47.4	47.2	47.3
Method B:				Avg.=	126.433			**46.7**
Method C:	as-received	138.8	139.7	0.6	139.3	41.4	41.1	**41.2**
Method C(W):	washed	145.9	145.8	0.1	145.9	38.4	38.5	**38.5**

Brooksville (L5)

						Uncompacted Voids (FAA)		
	Gradation	Sample A Weight [g.]	Sample B Weight [g.]	Relative Error [%]	Avg. [g.]	Sample A [%]	Sample B [%]	**Avg. [%]**
Gradation 1	G-1	128.0	128.1	0.1	128.1	50.0	50.0	**50.0**
Method A:	G-A	123.3	123.1	0.2	123.2	51.8	51.9	**51.9**
Gradation 3:	G-3	125.5	125.5	0.0	125.5	51.0	51.0	**51.0**
	Ret.in #16	116.3	116.7	0.3	116.5	54.6	54.4	54.5
	Ret.in #30	112.5	112.6	0.1	112.6	56.1	56.0	56.0
	Ret.in #50	113.0	113.2	0.2	113.1	55.9	55.8	55.8
Method B:				Avg.=	114.05			**55.4**
Method C:	as-received	140.6	140.5	0.1	140.6	45.1	45.1	**45.1**
Method C(W):	washed	127.3	126.3	0.8	126.8	50.3	50.7	**50.5**

Cabbage Grove (L6)

						[---Uncompacted Voids (FAA)---]		
		Sample A	Sample B	Relative	Avg.	Sample A	Sample B	**Avg.**
	Gradation	Weight [g.]	Weight [g.]	Error [%]	[g.]	[%]	[%]	**[%]**
Gradation 1	G-1	146.6	145.5	0.8	146.1	45.3	45.7	**45.5**
Method A:	G-A	142.0	142.2	0.1	142.1	47.0	46.9	**47.0**
Gradation 3:	G-3	143.4	144.2	0.6	143.8	46.5	46.2	**46.3**
	Ret.in #16	133.8	134.3	0.4	134.1	50.1	49.9	50.0
	Ret.in #30	128.9	130.1	0.9	129.5	51.9	51.5	51.7
	Ret.in #50	125.5	124.5	0.8	125.0	53.2	53.5	53.4
Method B:				Avg.=	129.517			**51.7**
Method C:	as-received	155.0	155.5	0.3	155.3	42.2	42.0	**42.1**
Method C(W):	washed	157.9	158.7	0.5	158.3	41.1	40.8	**40.9**

Ruby (G1)

						[---Uncompacted Voids (FAA)---]		
		Sample A	Sample B	Relative	Avg.	Sample A	Sample B	**Avg.**
	Gradation	Weight [g.]	Weight [g.]	Error [%]	[g.]	[%]	[%]	**[%]**
Gradation 1	G-1	155.3	155.1	0.1	155.2	41.6	41.7	**41.7**
Method A:	G-A	149.8	150.2	0.3	150.0	43.7	43.5	**43.6**
Gradation 3:	G-3	152.9	153	0.1	153.0	42.5	42.5	**42.5**
	Ret.in #16	141.1	141.0	0.1	141.1	47.0	47.0	47.0
	Ret.in #30	136.4	137.2	0.6	136.8	48.7	48.4	48.6
	Ret.in #50	135.3	135.6	0.2	135.5	49.1	49.0	49.1
Method B:				Avg.=	137.767			**48.2**
Method C:	as-received	163.1	163.4	0.2	163.3	38.7	38.6	**38.6**
Method C(W):	washed	159.5	160.7	0.8	160.1	40.0	39.6	**39.8**

Nova Scotia (G2)

						[---Uncompacted Voids (FAA)---]		
		Sample A	Sample B	Relative	Avg.	Sample A	Sample B	**Avg.**
	Gradation	Weight [g.]	Weight [g.]	Error [%]	[g.]	[%]	[%]	**[%]**
Gradation 1	G-1	144.5	143.9	0.4	144.2	44.4	44.7	**44.5**
Method A:	G-A	144.4	144.7	0.2	144.6	44.5	44.3	**44.4**
Gradation 3:	G-3	147.9	147.9	0.0	147.9	43.1	43.1	**43.1**
	Ret.in #16	142.6	142.1	0.4	142.4	45.2	45.3	45.3
	Ret.in #30	132.7	133.2	0.4	133.0	49.0	48.8	48.9
	Ret.in #50	128.6	128.6	0.0	128.6	50.5	50.5	50.5
Method B:				Avg.=	134.633			**48.2**
Method C:	as-received	164.4	163.1	0.8	163.8	36.8	37.3	**37.0**
Method C(W):	washed	161.3	160.8	0.3	161.1	38.0	38.2	**38.1**

Chattahoochee 3 (G3)

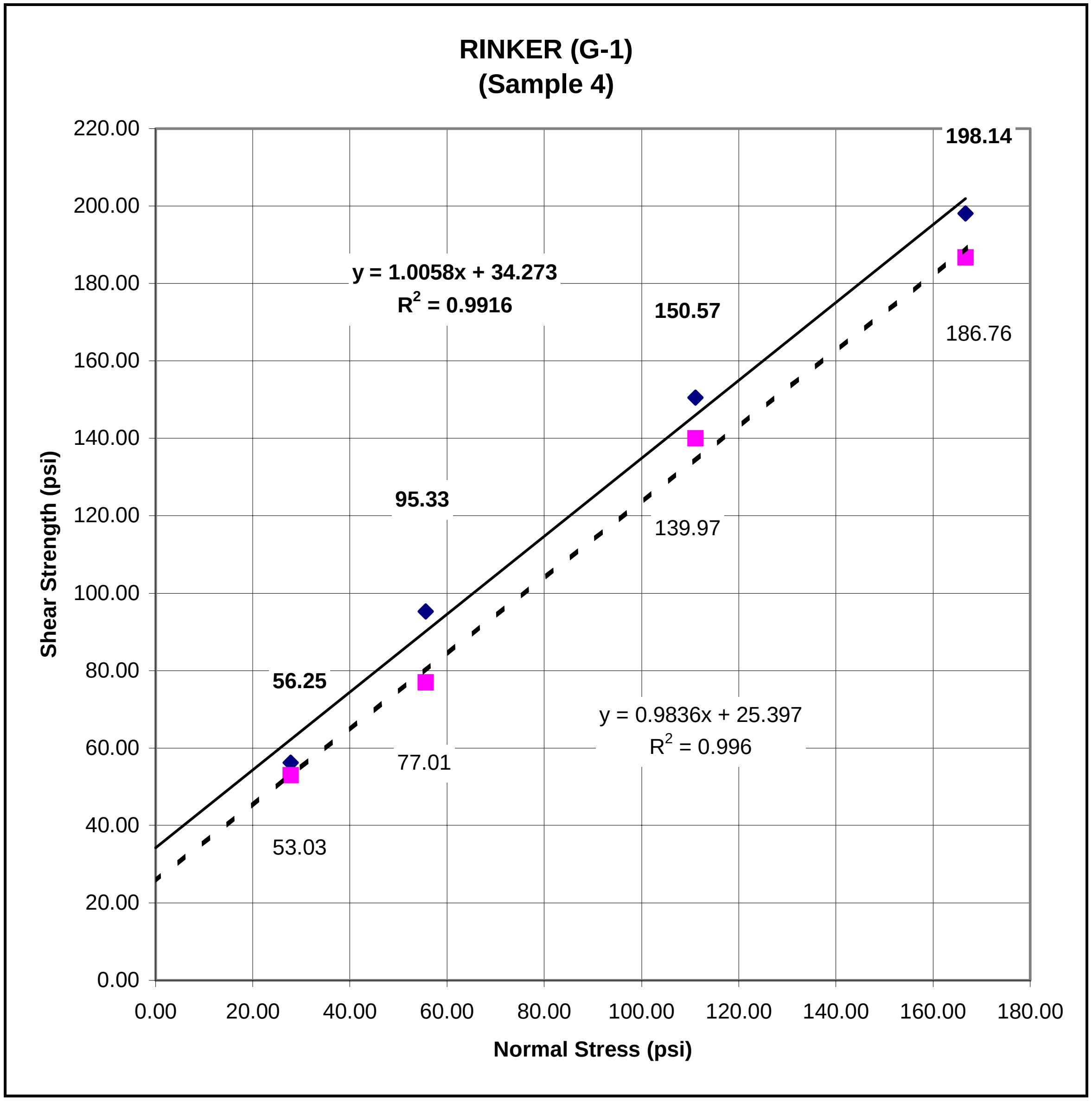
APPENDIX C
STRENGTH ENVELOPE FROM DIRECT SHEAR TEST (DST) OF MATERIALS TESTED

Material: **RINKER (G-1)**
(Sample 4)

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**56.25**	53.03
272.70	55.55	**95.33**	77.01
545.40	111.11	**150.57**	139.97
818.10	166.66	**198.14**	186.76
	Angle of Int. Frict. =	**45.17**	44.53
	C =	**34.27**	25.40

Note:
G-1 refers to Gradation 1, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	71.5	28.5
#30	50	50
#50	27.5	72.5
#100	0	100

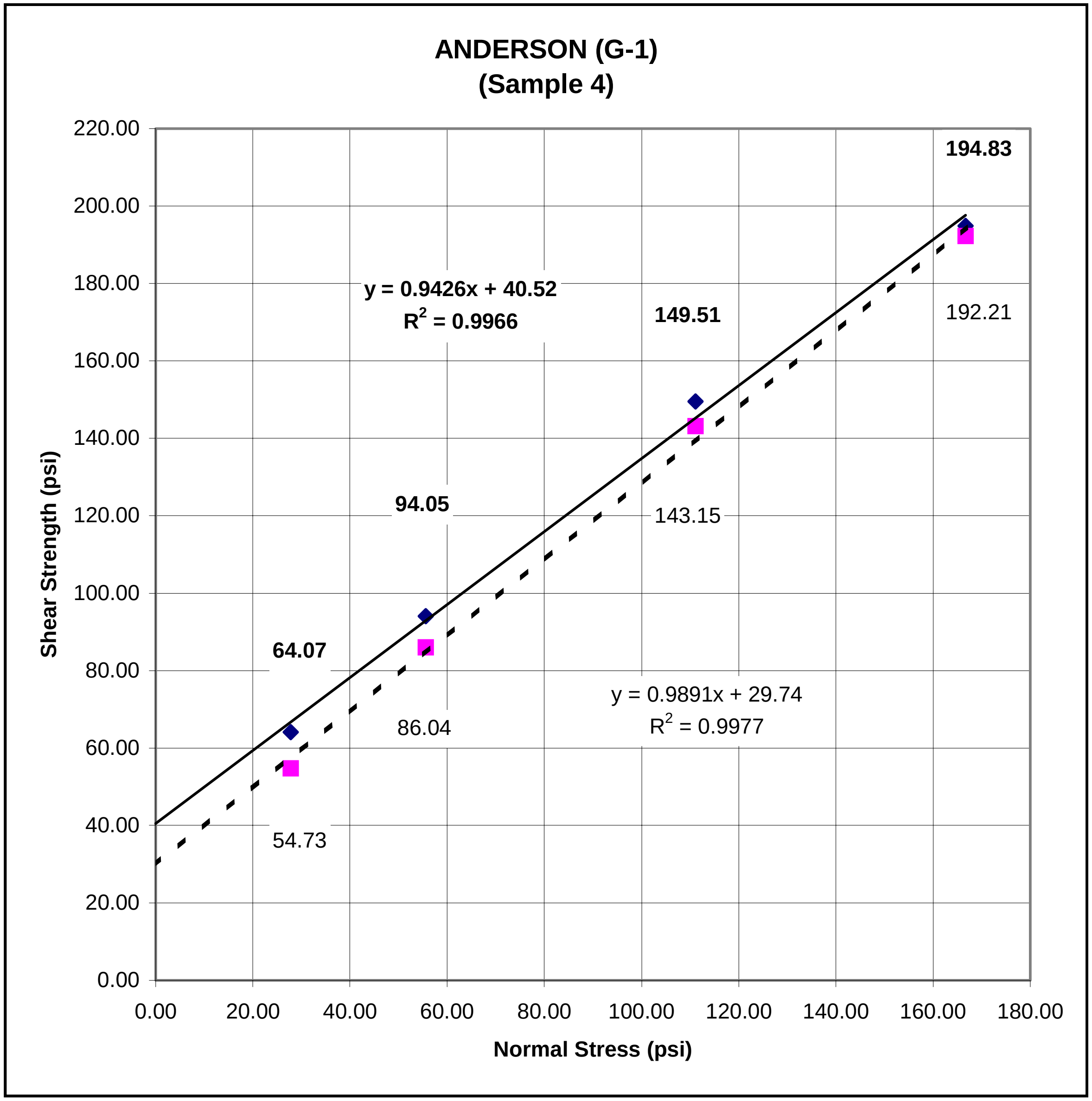


Material: **ANDERSON (G-1) (Sample 4)**

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**64.07**	54.73
272.70	55.55	**94.05**	86.04
545.40	111.11	**149.51**	143.15
818.10	166.66	**194.83**	192.21
	Angle of Int. Frict. =	**43.31**	44.69
	C =	**40.52**	29.74

Note:
G-1 refers to Gradation 1, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	71.5	28.5
#30	50	50
#50	27.5	72.5
#100	0	100

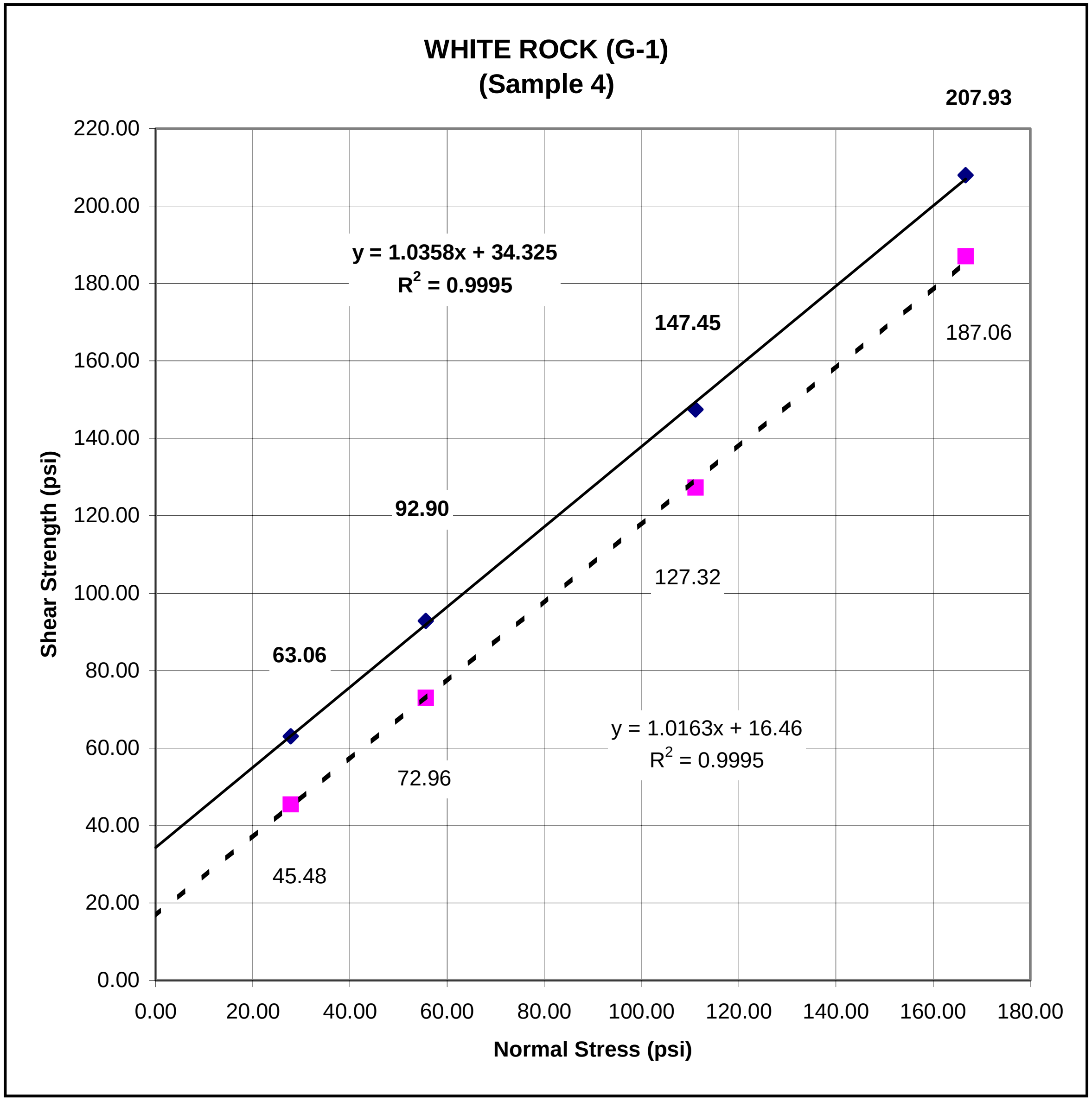


Material: **WHITE ROCK (G-1) (Sample 4)**

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**63.06**	45.48
272.70	55.55	**92.90**	72.96
545.40	111.11	**147.45**	127.32
818.10	166.66	**207.93**	187.06
	Angle of Int. Frict. =	**46.01**	45.46
	C =	**34.33**	16.46

Note:
G-1 refers to Gradation 1, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	71.5	28.5
#30	50	50
#50	27.5	72.5
#100	0	100



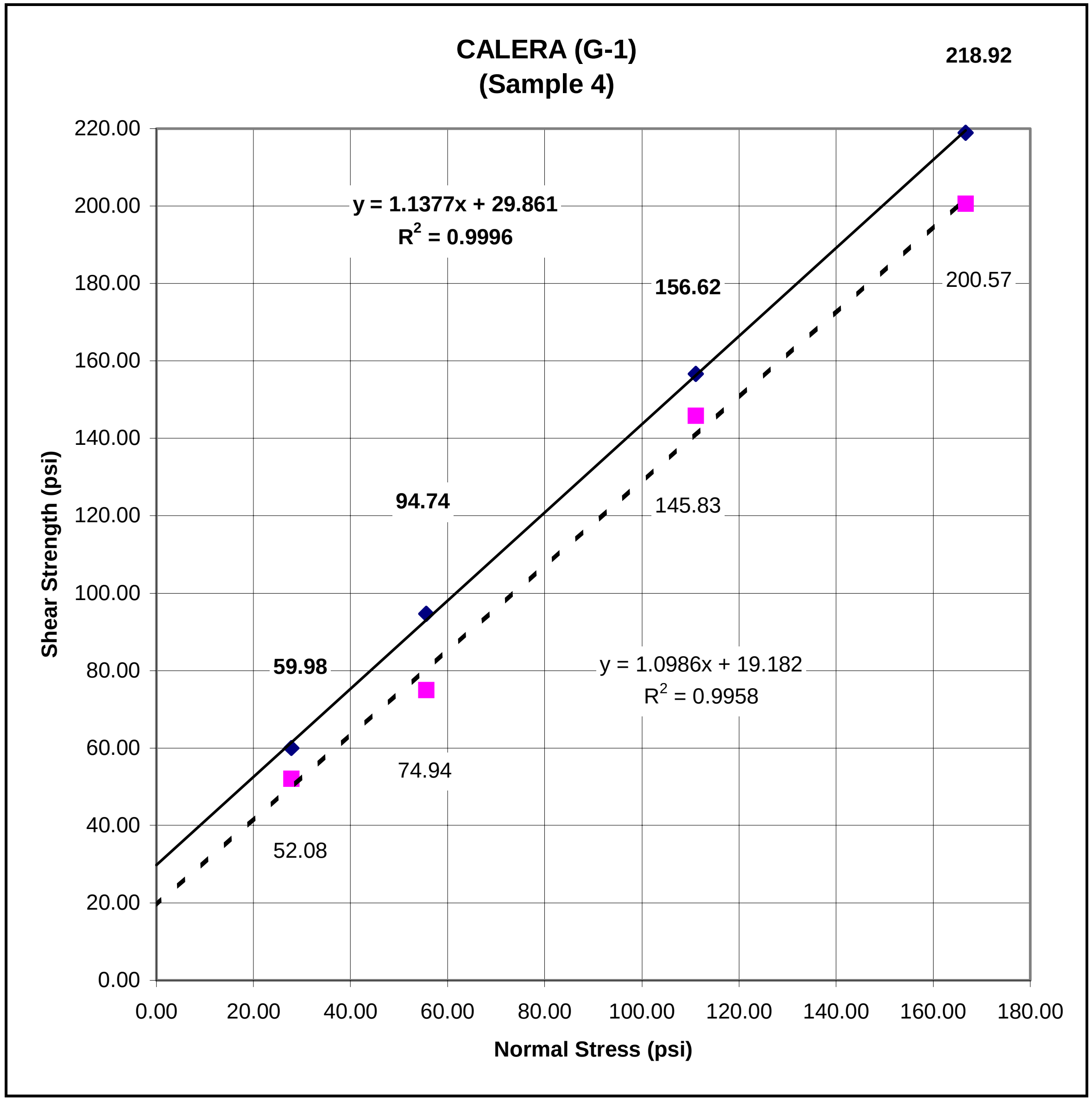
Material: **CALERA (G-1)**
(Sample 4)

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**59.98**	52.08
272.70	55.55	**94.74**	74.94
545.40	111.11	**156.62**	145.83
818.10	166.66	**218.92**	200.57

Angle of Int. Frict. =	**48.69**	47.69
C =	**29.86**	19.18

Note:
G-1 refers to Gradation 1, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	71.5	28.5
#30	50	50
#50	27.5	72.5
#100	0	100

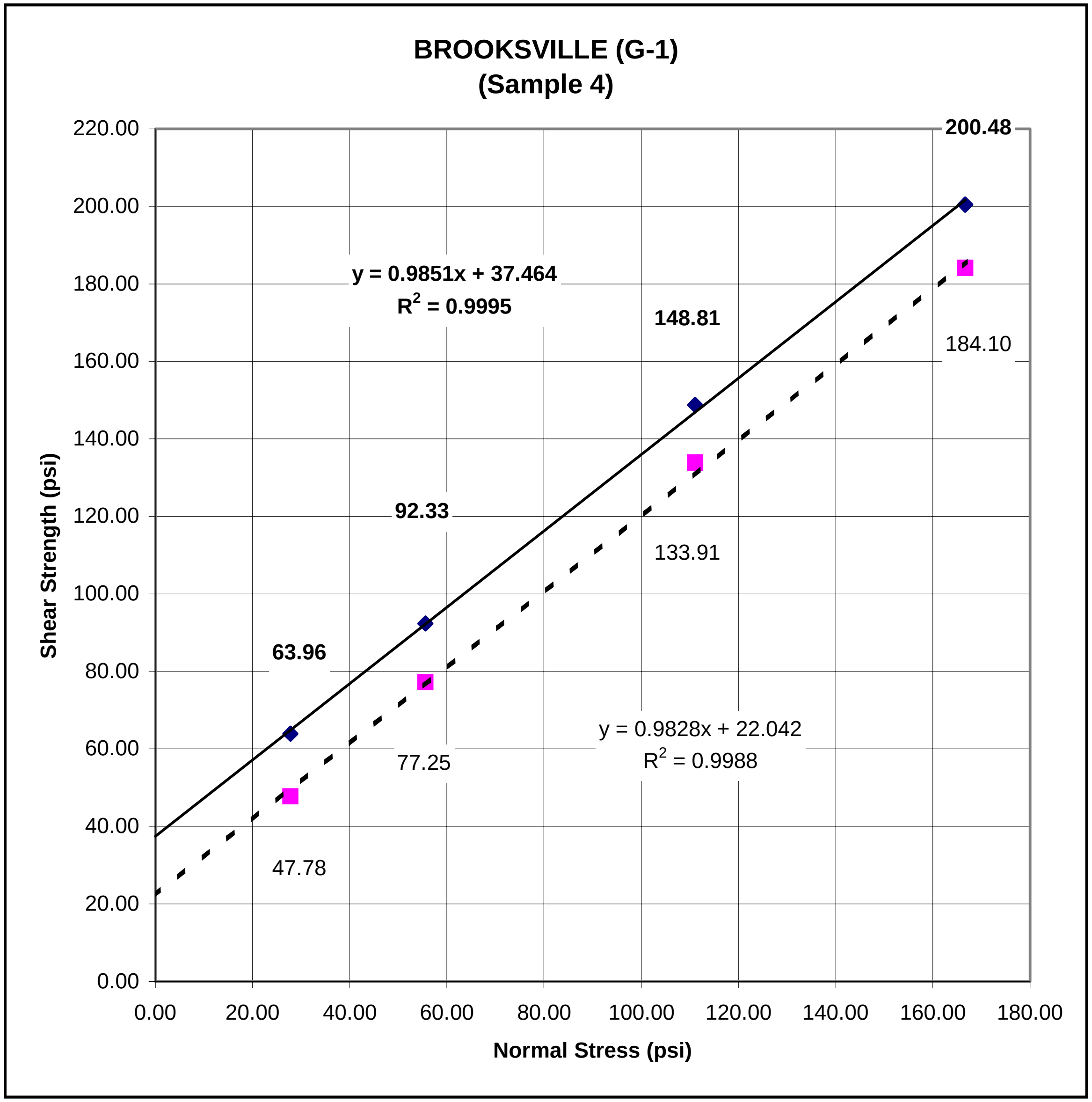


Material: **BROOKSVILLE (G-1)**
(Sample 4)

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**63.96**	47.78
272.70	55.55	**92.33**	77.25
545.40	111.11	**148.81**	133.91
818.10	166.66	**200.48**	184.10
	Angle of Int. Frict. =	**44.57**	44.50
	C =	**37.46**	22.04

Note:
G-1 refers to Gradation 1, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	71.5	28.5
#30	50	50
#50	27.5	72.5
#100	0	100

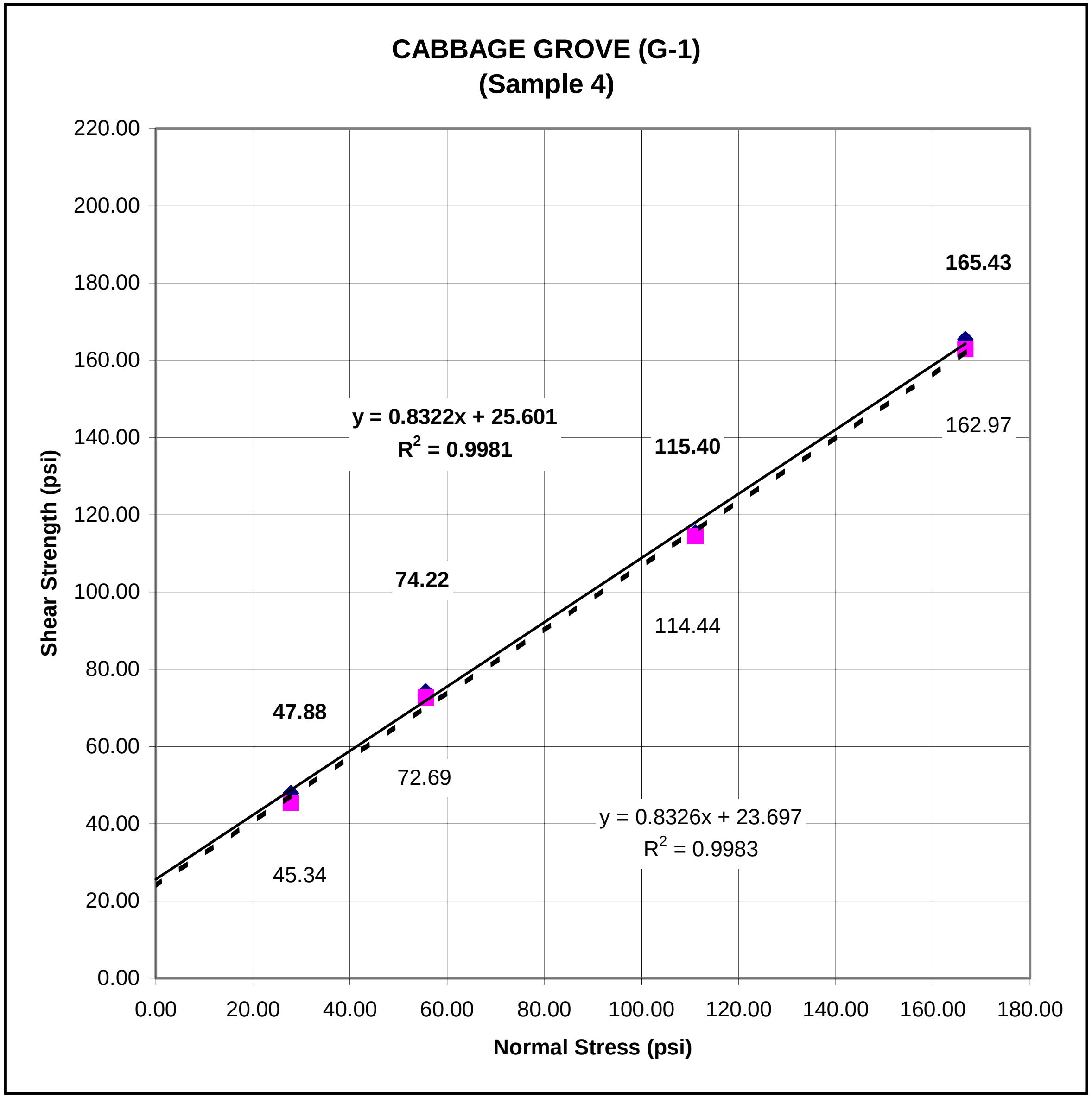


Material: **CABBAGE GROVE (G-1) (Sample 4)**

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**47.88**	45.34
272.70	55.55	**74.22**	72.69
545.40	111.11	**115.40**	114.44
818.10	166.66	**165.43**	162.97
	Angle of Int. Frict. =	**39.77**	39.78
	C =	**25.60**	23.70

Note:
G-1 refers to Gradation 1, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	71.5	28.5
#30	50	50
#50	27.5	72.5
#100	0	100

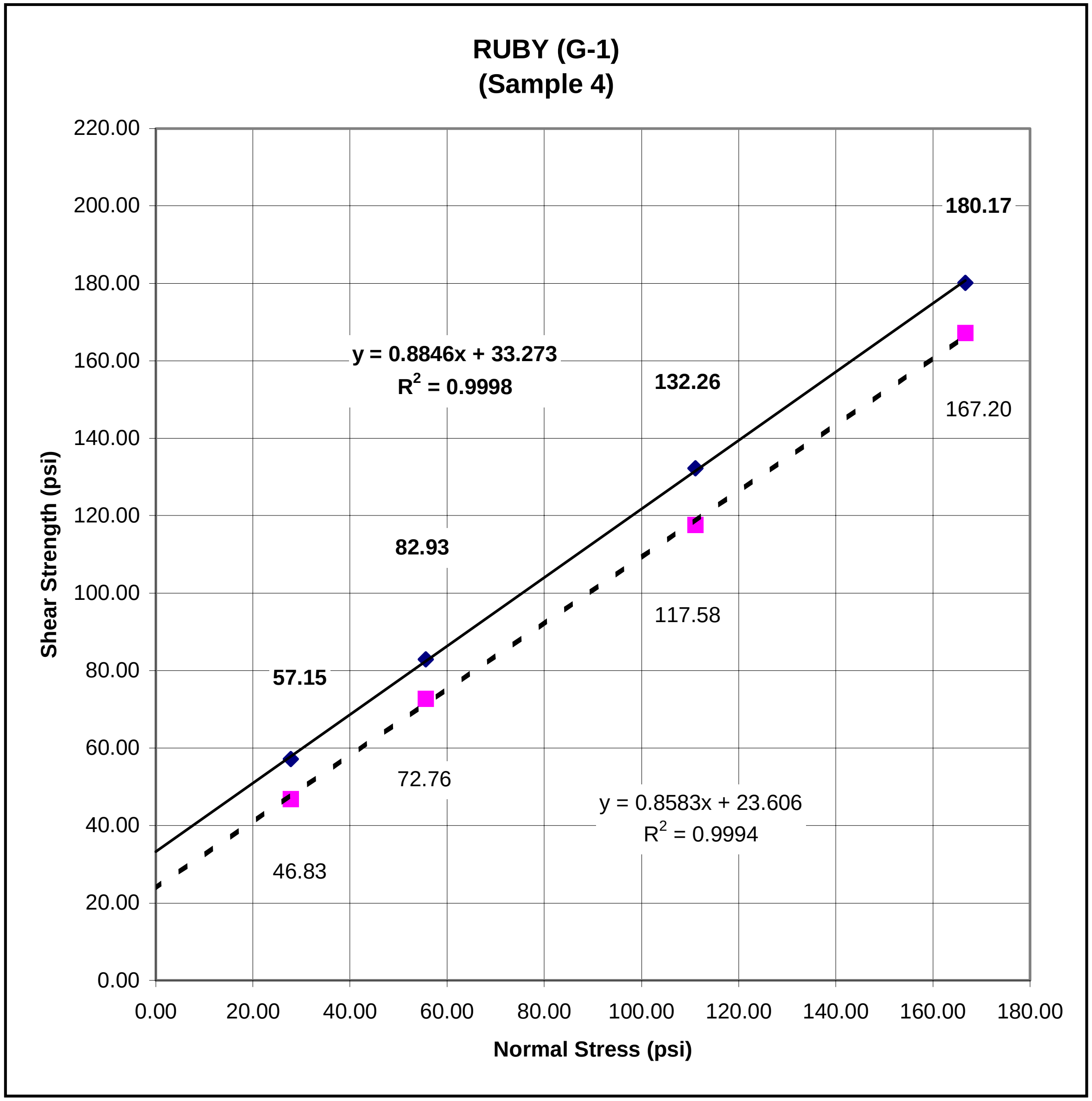


Material: **RUBY (G-1)**
(Sample 4)

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**57.15**	46.83
272.70	55.55	**82.93**	72.76
545.40	111.11	**132.26**	117.58
818.10	166.66	**180.17**	167.20
	Angle of Int. Frict. =	**41.50**	33.27
	C =	**33.27**	23.61

Note:
G-1 refers to Gradation 1, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	71.5	28.5
#30	50	50
#50	27.5	72.5
#100	0	100



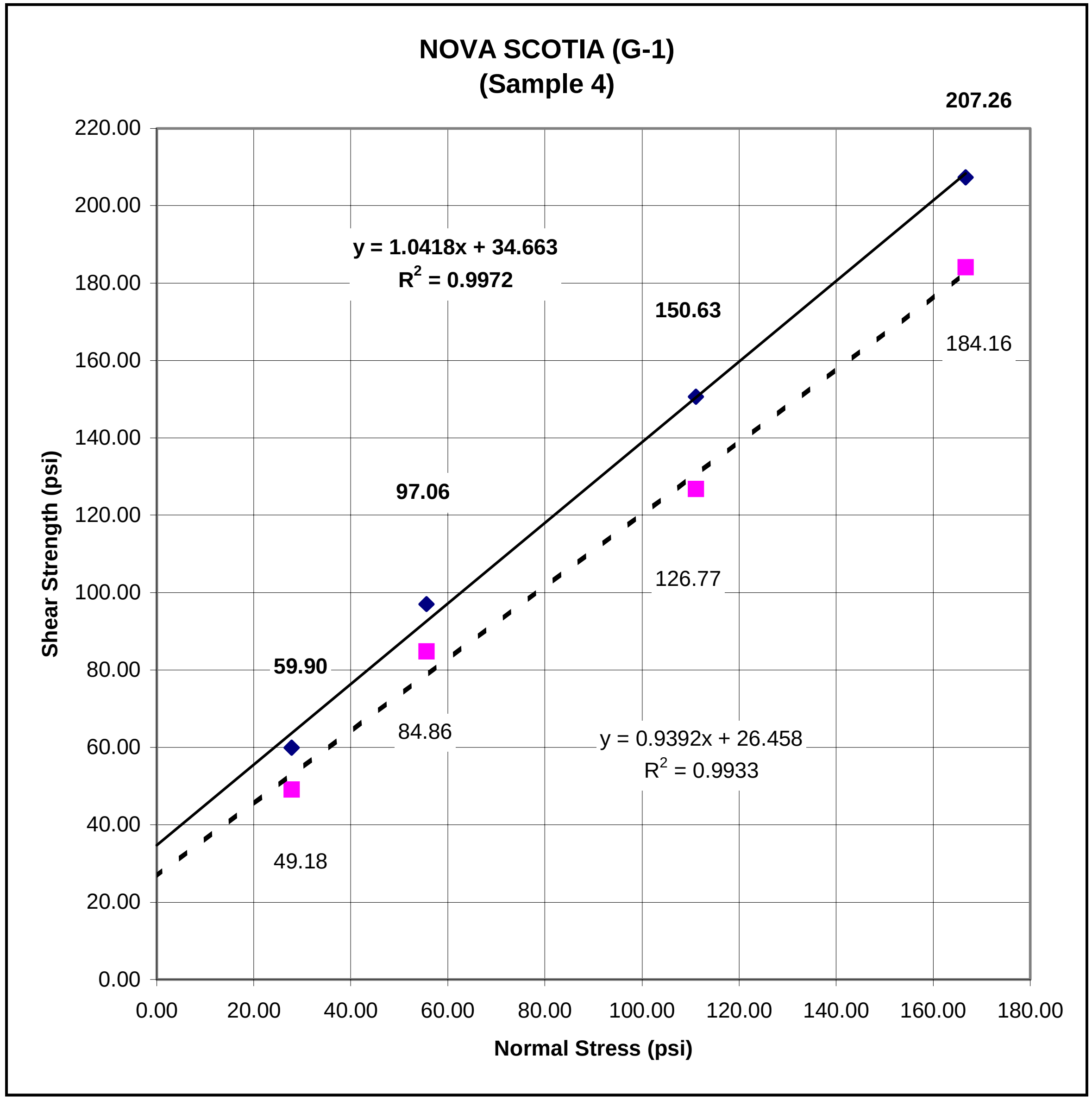
Material: **NOVA SCOTIA (G-1)**
(Sample 4)

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**59.90**	49.18
272.70	55.55	**97.06**	84.86
545.40	111.11	**150.63**	126.77
818.10	166.66	**207.26**	184.16

Angle of Int. Frict. =		**45.42**	43.20
C =		**34.67**	26.46

Note:
G-1 refers to Gradation 1, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	71.5	28.5
#30	50	50
#50	27.5	72.5
#100	0	100



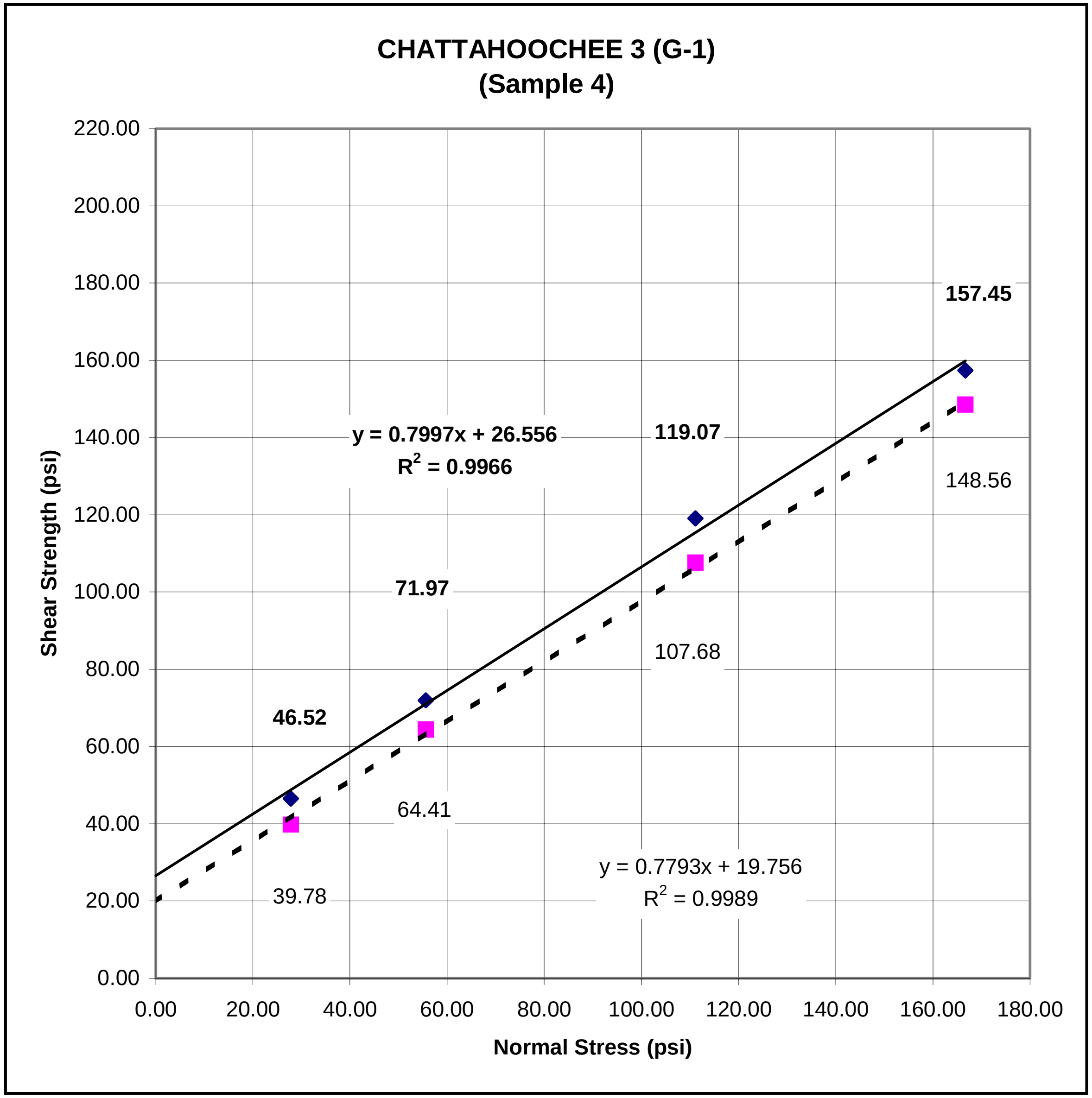
Material: **CHATTAHOOCHEE 3 (G-1) (Sample 4)**

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**46.52**	39.78
272.70	55.55	**71.97**	64.41
545.40	111.11	**119.07**	107.68
818.10	166.66	**157.45**	148.56

Angle of Int. Frict. =		**38.65**	37.93
C =		**26.56**	19.76

Note:
G-1 refers to Gradation 1, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	71.5	28.5
#30	50	50
#50	27.5	72.5
#100	0	100

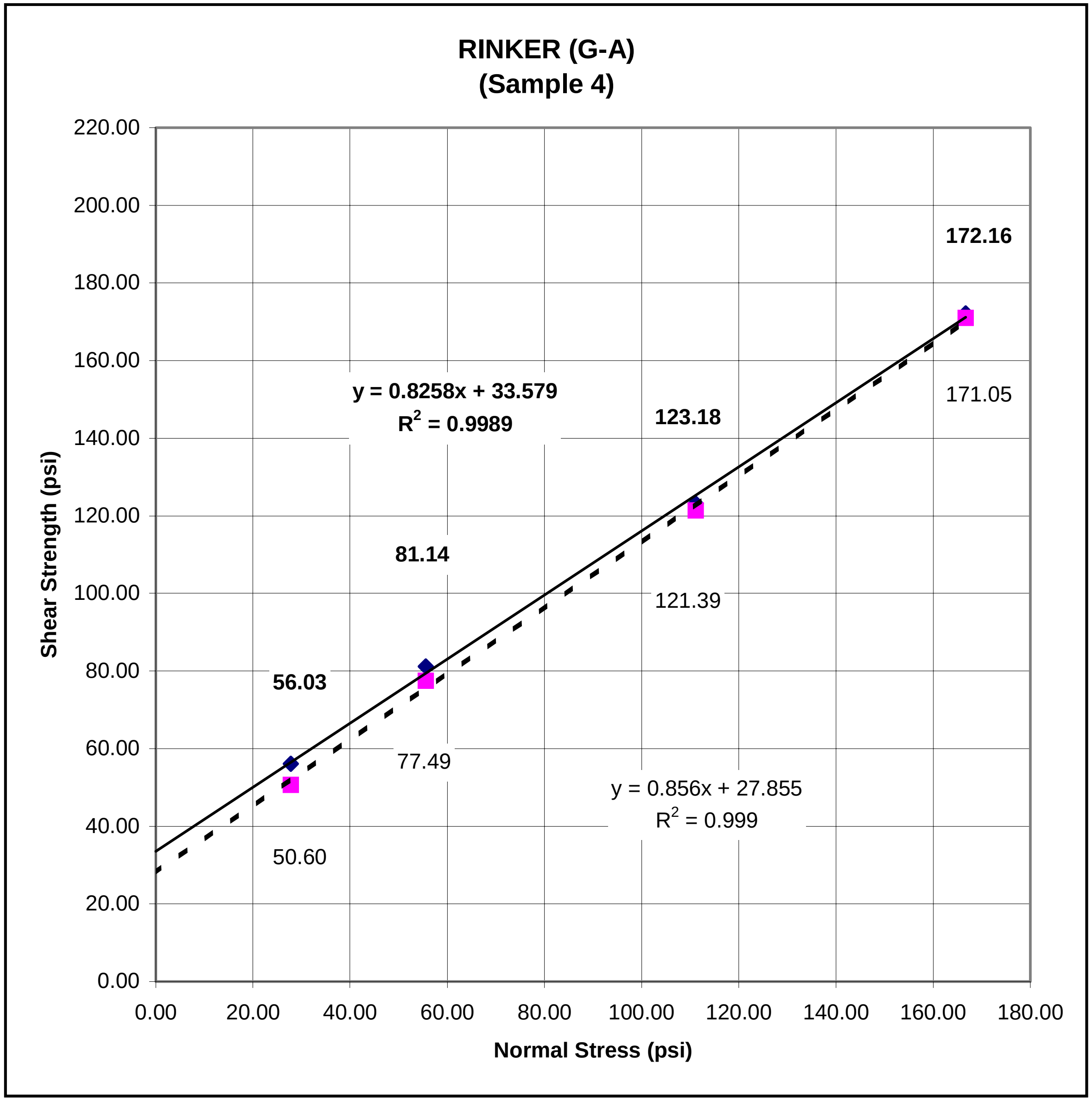


Material: **RINKER (G-A)**
(Sample 4)

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**56.03**	50.60
272.70	55.55	**81.14**	77.49
545.40	111.11	**123.18**	121.39
818.10	166.66	**172.16**	171.05
	Angle of Int. Frict. =	**39.55**	40.56
	C =	**33.58**	27.86

Note:
G-A refers to Gradation A, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100.0	0.0
#16	76.8	23.2
#30	46.8	53.2
#50	8.9	91.1
#100	0.0	100.0



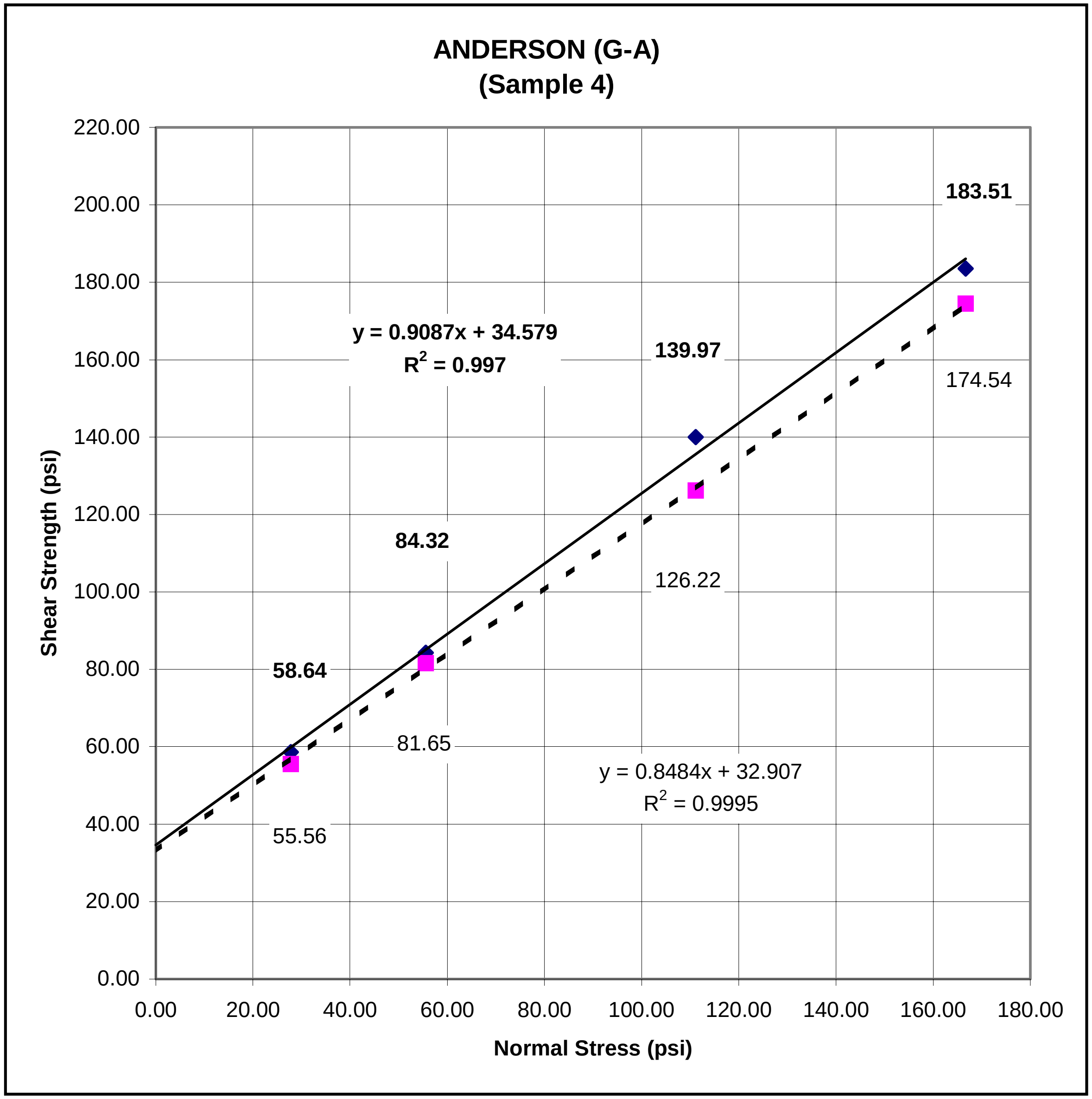
Material: **ANDERSON (G-A) (Sample 4)**

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**58.64**	55.56
272.70	55.55	**84.32**	81.65
545.40	111.11	**139.97**	126.22
818.10	166.66	**183.51**	174.54

Angle of Int. Frict. =	**42.26**	40.31
C =	**34.58**	32.91

Note:
G-A refers to Gradation A, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100.0	0.0
#16	76.8	23.2
#30	46.8	53.2
#50	8.9	91.1
#100	0.0	100.0

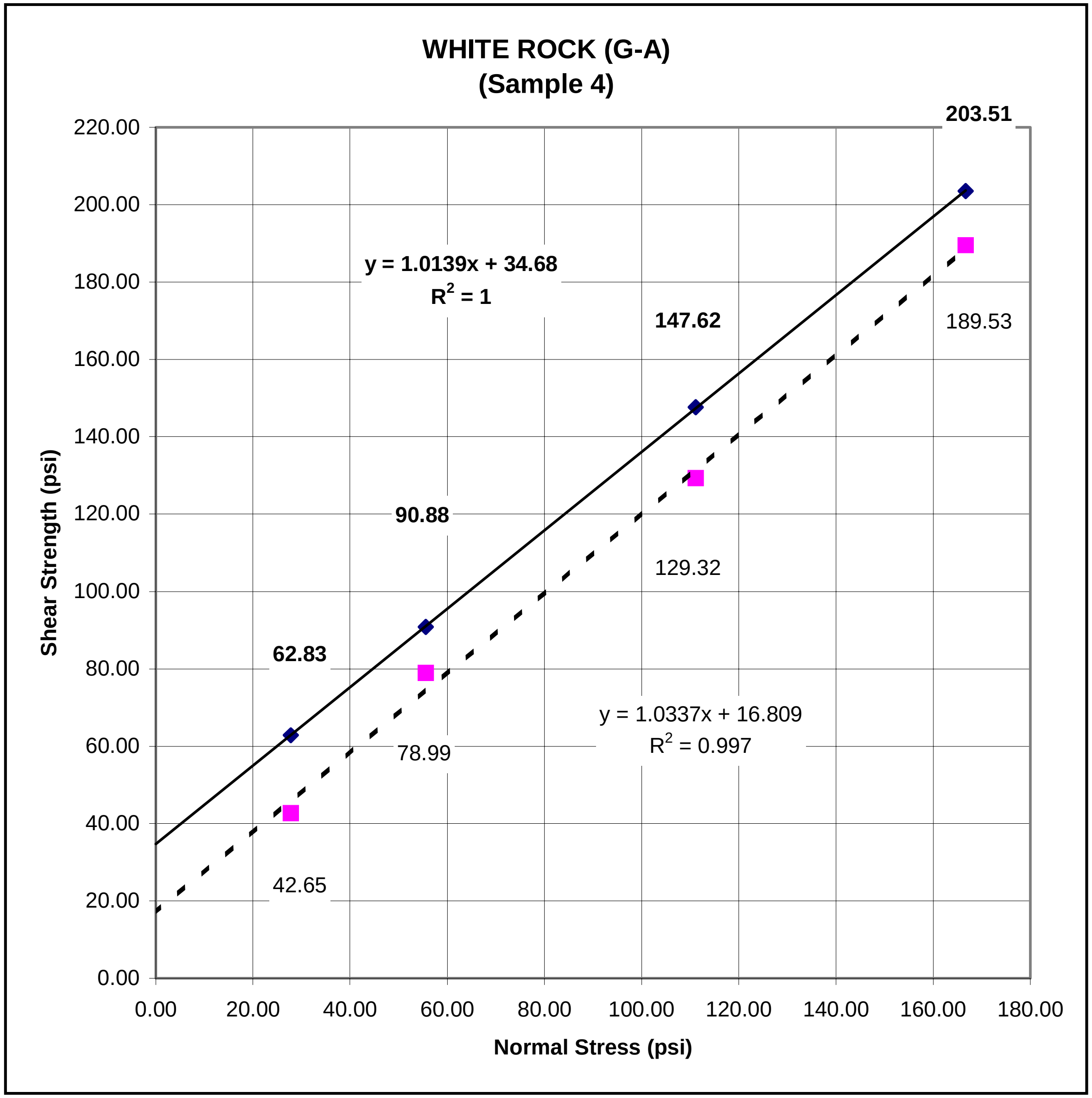


Material: **WHITE ROCK (G-A)**
(Sample 4)

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**62.83**	42.65
272.70	55.55	**90.88**	78.99
545.40	111.11	**147.62**	129.32
818.10	166.66	**203.51**	189.53
	Angle of Int. Frict. =	**45.40**	43.71
	C =	**34.68**	27.35

Note:
G-A refers to Gradation A, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100.0	0.0
#16	76.8	23.2
#30	46.8	53.2
#50	8.9	91.1
#100	0.0	100.0



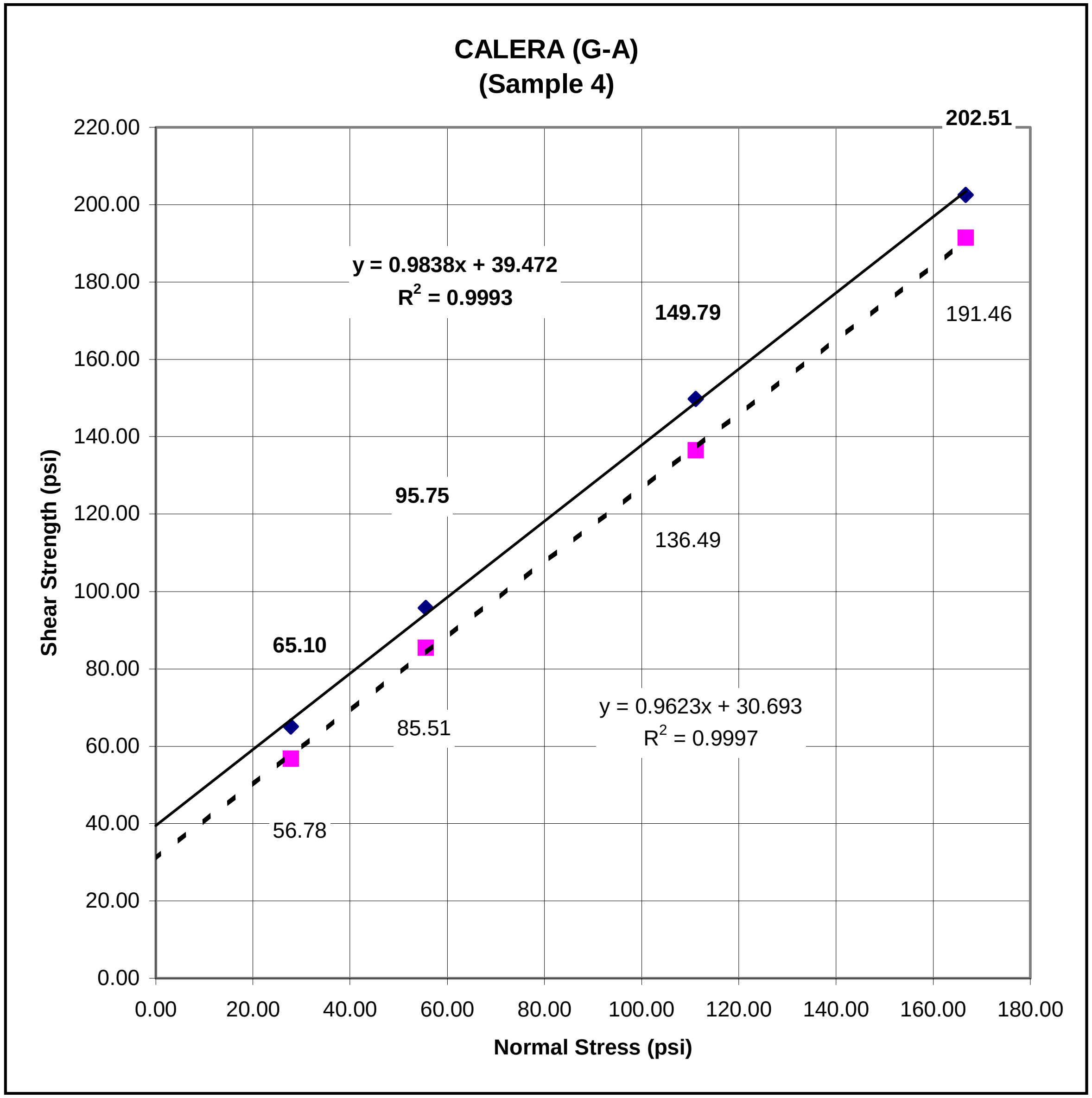
Material: **CALERA (G-A) (Sample 4)**

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**65.10**	56.78
272.70	55.55	**95.75**	85.51
545.40	111.11	**149.79**	136.49
818.10	166.66	**202.51**	191.46

Angle of Int. Frict. =		**44.53**	43.90
C =		**39.47**	30.69

Note:
G-A refers to Gradation A, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100.0	0.0
#16	76.8	23.2
#30	46.8	53.2
#50	8.9	91.1
#100	0.0	100.0



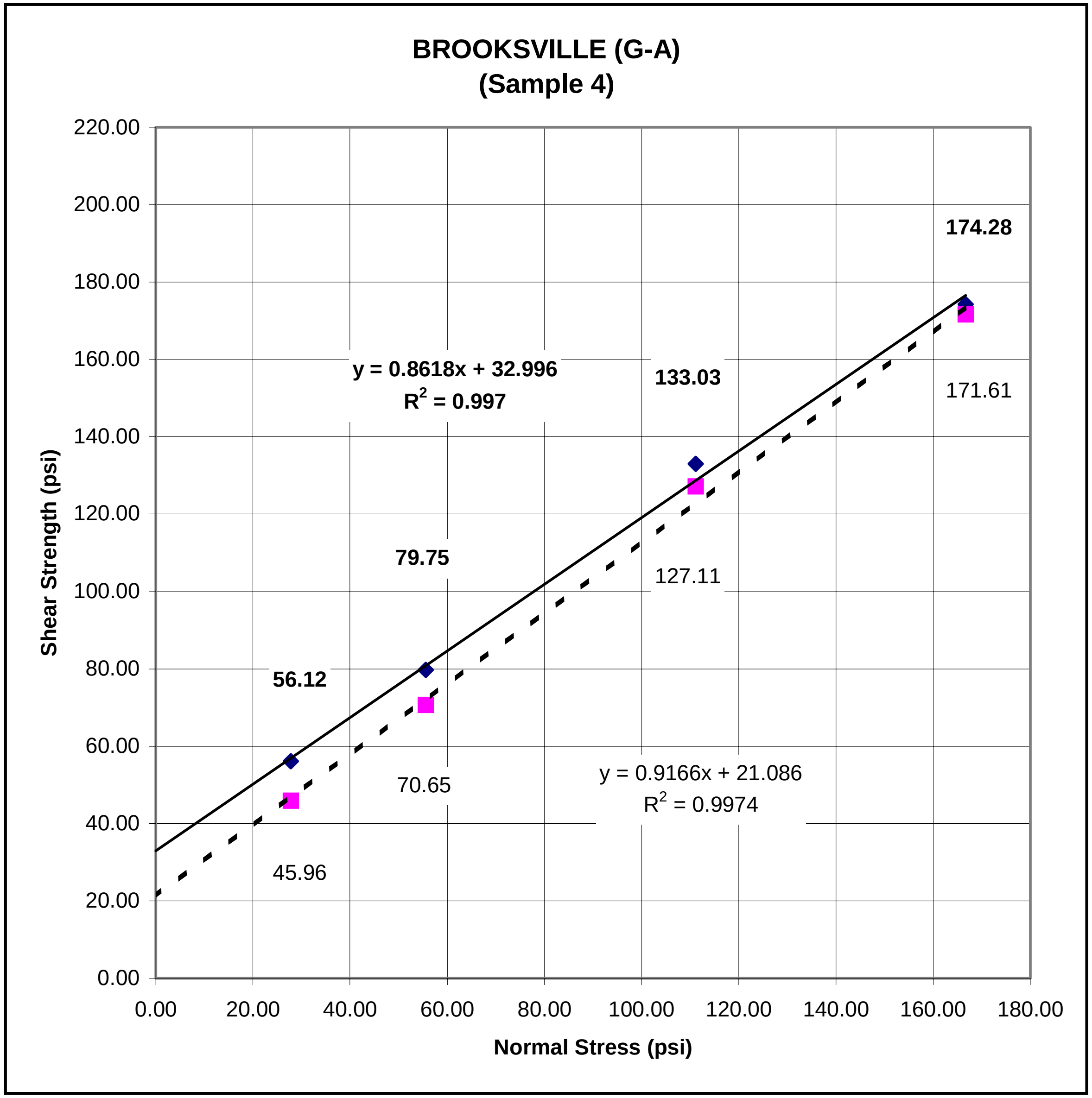
Material: **BROOKSVILLE (G-A) (Sample 4)**

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**56.12**	45.96
272.70	55.55	**79.75**	70.65
545.40	111.11	**133.03**	127.11
818.10	166.66	**174.28**	171.61

Angle of Int. Frict. =		**40.75**	42.51
C =		**33.00**	21.09

Note:
G-A refers to Gradation A, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100.0	0.0
#16	76.8	23.2
#30	46.8	53.2
#50	8.9	91.1
#100	0.0	100.0

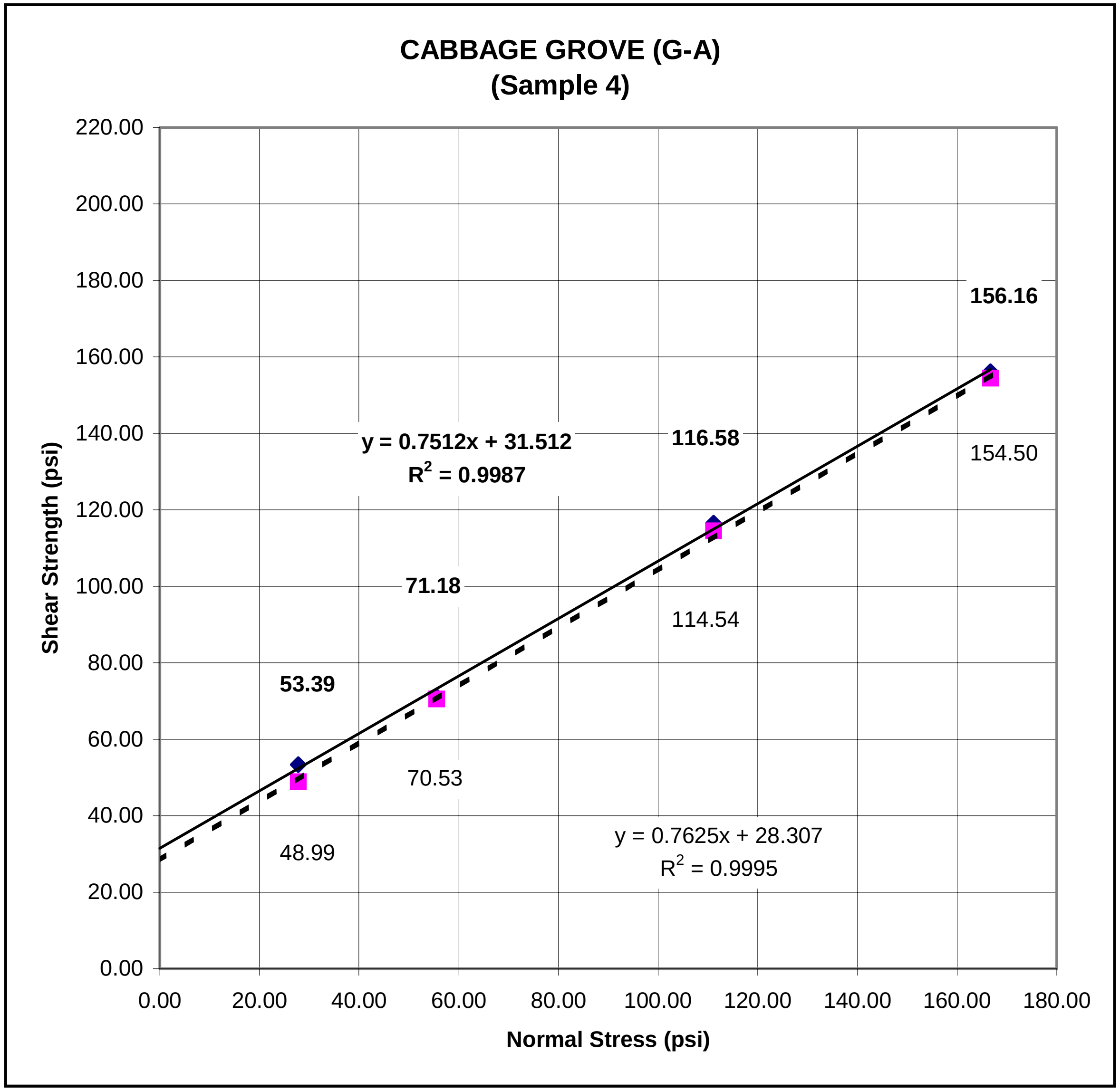


Material: **CABBAGE GROVE (G-A) (Sample 4)**

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**53.39**	48.99
272.70	55.55	**71.18**	70.53
545.40	111.11	**116.58**	114.54
818.10	166.66	**156.16**	154.50
	Angle of Int. Frict. =	**36.91**	37.33
	C =	**31.51**	28.31

Note:
G-A refers to Gradation A, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100.0	0.0
#16	76.8	23.2
#30	46.8	53.2
#50	8.9	91.1
#100	0.0	100.0



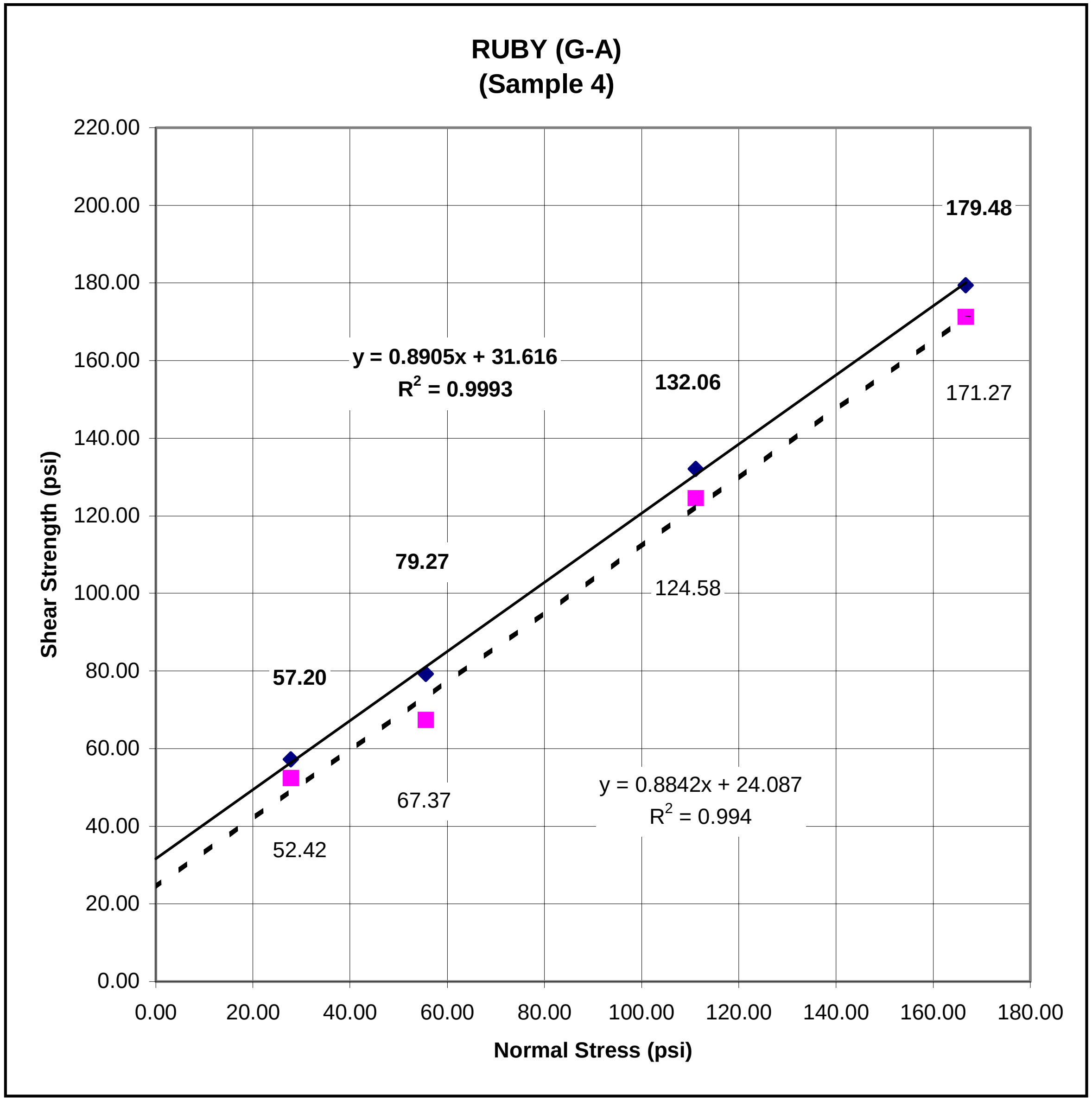
Material: **RUBY (G-A)**
(Sample 4)

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**57.20**	52.42
272.70	55.55	**79.27**	67.37
545.40	111.11	**132.06**	124.58
818.10	166.66	**179.48**	171.27

Angle of Int. Frict. =	**41.69**	41.48
C =	**31.62**	24.09

Note:
G-A refers to Gradation A, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100.0	0.0
#16	76.8	23.2
#30	46.8	53.2
#50	8.9	91.1
#100	0.0	100.0

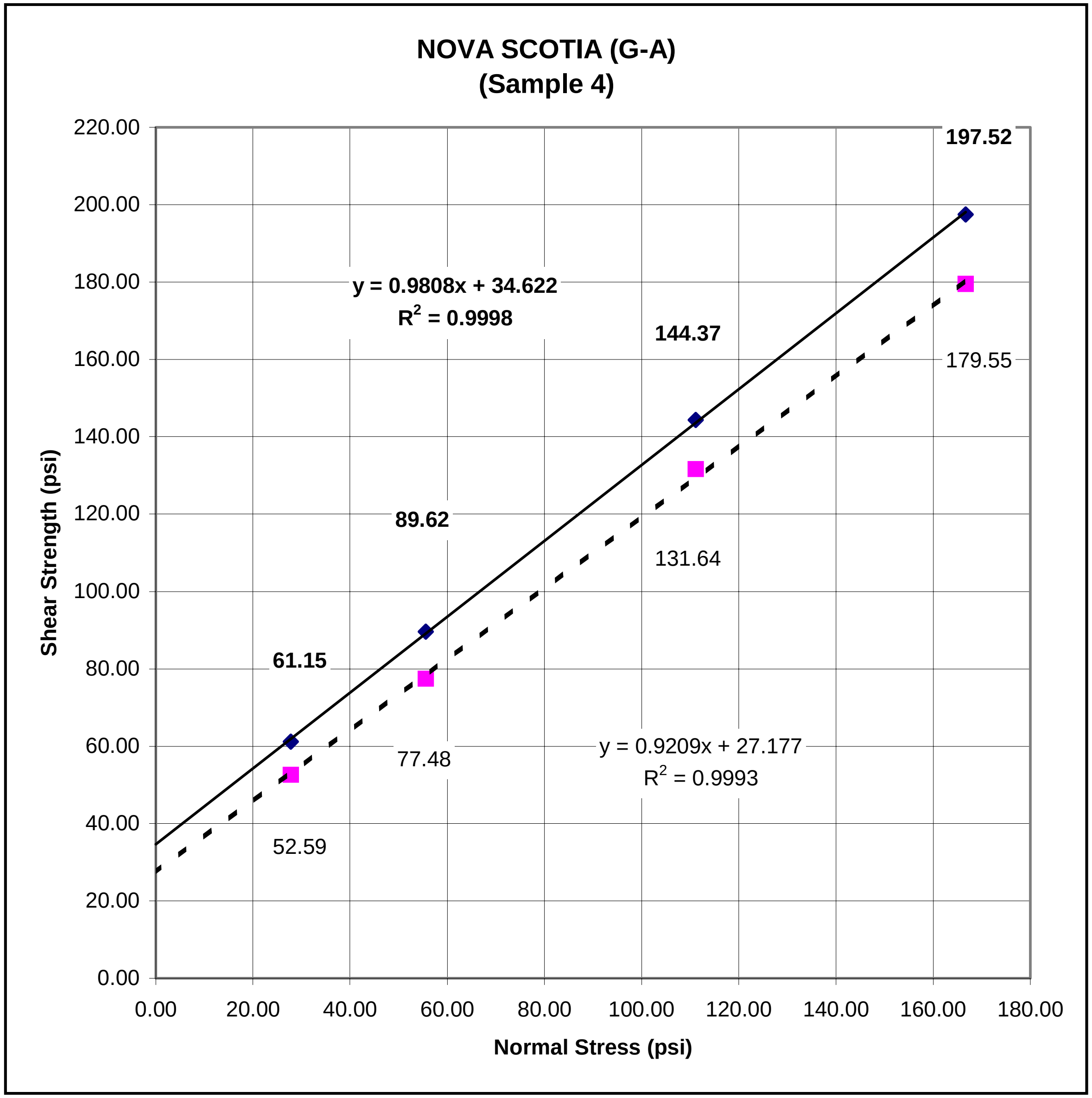


Material: **NOVA SCOTIA (G-A) (Sample 4)**

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**61.15**	52.59
272.70	55.55	**89.62**	77.48
545.40	111.11	**144.37**	131.64
818.10	166.66	**197.52**	179.55
	Angle of Int. Frict. =	**44.44**	42.64
	C =	**34.62**	27.18

Note:
G-A refers to Gradation A, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100.0	0.0
#16	76.8	23.2
#30	46.8	53.2
#50	8.9	91.1
#100	0.0	100.0

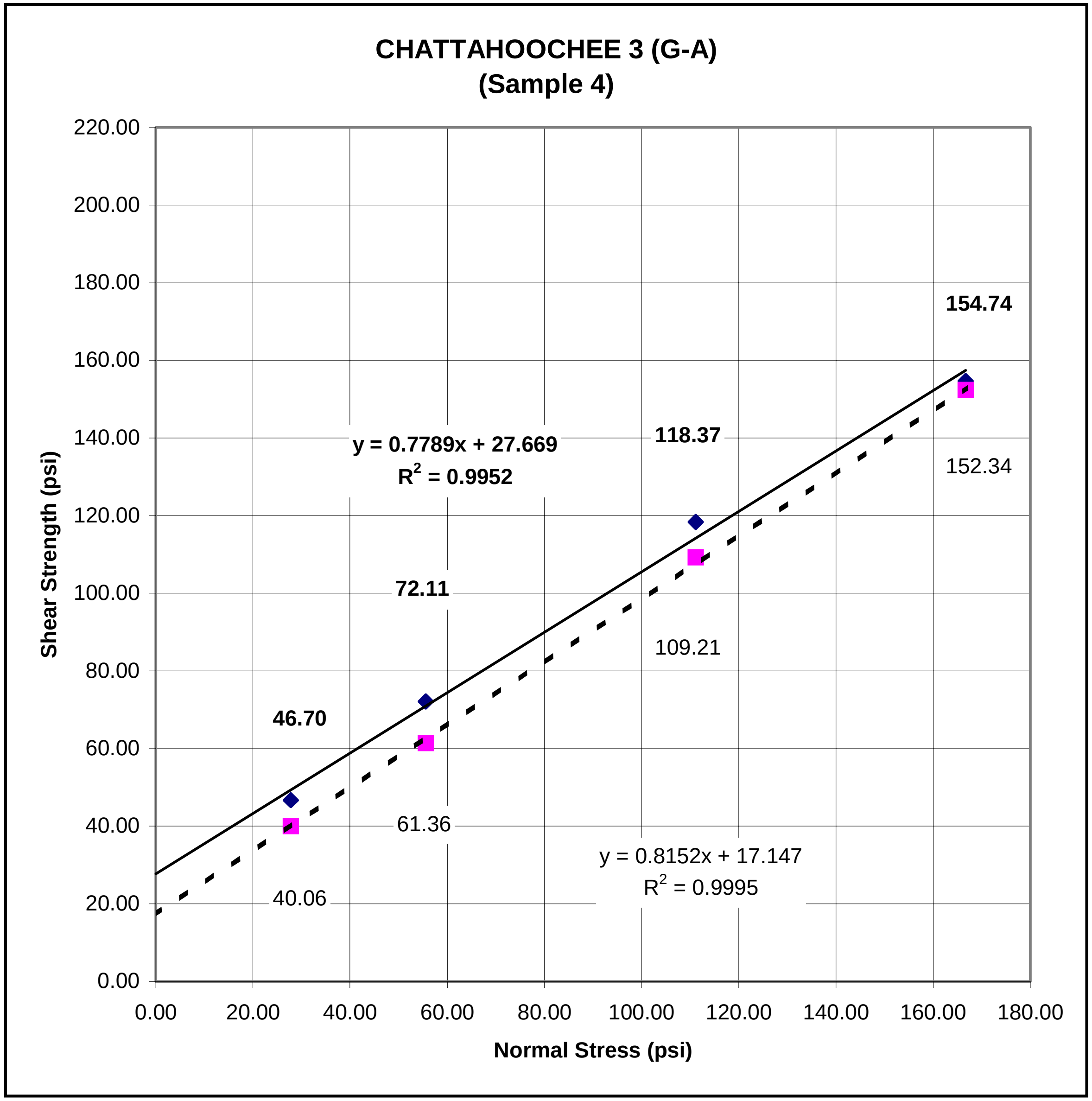


Material: **CHATTAHOOCHEE 3 (G-A) (Sample 4)**

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**46.70**	40.06
272.70	55.55	**72.11**	61.36
545.40	111.11	**118.37**	109.21
818.10	166.66	**154.74**	152.34
	Angle of Int. Frict. =	**37.92**	39.19
	C =	**27.67**	17.15

Note:
G-A refers to Gradation A, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100.0	0.0
#16	76.8	23.2
#30	46.8	53.2
#50	8.9	91.1
#100	0.0	100.0



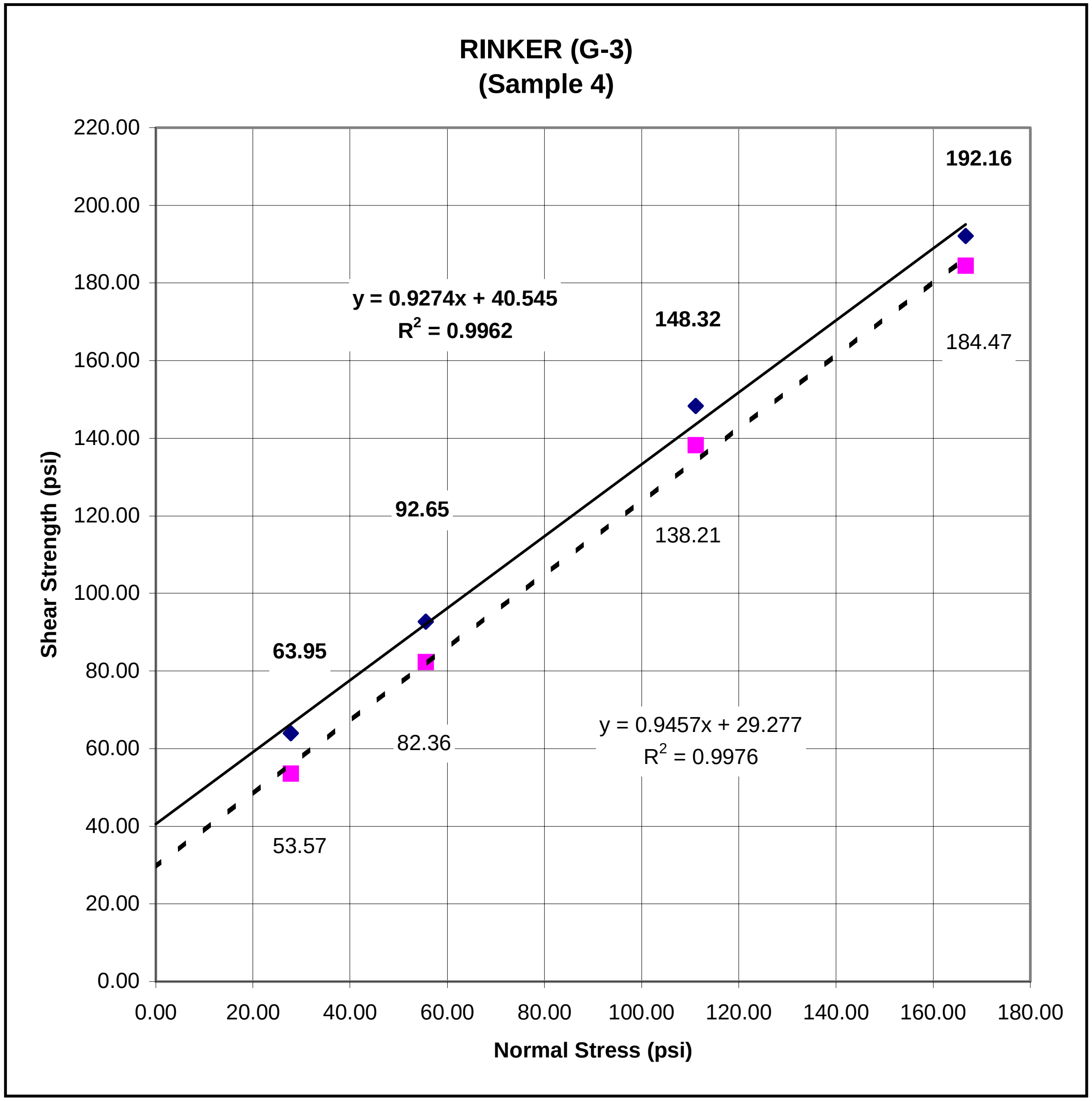
Material: **RINKER (G-3)**
(Sample 4)

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**63.95**	53.57
272.70	55.55	**92.65**	82.36
545.40	111.11	**148.32**	138.21
818.10	166.66	**192.16**	184.47

Angle of Int. Frict. =		**42.84**	43.40
C =		**40.55**	29.28

Note:
G-3 refers to Gradation 3, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	55.5	44.5
#30	26.5	73.5
#50	7.5	92.5
#100	0	100



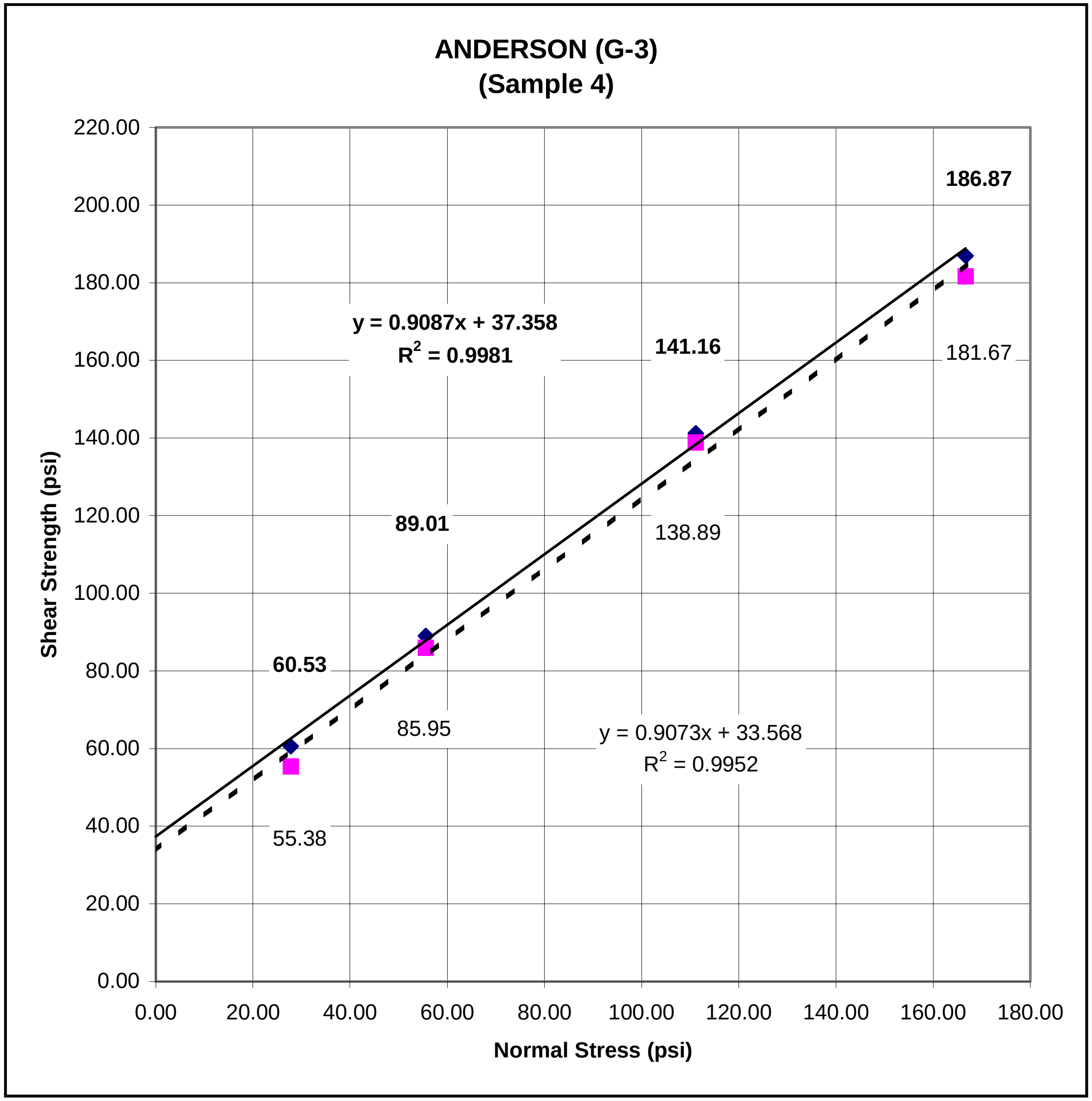
Material: **ANDERSON (G-3)**
(Sample 4)

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**60.53**	55.38
272.70	55.55	**89.01**	85.95
545.40	111.11	**141.16**	138.89
818.10	166.66	**186.87**	181.67

Angle of Int. Frict. =	**42.26**	42.22
C =	**37.36**	33.57

Note:
G-3 refers to Gradation 3, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	55.5	44.5
#30	26.5	73.5
#50	7.5	92.5
#100	0	100

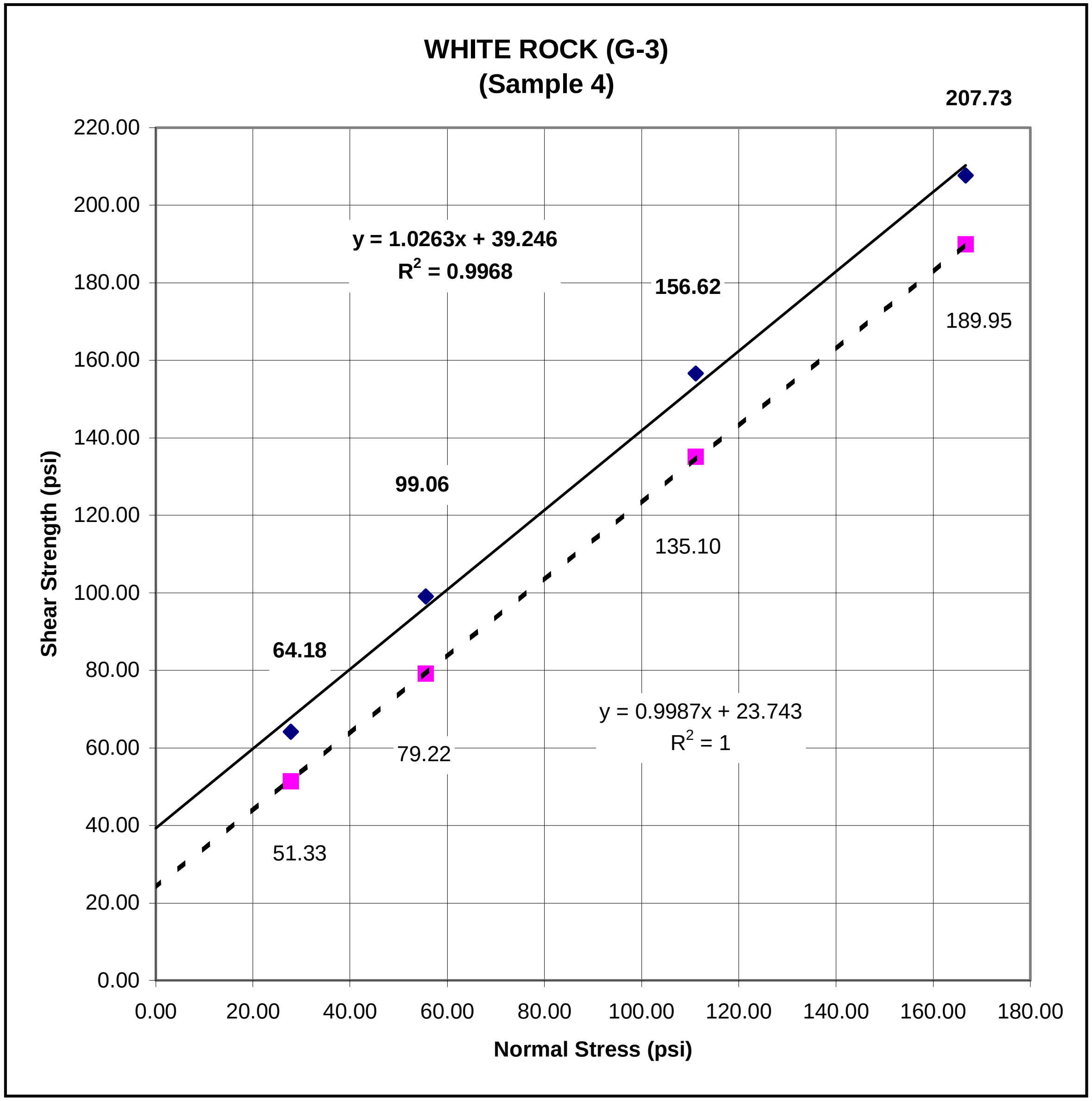


Material: **WHITE ROCK (G-3) (Sample 4)**

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**64.18**	51.33
272.70	55.55	**99.06**	79.22
545.40	111.11	**156.62**	135.10
818.10	166.66	**207.73**	189.95
	Angle of Int. Frict. =	**45.74**	44.96
	C =	**39.25**	23.74

Note:
G-3 refers to Gradation 3, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	55.5	44.5
#30	26.5	73.5
#50	7.5	92.5
#100	0	100



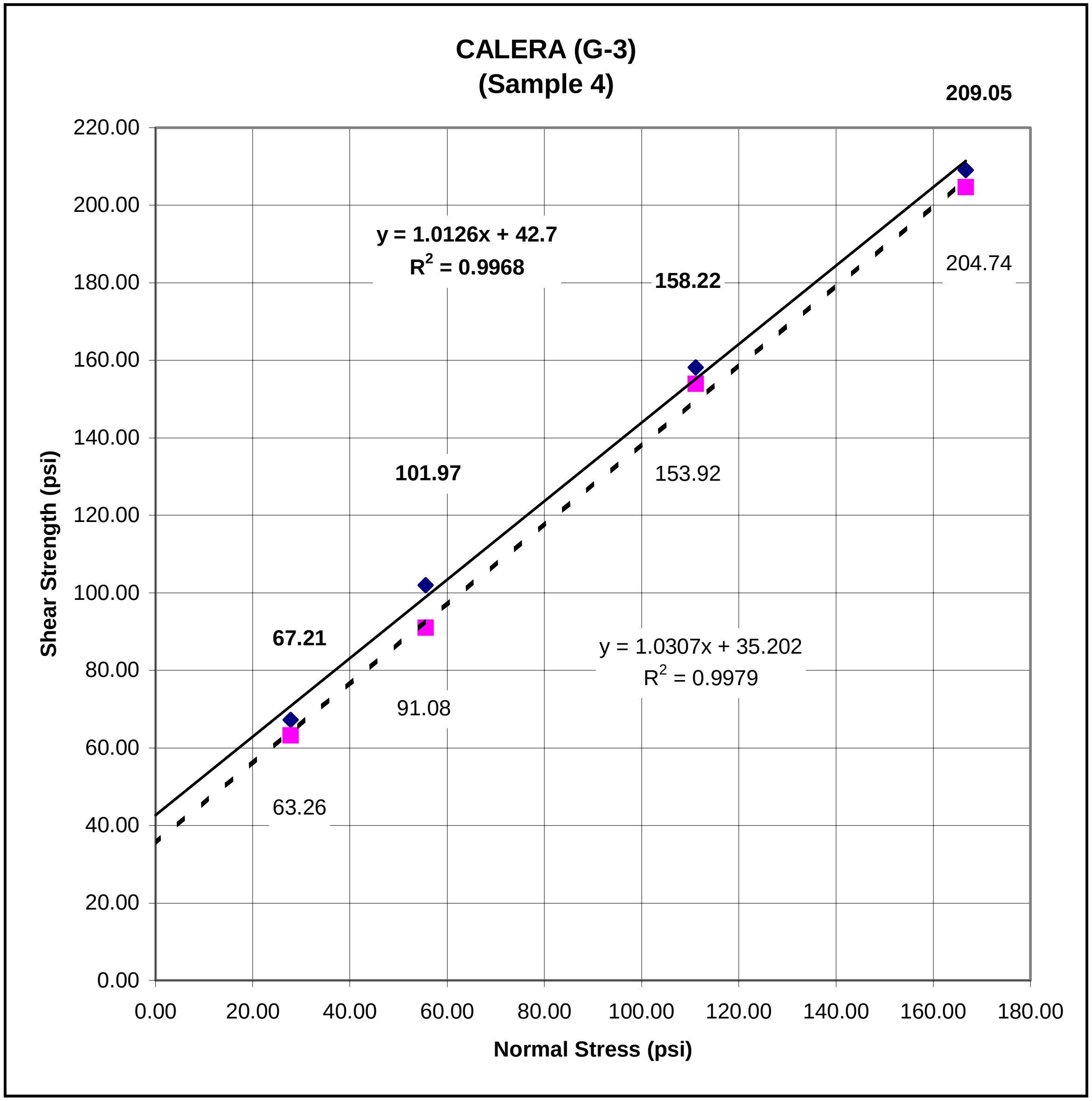
Material: **CALERA (G-3)**
(Sample 4)

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**67.21**	63.26
272.70	55.55	**101.97**	91.08
545.40	111.11	**158.22**	153.92
818.10	166.66	**209.05**	204.74

Angle of Int. Frict. =	**45.36**	45.87
C =	**42.70**	35.20

Note:
G-3 refers to Gradation 3, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	55.5	44.5
#30	26.5	73.5
#50	7.5	92.5
#100	0	100

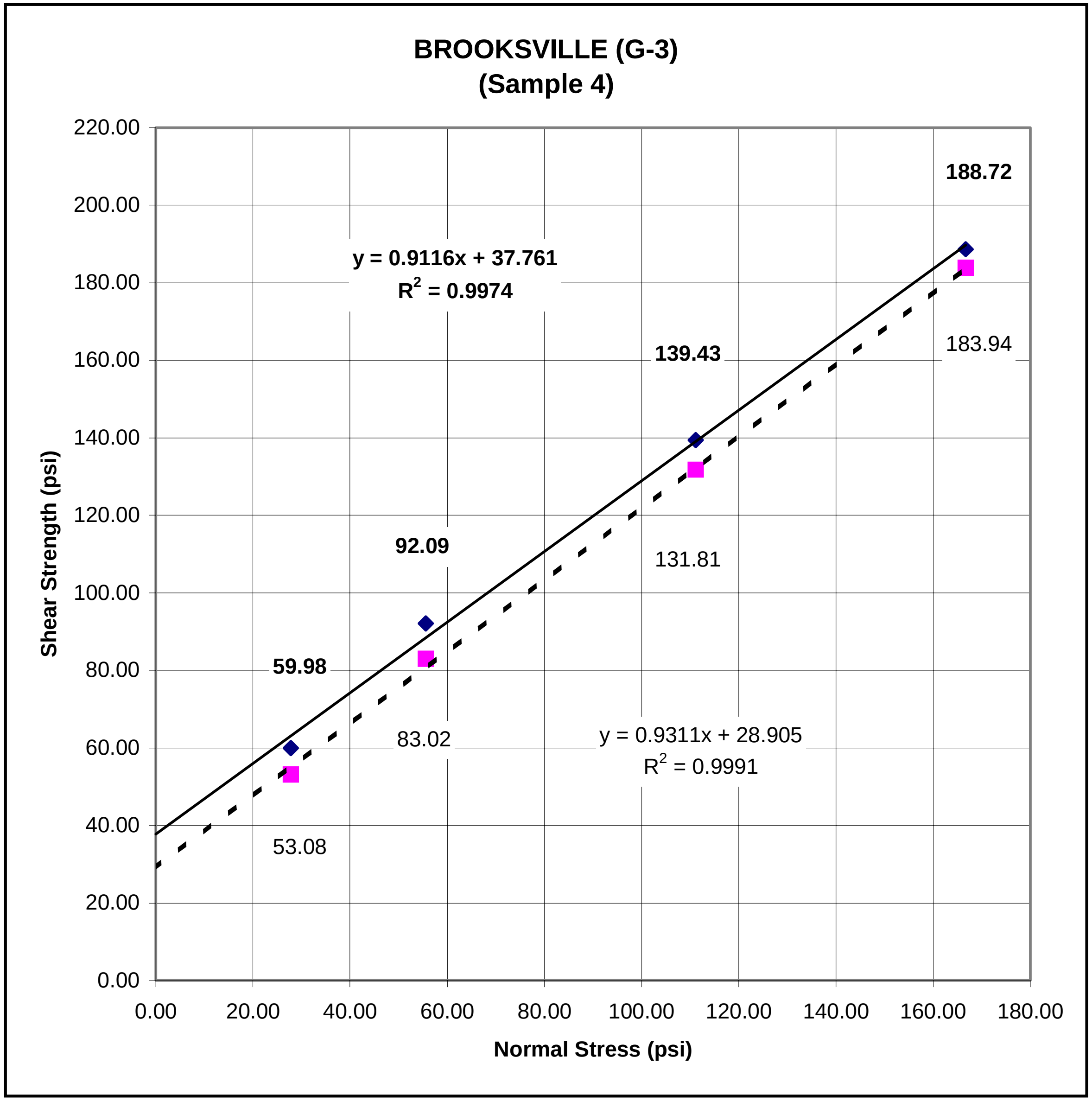


Material: **BROOKSVILLE (G-3) (Sample 4)**

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**59.98**	53.08
272.70	55.55	**92.09**	83.02
545.40	111.11	**139.43**	131.81
818.10	166.66	**188.72**	183.94
	Angle of Int. Frict. =	**42.35**	42.96
	C =	**37.76**	28.91

Note:
G-3 refers to Gradation 3, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	55.5	44.5
#30	26.5	73.5
#50	7.5	92.5
#100	0	100



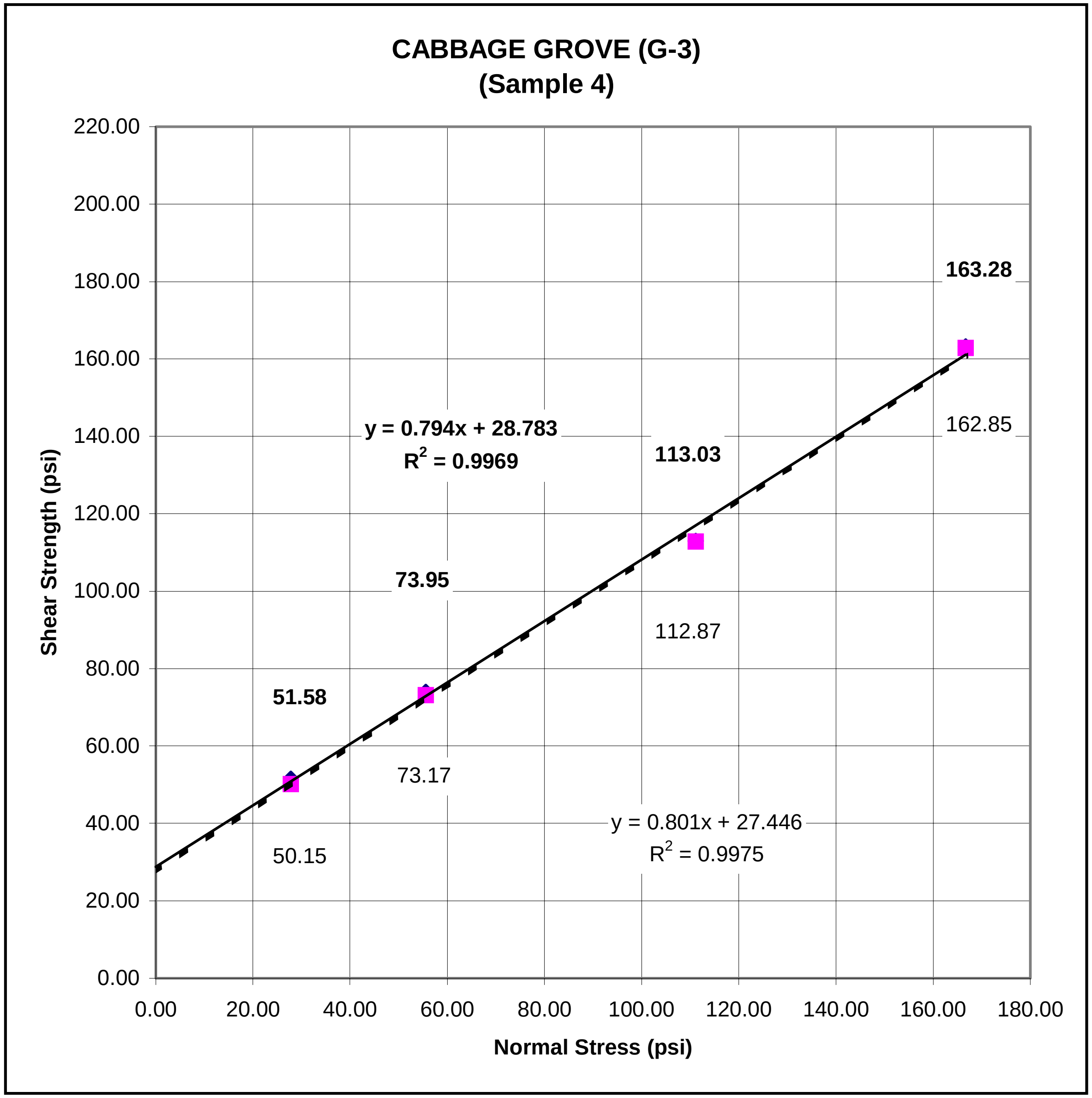
Material: **CABBAGE GROVE (G-3)**
(Sample 4)

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**51.58**	50.15
272.70	55.55	**73.95**	73.17
545.40	111.11	**113.03**	112.87
818.10	166.66	**163.28**	162.85

Angle of Int. Frict. =	**38.45**	38.69
C =	**28.78**	27.45

Note:
G-3 refers to Gradation 3, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	55.5	44.5
#30	26.5	73.5
#50	7.5	92.5
#100	0	100



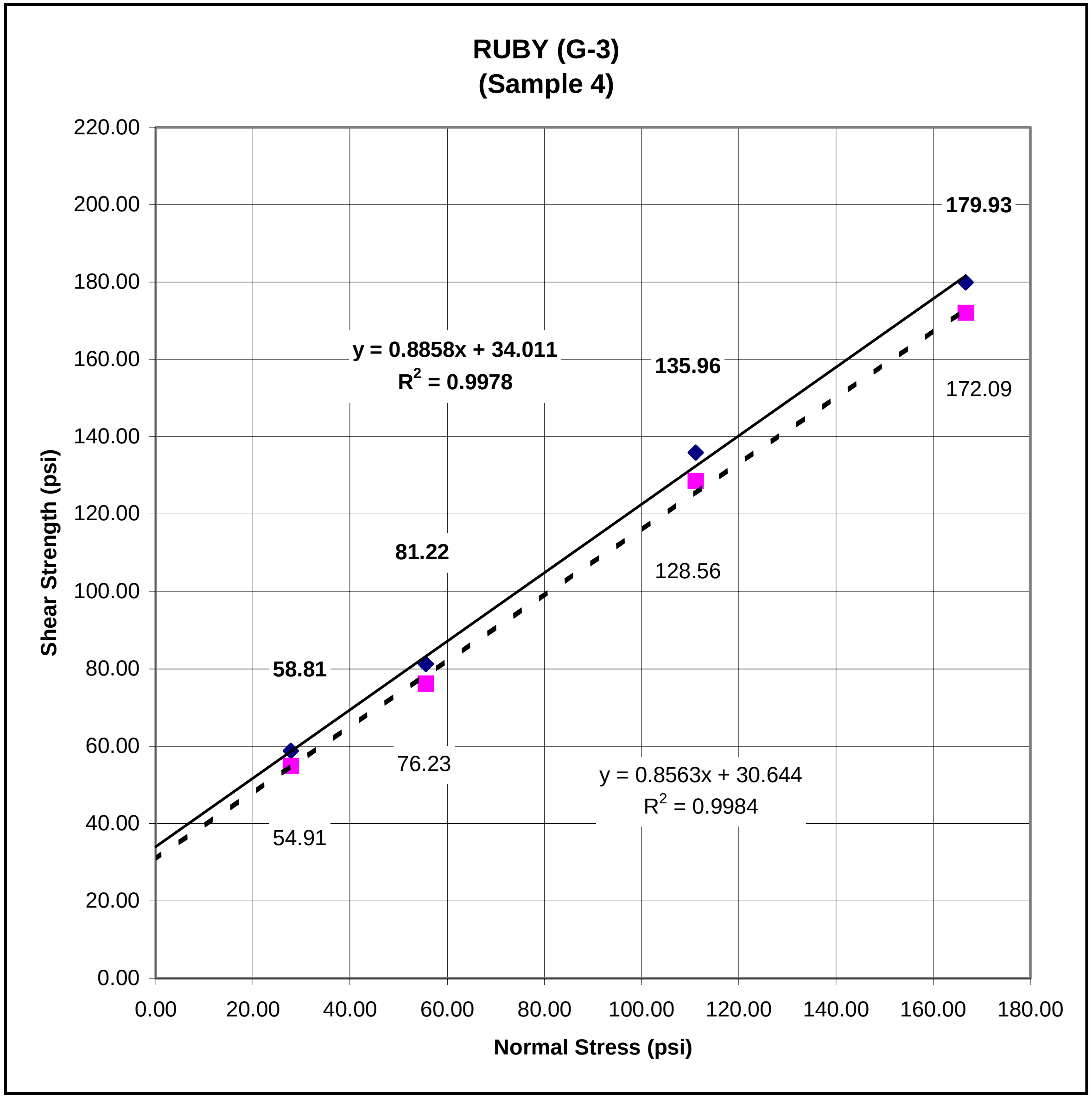
Material: **RUBY (G-3)**
(Sample 4)

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**58.81**	54.91
272.70	55.55	**81.22**	76.23
545.40	111.11	**135.96**	128.56
818.10	166.66	**179.93**	172.09

Angle of Int. Frict. =	**41.53**	40.57
C =	**34.01**	30.64

Note:
G-3 refers to Gradation 3, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	55.5	44.5
#30	26.5	73.5
#50	7.5	92.5
#100	0	100



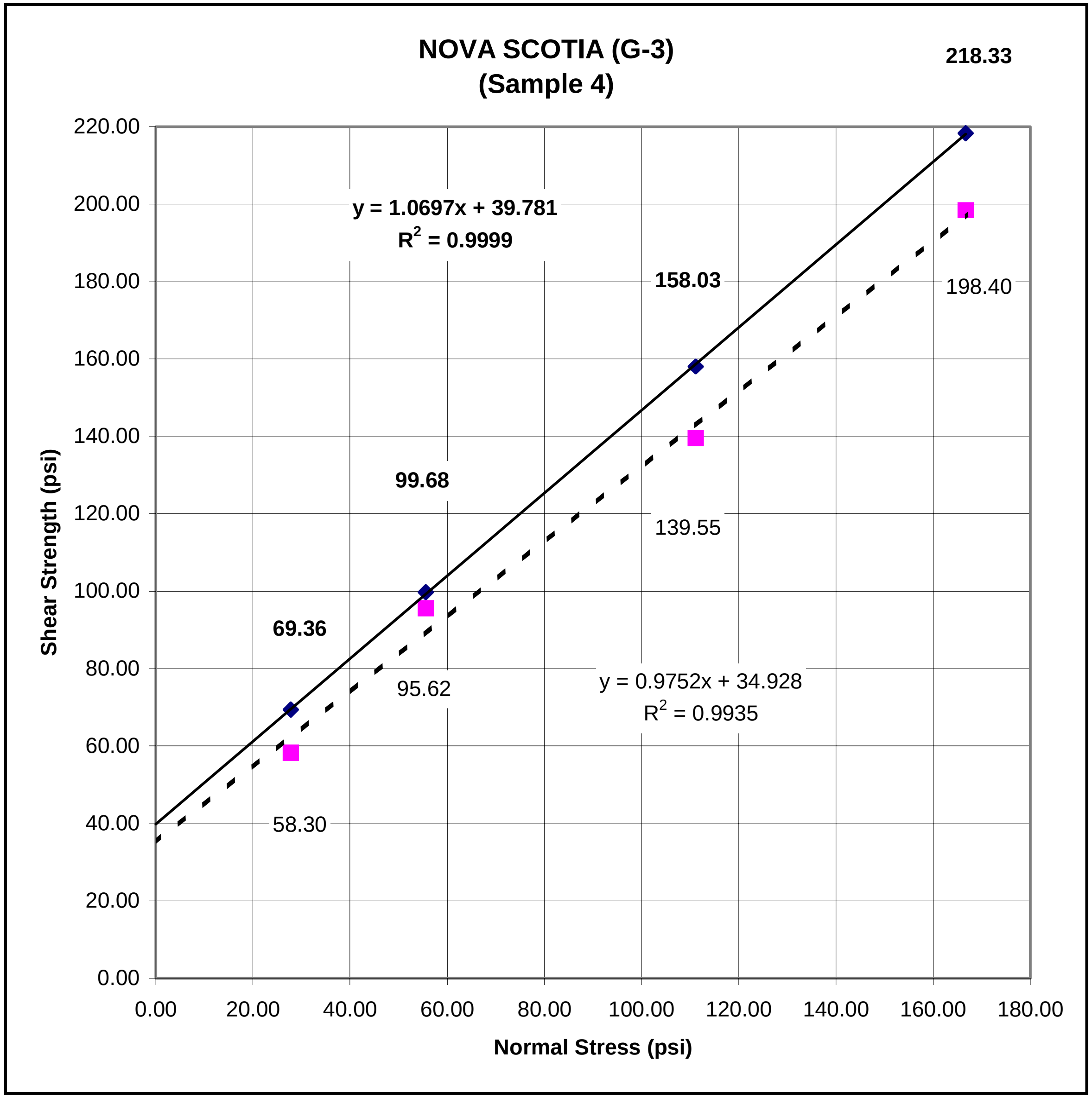
Material: **NOVA SCOTIA (G-3)**
(Sample 4)

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**69.36**	58.30
272.70	55.55	**99.68**	95.62
545.40	111.11	**158.03**	139.55
818.10	166.66	**218.33**	198.40

Angle of Int. Frict. =		**46.93**	44.28
C =		**39.78**	34.93

Note:
G-3 refers to Gradation 3, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	55.5	44.5
#30	26.5	73.5
#50	7.5	92.5
#100	0	100

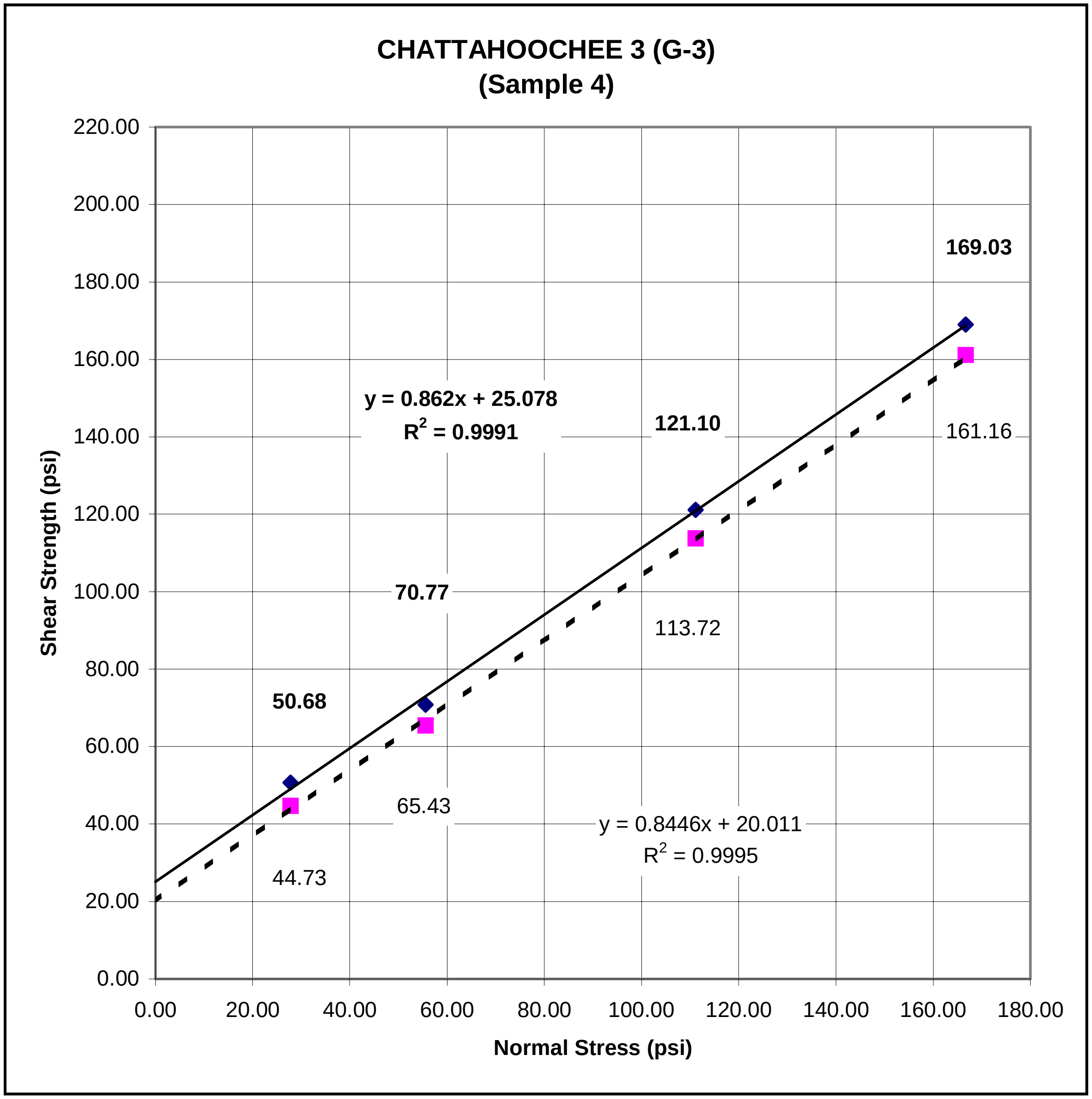


Material: **CHATTAHOOCHEE 3 (G-3) (Sample 4)**

Normal Load [lb]	Normal Stress [psi]	Shear Strength (Peak) [psi]	Shear Strength (CV) [psi]
136.35	27.78	**50.68**	44.73
272.70	55.55	**70.77**	65.43
545.40	111.11	**121.10**	113.72
818.10	166.66	**169.03**	161.16
	Angle of Int. Frict. =	**40.76**	40.18
	C =	**25.08**	20.01

Note:
G-3 refers to Gradation 3, which is as follows:

Sieve Size	[%] Passing	[%] Retained
#8	100	0
#16	55.5	44.5
#30	26.5	73.5
#50	7.5	92.5
#100	0	100



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APPENDIX D
AGGREGATE AND MIXTURE VOLUMETRIC PROPERTIES

Table D-1 Fine Gradations

Sieve Size	Fine				
mm	Chatt.	Ruby	Whiterock	Calera	Cabb-Grove
25(1")	100.0	100.0	100.0	100.0	100.0
19(3/4")	100.0	100.0	100.0	100.0	100.0
12.5(1/2")	95.0	95.1	94.9	94.9	94.7
9.5(3/8")	84.7	85.0	84.4	84.6	83.8
4.75(#4)	67.9	68.5	67.2	67.6	66.0
2.36(#8)	50.8	51.2	50.0	50.6	49.4
1.18(#16)	34.0	34.3	33.2	33.9	33.3
0.6(#30)	22.2	22.4	21.4	22.2	21.9
0.3(#50)	14.0	14.0	13.1	14.0	13.9
0.15(#100)	6.9	6.8	6.0	6.9	7.0
0.075(#200)	4.3	4.2	3.4	4.3	4.5

Table D-2 Coarse Gradations

Sieve Size	Coarse				
mm	Chatt.	Ruby	Whiterock	Calera	Cabb-Grove
25(1")	100.0	100.0	100.0	100.0	100.0
19(3/4")	100.0	100.0	100.0	100.0	100.0
12.5(1/2")	97.5	97.5	97.4	97.5	97.4
9.5(3/8")	89.4	89.5	89.1	89.3	88.8
4.75(#4)	56.9	57.6	56.0	56.5	54.8
2.36(#8)	31.3	31.6	30.2	31.2	30.4
1.18(#16)	20.9	21.1	19.7	20.9	20.5
0.6(#30)	15.0	15.1	13.6	15.0	14.8
0.3(#50)	11.0	11.0	9.5	11.0	11.0
0.15(#100)	7.1	7.0	5.4	7.1	7.2
0.075(#200)	5.2	5.2	3.6	5.3	5.5

Table D-3 Properties for Coarse Ruby Granite Mixtures

% AC	6.25										
Sample	CR-1	CR-2	CR-3	CR-4	CR-10	CR-11	CR-5	CR-6	CR-7	CR-8	CR-9
Agg. Weight (g)	4668	4668	4668	4668	4668	4668	4668	4668	4668	4668	4668
AC Weight (g)	311	311	311	311	311	311	311	311	311	311	311
Weight before mix (g)	4979	4979	4979	4979	4979	4979	4979	4979	4979	4979	4979
Weight after mix (g)	4932.3	4984	4952.9	4946	4942.1	4940.6	4953.4	4959.5	4956.7	4957.6	4953.8
% Weight Loss	0.94	0.00	0.52	0.66	0.74	0.77	0.51	0.39	0.45	0.43	0.51
Weight in Water (g)	2824.7	2870	2841.4	2833.6	2834.6	2830	2810.1	2820.2	2832.1	2826.4	2811
SSD Weight (g)	4936.6	4986.5	4956.8	4951.5	4946.1	4943.3	4960.3	4968	4962.7	4963.9	4963.5
Spec. Gravity	2.335	2.355	2.341	2.335	2.341	2.338	2.304	2.309	2.326	2.319	2.301

Rice Test

Sample	RCR-1	RCR-2	RCR-3	RCR-4	RCR-5	RCR-6	
Weight (g)	834	820	800	855.3	830	825	
Weight of Flask and Water (g)	3332.9	3236	3204.2	3236	3332.9	3231.7	
Weight of Flask, Water, Sample (g)	3818.1	3713.8	3668.2	3731.9	3815.4	3712.3	
Multiplier	1.000253	1.000127	0.999466	0.999466	0.999738	0.999738	
Gmm	2.392	2.397	2.380	2.379	2.388	2.395	
Average Gmm		2.394		2.379		2.391	2.393
Gse	2.621	2.627	2.605	2.604	2.616	2.625	
Average Gse		2.624		2.605		2.620	2.622

Specific Gravity

Aggregate	S1a	S1b	Ruby Scrn	Filler
Individual % by mass	9.2	33.2	52.4	5.2
Individual Spec. Gravity	2.4252	2.4509	2.68	2.69
Bulk Spec. Gravity of Aggregate	2.576			

Sample	CR-1		CR-2		CR-3		CR-4		CR-5
No. of Gyrations	174	109	174	109	174	109	174	109	109
Height (mm)	122.2	124.3	122.2	123.6	122.4	124.5	122.7	124.7	124.7
Volume (m)	2.158	2.195	2.158	2.183	2.162	2.199	2.167	2.203	2.203
Individual Spec. Gravity		2.296		2.328		2.302		2.298	2.300
Average Spec. Gravity				2.312		2.299		2.299	
% Air Voids (V_a)	2.393	4.042	1.584	2.699	2.147	3.798	2.399	3.964	3.876
Average Va				3.370		3.920		3.935	
% VMA		16.426		15.256		16.213		16.358	16.281
Average % VMA				15.841		16.320		16.332	
% VFA		75.394		82.310		76.576		75.766	76.196
Average % VFA				78.724		75.981		75.909	
Height (mm) at N_{int}		141.4		131.5		141.4		141.4	141.2
Spec. Gravity at N_{int}		2.018		2.188		2.027		2.026	2.034
Va at N_{int}		15.656		8.554		15.305		15.316	14.981

Sample	CR-6	CR-7	CR-8	CR-9	CR-10		CR-11		Average
No. of Gyrations	109	109	109	109	174	109	174	109	
Height (mm)	124.9	123.9	124.2	125	122.3	124.2	122.7	124.6	
Volume (m)	2.206	2.188	2.194	2.208	2.160	2.194	2.167	2.201	
Individual Spec. Gravity	2.309	2.326	2.319	2.301		2.305		2.302	2.308
Average Spec. Gravity	2.300		2.323	2.301				2.303	
% Air Voids (V_a)	3.499	2.771	3.067	3.816	2.180	3.677	2.293	3.783	3.853
Average Va	3.876		2.919	3.816				3.251	
% VMA	15.953	15.319	15.577	16.229		16.108		16.201	16.094
Average % VMA	16.281		15.448	16.229				16.154	
% VFA	78.065	81.912	80.310	76.485		77.174		76.648	77.311
Average % VFA	76.196		81.104	76.485				76.911	
Height (mm) at N_{int}	141.4	139.9	140.2	141.4		140.5		140.9	

Table D-4 Properties for Coarse Calera Mixtures

% AC	5.4	5.6			5.8		
Sample	CC-1	CC-2	CC-3	CC-4	CC-5	CC-6	CC-7
Agg. Weight (g)	4559	4559	4559	4559	4559	4559	4559
AC Weight (g)	260	270	270	270	281	281	281
Weight before mix (g)	4819	4829	4829	4829	4840	4840	4840
Weight after mix (g)	4803.7	4807.3	4809.1	4809	4829.7	4826.5	4816.3
% Weight Loss	0.32	0.45	0.41	0.41	0.21	0.28	0.49
Weight in Water (g)	2789.3	2798.2	2795.7	2796.6	2817.6	2817.3	2807.8
Temp. Coeff.	0.999711	0.999948	0.999948	0.999948	0.999521	0.999521	0.999922
SSD Weight (g)	4807.6	4815.9	4815.9	4812.9	4831.7	4828.3	4818.7
Spec. Gravity	2.379	2.382	2.380	2.385	2.397	2.399	2.395

Rice Test

	5.4% AC		5.6% AC		5.8% AC		
Sample	RCC-1	RCC-2	RCC-3	RCC-4	RCC-5	RCC-6	
Weight (g)	800	803.3	800	821.6	819.3	787.1	
Weight of Flask and Water (g)	3329.7	3205.8	3329.7	3205.5	3328.7	3230.7	
Weight of Flask, Water, Sample (g)	3802.8	3681.3	3804.2	3692.5	3814.3	3697	
Multiplier	0.999355	0.999299	0.999711	0.999521	0.999658	0.999738	
Gmm	2.446	2.449	2.457	2.454	2.454	2.453	
Average Gmm		2.447		2.456		2.454	2.454
Gse	2.652	2.656	2.675	2.672	2.681	2.679	
Average Gse		2.654		2.673		2.680	2.680

Specific Gravity

Aggregate	S1a	S1b	Calera	Filler
Individual % by mass	9.4	34.0	52.2	5.3
Individual Spec. Gravity	2.4252	2.4509	2.6	2.69
Bulk Spec. Gravity of Aggregate	2.535			

Sample	CC-1		CC-2		CC-3		CC-4	
No. of Gyrations	174	109	174	109	174	109	174	109
Height (mm)	117.1	119.2	116.2	118.4	116.8	119	116.8	119.1
Volume (m)	2.068	2.105	2.052	2.091	2.063	2.102	2.063	2.104
Individual Spec. Gravity		2.337		2.338		2.336		2.339
Average Spec. Gravity				2.338		2.337		
% Air Voids (V_a)	2.773	4.486	2.982	4.785	3.066	4.858	2.880	4.756
% VMA		12.786		12.944		13.011		12.918
Average % VMA								12.914
% VFA		64.912		63.035		62.663		63.183
Height (mm) at N_{int}		136		135.9		135.9		136.6
Spec. Gravity at N_{int}		2.049		2.037		2.046		2.039
Va at N_{int}		16.285		17.046		16.689		16.958

Sample	CC-5		CC-6		CC-7		Avg. Values
No. of Gyrations	174	109	174	109	174	109	
Height (mm)	116	118.1	115.9	118	115.9	118.2	
Volume (m)	2.049	2.086	2.047	2.084	2.047	2.088	
Individual Spec. Gravity		2.354		2.356		2.348	2.353
% Air Voids (V_a)	2.317	4.053	2.231	3.971	2.393	4.293	4.106
% VMA		12.534		12.458		12.752	12.581
Average % VMA						12.581	
% VFA		67.660		68.128		66.337	67.375
Average % VFA						67.375	
Height (mm) at N_{int}		134.9		135		135.5	
Spec. Gravity at N_{int}		2.061		2.060		2.048	2.056
Va at N_{int}		16.002		16.063		16.512	16.193

Table D-5 Properties for Coarse Cabbage Grove Mixtures

% AC	6.5		
Sample	CCG-1	CCG-2	CCG-3
Agg. Weight (g)	4382	4382	4382
AC Weight (g)	305	305	305
Weight before mix (g)	4687	4687	4687
Weight after mix (g)	4673.1	4670.6	4668.3
% Weight Loss	0.30	0.35	0.40
Weight in Water (g)	2679.1	2680.9	2678.9
SSD Weight (g)	4676.2	4674.4	4672.5
Spec. Gravity	2.340	2.343	2.342

Rice Test

Sample	RCCG-1	RCCG-2	
Weight (g)	750	804.8	
Weight of Flask and Water (g)	3332.9	3254.9	
Weight of Flask, Water, Sample (g)	3769	3721.7	
Multiplier	1.000495	1.000495	
Gmm	2.390	2.382	
Average Gmm		2.386	2.386
Gse	2.630	2.619	
Average Gse		2.625	2.625

Specific Gravity

Aggregate	S1a	S1b	Cabb. GR. Scrn	Filler
Individual % by mass	9.8	35.4	49.3	5.5
Individual Spec. Gravity	2.4252	2.4509	2.367	2.69
Bulk Spec. Gravity of Aggregate	2.418			

Sample	CCG-1		CCG-2		CCG-3		Avg. Values
No. of Gyrations	174	109	174	109	174	109	
Height (mm)	115.3	117.5	114.9	117.2	115.2	117.4	
Volume (m)	2.036	2.075	2.029	2.070	2.035	2.074	2.053
Individual Spec. Gravity		2.296		2.297		2.298	2.297
Average Spec. Gravity				2.297		2.297	
% Air Voids (V_a)	1.945	3.781	1.821	3.747	1.874	3.713	3.747
Average Va				3.764		3.747	
% VMA		11.211		11.180		11.148	11.180
Average % VMA				11.195		11.180	
% VFA		66.274		66.481		66.696	66.484
Average % VFA				66.377		66.484	
Height (mm) at N_{int}		135.1		135.1		135.2	
Spec. Gravity at N_{int}		1.997		1.993		1.995	1.995
Va at N_{int}		16.548		16.732		16.622	16.634

Table D-6 Properties for Coarse Chattahoochee Mixtures

% AC	6			5.7		
Sample	CCH-1	CCH-2	CCH-3	CCH-4	CCH-5	CCH-6
Agg. Weight (g)	4595	4595	4595	4595	4595	4595
AC Weight (g)	293	293	293	278	278	278
Weight before mix (g)	4888	4888	4888	4873	4873	4873
Weight after mix (g)	4869.2	4864	4855.4	4850.5	4848.2	4851.9
% Weight Loss	0.38	0.49	0.67	0.46	0.51	0.43
Weight in Water (g)	2782.1	2774.3	2764	2770.8	2754.5	2762.7
Temp. Coeff.	1.000495	1.000495	1.000495	1.000728	1.000728	1.000728
SSD Weight (g)	4872.5	4867.2	4857.8	4854.5	4853.1	4855.6
Spec. Gravity	2.330	2.325	2.320	2.330	2.312	2.320

Rice Test

	6% AC		4.85% AC		5.7% AC		
Sample	RCCH-1	RCCH-2	RCCH-3	RCCH-4	RCCH-5	RCCH-6	
Weight (g)	750	873	800	806.2	800	820	
Weight of Flask and Water (g)	3335.7	3248.6	3335.7	3248.6	3239.5	3347.9	
Weight of Flask, Water, Sample (g)	3769.1	3753	3805.5	3720.9	3704.6	3825.9	
Multiplier	1.000025	1	1.000351	1.000302	1.000351	1.000423	
Gmm	2.369	2.368	2.424	2.415	2.390	2.399	
Average Gmm		2.369		2.419		2.394	2.394
Gse	2.581	2.581	2.638	2.627	2.595	2.606	
Average Gse		2.581		2.632		2.601	2.601

Specific Gravity

Aggregate	S1a	S1b	Chatt. Screen	Filler
Individual % by mass	9.3	33.8	51.6	5.2
Individual Spec. Gravity	2.4252	2.4509	2.6	2.69
Bulk Spec. Gravity of Aggregate	2.535			

Sample	CCH-1		CCH-2		CCH-3	
No. of Gyrations	174	109	174	109	174	109
Height (mm)	120.7	122	120.9	122.3	121	122.3
Volume (m)	2.132	2.155	2.135	2.160	2.137	2.160
Individual Spec. Gravity		2.306		2.299		2.295
Average Spec. Gravity				2.302		2.301
% Air Voids (V_a)	2.660	3.697	2.880	3.991	3.093	4.123
Average Va				3.844		3.910
% VMA		14.515		14.777		14.893
Average % VMA				14.646		14.704
% VFA		74.531		72.988		72.315
Average % VFA				73.752		73.409
Height (mm) at N_{int}		135.1		135.1		135.2
Spec. Gravity at N_{int}		2.082		2.081		2.076
Va at N_{int}		12.112		12.165		12.351

Sample	CCH-4		CCH-5		CCH-6		Avg. Values
No. of Gyrations	174	109	174	109	174	109	
Height (mm)	120.6	122.3	121.4	123	121.1	122.7	
Volume (m)	2.130	2.160	2.144	2.172	2.139	2.167	
Individual Spec. Gravity		2.297		2.282		2.290	2.290
Average Spec. Gravity						2.290	
% Air Voids (V_a)	2.699	4.052	3.436	4.692	3.099	4.362	4.369
Average Va						4.369	
% VMA		14.558		15.128		14.835	14.840
Average % VMA						14.840	
% VFA		72.170		68.986		70.594	70.583
Average % VFA						70.583	
Height (mm) at N_{int}		135.7		135.2		135.1	
Spec. Gravity at N_{int}		2.070		2.076		2.080	2.075
Va at N_{int}		14.415		14.183		14.033	14.210

Table D-7 Properties for Fine Calera Mixtures

% AC	6.1	5.7	5.1			5.3		
Sample	FC-1	FC-2	FC-3	FC-4	FC-5	FC-6	FC-7	FC-8
Agg. Weight (g)	4553	4553	4553	4553	4553	4553	4553	4553
AC Weight (g)	296	275	245	245	245	255	255	255
Weight before mix (g)	4849	4828	4798	4798	4798	4808	4808	4808
Weight after mix (g)	4835.9	4819.8	4797.6	4797.3	4786.8	4801.3	4798.8	4798.8
% Weight Loss	0.27	0.17	0.01	0.01	0.23	0.14	0.19	0.19
Weight in Water (g)	2832.5	2820	2807.2	2801.2	2801.6	2829.2	2809.8	2812.6
SSD Weight (g)	4838	4821.8	4799.9	4799.9	4789.8	4803.5	4802.2	4801.5
Bulk Spec. Gravity (for 174 gyr.)	2.411	2.408	2.409	2.400	2.407	2.432	2.409	2.413

Rice Test	Water Temp		25.0 C	25.3 C	23.3 C	26.1 C	24.3 C
	Coeff.		1	0.999922	1.000423	0.999711	1.000177

Sample	RFC-1	RFC-2	RFC-3	RFC-4	RFC-5	RFC-6	RFC-7	RFC-8
AC %	6.1	6.1	5.7	5.7	5.1	5.1	5.3	5.3
Weight (g)	800.1	812.4	800	805.6	800	798.5	800	801.3
Weight of Flask and Water (g)	3332.6	3245.6	3332.6	3245.6	3329.7	3205.8	3329.7	3205.8
Weight of Flask, Water, Sample (g)	3803.5	3723	3805.6	3720.1	3808.5	3683.1	3807.7	3683.7
Multiplier	0.999684	0.999631	0.999711	0.999521	0.999711	0.999576	0.999658	0.999684
Gmm	2.430	2.424	2.446	2.432	2.490	2.485	2.484	2.477
Average Gmm		2.427		2.439		2.487		2.480
Gse	2.663	2.656	2.665	2.648	2.693	2.687	2.695	2.686
Average Gse		2.659		2.657		2.690		2.691

Specific Gravity

Aggregate	S1a	S1b	Calera Scn	Filler
Individual % by mass	18.7	13.7	63.3	4.3
Individual Spec. Gravity	2.4252	2.4509	2.56	2.69
Bulk Spec. Gravity of Aggregate	2.524			

Sample	FC-1		FC-2		FC-3		FC-4	
No. of Gyrations	174	109	174	109	174	109	174	109
Height (mm)	115.1	116.3	114.9	116.5	114.4	115.9	115	116.6
Volume (m)	2.033	2.054	2.029	2.058	2.021	2.047	2.031	2.059
Individual Bulk Spec. Gravity		2.386		2.374		2.377		2.367
Average Spec. Gravity								
% Air Voids (V_a)	0.643	1.668	1.284	2.640	3.169	4.422	3.535	4.858
Average Va								
% VMA		11.203		11.271		10.596		11.003
Average % VMA		11.203		11.271				
% VFA		85.109		76.581		58.262		55.847
Average % VFA		85.109		76.581				
Height at N_{int}		128.8		129.2		128.3		129.2
Spec. Gravity at N_{int}		2.155		2.141		2.148		2.136
Va at N_{int}		11.211		12.210		13.660		14.137

Sample	FC-5		FC-6		FC-7		FC-8		Avg. Values
No. of Gyrations	174	109	174	109	174	109	174	109	
Height (mm)	114.5	116.1	113.3	114.7	114.4	116.1	114.4	115.9	
Volume (m)	2.022	2.051	2.001	2.026	2.021	2.051	2.021	2.047	
Individual Bulk Spec. Gravity		2.374		2.403		2.374		2.382	2.403
Average Spec. Gravity									
% Air Voids (V_a)	3.237	4.571	1.934	3.131	2.875	4.297	2.704	3.963	3.797
Average Va									
% VMA		10.735		9.838		10.924		10.613	10.458
Average % VMA		10.800							
% VFA		57.419		68.180		60.663		62.657	63.833
Average % VFA		57.055							
Height at N_{int}		130.5		127.7		128.6		128.8	
Spec. Gravity at N_{int}		2.112		2.158		2.143		2.143	2.148
Va at N_{int}		15.101		12.992		13.600		13.582	13.391

Table D-8 Properties for Fine Chattahoochee Mixtures

% AC	5.7			5.5			
Sample	FCH-1	FCH-2	FCH-3	FCH-4	FCH-5	FCH-6	
Agg. Weight (g)	4598	4598	4598	4598	4598	4598	
AC Weight (g)	278	278	278	268	268	268	
Weight before mix (g)	4876	4876	4876	4866	4866	4866	
Weight after mix (g)	4875.6	4868.8	4826	4854	4847.5	4850.2	
% Weight Loss	0.01	0.15	1.03	0.25	0.38	0.32	
Weight in Water (g)	2814.7	2804.3	2777.1	2783.7	2781.4	2778.6	
SSD Weight (g)	4877.1	4871.5	4828	4857	4850.6	4857.3	
Bulk Spec. Gravity (for 174 gyr.)	2.365	2.356	2.354	2.342	2.344	2.334	2.340

Rice Test Water Temp 23.0 C

Coeff. 1.000495

Sample	RFCH-1	RFCH-2	RFCH-3	RFCH-4
AC %	5.7	5.7	5.5	5.5
Weight (g)	800	825.4	800	817.7
Weight of Flask and Water (g)	3347.9	3239.5	3335.7	3248.6
Weight of Flask, Water, Sample (g)	3816.6	3719.9	3803.6	3725.9
Multiplier	1	1.000025	1.000495	1.000471
Gmm	2.415	2.393	2.410	2.403
Average Gmm		2.404		2.407
Gse	2.626	2.599	2.612	2.604
Average Gse		2.612		2.608

Specific Gravity

Aggregate	S1a	S1b	Chatt. Scn	Filler
Individual % by mass	18.6	13.5	63.7	4.3
Individual Spec. Gravity	2.4252	2.4509	2.6	2.69
Bulk Spec. Gravity of Aggregate	2.549			

Sample	FCH-1		FCH-2		FCH-3	
No. of Gyrations	174	109	174	109	174	109
Height (mm)	118.2	119.1	118.8	119.8	117.7	118.6
Volume (m)	2.088	2.104	2.098	2.116	2.079	2.095
Individual Bulk Spec. Gravity		2.347		2.337		2.336
Average Spec. Gravity						2.340
% Air Voids (V_a)	1.598	2.342	1.964	2.782	2.053	2.796
Average Va						2.387
% VMA		13.146		13.538		13.551
Average % VMA						13.411
% VFA		82.187		79.450		79.363
Average % VFA						80.333
Height at N_{int}		129.7		130.3		130.3
Spec. Gravity at N_{int}		2.155		2.148		2.127
Va at N_{int}		10.560		10.852		11.759

Sample	FCH-4		FCH-5		FCH-6		Avg. Values
No. of Gyrations	174	109	174	109	174	109	
Height (mm)	119.1	120.3	118.8	119.9	119.6	120.8	
Volume (m)	2.104	2.125	2.098	2.118	2.112	2.134	
Individual Bulk Spec. Gravity		2.319		2.322		2.311	2.311
Average Spec. Gravity							
% Air Voids (V_a)	2.674	3.645	2.612	3.505	3.003	3.966	3.705
Average Va							
% VMA		14.013		13.889		14.300	14.067
Average % VMA							
% VFA		73.991		74.763		72.265	73.673
Average % VFA							
Height at N_{int}		129.7		130.5		130.2	
Spec. Gravity at N_{int}		2.151		2.134		2.144	2.143
Va at N_{int}		10.750		11.464		11.021	11.079

Table D-9 Properties for Fine Cabbage Grove Mixtures

% AC	6.1			6.3			6.8			6.7			
Sample	FCG-1	FCG-2	FCG-3	FCG-4	FCG-5	FCG-6	FCG-7	FCG-8	FCG-9	FCG-10	FCG-11	FCG-12	
Agg. Weight (g)	4336	4336	4336	4336	4336	4336	4336	4336	4336	4336	4336	4336	
AC Weight (g)	282	282	282	292	292	292	316	316	316	311	311	311	
Weight before mix (g)	4618	4618	4618	4628	4628	4628	4652	4652	4652	4647	4647	4647	
Weight after mix (g)	4608.1	4606.7	4606.8	4624.9	4624.6	4618.1	4659.5	4636.5	4638.5	4647	4636.4	4633.1	
% Weight Loss	0.21	0.24	0.24	0.07	0.07	0.21	0.00	0.33	0.29	0.00	0.23	0.30	
Weight in Water (g)	2614.7	2613.9	2608.5	2635.4	2629.3	2625.4	2665.3	2652.1	2651.7	2652.5	2643.3	2652.6	
SSD Weight (g)	4613.8	4613.3	4615.7	4629.7	4632.2	4624.5	4664	4639.7	4643.4	4652.9	4642.4	4638	
Bulk Spec. Gravity (for 174 gyr.)	2.305	2.304	2.295	2.319	2.309	2.310	2.331	2.333	2.329	2.323	2.319	2.334	2.325

Rice Test

Sample	RFCG-1	RFCG-2	RFCG-3	RFCG-4	RFCG-5	RFCG-6	RFCG-7	RFCG-8	
AC %	6.1	6.1	6.3	6.3	6.8	6.8	6.7	6.7	
Weight (g)	750	785.4	750	788.1	750	803.7	755	794.2	
Weight of Flask and Water (g)	3332.9	3254.9	3332.9	3254.9	3208.3	3254.9	3236	3236	
Weight of Flask, Water, Sample (g)	3772.3	3714.6	3771.4	3715.9	3642.6	3720.3	3673.4	3697.1	
Multiplier	1.000495	1.000495	1.000951	1.00084	1.000375	1.000375	1.000127	0.99987	
Gmm	2.416	2.413	2.410	2.411	2.377	2.377	2.378	2.384	
Average Gmm		2.414		2.411		2.377		2.381	2.381
Gse	2.645	2.641	2.646	2.648	2.625	2.625	2.626	2.634	
Average Gse		2.643		2.647		2.625		2.630	2.630

Specific Gravity

Aggregate	S1a	S1b	Cabb. Gr. Scrn	Filler
Individual % by mass	19.7	14.3	61.5	4.5
Individual Spec. Gravity	2.4252	2.4509	2.367	2.69
Bulk Spec. Gravity of Aggregate	2.403			

Sample	FCG-1		FCG-2		FCG-3		FCG-4		FCG-5		FCG-6	
No. of Gyrations	174	109	174	109	174	109	174	109	174	109	174	109
Height (mm)	114.9	116.7	115.3	117.1	115.6	117.4	114.6	116.5	115.6	117.4	115.4	117.2
Volume (m)	2.029	2.061	2.036	2.068	2.042	2.074	2.024	2.058	2.042	2.074	2.038	2.070
Individual Bulk Spec. Gravity		2.270		2.269		2.260		2.281		2.274		2.275
Average Spec. Gravity						2.266						
% Air Voids (V_a)	4.521	5.994	4.565	6.032	4.934	6.391	3.801	5.370	4.220	5.689	4.173	5.645
Average Va						6.139						5.568
% VMA		11.322		11.358		11.697		11.055		11.355		11.313
Average % VMA						11.459						11.241
% VFA		47.060		46.894		45.360		51.426		49.900		50.106
Average % VFA						46.438						50.477
Height at N_{ini}		129.7		130.3		130.3		129.7		130.5		130.2
Spec. Gravity at N_{ini}		2.042		2.039		2.036		2.049		2.045		2.047
Va at N_{ini}		15.267		15.402		15.510		14.976		15.132		15.042

Sample	FCG-7		FCG-8		FCG-9		FCG-10		FCG-11		FCG-12		Avg. Values
No. of Gyrations	174	109	174	109	174	109	174	109	174	109	174	109	
Height (mm)	114.9	116.4	114.2	116.1	114.7	116.5	115.1	116.9	115.1	117.1	114.3	116.1	
Volume (m)	2.029	2.056	2.017	2.051	2.026	2.058	2.033	2.065	2.033	2.068	2.019	2.051	
Individual Bulk Spec. Gravity		2.301		2.295		2.293		2.287		2.280		2.297	2.288
Average Spec. Gravity													
% Air Voids (V_a)	1.907	3.171	1.846	3.452	2.006	3.520	2.424	3.926	2.583	4.247	1.980	3.500	3.891
Average Va						3.381							
% VMA		10.754		11.014		11.076		11.201		11.497		10.807	11.168
Average % VMA						10.948							
% VFA		70.517		68.657		68.223		64.949		63.063		67.613	65.208
Average % VFA						69.132							
Height at N_{ini}		130.4		130.2		130.1		130.8		131.2		129.8	
Spec. Gravity at N_{ini}		2.054		2.046		2.053		2.044		2.035		2.055	2.045
Va at N_{ini}		13.567		13.908		13.605		13.986		14.388		13.534	13.969

Table D-10 Properties for Fine Ruby Granite Mixtures

% AC	6		5.7	6.4		5.9						
Sample	FR-1	FR-2	FR-3	FR-4	FR-5	FR-6	FR-7	FR-8	FR-9	FR-10	FR-11	
Agg. Weight (g)	4688	4688	4688	4688	4688	4688	4688	4688	4688	4688	4688	
AC Weight (g)	300	300	283	320	320	294	294	294	294	294	294	
Weight before mix (g)	4988	4988	4971	5008	5008	4982	4982	4982	4982	4982	4982	
Weight after mix (g)	4989.1	4987.6	4945.4	4981.2	4982.8	4965.9	4967.1	4966.9	4971.4	4970.2	4962.8	
% Weight Loss	0.00	0.01	0.51	0.54	0.50	0.32	0.30	0.30	0.21	0.24	0.39	
Weight in Water (g)	2846.2	2867	2819.7	2874.4	2865	2851.9	2859.8	2830.9	2826.7	2839.1	2831.7	
SSD Weight (g)	4993.4	4991.2	4953.9	4983.2	4984.2	4968.4	4970.5	4974.3	4979.8	4975.2	4968.6	
Bulk Spec. Gravity (for 174 gyr.)	2.324	2.348	2.32	2.36	2.35	2.346	2.353	2.317	2.309	2.327	2.322	2.329

Rice Test

Sample	RFR-1	RFR-2	RFR-3*		RFR-4*	RFR-5	RFR-6	RFR-7	RFR-8	*Predicted
Weight (g)	800	859.3				836	824.8	800	857.9	
Weight of Flask and Water (g)	3332.9	3208.3				3334.3	3231.7	3204.2	3255.1	
Weight of Flask, Water, Sample (g)	3800.9	3711				3824.1	3714.3	3674.6	3757.6	
Multiplier	0.999466	0.999466				0.99987	0.999466	1.000127	0.99987	
Gmm	2.408	2.408	2.419		2.395	2.414	2.409	2.427	2.414	
Average Gmm		2.408	2.419		2.395		2.412		2.421	2.416
Gse	2.631	2.631				2.635	2.628	2.651	2.634	
Average Gse		2.631	2.631		2.631		2.631		2.642	2.637

Specific Gravity

Aggregate	S1a	S1b	Ruby Scrn	Filler
Individual % by mass	18.2	13.3	64.4	4.2
Individual Spec. Gravity	2.4252	2.4509	2.68	2.69
Bulk Spec. Gravity of Aggregate	2.599			

Sample	FR-1		FR-2		FR-3		FR-4		FR-5	
No. of Gyrations	174	109	174	109	174	109	174	109	174	109
Height (mm)	124	125.6	122.3	123.7	123.1	124.5	121.5	122.9	122.1	123.5
Volume (m)	2.190	2.218	2.160	2.185	2.174	2.199	2.146	2.171	2.157	2.181
Individual Bulk Spec. Gravity		2.294		2.321		2.291		2.335		2.325
Average Spec. Gravity				2.308		2.291				2.330
% Air Voids (V_a)	3.523	4.752	2.508	3.611	4.208	5.285	1.374	2.497	1.826	2.939
Average Va				4.182		5.285				2.718
% VMA		17.017		16.023		16.854		15.885		16.266
Average % VMA				16.520		16.854				16.075
% VFA		72.076		77.464		68.642		84.280		81.931
Average % VFA				74.689		68.642				83.105
Height at N_{int}		138.2		136.1		136.5		135.4		135.6
Spec. Gravity at N_{int}		2.085		2.110		2.090		2.120		2.117
Va at N_{int}		13.494		12.452		13.289		12.049		12.150

Sample	FR-6		FR-7		FR-8	FR-9	FR-10		FR-11		Avg. Values
No. of Gyrations	174	109	174	109	109	109	174	109	174	109	
Height (mm)	121.8	123.3	121.6	123	123.7	124	122.9	124.4	122.3	123.8	
Volume (m)	2.151	2.178	2.148	2.172	2.185	2.190	2.171	2.197	2.187	2.160	
Individual Bulk Spec. Gravity		2.318		2.327	2.317	2.309		2.299		2.294	2.311
Average Spec. Gravity											
% Air Voids (V_a)	2.891	4.073	2.601	3.710	4.091	4.436	3.699	4.860	3.878	5.043	4.369
Average Va											
% VMA		16.067		15.750	16.083	16.386		16.756		16.916	16.326
Average % VMA											
% VFA		74.652		76.447	74.565	72.925		70.995		70.188	73.295
Average % VFA											
Height at N_{int}		135.4		134.9	136.1	136.1		136.8		136.1	
Spec. Gravity at N_{int}		2.111		2.121	2.094	2.099		2.090		2.113	2.105
Va at N_{int}		12.423		11.980	13.102	12.922		13.264		12.343	12.672

APPENDIX E
MIXTURE PROPERTIES

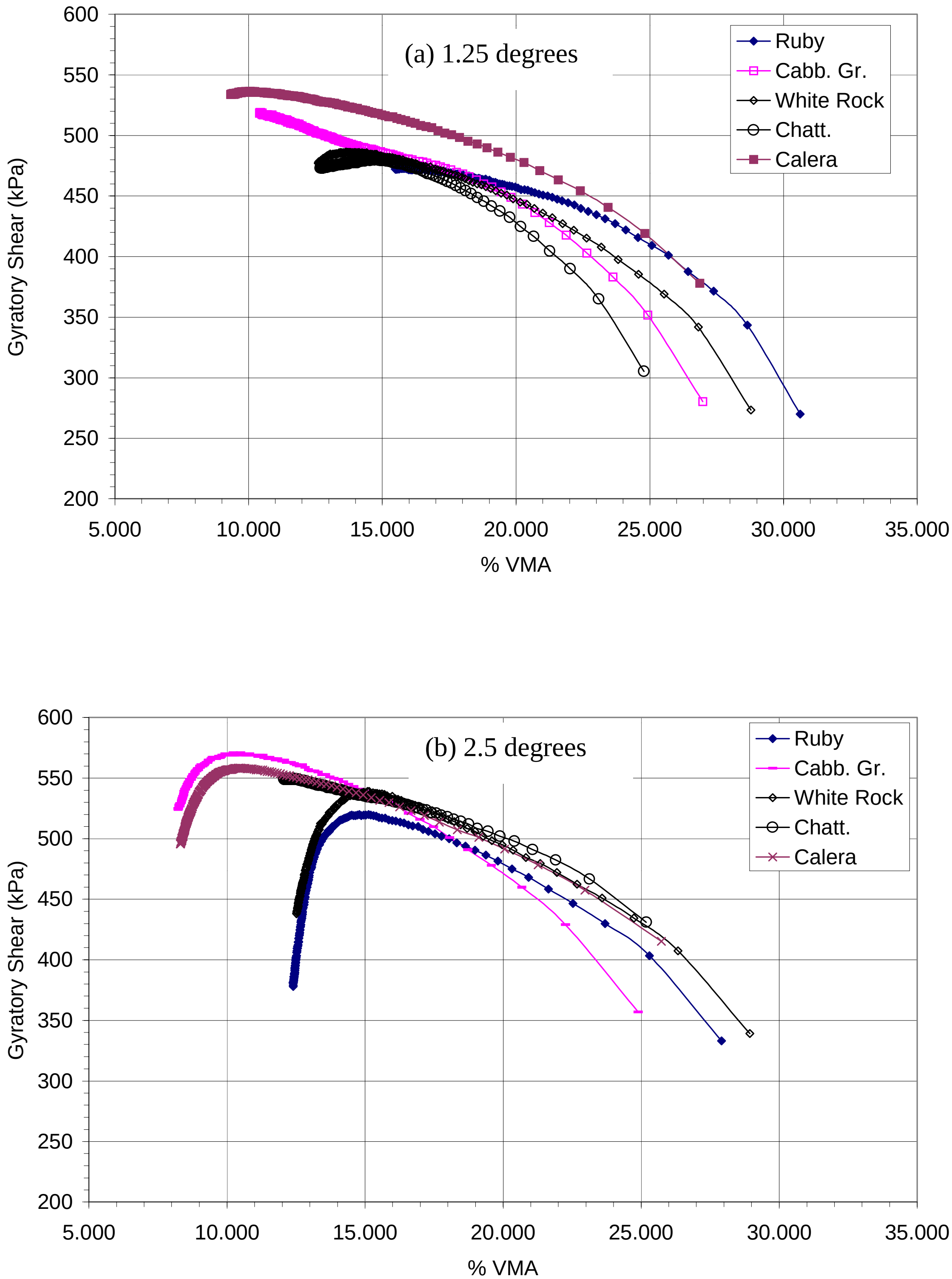
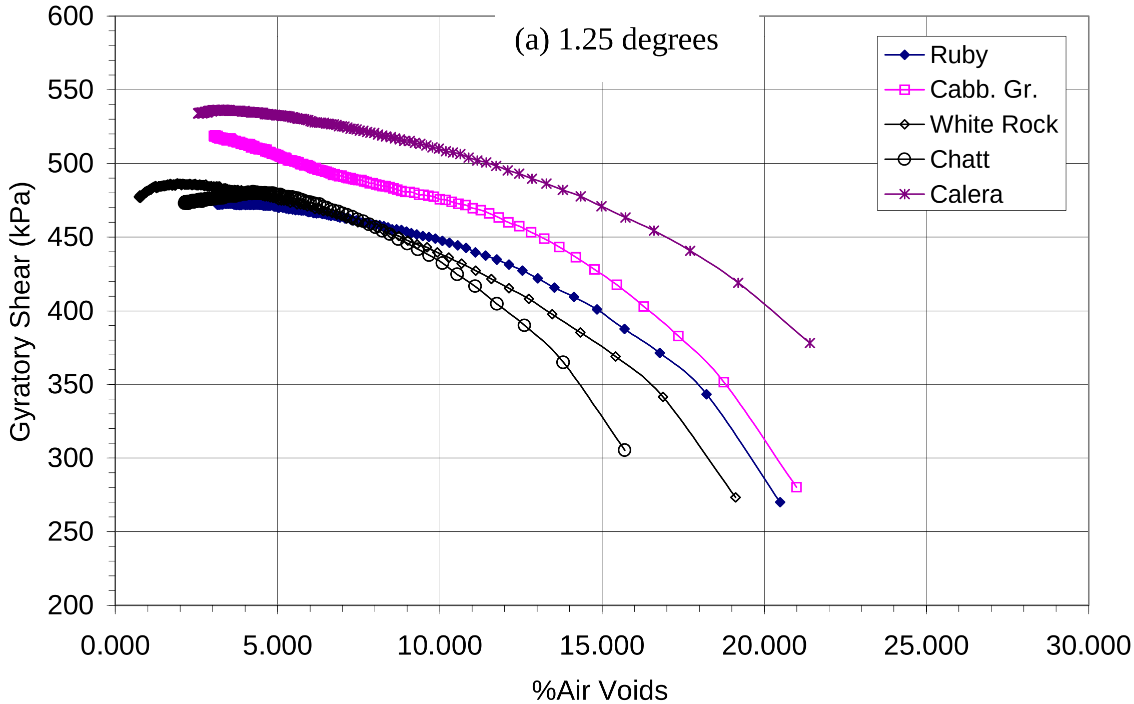


Figure E-1 Servopac Gyratory Shear versus %VMA for Fine Mixtures



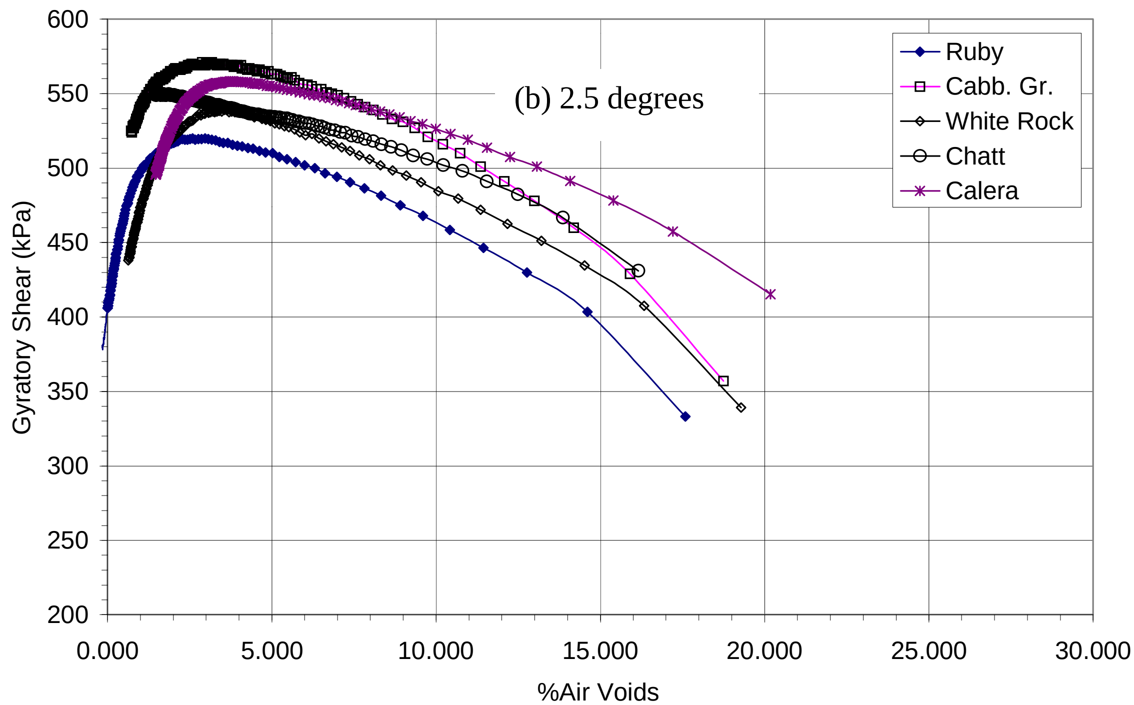


Figure E-2 Servopac Gyratory Shear versus % Air Voids for Fine Mixtures

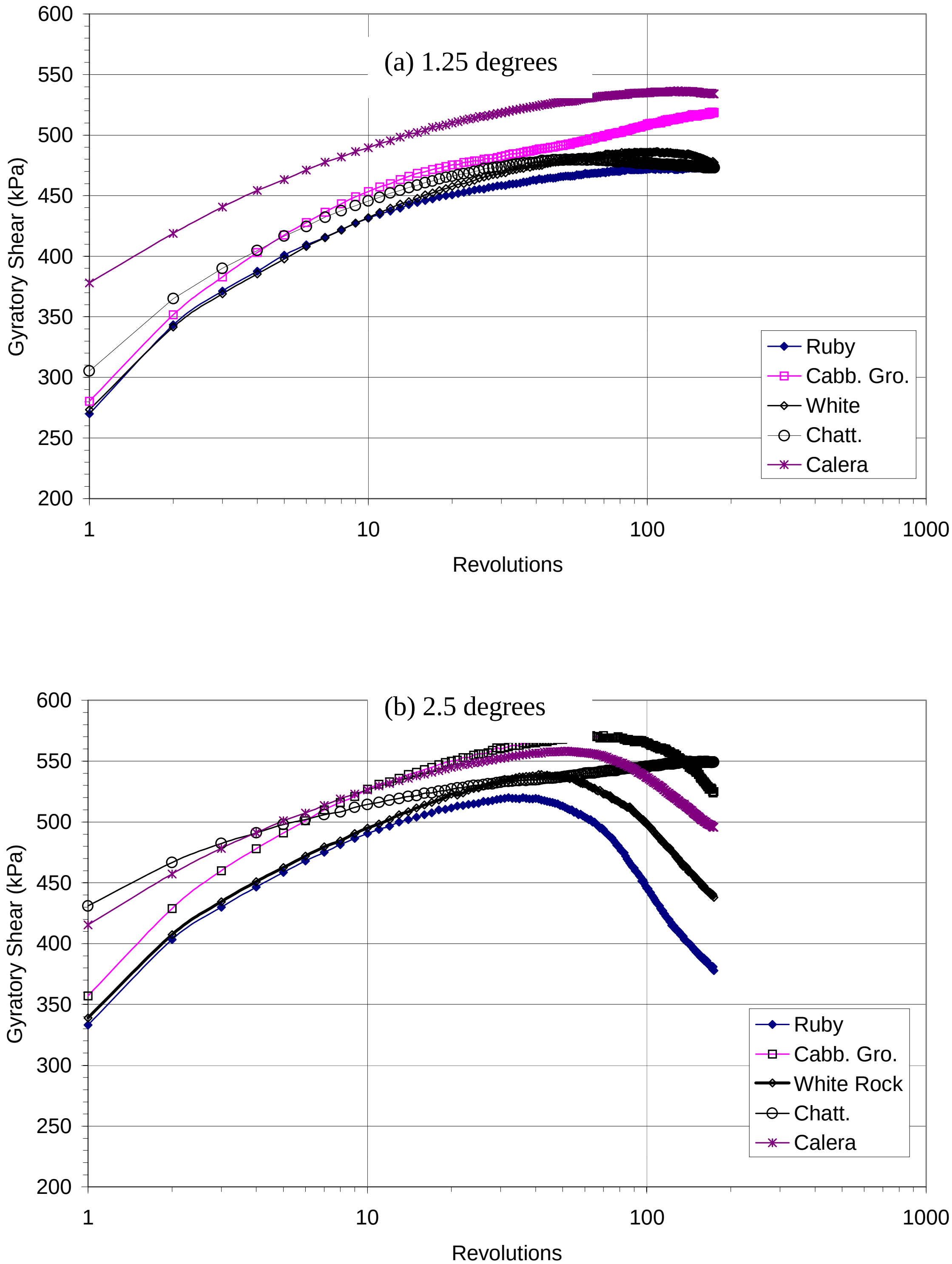
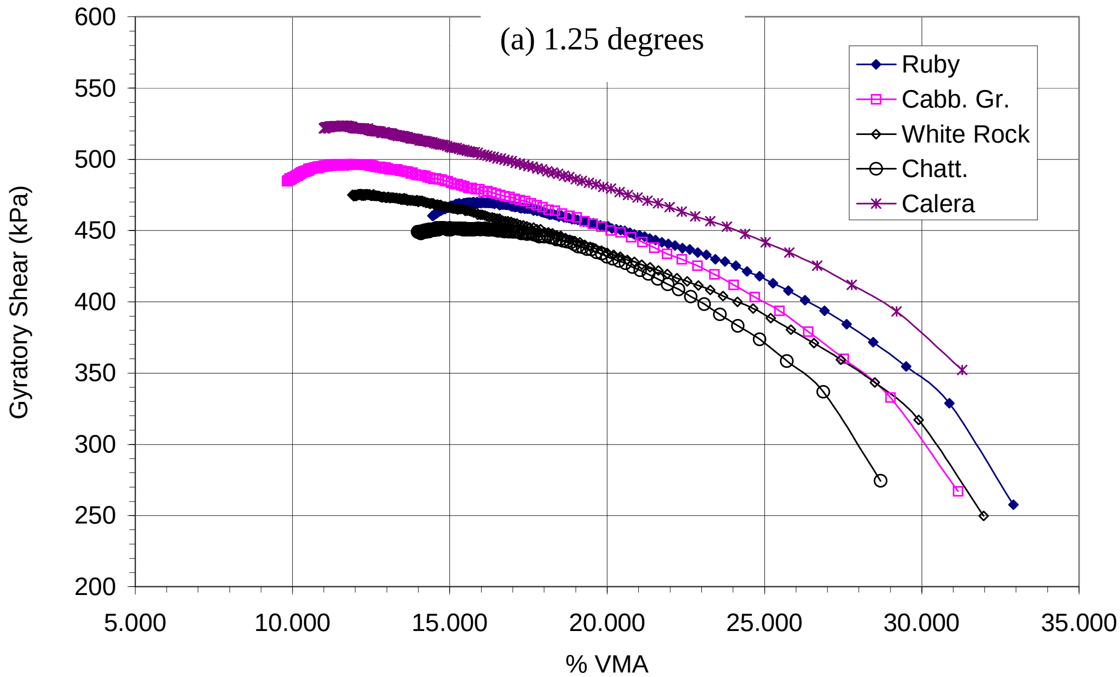


Figure E-3 Servopac Gyratory Shear versus No of Revolutions for Fine Mixtures



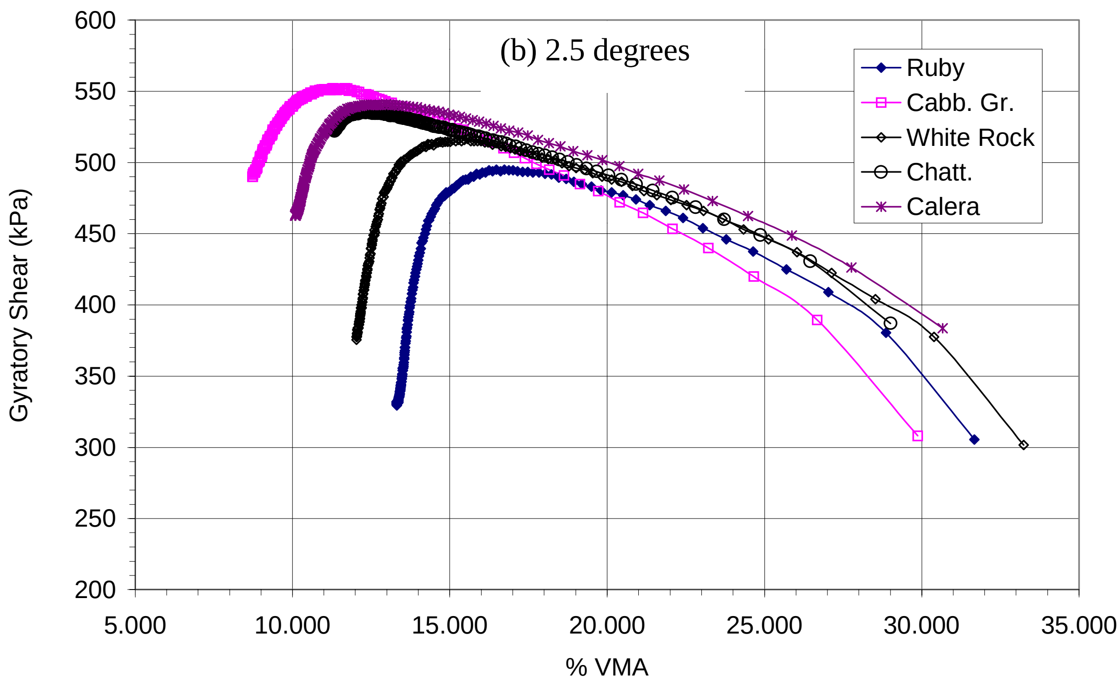
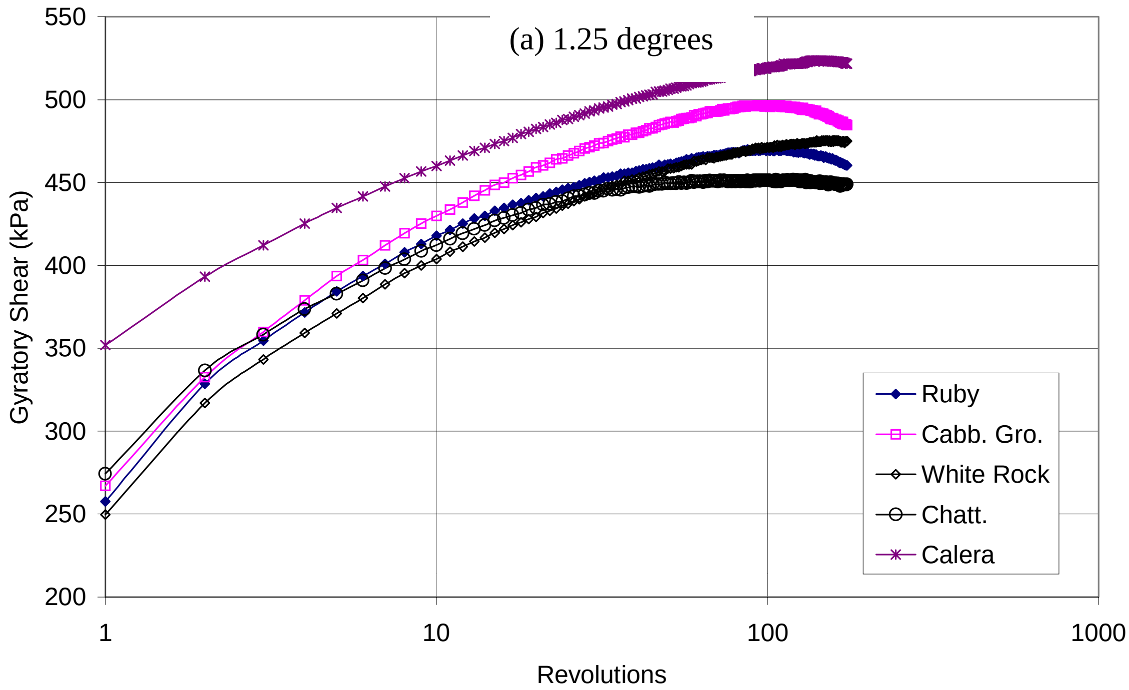


Figure E-4 Servopac Gyratory Shear versus % VMA for Coarse Mixtures



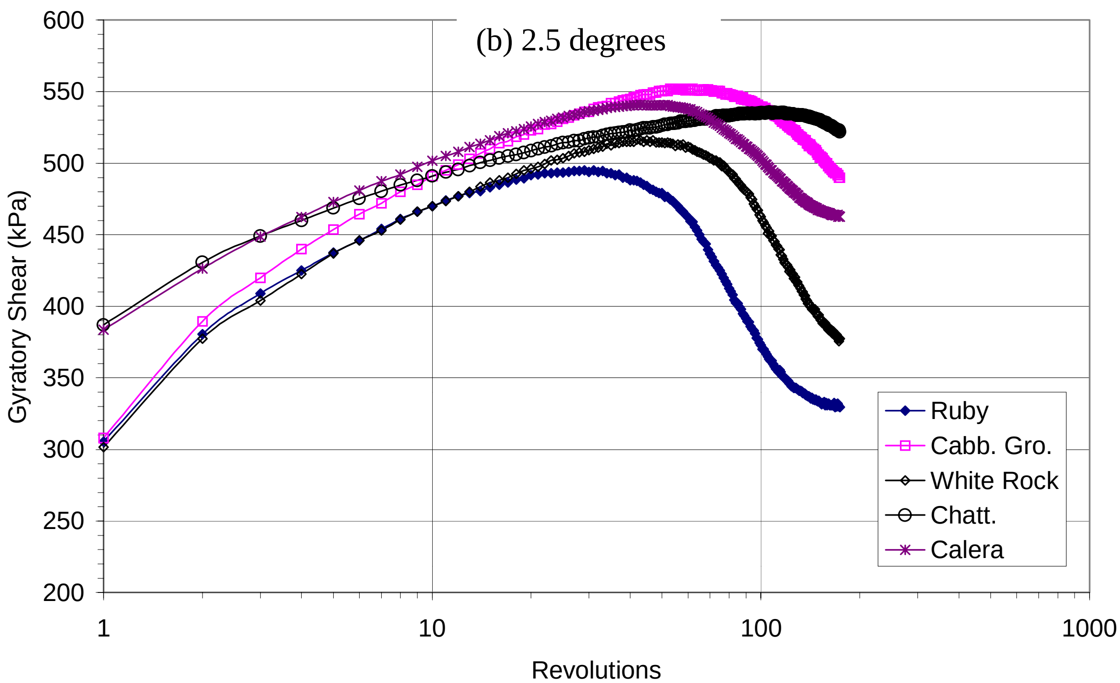


Figure E-5 Servopac Gyratory Shear versus Number of Revolutions for Coarse Mixtures

REFERENCES

American Association of Society of State Highway Transportation Officials, 1994.

American Society of Testing and Materials, 1999.

Anderson, R. M., and Bahia, H. U., "Evaluation and Selection of Aggregate Gradations for Asphalt Mixtures Using Superpave," *Transportation Research Record 1583*, Transportation Research Board (TRB), National Research Council (NRC), Washington, DC, 1997, pp. 91-97.

Asphalt Institute, *Superpave Level 1 Mix Design*, Asphalt Institute, Lexington, KY, 1996.

Aschenbrener, T., and MacKean, C., "Factors That Affect the Voids in the Mineral Aggregate of Hot-Mix Asphalt," *Transportation Research Record 1469*, TRB, NRC, Washington, DC, 1994, pp. 1-8.

Benson, R.B., "Effects of Aggregate Size, Shape, and Surface Texture on the Properties of Bituminous Mixtures – A Literature Survey," *HRB SR 109*, Highway Research Board, Washington, DC, 1970, pp. 12-22.

Brown, R.B., and Cross, S. A., "A National Study of Rutting in Asphalt Pavement," *Proceedings*, Association of Asphalt Pavement Technologists, Vol. 61, 1992, pp. 535-573.

Butcher, M., "Determining Gyratory Compaction Characteristics Using the Servopac Gyratory Compactor," *Transportation Research Record 1630*, TRB, NRC, Washington, DC, 1998, pp. 89-97.

Chowdhury, A., Button, J. W., Kohale, V., and Jahn, D.W., "Evaluation of Superpave Fine Aggregate Angularity Specification, *Report No. 404011-1*, International Center for Aggregate Research International Center for Aggregate Research, 2001.

Fernandes, J.L., Roque, R., Tia, M., and Casanova, L., "Evaluation of Uncompacted Void Content of Fine Aggregate as a Quality Indicator of Materials Used in Superpave Mixtures," *Journal of the Transportation Research Board*, NRC, Washington, DC, 2000.

Foster, C.R., "Dominant Effect of fine Aggregate on Strength of Dense-Graded Asphalt Mixes," *HRB SR 109*, Highway Research Board, Washington, DC, 1970, pp. 1-3.

Huber, G.A., "Methods to Achieve Rut-Resistant Durable Pavements," *Synthesis of Highway Practice 274*, NCHRP, NRC, Washington, DC, 1999.

Huber, G.A., Jones, J.C., Messersmith, P.E., and Jackson, N.M., "Contribution of Fine Aggregate Angularity and Particle Shape to Superpave Mixture Performance," *Transportation Research Report 1609*, TRB, NRC, Washington, DC, 1998, pp. 28-35.

Kandhal, P.S., and Mallick, R.B., "Evaluation of Asphalt Pavement Analyzer for HMA Mix Design," TRB, NRC, Washington, DC, 1999.

Kandhal, P.S., Khatri, M., and Potter, J. B., "Evaluation of Particle Shape and Texture of Mineral Aggregates and Their Blends," *Proceedings*, Association of Asphalt Pavement Technologists, Vol. 61, 1992, pp. 217-240.

Lee, C.J., Pan, C., and White, T., "Review of Fine Aggregate Angularity Requirements in Superpave," *Proceedings*, Association of Asphalt Pavement Technologists, Vol. 68, 1999.

Mallick, R.B., "Use of Superpave Gyratory Compactor to Characterize Hot Mix Asphalt (HMA)," *Transportation Research Record 1681*, TRB, NRC, Washington, DC, 1999, pp. 86-96.

National Center for Asphalt Technology, *Hot Mix Asphalt Materials, Mixture Design and Construction*, NAPA Education Foundation, Lanham, MD, 1996.

Parker, Jr., F., "Evaluation of Tests Methods for Shape and Texture of Fine Aggregate Particles," National Center for Asphalt Technology, Auburn University, AL, 1977.

Schklarsky, E., and Livneh, M., "The Use of Gravels for Bituminous Paving Mixtures," *Proceedings*, Association of Asphalt Pavement Technologists, Vol. 33, 1964, pp. 584-610.

Tayebali, A.A., Tsai, B., and Monismith, C.L., "Stiffness of Asphalt-Aggregate Mixes," *Publication No. SHRP-A-388*, National Research Council, Washington, DC, 1994.

Vavrick, W.R., Fries, R.J., and Carpenter, S.H., "Effect of Flat and Elongated Coarse Aggregate on Characteristics of Gyratory Compacted Samples," *Transportation Research Record 1681*, TRB, NRC, Washington, DC, 1999, pp. 28-36.

Wang, L.B., and Lai, J.S., "Quantify Specific Surface Area of Aggregates Using Imaging Technique," TRB, NRC, Washington, DC, 1998.