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Resilient Modulus at the Limits of Gradation and Varying Degrees of Saturation

FINAL REPORT

Research Report RC-1497

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Findings showed that the stiffness is dependent on material type. As a generalization, natural gravel is always softest, dolomite and slag behave similarly and are stiffest, and crushed concrete occupies an intermediate position. The stiffness is also dependent upon the ratio of fine to coarse aggregate within the specification. As the ratio increases, the material's compacted stiffness decreases. Significant stiffness differences occur within the limits of the 4G specification band; stiffnesses could vary by up to 50%. For every material type it was also observed that the effect of moisture content increases as the ratio of fine to coarse fraction increases. An increase in moisture content was shown to decrease stiffness.</td></tr>
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EXECUTIVE SUMMARY

This report details a laboratory study which was intended to evaluate the 4G aggregate specification as a quality control specification. The study variables were the gradation, the material, and the moisture condition. The characteristic to be controlled was the stiffness, and the stiffness of each compacted unbound granular material was measured by the resilient modulus.

Four materials were used. They were a natural gravel, crushed dolomite, slag, and recycled crushed concrete. Each material was judged at the gradation limits and at various moisture contents by a comparison to its as-compacted behavior. Each material was also compared to the other three materials at the various moisture contents and gradation limits. The compacted condition used was 98% of each material's T99 maximum unit weight.

More than 100 resilient modulus tests were performed, including many at a saturated condition. This condition was used to model a worst case scenario in the field when downward drainage could not occur and snow melt or rains provided sufficient water to fill the void spaces. In order to analyze these results a statistical approach was developed and the results were expressed as zones at a 95% confidence level in the relation between resilient modulus and bulk stress.

The experimental program was judged to be a success. It provided very reproducible results and conclusions could be drawn concerning the variability of stiffness as measured by the resilient modulus within the limits of the 4G specification.

Findings showed that the stiffness is dependent on material type. As a generalization, natural gravel is always softest, dolomite and slag behave similarly and are stiffest, and crushed concrete occupies an intermediate position. The stiffness is also dependent upon the ratio of fine to coarse aggregate within the specification. As the ratio increases, the material's compacted stiffness decreases. For every material type it was also observed that the effect of moisture content increases as the ratio of fine to coarse fraction increases.

Significant stiffness differences occur within the limits of the 4G specification band. The Uniformity Clause of the 4G specification adds an additional constraint which limits the aggregate's grain size distribution between the broad 4G gradation limits. Without this additional constraint stiffnesses could vary by up to 50%.

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SYMBOLS~DEFINITIONS

Base/Sub-base Course	Generally densified, graded aggregate (stabilized or unstabilized) which helps to distribute load stresses.
Bulk stress	$\sigma_1 + \sigma_2 + \sigma_3$ (isotropic compression).
'B' Parameter	Δu / $\Delta\sigma_3$
Elastic deformation	Strain/deformation recovered on unloading.
Plastic strain/deformation	Unrecoverable or permanent strain/deformation.
Elasto-plastic	Strain/deformation with both recoverable and unrecoverable components after loading.
u	Pore pressure.
k_1, k_2	Regression coefficients used in best-fit-line equations for resilient modulus curves.
M_r	Resilient modulus – symbol used universally (this paper) for resilient modulus of base, sub-base or subgrade.
Normally consolidated	Soil that has never before been subjected to a vertical effective stress higher than the current value.
Overconsolidated	Soil which has seen higher vertical stresses than the current vertical stresses that are being applied.
Soil – Aggregate	Natural or prepared mixtures consisting predominately of stone, gravel or sand.
σ_1	Major principal stress.
σ_2	Intermediate principal stress.
σ_3	Minor principal stress.
σ'	Effective stress.
σ_d	Deviator stress ($\sigma_{1maximum}$ - $\sigma_{1minimum}$).
θ	Bulk stress ($\sigma_1 + \sigma_2 + \sigma_3$).

1 INTRODUCTION

This report, *Resilient Modulus at the Limits of Gradation and Varying Degrees of Saturation*, is the final report for a contract between Michigan Technological University and the Michigan Department of Transportation (MDOT) which was first proposed to MDOT on June 1, 2003.

The focus of this testing program was to determine the influence of gradation on the stiffness characteristics of the unbound base course aggregate. The "uniformity clause" assumes that gradation has a considerable influence on the stiffness characteristics of the unbound aggregate course. This clause is described in the *2003 Standard Specifications for Construction, Michigan Department of Transportation (MDOT)* under <u>Section 303.03. Open-Graded Drainage Courses/2b. In-Place Acceptance Criteria</u>**:**

> For gradation the Engineer will obtain at least three random samples from the test area. To be acceptable, the gradation of each sample must meet the specified 4G gradation, and the test results among them must not vary by more than 5 percent on any sieve.

The gradation of the aggregate determines both the frictional particle-to-particle contact area of the individual aggregate particles and the mechanical interlock between particles. Stiffness is a function of both.

The 4G gradation is intended to provide an open graded pavement course that allows for greater permeability or lower field saturation levels, than "densely graded" pavement courses. The 4G specification recognizes that an increase in pore fluid pressure, due to vehicle wheel loading, will degrade the frictional strength properties, e.g. stiffness, of an unbound aggregate.

The "uniformity clause" attempts to further limit the range of stiffness which can occur at the limiting bounds of the 4G gradation specification. The "uniformity clause" assumes that the gradation of the unbound aggregate is very influential in developing the stiffness of that aggregate base course. Also, it is postulated that at the bounds of the 4G gradation specifications the same moisture content will result in considerably different performance, i.e. stiffness.

1.1 OBJECTIVE STATEMENT

The objective of this testing program was to determine whether the dynamic stiffness of an unbound pavement base course, represented by a lab specimen, of a 4G gradation varies significantly over the acceptable gradation limits and a broad range of degrees of saturation.

To achieve this objective the stiffness characteristics of several unbound aggregate types, of a 4G gradation, were tested at the upper and lower bound gradation curves of the 4G gradation specification. Furthermore, aggregate specimens constructed at the upper and lower bound gradation curves were tested at four different degrees of saturation. The stiffness was characterized by the material's resilient modulus.

1.2 PLAN OF THE REPORT

Four different aggregates were tested at four different moisture conditions. Each combination was tested several times for a total of more than 100 resilient modulus tests. In following sections of this report the materials and testing procedures are described. Following these descriptions the results of a few typical tests are described, feature by feature, to explain the traditional log-log representation of results along with a much more meaningful representation which was developed for this study.

In the results and analysis of results sections, most representations are the average of several tests on like-material and moisture condition. The entire set of individual test results is given in the CD, which is a part of this report. It is intended that the printed portion of the report can stand by itself, but for completeness the material contained in the CD *Appendix – Test Data and Data Reduction* is included.

2 TEST PROGRAM, DESCRIPTION OF MATERIALS, SPECIMEN PREPARATION, AND TESTING PROCEDURES

This chapter describes the test program, the unbound granular materials tested, the procedures used to build the test specimens, and the testing protocols used to develop the Resilient Modulus. Section 2.1 describes the general testing program relative to the objectives of the program. Section 2.2 describes the materials used as well as their as-received and as-tested gradations. Section 2.3 describes the methods used to build the test specimens and their constructed unit weights. Also included in this section are descriptions of the resilient modulus testing protocols and the methods used for data reduction to acquire the modulus values. Finally, the resilient modulus testing equipment that was used is described.

2.1 TEST PROGRAM

The objective of this testing program is to determine whether the resilient modulus of an unbound pavement base course, represented by a lab specimen, of a 4G gradation varies significantly over the acceptable gradation limits and a broad range of degrees of saturation.

To achieve this objective four unbound aggregate types will be tested in a tri-axial chamber to characterize their stiffness characteristics. Each material type will be tested at three different gradations and each gradation will be tested at four different degrees of saturation or moisture contents. A summary of the resilient modulus tests that were conducted is shown in Table 2.1-1.

Table 2.1-1 Summary of Resilient Modulus Tests

		Natural Gravel	Dolomite	Slag	Crushed Concrete
Lower Bound Gradation	As-compacted MC	X	X	X	X
	Wetting Curve MC	X	X	X	X
	Drying Curve MC	X	X	X	X
	Fully Saturated	X	X	X	X
Upper Bound Gradation	As-compacted MC	X	X	X	X
	Wetting Curve MC	X	X	X	X
	Drying Curve MC	X	X	X	X
	Fully Saturated	X	X	X	X
Maximum Density Gradation	As-compacted MC	X	X	X	X
	Wetting Curve MC	X	X	X	X
	Drying Curve MC	X	X	X	X
	Fully Saturated	X	X	X	X

2.2 DESCRIPTION OF MATERIALS

Sections 2.2.1 and 2.2.2 describe the materials used, their sources and as-received gradations. Section 2.2.3 discusses the as-tested gradations and how they were developed. The three as-tested gradations are known as Lower Bound Gradation, Upper Bound Gradation, and Maximum Density Gradation. The materials and their source locations were determined by MDOT.

2.2.1 MATERIAL TYPES AND SOURCES

Four different unbound granular materials (UGM) were used for this testing program. Two materials were natural rock and two materials were recycled or industrial by-products. These four materials were Natural Gravel, Dolomite, Blast Furnace Slag (Slag) and Crushed Concrete.

The Natural Gravel is produced by crushing and screening natural gravel. It is composed of a variety of mineral types, but is predominately quartzic and was formed by the disintegration of rock under glacial working or fluvial/alluvial transport. The textures and colors of the rock are numerous and varied.

The other natural material is Dolomite from the dock at Ferrysburg, Michigan. It is a carbonate which is quarried and then crushed. Dolomite is typically light to dark gray in color, with a fairly smooth texture.

Blast Furnace Slag (slag) is the industrial by-product tested as a UGM. It is produced by crushing air cooled iron blast furnace slag. It is light brown to dark gray in color and has a very porous texture. Upon wetting, it gives off a sulfurous odor.

Finally recycled Crushed Concrete was tested as a UGM. The material comes from recycled Portland Cement Concrete that has been used MDOT projects, which has been crushed and screened. Crushed concrete is comprised of Portland cement and a natural gravel aggregate; it is light gray in color and has a fine rough texture.

2.2.2 GRADATIONS AS RECEIVED

Figure 2.2-1 through Figure 2.2-4 show the as-received gradations of the Natural Gravel, Dolomite, Slag and Crushed Concrete, respectively, unbound granular materials as delivered by a contract hauler to Michigan Technological University. Several samples of each material were taken and then analyzed. All the samples for each material were then averaged to develop an average as-received gradation curves. The following figures also show how the as-received gradation falls within the upper and lower bound gradation specifications for MDOT 4G as shown in Table 2.1-1.

Table 2.2-1 MDOT "at pit" 4G Gradation Specification

Sieve Size	Lower Bound Gradation Spec.'s % Passing	Upper Bound Gradation Spec.'s % Passing
1.5 in.	100	100
3/4 in.	60	80
1/2 in.	35	65
#8	10	25
#30	5	18
LBW	0	6
		Note: "at the pit" gradation

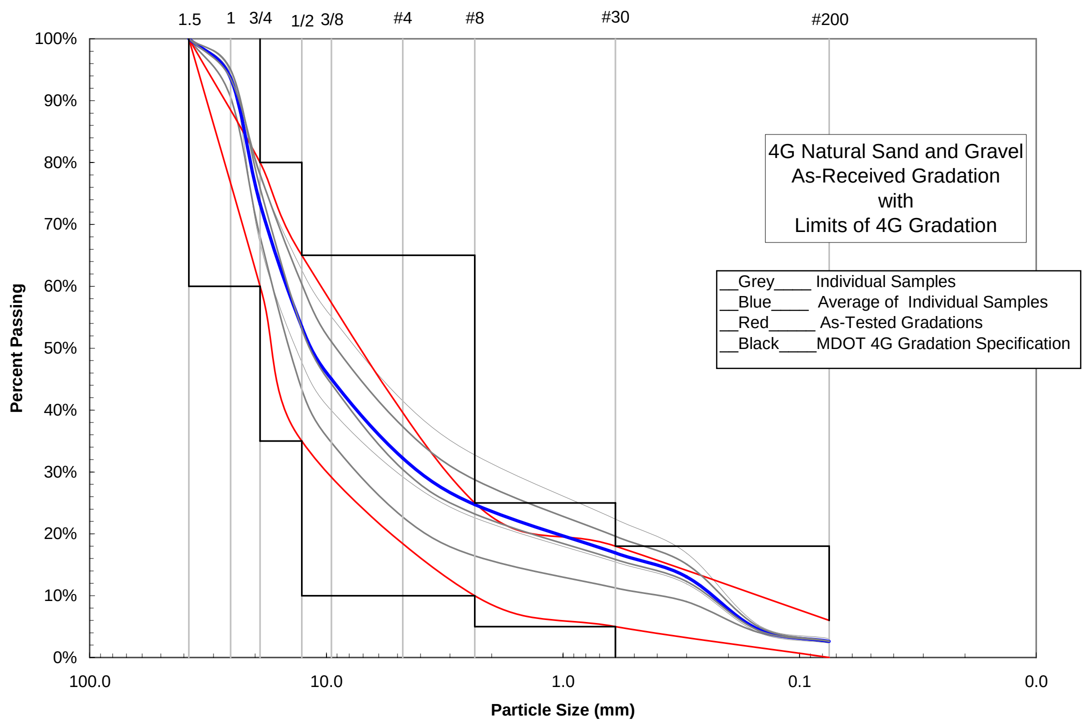

Figure 2.2-1 As-Received and As-Tested Gradations; 4G Natural Gravel

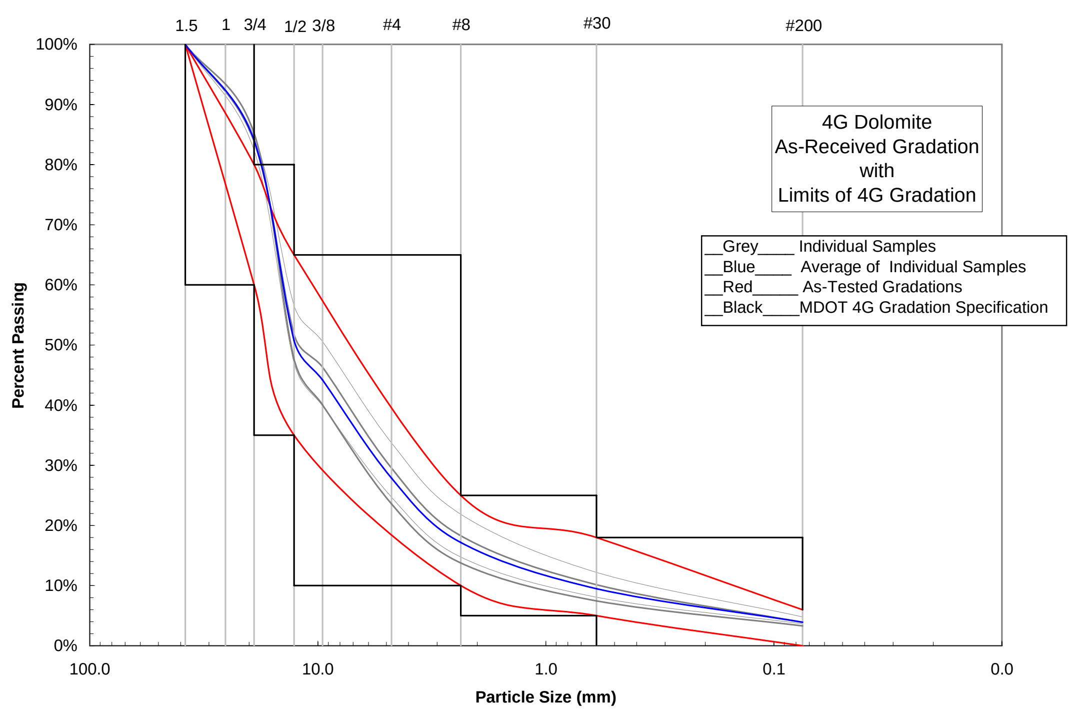

Figure 2.2-2 As-Received and As-Tested Gradations; 4G Dolomite

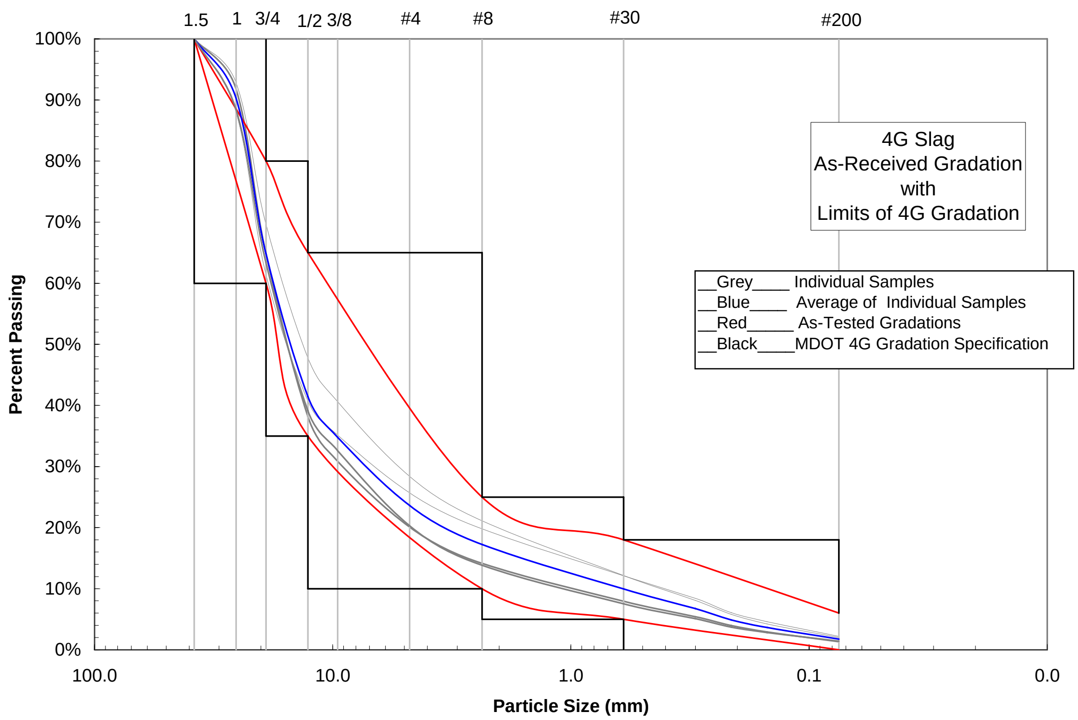

Figure 2.2-3 As-Received and As-Tested Gradations; 4G Slag

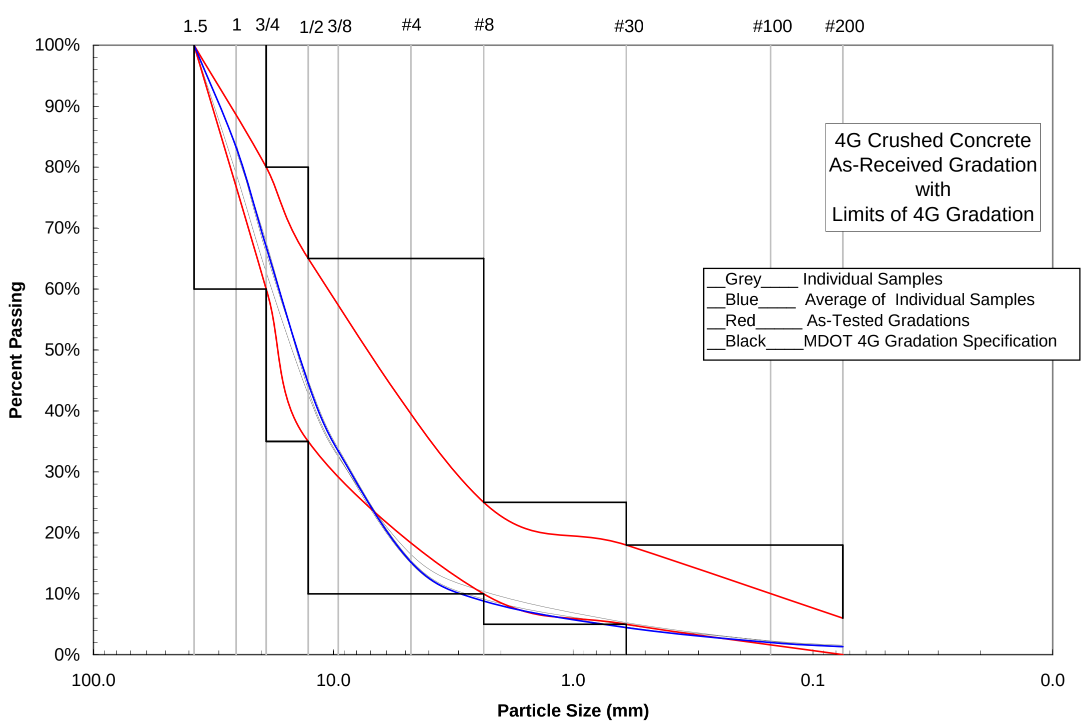

Figure 2.2-4 As-Received and As-Tested Gradations; 4G Crushed Concrete

2.2.3 GRADATIONS AS TESTED

The as-received material, after being analyzed for its gradation curve, was then washed of fines and dried. Each was then screened to produce seven different fractions: 1) Passing (P) 1.5" – Retained (R) ¾", 2) P ¾" – R ½", 3) P½" – R⅜", 4) P⅜" – R #4, 5) P #4 – R #8, 6) P #8 – R #30, and, 7) P #30 – R #200. These fractions were combined with fines, as required, to produce the three as-tested gradations shown in Table 2.2-2.

The three as-tested gradations are 4G Upper Bound Gradation, 4G Lower Bound Gradation and Line of Maximum Density Gradation. Their gradation curves are shown in Figure 2.2-5. All three gradations are based on M-DOT's 4G specification. Each fraction for the specification has tolerance limits for the percent passing. Hence, the names of the gradations, Upper Bound and Lower Bound, these names describe the upper and lower limits or bounds of the gradation specification tolerances. The *upper bound gradation* is biased towards fine aggregate content, while the *lower bound gradation* is biased towards a coarse aggregate content. The line of maximum density gradation is developed using the Power 0.45 method to create the densest gradation configuration. In this case the fractions available were used to configure the "line of maximum density". For added reproducibility, of the gradation for this study the percent passing was also specified at the ⅜" and #4 sieves. The percent passing at these two fractions simply intersects the percent passing curve and does not change the gradation. These two points are demarcated on the gradation curves in Figure 2.2-5 as red stars, as opposed to the solid diamonds that represent the actual specification numbers. For the *upper bound gradation* and the *maximum density gradation,* which required fines, fines were added to the washed material for tight fines control.

Table 2.2-2 As-Tested Gradations

Sieve Size	Upper Bound Gradation Spec's % Passing	Lower Bound Gradation Spec's % Passing	Line of Maximum Density % Passing
1.5	100	100	100.0
3/4 in.	80	60	87.8
1/2 in.	65	35	72.7
3/8 in.**	57.5	29	65.0
#4**	39.5	18.5	49.0
#8	25	10	34.3
#30	18	5	18.5
LBW	6	0	7.3

** Not an M-Dot Standard Specification

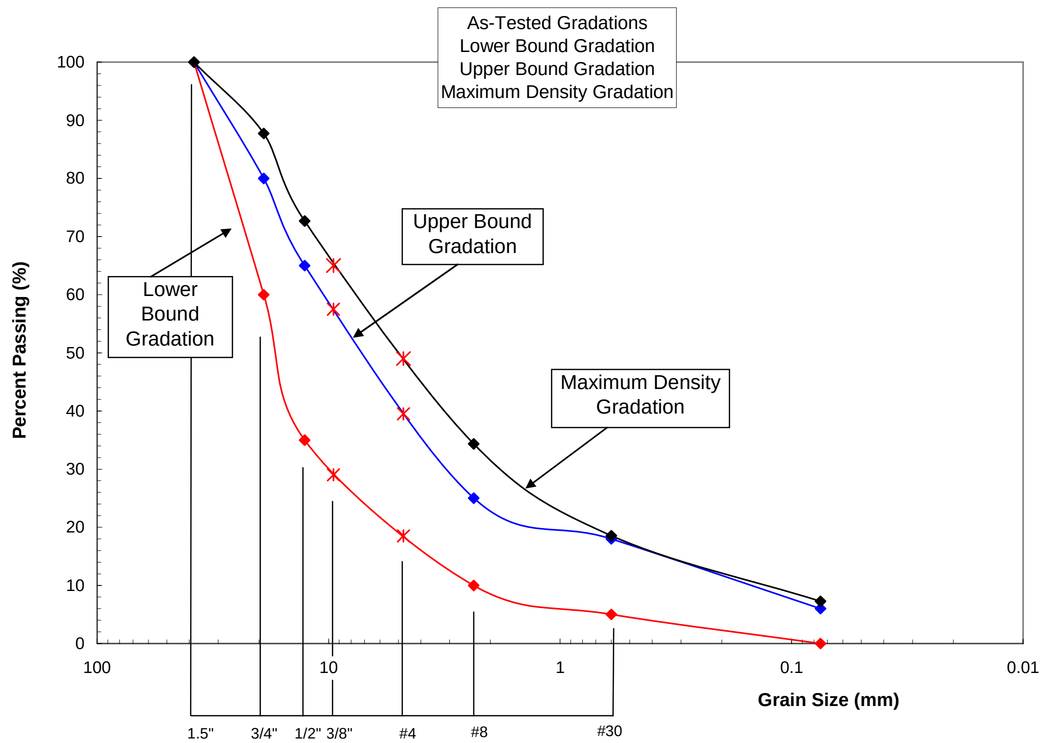

Figure 2.2-5 As-Tested Gradations; Lower Bound Gradation, Upper Bound Gradation, Maximum Density Gradation

2.3 SPECIMEN PREPARATION AND TESTING PROCEDURES

The following sections describe test specimen preparation and the resilient modulus testing protocols. Section 2.3.1 describes the preparation of the test specimen; development of the as-tested unit weights and moisture contents at compaction, and the procedure for creating test specimens at a particular moisture content – Drying Curve Moisture Content (MC), Wetting Curve MC, and Fully Saturated MC. The specimen compaction method also is described.

Section 2.3.2 describes the testing method used to acquire the resilient modulus. It also describes the modified testing protocol when testing *undrained fully-saturated* specimens. The modified testing protocol for *undrained fully-saturated* conditions is not an AASHTO standard.

2.3.1 PREPARATION OF TEST SPECIMEN

This section discusses the as-tested unit weights and compaction moisture contents used in this testing program. The specimen compaction method will also be described. Also discussed is the procedure for creating test specimens at a particular moisture content – Drying Curve Moisture Content (MC), Wetting Curve MC, and Fully Saturated MC.

As-Tested Unit Weights and Compaction Moisture Contents

The AASHTO *Designation T 99 Moisture-Density Relations* (standard Proctor) procedure for developing a maximum dry unit weight was used on all four materials to develop an as-tested unit weight. All specimens were tested at 98% of the maximum dry unit weight gathered from the T-99 procedure as shown in Table 2.3-1.

"Because these soils (cohesionless soils) are relatively pervious even when compacted, they are not affected significantly by their water content during the compaction process. Consequently, the peaked curved relationship between dry density and water content (Proctor curve) that is characteristic of all cohesive soils is ill defined or nonexistent for clean sands and gravels (Hilf 1991)." For this research program the compaction moisture content was developed empirically and typically is the moisture content at a degree of saturation of about 40% or less. Higher moisture contents allowed for less compaction effort but also caused migration and segregation of fines and fine aggregate as shown in Figure 2.3-1. The figure shows the fines lens developed on the right side specimen half. This lens forms at the interface of each individual lift. By, compacting at a lower moisture content it was possible to prevent the migration and segregation of fines. The moisture contents at compaction used to prevent segregation of fines are shown in Table 2.3-1. **It is postulated that this same segregation would occur during field compaction at excessively high moisture contents.**

Densification / Compaction were achieved using a servo-hydraulic vibrator mounted on a rigid load frame. A specimen was built in six lifts, each lift brought to the target density, and each lift was scarified to prevent shear planes developing between lifts, all according to *AASHTO's Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials,* ***Designation T 307-99***. The material was compacted through vibration with a sine wave at a frequency between 40 Hz and 55 Hz and double amplitude of 0.03 to 0.04 inches. A constant surcharge of 200 lbs, or approximately 7 psi was applied vertically during densification.

Table 2.3-1 Unit Weights and Moisture Content at Compaction

	Gradation	Dry Unit Wt. (pcf)	Moisture Content (%)
Natural Gravel	LOWER Bound	122	3.5
	UPPER Bound	140	3.5
	MAXIMUM Density	143	4.5
Dolomite	LOWER Bound	128	2.6
	UPPER Bound	148	3.2
	MAXIMUM Density	150	3.5
Slag	LOWER Bound	105	4.5
	UPPER Bound	116	5.5
	MAXIMUM Density	127.5	7.5
Crushed Concrete	LOWER Bound	102	6
	UPPER Bound	119	7
	MAXIMUM Density	120	8.6

Figure 2.3-1 Example of Fines and Fine Aggregate Migration and Segregation at Lift Interfaces

Development of Specimen Moisture Contents

Each gradation, *lower bound*, *upper bound* and *maximum density* gradations were tested at four different moisture contents. These four moisture contents are as follows: 1) As-compacted moisture content, 2) Wetting Curve moisture content, 3) Drying Curve moisture content, and 4) Fully Saturated moisture content. These moisture contents represent an environmental variable.

The as-compacted moisture content is simply the moisture content (MC) at which the specimen is compacted or built. This represents the construction environment in the field. These moisture contents can be seen in Table 2.3-1.

The Wetting Curve models the environmental condition of wetting or the movement of water (from a source) upward through the base course by capillary action. The built specimen, at the as-compacted moisture content, is exposed to a water source with its free surface at the base of the specimen. The water source is placed on a scale which then records the movement of water out of the source beaker. If there is capillary movement of water through the specimen, the weight of the source beaker will decrease with time. No test specimen showed any propensity for capillary movement of water.

The Drying Curve models the environmental condition of draining after a rain event. The built specimen is fully saturated with water. The specimen is then allowed to freely drain. The draining water is monitored by weighing. Simultaneously, the mass per time is plotted, when the drainage comes to equilibrium, the specimen is said to be at the Drying Curve MC. These Drying Curve plots (Volume of Drainage Water vs. Time) are shown in the Results Chapter in Figure 3.1-1 through Figure 3.1-13**.**

The Fully Saturated moisture content models the environmental condition of full saturation of available voids, in the base course aggregate, without possible drainage or drainage which is significantly slower than required by a dynamic loading. This would be similar to thaw conditions, where the base is saturated and fluid and the surrounding ditch cut or original ground is frozen. The fully saturated specimen is tested during the resilient modulus testing protocol in an undrained state. The development of excess pore water pressure is not allowed to dissipate. The saturation process is lengthy and complex in the laboratory, but procedures were employed to assure that complete saturation was achieved.

To nominally saturate a specimen is not difficult; however, to fully saturate a specimen without occluded air bubbles remaining in the specimen is difficult and requires a lengthy procedure. Occluded air bubbles act as a damping component and therefore absorb or lessen the impact of the vertical loading. Pore volumes of de-aired water are cycled through the specimen while slowly increasing the neutral pore water pressure, while keeping the effective stress at a targeted constant value. The neutral pore water pressure is increased until it eventually reaches the neutral pressure at which *back-pressuring* will take place. At a high neutral pore water pressure, the occluded air bubbles in the specimen become very small. With time, these very small air bubbles are able to dissolve into the surrounding de-aired water. After back-saturating for a given time period, the sample is tested to determine how close it is to being fully saturated, or how close the specimen is to a *degree of saturation* of 100% . "In a saturated soil from which no drainage is permitted, the compression of the soil structure under stress is the same as the compression of the water in the voids, assuming that the compressibility of the soil grains can be neglected. Therefore, an increase in the isotropic stress of $\Delta\sigma_3$ causes an increase in pore water pressure (Head 1986)." If the specimen has a degree of saturation equal to 100% then the increase in σ_3 will cause an equal increase in the pore water pressure (u). This ratio between $\Delta\sigma_3$ and Δu is defined as the "B" parameter. "In practice, the theoretical times to achieve 100% saturation often exceed one day, and can extend to several weeks (Head 1986)." This being said, the specimens in this testing program were back-saturated to a "B" parameter of 0.95, which for a medium stiff skeleton of a natural soil is equivalent to a *degree of saturation* between 99% and 99.5%. This required between 24 hrs and 36 hrs of back-saturating depending on the material type and gradation. However with Slag it was only possible to develop a "B" parameter of 0.85. This may be due to its external roughness and/or internal porosity. Correlations between degree of saturation and the 'B' parameter are not known for this material.

2.3.2 RESILIENT MODULUS TESTING

This section describes the testing protocols used to derive the resilient moduli of the specimens tested in this program. One test protocol is for testing specimens that are partially saturated under drained conditions and one protocol is for testing specimens that are fully saturated under undrained conditions. Also described in this section are the methods and procedures used for data reduction, the calculation of the resilient moduli, and a description of the resilient modulus testing system.

Standard Resilient Modulus Test

All specimens other than those tested under *undrained fully saturated* conditions followed *AASHTO's Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials,* ***Designation T 307-99***.

Fully Saturated – Undrained Resilient Modulus Test

Procedural modifications were made to *Designation T 307-99* to test specimens that were in an *undrained fully saturated* state. These modifications are not covered in *T 307-99*, but were designed specifically for this testing program.

T 307-99 is designed to test the modulus of a specimen in a partially saturated state during drained conditions. During a *drained test*, drainage of the pore fluid from the specimen is permitted and no excess pore pressure develops during the application of the deviator stress. However, a segment of this testing program called for *undrained fully saturated* specimen testing conditions. During an ***un****drained test*, drainage of pore fluid from the specimen is ***not*** permitted during the application of the deviator stress. There is no dissipation of pore pressure. The increase of pore pressure during the application of the deviator stress decreases the effective stress and therefore a softening of the material occurs. There are two variations of pore pressure increase, one of which is in response to an elastic condition, and the other is in response to elasto-plastic conditions. If the deviator stress applied creates only an elastic response of the soil skeleton, then the pore fluid pressure **only** increases during the application of the deviator stress. The loss of effective stress is a function of the elastic stiffness of the soil. If, during the application of the deviator stress, there is also a plastic response, i.e. the soil skeleton has a tendency towards collapse, then the deviator stress will cause an increase in pore fluid pressure and this increase in pore fluid pressure is cumulative…continuously increasing. Thus the pore fluid pressure is a function of the elastic stiffness of the soil skeleton and the tendency of plastic deformation of the soil skeleton. This being said, because *T 307-99* is a staged test, it was necessary to change the testing protocol due to the possibility of the accumulation of pore fluid pressure in the specimen during testing.

Staged testing involves testing one specimen at different stress states with the assumption that the previous stages have no material effect on the proceeding stages. The *T 307-99* test protocol has 15 different stages or 15 different stress states at which one specimen is tested. These stages are shown in Table 2.3-2. Since pore pressures can accumulate during the application of deviatoric stress after each stage, the test was halted and the specimen was allowed to drain any accumulated pore fluid pressure. The next stage or sequence was begun when the pore pressure had returned to the targeted effective stress of that stage. At this point, the valves were shut and the test continued at an undrained condition to the next stage, where the process was repeated until the culmination of the test. Table 2.3-2 shows the 15 sequences or stages and the stress states at those stages. σ_3 is the confinement stress, $\Delta\sigma$ is the deviator stress and σ_1 is the major principal stress ($\sigma_3 + \Delta\sigma$). In a drained test the total stress is equal to the effective stress (σ') which is also the confinement stress in a tri-axial chamber.

Table 2.3-2 Summary of T 307-99 Stress States

Sequence	Confinement Pressure ($\sigma_3 = \sigma'$) *psi*	$\Delta\sigma$ *psi*	σ_1 *psi*
1	3	3	6
2	3	6	9
3	3	9	12
4	5	5	10
5	5	10	15
6	5	15	20
7	10	10	20
8	10	20	30
9	10	30	40
10	15	10	25
11	15	15	30
12	15	30	45
13	20	15	35
14	20	20	40
15	20	40	60

Full saturation of the specimens was accomplished by a combination of high confining stress and high pore water pressure. This allowed the pore air to be dissolved into the pore water. The specimen was held at this back-pressure state so that the dissolved air would not come out of solution. Confinement pressure was held constant at 115 psi while the pore pressure was adjusted to achieve the targeted effective stress. The effective stress in an undrained test is the result of the combination of both confinement stress and pore water pressure ($\sigma' = \sigma - u'$) which is the principle of effective stress. This results in the specimen being tested at the same stress states as the stress states required by *T 307-99*. This is shown in Table 2.3-3. The compacted soil behavior responds to effective stress not total stress. Therefore, the high total stress when combined with high pore water pressure does not affect the results.

Table 2.3-3 Summary of Effective Stress Conditions for Each of the 15 Stress States for the Undrained Condition

Sequence	Confinement Pressure (σ_3) *psi*	Pore Pressure (u) *psi*	Effective Stress (σ') *psi*
1	115	112	3
2	115	112	3
3	115	112	3
4	115	110	5
5	115	110	5
6	115	110	5
7	115	105	10
8	115	105	10
9	115	105	10
10	115	100	15
11	115	100	15
12	115	100	15
13	115	95	20
14	115	95	20
15	115	95	20

Data Reduction and Development of the Resilient Modulus

A description of the data acquisition, reduction and analysis is given as an example, such that it will be easier to understand and navigate through the data spreadsheets given in the digitally recorded disk that is *Appendix - Test Data and Data Reduction.* All data, load, displacement, and pressure, from the resilient modulus test are run through Dasylab8 Data Acquisition software. The data is recorded at a 500 Hz sampling rate with a running arithmetic mean applied to every 5 samples. Peak and valley or the maximum and minimum values of load, displacement, and pressure are recorded for every deviator loading cycle. This data is streamed into a spreadsheet application. Each test sequence in *T 307-99* is one hundred cycles, or 200 minimum and maximum data points, an example of a few recorded data points is shown in Figure 2.3-2. .The testing system logger allows 9 channels of data to be recorded. The experimental equipment contains eleven possible transducer outputs. They are one load transducer, three internal LVDTs, four external LVDTs, and three pressure transducers. Figure 2.3-2 below shows the output of eight active transducers being recorded. In this example columns 2, 3, and 4 are not active.

Load (lbf)	INTERNAL LVDT (mm)	INTERNAL LVDT (mm)	Radial (mm)	EXTERNAL LVDT (in)	EXTERNAL LVDT (in)	Pore Pressure Base (psi)	Pore Pressure Top (psi)	Cell Pressure (psi)	Big Red LVDT (in)	Big Green LVDT (in)
12.70839	0.02819	0.01196	-10.1188	0.05019	0.04346	111.7265	111.9028	114.8985	0.4793	0.47839
74.70989	0.02878	0.01242	-10.1188	0.05164	0.04497	111.7082	112.0675	114.9335	0.48111	0.4798
13.25853	0.03229	0.01941	-10.1187	0.05022	0.04348	111.6929	111.9004	114.8786	0.47943	0.47847
77.29558	0.02819	0.01155	-10.1187	0.0517	0.04505	111.7143	112.0838	114.9122	0.48095	0.47994
12.9697	0.0331	0.01956	-10.1187	0.05022	0.04347	111.7041	111.9053	114.9015	0.47942	0.47839
79.00102	0.02959	0.01325	-10.1187	0.05176	0.04509	111.7763	112.0842	115.0143	0.48097	0.47998
11.88315	0.02694	0.0097	-10.1187	0.05019	0.04344	111.7011	111.9122	114.9243	0.47934	0.47841
80.03255	0.02921	0.01299	-10.1187	0.05179	0.04513	111.7092	112.0899	114.9167	0.4812	0.47999

Figure 2.3-2 Part of 100 Cycles of Raw Minimum and Maximum Data from One Test Sequence

The "Data Recorded – Reduced" sheet in the Data workbook as seen in *Appendix - Test Data and Data Reduction* reduces, manipulates and analyzes the raw data laid out as shown below in Figure 2.3-2. Of the hundred cycles in one sequence of *T 307*-99 only the last five cycles or ten wave segments are used in the analysis. Data analysis of the last 5 cycles of sequence one is shown in Figure 2.3-3. These figures below are visual examples of what the reader will see when opening the appropriate page in the Exel spreadsheet workbook.

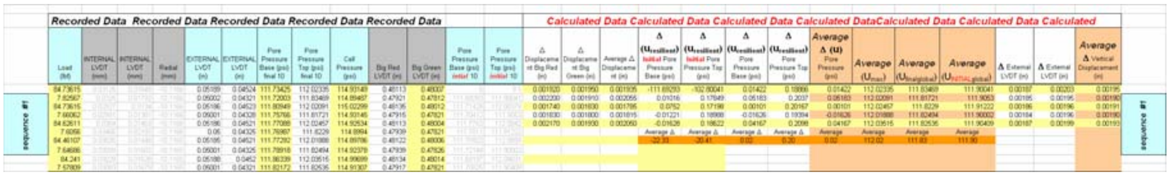

Figure 2.3-3 Reduction and Analysis of Load, Displacement, and Pressure of the Last Five Cycles of a Test Sequence

The "Res Modulus" sheet in the Data workbook as seen in *Appendix - Test Data and Data Reduction* takes the appropriate data from the table in Figure 2.3-3 and uses it to calculate the resilient modulus. The first three test sequences are shown as an example in Figure 2.3-4. In each sequence averages and standard deviations are calculated for test target values of load and stress. The actual average values are compared to the test target value for quality control. The average resilient modulus of the last five cycles of that sequence is shown in the lower right cell, highlighted in blue. This is the recorded resilient modulus for that sequence.

				1	2	3	4	5	6	7	8	9	10	11
			Parameter	Chamber Confining Pressure	Nominal Maximum Axial Stress	Cycle No.	Actual Applied Max Axial Load	Actual Applied Contact Load	Actual Applied Max Axial Stress	Actual Applied Cyclic Stress	Actual Applied Contact Stress	Recoverable Deformation Average of 2 Externals	EXTERNAL LVDT Resilient Strain (average 1 & 2)	EXTERNAL LVDT Resilient Modulus
			Designation	S_3	S_{cyclic}	c_i	P_{max}		S_{max}	S_{cyclic}	$S_{contact}$	H_{avg}	ε_r	M_r
Recorded Data			Unit	psi	psi	#	lbf	lbf	psi	psi	psi	in	in/in	psi
Load (lbf)	Average Δ Displacement (in)	Cell Pressure (psi)												
84.7086	0.002590	3.1												
6.83537	0.002490	3.1	sequence #1	3	3	96	84.7	6.8	3.0	2.8	0.2	0.002590	0.000216	12760.78
84.5023	0.002535	3.1		3	3	97	84.5	6.9	3.0	2.7	0.2	0.002490	0.000208	13233.41
6.86287	0.002540	3.1		3	3	98	84.9	6.7	3.0	2.8	0.2	0.002535	0.000211	13099.82
84.91491	0.002520	3.2		3	3	99	84.3	6.8	3.0	2.7	0.2	0.002540	0.000212	12952.23
6.67032		3.1		3	3	100	84.5	6.8	3.0	2.7	0.2	0.002520	0.000210	13082.82
84.33726		3.2			Column St. Dv.		0.2	0.1	0.0	0.0	0.0	0.000036	0.000003	178.52
6.82161		3.1			Column Avg.		84.6	6.8	3.0	2.8	0.2	0.002535	0.000211	**13025.8**
84.5023		3.1			Values as dictated by test standard:				3.0	2.7	0.3			
6.82162		3.1												
Load	Δ Ave Disp	Cell												
169.0328	0.004385	3.1												
15.66569	0.004380	3.1	sequence #2	3	6	96	169.0	15.7	6.0	5.4	0.6	0.004385	0.000365	14844.02
168.9365	0.004360	3.2		3	6	97	168.9	16.2	6.0	5.4	0.6	0.004380	0.000365	14799.66
16.2021	0.004360	3.1		3	6	98	168.9	15.9	6.0	5.4	0.6	0.004360	0.000363	14887.63
168.8815	0.004320	3.2		3	6	99	169.2	15.9	6.0	5.4	0.6	0.004360	0.000363	14923.77
15.94078		3.1		3	6	100	169.0	15.8	6.0	5.4	0.6	0.004320	0.000360	15045.74
169.2116		3.1			Column St. Dv.		0.1	0.2	0.0	0.0	0.0	0.000026	0.000002	93.76
15.89954		3.1			Column Avg.		169.0	15.9	6.0	5.4	0.6	0.004361	0.000363	**14900.2**
168.9778		3.1			Values as dictated by test standard:				6.0	5.4	0.6			
15.83078		3.1												
Load	Δ Ave Disp	Cell												
253.783	0.005820	3.2												
23.35412	0.005765	3.1	sequence #3	3	9	96	253.8	23.4	9.0	8.1	0.8	0.005820	0.000485	16803.62
253.9343	0.005795	3.1		3	9	97	253.9	23.3	9.0	8.2	0.8	0.005765	0.000480	16980.13
23.28535	0.005735	3.1		3	9	98	253.7	22.9	9.0	8.2	0.8	0.005795	0.000483	16904.31
253.728	0.005715	3.1		3	9	99	253.6	23.5	9.0	8.1	0.8	0.005735	0.000478	17032.31
22.914		3.1		3	9	100	253.0	23.0	8.9	8.1	0.8	0.005715	0.000476	17080.68
253.6455		3.2			Column St. Dv.		0.4	0.2	0.0	0.0	0.0	0.000043	0.000004	109.26
23.49167		3.1			Column Avg.		253.6	23.2	9.0	8.1	0.8	0.005766	0.000481	**16960.2**
252.999		3.1			Values as dictated by test standard:				9.0	8.1	0.9			
22.99654		3.1												

Figure 2.3-4 Example of the Calculation of the Resilient Modulus for the First Three Sequences of T 307-*99*

2.4 DESCRIPTION OF TESTING EQUIPMENT

Resilient modulus testing was run on a Material Testing System (MTS) closed loop servo-hydraulic system with a rated capacity of 24.5kN (5.5kip) and loading frame rated to 98kN (22kip). System functions and limits were controlled using TestStar™ II while test command programming used TestWare-SX™ – both MTS products. All system functions were officially calibrated by a certified MTS technician.

The 2 in. stroke (for undrained test where catastrophic failure is possible) and 0.5 in. stroke (standard test) spring loaded LVDTs, used for deformation measurements are made by SensoTec as is the 2000 lb. load cell used to measure and control the deviator load. Three 150 psi pressure transducers are made by SensoTec. One pressure transducer measures confinement pressure, and the other two pressure transducers measure pore pressure at the top and bottom of the specimen. Linearity, Repeatability and Minimum Sensitivity of all the above instrumentation are within the tolerances given by AASHTO.

Confining stresses and pore fluid pressures are regulated using a ELE International Tri-Flex 2 regulating board. The triaxial chamber capable of testing 6 in. diameter by 12 in. long specimens was made by Research Engineering, Inc.

3 RESULTS

This chapter shows either representative or averaged results of this testing program. Section 3.1 shows the Drying Curve plots which describe the volume versus time relationship of a draining specimen. Section 3.2 shows the representative plots of the Resilient Modulus versus Bulk Stress of the various gradations and gradation-moisture content combinations. Section 3.3 summarizes the regression coefficients of the Resilient Modulus versus Bulk Stress representative curves in a tabular format. Wetting curves which would describe the uptake of water from the as-compacted condition could not be shown because the results did not indicate measurable uptake of capillary water into the samples.

3.1 DRYING CURVES

Sample drainage from the saturated condition was used to simulate an environmental condition. For experimental purposes both the volume which naturally drains from the sample by gravity and the time at which drainage is complete are both necessary to the program. The volume of drainage water allows for the equilibrium degree of saturation to be computed, and the time at which drainage is essentially complete allows subsequent resilient modulus testing to commence. The volume vs square root of time representation was chosen since it better shows the final equilibrium condition better than does the log-time method.

The following sections show the volume versus time – or flow of water draining from an initially saturated specimen for Natural Gravel, Dolomite, Slag, and Crushed Concrete. For each material this drainage rate is shown for the *lower bound gradation*, the *upper bound gradation*, and the *maximum density gradation*.

3.1.1 NATURAL GRAVEL

In this section Figure 3.1-1 through Figure 3.1-4 show representative drainage results for Natural Gravel.

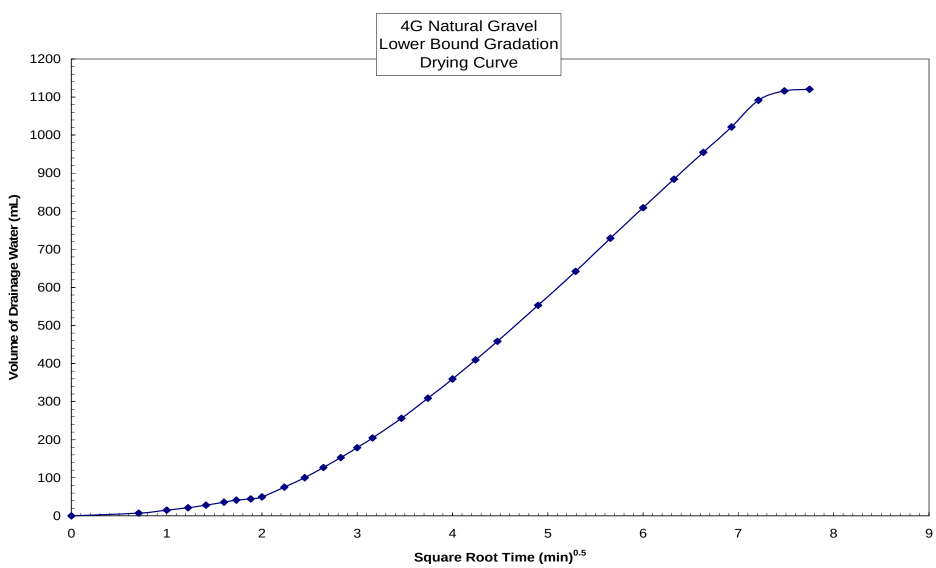

Figure 3.1-1 Drying Curve, Lower Bound Gradation, Natural Gravel

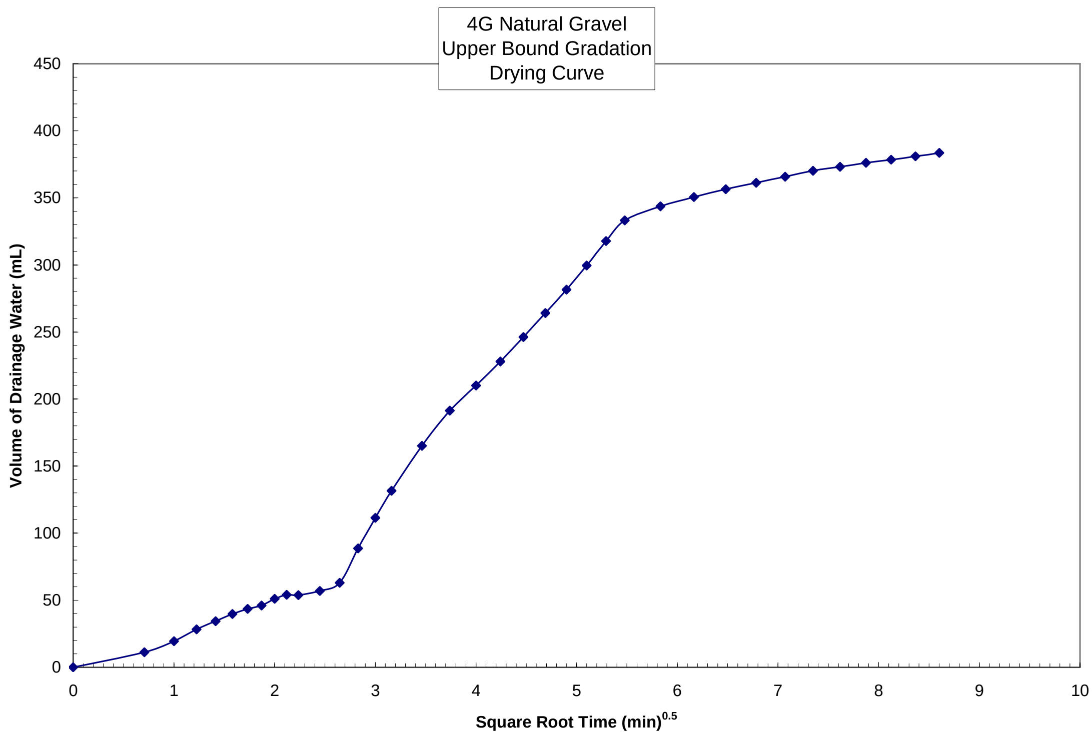

Figure 3.1-2 Drying Curve, Upper Bound Gradation, Natural Gravel

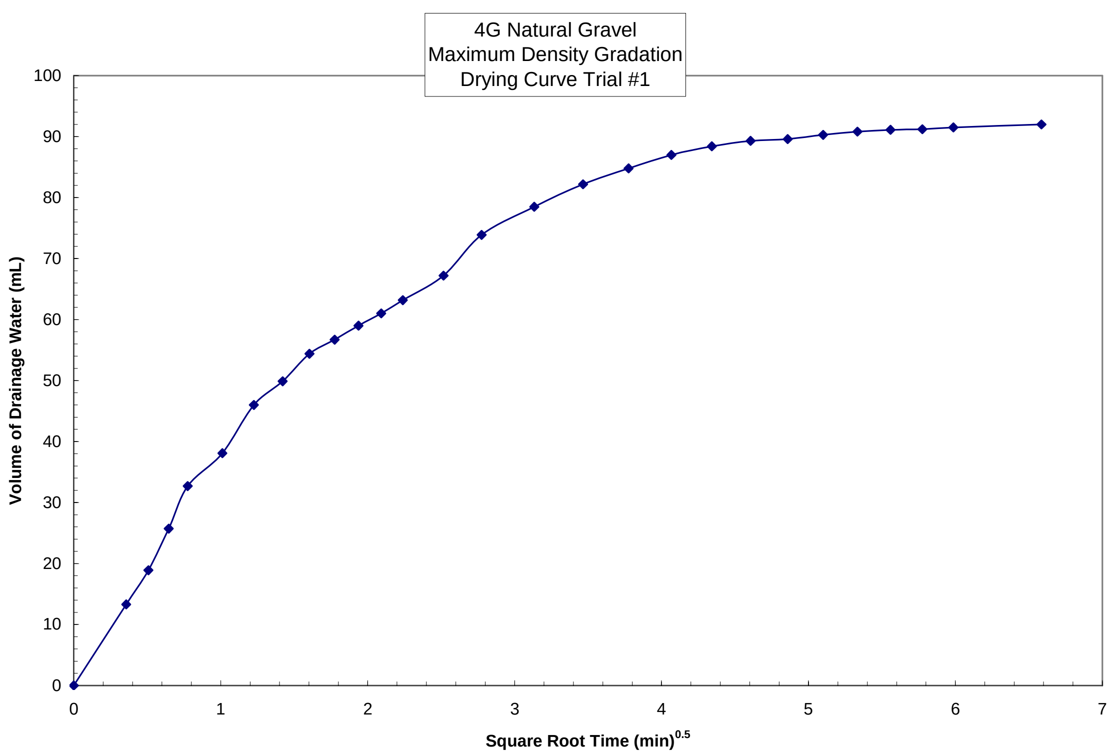

Figure 3.1-3 Drying Curve, Maximum Density Gradation, Natural Gravel Trial no. 1

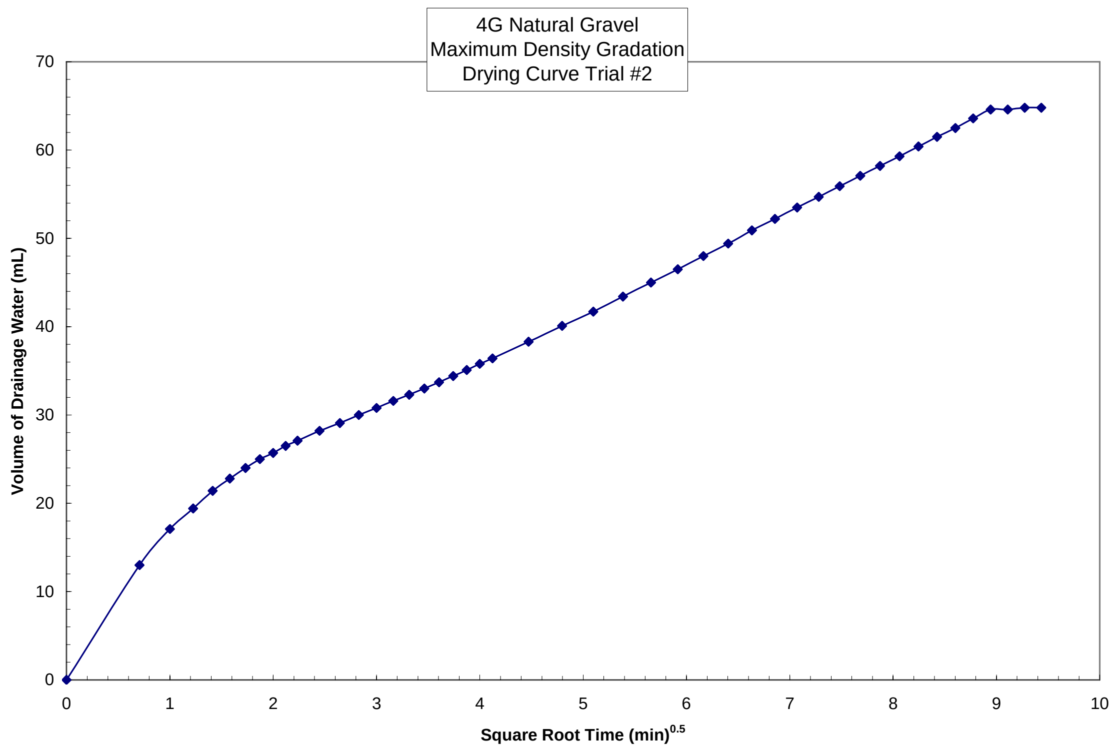

Figure 3.1-4 Drying Curve, Maximum Density Gradation, Natural Gravel Trial no. 2

3.1.2 DOLOMITE

In this section Figure 3.1-5 through Figure 3.1-7 show representative drainage results for Dolomite.

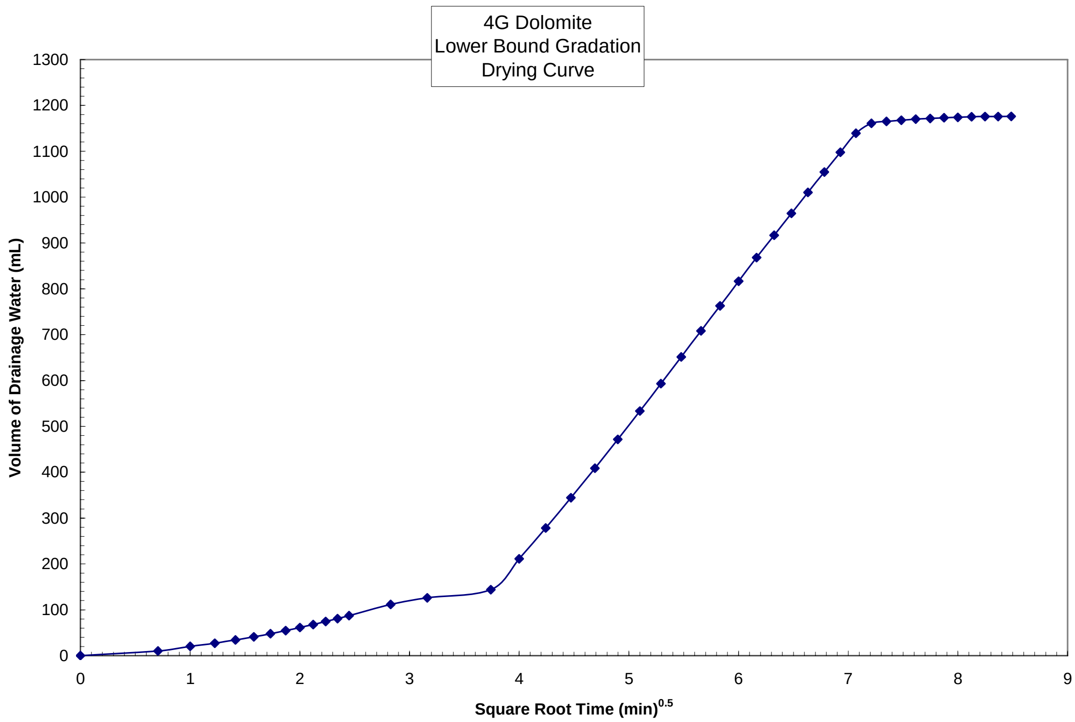

Figure 3.1-5 Drying Curve, Lower Bound Gradation, Dolomite

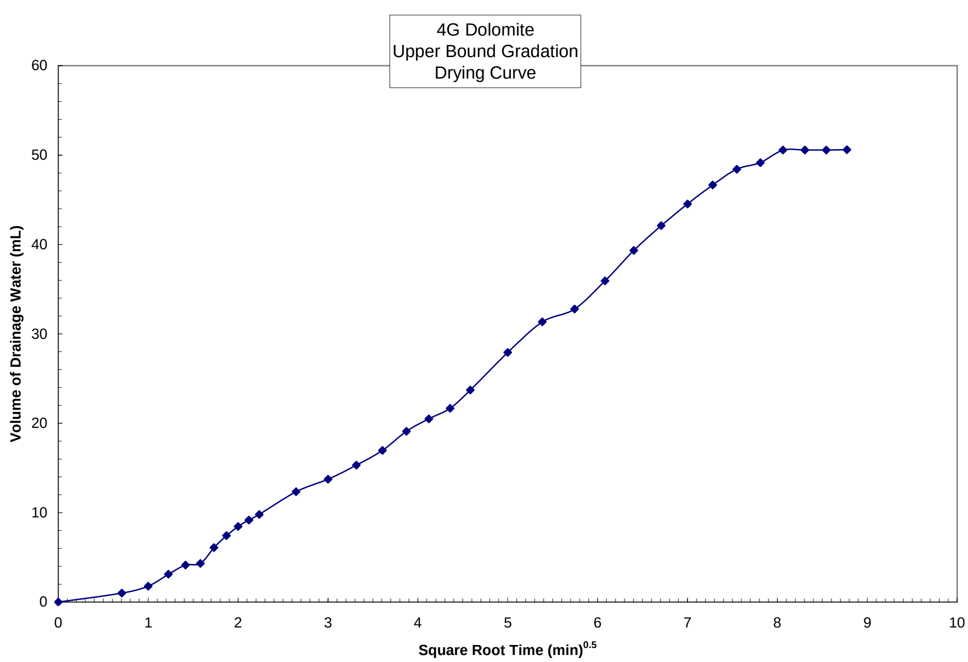

Figure 3.1-6 Drying Curve, Upper Bound Gradation, Dolomite

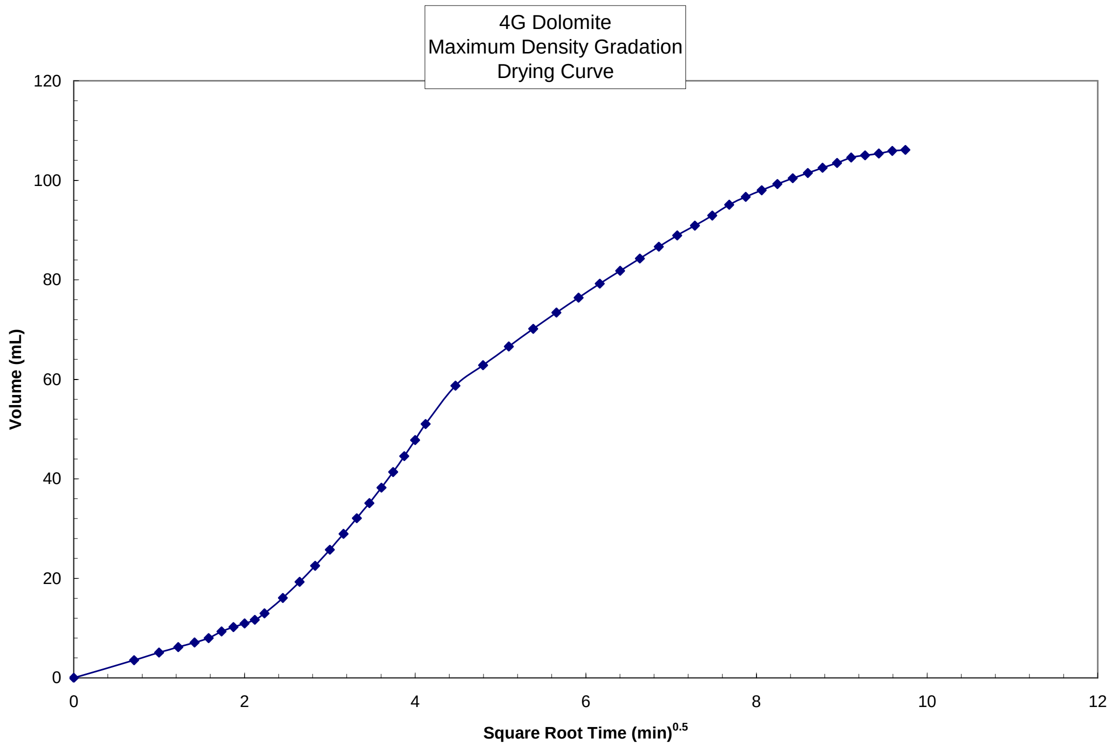

Figure 3.1-7 Drying Curve, Maximum Density Gradation, Dolomite

3.1.3 SLAG

In this section Figure 3.1-8 through Figure 3.1-10 show representative drainage results for Slag.

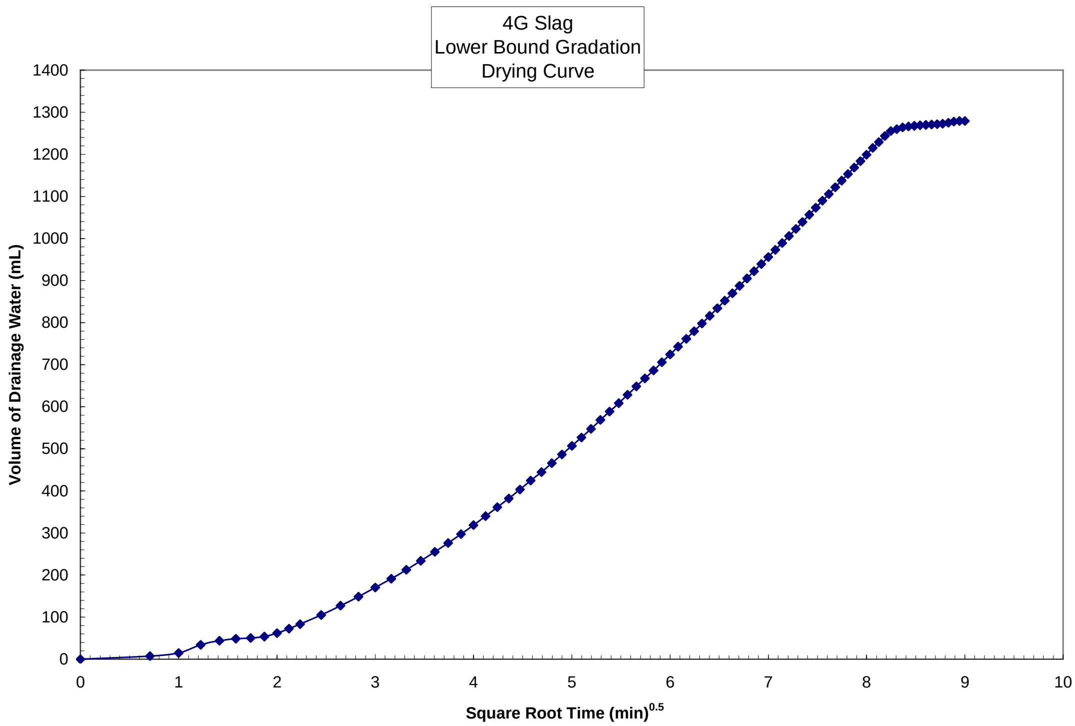

Figure 3.1-8 Drying Curve, Lower Bound Gradation, Slag

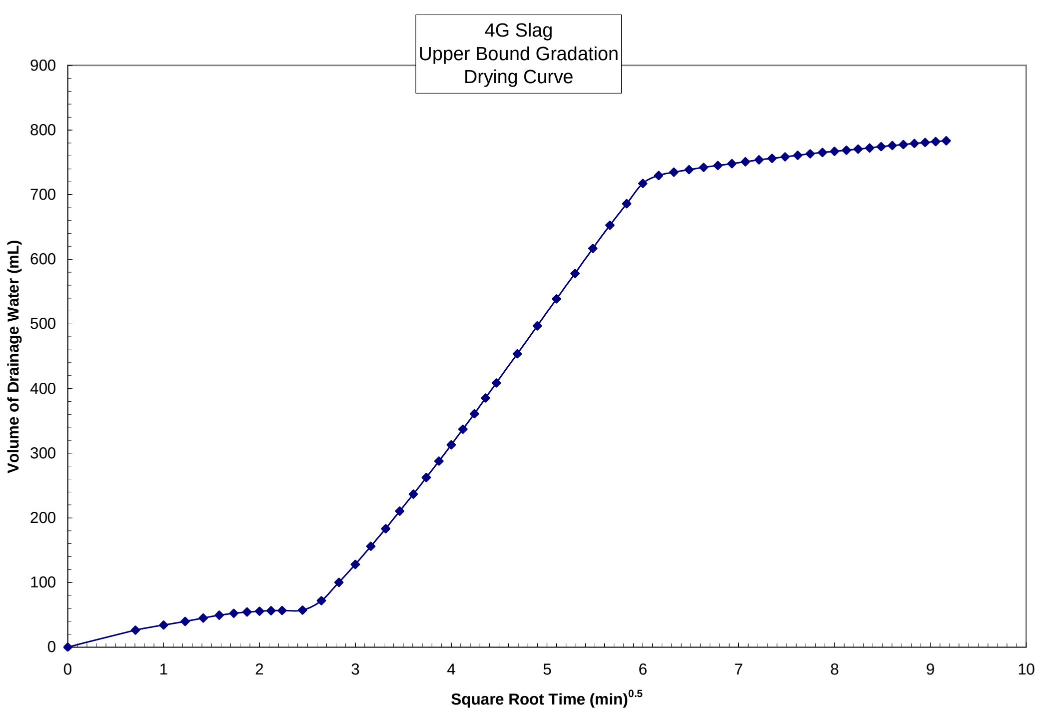

Figure 3.1-9 Drying Curve, Upper Bound Gradation, Slag

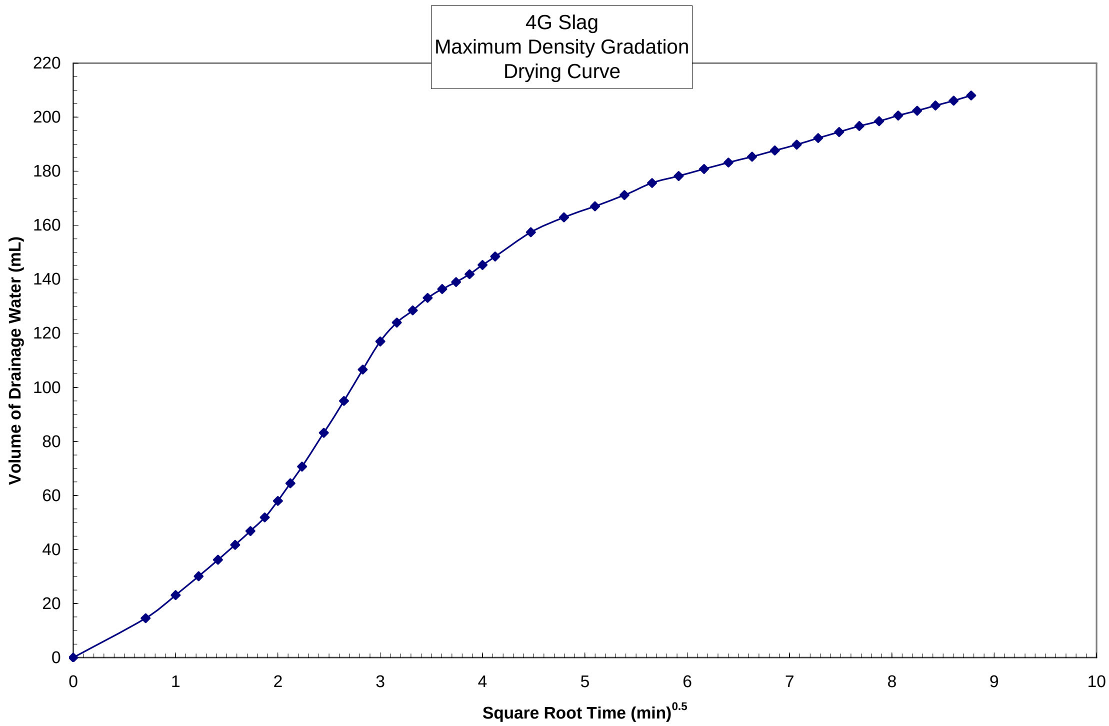

Figure 3.1-10 Drying Curve, Maximum Density Gradation, Slag

3.1.4 CRUSHED CONCRETE

In this section Figure 3.1-11 through Figure 3.1-13 show representative drainage results for Crushed Concrete.

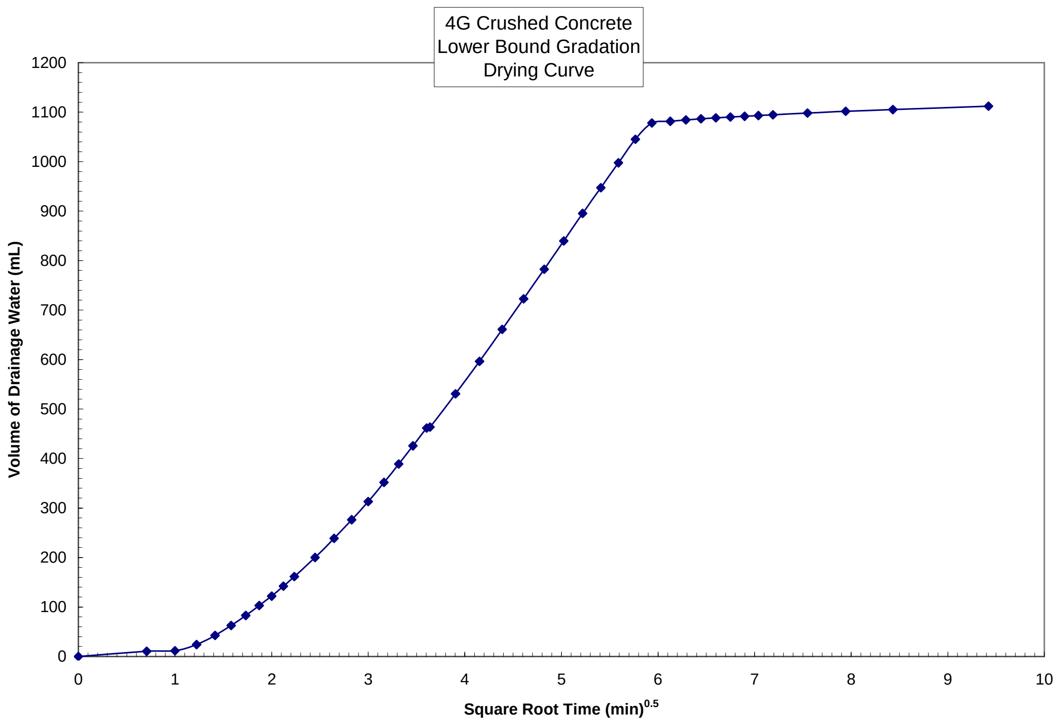

Figure 3.1-11 Drying Curve, Lower Bound Gradation, Crushed Concrete

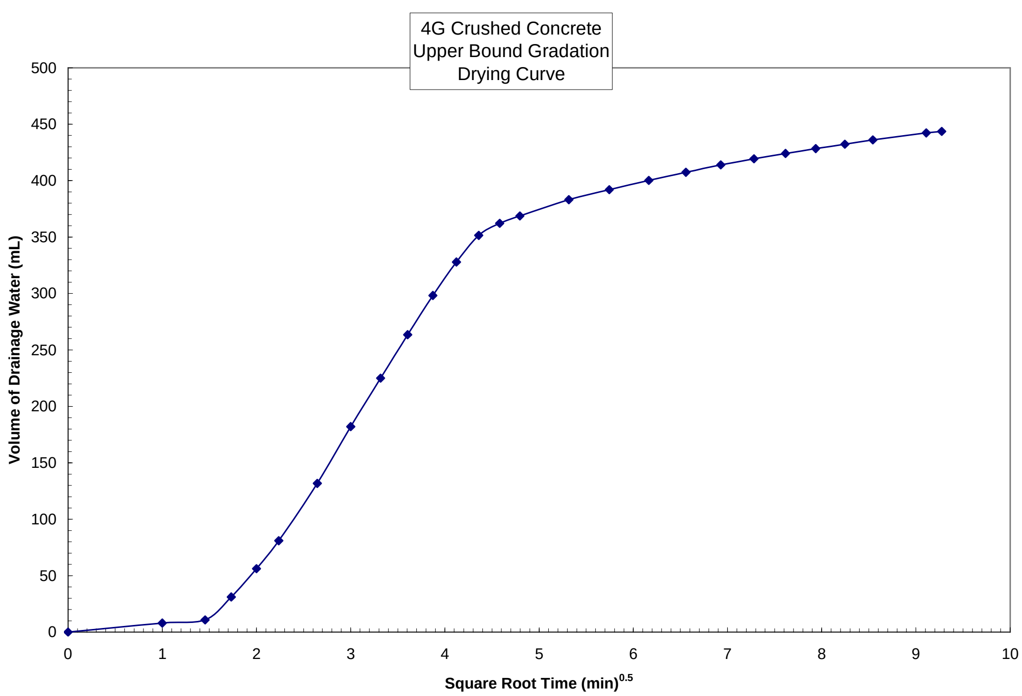

Figure 3.1-12 Drying Curve, Upper Bound Gradation, Crushed Concrete

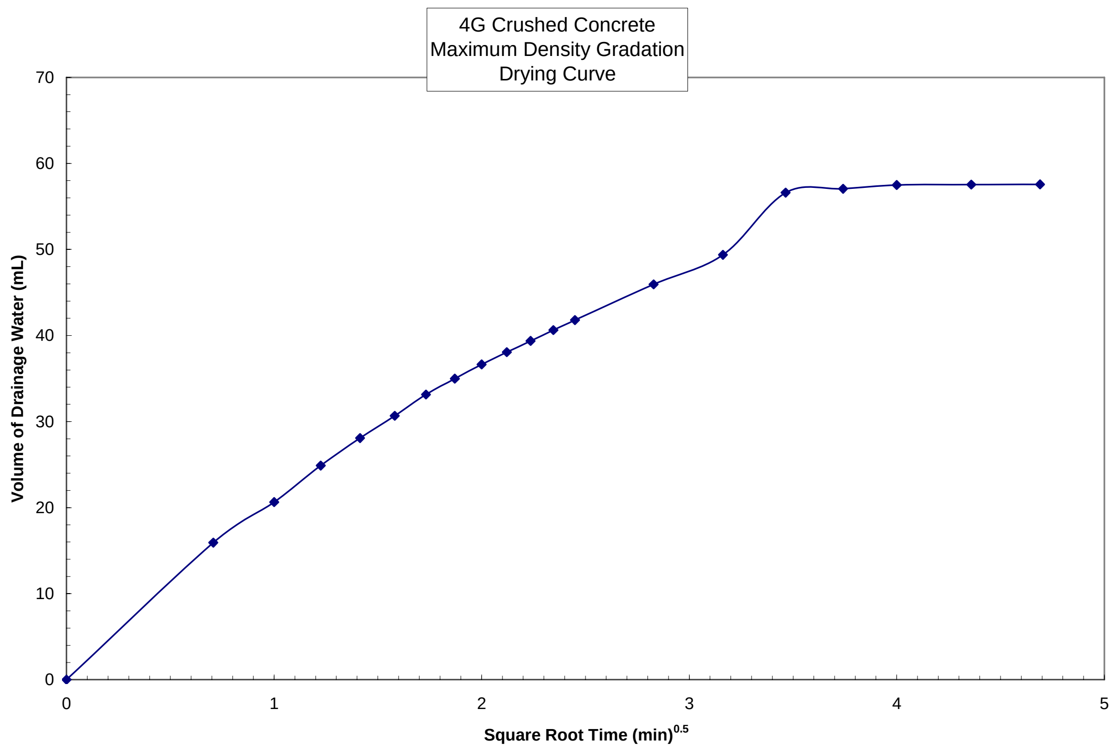

Figure 3.1-13 Drying Curve, Maximum Density Gradation, Crushed Concrete

3.2 MOISTURE CONDITION AFTER ENVIRONMENTAL SIMULATION

In the previous chapter the various moisture conditions, as-compacted MC, wetting Curve MC, drying curve MC, and fully saturated MC were described. These moisture contents or degrees of saturation were the starting point moisture contents for the resilient modulus tests that were conducted. They are also results in this program since they show the effects of material type and gradation on the resulting moisture condition. These results are summarized in Table 3.2-1 shown below. The associated compacted dry unit weights have already been reported in Table 2.3-1.

Table 3.2-1 Equilibrium Moisture Condition Used for Resilient Modulus Testing

	Initial Moisture Conditions and Void Ratio				
	Natural Gravel	Void Ratio	Degree of Saturation (%)	Moisture Content (%)	Time to Drainage Equilibrium (min)
Lower Bound Gradation	as-compacted	0.41	23.6	3.5	na
	wetting	0.41	23.6	3.5	na
	drying	0.41	28.4	4.2	50
	fully saturated	0.41	100	14.8	na
Upper Bound Gradation	as-compacted	0.23	42.5	3.5	na
	wetting	0.23	42.5	3.5	na
	drying	0.23	58.0	4.8	30
	fully saturated	0.23	100.0	8.2	na
Maximum Density Gradation	as-compacted	0.20	61.7	4.5	na
	wetting	0.20	61.7	4.5	na
	drying	0.20	84.0	6.1	16
	fully saturated	0.20	100.0	7.3	na

	Initial Moisture Conditions and Void Ratio				
	Dolomite	Void Ratio	Degree of Saturation (%)	Moisture Content (%)	Time to Drainage Equilibrium (min)
Lower Bound Gradation	as-compacted	0.38	19.2	2.6	na
	wetting	0.38	19.2	2.6	na
	drying	0.38	22.2	3.0	52
	fully saturated	0.38	100.0	13.5	na
Upper Bound Gradation	as-compacted	0.20	45.1	3.2	na
	wetting	0.20	45.1	3.2	na
	drying	0.20	89.7	6.4	42
	fully saturated	0.20	100.0	7.1	na
Maximum Density Gradation	as-compacted	0.19	53.6	3.5	na
	wetting	0.19	53.6	3.5	na
	drying	0.19	82.9	5.4	21
	fully saturated	0.19	100.0	6.5	na

	Initial Moisture Conditions and Void Ratio				
	Slag	Void Ratio	Degree of Saturation (%)	Moisture Content (%)	Time to Drainage Equilibrium (min)
Lower Bound Gradation	as-compacted	0.73	17.9	4.5	na
	wetting	0.73	17.9	4.5	na
	drying	0.73	43.5	10.9	68
	fully saturated	0.73	100.0	25.1	na
Upper Bound Gradation	as-compacted	0.54	29.0	5.5	na
	wetting	0.54	29.0	5.5	na
	drying	0.54	55.2	10.5	37
	fully saturated	0.54	100.0	19.0	na
Maximum Density Gradation	as-compacted	0.41	53.1	7.5	na
	wetting	0.41	53.1	7.5	na
	drying	0.41	82.0	11.6	17
	fully saturated	0.41	100.0	14.1	na

	Initial Moisture Conditions and Void Ratio				
	Crushed Concrete	Void Ratio	Degree of Saturation (%)	Moisture Content (%)	Time to Drainage Equilibrium (min)
Lower Bound Gradation	as-compacted	0.62	25.7	6.0	na
	wetting	0.62	25.7	6.0	na
	drying	0.62	45.6	10.6	35
	fully saturated	0.62	100.0	23.3	na
Upper Bound Gradation	as-compacted	0.39	47.5	7.0	na
	wetting	0.39	47.5	7.0	na
	drying	0.39	66.5	9.8	19
	fully saturated	0.39	100.0	14.7	na
Maximum Density Gradation	as-compacted	0.38	60.2	8.6	na
	wetting	0.38	60.2	8.6	na
	drying	0.38	91.0	13.0	12
	fully saturated	0.38	100.0	14.3	na

3.3 RESILIENT MODULUS VS. BULK STRESS

This section shows the curves for the Resilient Modulus versus Bulk Stress relationship. The equation of the line, shown for this relationship, is the power curve or K-θ model. These curves are representative or average values of multiple trials for a given gradation or gradation-moisture content condition. This log modulus vs. log bulk stress representation is the one traditionally used. Plots are grouped by material type. Within each material type the plots are order as follows: 1) Lower Bound gradation, 2) Upper Bound gradation, 3) Maximum Density gradation, 4) Lower Bound gradations at Wetting Curve MC, Drying Curve MC, and Fully Saturated MC, 5) Upper Bound gradations at Wetting Curve MC, Drying Curve MC, and Fully Saturated MC, and 6) Maximum Density gradations at Wetting Curve MC, Drying Curve MC, and Fully Saturated MC.

3.3.1 NATURAL GRAVEL

For simplicity Figure 3.3-1 through Figure 3.3-3 each show the effect of a different gradation for the Natural Gravel at the as-compacted moisture content. Figure 3.3-4 through Figure 3.3-6 each compare the results of the three environmental conditions for one of the three gradations used.

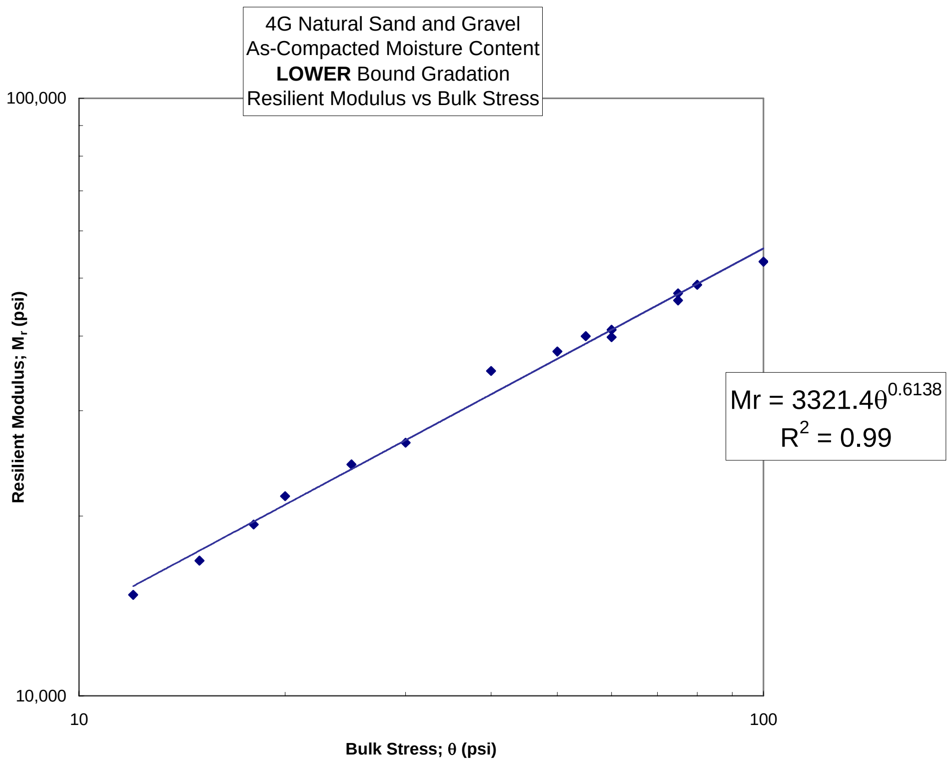

Figure 3.3-1 Natural Gravel, Lower Bound Gradation

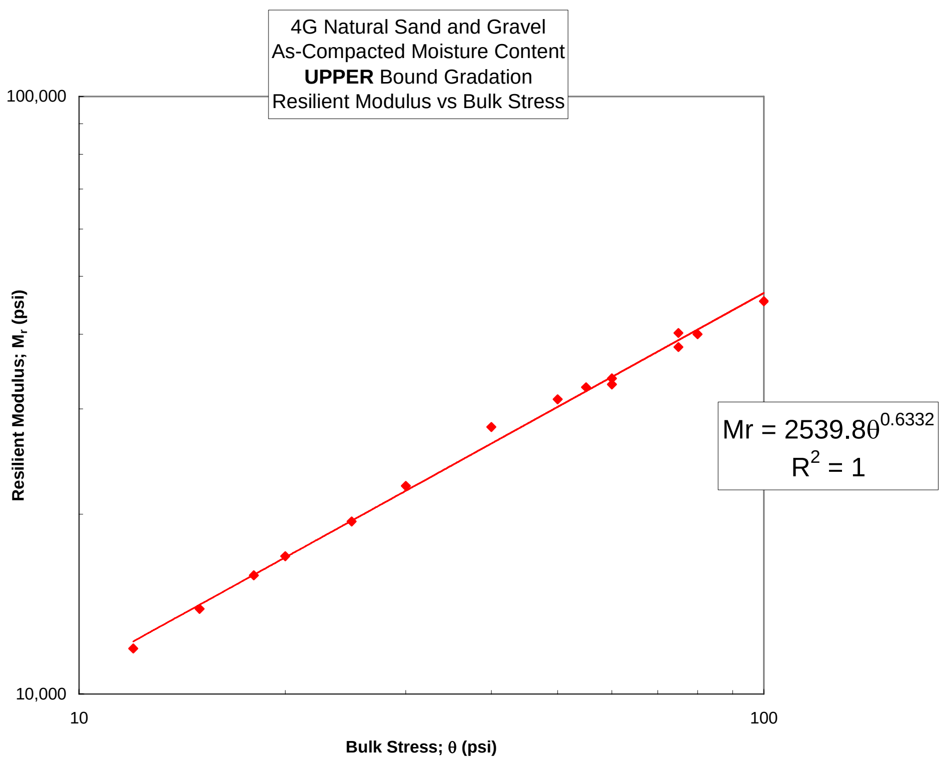

Figure 3.3-2 Natural Gravel, Upper Bound Gradation

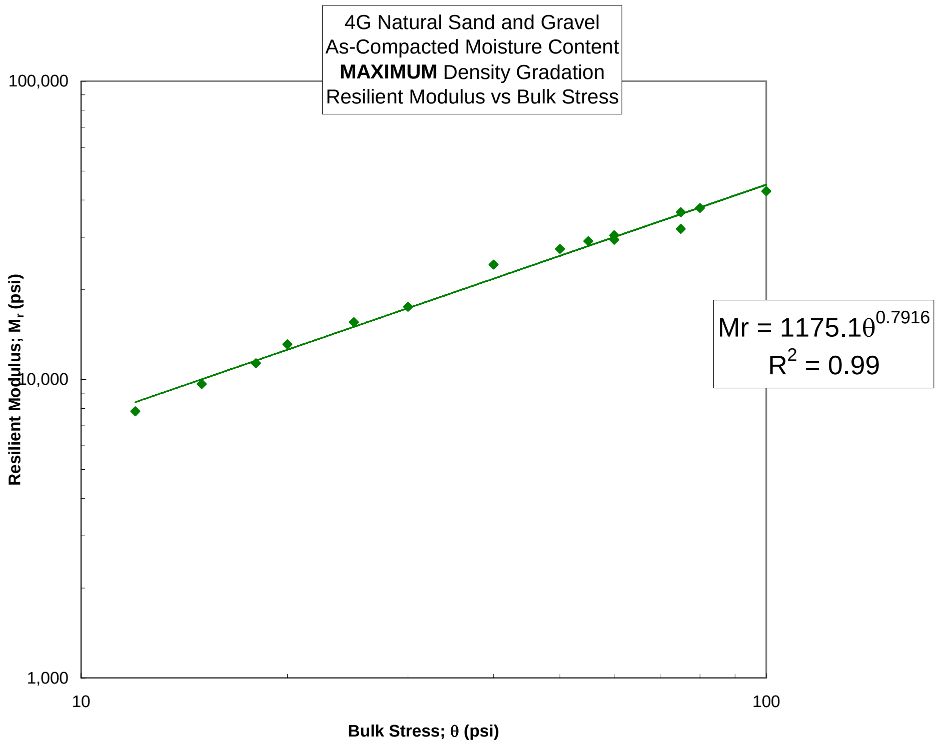

Figure 3.3-3 Natural Gravel, Maximum Density Gradation

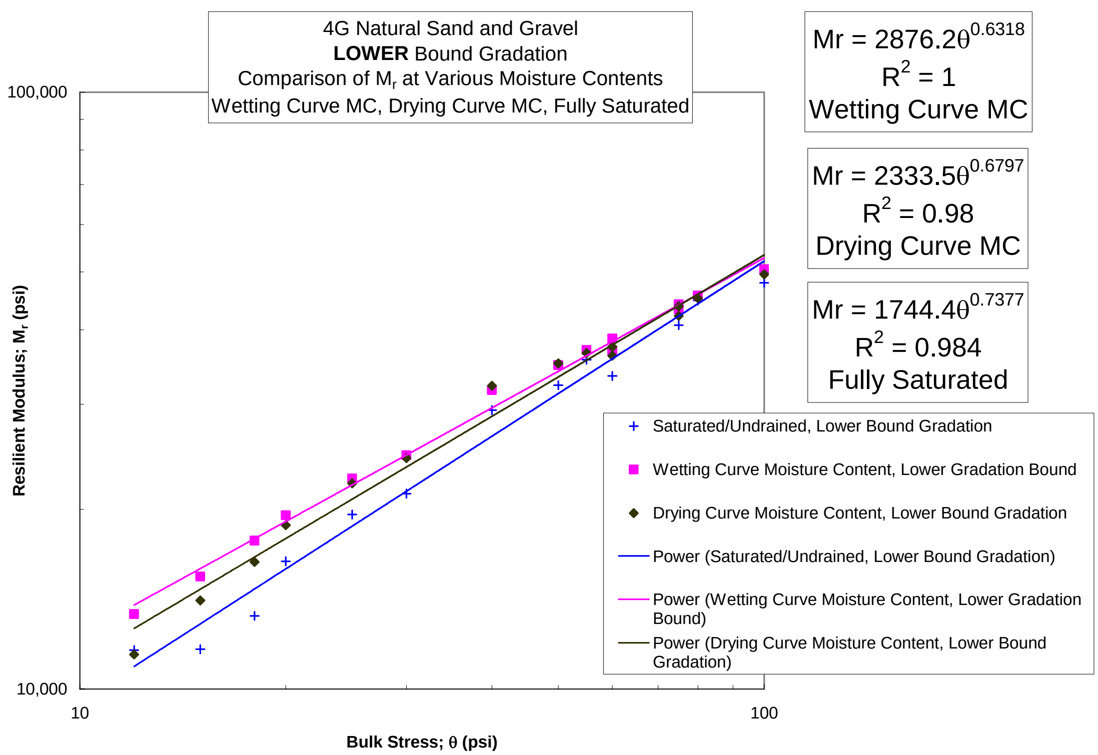

Figure 3.3-4 Natural Gravel, Lower Bound Gradations, Wetting and Drying Curve MC, Fully Saturated MC

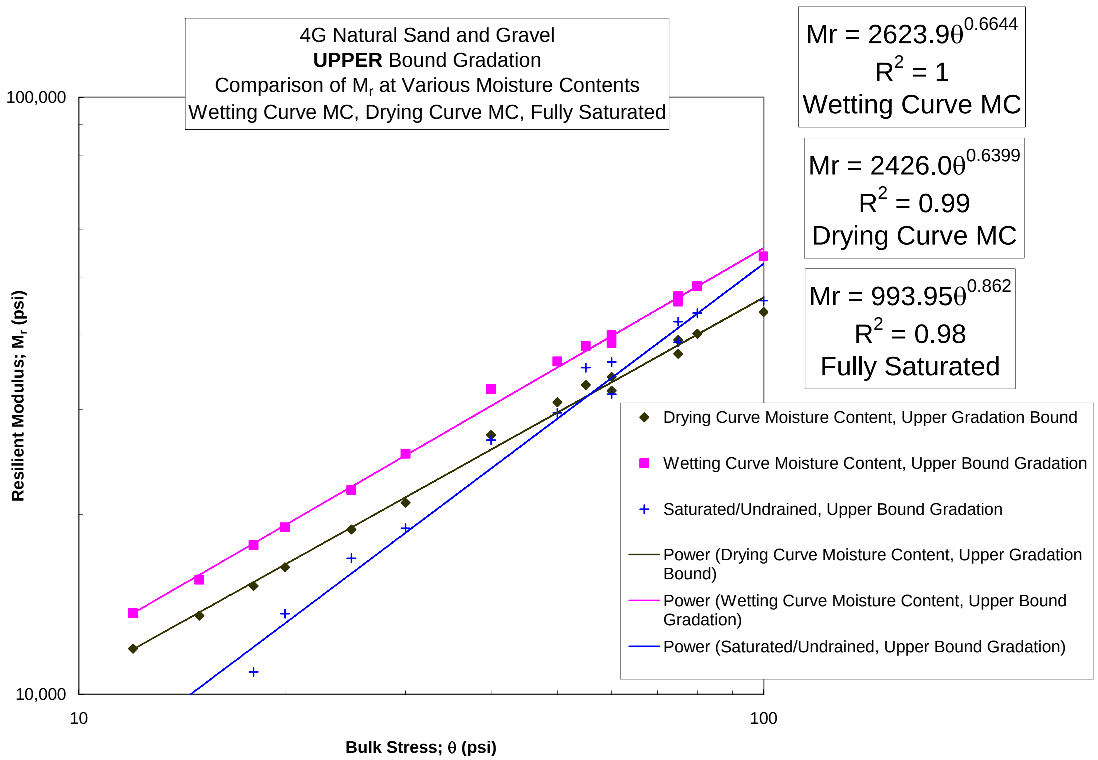

Figure 3.3-5 Natural Gravel, Upper Bound Gradations, Wetting and Drying Curve MC, Fully Saturated MC

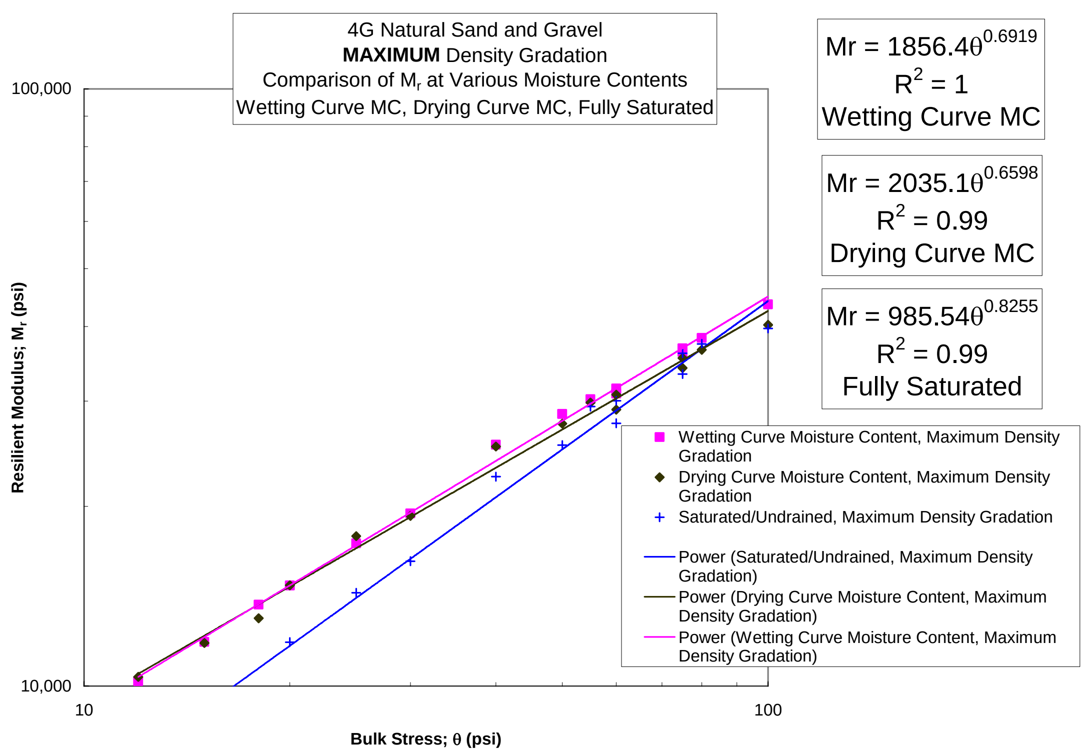

Figure 3.3-6 Natural Gravel, Maximum Density Gradations, Wetting and Drying Curve MC, Fully Saturated MC

3.3.2 DOLOMITE

For simplicity Figure 3.3-7 through Figure 3.3-9 each show the effect of a different gradation for the Dolomite at the as-compacted moisture content. Figure 3.3-10 through Figure 3.3-12 each compare the results of the three environmental conditions for one of the three gradations used.

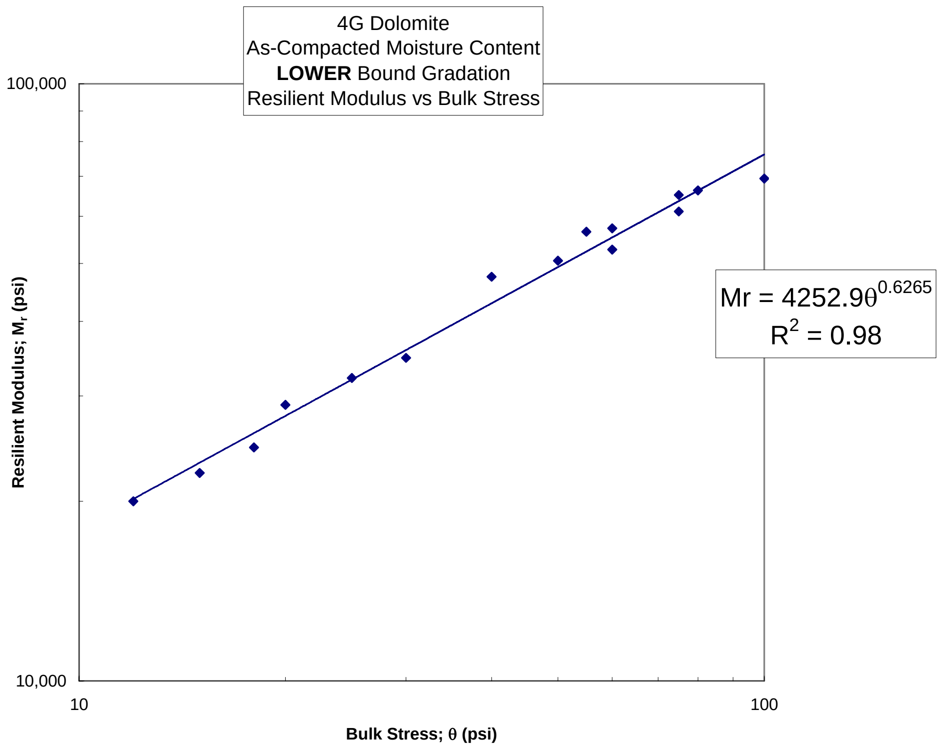

Figure 3.3-7 Dolomite, Lower Bound Gradation

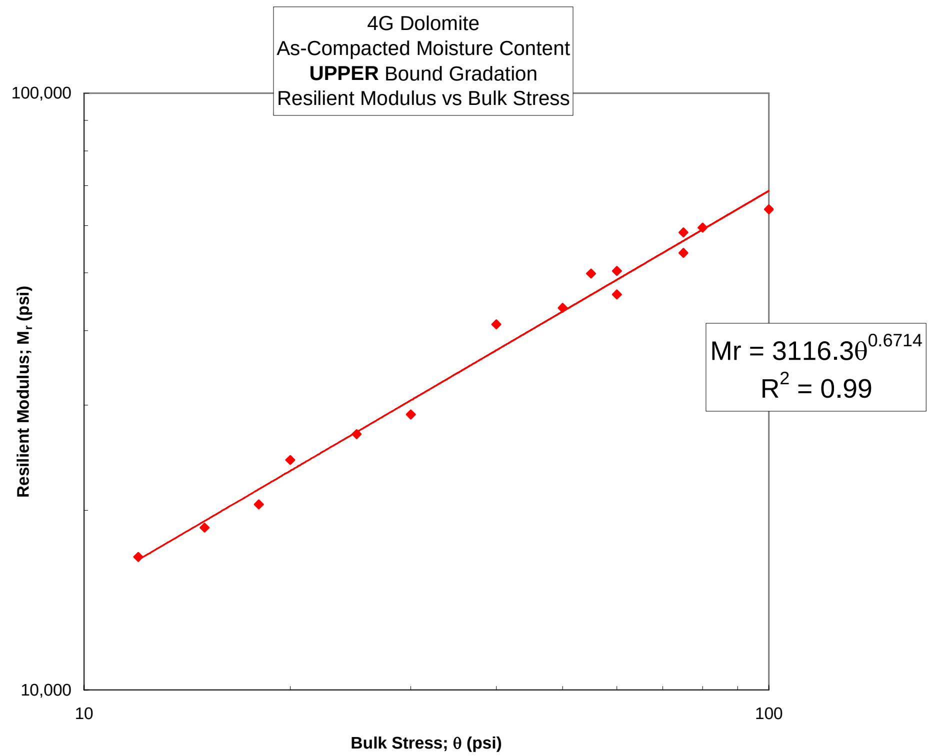

Figure 3.3-8 Dolomite, Upper Bound Gradation

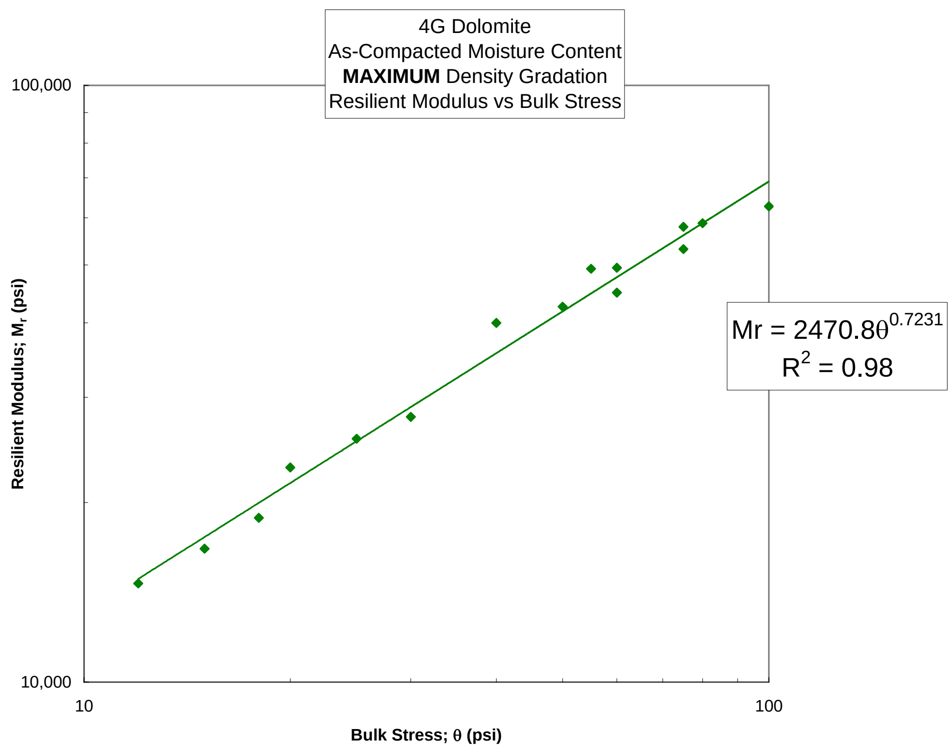

Figure 3.3-9 Dolomite, Maximum Density Gradation

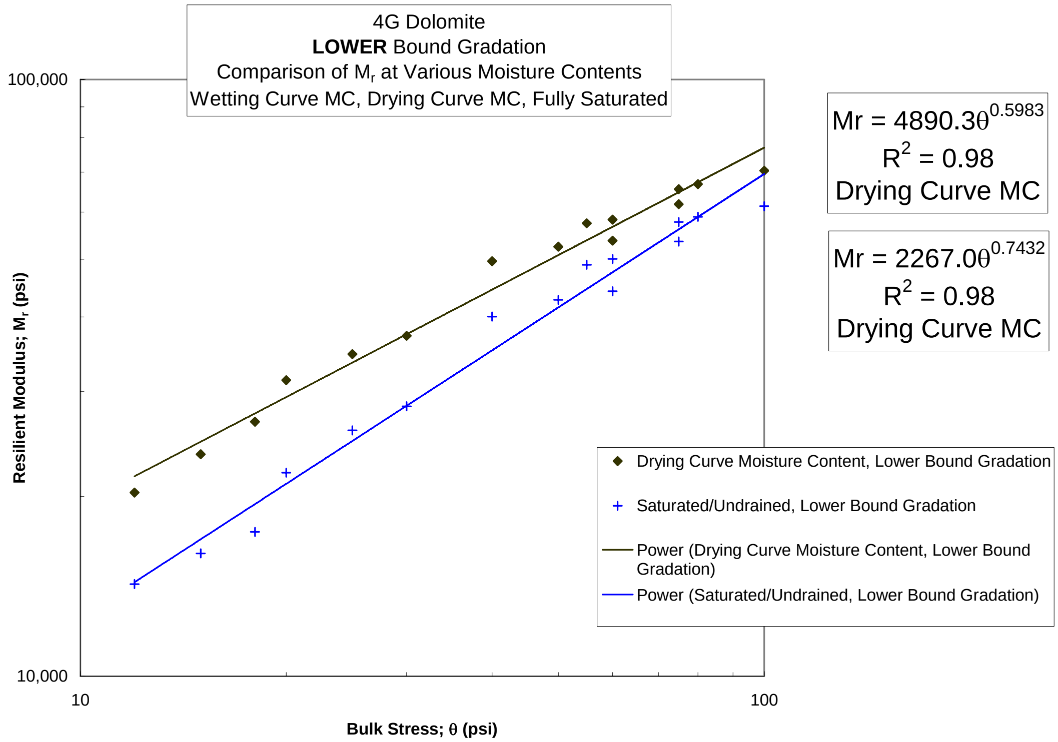

Figure 3.3-10 Dolomite, Lower Bound Gradations, Drying Curve MC, Fully Saturated MC

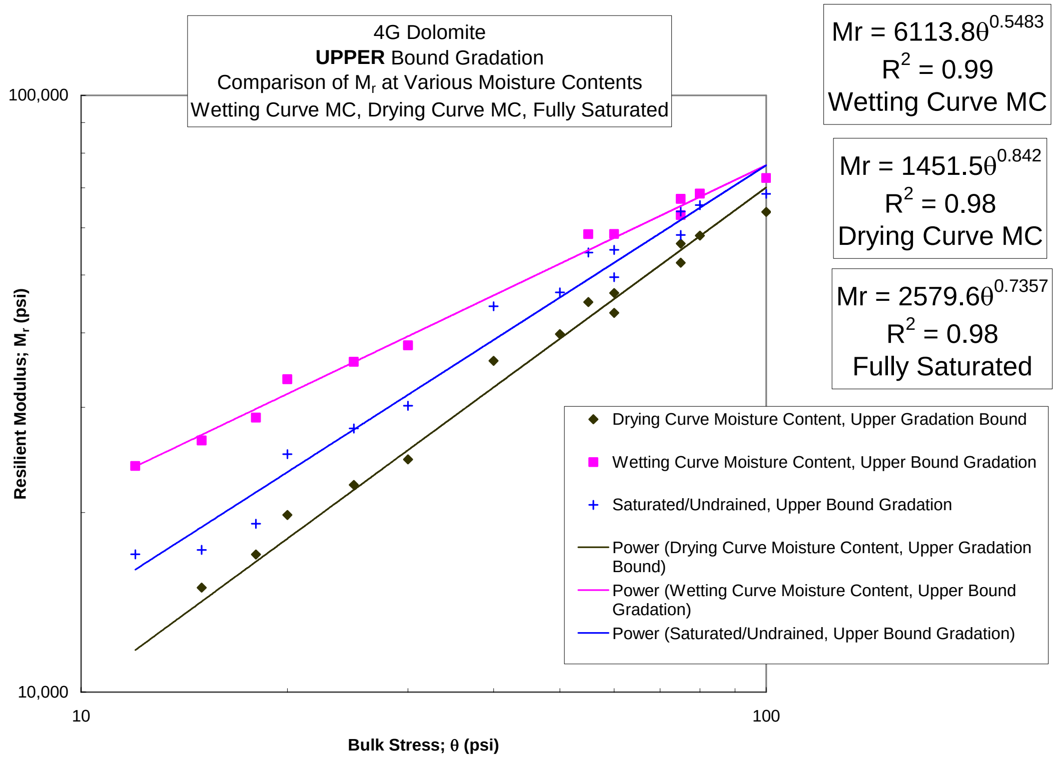

Figure 3.3-11 Dolomite, Upper Bound Gradations, Wetting and Drying Curve MC, Fully Saturated MC

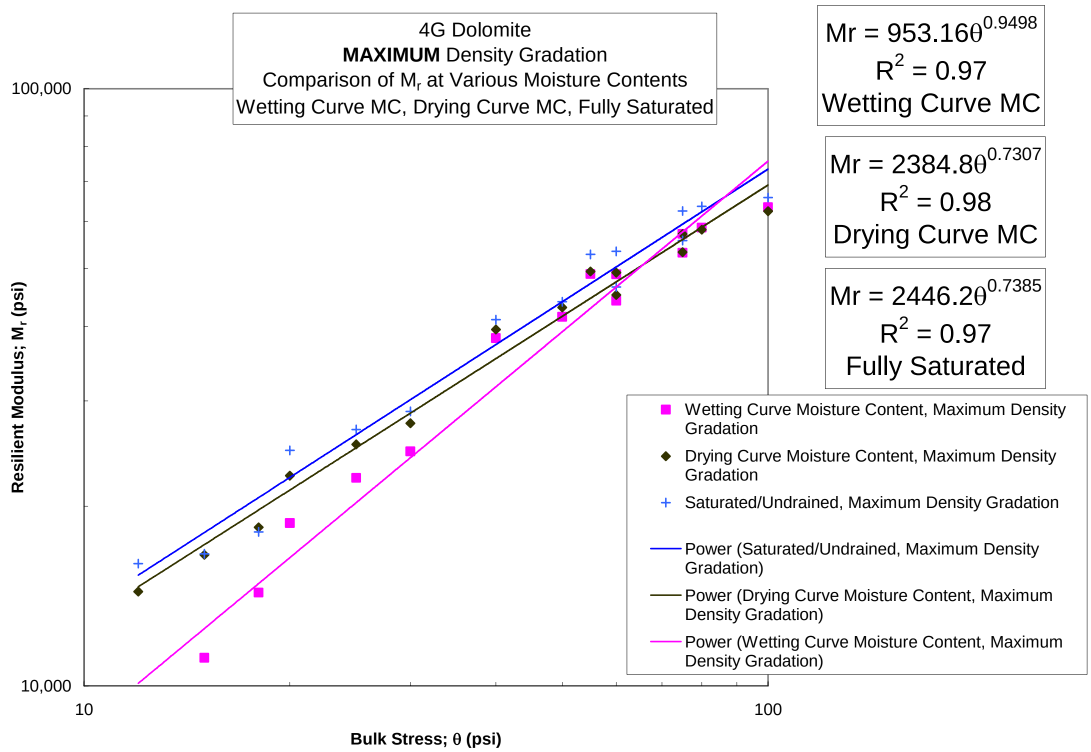

Figure 3.3-12 Dolomite, Maximum Density Gradations, Wetting and Drying Curve MC, Fully Saturated MC

3.3.3 SLAG

For simplicity Figure 3.3-13 through Figure 3.3-15 each show the effect of a different gradation for the Slag at the as-compacted moisture content. Figure 3.3-16 through Figure 3.3-18 each compare the results of the three environmental conditions for one of the three gradations used.

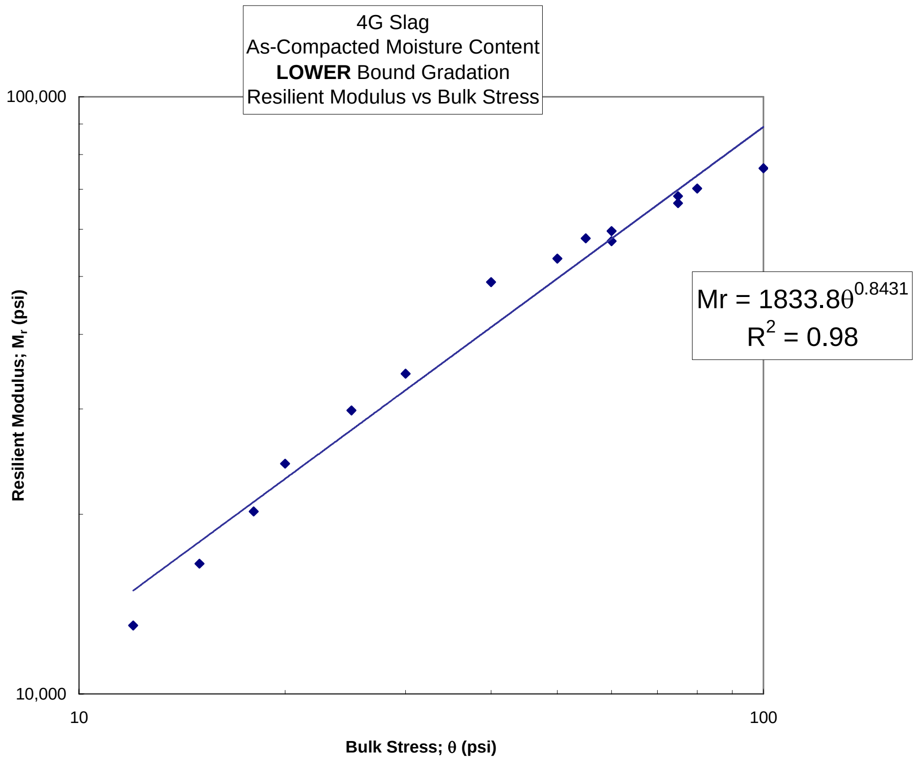

Figure 3.3-13 Slag, Lower Bound Gradation

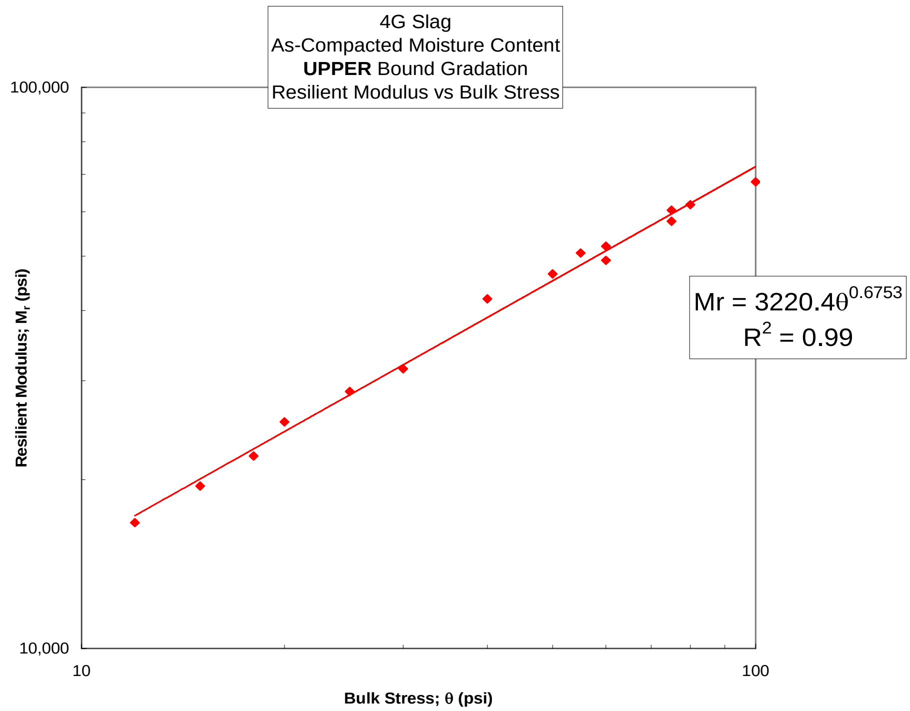

Figure 3.3-14 Slag, Upper Bound Gradation

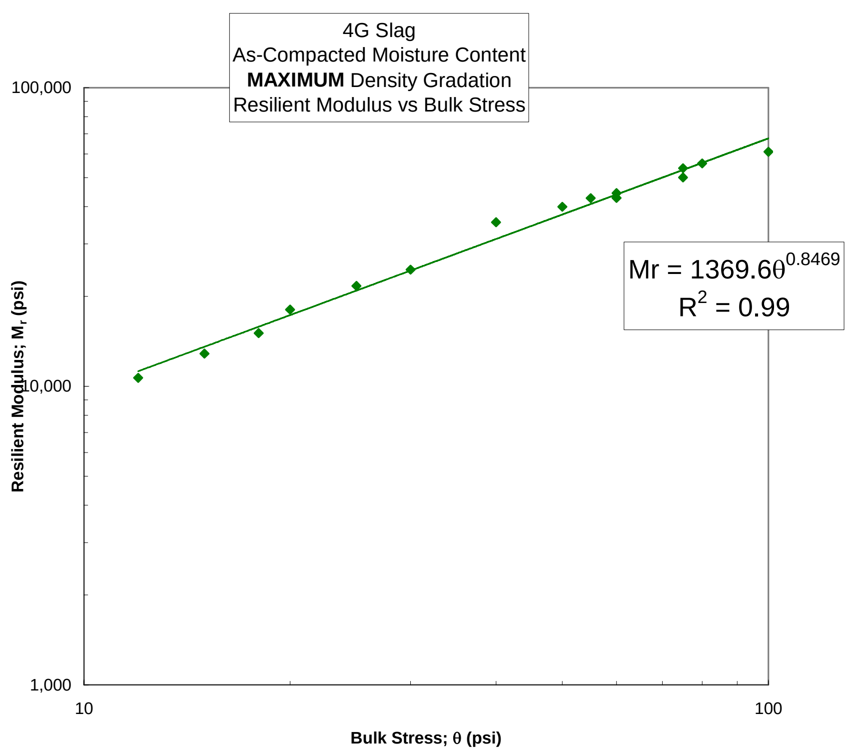

Figure 3.3-15 Slag, Maximum Density Gradation

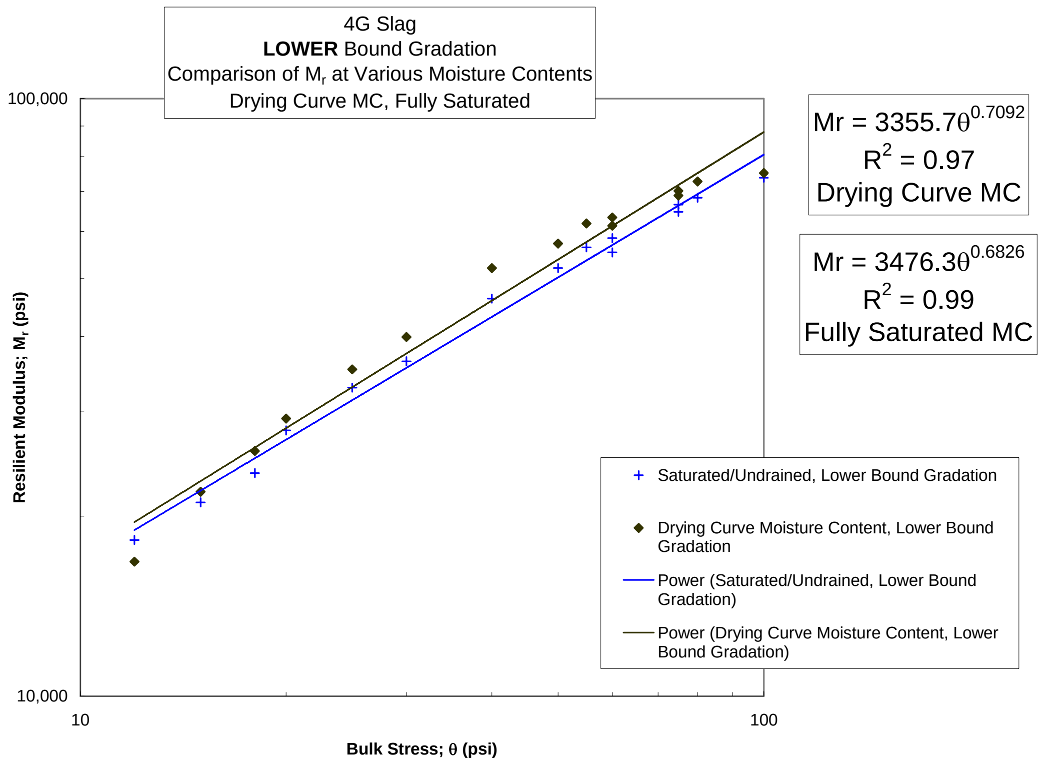

Figure 3.3-16 Slag, Lower Bound Gradations, Drying Curve MC, Fully Saturated MC

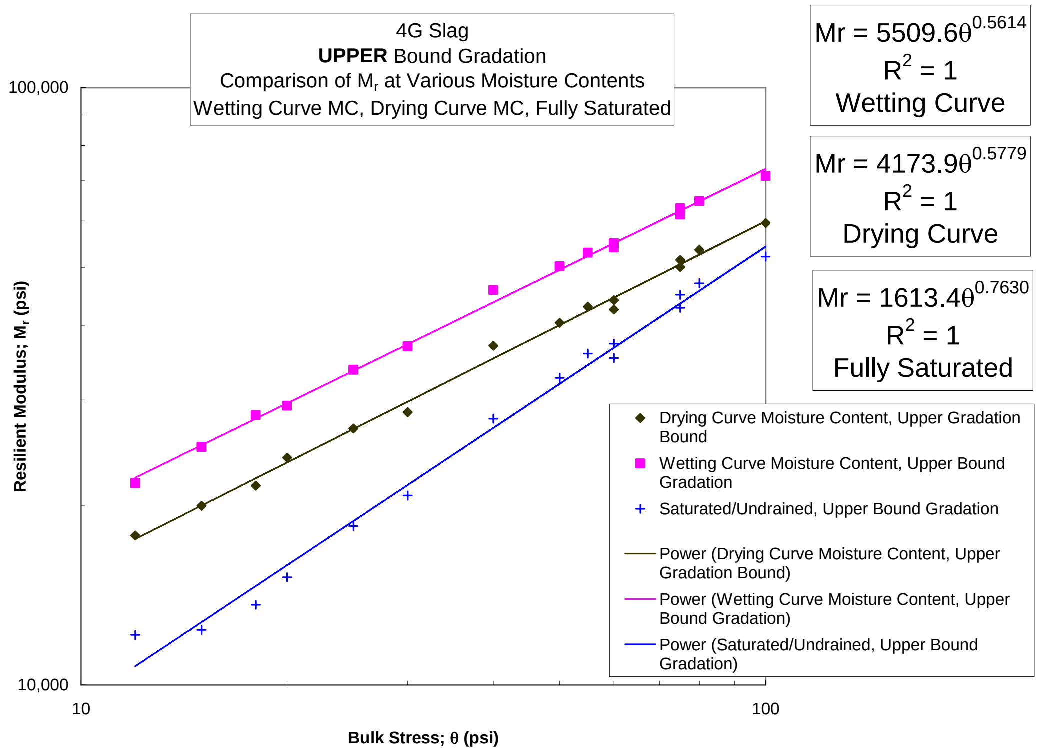

Figure 3.3-17 Slag, Upper Bound Gradations, Wetting and Drying Curve MC, Fully Saturated MC

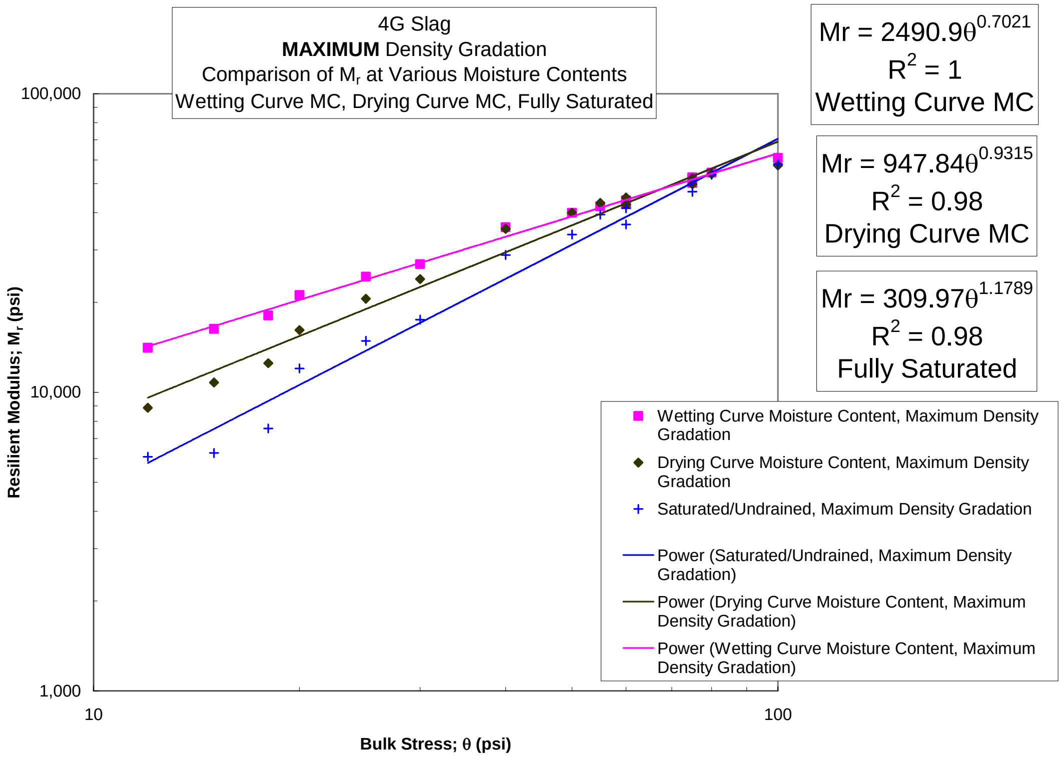

Figure 3.3-18 Slag, Maximum Density Gradations, Wetting and Drying Curve MC, Fully Saturated MC

3.3.4 CRUSHED CONCRETE

For simplicity Figure 3.3-19 through Figure 3.3-21 each show the effect of a different gradation for the Crushed Concrete at the as-compacted moisture content. Figure 3.3-22 through Figure 3.3-24 each compare the results of the three environmental conditions for one of the three gradations used.

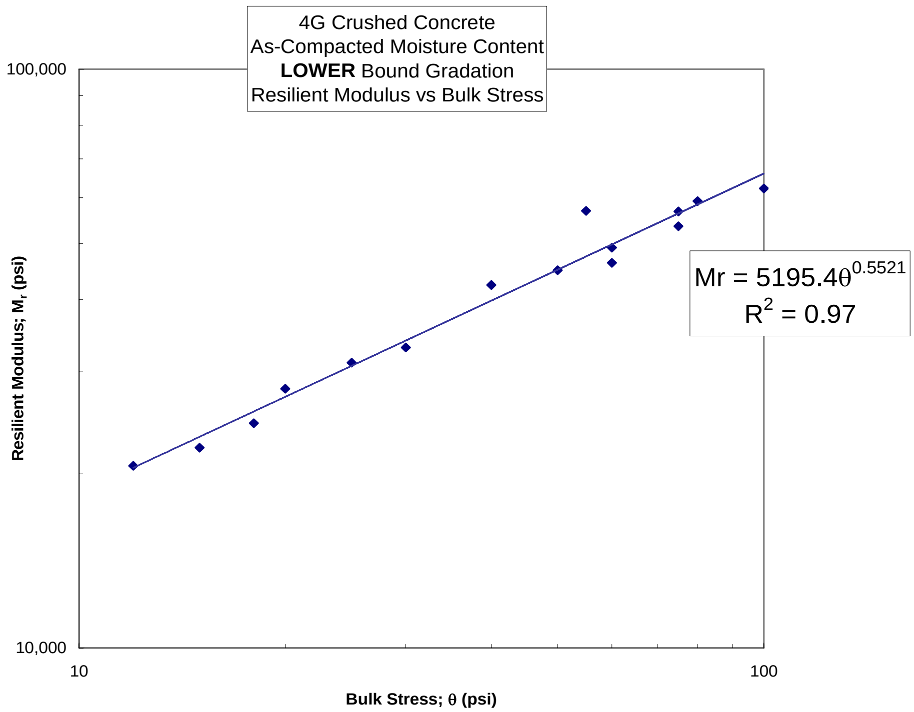

Figure 3.3-19 Crushed Concrete, Lower Bound Gradation

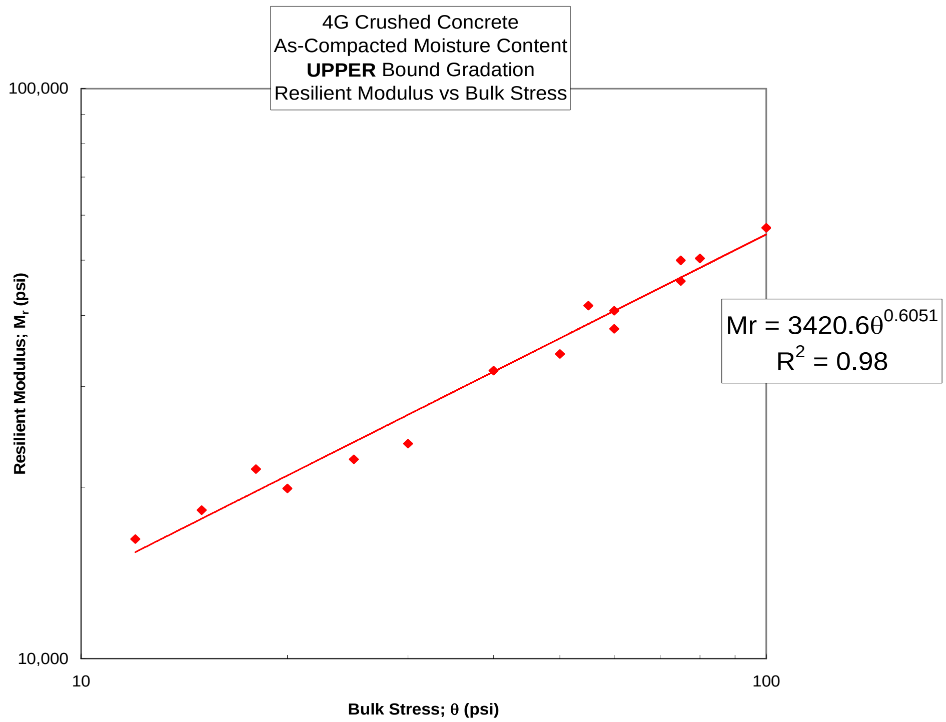

Figure 3.3-20 Crushed Concrete, Upper Bound Gradation

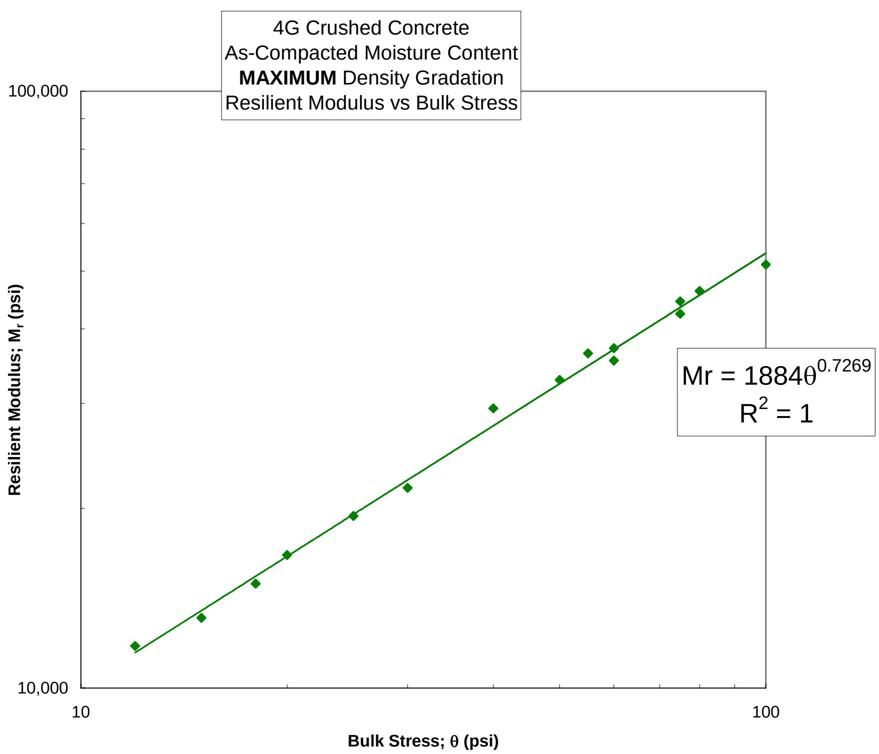

Figure 3.3-21 Crushed Concrete, Maximum Density Gradation

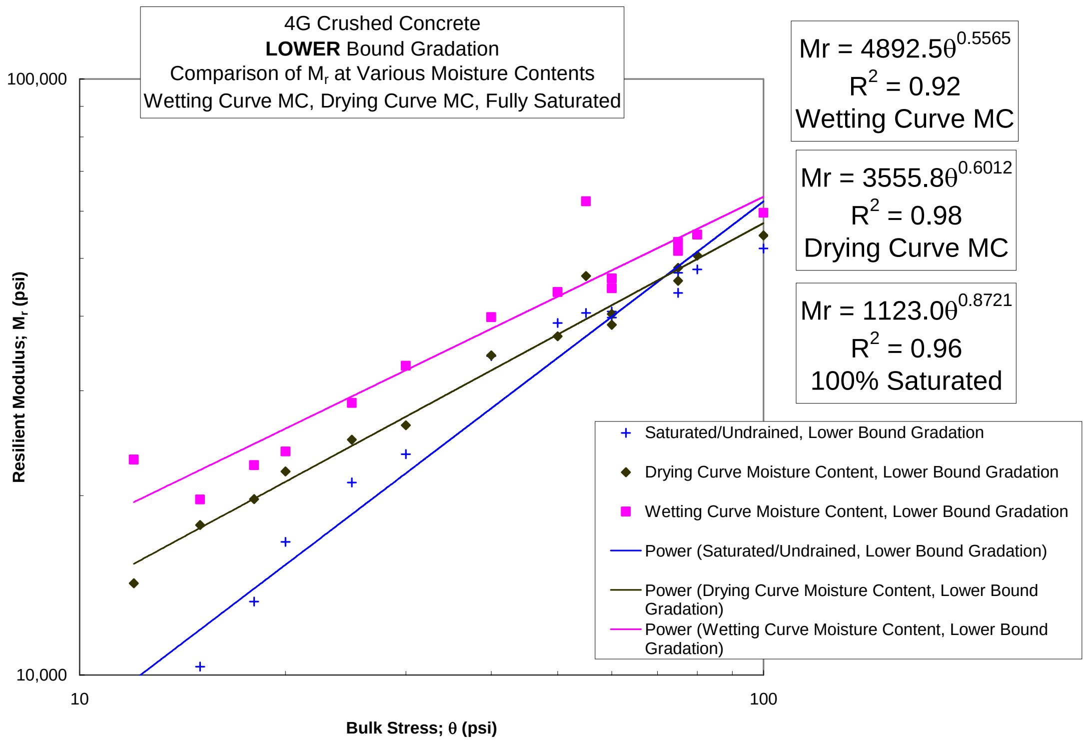

Figure 3.3-22 Crushed Concrete, Lower Bound Gradations, Wetting and Drying Curve MC, Fully Saturated MC

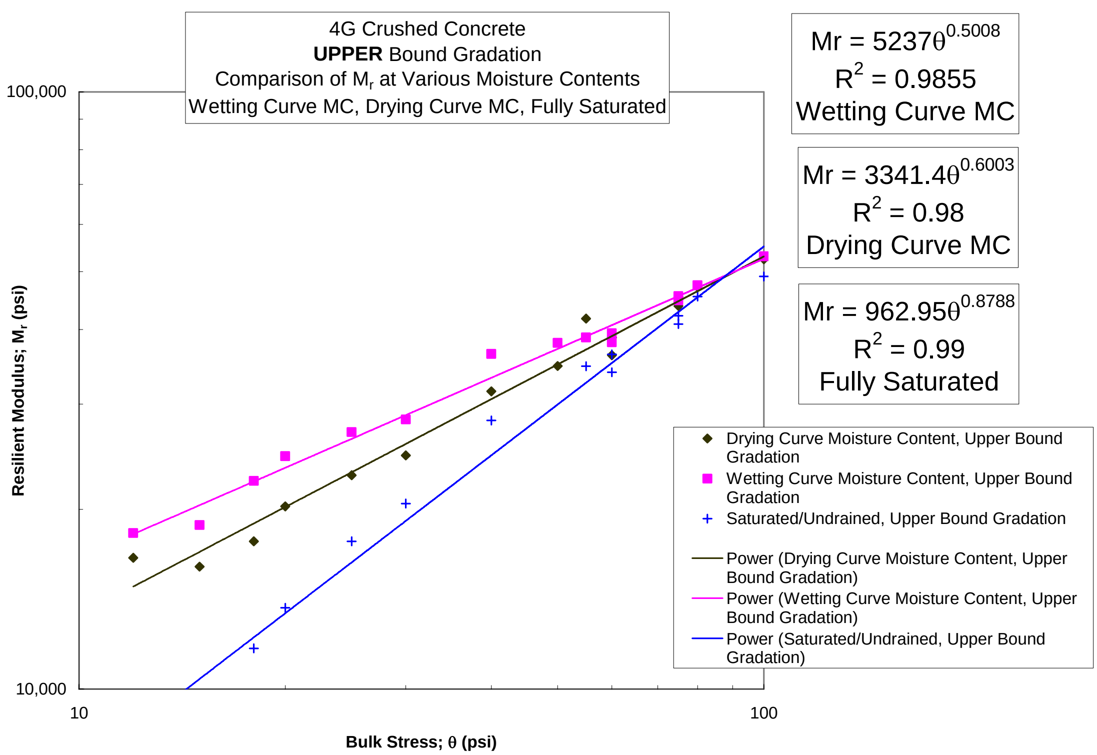

Figure 3.3-23 Crushed Concrete, Upper Bound Gradations, Wetting and Drying Curve MC, Fully Saturated MC

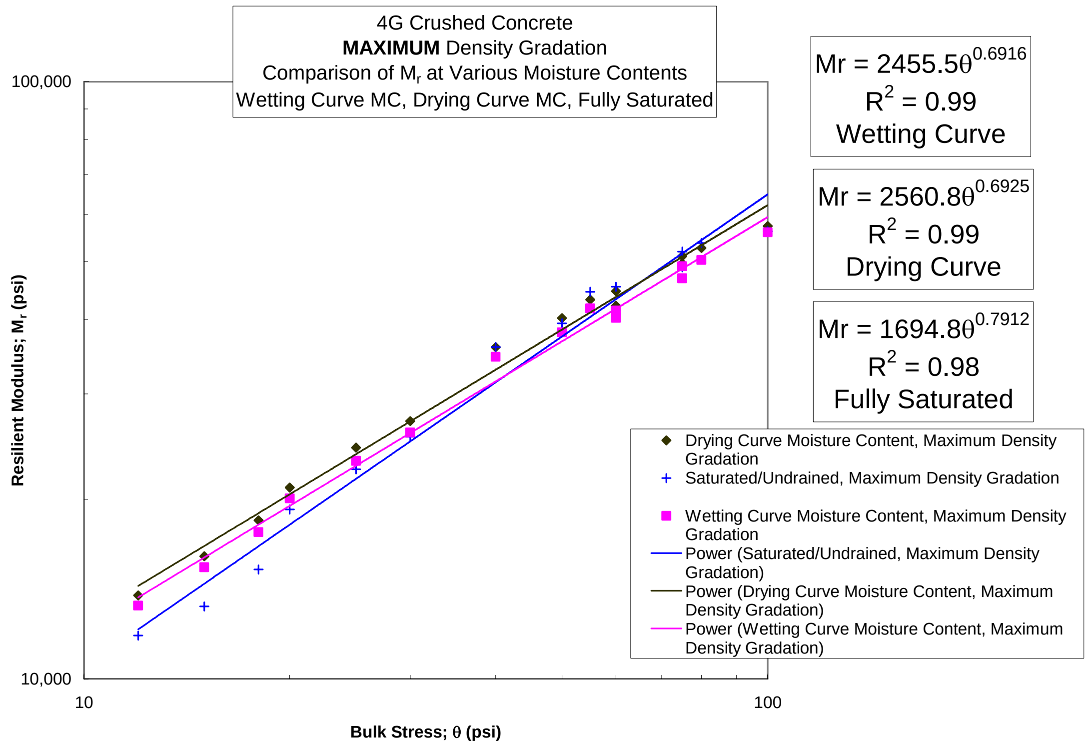

Figure 3.3-24 Crushed Concrete, Maximum Density Gradations, Wetting Curve MC, Drying Curve MC, Fully Saturated MC

3.4 SUMMARY OF REGRESSION CONSTANTS K_1 AND K_2

The resilient modulus values are traditionally plotted versus bulk stress, as shown in Section 0. This relationship is described by a power curve equation in the form: $y = k_1 x^{k2}$ or $M_r = k_1 \theta^{k2}$, where M_r is the Resilient Modulus and θ is the Bulk Stress. K_1 and K_2 are regression constants. Table 3.4-1 summarizes the regression constants of all the relationships shown in section 3.3.

Table 3.4-1 Summary of Regression Constants K1 and K2 (psi)

		Natural Gravel		Dolomite		Slag		Crushed Concrete	
		K_1	K_2	K_1	K_2	K_1	K_2	K_1	K_2
Lower Bound Gradation	As-compacted MC	3321.4	0.6138	4252.9	0.6265	1833.8	.8431	5195.4	0.5521
	Wetting Curve MC	2876.2	0.6318	NA	NA	NA	NA	4892.5	0.5565
	Drying Curve MC	2333.5	0.6797	4890.3	0.5983	3355.7	0.7092	3555.8	0.6012
	Fully Saturated	1744.4	0.7377	2267.0	0.7432	3476.7	0.6826	1123.0	0.8721
Upper Bound Gradation	As-compacted MC	2539.8	0.6332	3116.3	0.6714	3220.4	0.6753	3420.6	0.6051
	Wetting Curve MC	2623.9	0.6644	6113.8	0.5483	5509.6	0.5614	5237.0	0.5008
	Drying Curve MC	2426.0	0.6399	1451.5	0.842	4173.9	0.5779	3341.4	0.6003
	Fully Saturated	993.95	0.8620	2579.6	0.7357	1613.4	0.7630	962.95	0.8788
Maximum Density Gradation	As-compacted MC	1175.1	.7916	2470.8	0.7231	1369.6	.8469	1884	.7269
	Wetting Curve MC	1856.4	0.6919	953.16	0.9498	2490.9	0.7021	2455	0.6916
	Drying Curve MC	2035.1	0.6598	2384.8	0.7307	947.84	0.9315	2560.8	0.6925
	Fully Saturated	985.54	0.8255	2446.2	0.7385	309.97	1.1789	1694.8	0.7912

4 ANALYSIS OF RESULTS

The analysis, material by material, consists of statistical comparisons to determine whether material type, gradation, and/or environmental condition (partially saturated and saturated) influence the resilient modulus. Section 4.1 examines the effect of gradation on the stiffness as measured by the resilient modulus for each of the four materials. Section 4.2 examines the effect of degree of saturation, an environmental variable, on the stiffness for each of the four materials. Finally section 4.3 investigates how material type affects the stiffness of these unbound granular materials. The qualitative ordering of stiffness is accomplished by comparing population parameters of regression analysis curves which have been developed.

4.1 EFFECTS OF GRADATION

This section investigates whether the difference in 3 gradations (upper and lower 4G gradation bounds, and maximum density gradation), see Figure 4.1-1, has an effect on the Resilient Modulus of that particular material. Each material will receive 2 comparisons: 1) Upper Bound Gradation vs. Lower Bound Gradation and 2) Upper Bound Gradation vs. Maximum Density Gradation.

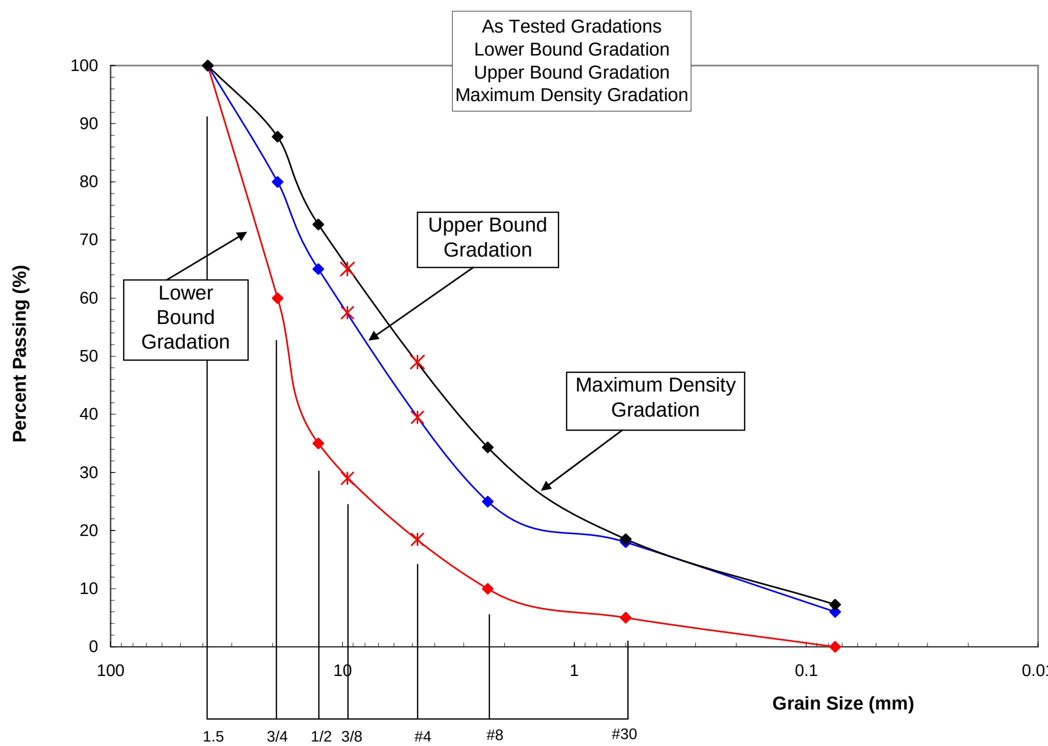

Figure 4.1-1 Lower and Upper Bounds of 4G Gradation Curves and the Curve of Maximum Density

The following sub-sections, *Comparison of Population Parameters in Log-Log Space* and *Comparison of Population Parameters in Linear-Linear Space* describe in step-by-step detail the procedure and rationale of the analysis of the stiffness comparison between the three gradations as applied to Natural Gravel. Successive analysis of the remaining materials will be more concise, without the detailed explanation, but it is to be understood that the method was the same. Section 4.1.5 summarizes the analyses presented in Sections 4.1.1 through 4.1.4.

4.1.1 NATURAL GRAVEL

The rationale and procedure of the analysis process is first presented with the resilient modulus vs. bulk stress relationship in log-log space. This is how this relationship is traditionally presented. However, as will be explained in *Comparison of Population Parameters in Linear-Linear Space* there are some problems with statistical analysis in transformed space and its relationship to true-measured data. The final analyses will use un-transformed data in linear-linear space as outlined. However, as an introduction to the analysis procedure the more accustomed log-log space is used for demonstration purposes.

Comparison of Population Parameters in Log-Log Space

Figure 4.1-2, shows the resilient modulus as a function of the bulk stress. An equation of this relationship is quantified by a linear regression in log-log space. The resulting equation characterizing this relationship is a power equation in the form $y = k_1 x^{k_2}$. When specifically applied it is $M_r = k_1 \theta^{k_2}$, where M_r is the Resilient Modulus, θ is the Bulk Stress, and k_1 and k_2 are regression constants.

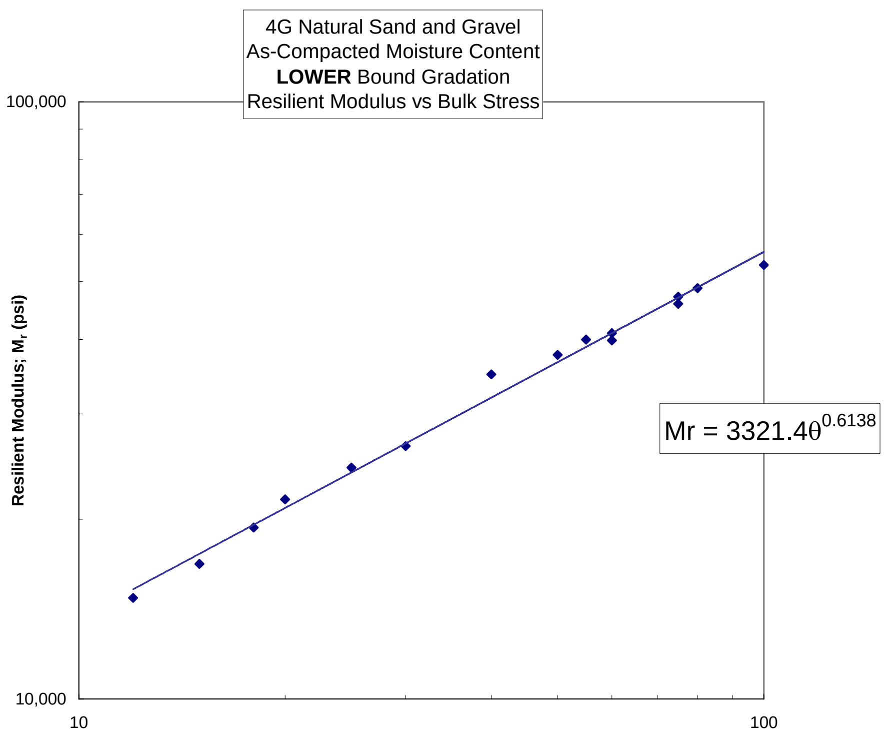

Figure 4.1-2 Natural Gravel Resilient Modulus vs Bulk Stress; Log-Log Space

The questions asked in this analysis are whether, is one gradation stiffer than another gradation and/or does an increased moisture content soften the response for a specific gradation. However, unique values are not being compared, but rather a curve or function is being compared to another curve or function. Thus, we are comparing groups of data which have both a y-intercept and a slope. Inherent in the regression analysis is variability; variability of stiffness due to the testing protocol requiring testing at fifteen different stress states, and variability of stiffness from one test to another because of the natural variability in the testing of unbound granular material. Therefore, when trying to quantify the difference in stiffness between two conditions (two curves), the difference between curves is over a range of stress states (100 psi) and stiffness responses (approx. 70,000 psi). An inspection of Figure 4.1-3 demonstrates the difficulty of qualifying which curve is stiffer than another, where different curves have different and sometimes intercepting slopes and intercepts, and where over the stiffness response changes over a range of 70,000 psi – what constitutes a real difference.

A statistical analysis of population parameters is an appropriate way to begin to quantify the differences between these curves. Hypothesis testing on both the y-intercept and again on the slope would be possible, with each test either accepting or rejecting whether two y-intercepts or two slopes came from the same population distribution. Thus, it could be decided if two curves or gradations actually behaved the same or differently. However, the hypothesis testing is not visual and it would be difficult to both qualify and quantify the curves; if two curves had y-intercepts from the same population but slopes from different populations…then what could be said? Or, if the slopes came from the same population, but the intercepts were different…the same question is developed. Therefore it was decided to take a visual approach to the statistical analysis.

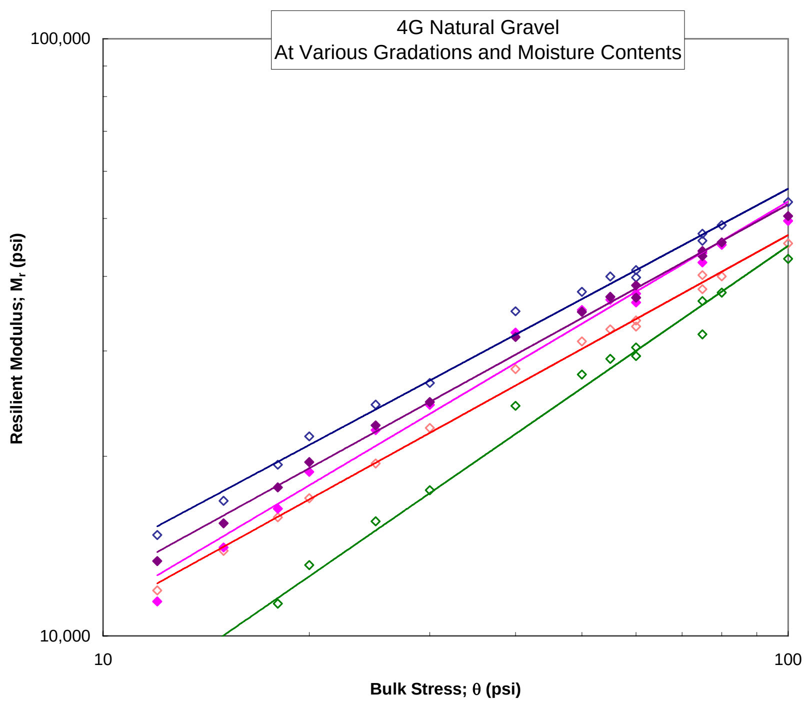

Figure 4.1-3 Resilient Modulus vs Bulk Stress for Natural Gravel at Various Gradations and Moisture Contents

Confidence intervals (CI) provide a way for assessing the quality of the correlation over the full range, not just a yes-no response to a hypothesis at a point. Each test presented as the Resilient Modulus as a function of the Bulk Stress, is shown with its upper and lower limits of confidence is shown in Figure 4.1-4. The level of significance (1-α) chosen for analysis was 0.05, producing a 95% confidence interval. "…Such confidence intervals permit one to simultaneously make confidence statements about estimates of Y for a number of values of the predictor variable (Ayyub and McCuen, 1997)." Having the Resilient Modulus response curve enveloped by confidence intervals allows us to determine if two curves are actually different or similar statistically, by quantifying the variability inherent in each curve.

Using Figure 4.1-4, Figure 4.1-5, and Figure 4.1-6 it will be shown how the confidence intervals are used for analysis. Query: Is there a difference in stiffness response between the Upper Bound 4G gradation and the Lower Bound 4G gradation? Figure 4.1-4 and Figure 4.1-5 are the Resilient Modulus vs Bulk Stress curves with confidence intervals for the Upper Bound 4G gradation and the Lower Bound 4G gradation, respectively, for Natural Gravel. The two curves are compared on one plot in Figure 4.1-6.

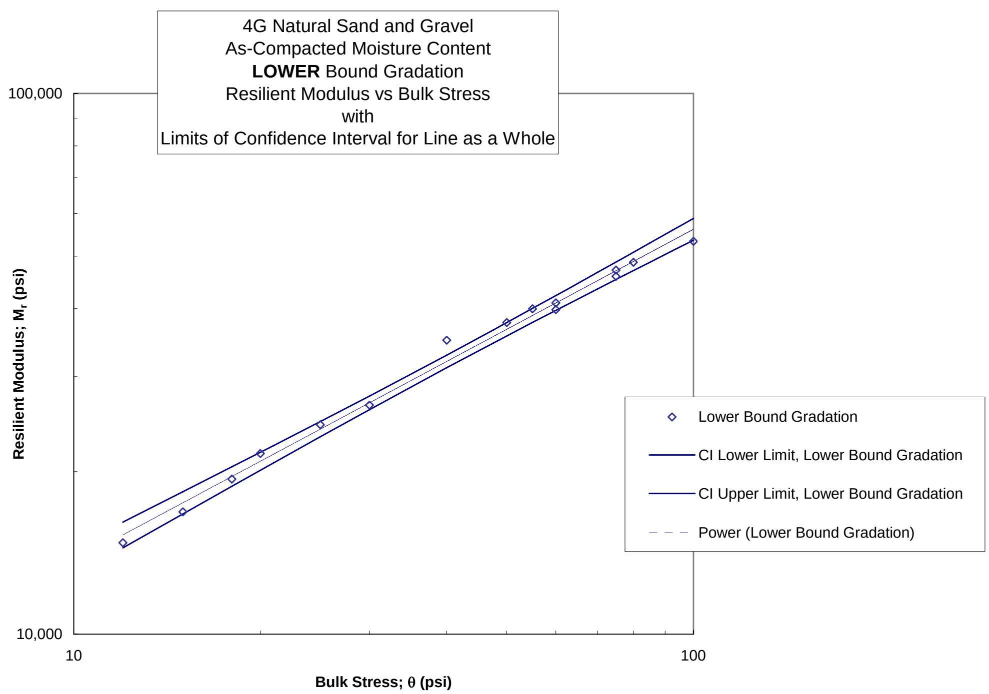

Figure 4.1-4 Resilient Modulus vs Bulk Stress with Limits of 95% Confidence Interval; Log-Log Space

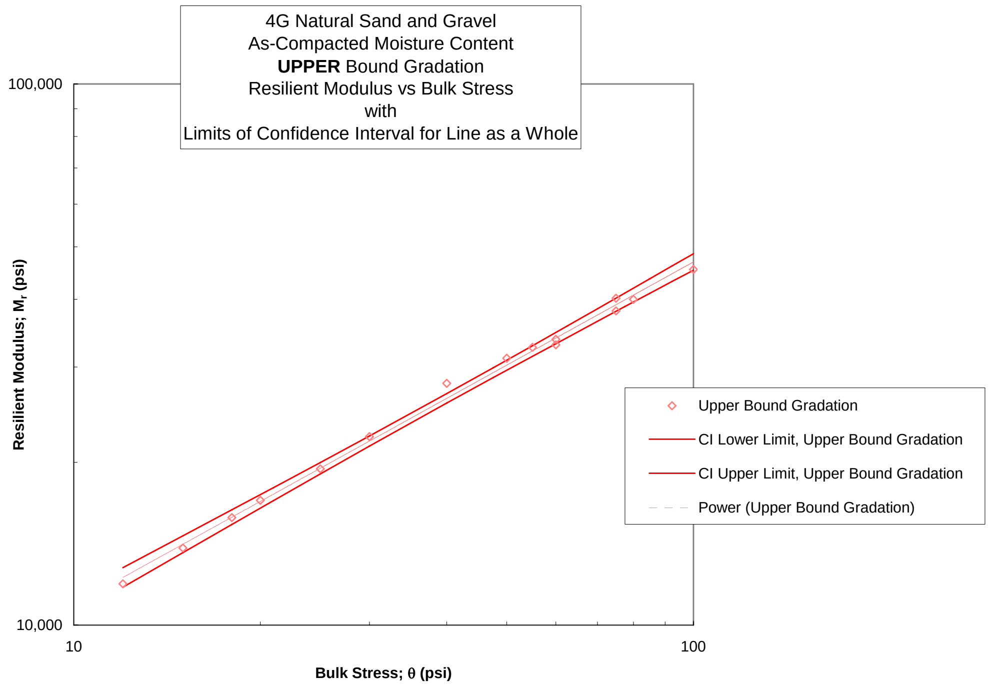

Figure 4.1-5 Resilient Modulus vs Bulk Stress with Limits of 95% Confidence Interval; Log-Log Space

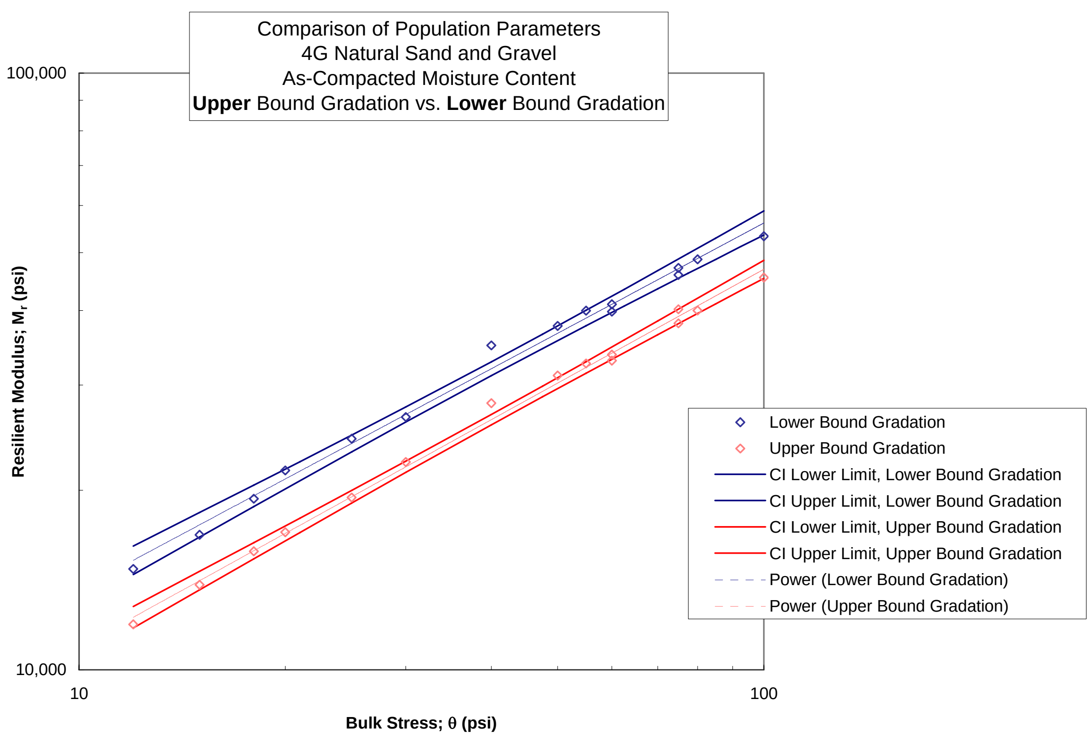

Figure 4.1-6 Comparison of Population Parameters between Upper and Lower Bound Gradation

Figure 4.1-6, shows the comparison between Upper and Lower bound gradation stiffness response. The confidence intervals around each curve demonstrate an hourglass shape. As the limits of confidence approach the value of the mean, the narrower the band becomes. Thus, curves will be compared at their means or the tightest point of the confidence interval. If the two curves do not intercept at the mean or narrowest point, then the means of each curve come from different population distributions and are considered different curves. Since the Lower Bound Curve lies above the Upper Bound curve it can then be said that the Lower Bound gradation is statistically stiffer than the Upper Bound Gradation. In this scenario, the slopes of both curves are essentially parallel, the confidence intervals are tight due to low variability, and statistically their means are significantly different. This makes it relatively simple to make both a qualitative and quantitative decision.

However, three other conditions or scenarios exist which may or may not be as simple to qualify and may require more judgment. Figure 4.1-7, Figure 4.1-8, and Figure 4.1-9 show these other scenarios. Figure 4.1-7 shows the confidence interval of two curves clearly intersecting at the mean and over the rest of the line as a whole. It would be said then that these two curves are statistically the same and neither gradation was stiffer than the other. Figure 4.1-8 shows two curves both with greater variability of data, and therefore wider CI bands. Both CI curves also intersect where there is less confidence in the prediction, however, where the CI band is narrowest around the mean, the CI bands do not intersect. Thus, these two curves would be considered statistically different, and one curve shows a stiffer response, albeit less of a difference than in Figure 4.1-6. Finally Figure 4.1-9 shows the CI bands intersecting at the mean, but clearly having different slopes. The amount of band intersection and difference in slope will determine whether these two curves will be qualified as behaving similarly or different.

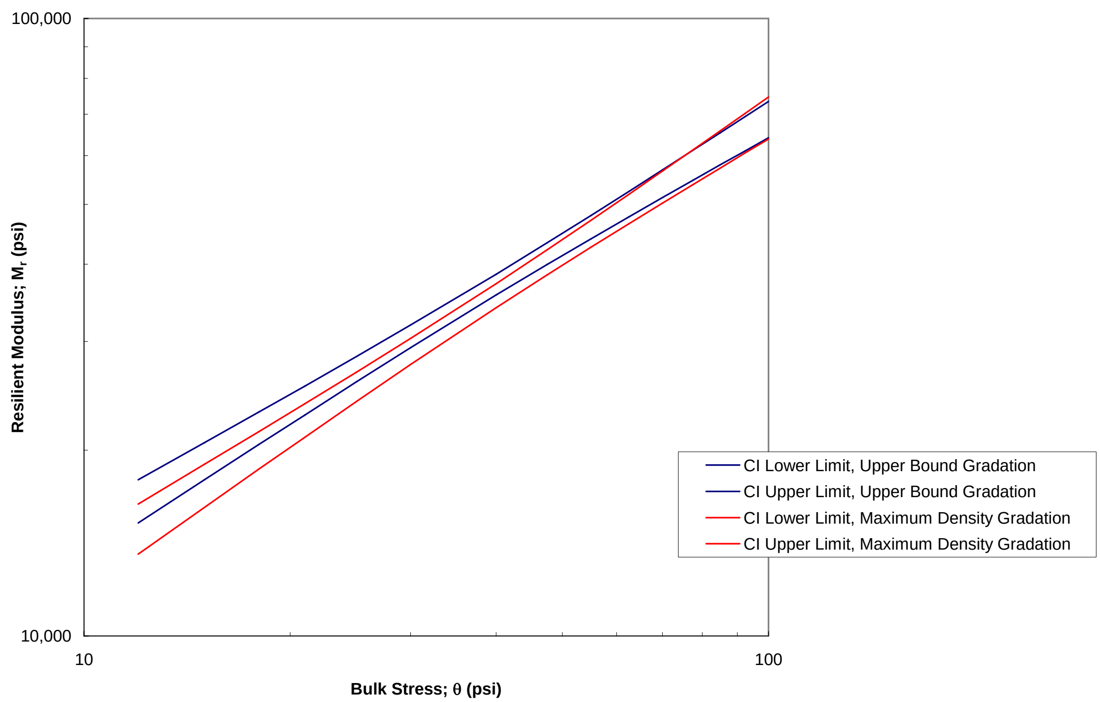

Figure 4.1-7 Statistically Similar Curves

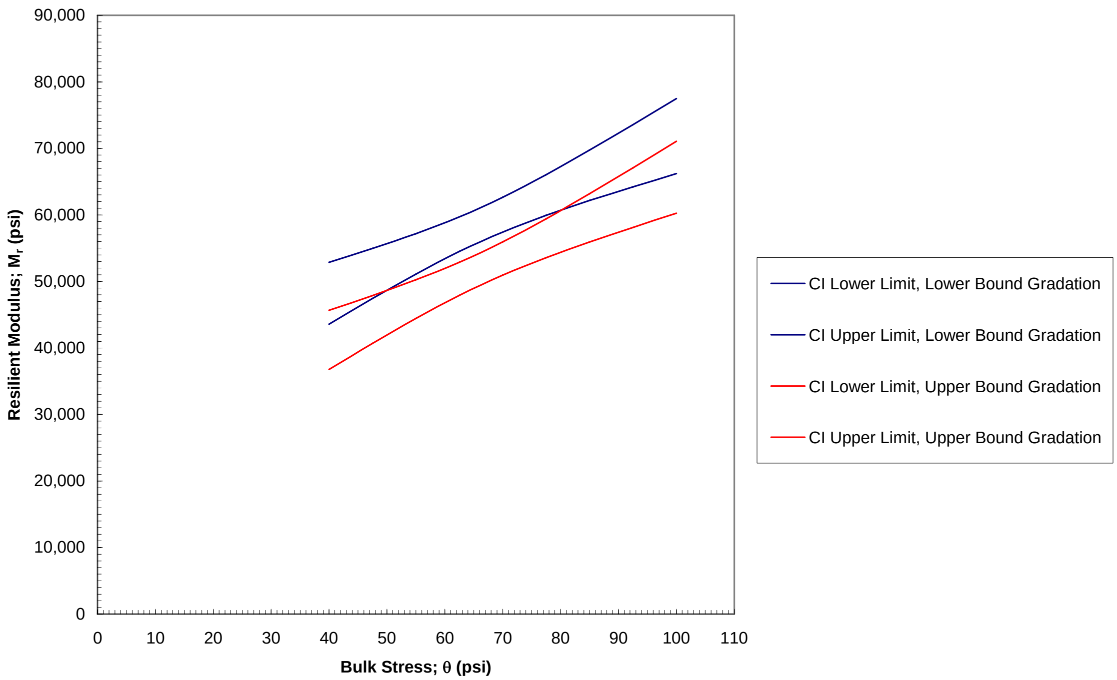

Figure 4.1-8 Statistically Different Curves Albeit Close in Behavior

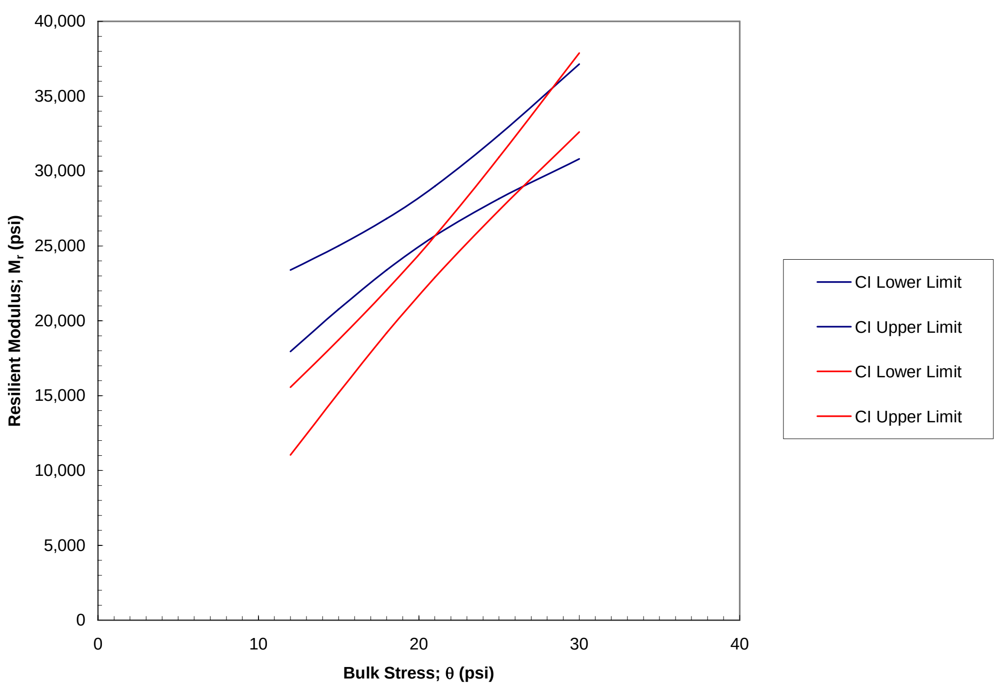

Figure 4.1-9 Statistically Similar Means with Different Slopes

Comparison of Population Parameters in Linear-Linear Space

The relationship between the resilient modulus and bulk stress is typically presented in log-log space, in which the relationship is linear. However, for statistical comparisons it is necessary to analyze the data un-transformed. "For nonlinear models, in which the criterion variable Y is not transformed, the goodness-of-fit statistics are valid indicators of the reliability of the model; however, when the criterion variable is transformed, such as is necessary for the power model form, the principle of least squares is applied in the log-log space. As a result, the residuals that are used to compute the standard error of estimate, and the correlation coefficient, are measured in the domain of the logarithm of Y and not the Y domain (Ayyub and McCuen, 1997)." Any statistical analysis in log-log space then is only valid in the transformed space and is not reliable as a model or indicator in *measurement non-transformed* space.

The resilient modulus/bulk stress relationship is not linear in un-transformed space. The statistical comparison of two curves requires a linear relationship whether in log-log space or un-transformed space. In un-transformed space it is necessary to break the resilient modulus/bulk stress relationship into two curves. There is a very natural inflection point, as shown in Figure 4.1-10, where the material exhibits two distinct behaviors in the resilient modulus testing protocol. This inflection point occurs around a bulk stress of 40 psi. It is thought that at this point the behavior of the material changes from over-consolidated behavior to normally consolidated behavior (Mayrberger and Hodek, 2003). The normally consolidated region is to the right of the inflection point. When, each range of behavior is treated separately it is possible to have a very linear relationship between the resilient modulus and the bulk stress. The confidence interval is then computed for both regions of behavior, as shown in Figure 4.1-1. The comparison of population parameters of various curves are then analyzed as described in section *Comparison of Population Parameters in Log-Log Space.*

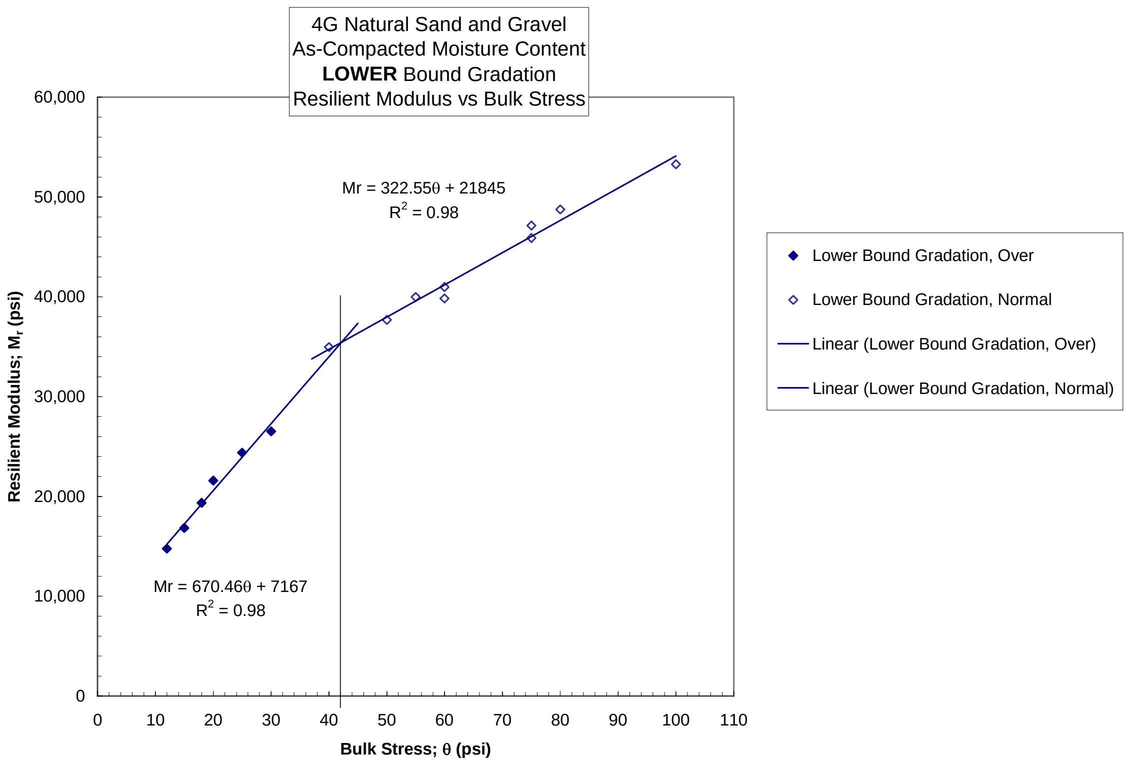

Figure 4.1-10 Natural Gravel Lower Bound Gradation; Linear-Linear Space with Inflection between Overconsolidated State and Normally Consolidated State

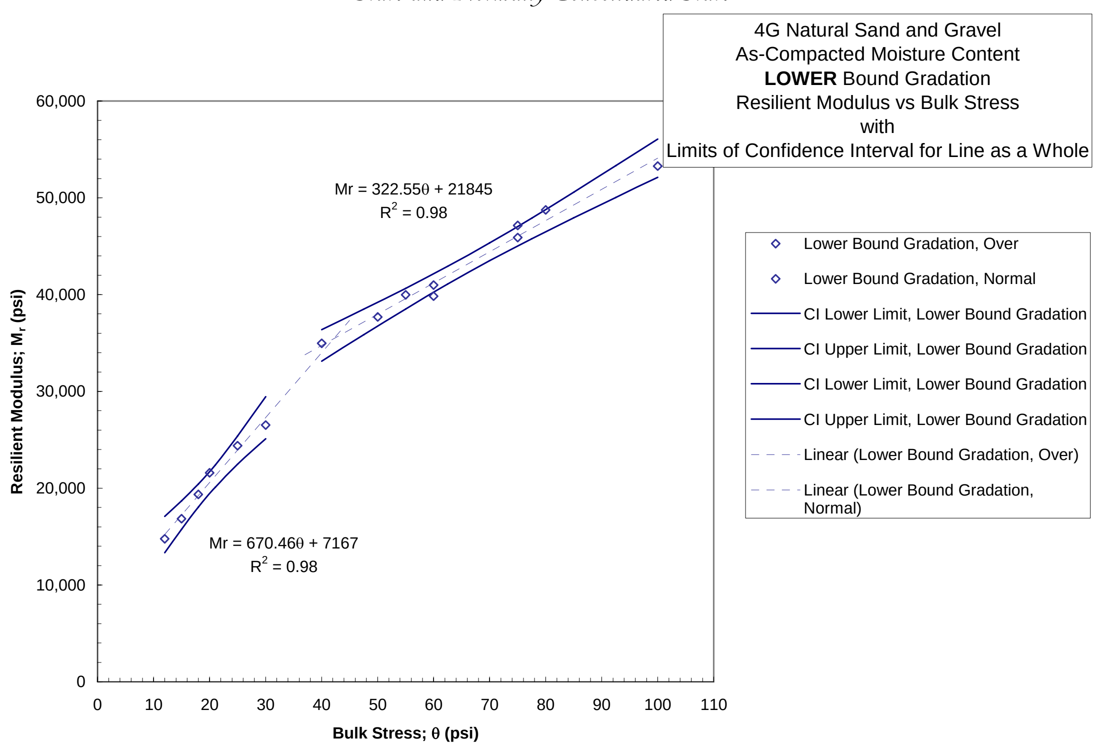

Figure 4.1-11 Resilient Modulus vs Bulk Stress with Limits of 95% Confidence Interval; Linear-Linear Space

Figure 4.1-12 shows the Resilient Modulus – Bulk Stress relationship for all three gradations (Lower Bound, Upper Bound and Maximum Density) on one plot. The Lower and Upper Bound gradation M_r curves for Natural Gravel are pulled off of Figure 4.1-12 and are compared in Figure 4.1-13. Clearly the CI bands do not intersect in the overconsolidated region or the normally consolidated region, while the slopes of both gradations are nearly parallel. One can observe that the lower bound gradation for Natural Gravel is stiffer than the upper bound gradation.

In Figure 4.1-14 the difference in stiffness as a function of bulk stress from Figure 4.1-13 is quantified. The CI band is narrowest around the mean of the curve; this is chosen as the point of comparison. In the normally consolidated region this occurs at a bulk stress of 67 psi. The lower limit of the CI band for the *lower bound gradation* is compared to the upper limit of the CI band of the *upper bound gradation*; this comparison shows that there is **at least** a 5,500 psi difference in stiffness between the two gradations in the normally consolidated region - a 15% increase in stiffness. When the upper limit of the CI band of the *lower bound gradation* curve is compared to the lower limit of the CI band of the *upper bound gradation* there can be **at most** be a 9,500 psi difference in stiffness. The same analysis is applied to the curves of the over-consolidated region. Again there is **at least** a 2,500 psi difference in stiffness, while it is possible that they can vary by **as much** as 5,500 psi, or a range of stiffness difference between 14% – 33 %. The values of all the forthcoming visual analyses will be put into tabular form at the end of this section.

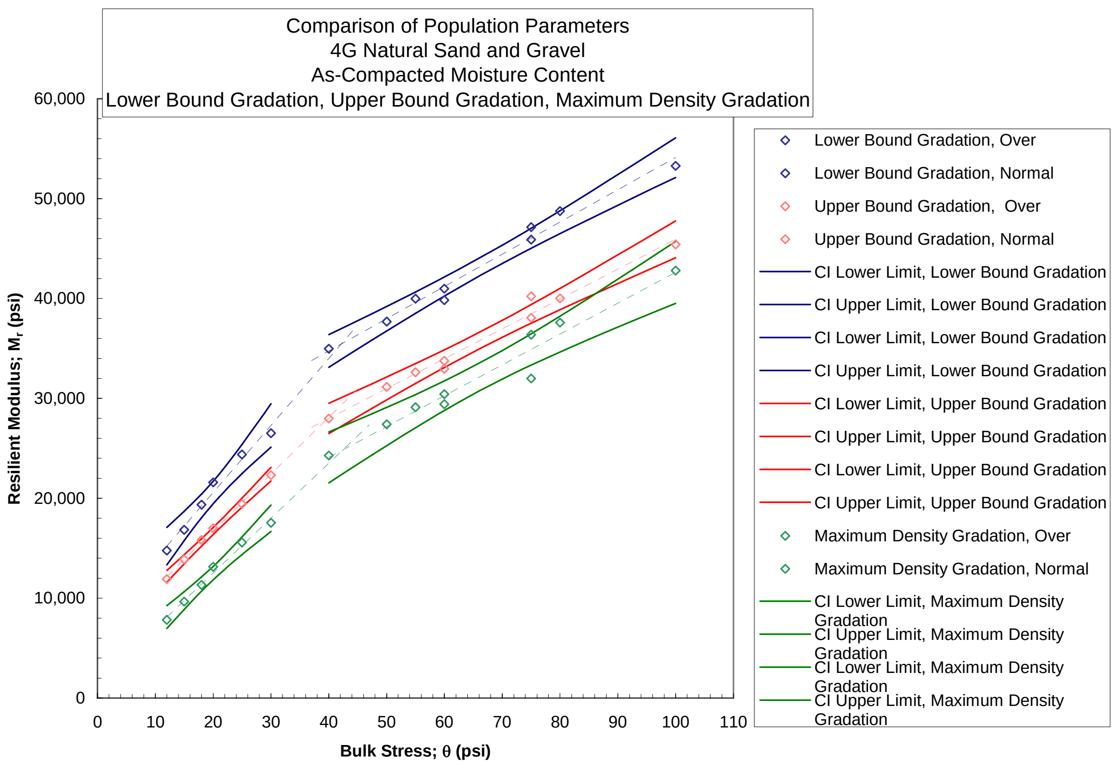

Figure 4.1-12 Comparison of Lower Bound, Upper Bound, and Maximum Density Gradations with CI Intervals

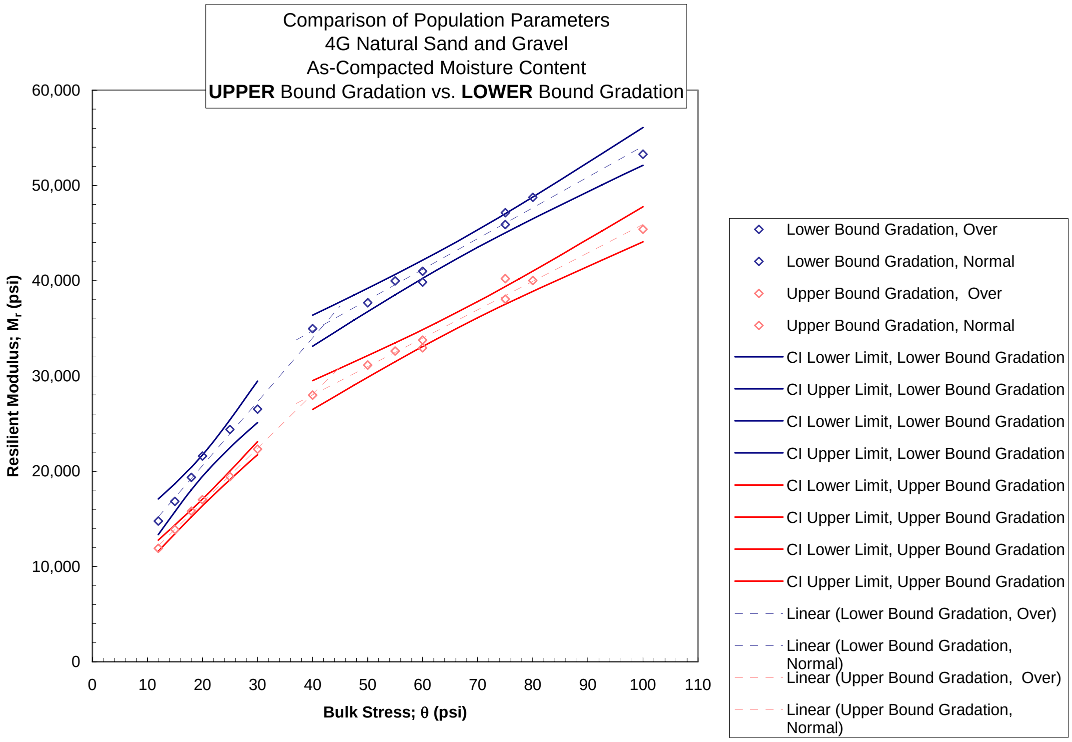

Figure 4.1-13 Comparison of Population Parameters in Linear-Linear Space

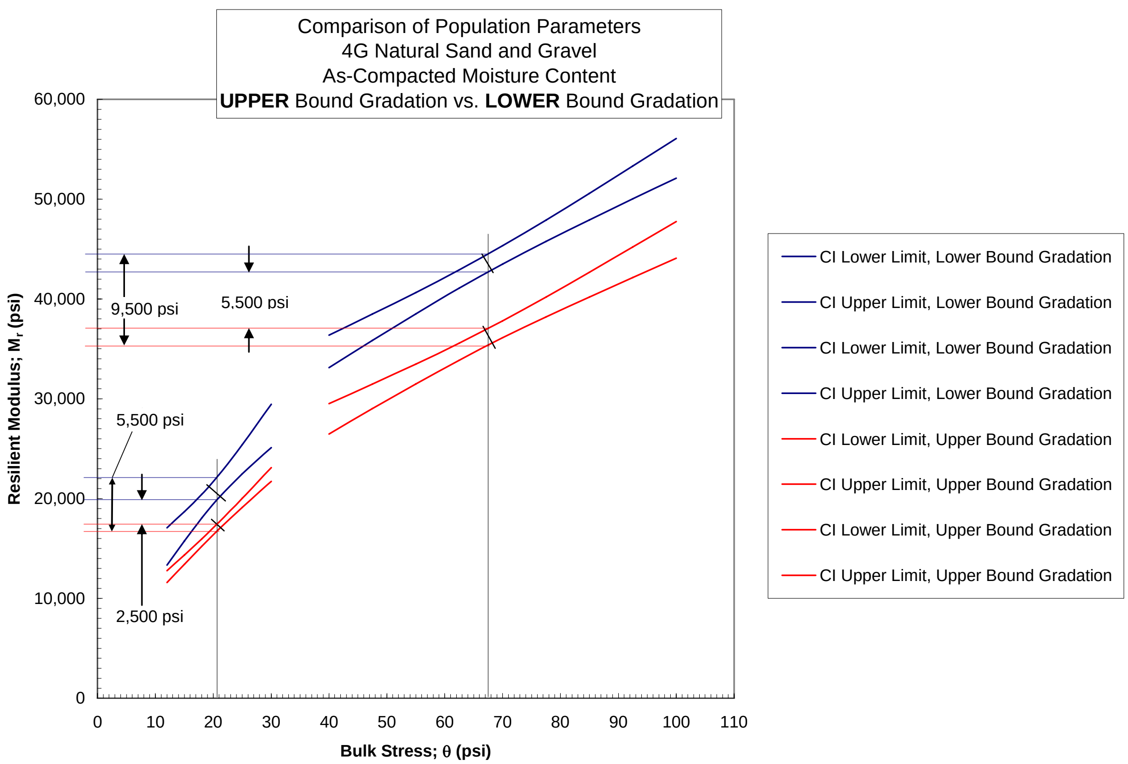

Figure 4.1-14 Stiffness Difference between Upper and Lower Bound Gradations; Natural Gravel

Figure 4.1-15 shows that the *upper bound gradation* is stiffer than the *maximum density gradation*, in both the overconsolidated and normally consolidated regions. The *upper bound gradation* shows "at least" a 22 % and 4% increase in stiffness in the respective regions.

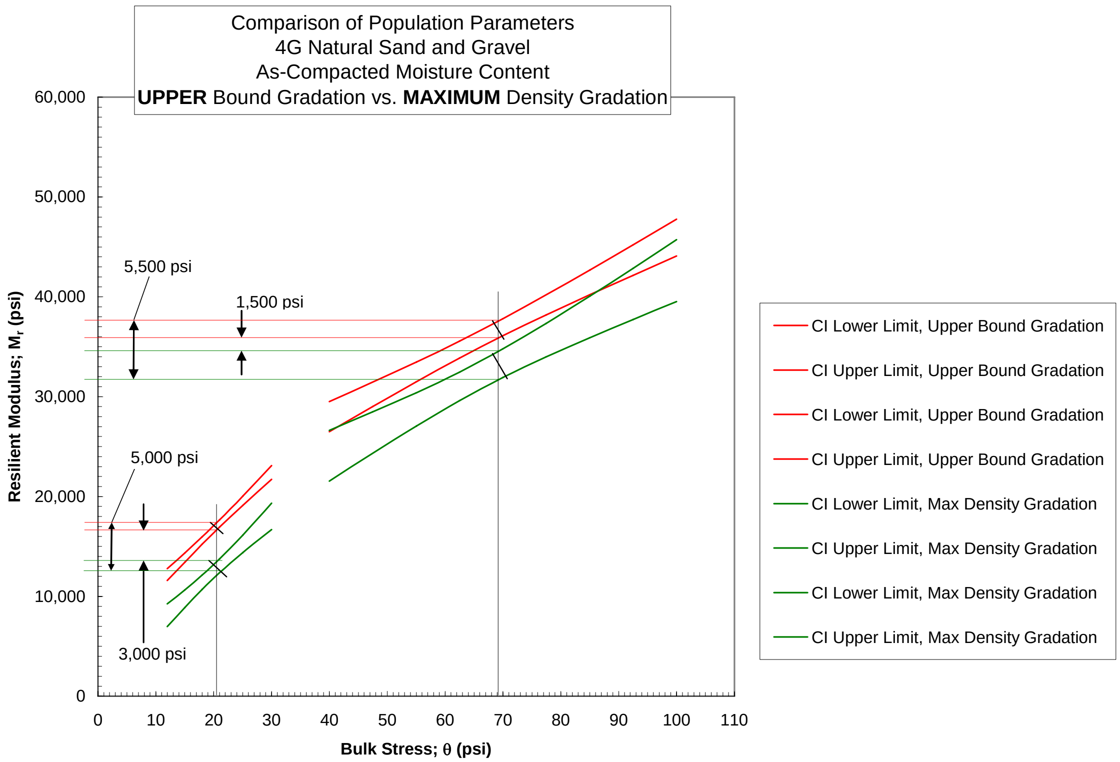

Figure 4.1-15 Stiffness Difference between Upper Bound and Maximum Density Gradations; Natural Gravel

4.1.2 DOLOMITE

The Dolomite evaluations are demonstrated in Figure 4.1-16 through Figure 4.1-18. Figure 4.1-16 shows the Resilient Modulus – Bulk Stress relationship for all three gradations (Lower Bound, Upper Bound and Maximum Density) on one plot. Figure 4.1-17 shows that the *lower bound gradation* is stiffer than the *upper bound gradation*, in both the overconsolidated and normally consolidated regions. The *lower bound gradation* shows "at least" a 6% and 4% increase in stiffness in the respective regions.

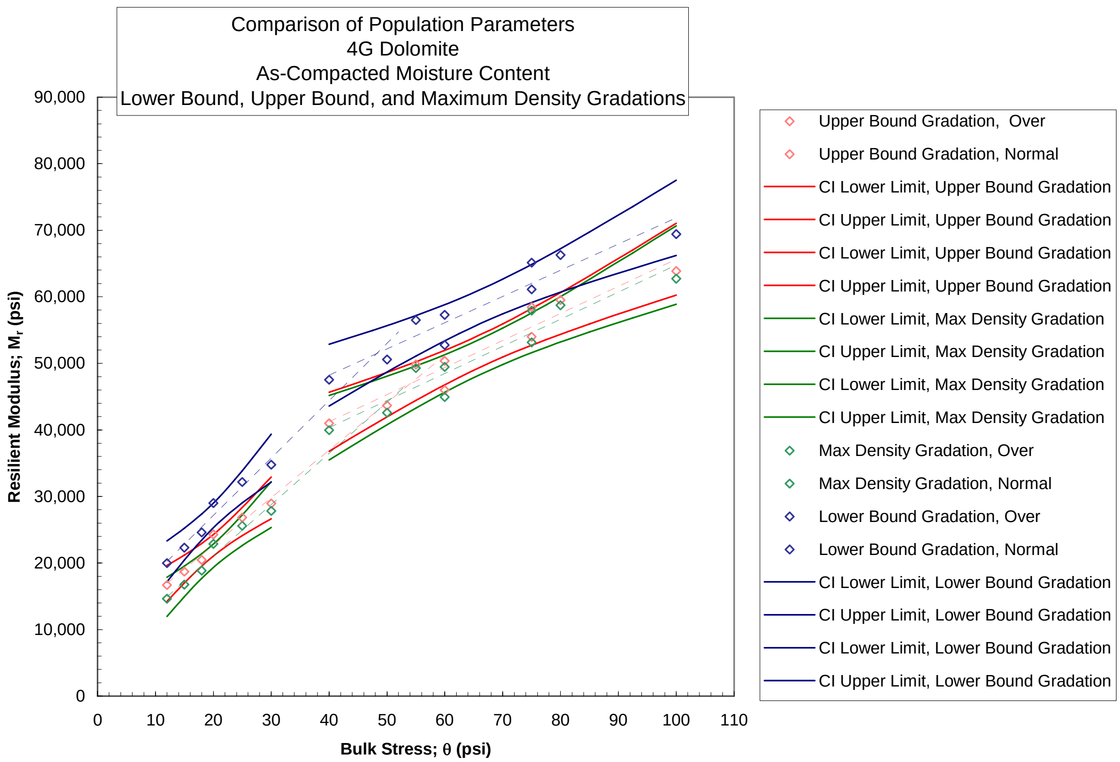

Figure 4.1-16 Comparison of Lower Bound, Upper Bound, and Maximum Density Gradations with CI Intervals

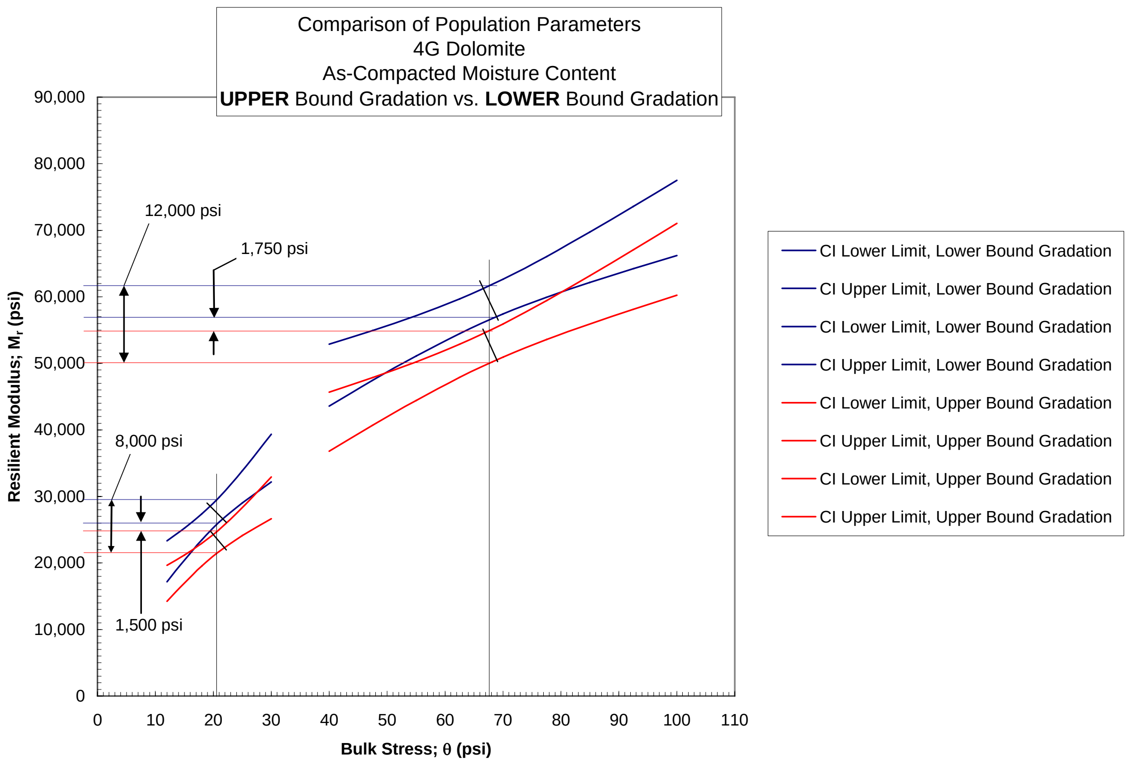

Figure 4.1-17 Stiffness Difference between Upper and Lower Bound Gradations; Dolomite

Statistically the upper bound gradation and the maximum density gradation are similar for 4G Dolomite. Therefore neither gradation shows any superior stiffness characteristics. This is shown in Figure 4.1-18.

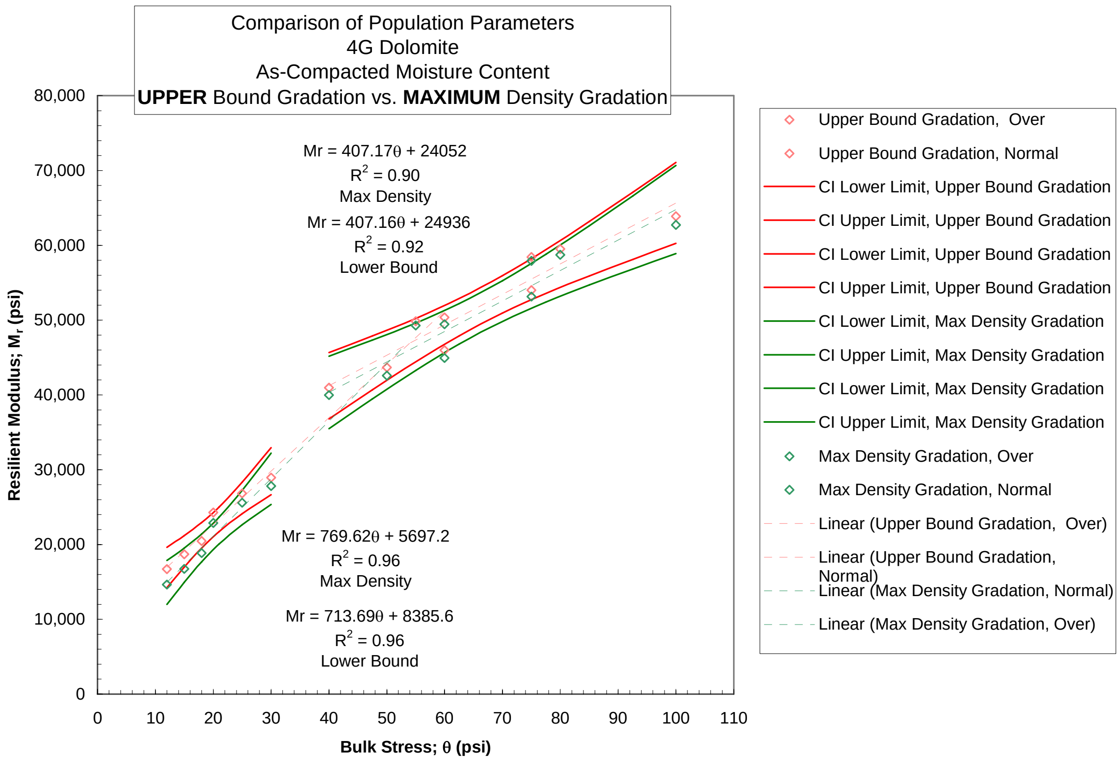

Figure 4.1-18 Stiffness Difference between Upper Bound Gradation and Maximum Density Gradations; Dolomite

4.1.3 SLAG

The Slag evaluations are demonstrated in Figure 4.1-19 through Figure 4.1-21. Figure 4.1-19 shows the Resilient Modulus – Bulk Stress relationship for all three gradations (Lower Bound, Upper Bound and Maximum Density) on one plot. Figure 4.1-20 shows that the *lower bound gradation* is stiffer than the *upper bound gradation*, in the normally consolidated region. However, in the overconsolidated region, the means intersect but the slopes are clearly different. Within the bulk stress range, however this slope difference is inconsequential and both curves can be seen as statistically similar. The *lower bound gradation* in the normally consolidated region shows "at least" an 8% increase in stiffness.

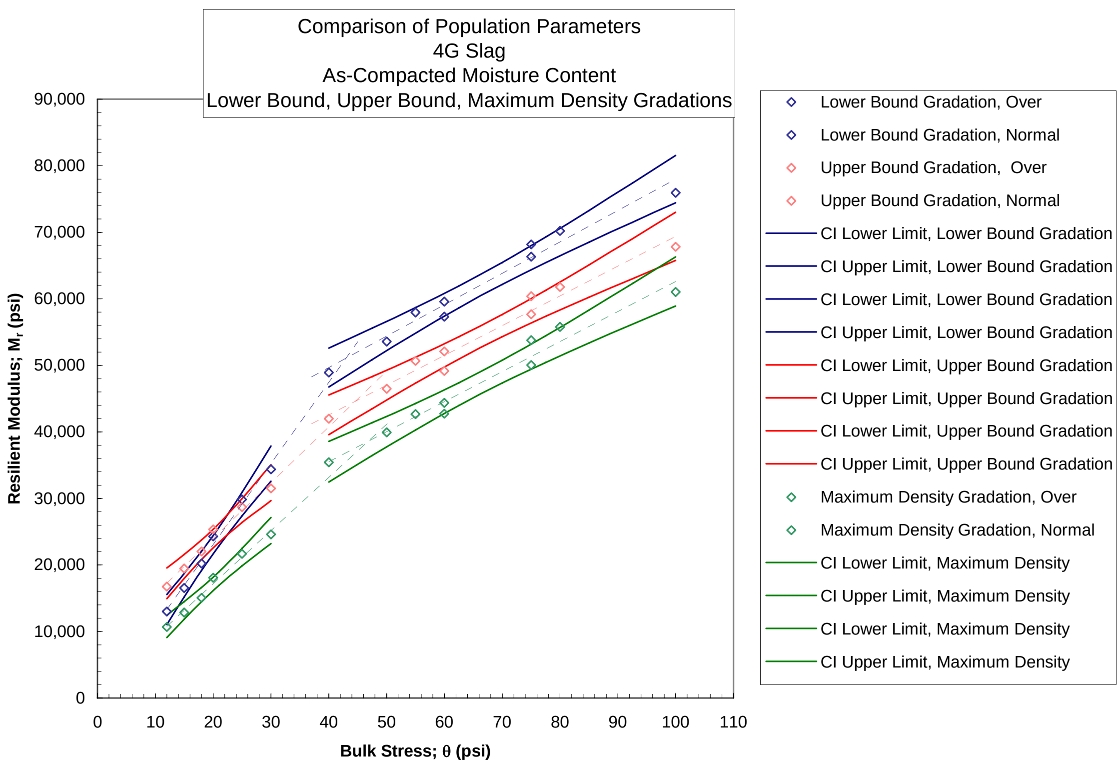

Figure 4.1-19 Comparison of Lower Bound, Upper Bound, and Maximum Density Gradations with CI Intervals

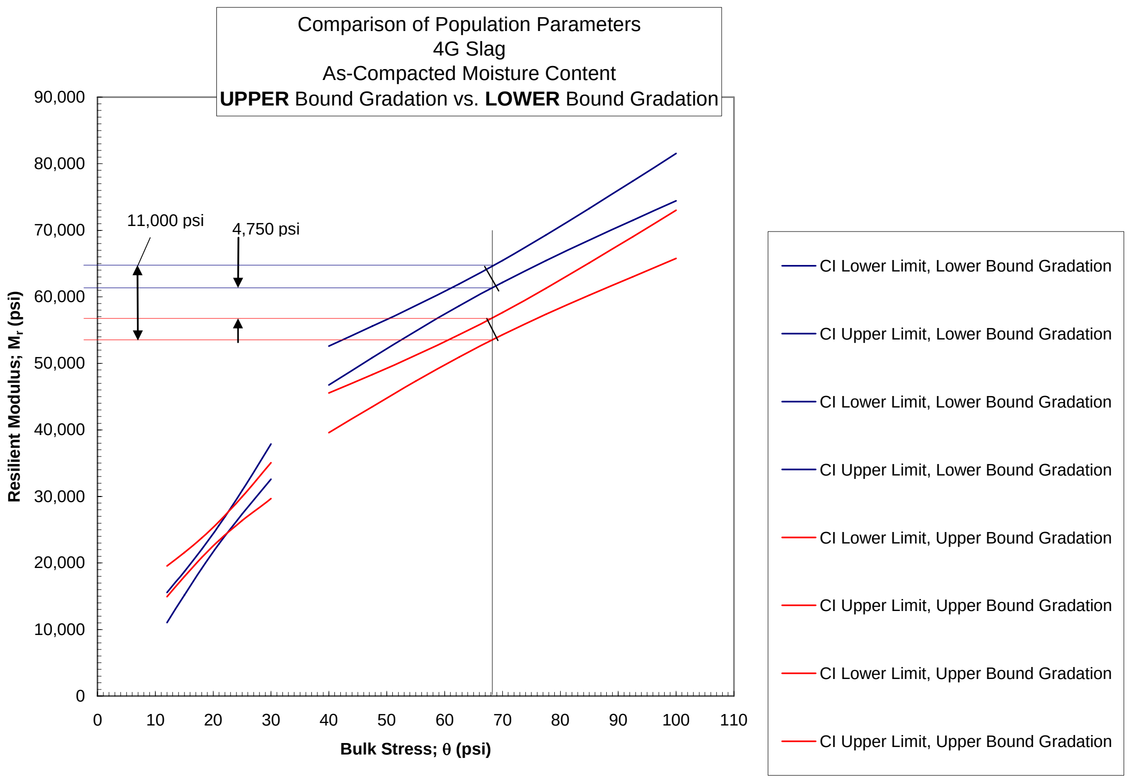

Figure 4.1-20 Stiffness Difference between Upper and Lower Bound Gradations; Slag

Figure 4.1-21 shows that *upper bound gradation* is stiffer than the *maximum density gradation*, in both the overconsolidated and normally consolidated regions. The *upper bound gradation* shows "at least" a 27% and 7% increase in stiffness in the respective regions.

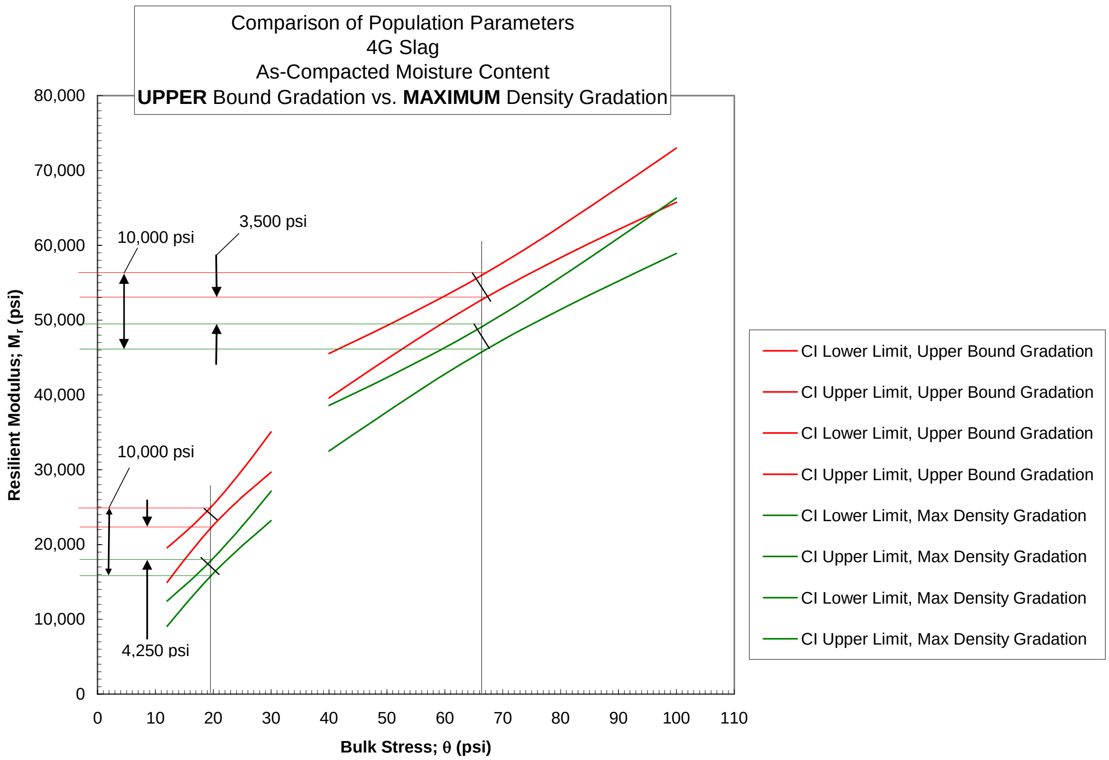

Figure 4.1-21 Stiffness Difference between Upper Bound Gradation and Maximum Density Gradations; Slag

4.1.4 CRUSHED CONCRETE

The behavior of 4G Crushed Concrete material was analyzed in the same manner. Figure 4.1-22 shows the Resilient Modulus – Bulk Stress relationship for all three gradations (Lower Bound, Upper Bound and Maximum Density) on one plot. The *lower bound gradation* is stiffer than the *upper bound gradation*, in both the overconsolidated and normally consolidated regions. The *lower bound gradation* shows "at least" a 6 % and 13% increase in stiffness in the respective regions. This is shown in Figure 4.1-23.

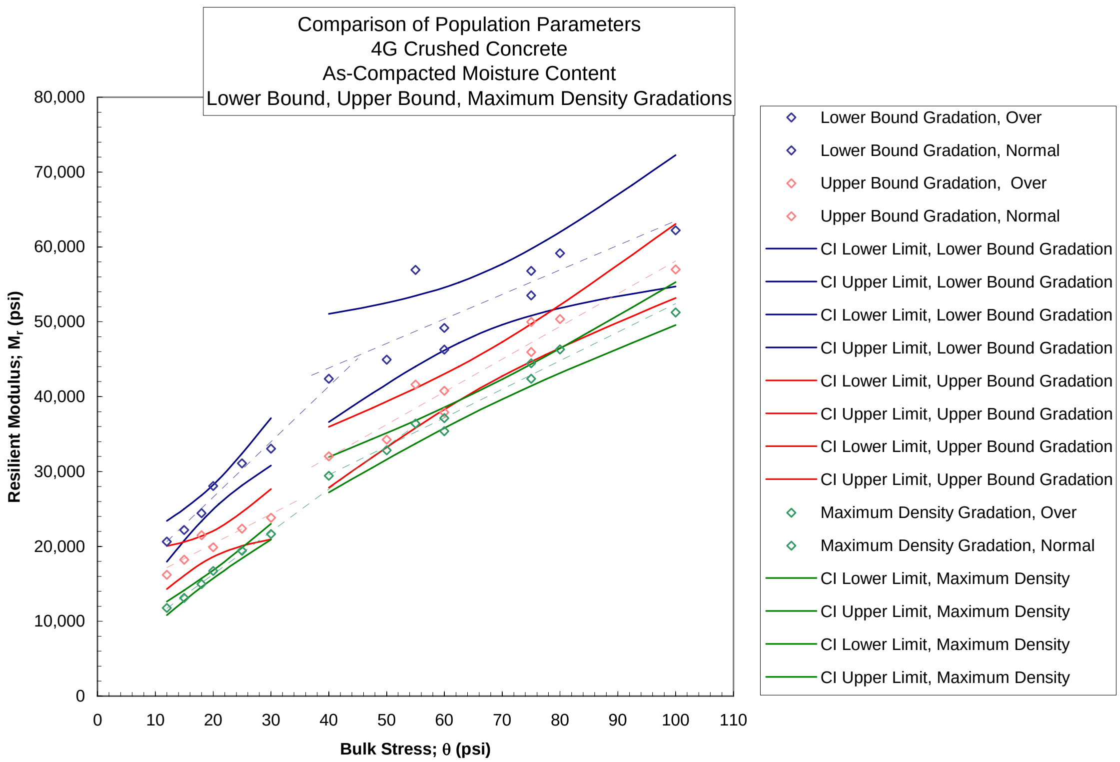

Figure 4.1-22 Comparison of Lower Bound, Upper Bound, and Maximum Density Gradations with CI Intervals

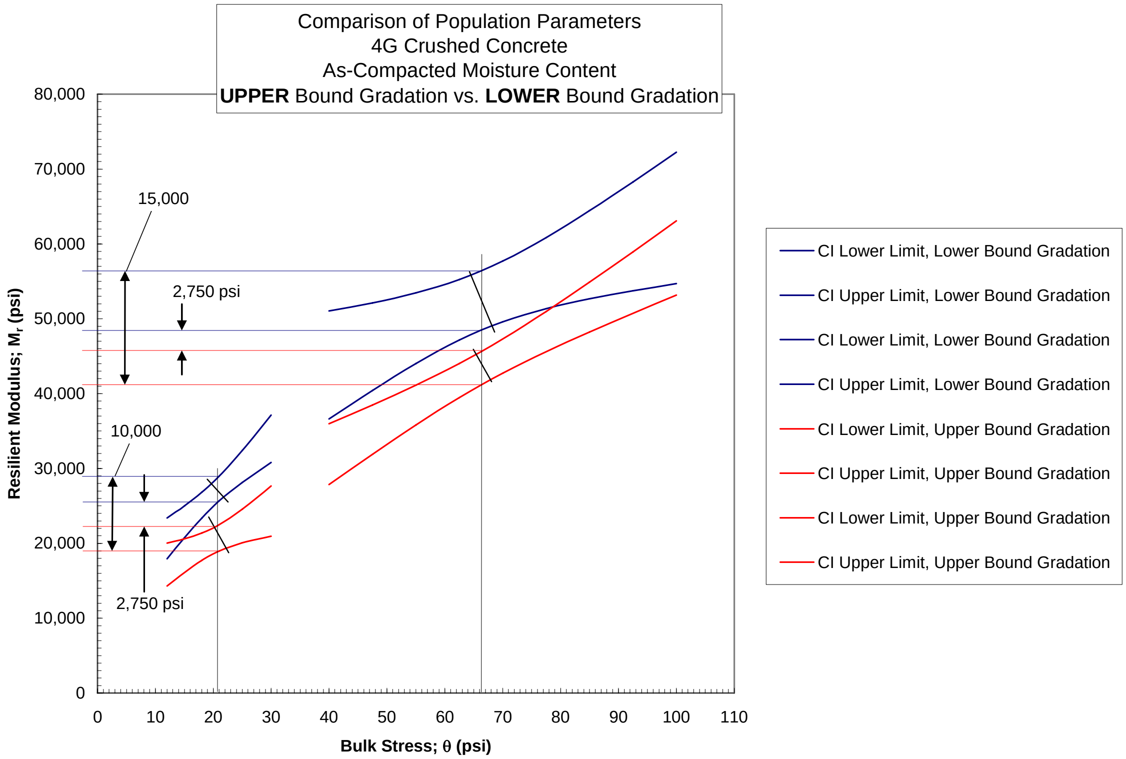

Figure 4.1-23 Stiffness Difference between Upper and Lower Bound Gradations; Crushed Concrete

Statistically the *upper bound gradation* and the *maximum density gradation* are very close in stiffness as seen in Figure 4.1-24. However, none of the CI intervals actually intersect, therefore they are statistically different. As shown in Figure 4.1-25, the overconsolidated region of the *upper bound gradation* shows an increase of 3% over the *maximum density gradation.* While in the normally consolidated region, at minimum there is no difference in stiffness, while at most it could be expected that the *upper bound gradation* be 19% stiffer.

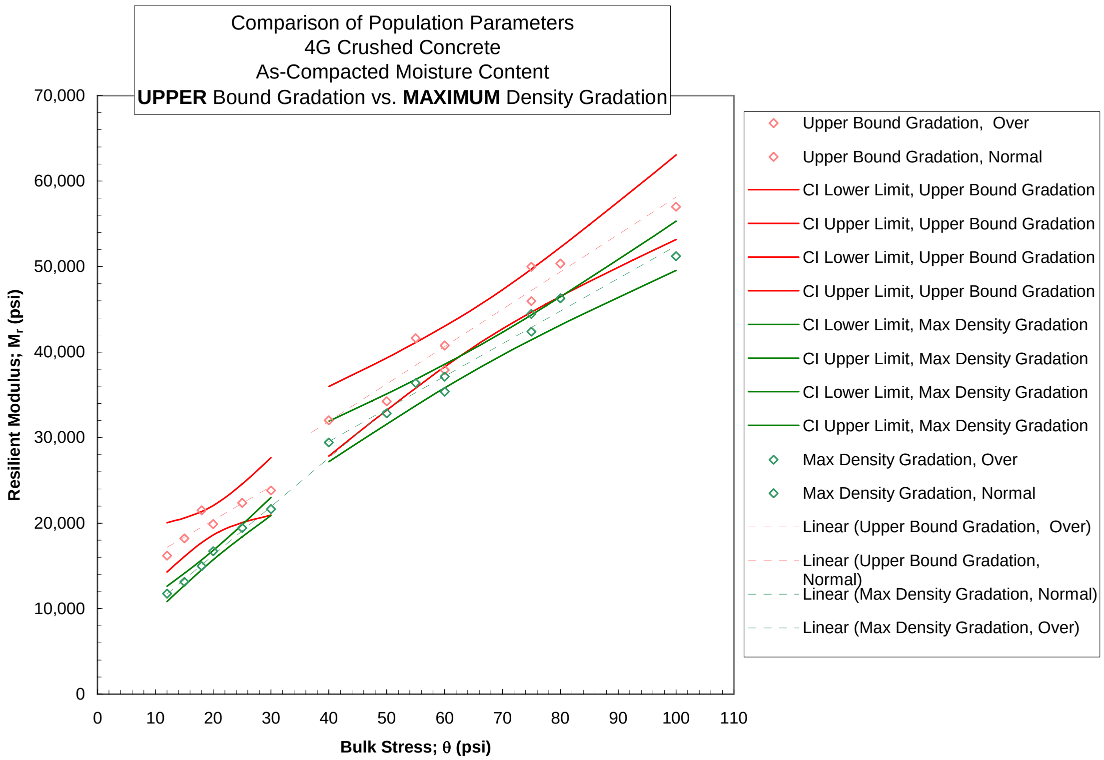

Figure 4.1-24 Stiffness Difference between Upper Bound and Maximum Density Gradations; Crushed Concrete

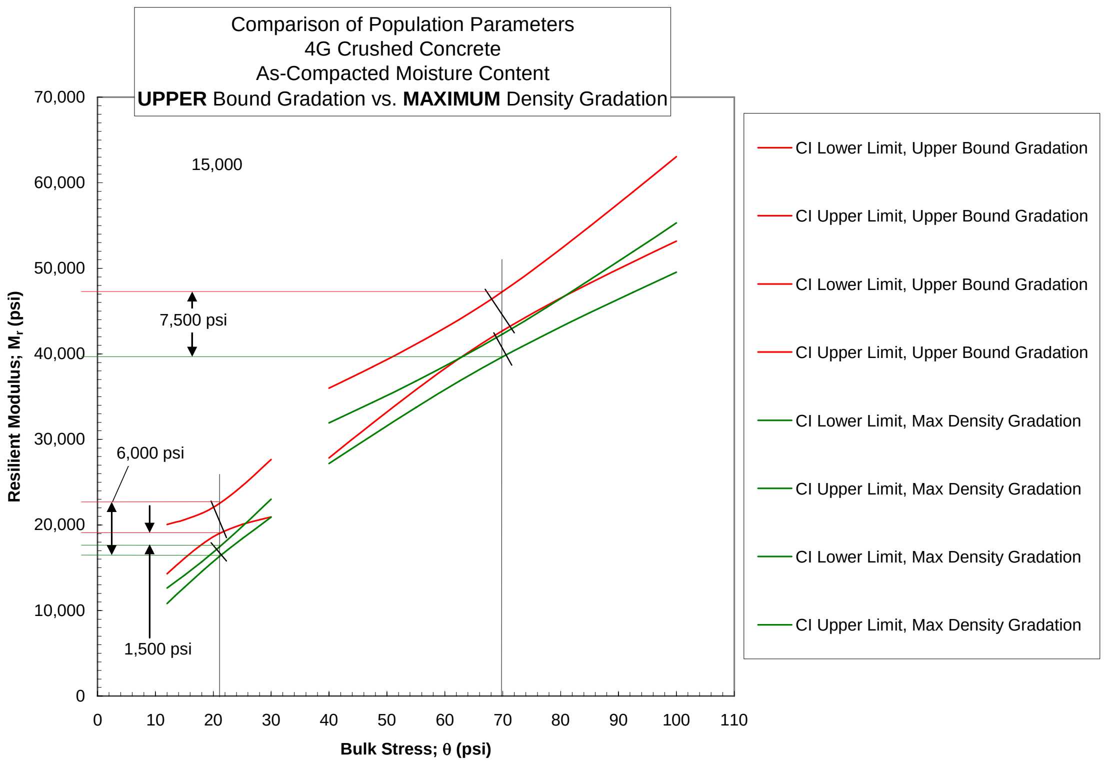

Figure 4.1-25 Stiffness Difference between Upper Bound Gradation and Maximum Density Gradations; Crushed Concrete

4.1.5 EFFECTS OF GRADATION – ANALYSIS SUMMARY

This section summarizes the analyses of sections 4.1.1 through 4.1.4, which investigated what the effects of gradation had on the stiffness of different materials. It was clear that the *lower bound gradation*, or the gradation whose ratio of fine aggregate to coarse aggregate was least, was stiffer for every material type tested. The stiffness difference between the *upper bound gradation* and the *maximum density gradation* was not as pronounced but the *upper bound gradation* was always stiffer than the *maximum density gradation*, except with Dolomite, where the curves were nearly identical. With a broad stroke it can be said that the *lower bound gradation* is stiffer than the *upper bound gradation* which is stiffer than the *maximum density gradation*. Or, in other words the stiffness decreases as ratio of fine aggregate to coarse aggregate increases.

Table 4.1-1 below summarizes the stiffness differences between the *lower* and *upper bound gradations* and between the *upper bound* and *maximum density gradations*, by material type. Values and comparisons are given for the overconsolidated (OC) range and the normally consolidated (NC) range. For each material type there are 4 columns of values: 1) At Least Stiffer – this is the minimum stiffness difference given in *pounds per square inch* (psi), 2) At Most Stiffer – this is the maximum stiffness possible, given in psi, 3) At Least Stiffer Percent Difference – this is the minimum percent difference between the two gradations, and 4) At Most Stiffer Percent Difference – this is the maximum percent difference between the two gradations. This then describes a range of expected values – from the minimum stiffness difference to the maximum stiffness difference. The percent difference helps to quantify how the actual difference may affect the pavement cross section design.

Finally, the last group of tabulated data in Table 4.1-1 averages these values from the four different materials tested. Averaging this data is a broad stroke and is only done to give a gross generalization. By averaging this data we make the assumption that material characteristics have no effect, only the gradation has an effect on the stiffness. By averaging the data for all materials, we observe the following:

1. In the OC range of bulk stress, the *lower bound gradation* can be between 9% and 32% stiffer than the *upper bound gradation*.

2. In the NC range of bulk stress, the *lower bound gradation* can be between 10% and 38% stiffer than the *upper bound gradation.*

3. In the OC range of bulk stress, the *upper bound gradation* can be between 16% and 50% stiffer than the *maximum density gradation.*

4. In the NC range of bulk stress, the *upper bound gradation* can be between 4% and 19% stiffer than the *maximum density gradation.*

Table 4.1-1 Stiffness Differences Between Lower Bound, Upper Bound, and Maximum Density Gradations by Material

Material	Comparison	Range	AT LEAST Stiffer (psi)	AT MOST Stiffer (psi)	AT LEAST Stiffer Percent Difference (%)	AT MOST Stiffer Percent Difference (%)
Natural Gravel	Lower Bound Gradation Stiffer THAN Upper Bound Gradation By:	OC Range	2,500	5,500	14	33
		NC Range	5,500	9,500	15	27
	Upper Bound Gradation STIFFER THAN Maximum Density Gradation By:	OC Range	3,000	5,000	22	41
		NC Range	1,500	5,500	4	17

Material	Comparison	Range	AT LEAST Stiffer (psi)	AT MOST Stiffer (psi)	AT LEAST Stiffer Percent Difference (%)	AT MOST Stiffer Percent Difference (%)
Dolomite	Lower Bound Gradation Stiffer THAN Upper Bound Gradation By:	OC Range	1,500	8,000	6	38
		NC Range	2,000	12,000	4	24
	Upper Bound Gradation STIFFER THAN Maximum Density Gradation By:	OC Range	0	0	0	0
		NC Range	0	0	0	0

Material	Comparison	Range	AT LEAST Stiffer (psi)	AT MOST Stiffer (psi)	AT LEAST Stiffer Percent Difference (%)	AT MOST Stiffer Percent Difference (%)
Slag	Lower Bound Gradation Stiffer THAN Upper Bound Gradation By:	OC Range	0	0	0	0
		NC Range	4,750	11,000	8	20
	Upper Bound Gradation STIFFER THAN Maximum Density Gradation By:	OC Range	4,250	10,000	24	63
		NC Range	3,500	10,000	7	22

Material	Comparison	Range	AT LEAST Stiffer (psi)	AT MOST Stiffer (psi)	AT LEAST Stiffer Percent Difference (%)	AT MOST Stiffer Percent Difference (%)
Crushed Concrete	Lower Bound Gradation Stiffer THAN Upper Bound Gradation By:	OC Range	2,750	10,000	6	24
		NC Range	2,750	15,000	13	79
	Upper Bound Gradation STIFFER THAN Maximum Density Gradation By:	OC Range	1,500	6,000	3	45
		NC Range	500	7,500	1	19

Comparison of Stiffness Differences Between Lower Bound, Upper Bound and Maximum Density Gradations - Averaged Differences of the Above Four Materials -	Range	AVERAGE AT LEAST Stiffer (psi)	AVERAGE AT MOST Stiffer (psi)	AVERAGE AT LEAST Stiffer Percent Difference (%)	AVERAGE AT MOST Stiffer Percent Difference (%)
Lower Bound Gradation Stiffer THAN Upper Bound Gradation By:	OC Range	2,250	7,833	9	32
	NC Range	3,750	11,875	10	38
Upper Bound Gradation STIFFER THAN Maximum Density Gradation By:	OC Range	2,917	5,250	16	50
	NC Range	1,833	5,750	4	19

4.2 EFFECTS OF ENVIRONMENTAL CONDITION WITH GRADATION

This section reports the investigation of how environmental conditions (Degree of Saturation/Moisture Content) affect the Resilient Modulus of the four different aggregate materials at their three different gradations. Each material's three different gradations (Lower Bound, Upper Bound and Maximum Density Gradation) were tested at four different environmental conditions as reflected by moisture content (MC). They are: 1) Wetting Curve MC, 2) Drying Curve MC, 3) Fully Saturated MC, and 4) As-compacted MC as described in Chapter 2.

Each material (Natural Gravel, Dolomite, Slag, and Crushed Concrete) will have three comparisons for each of the gradations: 1) **Lower Bound** Gradation, As-compacted MC vs. Wetting Curve MC, Drying Curve MC and Fully Saturated MC 2) **Upper Bound** Gradation, As-compacted MC vs. Wetting Curve MC, Drying Curve MC and Fully Saturated MC, 3) **Maximum Density** Gradation, As-compacted MC vs. Wetting Curve MC, Drying Curve MC and Fully Saturated MC.

Section 4.2.1, will describe in step-by-step detail the procedure and rationale of the analysis of the, stiffness comparison relative to moisture content and gradation, as applied to Natural Gravel. Successive analysis of the remaining materials will be more concise, without the detailed explanation, but it is to be understood that the method was the same. Section 4.2.5 provides a summary of the analyses of Sections 4.2.1 through 4.2.4.

The environmental condition simulated by the capillary uptake of moisture, i.e. the Wetting Curve, did not show measurable moisture uptake. It was not assumed that this alone would give similar to the As-compacted MC condition. A very small change in moisture content or moisture pressure caused by the Wetting Curve process could cause significant changes in internal effective stress. For this reason Wetting Curve resilient modulus determinations were conducted.

4.2.1 NATURAL GRAVEL

The procedure used to quantify the effect moisture content has on the stiffness of the *lower bound, upper bound* and *maximum density* gradation is very similar to the analysis procedure described in *Comparison of Population Parameters in Linear-Linear*. The Resilient Modulus vs. Bulk stress curve at the ***As-compacted moisture content*** will be used as the standard or datum to which the other tests at other moisture contents will be compared. So then it could be said, for example, the *fully saturated* state is softer than the *as-compacted* moisture content – full saturation has an effect on the stiffness; or a *70% saturated specimen* has the same stiffness as the *As-compacted moisture content* state – 70% saturation has no effect on the stiffness. The following paragraph uses the lower bound gradation of Natural Gravel as a detailed example of how the analysis process is performed.

The *As-compacted MC* condition is used as the standard for comparison, see Figure 4.2-1. However, the actual measured data will be deleted and only the confidence interval (CI) band will be used as in Figure 4.2-2. Figure 4.2-3 shows the Resilient Modulus vs. Bulk Stress curves of the *lower bound* gradation at three different moisture contents (Drying Curve MC, Wetting Curve MC, and Fully Saturated). Then as in Figure 4.2-4, the *As-compacted MC* CI band will be superimposed over the three curves of varying moisture contents of Figure 4.2-3. If a curve falls within the band of the *As-compacted MC* CI it can be said that compared to the as-compacted moisture content, that particular moisture content had no effect on the stiffness. If the curve falls above the *As-compacted MC* CI band, it is stiffer than the as-compacted moisture condition. If the curve falls below the *As-compacted MC* CI band, it is softer than the as-compacted moisture condition. As in Figure 4.2-4, the three curves fall outside of the *As-compacted MC* CI band, however the Drying Curve MC and Wetting Curve MC are sufficiently close to the CI limit that further investigation is required. By developing a CI band for the Wetting Curve MC data, as in Figure 4.2-5, it is shown that the Drying Curve data falls into the CI band of the Wetting Curve MC – it can be said they are the same curve. It is also shown that the CI band of the Wetting Curve MC intersects or is very close to the CI band of the As-compacted standard. It can be said that the moisture contents of the Wetting and Drying Curve specimens have marginal effects on the stiffness. However, the Fully Saturated state MC clearly shows a softening affect due to full saturation. Based on the comparison of the CI bands in Figure 4.2-6, the Fully Saturated MC curve is 14% softer in the overconsolidated region and 7% in the normally consolidated region as compared to the As-compacted MC standard.

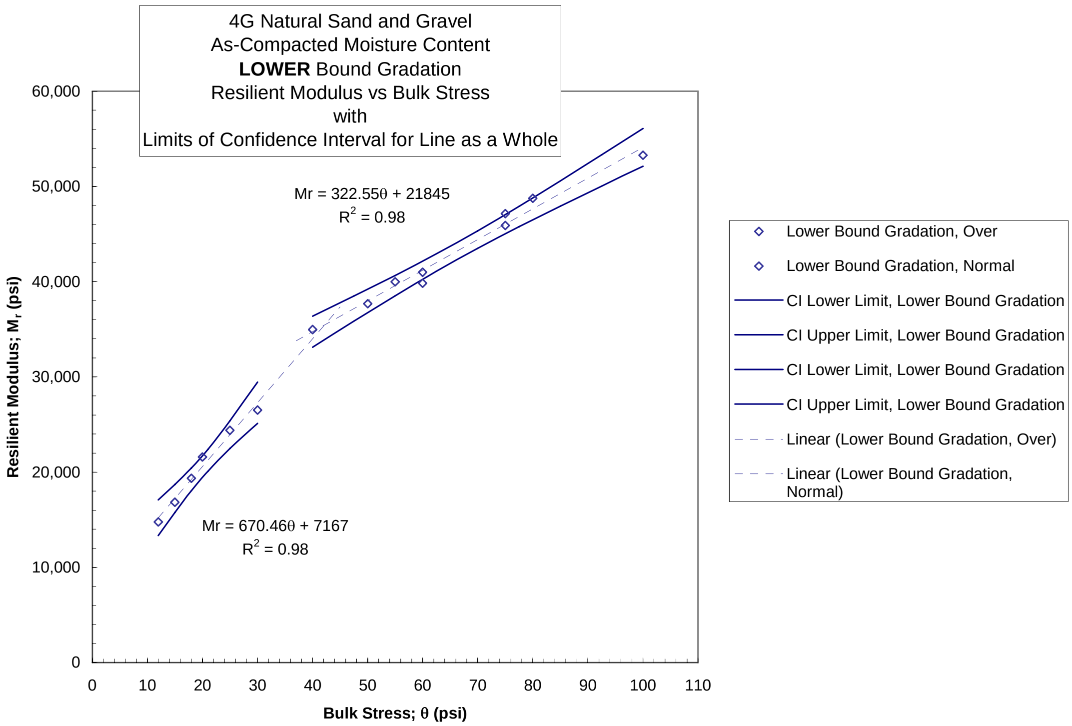

Figure 4.2-1 Resilient Modulus vs Bulk Stress with 95% CI Band - Natural Gravel Lower Bound Gradation Linear-Linear Space

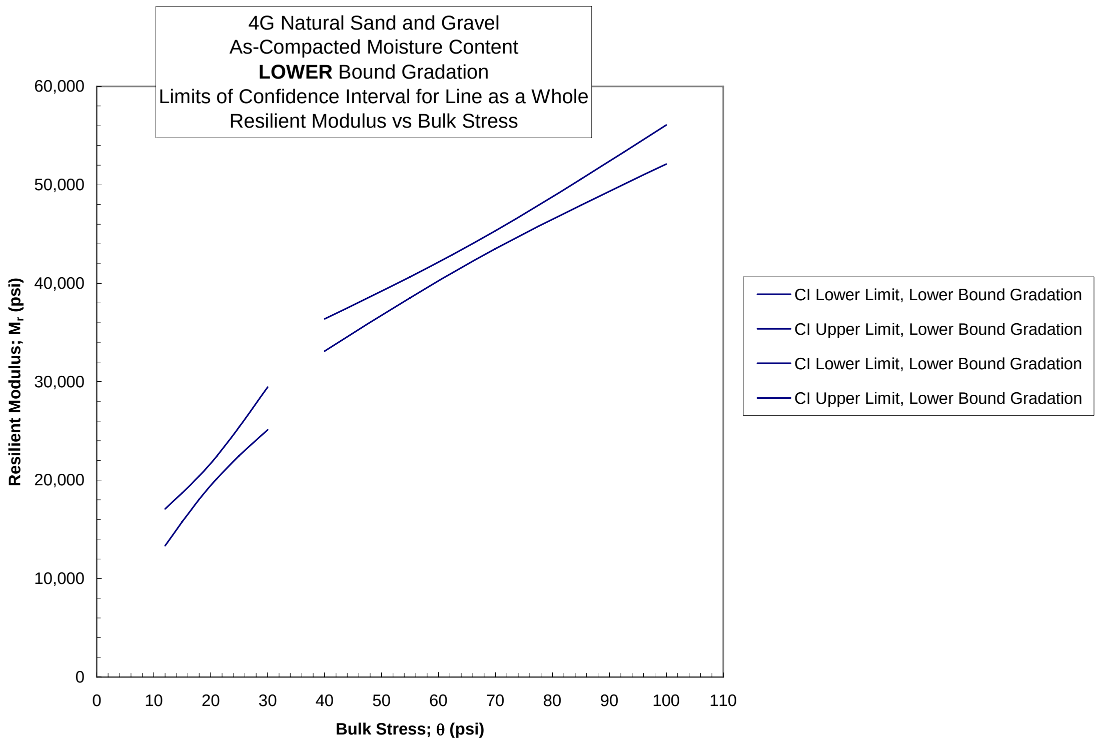

Figure 4.2-2 95% CI Band sans measured data - Natural Gravel Lower Bound Gradation as-compacted MC; Linear-Linear Space

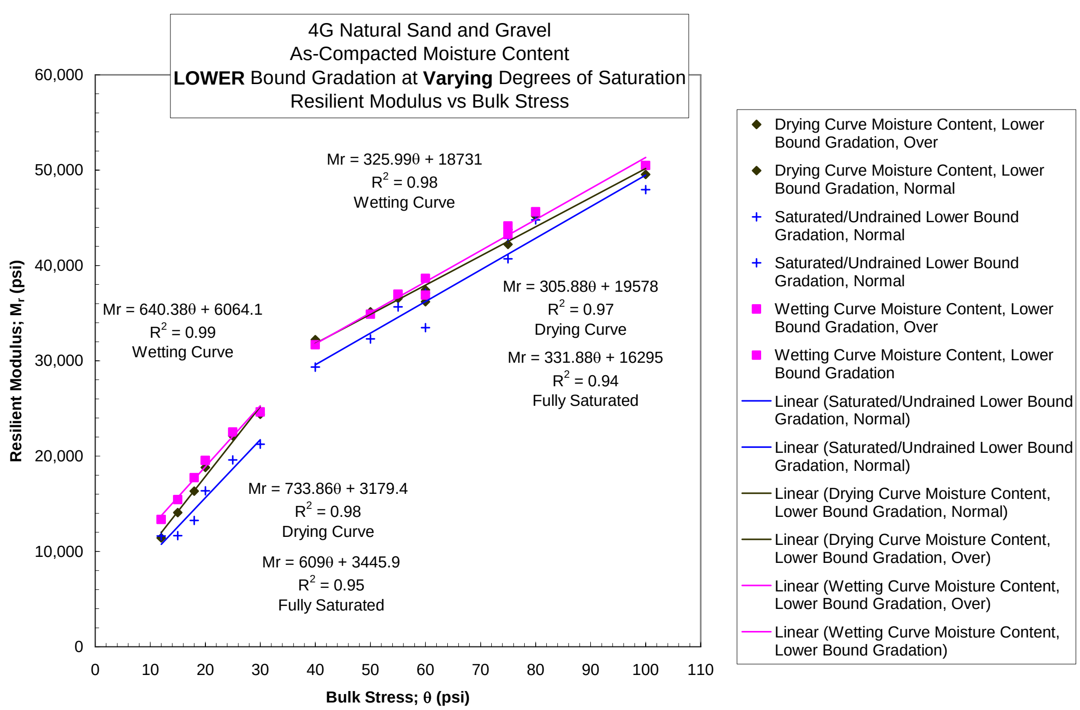

Figure 4.2-3 Resilient Modulus Curves for Wetting Curve MC, Drying Curve MC, and Fully Saturated MC. Natural Gravel Lower Bound Gradation; Linear-Linear Space

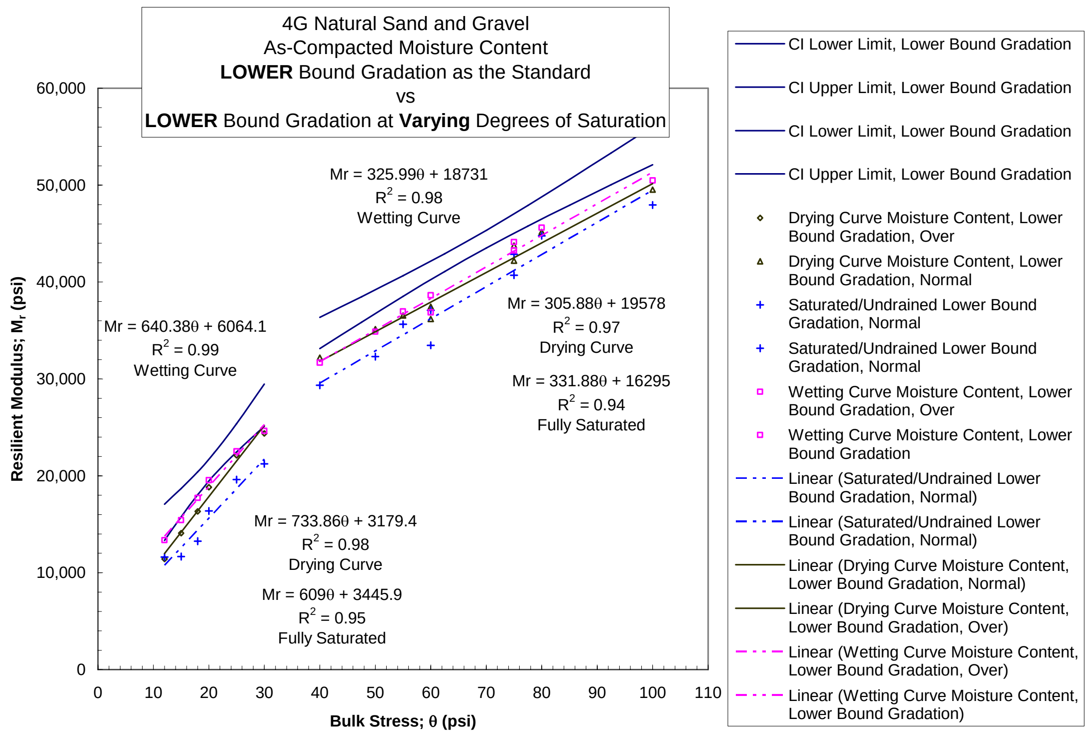

Figure 4.2-4 Resilient Modulus Curves for Wetting Curve MC, Drying Curve MC, and Fully Saturated MC with CI Band for as-compacted MC. Natural Gravel Lower Bound Gradation; Linear-Linear Space

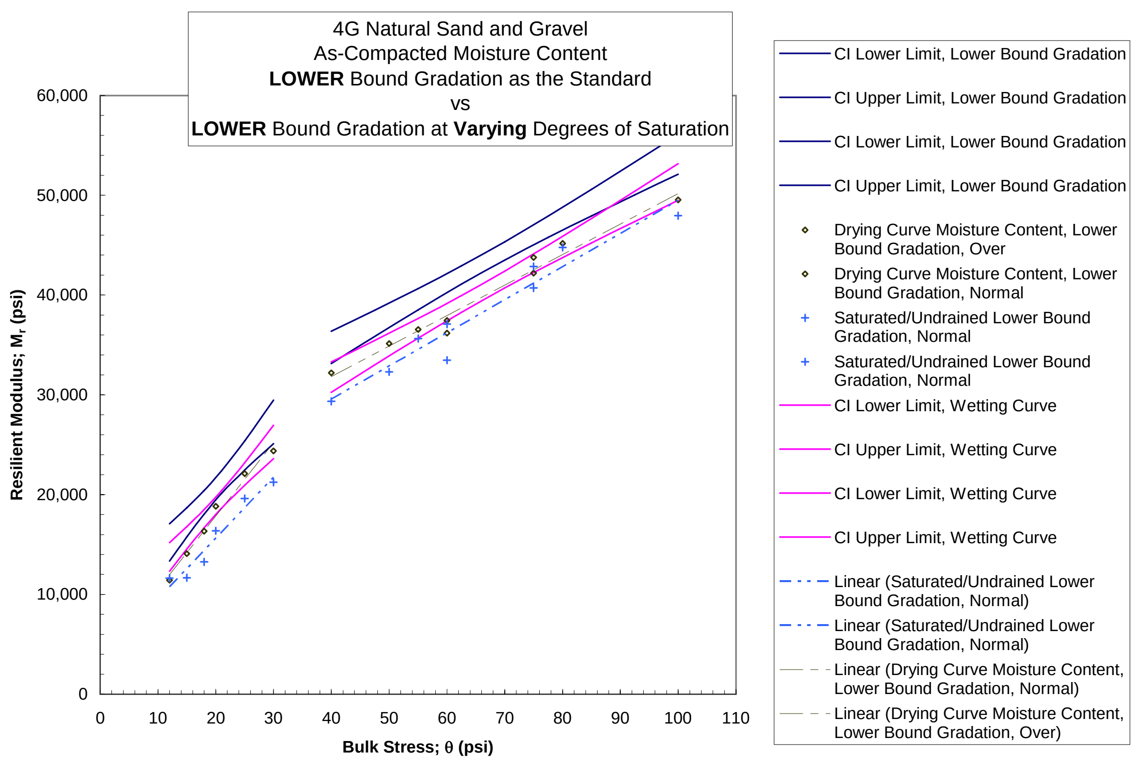

Figure 4.2-5 Natural Gravel Lower Bound Gradation Comparing Effect of MC with Wetting Curve MC CI Band

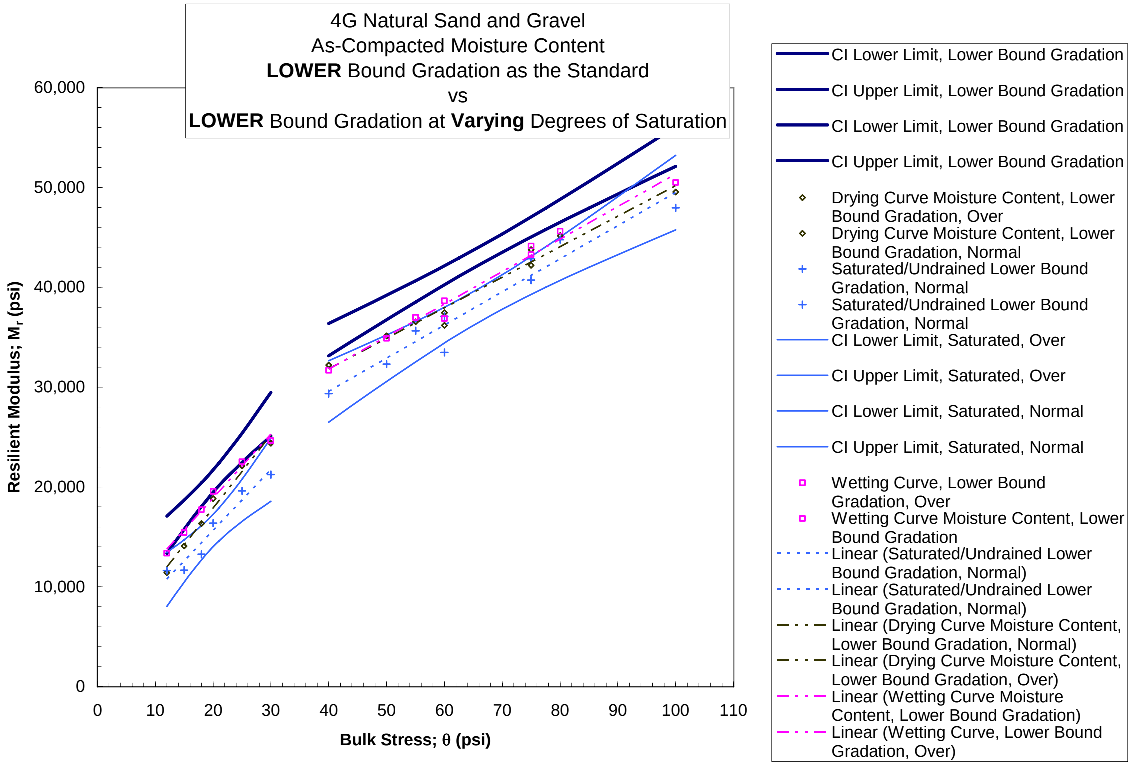

Figure 4.2-6 Natural Gravel Lower Bound Gradation Comparing Effect of MC with Fully Saturated MC CI Band

The *upper bound gradation* can be evaluated in the same manner as the *lower bound gradation*. It is shown in Figure 4.2-7. Both the Drying Curve MC and Fully Saturated MC curves fall in the As-compacted CI band, in the normally consolidated range, indicating no effect of moisture content on stiffness. The Drying Curve MC curve intersects the As-compacted CI band; increased moisture content has not effected its stiffness. However, both the Fully Saturated MC and Wetting Curve MC curves fall outside the As-compacted CI band, which is the standard. Figure 4.2-8 compares the CI bands of the three of the three moisture conditions in order to quantify the difference in stiffnesses. The Wetting Curve MC curve is stiffer than the As-compacted MC by 10% and 16% in the overconsolidated and normally consolidated regions, respectively. The Fully Saturated MC curve is softer than the As-compacted MC standard by 14% in the overconsolidated region.

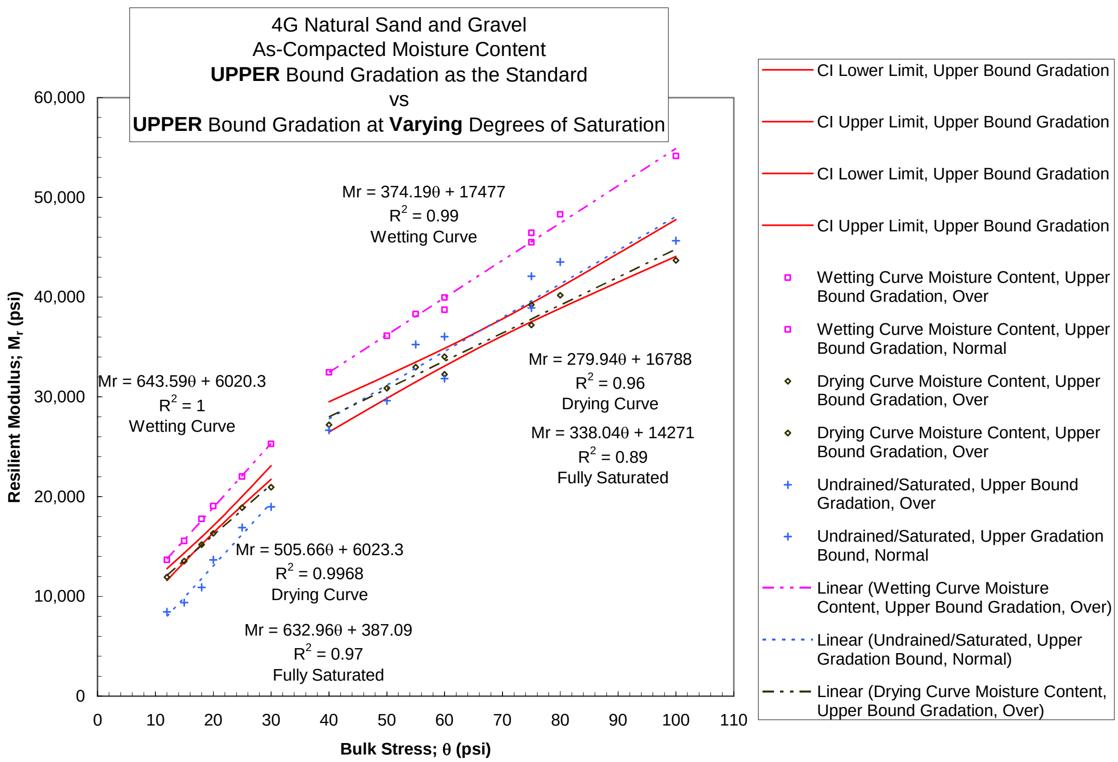

Figure 4.2-7 Natural Gravel Upper Bound Gradation Comparing Effect of MC

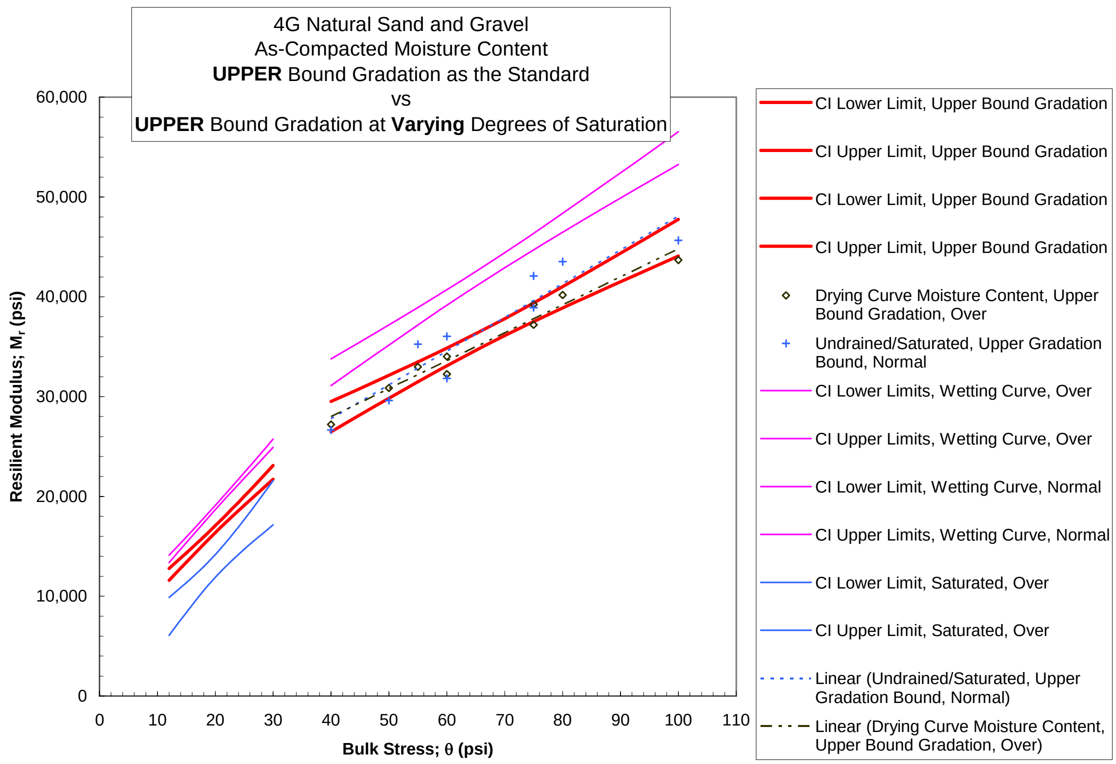

Figure 4.2-8 Natural Gravel Upper Bound Gradation Comparing Effect of MC with Wetting Curve MC CI Band and Full Saturated MC CI Band (overconsolidated region)

Similarly, the maximum density gradation analysis is shown in Figure 4.2-9. All three moisture contents, Wetting Curve, Drying Curve and Fully Saturated, fall within the CI band for the As-compacted moisture content. Moisture content does not have an effect on the stiffness response.

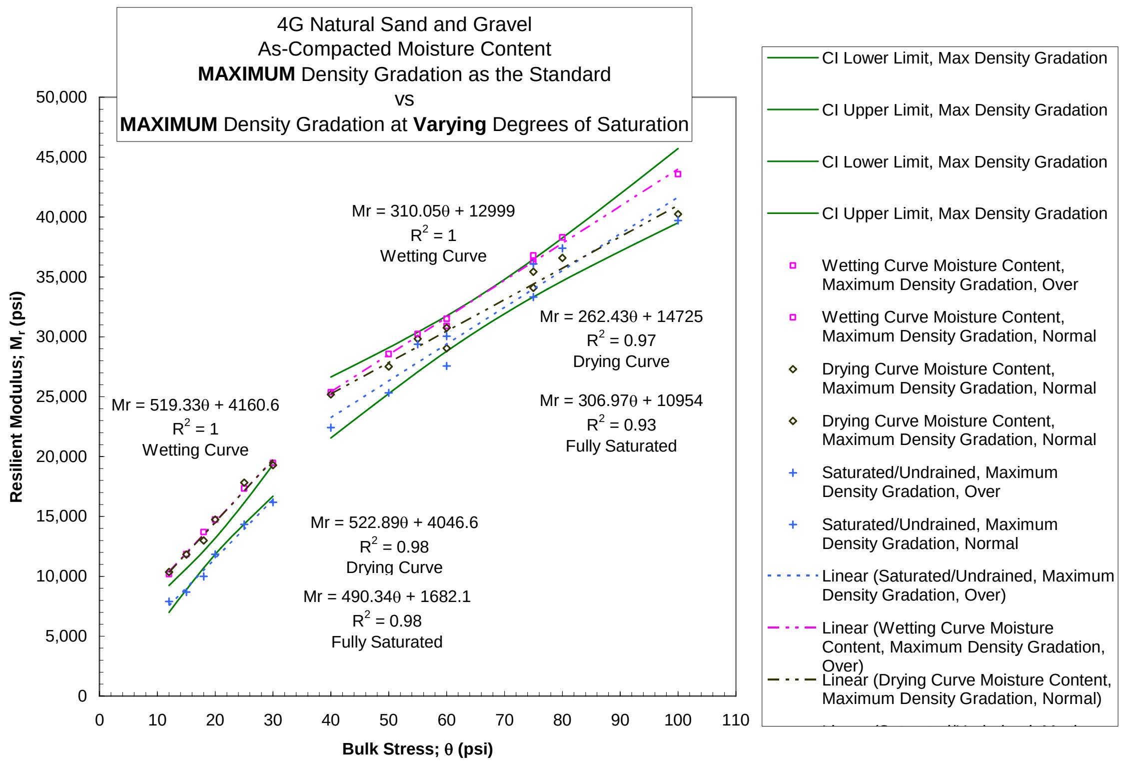

Figure 4.2-9 Natural Gravel Maximum Density Gradation Comparing Effect of MC

4.2.2 DOLOMITE

Figure 4.2-15 and Figure 4.2-16 show the effect of moisture content on the *lower bound gradation*. The Drying Curve MC curve fell within the CI band of the As-compacted MC standard in both the overconsolidated and normally consolidated regions. Figure 4.2-11, the Fully Saturated MC curve with CI band, shows a 21% softening in the overconsolidated region and a 10% softening in the normally consolidated region.

In the *upper bound gradation* shown in Figure 4.2-12, both the Drying Curve MC and Fully Saturated Curve MC curves either fall within or intersect the As-compacted MC CI band – increased moisture content does not appear to have an effect on the stiffness. While the Wetting Curve MC curve clearly falls above the As-compacted CI band. Figure 4.2-13 compares the Wetting Curve MC curve CI Band to the As-compacted standard CI band, there is an increase in stiffness of 20% and 12% in the overconsolidated and normally consolidated regions, respectively.

In the *maximum density gradation* shown in Figure 4.2-14 all three moisture contents, Wetting Curve, Drying Curve and Fully Saturated MC, fall within the CI band for the As-compacted moisture content. Moisture content does not have an effect on the stiffness response.

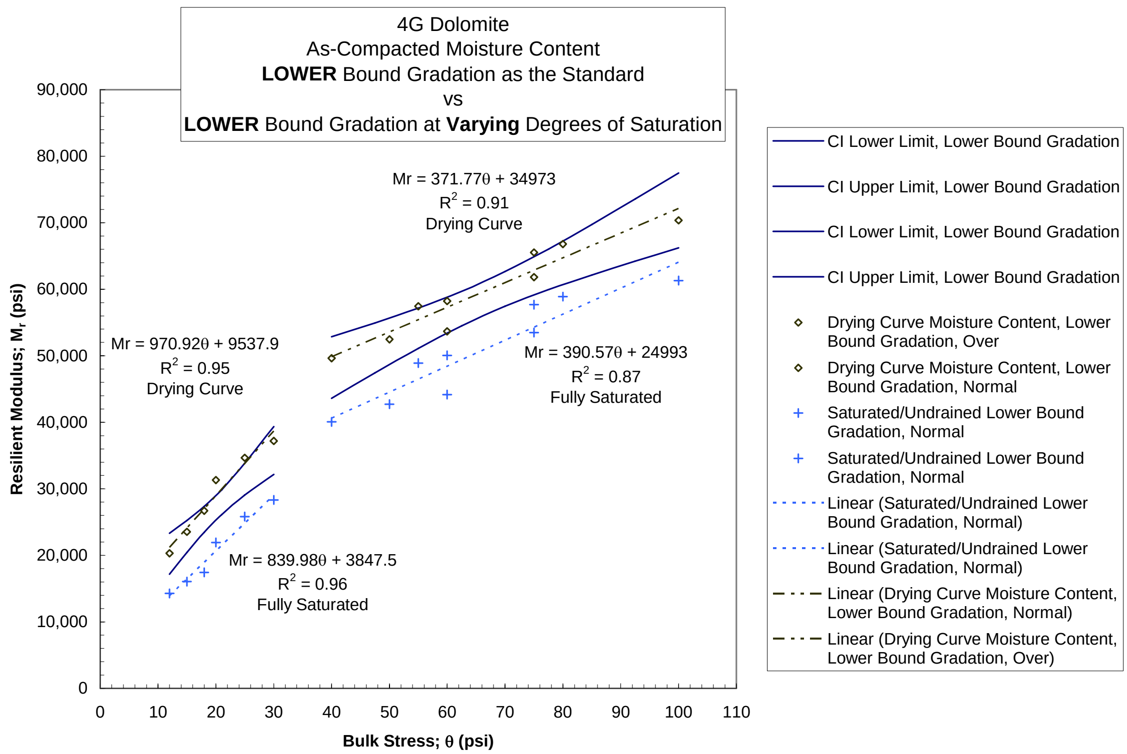

Figure 4.2-10 Dolomite Lower Bound Gradation Comparing Effect of MC

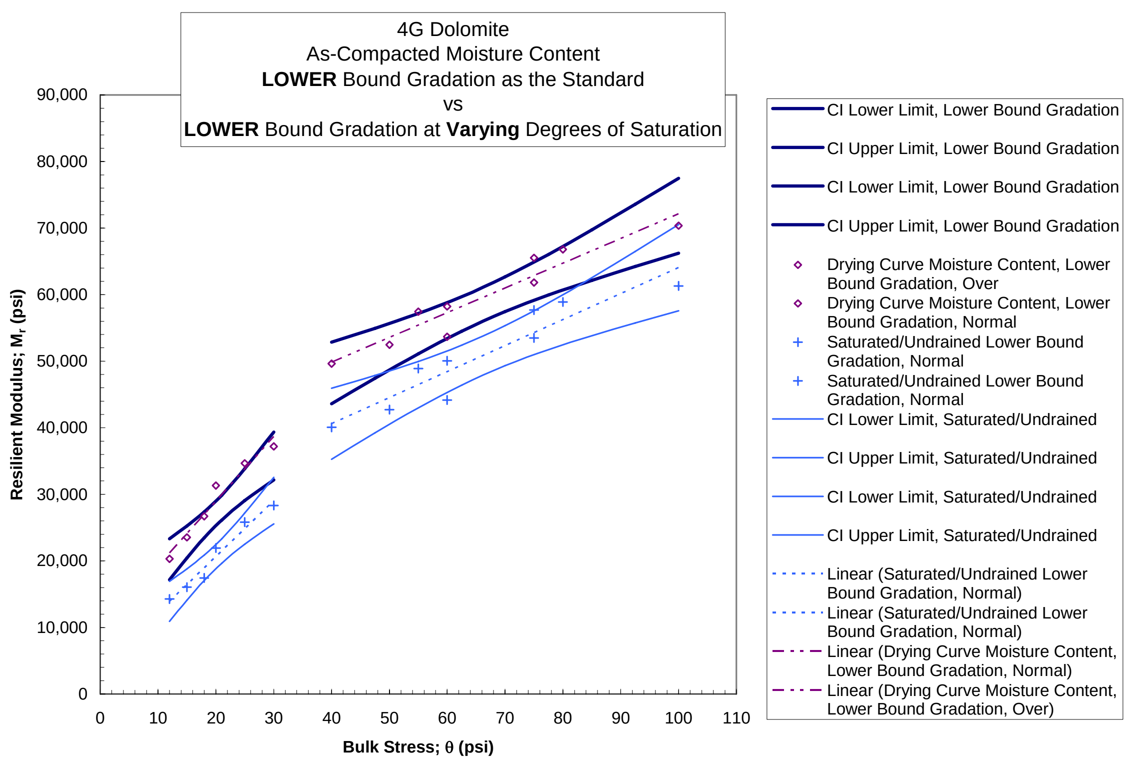

Figure 4.2-11 Dolomite Lower Bound Gradation Comparing Effect of MC with Fully Saturated CI Band

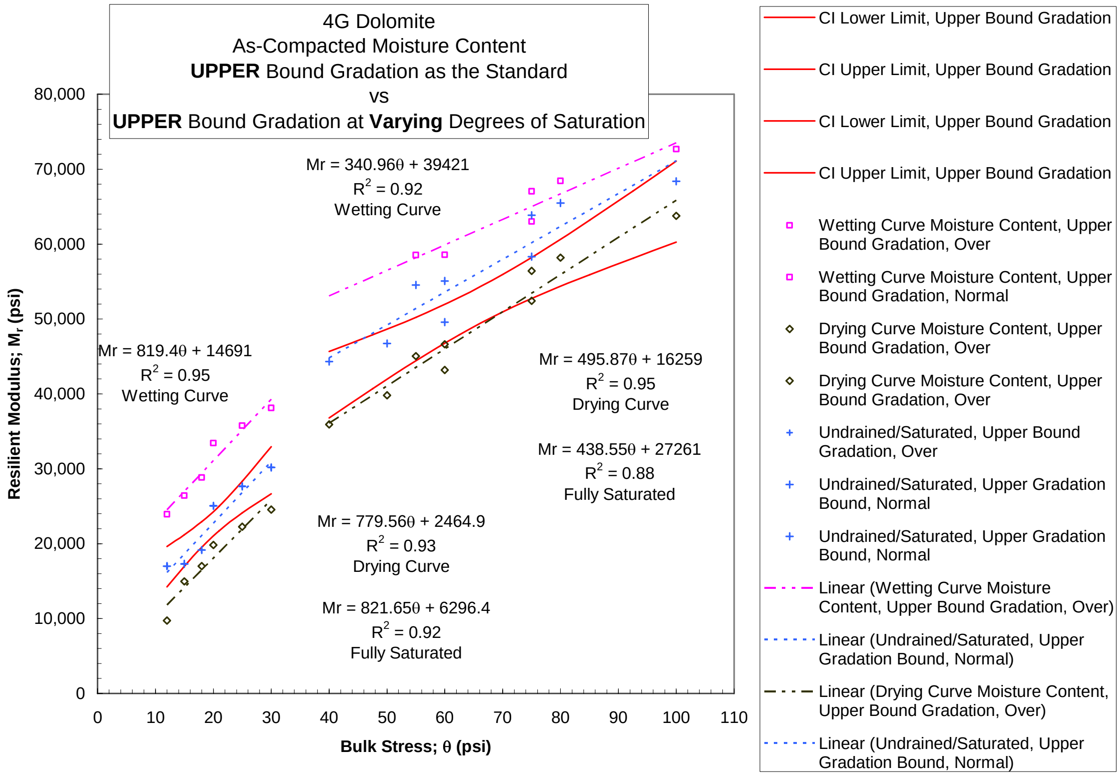

Figure 4.2-12 Dolomite Upper Bound Gradation Comparing Effect of MC

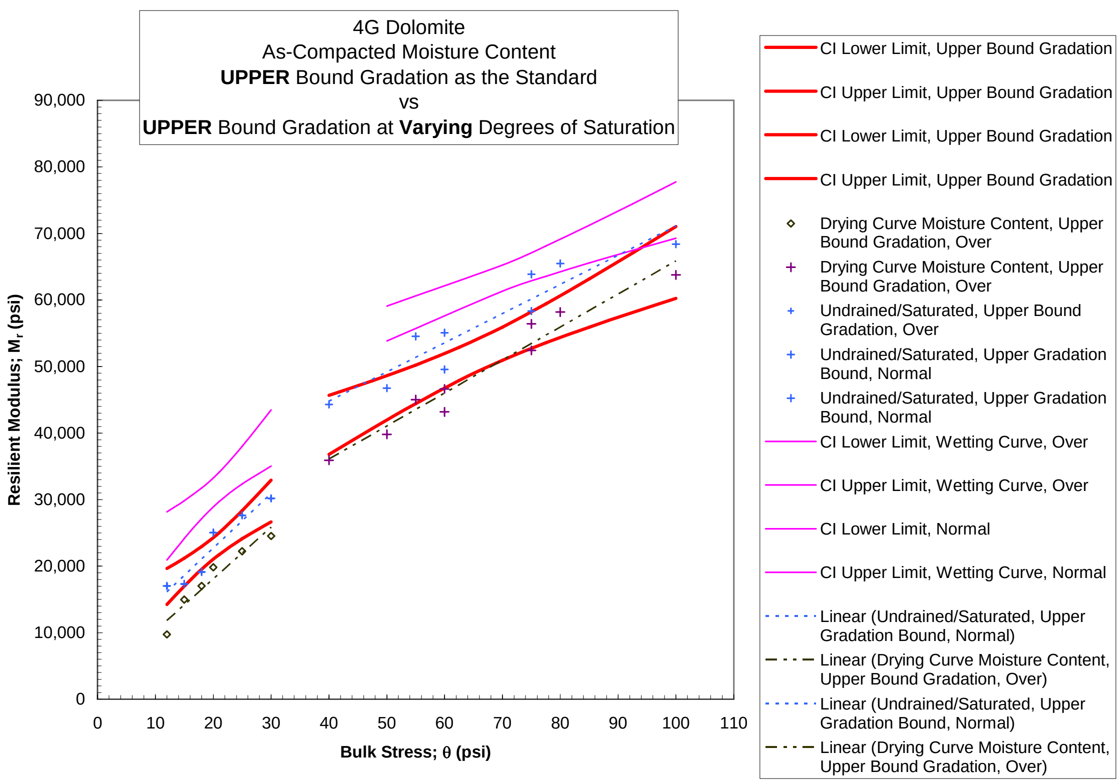

Figure 4.2-13 Dolomite Upper Bound Gradation Comparing Effect of MC with Wetting Curve MC CI Band

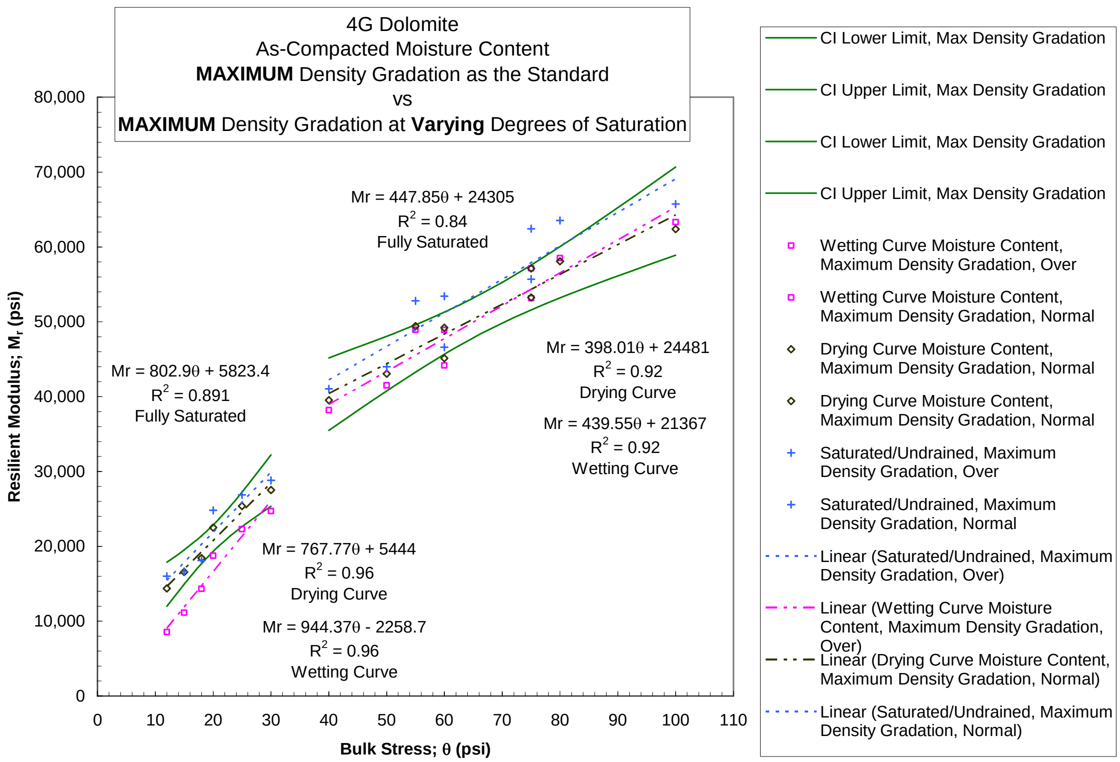

Figure 4.2-14 Dolomite Maximum Density Gradation Comparing Effect of MC

4.2.3 SLAG

Figure 4.2-10 and Figure 4.2-11 show the effect of moisture content on the *lower bound gradation*. Clearly the Drying Curve MC and Fully Saturated MC curves fall within or intersect the as-compacted CI band in the normally consolidated region. The two curves fall above the CI band in the overconsolidated region. However, once a CI band is applied to the Fully Saturated MC curve, it is seen that the Drying Curve MC curve falls within that CI band and the Fully Saturated MC CI band also intersects the As-compacted CI band. Therefore, the Fully Saturated MC curve and the Drying Curve MC curve have similar stiffness response as the As-compacted MC curve.

Figure 4.2-17 shows the effect of moisture content on the *upper bound gradation*. Clearly, moisture content had no effect on the Drying Curve MC curve stiffness in the overconsolidated region. Figure 4.2-18 and Figure 4.2-19 help quantify the stiffness difference for the Wetting Curve MC curve, and the Drying Curve MC and Fully Saturated MC curves, respectively. The Wetting Curve MC curve was only marginally stiffer in the normally consolidated region, while in the overconsolidated region there was a 25% increase in stiffness. Figure 4.2-19 shows that the Drying Curve MC and the Fully Saturated MC curves show an 11% and 25% softening in the normally consolidated region, and the Fully Saturated MC curve in the overconsolidated region shows a 36% softening.

Figure 4.2-20 shows the effect of moisture content on the *maximum density gradation*. The Fully Saturated MC curve shows a slight softening due to increased moisture content in the normally consolidated region. While the Wetting Curve MC and Drying Curve MC curves show a similar response as the As-compacted MC curve. In the overconsolidated region, the Fully Saturated MC shows a 33% softening due to increased moisture content. Clearly, moisture content had no effect on the Drying Curve MC curve stiffness in the overconsolidated region. While, the Wetting Curve MC curve shows a slight increase in stiffness response in the overconsolidated region.

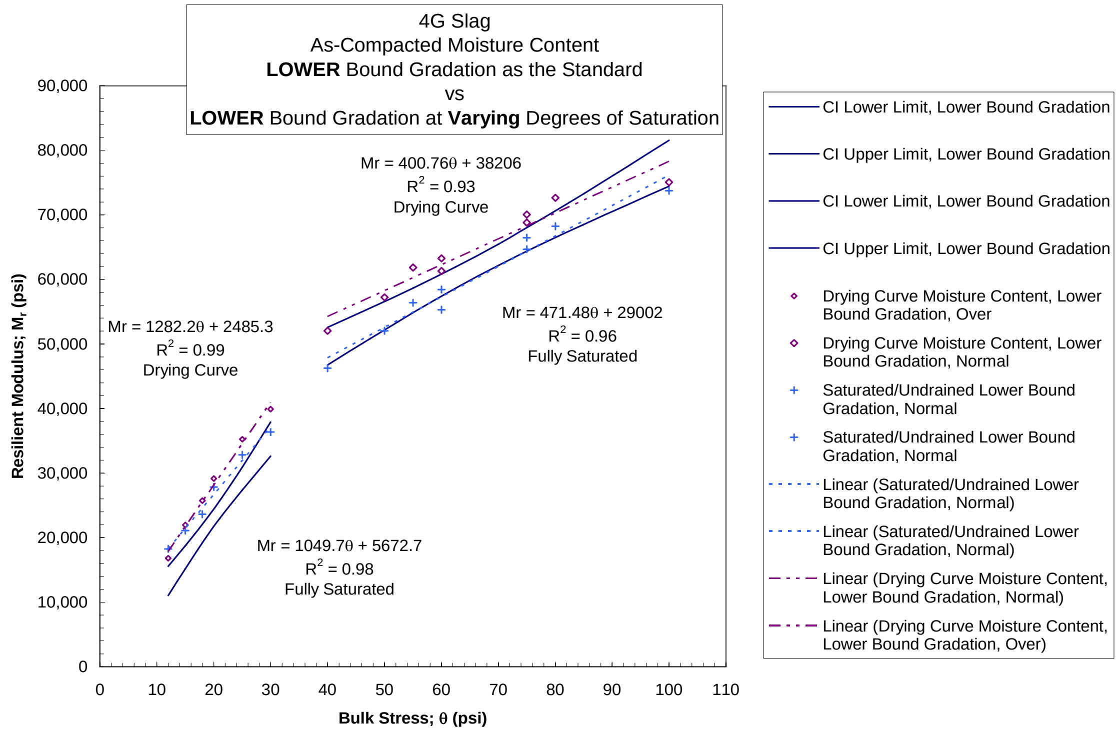

Figure 4.2-15 Slag Lower Bound Gradation Comparing Effect of MC

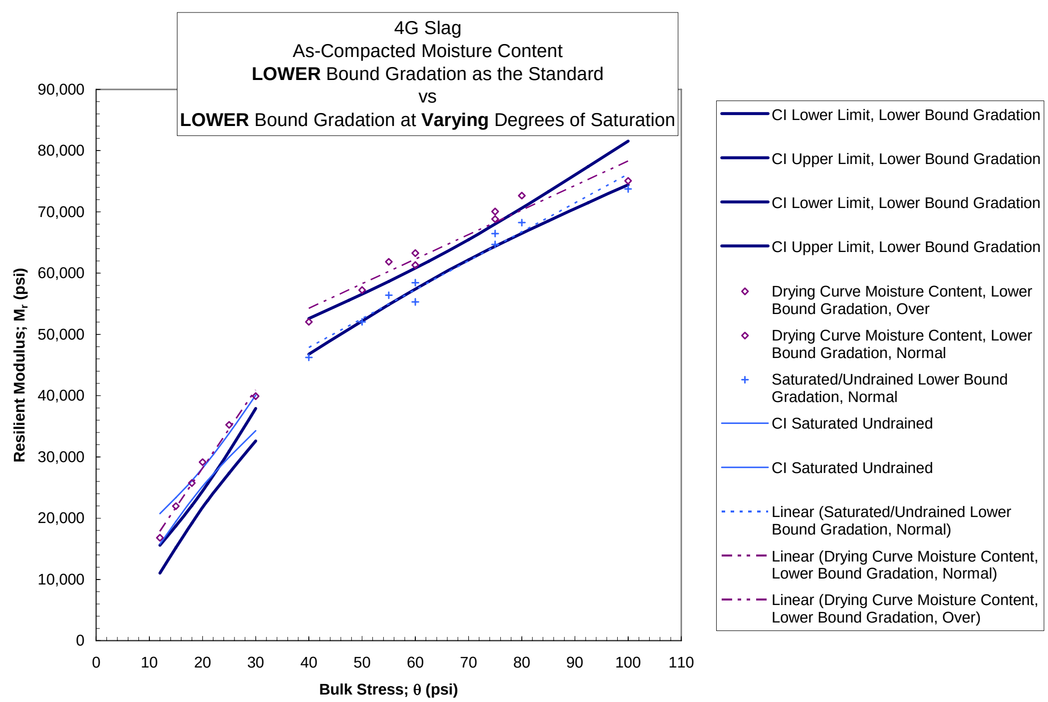

Figure 4.2-16 Slag Lower Bound Gradation Comparing Effect of MC with Saturated MC CI Band

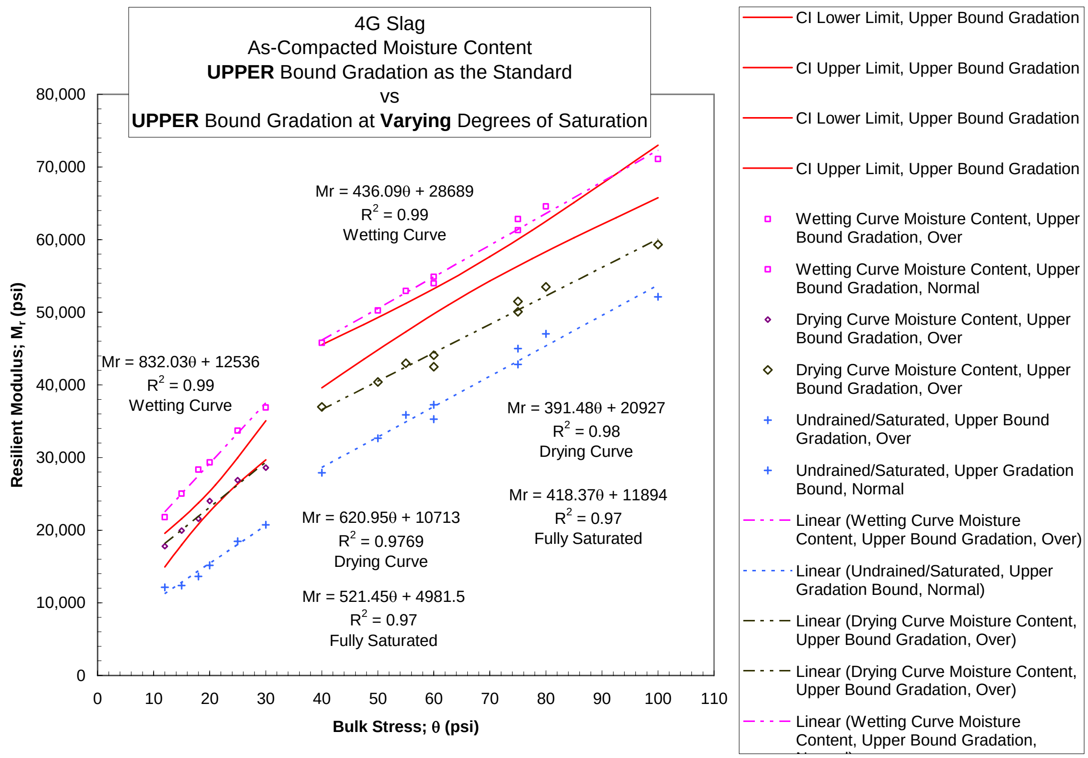

Figure 4.2-17 Slag Upper Bound Gradation Comparing Effect of MC

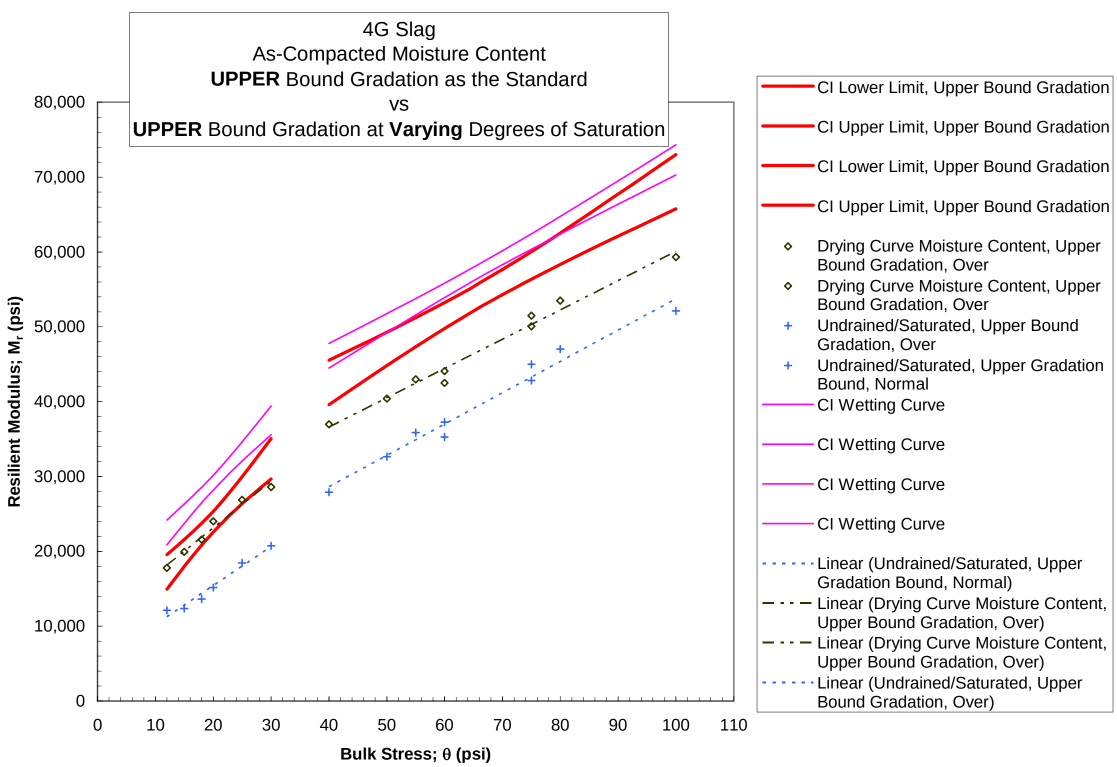

Figure 4.2-18 Slag Upper Bound Gradation Comparing Effect of MC with Wetting Curve MC CI Band

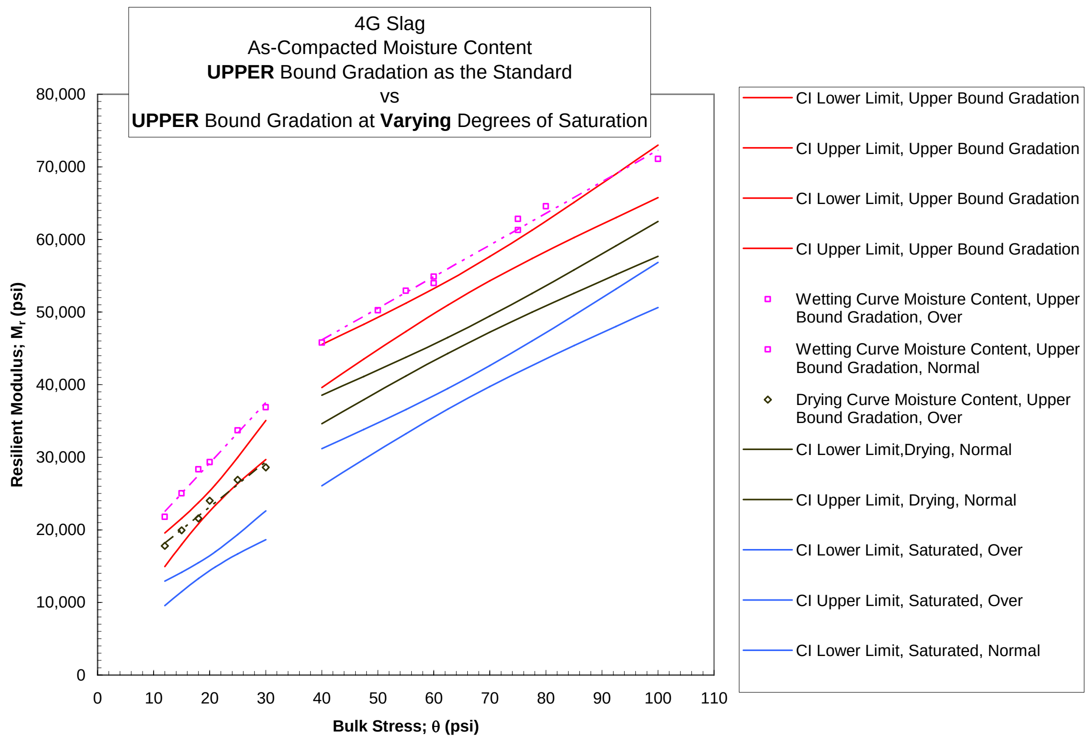

Figure 4.2-19 Slag Upper Bound Gradation Comparing Effect of MC with CI Bands for Drying MC and Fully Saturated MC curves

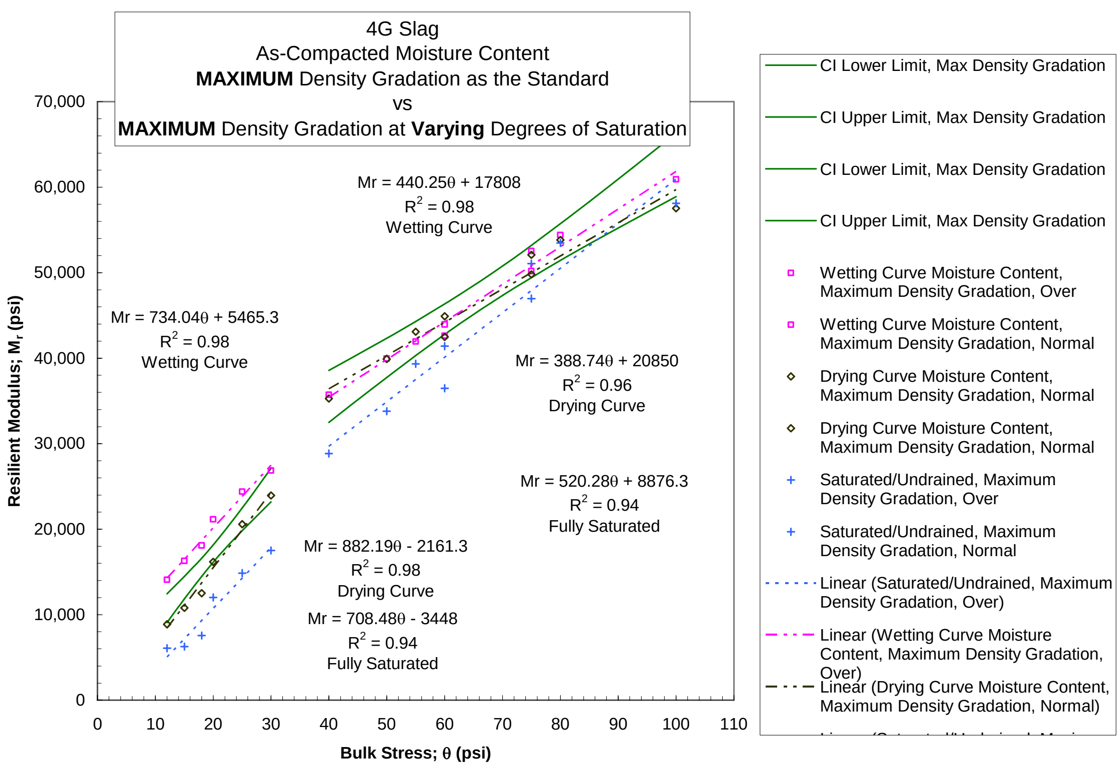

Figure 4.2-20 Slag Maximum Density Gradation Comparing Effect of MC

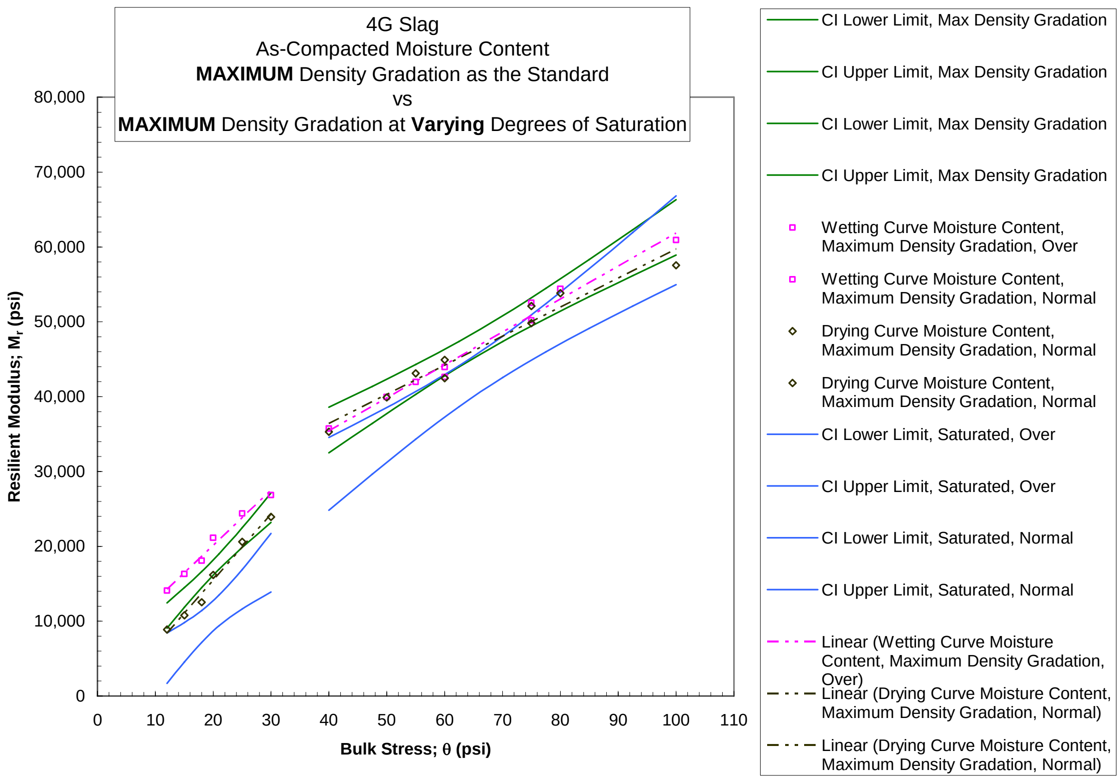

Figure 4.2-21 Slag Maximum Density Gradation Comparing Effect of MC with Fully Saturated CI Band

4.2.4 CRUSHED CONCRETE

Figure 4.2-22 and Figure 4.2-23 show the effect of moisture content on the *lower bound gradation*. The Wetting Curve MC curve shows a similar response as the As-compacted MC curve in both the normally consolidated and overconsolidated regions. Figure 4.2-23 shows that the Drying Curve MC curve falls within the Fully Saturated MC CI band, it can be concluded they have similar stiffnesses in the normally consolidated region. They showed a 14% softening due to increased moisture content. The Drying Curve MC and the Fully Saturated MC curves CI bands are distinctly different in the overconsolidated region. The Drying Curve MC and the Fully Saturated MC curves show a softening, compared to the standard As-compacted MC curve, of 15% and 33%, respectively.

Figure 4.2-24 shows the effect of moisture content on the *upper bound gradation*. All three moisture contents, Wetting Curve, Drying Curve and Fully Saturated MC, fall within the CI band for the As-compacted moisture content. Moisture content does not have an effect on the stiffness response.

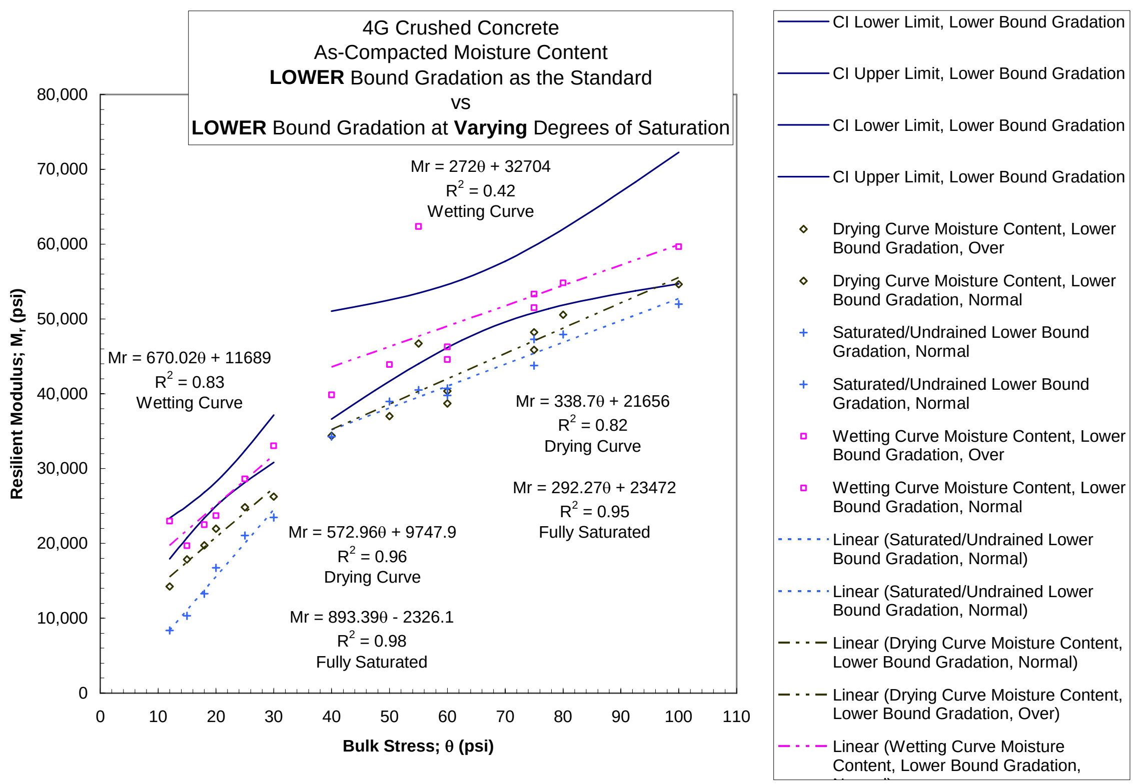

Figure 4.2-22 Crushed Concrete Lower Bound Gradation Comparing Effect of MC

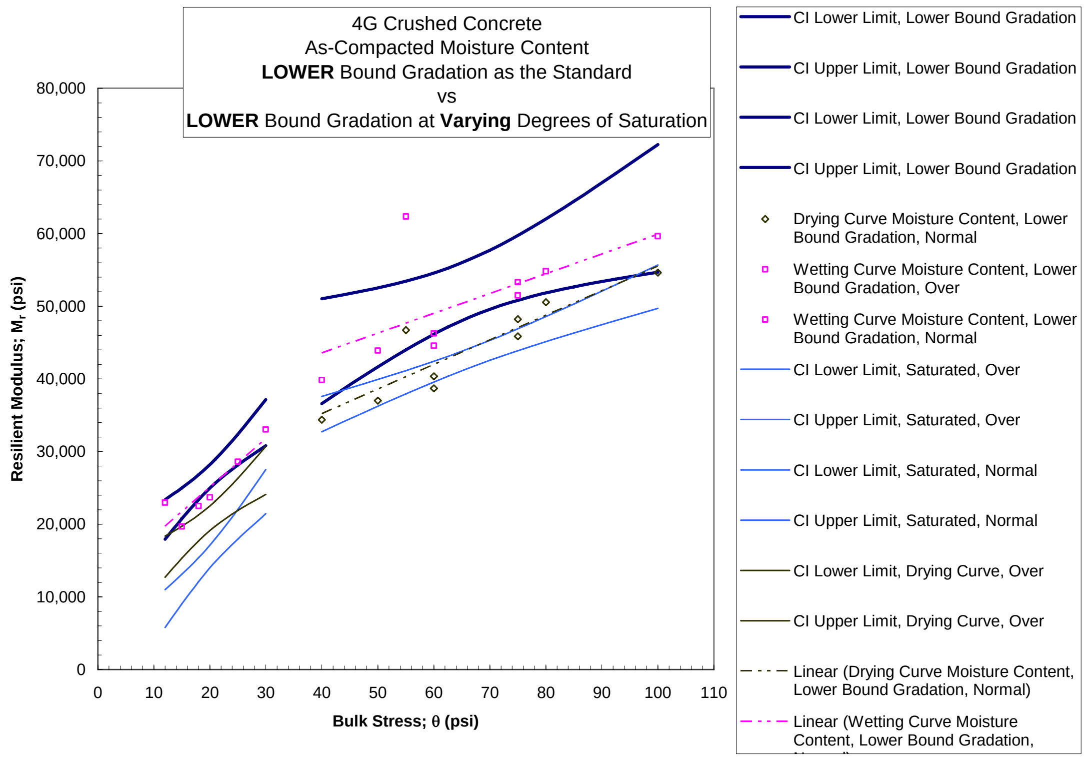

Figure 4.2-23 Crushed Concrete Lower Bound Gradation Comparing Effect of MC with Drying Curve MC and Fully Saturated Curve MC CI Bands

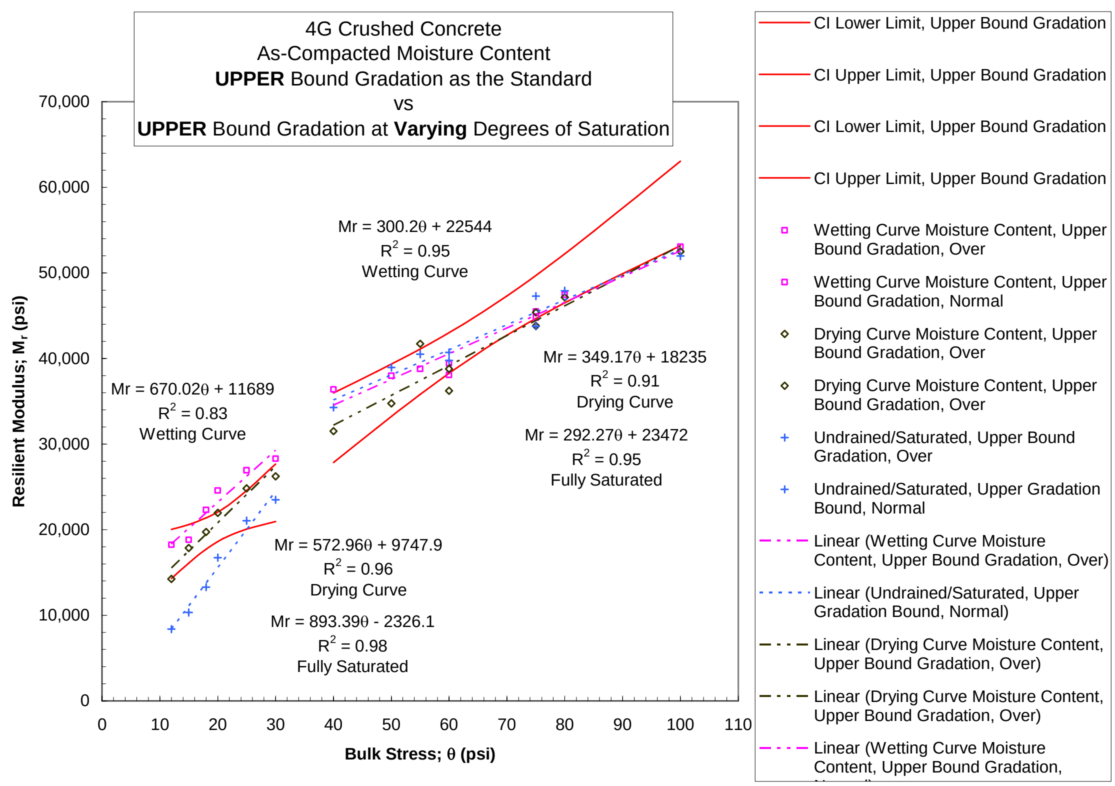

Figure 4.2-24 Crushed Concrete Upper Bound Gradation Comparing Effect of MC

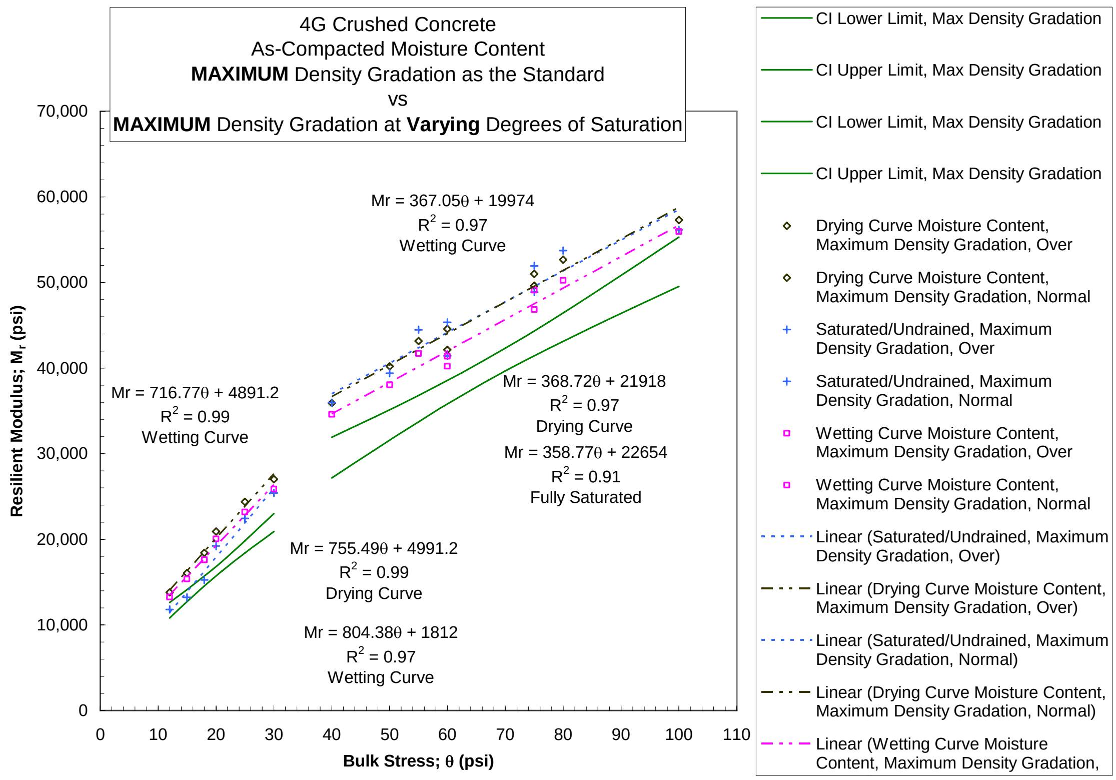

Figure 4.2-25 Crushed Concrete Maximum Density Gradation Comparing Effect of MC

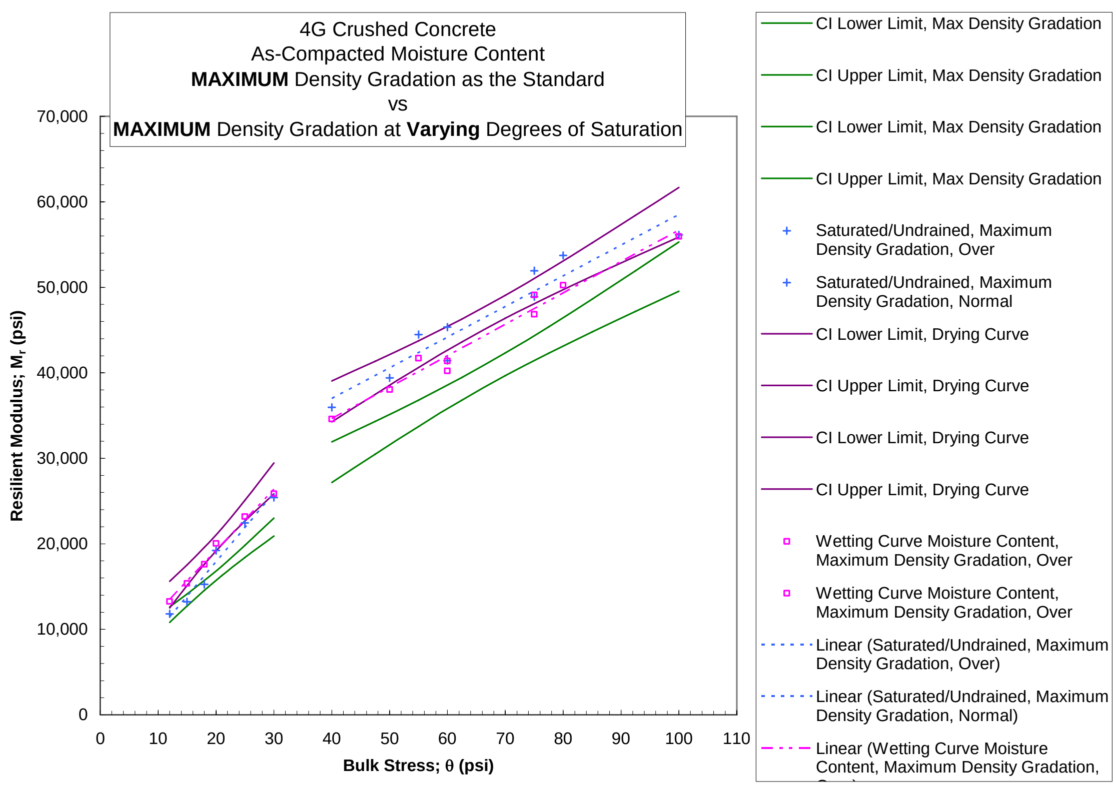

Figure 4.2-26 Crushed Concrete Maximum Density Gradation Comparing Effect of MC

Figure 4.2-25 shows that both the Drying Curve MC and Fully Saturated MC curves to be stiffer than the as-compacted MC curve in the normally consolidated region. Again, in the overconsolidated region the two are stiffer but only slightly so. Figure 4.2-26, shows a CI band imposed over the Drying Curve MC curve, which clearly contains the Fully Saturated MC curve in the normally consolidated region and intersects it in the overconsolidated region. Both the Drying Curve MC curve and the Fully Saturated MC curve have similar stiffness's. Both curves are also stiffer than the as-compacted MC standard, 9% in the normally consolidated region and 3% in the overconsolidated region. It would seem odd that a fully saturated specimen or a specimen with a high moisture content would be stiffer than the "standard" which is at a very low as-compacted MC. It would be expected that the increased excess pore water pressure would either, at most soften the specimen and at-least have no effect, stiffening would not be expected. Figure 4.2-27 demonstrates why this may have occurred.

After 2 weeks of hydrating, the specimen developed considerable cohesive strength with a considerable increase in stiffness. Hydration occurs as un-reacted Portland cement reacts with the specimen's pore water. This reaction or increase in cohesion occurs more readily in the maximum density gradation because there is more crushed paste available and tighter particle to particle contact. Both the Drying Curve MC and Fully Saturated MC involve saturating the specimen, so even more water is available for hydration. Both tests have more idle time, Drying Curve MC – time for specimen to drain, and Fully Saturated MC time for back-pressuring. Although not as much cohesive strength is developed over 24 hrs, one would still expect some strength and stiffness increase during this hydration period. This may explain why the fully saturated specimen and high moisture content specimen behaved stiffer than the as-compacted MC "standard".

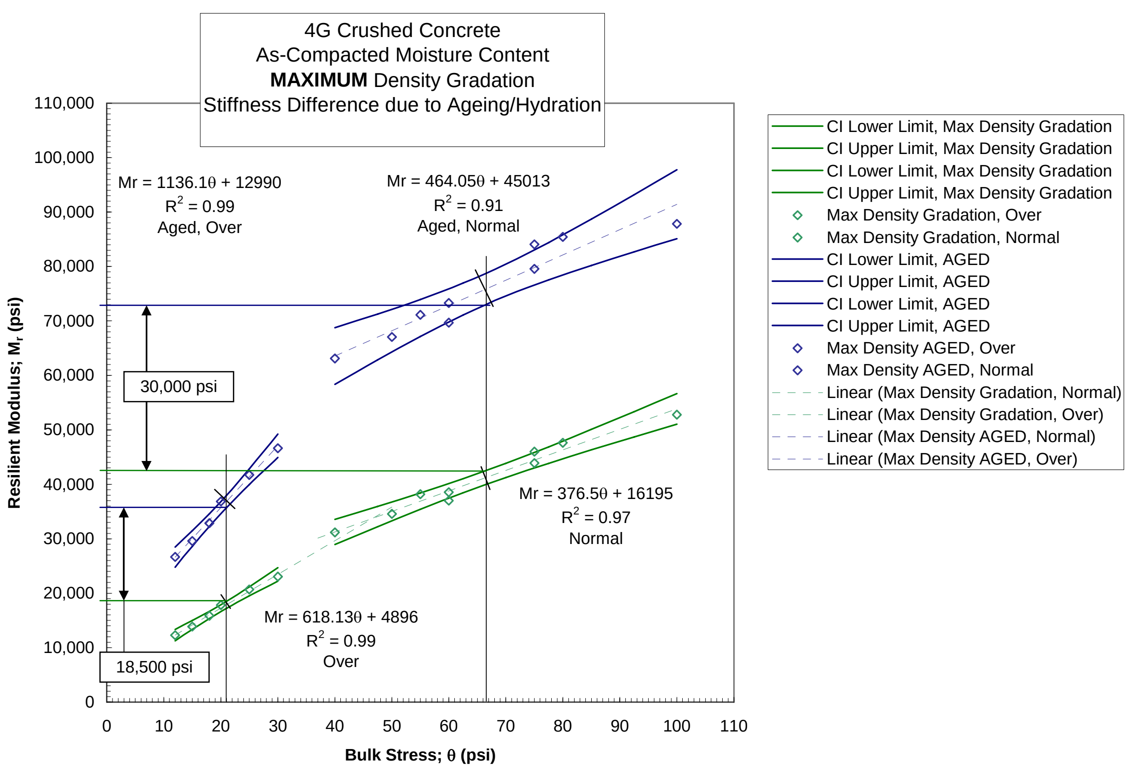

Figure 4.2-27 Increase in Stiffness due to Ageing and Hydration

Figure 4.2-27 compares the resilient modulus vs. bulk stress (Crushed Concrete, Maximum Density Gradation) of the same specimen tested again two weeks later. It has been seen that re-hydration occurs in Crushed Concrete. The pore water pH of Crushed Concrete is between 11.5 and 12 pH, a pH indicative of hydration. In the normally consolidated region there is an increase in stiffness of 75% while in the overconsolidated region there is an increase in stiffness of 102%. An unconfined compression test was performed on the aged specimen after the resilient modulus test. The ultimate strength of the unconfined specimen was 140 psi, considerable cohesive strength was developed during two weeks of hydration of un-reacted Portland cement.

4.2.5 EFFECTS OF ENVIRONMENTAL CONDITION WITH GRADATION – ANALYSIS SUMMARY

This section summarizes the analyses of sections 4.2.1 through 4.2.4, which investigated the effects of varying moisture conditions on the three different gradations stiffness. This was done for all four unbound granular material types. Those analyses produced over 12 plots with four curves per plot (representing the various moisture contents) and each one of those curves was broken down into the overconsolidated bulk stress range and the normally consolidated bulk stress range. This produced over 96 curves, which makes it very difficult to see patterns of behavior let alone a quantitative analysis. It was thought that a semi-quantitative method that involved averaging, descriptions, and engineering judgment would allow for the best characterization of moisture content effects on stiffness.

Table 4.2-1 through Table 4.2-4 describe by material, the effects of moisture content on the stiffness of a particular gradation. Each table is divided into the three different gradations, and then each gradation's stiffness response to the 4 different moisture contents. The As-compacted MC's stiffness is the standard to which the other MC's stiffness responses are compared to. For example if a response is described as **softer**, it means that particular moisture content caused a stiffness response that was softer than the stiffness of the As-compacted MC specimen. Based on the curves from sections 4.2.1 through 4.2.4 the relative stiffness differences were quantified as being:

1. **Softer** than the As-compacted MC stiffness
2. **Marginally Softer** than the As-compacted MC stiffness
3. **Similar** in stiffness to the As-compacted MC stiffness
4. **Marginally Stiffer** than the As-compacted MC stiffness
5. **Stiffer** than the As-compacted MC stiffness.

This rating is given for each gradation and for both the overconsolidated bulk stress range and the normally consolidated bulk stress range. To further reduce the data, the rating for a given moisture content at a given gradation was averaged for the OC and NC conditions. This single rating for each moisture content at a given gradation for a given material is then summarized for all materials in Table 4.2-5.

Table 4.2-5 then shows semi-quantitative averages of the different materials, relating to the effects that a moisture content or *degree of saturation* has on the stiffness of a particular gradation. Again, this averaging is a rather broad stroke that assumes material type has no effect on the stiffness response. It however, allows for a generalization which describes the relationship between gradation, moisture content, and stiffness. Each qualitative describer is assigned a numeric value as shown below:

- 1 = softer
- 2 = marginally softer
- 3 = similar
- 4 = marginally stiffer
- 5 = stiffer.

With these assigned numeric equivalents, the stiffness's were averaged on the right hand side of the table. Once the average number was calculated the number was then transformed into a descriptor based on the ranges given below:

- < 1 – 1 = Softer
- < 2.5 – 1.5 = Marginally softer
- 2.5 – 3.5 = Similar
- > 3.5 – 4.5 = Marginally stiffer
- > 4.5 – 5 = Stiffer

The values for the *upper bound* and *maximum density gradations* for Crushed Concrete are listed in Table 4.2-5 but are not included into the final average. The development of cementation in the Crushed Concrete did not represent the conditions in the other material types and was, therefore, left out of the final averaging. It can be generalized that:

1. For all three gradations a Fully Saturated Undrained environment caused a marginal softening. However, it must be remembered for certain materials a considerable softening was seen.

2. For all three gradations the Drying Curve MC caused marginal softening or had no effect on the stiffness response.

3. For all three gradations the Wetting Curve MC caused stiffening or had no effect on the stiffness response.

A trend of softening with increased moisture content can be seen. However, it is not dramatic as compared to the finer densely graded specifications such as MDOT's 22a. The 22a gradations tested for another program showed drastic softening and even failure during deviatoric stress application at higher moisture contents. All the gradations based on the 4G specification showed pore pressure increase with deviatoric loading in the undrained condition. However, these increases were not great and most importantly they were not cumulative. The pore pressure increase was elastic, i.e. the pressure increased during loading but returned to the targeted effective stress of the test. There was no tendency (during the hundred cycles of a sequence) to collapse in any of the specimens tested in an undrained state.

Table 4.2-1 Qualitative Effects of Moisture Condition on Stiffness – Natural Gravel

	Natural Gravel	Degree of Saturation (%)	Overconsolidated Region	Normally Consolidated Region	Qualitative Average of OC and NC Regions
			Stiffness Relative to As-compacted MC Stiffness		
Lower Bound Gradation	As-compacted MC	23.6	Standard	Standard	Standard
	Wetting MC	23.6	**similar**	**marginally softer**	**similar**
	Drying MC	28.4	**softer**	**softer**	**softer**
	Fully Saturated MC	100	**softer**	**softer**	**softer**
Upper Bound Gradation	As-compacted MC	42.5	Standard	Standard	Standard
	Wetting MC	42.5	**stiffer**	**stiffer**	**stiffer**
	Drying MC	58.0	**similar**	**similar**	**similar**
	Fully Saturated MC	100.0	**softer**	**similar**	**marginally softer**
Maximum Density Gradation	As-compacted MC	61.7	Standard	Standard	Standard
	Wetting MC	61.7	**marginally stiffer**	**similar**	**marginally stiffer**
	Drying MC	84.0	**similar**	**similar**	**similar**
	Fully Saturated MC	100.0	**similar**	**similar**	**similar**

Effect of Moisture Condition on Stiffness

Table 4.2-2 Qualitative Effects of Moisture Condition on Stiffness – Dolomite

	Dolomite	Degree of Saturation (%)	Overconsolidated Region	Normally Consolidated Region	Qualitative Average of OC and NC Regions
			Stiffness Relative to As-compacted MC Stiffness		
Lower Bound Gradation	As-compacted MC	19.2	Standard	Standard	Standard
	Wetting MC	19.2	**na**	**na**	**na**
	Drying MC	22.2	**similar**	**similar**	**similar**
	Fully Saturated MC	100	**softer**	**softer**	**softer**
Upper Bound Gradation	As-compacted MC	45.1	Standard	Standard	Standard
	Wetting MC	45.1	**stiffer**	**stiffer**	**stiffer**
	Drying MC	89.7	**marginally softer**	**similar**	**similar**
	Fully Saturated MC	100.0	**similar**	**similar**	**similar**
Maximum Density Gradation	As-compacted MC	53.6	Standard	Standard	Standard
	Wetting MC	53.6	**marginally softer**	**similar**	**similar**
	Drying MC	82.9	**similar**	**similar**	**similar**
	Fully Saturated MC	100.0	**similar**	**similar**	**similar**

Effect of Moisture Condition on Stiffness

Table 4.2-3 Qualitative Effects of Moisture Condition on Stiffness – Slag

	Slag	Degree of Saturation (%)	Overconsolidated Region	Normally Consolidated Region	Qualitative Average of OC and NC Regions
			Effect of Moisture Condition on Stiffness – Stiffness Relative to As-compacted MC Stiffness		
Lower Bound Gradation	As-compacted MC	17.9	Standard	Standard	Standard
	Wetting MC	17.9	**na**	**na**	**na**
	Drying MC	43.5	**marginally stiffer**	**similar**	**similar**
	Fully Saturated MC	100	**similar**	**similar**	**similar**
Upper Bound Gradation	As-compacted MC	29.0	Standard	Standard	Standard
	Wetting MC	29.0	**stiffer**	**marginally stiffer**	**marginally stiffer**
	Drying MC	55.2	**similar**	**softer**	**marginally softer**
	Fully Saturated MC	100.0	**softer**	**softer**	**softer**
Maximum Density Gradation	As-compacted MC	53.1	Standard	Standard	Standard
	Wetting MC	53.1	**marginally stiffer**	**similar**	**similar**
	Drying MC	82.0	**similar**	**similar**	**similar**
	Fully Saturated MC	100.0	**softer**	**marginally softer**	**softer**

Table 4.2-4 Qualitative Effects of Moisture Condition on Stiffness – Crushed Concrete

	Crushed Concrete	Degree of Saturation (%)	Overconsolidated Region	Normally Consolidated Region	Qualitative Average of OC and NC Regions
			Effect of Moisture Condition on Stiffness – Stiffness Relative to As-compacted MC Stiffness		
Lower Bound Gradation	As-compacted MC	25.7	Standard	Standard	Standard
	Wetting MC	25.7	**similar**	**similar**	**similar**
	Drying MC	45.6	**softer**	**softer**	**softer**
	Fully Saturated MC	100.0	**softer**	**softer**	**softer**
Upper Bound Gradation	As-compacted MC	47.5	Standard	Standard	Standard
	Wetting MC	47.5	**marginally stiffer**	**similar**	**similar**
	Drying MC	66.5	**similar**	**similar**	**similar**
	Fully Saturated MC	100.0	**marginally softer**	**similar**	**similar**
Maximum Density Gradation	As-compacted MC	60.2	Standard	Standard	Standard
	Wetting MC	60.2	**stiffer**	**stiffer**	**stiffer**
	Drying MC	91.0	**stiffer**	**stiffer**	**stiffer**
	Fully Saturated MC	100.0	**stiffer**	**stiffer**	**stiffer**

Table 4.2-5 Semi-quantitative Assessment of the Effects of Moisture Condition on Stiffness by Material

1 = softer	< 1.5 - 1 softer
2 = marginally softer	< 2.5 - 1.5 marginally softer
3 = similar	2.5 - 3.5 similiar
4 = marginally stiffer	> 3.5 - 4.5 marginally stiffer
5 = stiffer	> 4.5 - 5 stiffer

		Summary of Qualitative Averages of Moisture Condition Effects on Stiffness				Semi-quantitative Analysis of Moisture Condition Effects on Stiffness					
		Natural Gravel	Dolomite	Slag	Crushed Concrete	Natural Gravel	Dolomite	Slag	Crushed Concrete	Average	
Lower Bound Gradation	As-compacted MC	Standard	Standard	Standard	Standard	x	x	x	x	x	Standard
	Wetting MC	**similar**	**na**	**na**	**similar**	**3.0**			**3.0**	**3.0**	**similar**
	Drying MC	**softer**	**similar**	**similar**	**softer**	**1.0**	**3.0**	**3.0**	**1.0**	**2.0**	**marginally softer**
	Fully Saturated MC	**softer**	**softer**	**similar**	**softer**	**1.0**	**1.0**	**3.0**	**1.0**	**1.5**	**marginally softer**
Upper Bound Gradation	As-compacted MC	Standard	Standard	Standard	Standard	x	x	x	x	x	Standard
	Wetting MC	**stiffer**	**stiffer**	**marginally stiffer**	**similar**	**5.0**	**5.0**	**4.0**	**3.0****	**4.7**	**stiffer**
	Drying MC	**similar**	**similar**	**marginally softer**	**similar**	**3.0**	**3.0**	**2.0**	**3.0****	**2.7**	**similar**
	Fully Saturated MC	**marginally softer**	**similar**	**softer**	**similar**	**2.0**	**3.0**	**1.0**	**3.0****	**2.0**	**marginally softer**
Maximum Density Gradation	As-compacted MC	Standard	Standard	Standard	Standard	x	x	x	x	x	Standard
	Wetting MC	**marginally stiffer**	**similar**	**similar**	**stiffer**	**4.0**	**3.0**	**3.0**	**5.0****	**3.3**	**similar**
	Drying MC	**similar**	**similar**	**similar**	**stiffer**	**3.0**	**3.0**	**3.0**	**5.0****	**3.0**	**similar**
	Fully Saturated MC	**similar**	**similar**	**softer**	**stiffer**	**3.0**	**3.0**	**1.0**	**5.0****	**2.3**	**marginally softer**

** not included in the average

4.3 EFFECTS OF MATERIAL TYPE

This section investigates the effects that material type has on the Resilient Modulus. Natural Gravel, Dolomite, Slag, and Crushed Concrete will be compared at their *lower bound gradation*, *upper bound gradation*, and their *maximum density gradation*. The analysis procedure is identical to the procedure described in sub-section *Comparison of Population Parameters in Linear-Linear*. The quantitative differences cited are an "at least" difference, meaning the values are taken as the difference between the CI lower limit of one curve from the CI upper limit of another curve or vice versa.

A decision matrix was developed to decide which comparisons to make. CI bands, of different materials, that intersected were given a "no – the curves are not different" and CI bands that did not intersect were given a "yes – the curves are different". CI bands whose upper and lower limits just touched were given a "marginally" rating. From this matrix it was decided which materials to compare quantitatively.

It should be reiterated that some re-hydration occurs in the crushed concrete specimens due to the time between compaction and testing of the specimen as discussed briefly on page 85. This variable was not evaluated quantitatively, but contributes to the results to some unknown degree.

4.3.1 LOWER BOUND GRADATION

Figure 4.3-1 shows the comparison of stiffness between the *lower bound gradation* of Slag, Crushed Concrete, and Natural Gravel, while Figure 4.3-2 shows the comparison of stiffness between the *lower bound gradation* of Dolomite and Natural Gravel. The CI bands of Dolomite and Slag intersect and therefore their stiffness difference is marginal. In the overconsolidated region the Slag stiffness response spans the extreme stiffness values of Natural Gravel and Crushed Concrete, its mean value lies in between the stiffness values of Natural Gravel and Crushed Concrete. In the overconsolidated region, Crushed Concrete is "at least" 3,250 psi stiffer than Natural Gravel, while Dolomite is "at least" 4000 psi stiffer than Natural Gravel. In the normally consolidated region, Slag is "at least" 4,000 psi stiffer than Crushed Concrete and 16,000 psi stiffer than Natural Gravel, while Crushed Concrete is 4,000 psi stiffer than Natural Gravel. Dolomite is 12,000 psi stiffer than Natural Gravel.

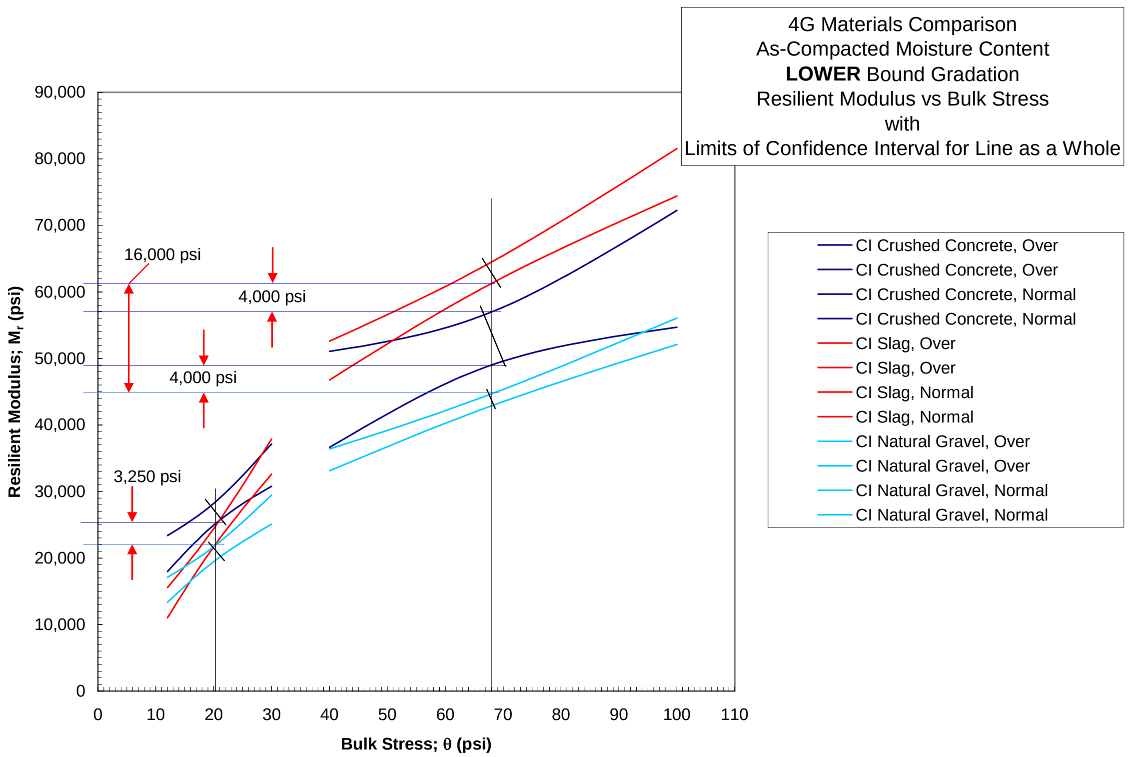

Figure 4.3-1 Lower Bound Gradation Comparing Slag, Crushed Concrete, and Natural Gravel

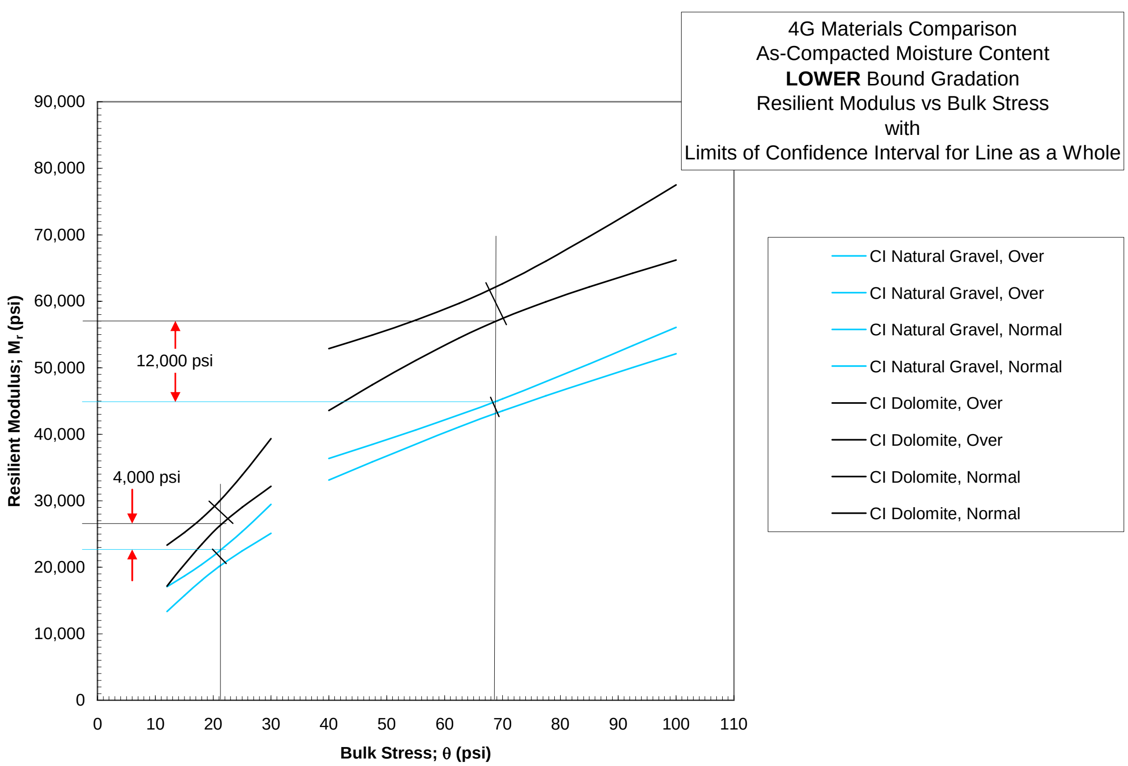

Figure 4.3-2 Lower Bound Gradation Comparing Dolomite and Natural Gravel

4.3.2 UPPER BOUND GRADATION

Figure 4.3-3 shows the comparison of stiffness between the *upper bound gradation* of Slag, Crushed Concrete, and Natural Gravel. Figure 4.3-4 shows the comparison of stiffness between the *upper bound gradation* of Dolomite, Crushed Concrete and Natural Gravel. The CI bands of Dolomite and Slag intersect and therefore their stiffness difference is marginal. In the overconsolidated region, the Crushed Concrete stiffness response intersects the Dolomite CI band, the two show marginal stiffness difference. In the overconsolidated region, Slag is "at least" 1,000 psi stiffer than Crushed Concrete and 6,000 psi stiffer than Natural Gravel, while Crushed Concrete is "at least" 1,250 psi stiffer than Natural Gravel. In the normally consolidated region, Slag is "at least" 7,000 psi stiffer than Crushed Concrete and 16,500 psi stiffer than Natural Gravel, while Crushed Concrete is 4,500 psi stiffer than Natural Gravel. Dolomite is 3,500 psi stiffer than Crushed Concrete and 13,000 psi stiffer than Natural Gravel.

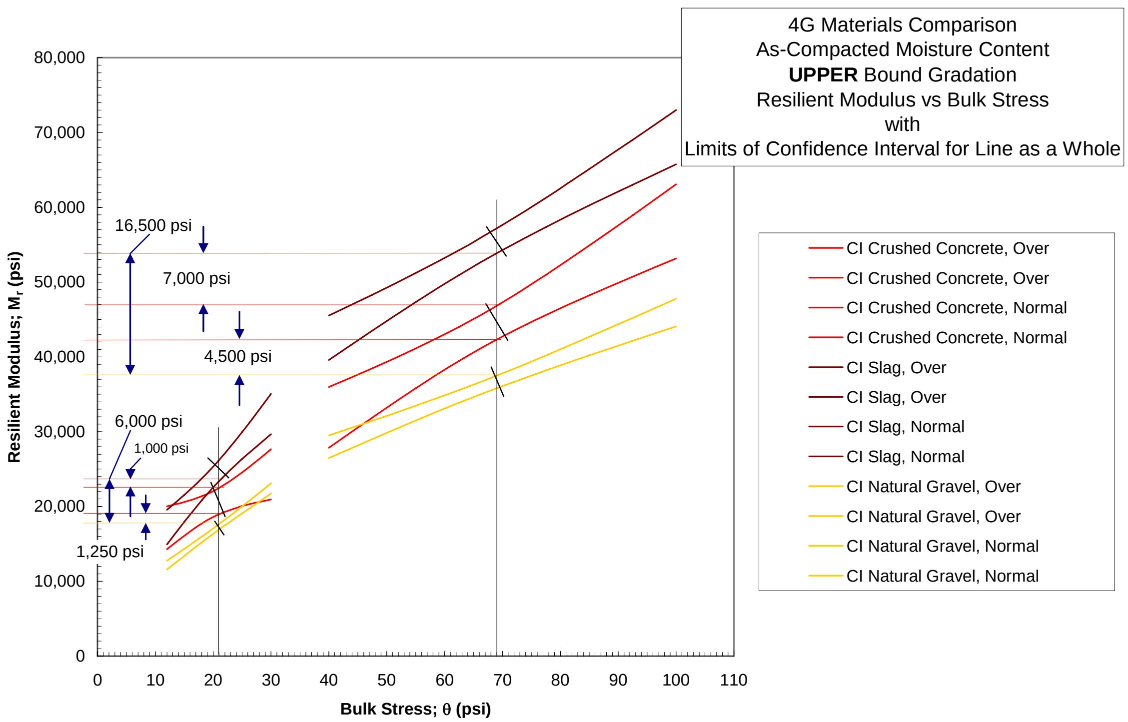

Figure 4.3-3 Upper Bound Gradation Comparing Slag, Crushed Concrete, and Natural Gravel

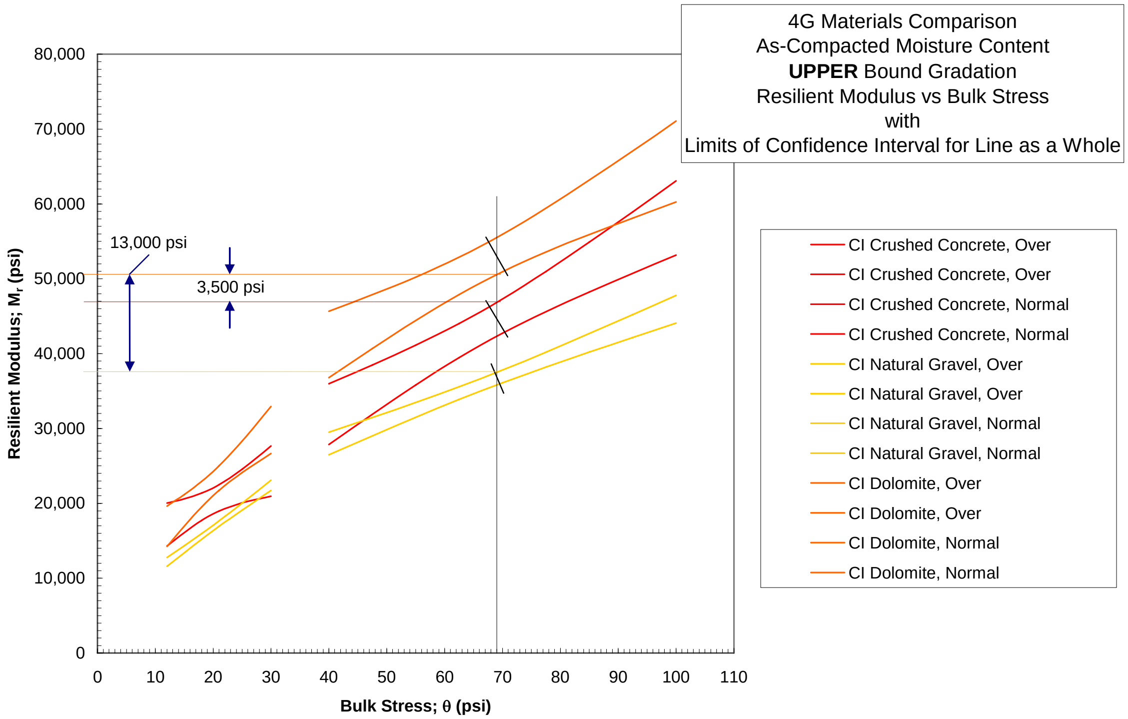

Figure 4.3-4 Upper Bound Gradation Comparing Dolomite, Crushed Concrete, and Natural Gravel

4.3.3 MAXIMUM DENSITY GRADATION

Figure 4.3-5 shows the comparison of stiffness between the *maximum density gradation* of Dolomite, Crushed Concrete, and Natural Gravel. While, Figure 4.3-6 shows the comparison of stiffness between the *maximum density gradation* of Slag, Crushed Concrete and Natural Gravel. The CI bands of Crushed Concrete and Slag intersect in the OC region and therefore their stiffness difference is marginal. In the overconsolidated region, the Crushed Concrete stiffness response intersects the Dolomite CI band, the two show marginal stiffness difference. In the overconsolidated region, Dolomite is "at least" 2,000 psi stiffer than Crushed Concrete and 6,500 psi stiffer than Natural Gravel, while Crushed Concrete is "at least" 3,750 psi stiffer than Natural Gravel. In the normally consolidated region, Dolomite is "at least" 6,000 psi stiffer than Crushed Concrete and 15,000 psi stiffer than Natural Gravel, while Crushed Concrete is 6,500 psi stiffer than Natural Gravel. Slag is 3,500 psi stiffer than Crushed Concrete and 12,500 psi stiffer than Natural Gravel.

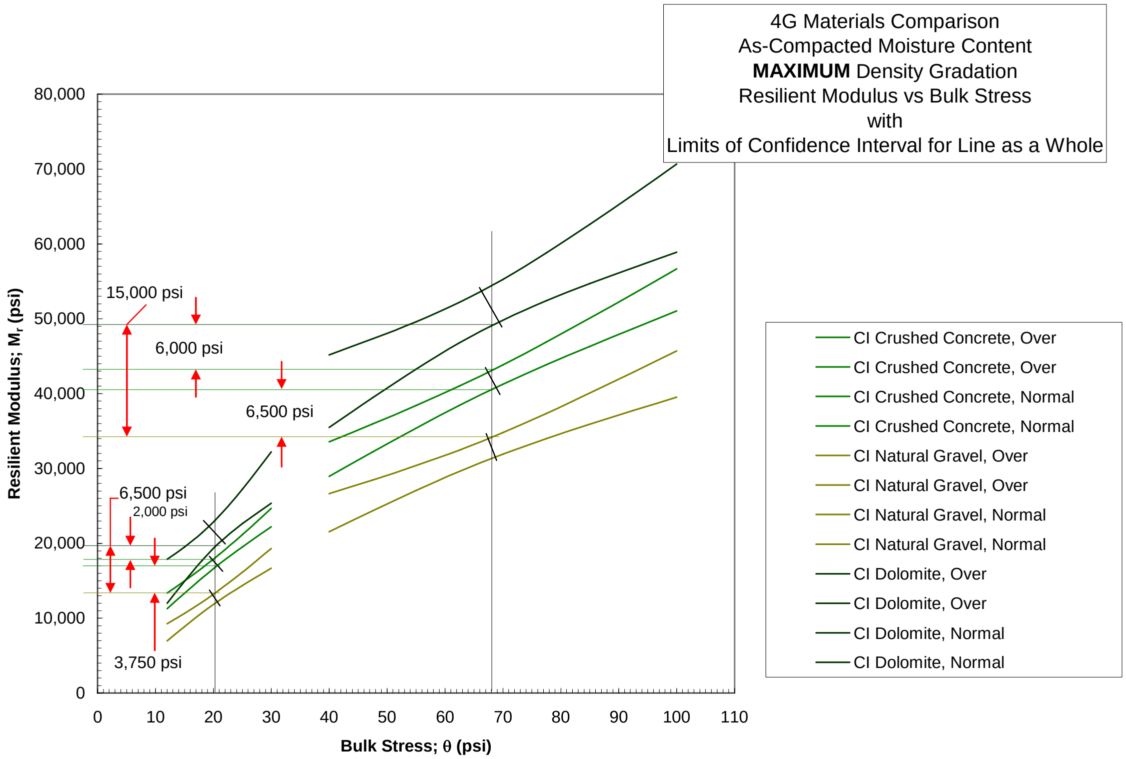

Figure 4.3-5 Maximum Density Gradation Comparing Dolomite, Crushed Concrete, and Natural Gravel

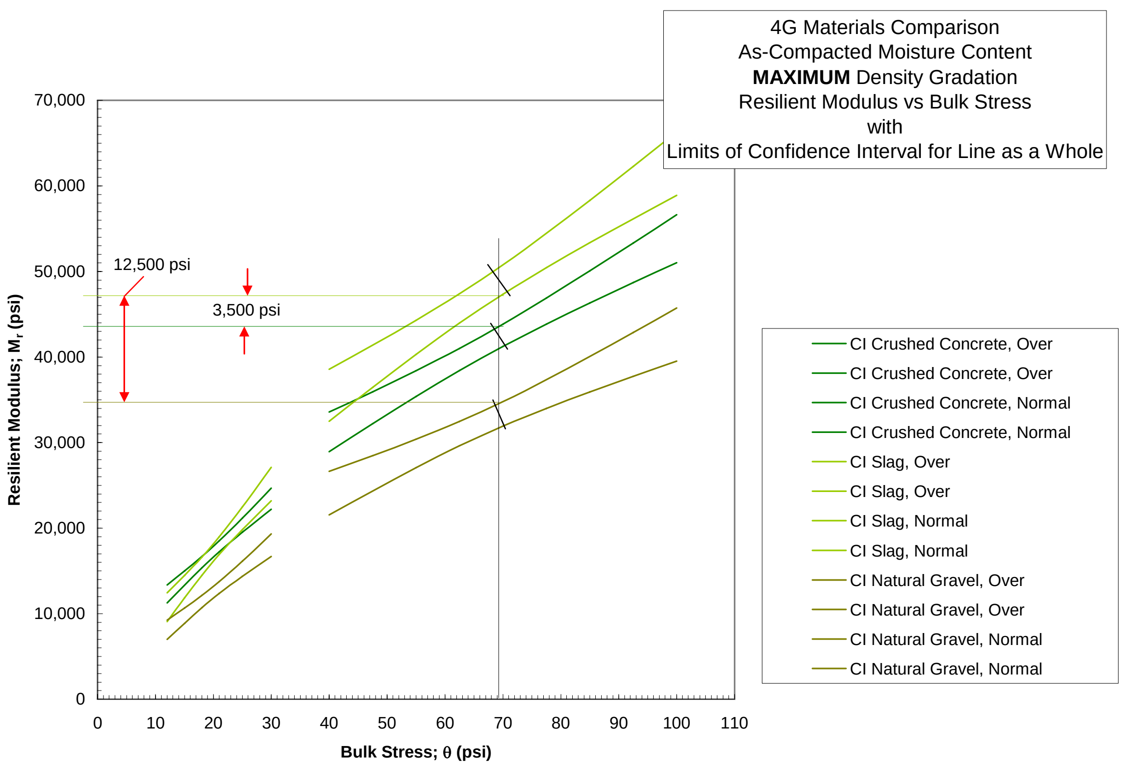

Figure 4.3-6 Maximum Density Gradation Comparing Slag, Crushed Concrete, and Natural Gravel

4.3.4 EFFECTS OF MATERIAL TYPE – ANALYSIS SUMMARY

This section summarizes the analyses of sections 4.3.1 through 4.3.3 to determine whether or not material type is a significant variable in regards to stiffness response. Again a mixed analytical and semi-quantitative method that involved engineering judgment was used. Table 4.3-1 through

Table 4.3-3 divide stiffness response into two parts, stiffness response in the overconsolidated bulk stress range and stiffness response in the normally consolidated bulk stress range. Each section provides a qualitative comparison of stiffness differences between the four materials, *reading as stiff to less stiff*. Two materials within parentheses separated by a slash (material A / material B) designates two materials that are similar in stiffness, i.e. their CI intervals intersect. Although their CI intervals intersect, Material A may be similar or marginally stiffer, but is never softer than Material B. The tables also provide an analytical value of stiffness difference between pairs of materials at a given gradation. These values are the actual minimum stiffness difference (psi) and the percent stiffness difference (%).

Table 4.3-4 qualitatively compares the stiffness differences between the four material types tested in this program. It is a simple evaluation which allows one to easily generalize how material type affects the stiffness response. Figure 4.3-7 through Figure 4.3-9 restate with details the results shown in Table 4.3-4 to produce diagrams which compare the stiffness differences of the four materials tested. Based on these evaluations it can be said:

1. Natural Gravel always produces the **softest** stiffness response of the four materials. By generalizing it can be said that for all gradations and over both the OC and NC bulk stress ranges:

    a. Slag/Dolomite is 15% - 50% stiffer than Natural Gravel

    b. Crushed Concrete is 7% - 29% stiffer than Natural Gravel

2. Dolomite and Slag are generally similar in stiffness and produce the **stiffest** responses of the four materials.

3. Crushed Concrete's stiffness response lies between Natural Gravel's and Dolomite/Slag's stiffness. It has the **middle** stiffest response. By generalizing it can be said that for all gradations and over both the OC and NC bulk stress ranges:

    a. Dolomite/Slag is 4% - 15% stiffer than Crushed Concrete

    b. Crushed Concrete is 7% - 29% stiffer than Natural Gravel

Table 4.3-1 Effects of Material Type on Stiffness, by Gradation – Lower Bound Gradation

Lower Bound Gradation				
Overconsolidated Range Stiff to Less Stiff ------------------------------> **(Dolomite / Crushed Concrete) > Slag > Natural Gravel**		AT LEAST Stiffer (psi)	AT LEAST Stiffer Percent Difference (%)
Dolomite is STIFFER than Natural Gravel:	OC Range	4,000	18
Crushed Concrete is STIFFER than Natural Gravel:	OC Range	3,250	15
Normally Consolidated Range Stiff to Less Stiff ------------------------------> **(Slag / Dolomite) > Crushed Concrete > Natural Gravel**		AT LEAST Stiffer (psi)	AT LEAST Stiffer Percent Difference (%)
Slag is STIFFER than Natural Gravel:	NC Range	16,000	36
Dolomite is STIFFER than Natural Gravel:	NC Range	12,000	27
Slag is STIFFER than Crushed Concrete:	NC Range	4,000	7
Crushed Concrete is STIFFER than Natural Gravel:	NC Range	4,000	9

Table 4.3-2 Effects of Material Type on Stiffness, by Gradation – Upper Bound Gradation

Upper Bound Gradation			
Overconsolidated Range Stiff to Less Stiff ------------------------------> **(Slag / Dolomite) > Crushed Concrete > Natural Gravel**		AT LEAST Stiffer (psi)	AT LEAST Stiffer Percent Difference (%)
Slag is STIFFER than Natural Gravel:	OC Range	6,000	33
Crushed Concrete is STIFFER than Natural Gravel:	OC Range	1,250	7
Slag is STIFFER than Crushed Concrete:	OC Range	1,000	4
Normally Consolidated Range Stiff to Less Stiff ------------------------------> **(Slag / Dolomite) > Crushed Concrete > Natural Gravel**		AT LEAST Stiffer (psi)	AT LEAST Stiffer Percent Difference (%)
Slag is STIFFER than Natural Gravel:	NC Range	16,500	44
Dolomite is STIFFER than Natural Gravel:	NC Range	13,000	35
Slag is STIFFER than Crushed Concrete:	NC Range	7,000	15
Crushed Concrete is STIFFER than Natural Gravel:	NC Range	4,500	12
Dolomite is STIFFER than Crushed Concrete:	NC Range	3,500	7

Table 4.3-3 Effects of Material Type on Stiffness, by Gradation – Maximum Density Gradation

Maximum Density Gradation			AT LEAST Stiffer (psi)	AT LEAST Stiffer Percent Difference (%)
	Overconsolidated Range Stiff to Less Stiff ------------------------------> **Dolomite > (Slag / Crushed Concrete) > Natural Gravel**			
	Dolomite is STIFFER than Natural Gravel:	OC Range	6,500	50
	Crushed Concrete is STIFFER than Natural Gravel:	OC Range	3,750	29
	Dolomite is STIFFER than Crushed Concrete:	OC Range	2,000	11
	Normally Consolidated Range Stiff to Less Stiff ------------------------------> **(Dolomite / Slag) > Crushed Concrete > Natural Gravel**		AT LEAST Stiffer (psi)	AT LEAST Stiffer Percent Difference (%)
	Dolomite is STIFFER than Natural Gravel:	NC Range	15,000	44
	Slag is STIFFER than Natural Gravel:	NC Range	12,500	37
	Crushed Concrete is STIFFER than Natural Gravel:	NC Range	6,500	19
	Dolomite is STIFFER than Crushed Concrete:	NC Range	6,000	14
	Slag is STIFFER than Crushed Concrete:	NC Range	3,500	8

Table 4.3-4 Qualitative Summary of Stiffness by Material Type for a Given Gradation

		Stiff to Less Stiff ⟶
Lower Bound Gradation	OC Range	(Dolomite / Crushed Concrete)** > Slag > Natural Gravel
	NC Range	(Slag / Dolomite) > Crushed Concrete > Natural Gravel
Upper Bound Gradation	OC Range	(Slag / Dolomite) > Crushed Concrete > Natural Gravel
	NC Range	(Slag / Dolomite) > Crushed Concrete > Natural Gravel
Maximum Density Gradation	OC Range	Dolomite > (Slag / Crushed Concrete) > Natural Gravel
	NC Range	(Dolomite / Slag) > Crushed Concrete > Natural Gravel

** **(material A / material B)** Two materials within parentheses separated by a slash designates two materials that are similar in stiffness, i.e. their CI intervals intersect. Material A may be similar or marginally stiffer than Material B, but CI intervals intersect.

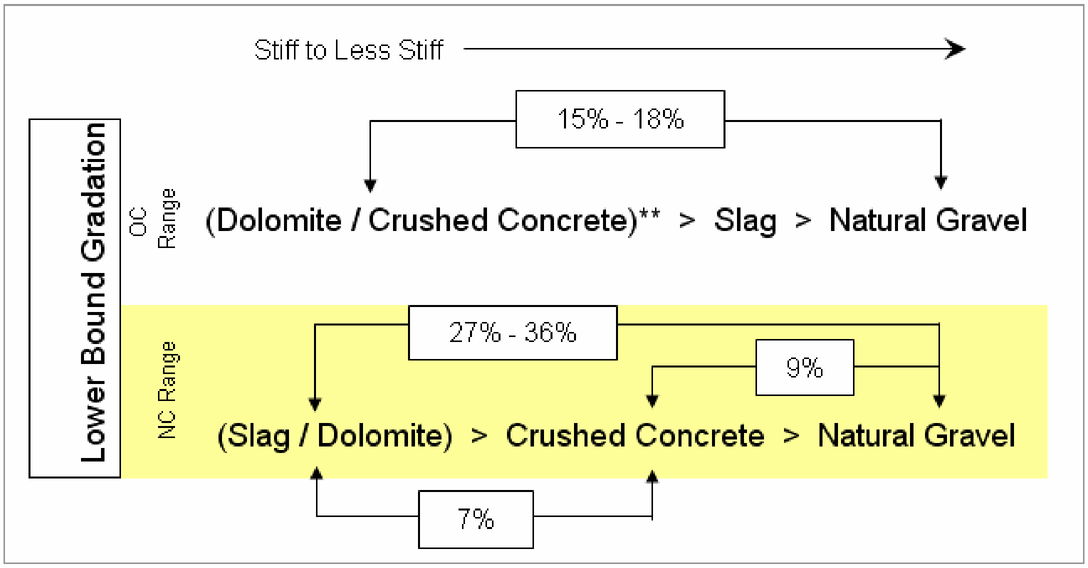

Figure 4.3-7 Quantitative Stiffness Comparison by Material Type for the Lower Bound Gradation

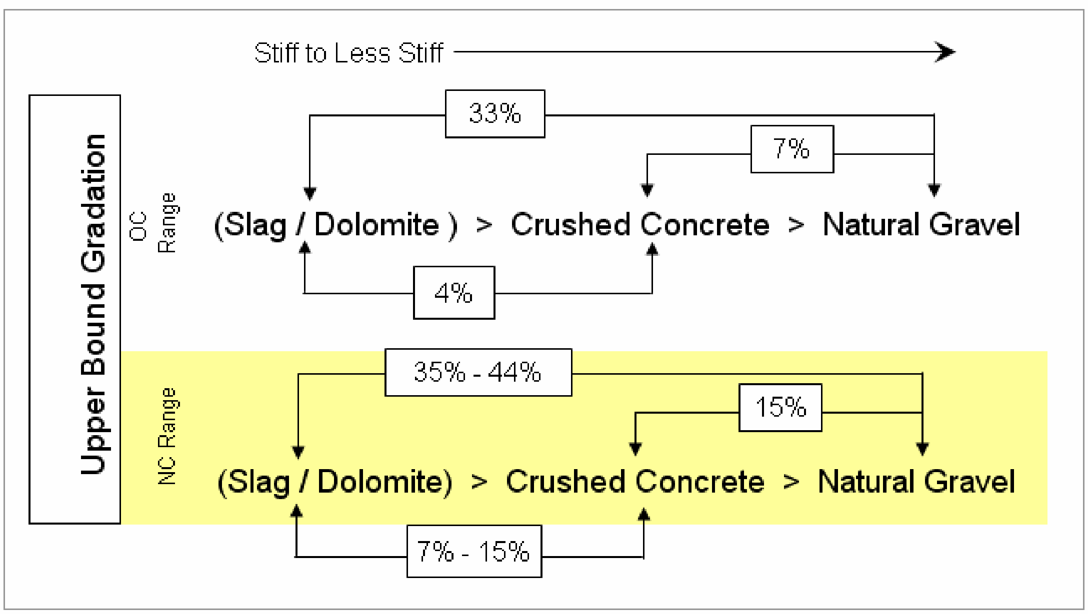

Figure 4.3-8 Quantitative Stiffness Comparison by Material Type for the Upper Bound Gradation

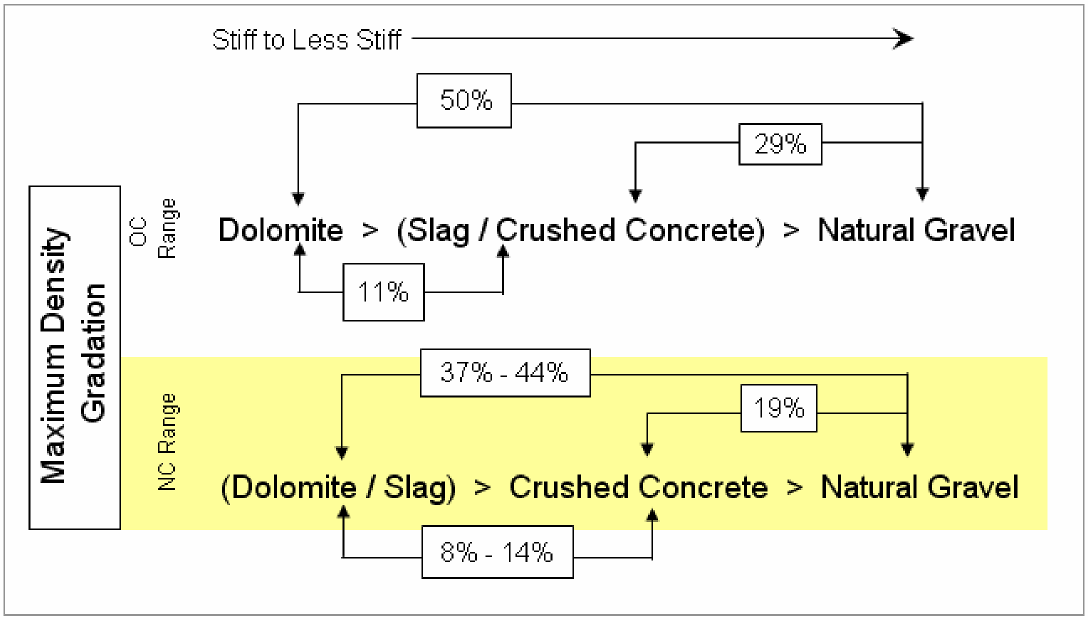

Figure 4.3-9 Quantitative Stiffness Comparison by Material Type for the Maximum Density Gradation

5 SUMMARY AND CONCLUSIONS

The objective of this testing program is to determine whether the dynamic stiffness of an unbound pavement base course, represented by a lab specimen, of a 4G gradation varies significantly over the acceptable gradation limits and a broad range of degrees of saturation. From this statement it is obvious that conclusions should be drawn, and they were. In the following two subsections important findings and methods developed in this study will be pointed out and then conclusions will be drawn to satisfy the Objective Statement.

5.1 SUMMARY OF IMPORTANT DEVELOPMENTS AND FINDINGS

1. The laboratory procedure was modified so that the critical boundary of an aggregate / water system without air voids could be tested.

2. A linear resilient modulus vs. linear bulk stress relationship was used. This allowed for a quantitative determination of the difference between the various resilient modulus curves.

3. For the four materials tested, the effect of moisture increased as the ratio of fine aggregate to coarse aggregate increased.

4. For the four materials tested at the as-compacted moisture content, stiffness decreased as the ratio of fine aggregate to coarse aggregate increased.

5. Modeling drainage from the saturated condition to a partially saturated condition was successful. That is, the determination of equilibrium was easily identified by means of volume of water drained vs. time plots, and the amount of drainage is clearly a function of the ratio of fine aggregate to coarse aggregate.

6. The stiffness of any particular gradation was found to be dependent on the material type. As a generalization (see pg. 124 for specifics) Natural Gravel is always softest, Dolomite and Slag behave similarly and are stiffest, and Crushed Concrete occupies an intermediate ranking.

7. The recycled Portland cement concrete showed a time-dependent increase in stiffness based on limited results.

5.2 CONCLUSIONS DRAWN FROM THIS RESEARCH PROGRAM

Many of the above seven findings have been expanded upon in sections 4.1.5, 4.2.5, and 4.3.4 - Analysis Summaries. General conclusions are as follows:

1. It has been shown that significant stiffness differences occur at the limits of the 4G gradation band. Therefore the *Uniformity Clause* has the beneficial effect of reducing the variability of stiffness for any particular aggregate. The *Uniformity Clause* adds an additional constraint which limits the aggregate's grain size distribution between the broad 4G gradation limits. Without this constraint, as discussed above, stiffnesses could vary by up to 50%.

2. It has been shown that the choice of bulk stress is extremely important in the resulting magnitude of the resilient modulus.

3. It has been shown that there is a significant change in the rate of change of the

resilient modulus at the transition between the overconsolidated and normally consolidated states.

4. As a generalization, using the As-compacted MC as the standard of comparison, the trend in stiffness is real and rational. As shown in Table 4.2-5 no major changes in stiffness occur as the environmental moisture content changes with the exception of the Upper Bound gradation Wetting Curve results.

6 REFERENCES

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