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An Improved Alternative Test Method for Resilient Modulus of Fine Grained Soils

Jonathan Michael Smolen
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Jonathan Michael Smolen entitled "An Improved Alternative Test Method for Resilient Modulus of Fine Grained Soils." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

Eric C. Drumm, Major Professor

We have read this thesis and recommend its acceptance:

Dayakar Penumadu, Baoshan Huang

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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AN IMPROVED ALTERNATIVE TEST METHOD FOR RESILIENT MODULUS OF FINE GRAINED SOILS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Jonathan Michael Smolen
August 2003

Dedication

To my beloved wife Patricia, who is, and forever will be, an inspiration to me.

Acknowledgments

I would like to thank Dr. Eric Drumm for the opportunity to attend graduate school and for his patience in my completing it. Thank you to Dr. Huang and Dr. Penumadu for being on my committee and for their suggestions. I would also like to thank Randy Rainwater for allowing me to use the lab and equipment and helping me to collect samples and conduct tests. Furthermore, I want to thank Ken Thomas for designing and building the new ATM device. I thank Jason Cathey for access to his research and for his ideas. Finally, I want to thank the Tennessee Department of Transportation for funding this project and therefore my education.

Abstract

Flexible Pavement is usually composed of several asphalt concrete layers, a granular base course and a soil subgrade. For mechanistic design of pavement systems based on elastic theory a modulus of elasticity must be designated for each design layer including the soil subgrade. The resilient modulus is used to characterize the soil in pavement design. The resilient modulus is defined as

$$M_R = \frac{\sigma_d}{\varepsilon_R}$$

Where σ_d is the deviator stress or the difference between the axial and confining stress, and ε_R is the recoverable axial strain.

The standard procedure for obtaining M_R is a repeated load tri-axial test at a constant confining pressure. There is not a singular resilient modulus value for a particular soil but rather the modulus is a function of the stress state. The standard test produces a range of resilient modulus values in a series of stress conditions.

The resilient modulus test is inherently complicated, time consuming, and expensive. For these reasons, most commercial and design laboratories will not conduct these tests but instead rely on empirical relationships. Therefore, it has been recommended that alternative tests be developed to approximate resilient modulus.

The Alternative Test Method was developed to be a simple and effective way of determining resilient modulus. The ATM design was based on a single degree of freedom, lumped mass spring system in which a hammer of known mass falls onto a volume of soil. Originally, there appeared to be good correlation between the Alternative Test Method and the standard test method for obtaining resilient modulus. However, subsequent testing failed to produce consistent results or confirm the correlation. Improvements have been made to the ATM to improve the overall consistency of results and correlation with the standard resilient modulus test results. The improvements to the ATM device include a new, more consistent drop mechanism, better data acquisition software, and a new calculation method.

ATM tests were conducted on 4 different soils from TDOT research sites. Standard tri-axial resilient modulus tests were conducted for comparison with ATM resilient modulus tests. The improved ATM appears to measure a material response that correlates reasonably well with the standard triaxial resilient modulus test results for those soils tested. Furthermore, the Improved ATM produces much more consistent results than the Original ATM. It is also believed that the limitations of the device are outweighed by its simplicity and commonality with other lab tests. Therefore, the improved Alternative Test Method for resilient modulus of fine grained soils is believed to be a viable alternative to the standard test method for obtaining resilient modulus values.

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Chapter 1 Introduction

Flexible Pavement is usually composed of several asphalt concrete layers, a granular base course and a soil subgrade. For mechanistic design of pavement systems based on elastic theory, a modulus of elasticity must be designated for each design layer including the soil subgrade. A pavement during its design life will receive repeated loadings at a stress much smaller than the ultimate strength of the soil subgrade. A modulus of elasticity representative of this loading condition is appropriate. However soil is not an ideal linear elastic material, it undergoes some permanent plastic deformation under each load. After many small repeated loads and accumulated deformation, the deformation under each subsequent load is almost completely recoverable, (Huang 1993). Figure 1 demonstrates this response. Thus, the modulus becomes nearly constant and the material can be considered linear elastic. The resulting modulus is referred to as the resilient modulus and is designated as the material property for mechanistic design of pavement in regards to soil subgrade (AASHTO 1993). The resilient modulus is defined as

$$M_R = \frac{\sigma_d}{\varepsilon_R}$$

Where σ_d is the deviator stress or the difference between the major and minor principal stresses, and ε_R is the recoverable axial strain (Huang 1993).

There is not a singular resilient modulus value for a particular soil but rather the modulus is a function of the stress state. For fine grained soils, the resilient

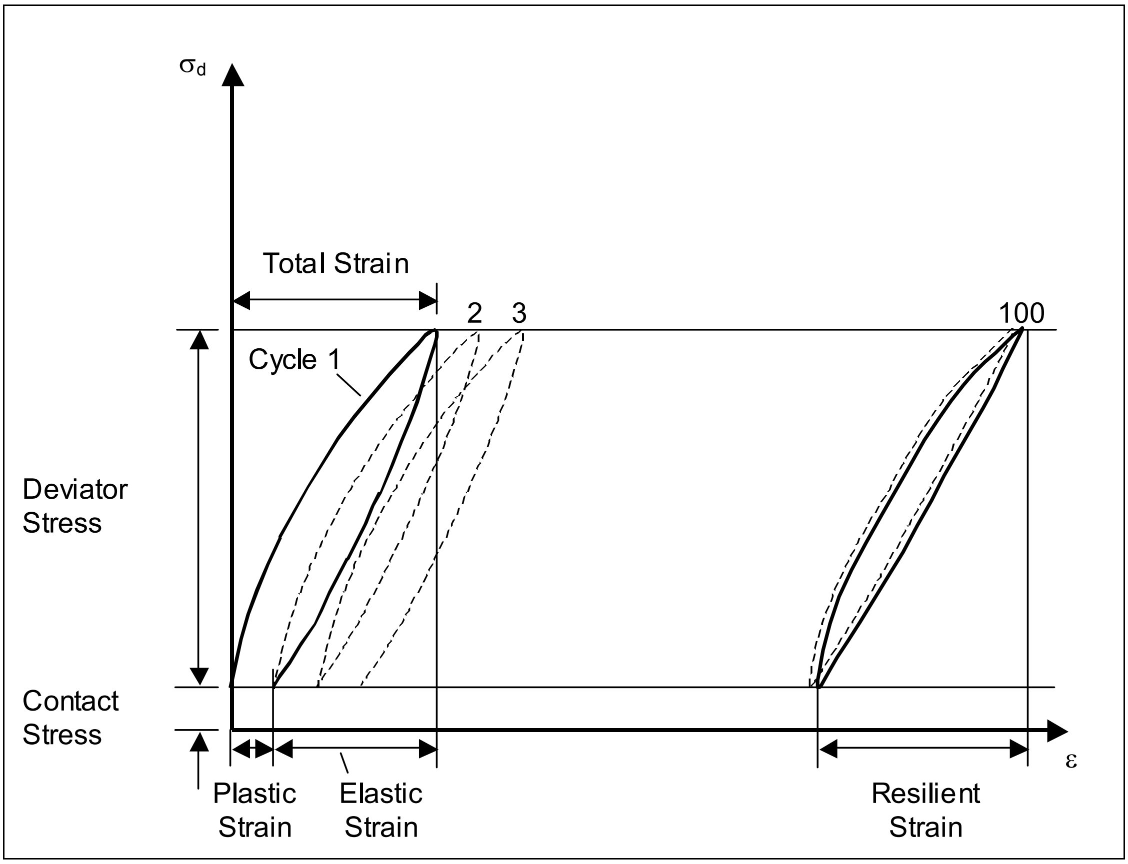

Figure 1 Resilient Behavior Under Repeated Loadings (Cathey 2001)

modulus usually tends to decrease with deviator stress and increase with confining stress, though the affect of confining stress on fine grained soils is usually small (Barksdale et al. 1997).

The AASHTO design method uses a single value of resilient modulus for each layer of an asphalt pavement based on a representative stress state (AASHTO 1993; Barksdale et al. 1997). However, resilient modulus testing is conducted in a sequence of stress states for assurance of reliable results (Barksdale et al. 1997). The standard procedure for obtaining resilient modulus is a repeated load tri-axial test at constant confining pressures of 41.4 kPa, 27.6 kPa, and 13.8 kPa. The test begins with a conditioning of 500 to 1000 load cycles of 27.6 kPa. The rest of the test of involves 100 load cycles of 13.8 kPa, 27.6 kPa, 41.4 kPa, 55.2 kPa and 68.9 kPa at each of the prescribed confining pressures. The average stress and strain values over the last 5 cycles of each load sequence are used to calculate the resilient modulus at that particular stress state. The full test procedure is described in AASHTO designation T 307-99. Typically, multiple tests are conducted and values are represented by an appropriate mathematical regression model for design purposes such as the Uzan and Witczak model (Barksdale et al. 1997).

The resilient modulus test is inherently complicated, time consuming, and requires expensive equipment and specialized training. For these reasons, many agencies will not conduct these tests but instead rely on empirical relationships.

The AASHTO Design Guide (1993) recommends, in the absence of actual resilient modulus data, the use of the empirical relationship of 1500 times the CBR value to obtain an estimate of resilient modulus in psi. However, this relationship has limited statistical relevance since it is based on a correlation range of between 750 to 3000 times the CBR value and the CBR is a test of relative shear strength, not modulus. Because the standard resilient modulus test is unattractive to commercial labs, it has been recommended that more statistically relevant tests based on easy to measure physical properties be developed (Barksdale et al. 1997). Many such empirical tests have been developed and used to approximate resilient modulus such as correlation with an automated cone penetrometer (George and Rahim 2002), estimation from standard tests (Drumm et al. 1990), and correlation with unconfined compression test (Lee et. al 1997). Other empirical relationships have been developed by Thompson (1992) in Illinois, Woolsturm (1990) in Nebraska, Li and Selig (1991,1994) in Massachusetts, Pezo and Hudson (1995) in Texas, Santha (1994) in Georgia, Elliot et al. (1988) in Arkansas, and Burczyk et al. (1994) in Wyoming (Barksdale 1997). The ATM is another attempt to provide designers with a reasonable approximation of and viable alternative to the standard resilient modulus test.

Chapter 2 Original ATM Design

The Alternative Test Method, or ATM, was designed to be an easier method of obtaining an approximate resilient modulus value. The original ATM was composed of a hammer of mass, M_0, falling a height, h_0, onto a cylinder of soil confined in a standard four inch proctor mold with inside diameter of 0.102 m and inside length of 0.108 m. The proctor mold was chosen both for its simplicity and its widespread use in construction materials testing. It was also believed that a constrained sample would give a good representation of the conditions beneath the pavement (Drumm et al. 1996).

The original method of analysis for the ATM was based on a single degree of freedom mass-spring model. An accelerometer mounted on the top inside of the hammer measures the deceleration in volts when the hammer strikes the soil. The accelerometer is ICP model 302A with a conversion factor of 10.01 mV/g. The acceleration data is collected by an oscilloscope card in a computer and the signal is displayed by wave analysis software. The data can be saved to be analyzed later. The peak acceleration signal is used to calculate a spring constant for the soil, which is then converted into a modulus of elasticity. However, because the soil is confined in a proctor mold, this modulus is a constrained modulus and must be converted to a resilient or Young's modulus. It was assumed that the hammer and soil surface have the same diameter. It was further assumed that the hammer is a rigid mass and the soil rests on a rigid, fixed surface. Side friction was assumed to be negligible. It was also assumed that when the hammer strikes the

soil, the hammer and soil stay together and therefore the acceleration reading of the hammer is also that of the soil. The true acceleration of the soil is actually much less than that of the hammer. However, the acceleration response of the hammer is dependant on the stiffness of the soil and therefore, provides a basis for empirical approximation of the standard resilient modulus test.

The following derivation, based on the assumption of a single degree of freedom lumped mass system, can be found in the paper by Drumm et al. (1996).

The motion, z(t), of the ATM model is governed by the differential equation:

$$M \cdot \ddot{z}(t) + K \cdot z(t) = 0$$

With initial conditions:

$$z(0) = Mg / K$$

and

$$\dot{z}(0) = \sqrt{(2gh)}$$

The solution to the governing differential equation is:

$$z(t) = g(1 - \cos\omega t) + \sqrt{2hz}\sin\omega t$$

Where K is the spring constant and ω is the natural frequency of the system represented by:

$$\omega = \sqrt{(K / M)}$$

Because the drop height is large in comparison to the deformation caused by the static load of the hammer, the static deflection can be neglected and the peak acceleration can be represented as:

$$A_p = \sqrt{\left(\frac{2ghK}{M}\right)}$$

Thus the soil stiffness, represented by the spring constant K, can be rewritten:

$$K = \frac{M}{2hg} \cdot A_p^2$$

The constrained modulus D is obtained from the spring constant K in the following manner:

$$D = \frac{K \cdot L}{A_{\sec}} = \frac{M \cdot L}{2hgA_{\sec}} A_p^2$$

Finally the constrained modulus is converted to resilient modulus using the resulting formula:

$$M_r = \frac{(1+\upsilon)(1-2\upsilon)}{1-\upsilon} \bullet \frac{M \cdot L}{2hgA_{\sec}} \bullet A_p^2$$

and the deviator stress is

$$\sigma_d = \frac{1-2\upsilon}{1-\upsilon} \bullet \frac{A_p \cdot M_0}{A_{\sec}}$$

Where:

υ = Poisson's ratio
M = mass of hammer plus participating soil
M_0 = mass of hammer
L = length of soil sample
h = drop height
g = acceleration due to gravity
A_p = Peak acceleration
A_{sec} = cross sectional area of hammer and soil

Originally, there appeared to be good correlation between the Alternative Test Method and the standard test method for obtaining resilient modulus. However, after the device was moved the results became inconsistent and subsequent testing failed to confirm the original correlation. The primary problems with the ATM results were that they did not correlate well with values calculated by the standard resilient modulus test method, they appeared to increase with deviator stress rather than decrease as expected, and the data in general was scattered (Cathey 2001). This is demonstrated in Figure 2. Because different acceleration responses were measured between materials of different stiffnesses, it was believed that the ATM was responding appropriately to the material and could be improved to better approximate the standard resilient modulus test. In planning to Improve the correlation of the device, it was important to review the previous assumptions and calculation methods.

In the original design concept, the soil was modeled as a spring with a constant stiffness. That is not to say that the soil is believed to be of a single stiffness overall, but rather that for each specific drop height and hammer mass that produces a response, the soil is modeled as a spring with particular linear stiffness corresponding to that stress state. This is not inconsistent with the standard tri-axial test where a different linear elastic value of modulus is calculated or modeled for each value of deviator stress.

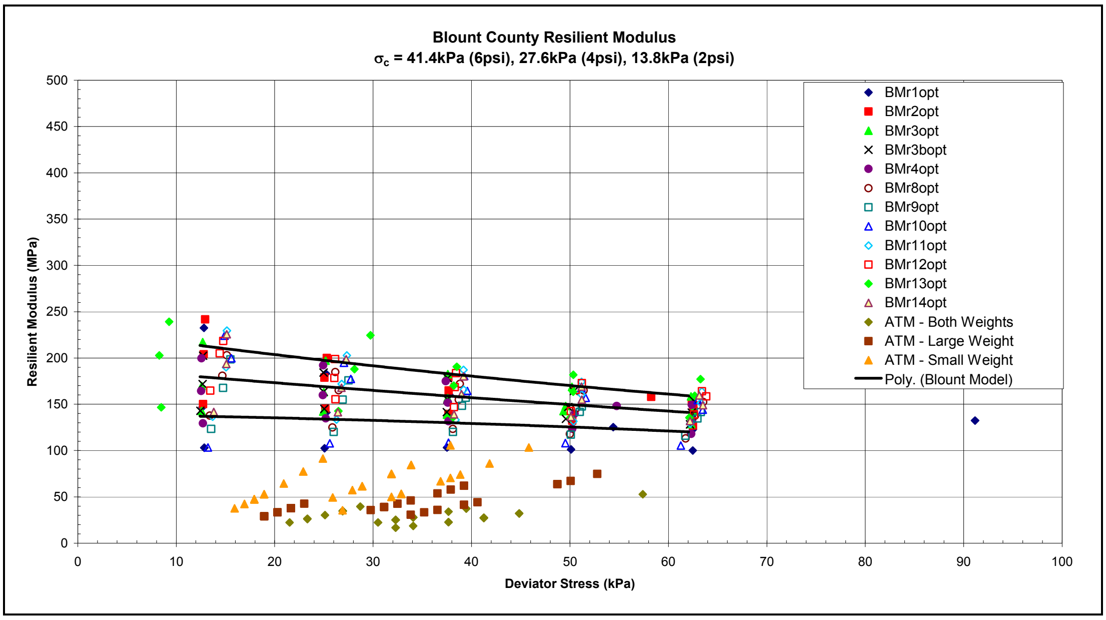

Figure 2 Previous ATM Results and Triaxial Results with Models (Cathey 2002)

A further complicating factor was that the sample was rigidly constrained in the Proctor mold. This required one to assume a value of Poisson's ratio to calculate the lateral stress. Previously a single Poisson's ratio of 0.45 was assumed because the sample is compressed and confined (Cathey 2001; Drumm 1996). While not

A further complicating factor was that the sample was rigidly constrained in the Proctor mold. This required one to assume a value of Poisson's ratio to calculate the lateral stress. Previously a single Poisson's ratio of 0.45 was assumed because the sample is compressed and confined (Cathey 2001; Drumm 1996). While not an unreasonable value, the final resilient modulus value was strongly dependent on the assumed value of Poisson's ratio. Furthermore, Poisson's ratio is not actually constant but is stress dependant like the modulus, a fact pointed out by the original designers (Drumm et al. 1996). Thus, it becomes necessary not only to assume one value of Poisson's ratio, but multiple values. Changing Poisson's ratio has a drastic effect on the calculation of both the deviator stress and resilient modulus. Not knowing the true Poisson's ratio, means not knowing the stress state upon which the calculations of resilient modulus and deviator stress are calculated. Testing the sample in the Proctor mold also required an assumption that the friction between the soil and the wall of the mold is negligible. Friction would affect the stress state and is itself affected by the changing Poisson's ratio.

Chapter 3 Improved ATM Design

With the previous facts in mind, some adjustments and improvements were made to the ATM. First of all, a decision was made to test all samples without confinement. This solution was proposed by Cathey (2001). This eliminated issues of uncertainty pertaining to assuming a value of Poisson's ratio since it was no longer needed to convert resilient (Young's) modulus from constrained modulus. Testing unconfined also eliminated the uncertainty related to the effects of friction between the soil and the wall of the mold.

Efforts were also made to improve the device itself. The purpose was to improve the repeatability and quality of the acceleration signal generated from the hammer striking the soil. One of the first ways of improving the results of the original ATM (Figure 3) was to physically redesign it. The major problem of the original ATM was getting the hammer face to hit flush with the soil face. This was impossible unless the device was perfectly level because the hammer was free hanging. Also, in order to have a large mass under the soil and the hammer, the previous device rested on a large concrete block. This was very cumbersome and virtually impossible to level.

The improved ATM (Figure 4) has guides made of anodized aluminum rods and slide bearings that direct the hammer to the soil face with negligible friction. Also, the base of the new device is a large block of aluminum so as to have enough mass and stiffness to be considered rigid with respect to the soil sample.

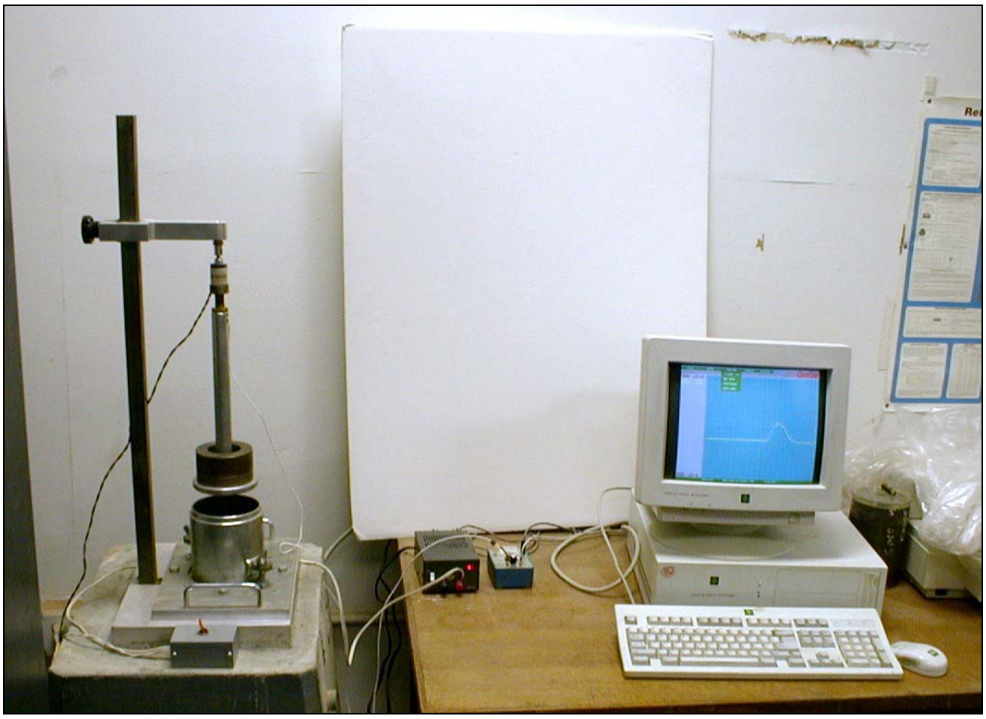

Figure 3. Original ATM Setup (Cathey 2001)

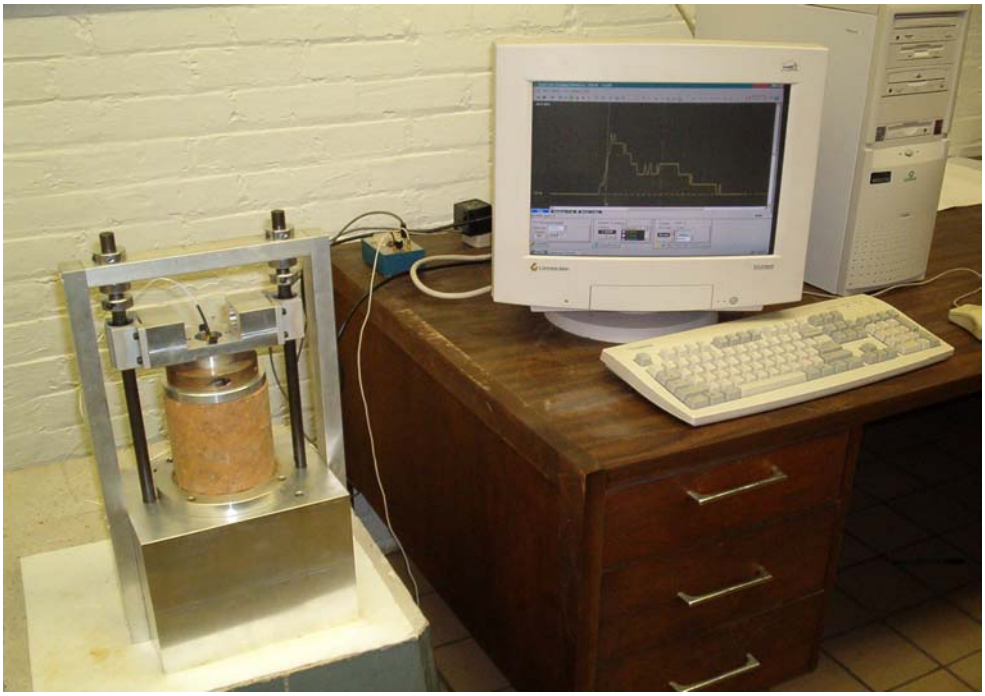

Figure 4. Improved ATM Setup

The data collection software was also upgraded from a DOS based program to a Windows interface program. The newer program is easier to operate and has more options for analysis. One option is automatic signal averaging. The averaging has a buffering affect on the signals. The new software allows the user to average up to 10 signals and then save the averaged signal for analysis. By saving multiple averaged signals, a more consistent plot of results is obtained.

The newer software also has a more consistent triggering algorithm. The old software that triggered the collection of data during an event was inconsistent in its timing. The older software would trigger at different voltage values while the mass of the hammer and drop height remained the same. This made it difficult to gage when the peak of the acceleration signal actually occurred. The new software allows the user to see the curves lined up with each other so they can be evaluated for discrepancies and outlier signals can be eliminated.

The combined result of a new ATM device and updated data collection software is a notable improvement of the overall signal quality and consistency. These improvements can be seen where Figure 5 is individual acceleration curves from the original ATM and Figure 6 is multiple averaged signals from the improved ATM.

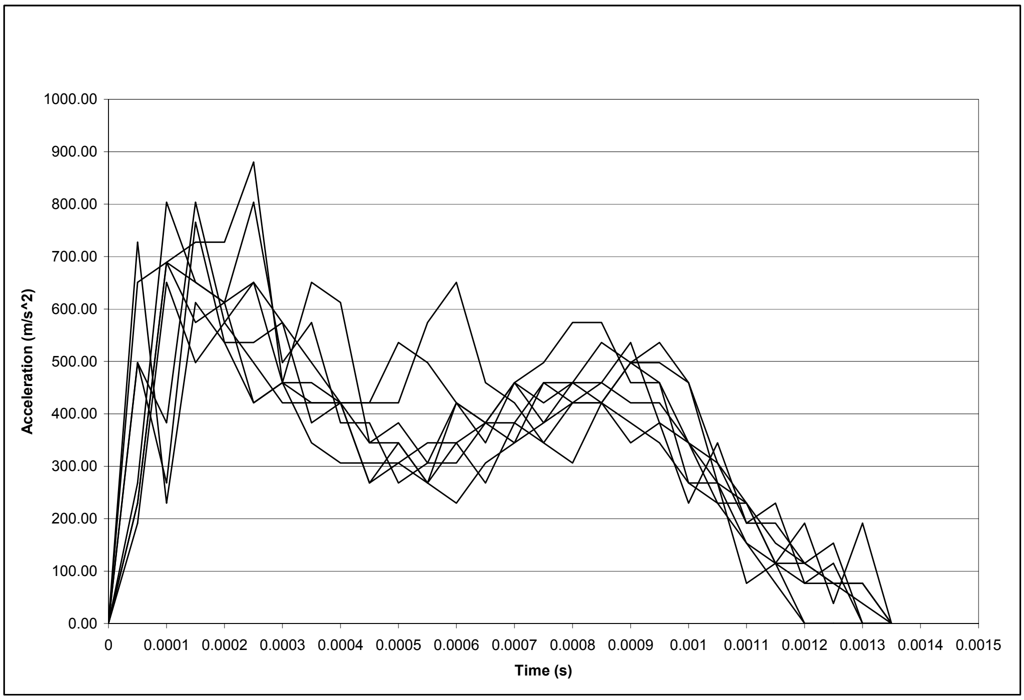

Figure 5. Typical Acceleration Data from Old Software

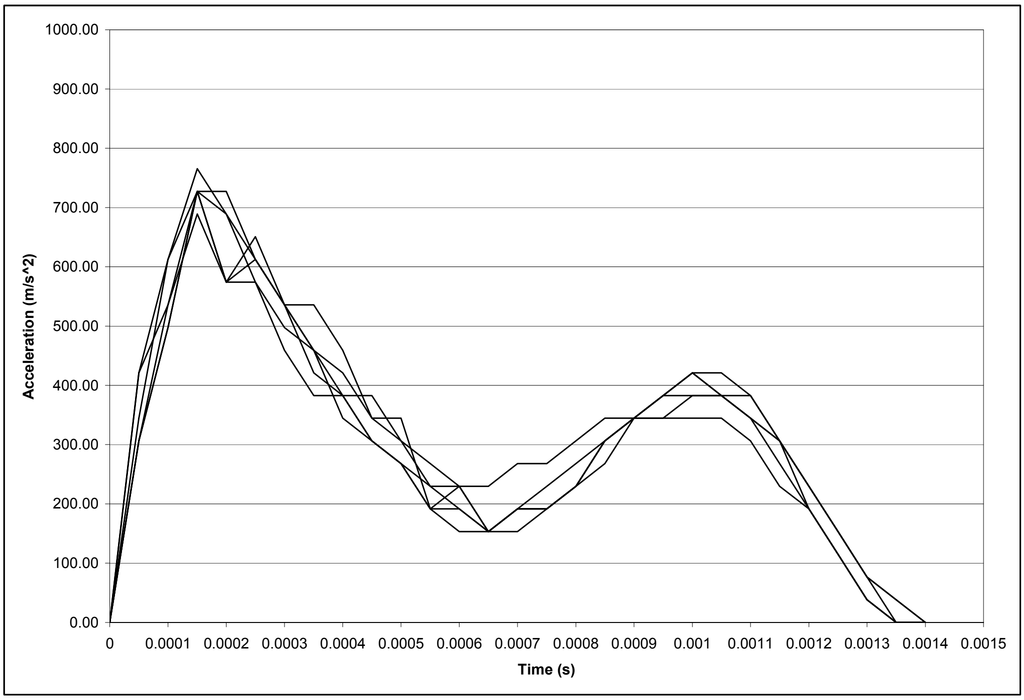

Figure 6. Typical Acceleration Data from New Software

In an effort to improve results, another method of resilient modulus calculation was suggested for the ATM by Cathey (2001) and than updated for the improved ATM. The so called "double integration method" involves numerically integrating the acceleration curve using the trapezoid rule to get the time-velocity curve, where the initial velocity is equal to the total area under the acceleration curve. It is assumed that the hammer stays in contact with the soil and that the acceleration signal measured on the hammer also represents that of the soil. The true acceleration of the soil is actually much less than that of the hammer. However, the acceleration response of the hammer is dependant on the stiffness of the soil and therefore, provides a basis for empirical approximation of the standard resilient modulus test. The time-deformation curve is then obtained from the numerical integration of the time-velocity curve. The time-deformation curve is used to calculate the strain with time. The axial stress with time is calculated from the mass of the hammer times the peak acceleration, divided by the surface area of the hammer. It is assumed that the axial stress is uniform throughout the sample and the strain is calculated over the total length of the sample.

Figure 7 shows a typical acceleration signal from a 10 mm drop of a 1 kg hammer. It can be seen in the figure that the peak acceleration is about 700 m/s^2. The sum of the area under the acceleration curve is 0.4421 m/s. This represents the change in velocity of the hammer from the time of impact to when the hammer rests. Figure 8 is the time-velocity curve obtained from integrating the

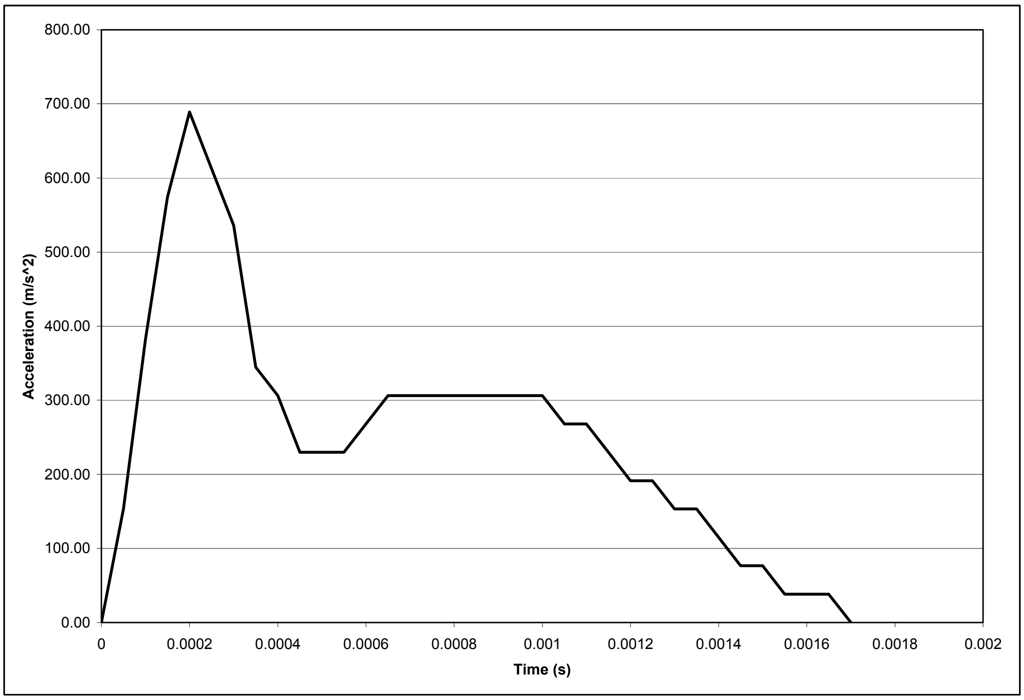

Figure 7 Typical Acceleration Signal for 10 mm Drop

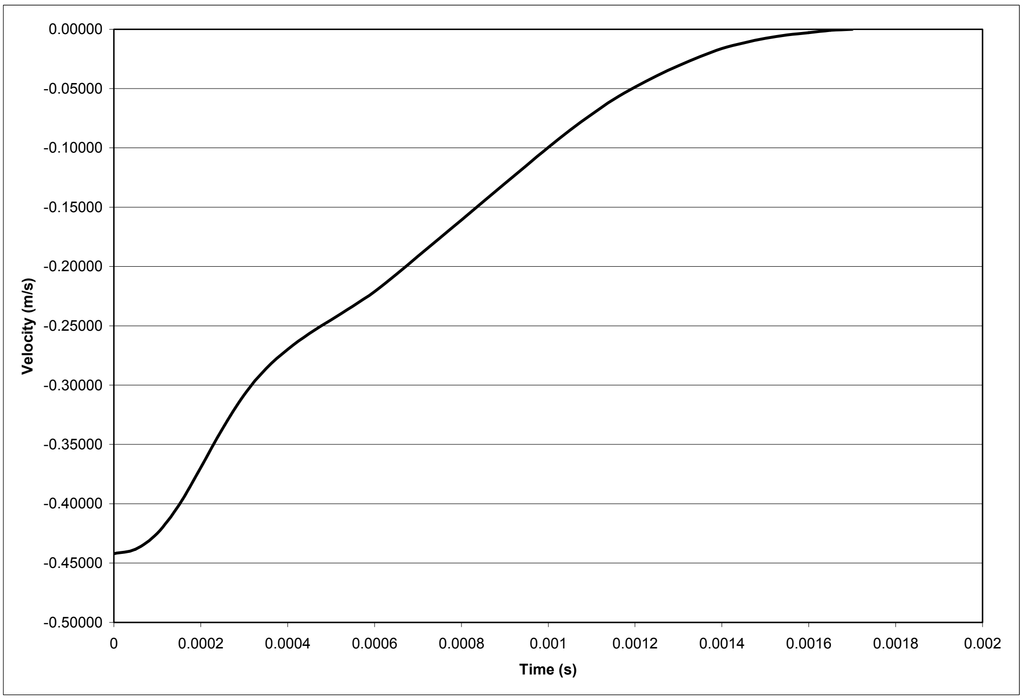

Figure 8 Time-Velocity Curve Integrated from Acceleration Curve

acceleration curve with the initial velocity equal to the sum of the area under the acceleration curve. The velocity is shown with a negative sign because the deceleration is recorded as positive instead of negative. If the accelerometer is measuring correct values of acceleration, then the area under the acceleration curve should be approximately the same as the velocity value calculated using a constant acceleration of gravity of 9.8 m/s^2 and a 10 mm drop. The calculated velocity for a 10 mm drop is 0.4429 m/s and is nearly equal to the integrated velocity sum of 0.4421 m/s. Although not all of the integrated velocity sums are as close to their expected value as in this example, this demonstrates that a very high deceleration value due to the sudden impact is plausible even with a relatively low initial velocity. Another way of looking at it is in terms of impulse and momentum. The falling hammer striking the soil produces an impulse against the hammer, causing it to stop. The impulse required to stop the hammer, neglecting the deformation of the soil and the static weight of the hammer, can be described by the equations (Hibbeler 1995)

$$M_0 \cdot V_0 + I = M_0 \cdot V_f$$

and

$$I = \int F dt$$

Where I is impulse, V_0 is the velocity at moment of impact, V_f is the final velocity at rest, and F is force. The final velocity is zero because the hammer is at rest. The equation can be rewritten

$$M_0 \cdot V_0 = \int F dt$$

By dividing out the mass of the Hammer, the final equation becomes

$$V_0 = \int Adt$$

Therefore, if the calculated initial velocity due to h_0 and g is approximately equal to the integral of the acceleration over the recorded time period, then the recorded acceleration is at least reasonable.

In the original version of the double integration method, the constrained modulus was obtained by dividing the peak stress by the peak strain (Cathey 2001). The resilient modulus and deviator stress were then obtained using an assumed value of Poisson's ratio as discussed earlier. For the improved ATM, testing is conducted without the Proctor mold, so the resilient modulus can be determined directly without a need to assume Poisson's ratio, since the major principle stress is zero.

A major problem with the original formula for the double integration method is that the peak stress was divided by the peak strain to calculate the modulus, but the peak stress and strain do not occur at the same time. The actual secant modulus at the time of the peak stress is greater than the modulus obtained using the peak stress and peak strain since the peak strain occurs at a later time than the peak stress. By dividing the peak stress with the strain occurring at the time of the peak stress, a more realistic determination of the modulus can be obtained. It

is this improved version of the double integration method for the ATM that was used to calculate the resilient modulus values presented in this paper:

$$M_r = \frac{\left(A_p M_0 / A_{\sec}\right)}{\left(\delta_p / L\right)}$$

and

$$\sigma_d = \sigma_a = \frac{A_p \cdot M_0}{A_{\sec}}$$

Where:

δ_p = deformation at moment of peak acceleration
M_0 = mass of hammer and any added weights
L = length of soil sample
A_p = peak acceleration
A_{sec} = cross sectional area of hammer and soil
σ_d = deviator stress
σ_a = axial stress
M_r = resilient modulus

Chapter 4 Resilient Modulus Testing

Four samples were tested from the Tennessee Department of Transportation pavement research sites in Blount, Overton, Sumner, and McNairy counties. The soil samples were prepared, tested, and classified in general accordance with ASTM standards. The USCS classifications of the soils can be seen in Table 1.

Moisture was added to each of the samples and covered in plastic containers for over 16 hours prior to compaction for ATM testing. Samples were compacted in general accordance with AASHTO T99 on both the dry and wet side of the moisture-density curve. The samples were than extracted from the mold and weighed prior to ATM testing. ATM tests were conducted using drop heights of approximately 5 mm, 10mm, and 15 mm. Tests were conducted by dropping the 1 kg hammer with and without the supplemental 0.2 kg and 0.5 kg weights. The acceleration signals obtained were averaged over 10 signals, then multiple averaged signals from various drop heights and masses were saved for analysis. The test procedure that was developed and used as part of the overall improvement to the ATM is provided in Appendix A. After ATM resilient modulus testing, a moisture content sample was extracted from the center of the sample. The moisture content and mass readings were used in formulating a moisture density curve for each soil sample and can be found in Appendix D. Table 2 gives the moisture and dry density of all of the ATM samples tested.

Table 1: Soil Classification

County	Percent Finer than #200 Sieve	Liquid Limit	Plastic Limit	Plasticity Index	USCS Classification
Blount	86.3	51	23	28	CH – Fat Clay
McNairy	41.8	26	16	10	SC – Clayey Sand
Overton	80.5	51	22	29	CH – Fat Clay with Sand
Sumner	54.9	44	22	22	CL – Sandy Lean Clay

Table 2: Moisture and Dry Density of All ATM Samples Tested

COUNTY	MAXIMUM DRY DENSITY g/cm^3	OPTIMUM MOISTURE CONTENT %	SAMPLE	MOISTURE CONTENT %	DRY DENSITY g/cm^3
Blount	1.6	23.5	B1	20.7	1.53
			B2	23.5	1.60
			B2a	22.8	1.62
			B2b	22.8	1.62
			B2c	22.8	1.63
			B3	25.2	1.58
			B4	26.4	1.55
McNairy	1.90	13	M1	10.5	1.82
			M2	11.9	1.89
			M2a	12.2	1.91
			M2b	12.1	1.92
			M2c	11.9	1.92
			M3	13.4	1.91
			M4	16.5	1.79
Overton	1.61	22.5	O1	20.2	1.53
			O2	22.1	1.59
			O2a	22.9	1.61
			O2b	23.0	1.61
			O2c	22.6	1.62
			O3	23.5	1.59
			O4	24.9	1.54
Sumner	1.77	18	S1	16.5	1.72
			S2	17.8	1.78
			S2a	18.3	1.76
			S2b	18.0	1.77
			S2c	18.0	1.77
			S3	19.0	1.75
			S4	20.8	1.68

Three standard triaxial resilient modulus tests were conducted on each of the samples in general accordance with AASHTO Designation T 307-99. The results from these standard triaxial resilient modulus tests were used to compare with and evaluate the ATM resilient modulus results. The moisture contents and dry densities of all of the standard resilient modulus test samples are in Table 3. The actual test results can be found in Appendix B.

Table 3: Moisture and Density of All Standard Resilient Modulus Test Samples

COUNTY	**MAXIMUM DRY DENSITY** g/cm^3	**OPTIMUM MOISTURE CONTENT** %	**SAMPLE**	**MOISTURE CONTENT** %	**DRY DENSITY** g/cm^3
Blount	1.6	23.5	BRM1	22.9	1.53
			BRM2	22.9	1.56
			BRM3	22.9	1.57
			BRM4	22.5	1.58
McNairy	1.90	13	MRM1	13.8	1.82
			MRM2	13.6	1.86
			MRM3	13.6	1.88
Overton	1.61	22.5	ORM1	22.4	1.60
			ORM2	21.7	1.61
			ORM3	21.4	1.60
Sumner	1.77	18	SRM1	18.9	1.72
			SRM2	19.3	1.71
			SRM3	17.2	1.78

Chapter 5 Resilient Modulus Test Results

Figure 9 compares the time-acceleration curves generated from 10 mm drops of the 1 kg hammer on two McNairy County soil samples prepared at different moisture contents. The acceleration curve with the smaller peak is at a moisture content of 13.4% and the curve with the larger peak is at a moisture content of 11.9%. As moisture content increases, soil becomes less stiff. A stiffer material deforms less under an impact load than a softer material. A smaller deformation for the same amount of energy results in a higher peak acceleration. In Figure 9, the higher acceleration peak corresponds to the drier, stiffer soil. This demonstrates the ATM device's responsiveness to differences in material stiffness due to changes in moisture content.

Figure 10 shows the moisture-density curves of all four of the soils tested. Figure 11 shows average ATM resilient modulus values corresponding to the moisture content and dry density of the samples in Figure 10. Figure 11 demonstrates that the ATM resilient modulus values decrease as moisture content increases, for each of the four soils. It was demonstrated in Figure 9 that the ATM measured acceleration response is sensitive to changes in stiffness due to changes in moisture content. Because the acceleration response is used to determine resilient modulus with the ATM, the ATM measures a change in resilient modulus with moisture.

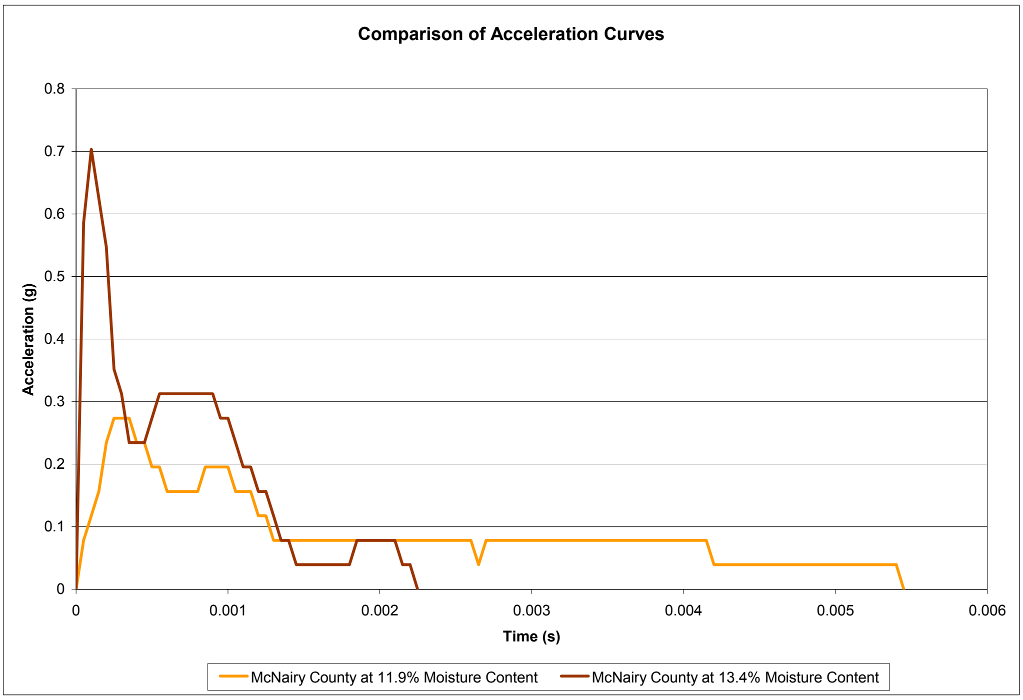

Figure 9 Comparison of Acceleration Curves

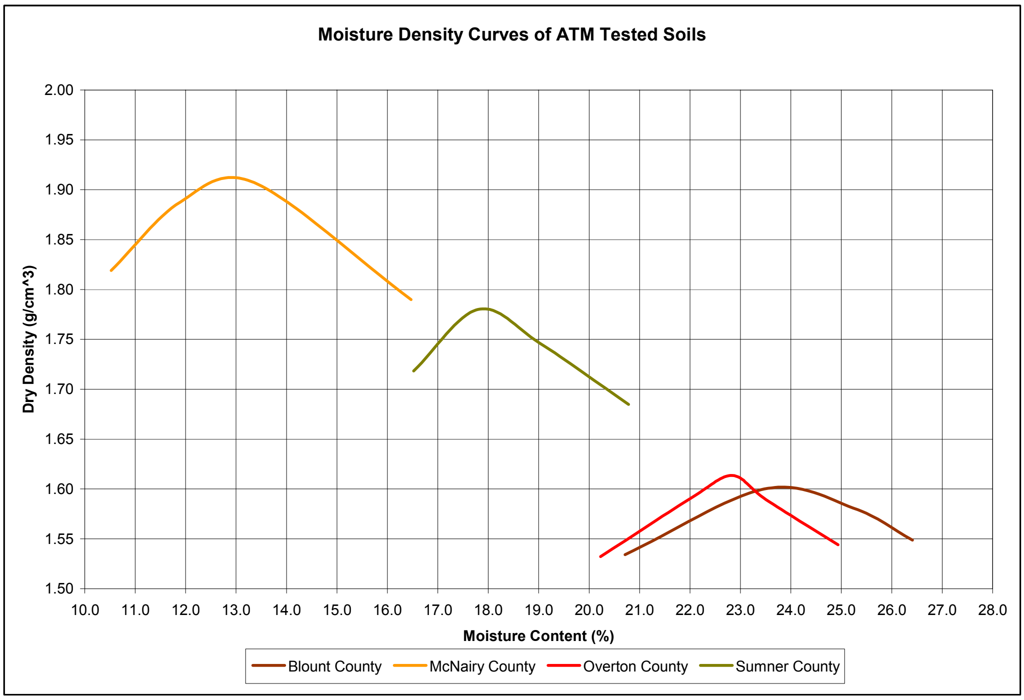

Figure 10 Moisture Density Curves of ATM Tested Soils

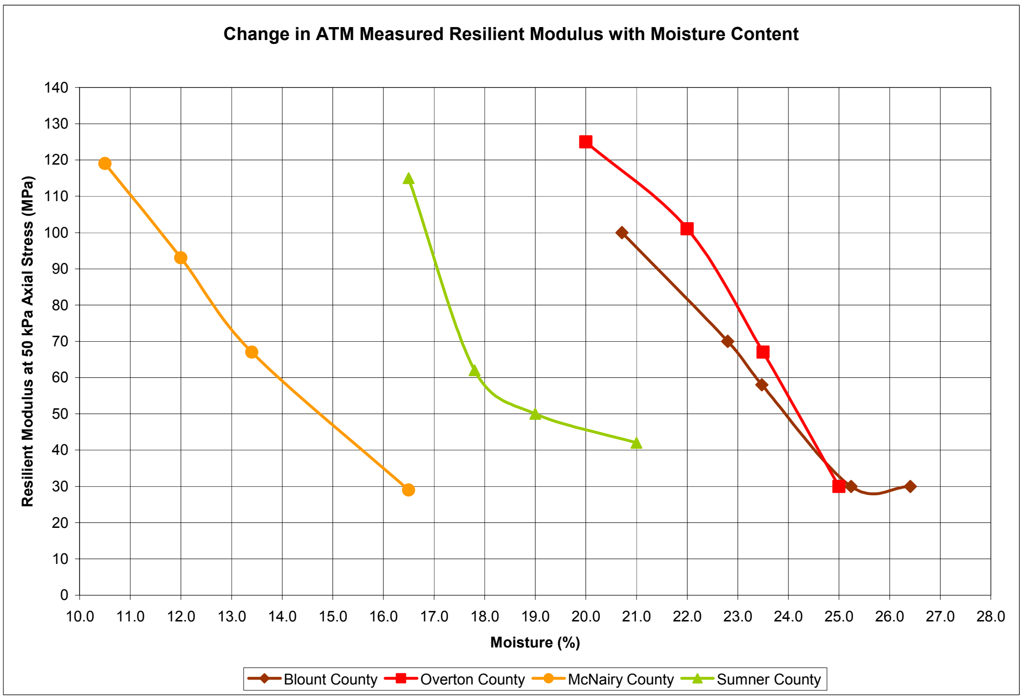

Figure 11 Changes in ATM Resilient Modulus with Moisture Content

Table 4 contains descriptive statistical values for each of the ATM samples tested for comparative purposes. The statistical values chosen include the mean, standard deviation, standard error, range, number of ATM values per sample and 95% confidence range of the mean. For the standard test, the smaller the confining pressure is, the less the decrease with increasing deviator stress. So, it is not unfounded to have resilient modulus curves from the ATM that are nearly flat. Because only one value of resilient modulus is used in design and that the ATM produced resilient modulus does not vary greatly with deviator stress, a mean value across all deviator stresses is used to quantify the ATM produced resilient modulus. From Table 4, one can judge that the ATM produces a reasonably reproducible resilient modulus value with acceptable ranges of deviation.

This is graphically demonstrated in Figure 12, Figure 13, Figure 14, and Figure 15, where three samples of each material were tested with the ATM at approximately the same moisture content and density. It was observed from these figures that the ATM resilient modulus values tend to remain constant with increasing axial stress. Also, the ATM resilient modulus values are more consistent and reproducible than earlier ATM resilient modulus values. Both of these developments are an improvement on the previous ATM, where the values tended to be more scattered and increase with deviator stress.

Table 4: Statistical Breakdown of All ATM Samples Tested

Sample	B1	B2	B2a	B2b	B2c	B3	B4
Mean ATM M_r Value	92	58	73	66	71	27	31
Standard Error	3.33	2.41	2.20	1.18	2.60	1.31	0.96
Standard Deviation	11.04	6.83	8.22	4.09	8.99	4.14	3.70
Range	39	17	26	14	28	14	14
Count	11	8	14	12	12	10	15
Confidence Level(95.0%)	7.42	5.71	4.75	2.60	5.71	2.96	2.05
Sample	**M1**	**M2**	**M2a**	**M2b**	**M2c**	**M3**	**M4**
Mean ATM M_r Value	119	98	86	88	92	67	29
Standard Error	3.92	2.61	1.24	1.75	3.43	0.89	0.63
Standard Deviation	14.15	9.39	3.51	6.05	10.84	3.33	1.88
Range	47	34	9	19	29	11	5
Count	13	13	8	12	10	14	9
Confidence Level(95.0%)	8.55	5.68	2.93	3.84	7.76	1.92	1.45
Sample	**O1**	**O2**	**O2a**	**O2b**	**O2c**	**O3**	**O4**
Mean ATM M_r Value	125.13	101.06	68.15	61.09	66.59	74.60	29.95
Standard Error	2.52	2.52	1.45	1.83	1.81	1.48	0.88
Standard Deviation	8.35	9.77	5.61	5.77	5.71	3.92	2.77
Range	29	29	19	16	16	10	9
Count	11	15	15	10	10	7	10
Confidence Level(95.0%)	5.61	5.41	3.11	4.13	4.09	3.63	1.98
Sample	**S1**	**S2**	**S2a**	**S2b**	**S2c**	**S3**	**S4**
Mean ATM M_r Value	114.37	61.67	50.50	48.26	55.08	47.13	41.96
Standard Error	1.66	1.61	1.38	1.30	0.76	1.09	1.23
Standard Deviation	6.44	5.59	4.36	3.67	2.41	3.27	4.61
Range	26	15	13	9	8	11	14
Count	15	12	10	8	10	9	14
Confidence Level(95.0%)	3.57	3.55	3.12	3.07	1.72	2.52	2.66

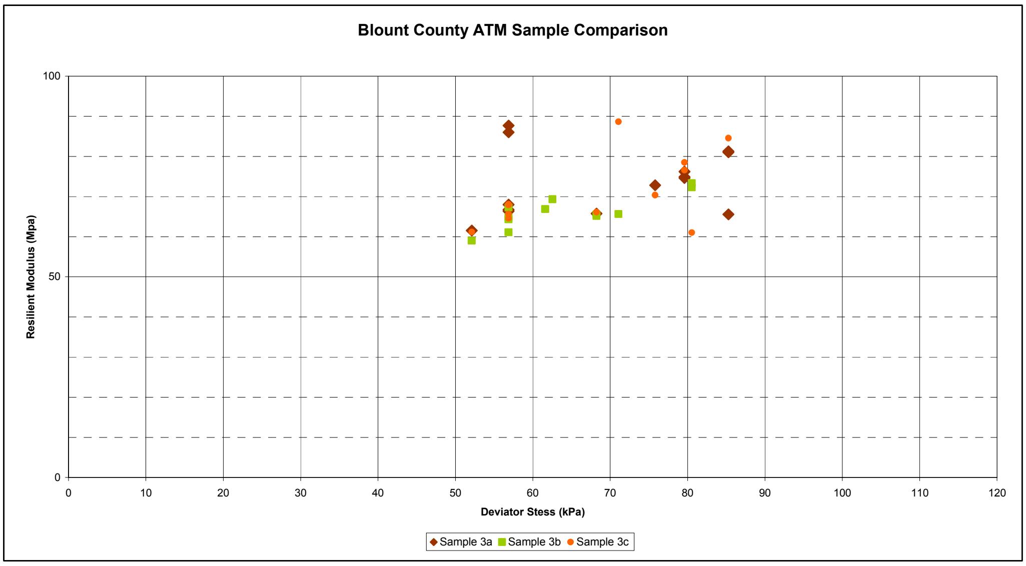

Figure 12 Blount County ATM Comparison

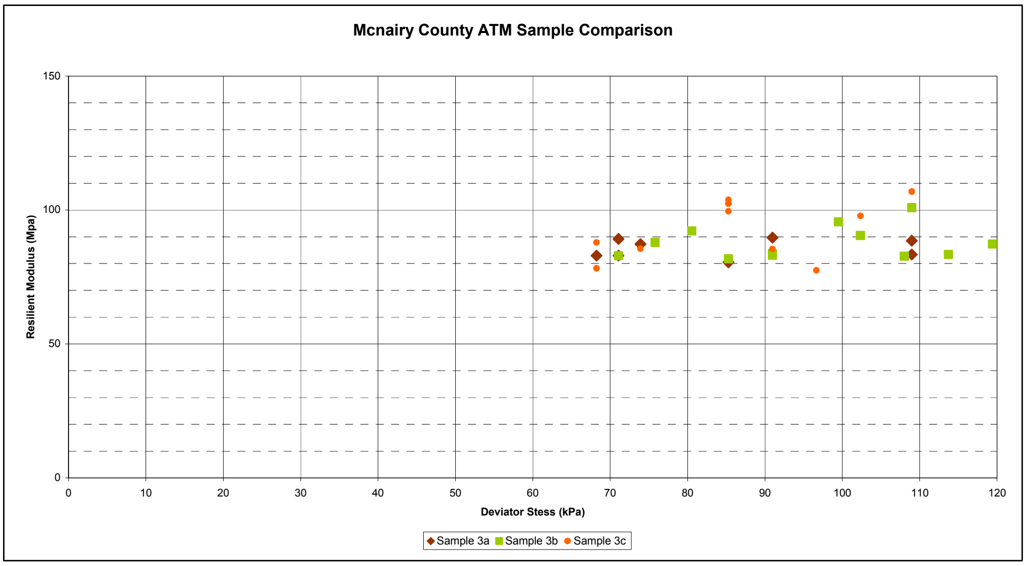

Figure 13 McNairy County ATM Comparison

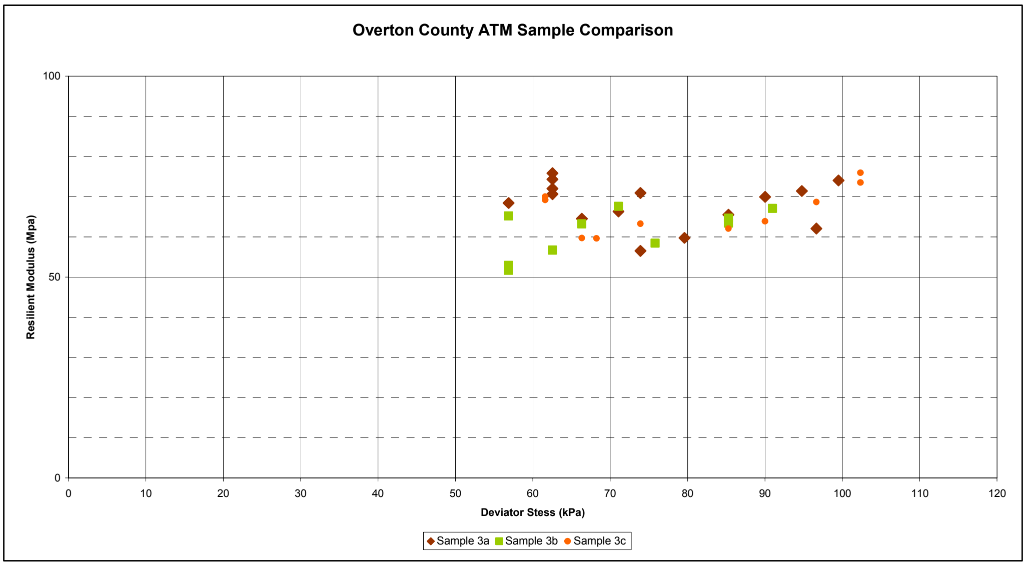

Figure 14 Overton County ATM Comparison

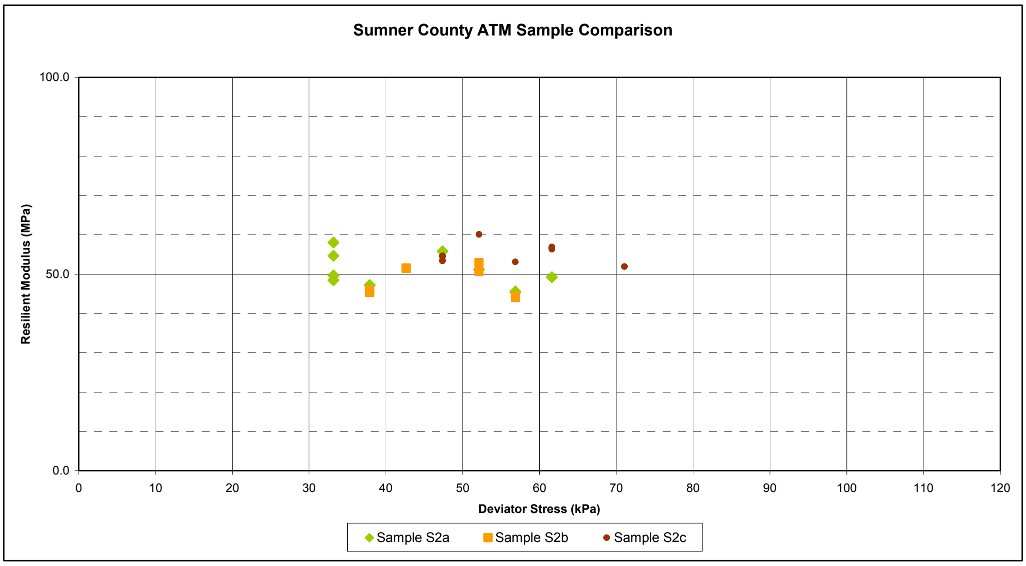

Figure 15 Sumner County ATM Comparison

Figure 16 compares the ATM resilient modulus value produced by the 1 kg hammer with the ATM resilient modulus value produced by the 1.5 kg hammer and Figure 17 compares the ATM resilient modulus value produced by the 1 kg hammer with the ATM resilient modulus value produced by the 1.2 kg hammer. Each comparison is done on one individual sample, Figure 16 is of a Blount County sample B2 and Figure 17 is of Overton County sample O2a. Although there are no resilient modulus values at exactly the same deviator stress produced by the different hammer sizes in each of the figures, the deviator stresses produced by each of the hammers overlap. For these overlapping deviator stress, it can be seen that the ATM produces basically the same values of resilient modulus for each hammer mass.

Figure 18 shows the ATM results for the Blount County soil near maximum density and optimum moisture content compared with standard triaxial resilient modulus values. The resilient modulus values from the standard test were obtained at a confining pressure of 13.8 kPa (AASHTO 1999). As stated previously, resilient modulus generally increases with increasing confining pressure. Since the ATM test is performed with no confining pressure one would expect the ATM results to be near or slightly below the standard test values for 13.8 kPa confining pressure. The results in Figure 18 from ATM sample B2 provide a reasonable approximation of the resilient modulus response obtained with the standard test.

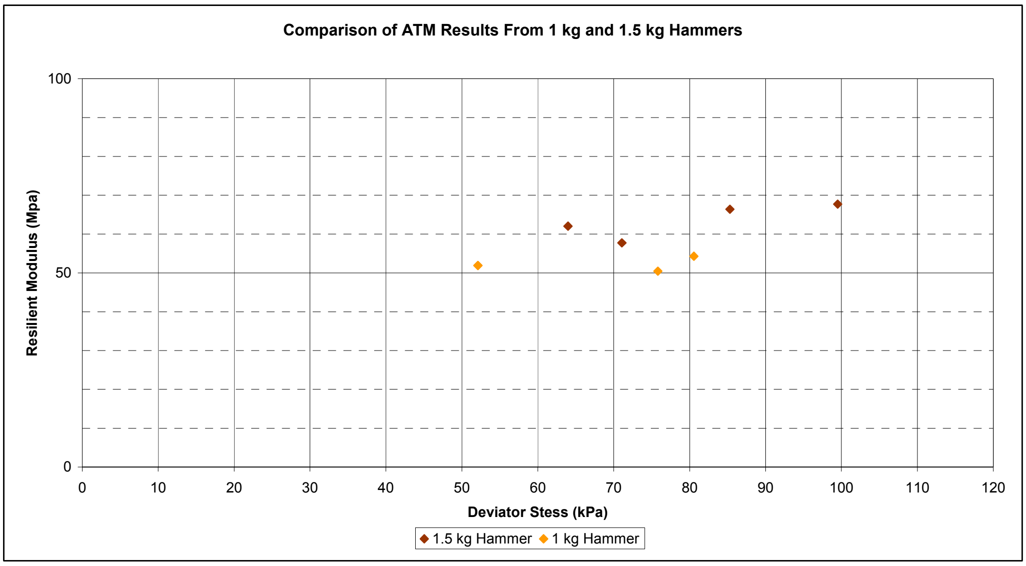

Figure 16 Comparison of ATM Results from 1 kg and 1.5 kg Hammers

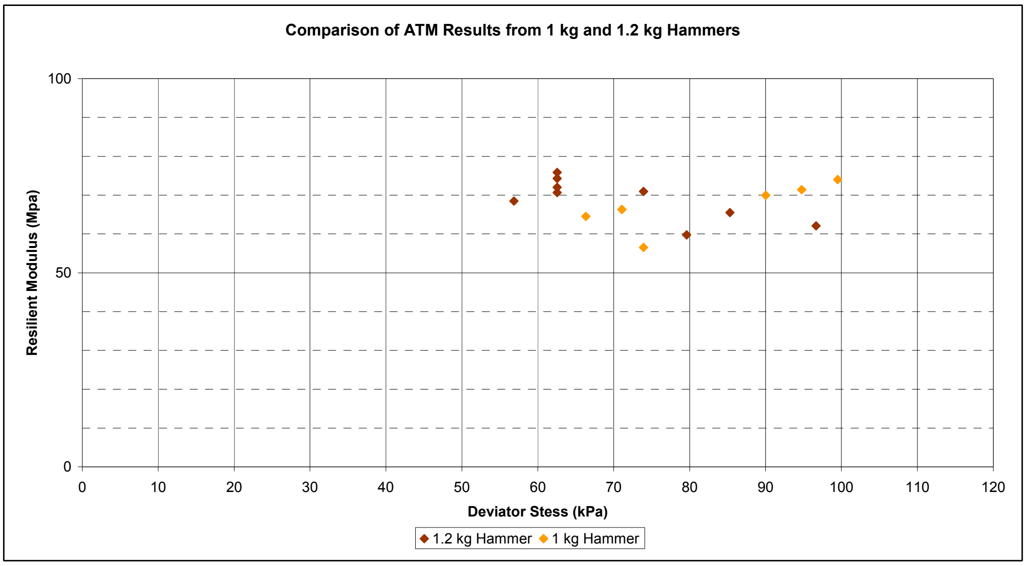

Figure 17 Comparison of ATM Results from 1 kg and 1.2 kg Hammers

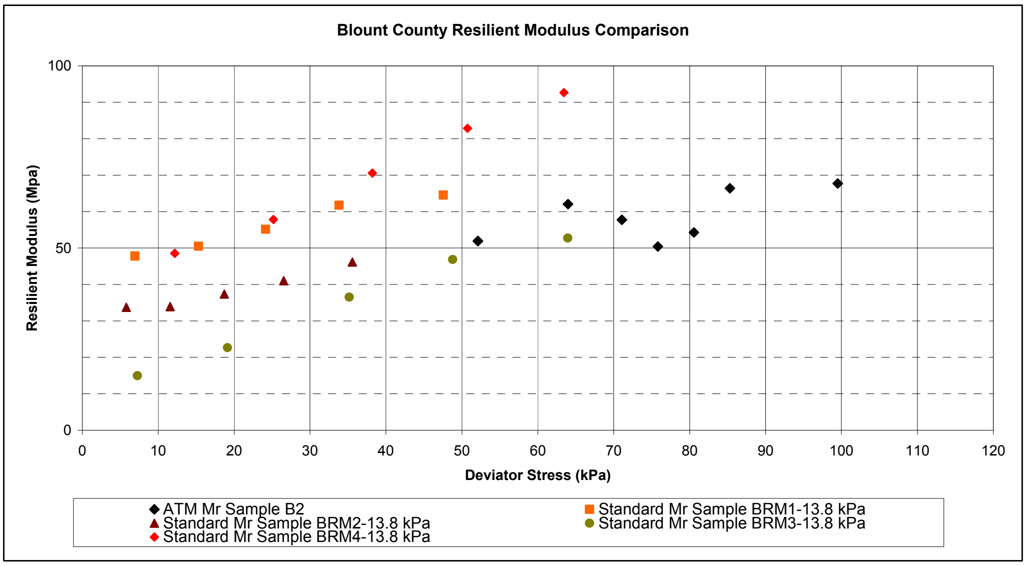

Figure 18 Comparison of Blount County ATM and Standard Resilient Modulus

A similar result can be seen in Figure 19 for McNairy County ATM sample M3, also near maximum density and optimum moisture. Again, it can be seen that the ATM resilient modulus values are similar to the resilient modulus values from the standard test at the lowest confining pressure.

Figure 20 compares the Overton County ATM resilient modulus values with the standard resilient modulus test values. Overton County sample O2 was compacted near optimum moisture. The ATM resilient modulus for Overton County is about, 100 MPa or about 50%, below the values for standard test at 13.8 kPa confining pressure. Of the four soils tested, the Overton County samples differ the most from the standard test. However, standard test values can vary 20% to 40% along segments of highway of limited length and can vary 10% to 15% for standard laboratory tests conducted under favorable conditions (Barksdale et al. 1997). While the correlation with the standard test is not as good a that for the Blount and McNairy County soils, just slightly lower values from the standard test would put them within the expected range of the ATM results. Therefore, the ATM resilient modulus values are still a reasonable approximation of the standard values.

Figure 21 shows Sumner County ATM resilient modulus values compared to the standard test values. The ATM sample S2 for Sumner County was compacted near optimum water content. The ATM resilient modulus values agree reasonably well with values obtained from the standard test.

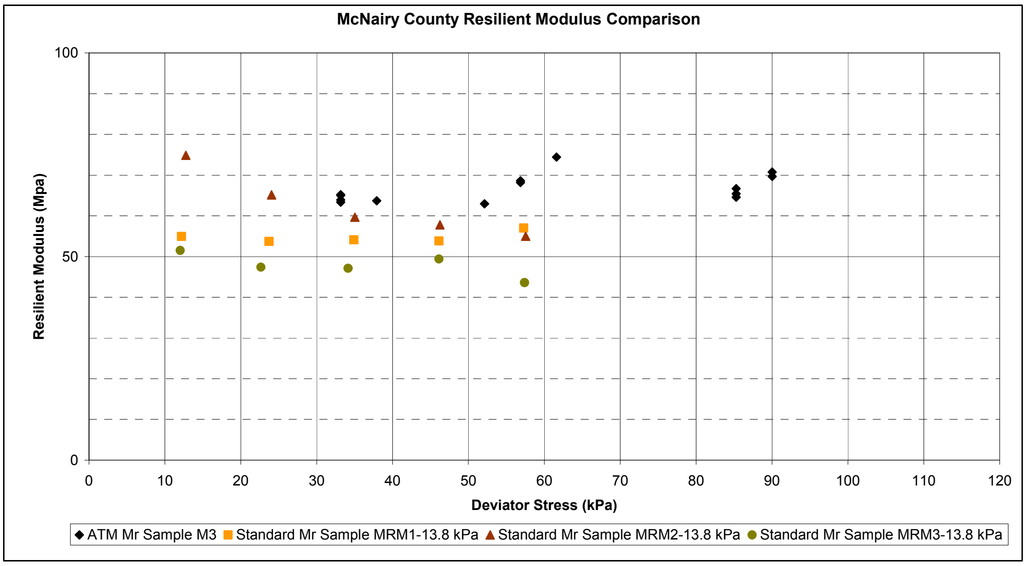

Figure 19 Comparison of McNairy County ATM and Standard Resilient Modulus

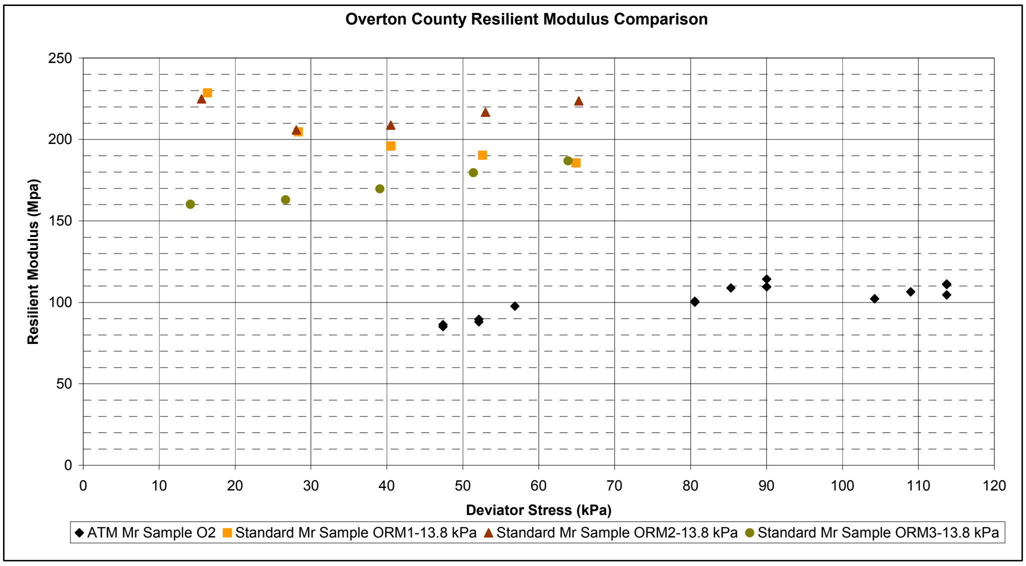

Figure 20 Comparison of Overton County ATM and Standard Resilient Modulus

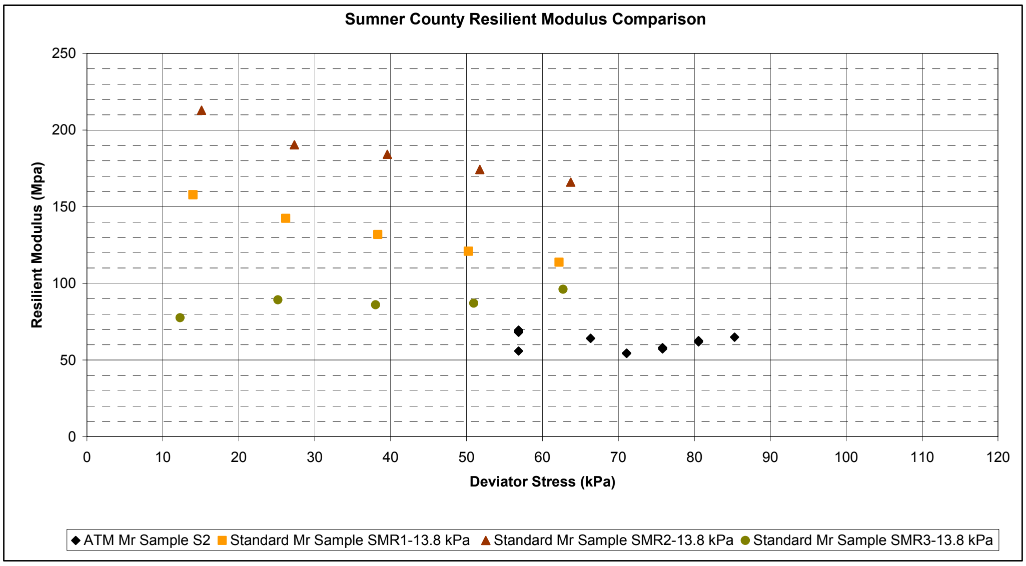

Figure 21 Comparison of Sumner County ATM and Standard Resilient Modulus

Chapter 6 Limitations of the ATM

One of the major advantages of the standard repeated load triaxial test for resilient modulus is that it measures resilient modulus at different confining pressures so a resilient modulus value at a representative stress condition can be chosen for design. The Improved ATM can only estimate resilient modulus under the condition of zero confining stress. However, confining pressure does not have a large effect on the resilient modulus of fine grained soils and the confining pressure near the surface of the subgrade is low. Furthermore, a standard unconfined, repeated load resilient modulus test exists and is considered to produce conservative values of resilient modulus (Barksdale et al. 1997). It could be argued that the improved ATM produces an appropriately conservative approximation of the resilient modulus and is significantly better than the commonly used relationship base on the CBR value. Therefore, the improved ATM model is considered a better alternative than the original ATM model, where the stress state was obtained only after assuming a value of Poisson's ratio, and the lack of confining pressure is a negligible limitation.

A more significant limitation of the ATM is the inability to dictate the level of axial stress. Instead the stress condition is dependent on the material response to the drop height and hammer mass. The weights and drop heights discussed previously were empirically determined to produce axial stresses between about 30 kPa and 120 kPa when testing materials near maximum dry density and optimum moisture content. If the soil properties are significantly different from

those tested here, then the height and weights being used may have to be adjusted. The less stiff samples tend to be in a lower axial stress range than the stiffer samples. However, it is simple enough to adjust the drop heights and hammer weights to test in the desired stress range.

One of the important assumptions when measuring material properties is that the states of stress and strain are reasonably uniform in the sample. This is not really true with the ATM. Because the ATM involves an impact load and thus is a dynamic situation, the stress propagates through the soil from top to bottom in a compression wave. While the stress conditions in the ATM samples may not be as uniform as in the standard triaxial resilient modulus test, the ATM clearly measures an appropriate acceleration response with changes in stiffness. This response is then converted to a resilient modulus in a semi-empirical manner based on theory and some general assumptions. Though some rational methods were used to devise the ATM test and formulas, the ATM is meant to be an empirical test that correlates reasonably well with the standard triaxial test.

Chapter 7 Conclusions

For the mechanistic design of asphalt pavement systems, the resilient modulus has been designated as the material property for characterizing the soil subgrade. The standard triaxial test for obtaining the resilient modulus is a somewhat complicated and difficult test that requires specialized training and expensive equipment. The standard test produces a range of resilient modulus values in a series of stress conditions for the purpose of obtaining a modulus value that represents the stress condition of the soil subgrade under the pavement. Because only one value of resilient modulus will be used for design of a pavement and most agencies or commercial labs will not conduct the standard test due to the cost and difficulty, it is desirable develop alternate means of determining resilient modulus. Furthermore, current methods of estimating resilient modulus are inadequate.

The Alternative Test Method was developed to be a simple and effective way of determining resilient modulus. It was based on a single degree of freedom spring-mass model. Improvements have been made to the ATM to improve the overall consistency of results and correlation with the standard resilient modulus test results. The improvements to the ATM device include a new, more consistent drop mechanism and better data acquisition software. Improvements to the ATM resilient modulus determination include testing the sample unconfined to eliminate uncertainty issues regarding Poisson's ratio, averaging the acceleration

signals to buffer “noise”, and developing a new calculation method involving the entire acceleration signal as opposed to just the peak acceleration.

Based on the results observed, the improved ATM appears to measure a material response that correlates reasonably well with the standard triaxial resilient modulus test results for those soils tested. Furthermore, the Improved ATM produces much more consistent results than the Original ATM. It is also believed that the stated limitations of the device are outweighed by its simplicity and commonality of equipment and procedures with other lab tests. Therefore, the improved Alternative Test Method for estimating resilient modulus of fine grained soils is believed to be a viable alternative to the standard test method for obtaining resilient modulus values.

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Appendices

Appendix A ATM Test Procedure

1. **Sample Preparation**
    a. Run a standard proctor test to obtain the maximum dry density and optimum moisture content
    b. Make sure the sample is air dried. Then take a moisture content sample.
    c. Weigh out approximately 2.5 kg of semi-dry soil for each ATM sample you wish to run and put in a covered container. Make sure you record the exact weight of the soil (obtain the moisture content of the semi-dry soil before proceeding)
    d. Use the moisture content and weight of the semi-dry soil to calculate the exact weight of the solids.
    e. Subtract the current moisture content from the optimum moisture content and multiply that times the weight of the solids to determine the amount of water to add to the soil (1 gm water = 1 ml water)
    f. Add the required water to the soil to put it at optimum water content. round down to the nearest 10 ml. Mix thoroughly and let sit overnight
    g. Compact the soil in the proctor mold in 3 equal lifts with 25 blows of the 5 lb proctor hammer
    h. Carefully extract the sample with a hydraulic jack without damaging the sample (use of a little vegetable spray is useful in extraction). Weigh and record the sample mass. Place the sample on the ATM platen.
2. **ATM Testing**
    a. Raise the hammer guide clamps all the way to the top and tighten with the hexagonal wrench. this is approximately a 15 mm drop.
    b. On the computer desktop, open the icon called "Gagescope." Then under "file" click "open setup" and pick ATM
    c. On the screen will be 2 graphs each representing a signal. The bottom line is triggered after each drop and the top line is the average of the last 10 drops.
    d. Along the top of the screen in the toolbar is an arrow that is the symbol for a one time trigger. Click it, then raise the ATM hammer all the way to the top and drop it to trigger the signal capture. Be careful to release with both hands at the same time to get a clean signal. The repeat it until the top line on the screen changes. Then do it ten more times until it changes again. (If you are unable to trigger the signal capture, it is likely your sample is too soft because it is too wet)
    e. After you have done 20 drops do ten more to trigger the average signal again. Then click on the disk icon up on the top tool bar or under "file" click "save channel" to save the averaged signal. Then pick "channel 3", which is the designation of the line the averaged signal is on. Then name the file something that is easy to

sort, because you will be saving many of these, such as OS15a, for Overton county, Small weight, 15 mm, "a" for the first in a series. Then save as a signal file, this allows you to open it in Gagescope. Then immediately hit save again and save the same channel, but this time as an ASCII file which will allow you to open it up in Excel spreadsheet.

f. Then repeat for 4 more averaged signals
g. Take the 10 mm measuring bar and place it on top of the hammer between the guide rods. Then loosen the guide clamps with the hex ranch and lower them down to the 10 mm measuring bar and re-tighten them.
h. Then proceed to produce and record 5 averaged signals at 10 mm drop height as done at the 15 mm drop height. If the sample is will not trigger at 10 mm, add the 0.2 kg weight and drop from 15 mm
i. After you finish, take a moisture content from the center of the sample to compare to the proctor curve. if the sample is more than 0.5% on the wet of optimum moisture, you'll need to do a test at -1% of optimum to interpolate. If it is more than -1% dry of optimum, you will need to prepare another sample and retest at optimum

3. **ATM Data Reduction**

a. Open up the excel file named "ATM Template". Open each of the saved ASCII acceleration signal files in sequential order. You will see two columns of numbers in the signal files as in the sample below on the left. The left column is time in seconds and the highlighted column on the right is the acceleration signal in volts. Click and Drag from the top of the signal column down to where you reach the first 0. Then paste it in the first column right below the 0 of the page named "signal" in the ATM Template as indicated below in yellow. Then click and paste the rest of the signals.

ASCII Signal File

0	0.117188
0.00005	0.390625
0.0001	0.351563
0.00015	0.585938
0.0002	0.46875
0.00025	0.46875
0.0003	0.390625
0.00035	0.3125
0.0004	0.351563
0.00045	0.273438
0.0005	0.3125

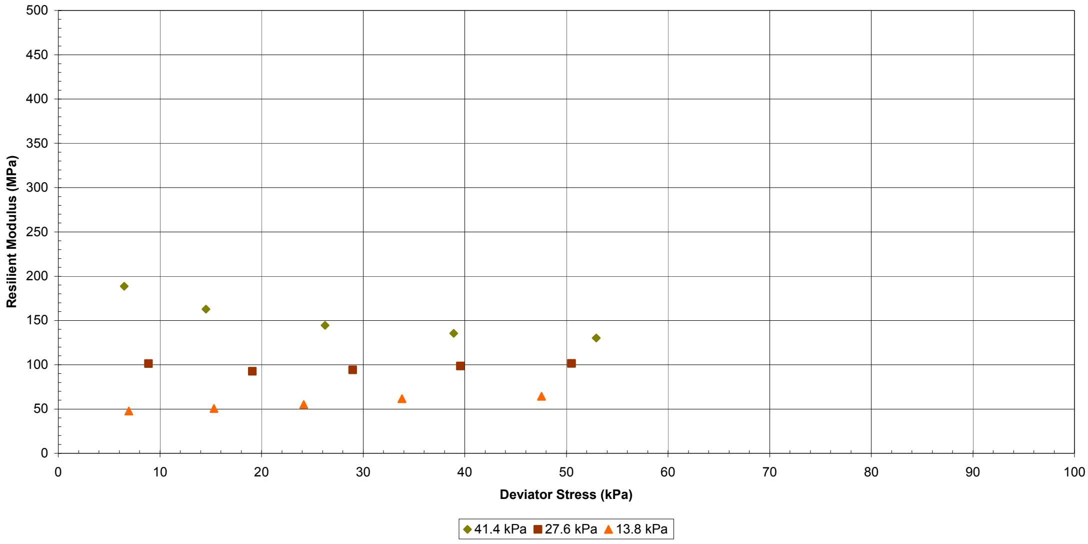
Excel File

t (s)	a (g/100)
0	0
0.00005	
0.0001	
0.00015	
0.0002	
0.00025	
0.0003	
0.00035	
0.0004	
0.00045	
0.0005	

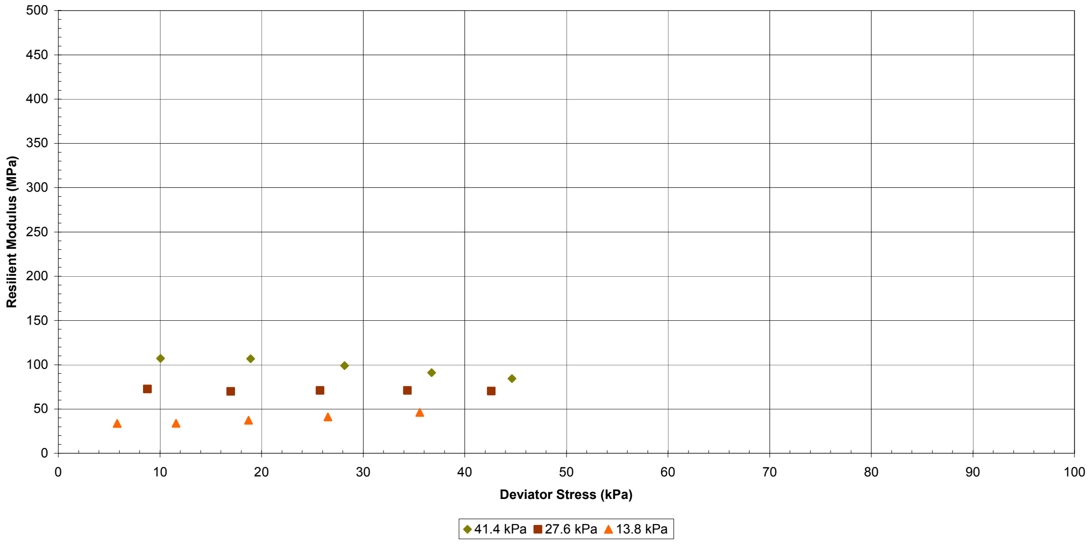
b. Go to the worksheet marked "Calculations" and across the top, enter the mass of the hammer used for each drop. The hammer is 1 kg and the hammer with the weight is 1.2 kg.
c. The top set of cells on the calculation page, is the stress. Under each column, find the cell with the cell with the largest stress value, then enter that cell number with an equals sign in front of it in the row marked "Peak Axial Stress" under the same column. For example if the peak stress value occurs in cell B7 you would enter "=B7."
d. Below the stress values are the strain values corresponding to each of the above stress values. Find the cell of the strain value that corresponds to the peak stress value and enter it into the appropriate cell for the row marked "Strain at Peak Stress" for example, under column B, the cell for the strain corresponding to the stress value in B7 would be B19 and would be entered "=B19."
e. Then repeat for each of the columns representing a recorded signal
f. When you are finished, an average value of resilient modulus will be displayed in the lower right corner. Also a graph displaying resilient modulus as a function of deviator stress will be on the sheet marked Mr Chart.

Appendix B Triaxial Resilient Modulus Results

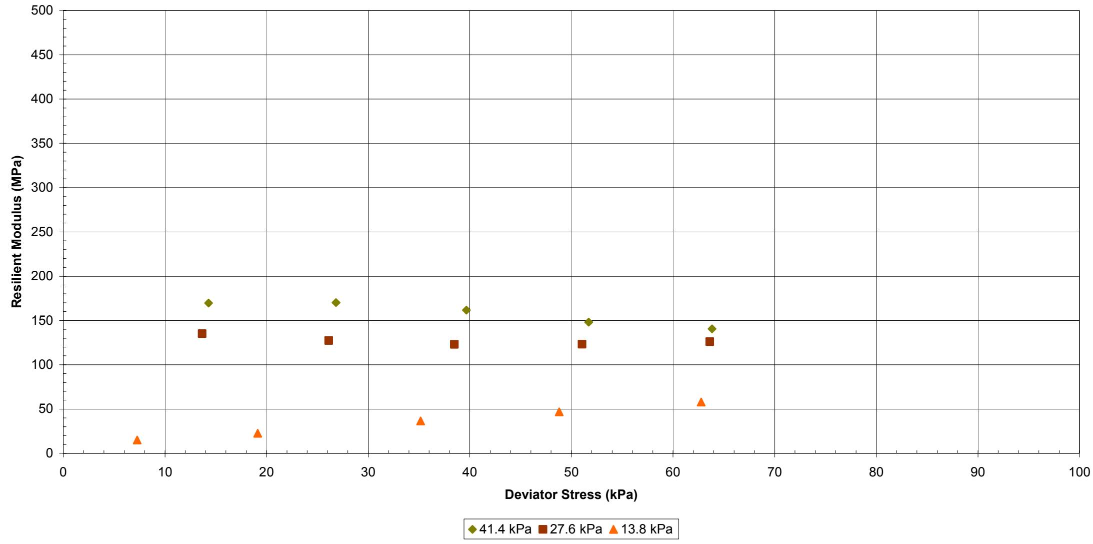
Blount County - Triaxial Resilient Modulus Sample BRM1



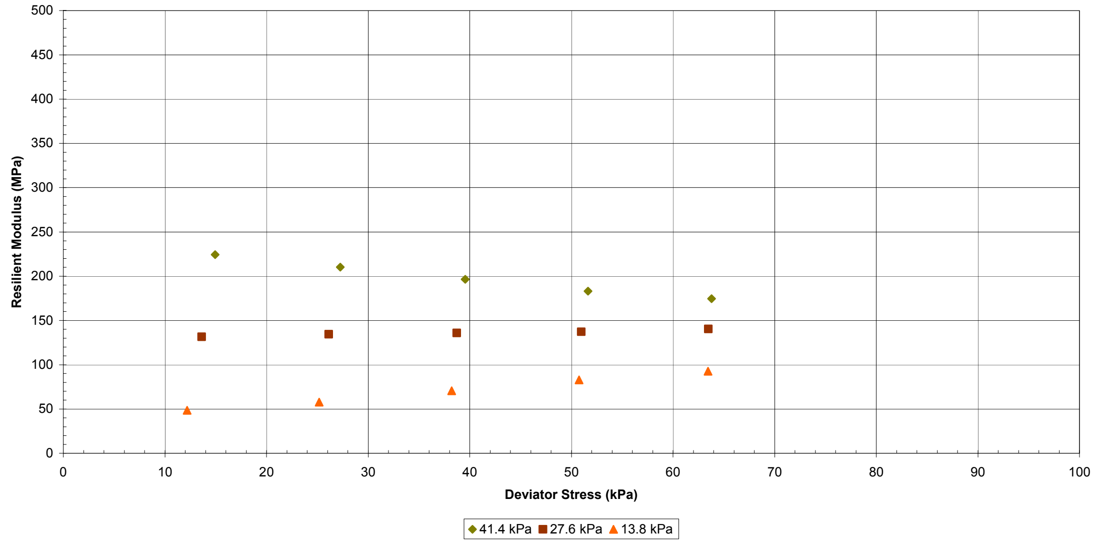
Blount County - Triaxial Resilient Modulus Sample BRM2

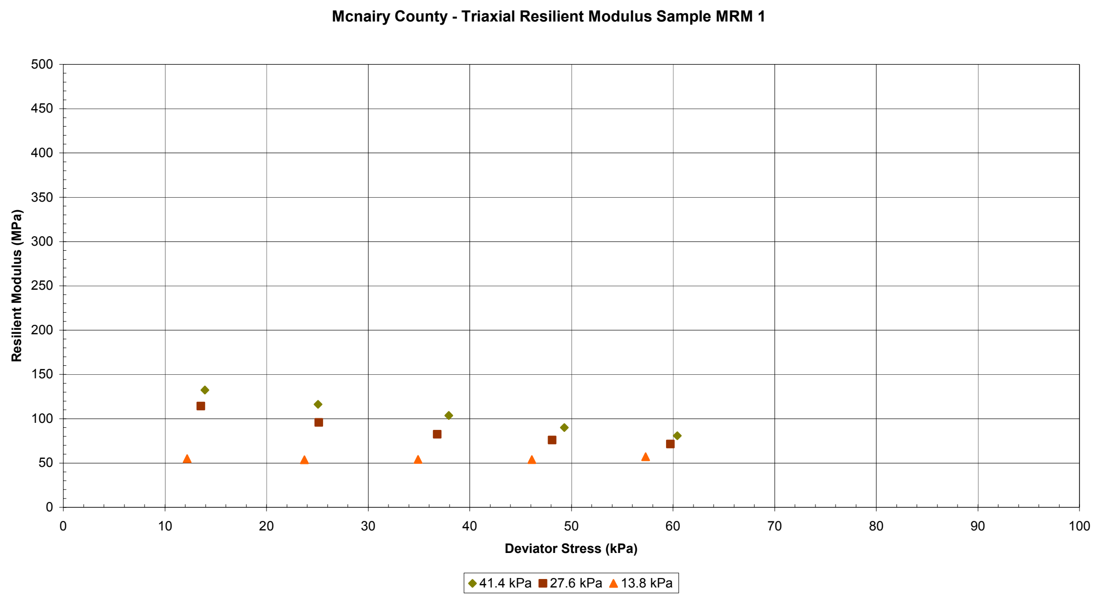


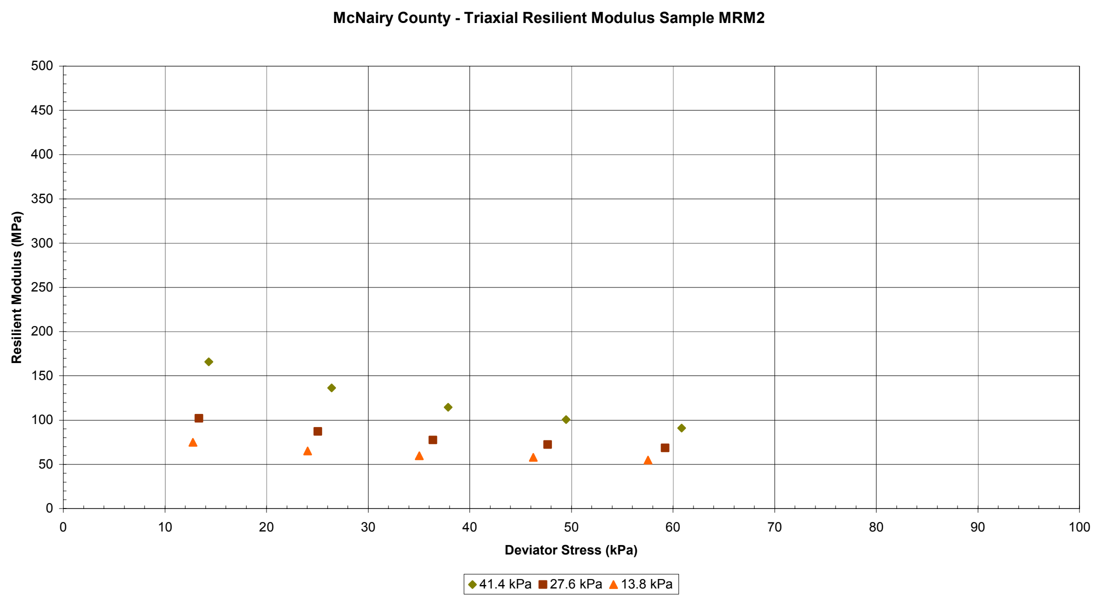
Blount County - Triaxial Resilient Modulus Sample BRM3



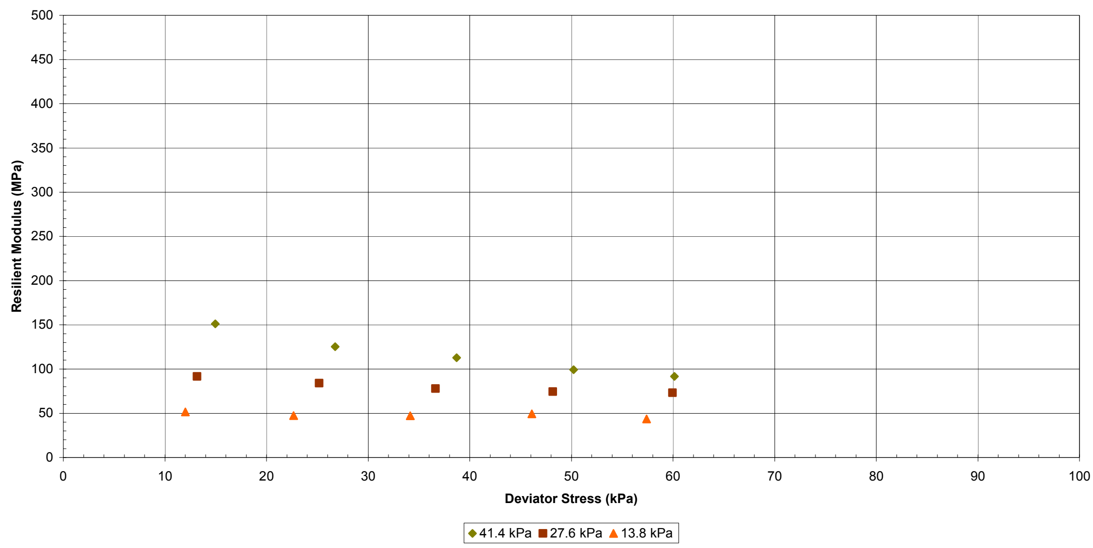
Blount County - Triaxial Resilient Modulus Sample BRM4



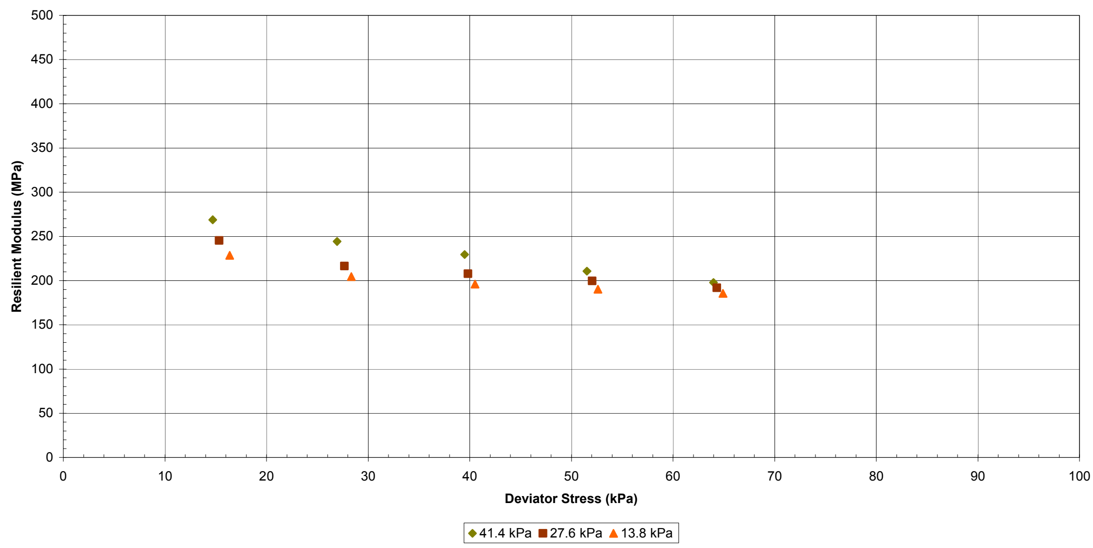

Mcnairy County - Triaxial Resilient Modulus Sample MRM 1
Resilient Modulus (MPa)
Deviator Stress (kPa)
41.4 kPa
27.6 kPa
13.8 kPa


McNairy County - Triaxial Resilient Modulus Sample MRM2
Resilient Modulus (MPa)
Deviator Stress (kPa)
41.4 kPa
27.6 kPa
13.8 kPa

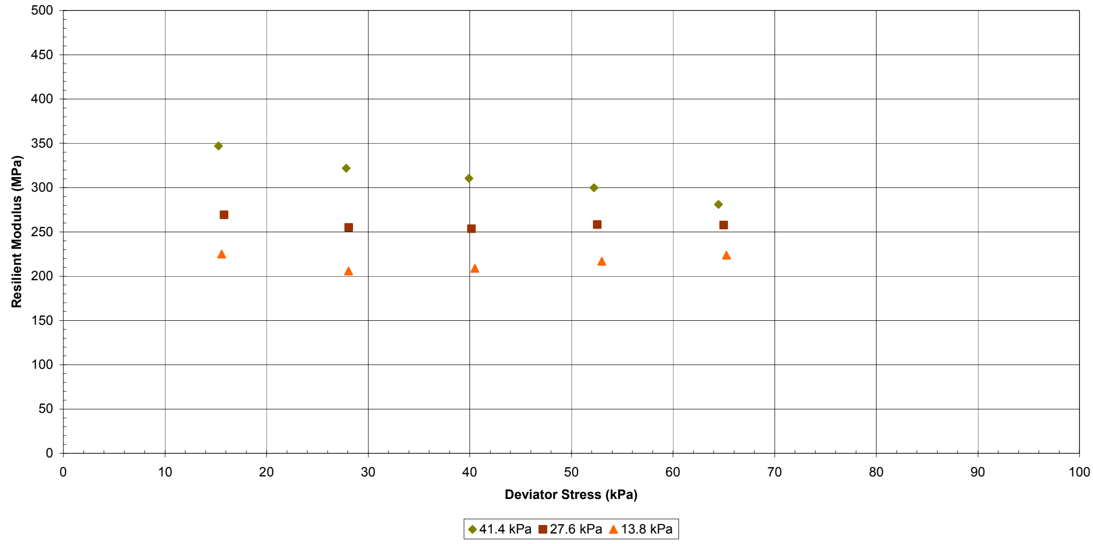
McNairy County - Triaxial Resilient Modulus Sample MRM3



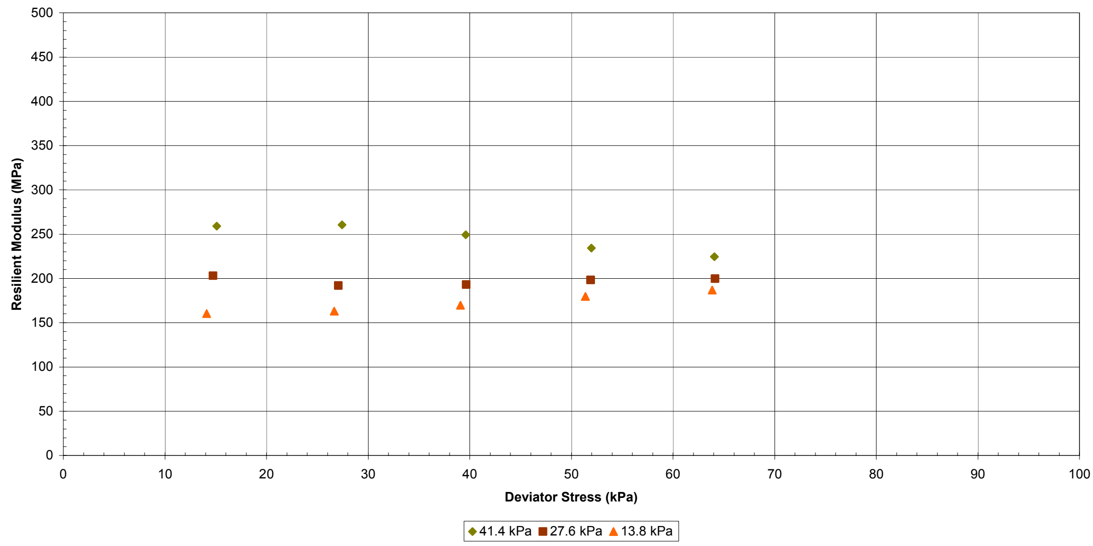
Overton County - Triaxial Resilient Modulus Sample ORM1



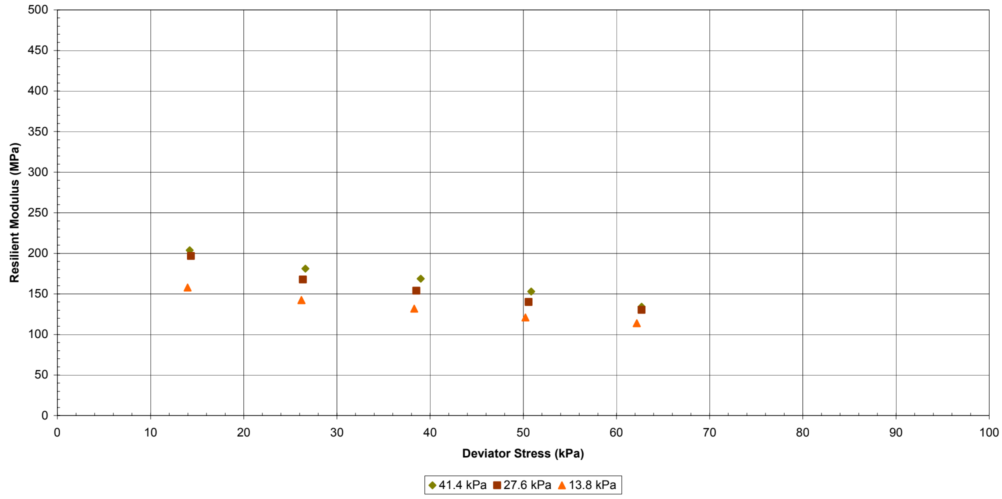
Overton County - Triaxial Resilient Modulus Sample ORM2



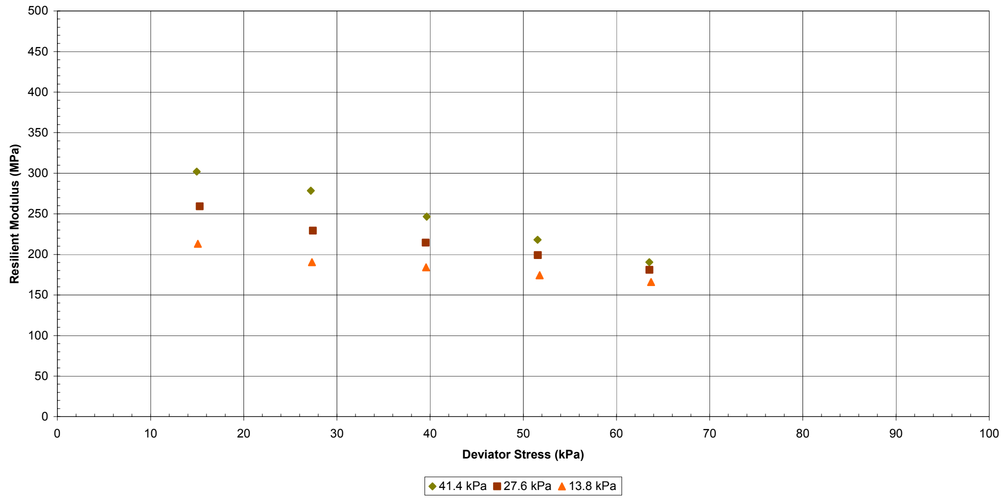
Overton County - Triaxial Resilient Modulus Sample ORM2

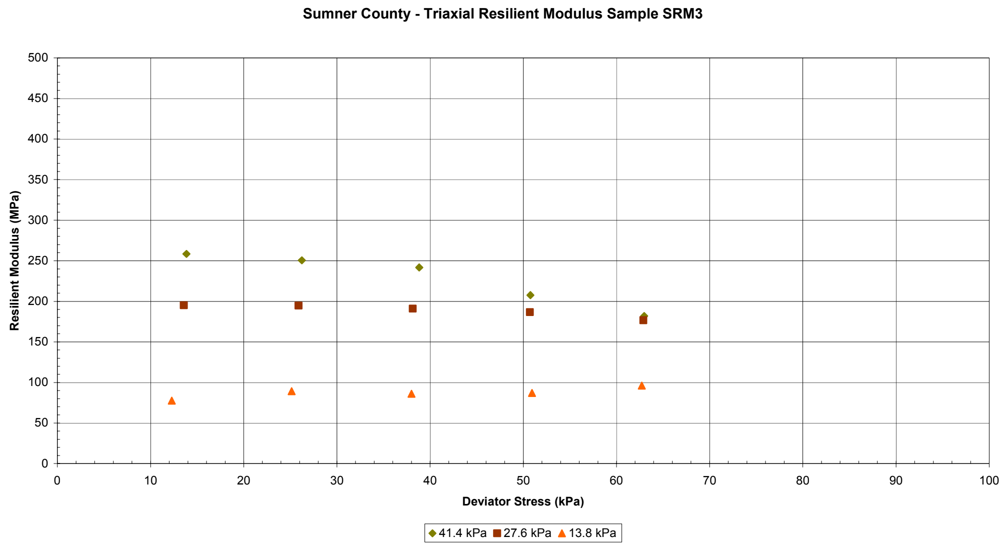


Sumner County - Triaxial Resilient Modulus Sample SRM1

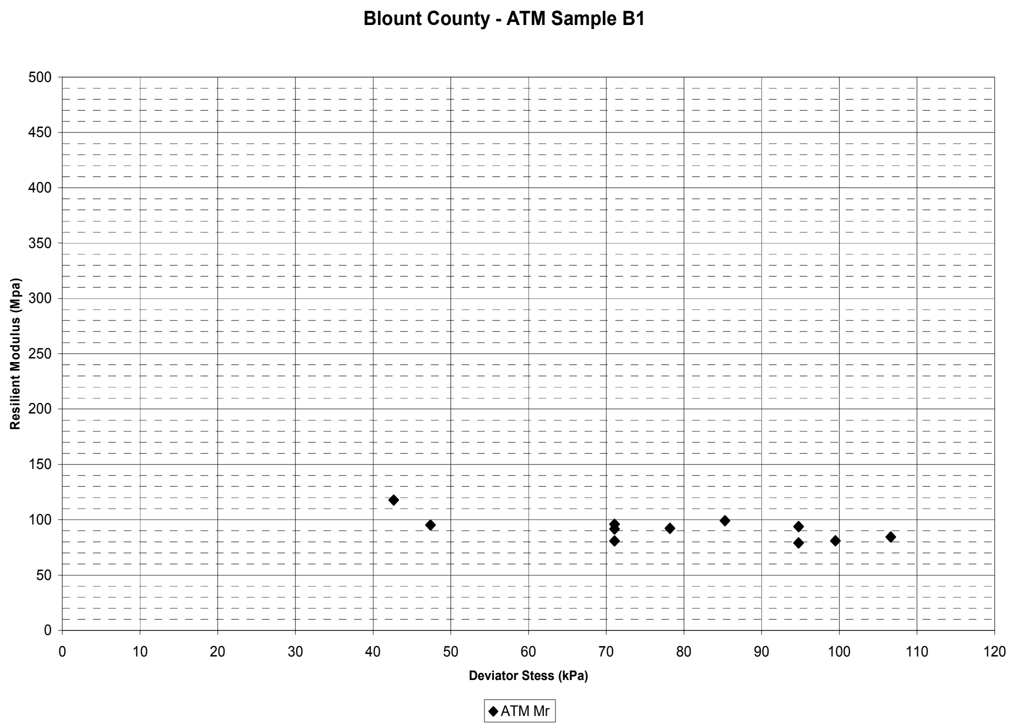


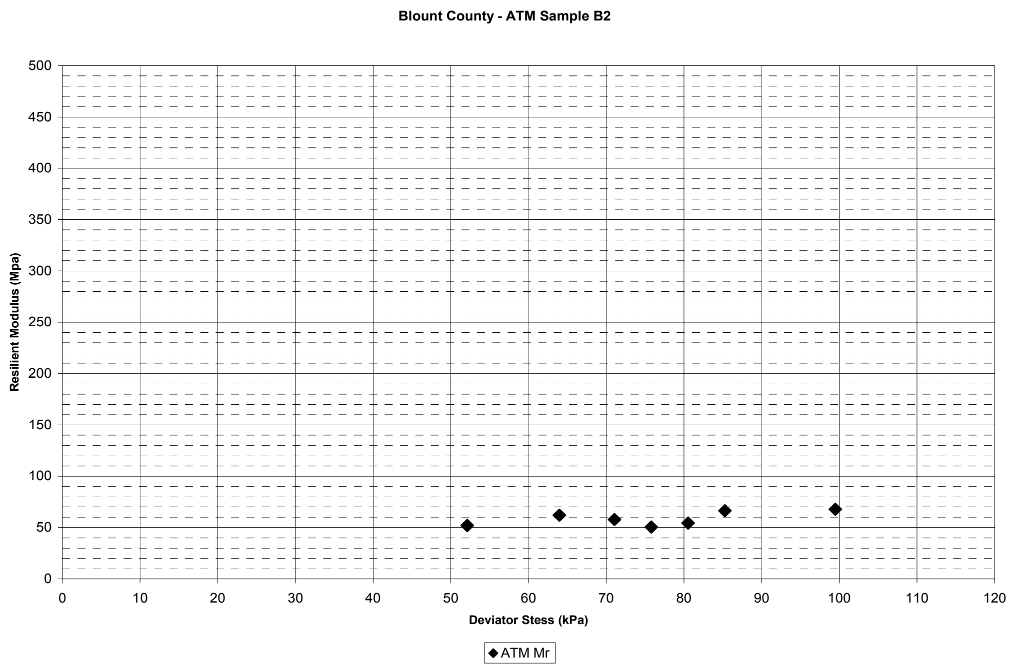
Sumner County - Triaxial Resilient Modulus Sample SRM2

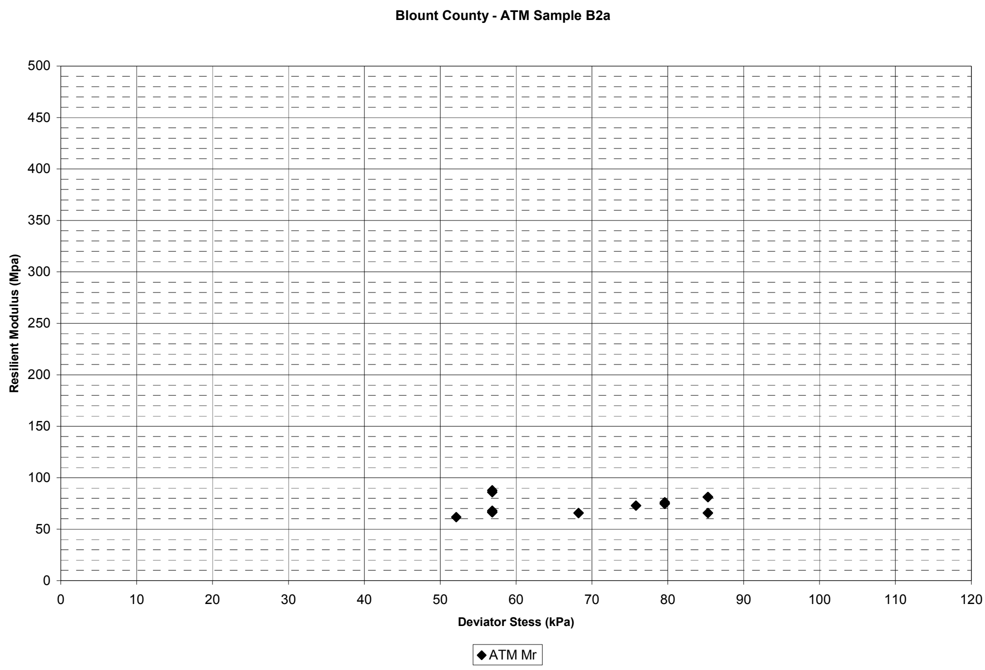


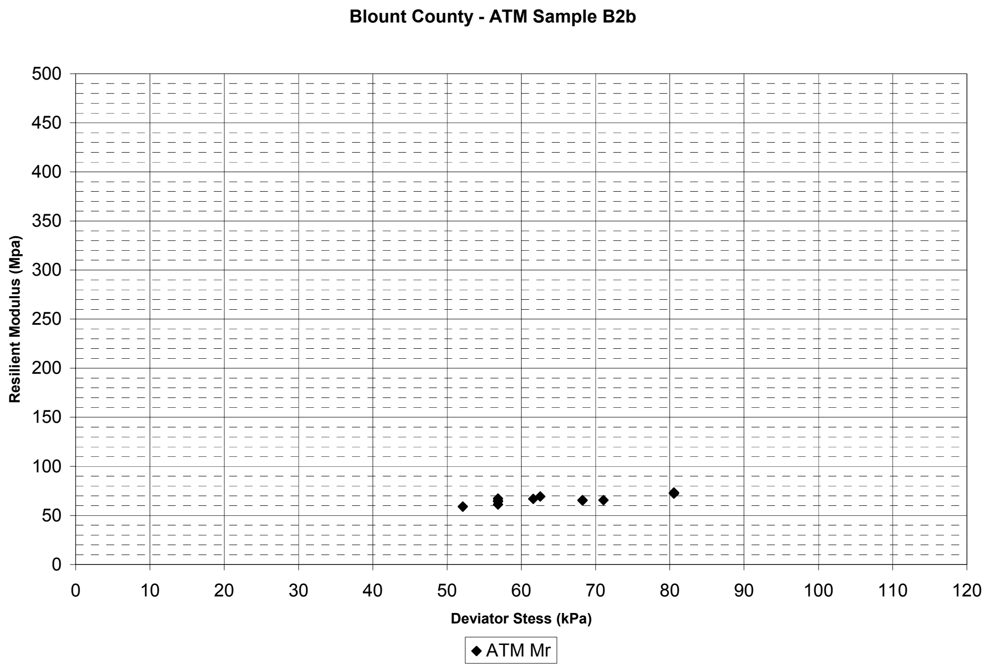

Sumner County - Triaxial Resilient Modulus Sample SRM3
Resilient Modulus (MPa)
500
450
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
Deviator Stress (kPa)
41.4 kPa
27.6 kPa
13.8 kPa

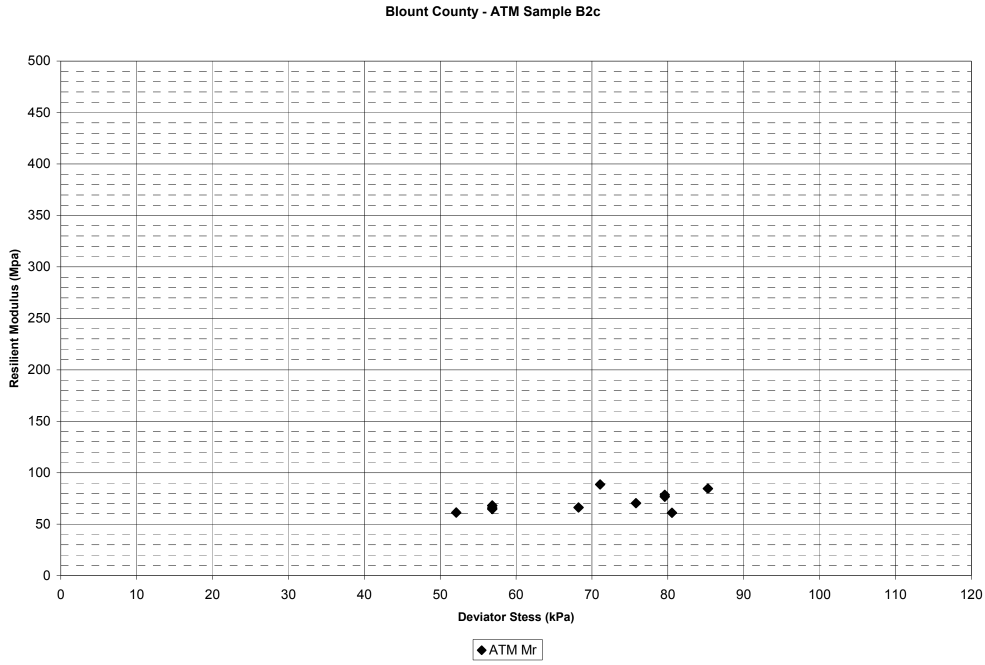
Appendix C ATM Resilient Modulus Results

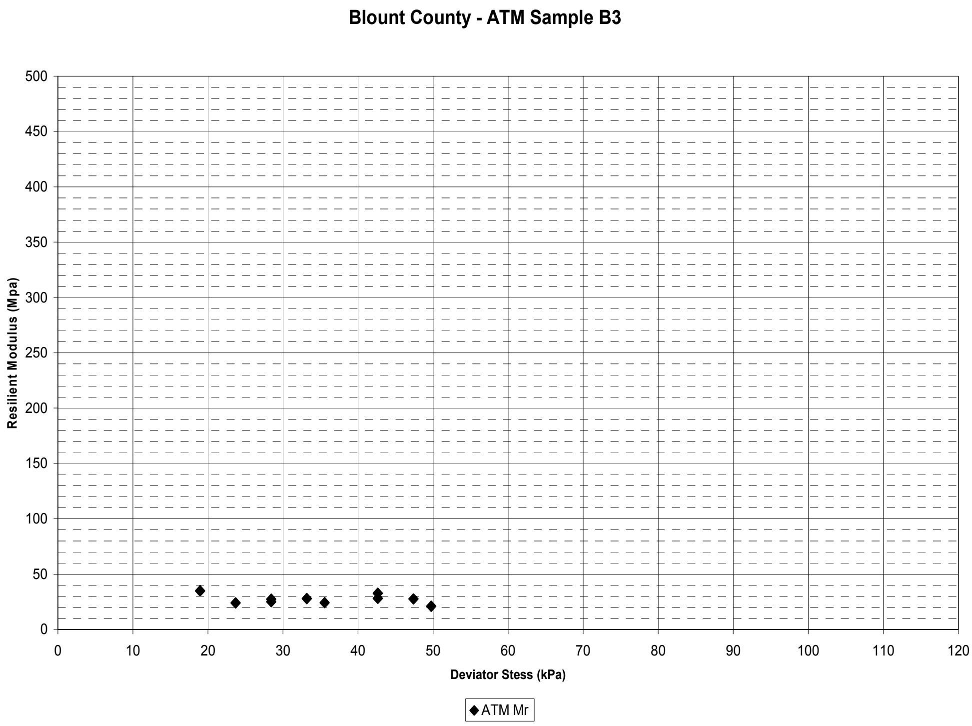

Blount County - ATM Sample B1
Resilient Modulus (Mpa)
Deviator Stess (kPa)
ATM Mr


Blount County - ATM Sample B2
Resilient Modulus (Mpa)
Deviator Stess (kPa)
ATM Mr

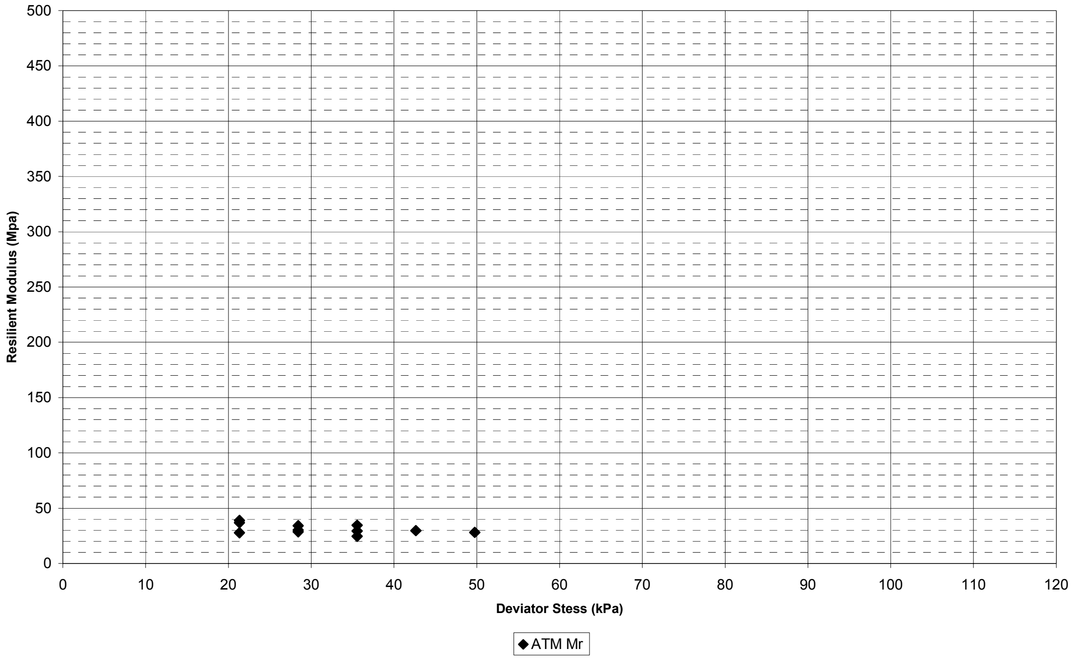

Blount County - ATM Sample B2a
Resilient Modulus (Mpa)
Deviator Stess (kPa)
ATM Mr


Blount County - ATM Sample B2b
Resilient Modulus (Mpa)
Deviator Stess (kPa)
ATM Mr

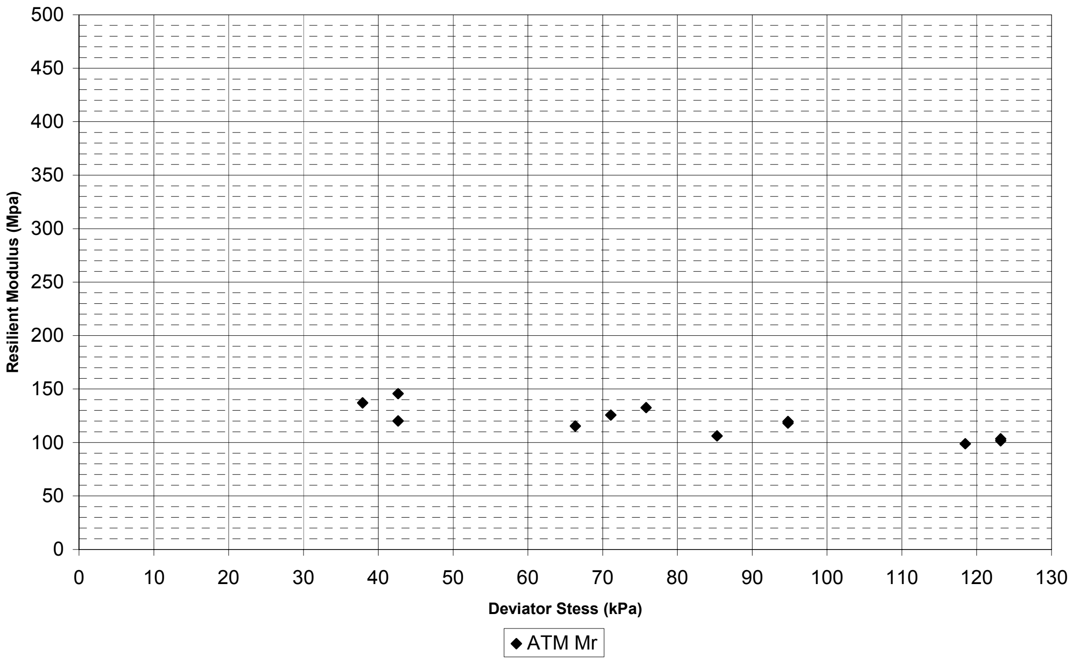

Blount County - ATM Sample B2c
Resilient Modulus (Mpa)
Deviator Stess (kPa)
ATM Mr

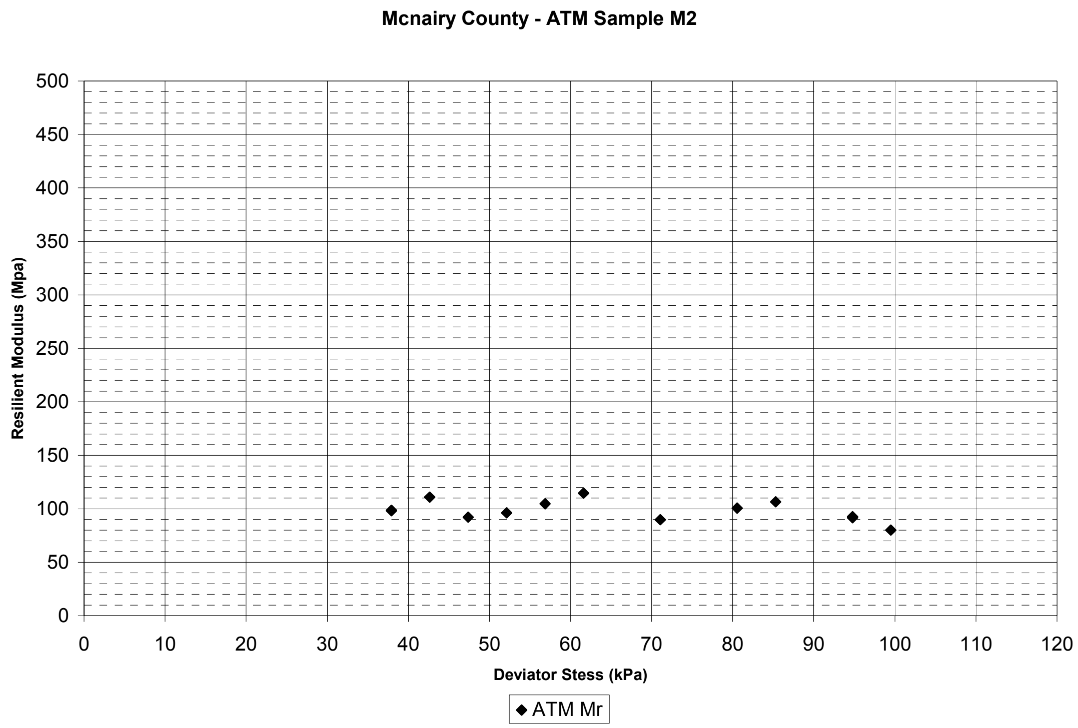

Blount County - ATM Sample B3
Resilient Modulus (Mpa)
Deviator Stess (kPa)
ATM Mr

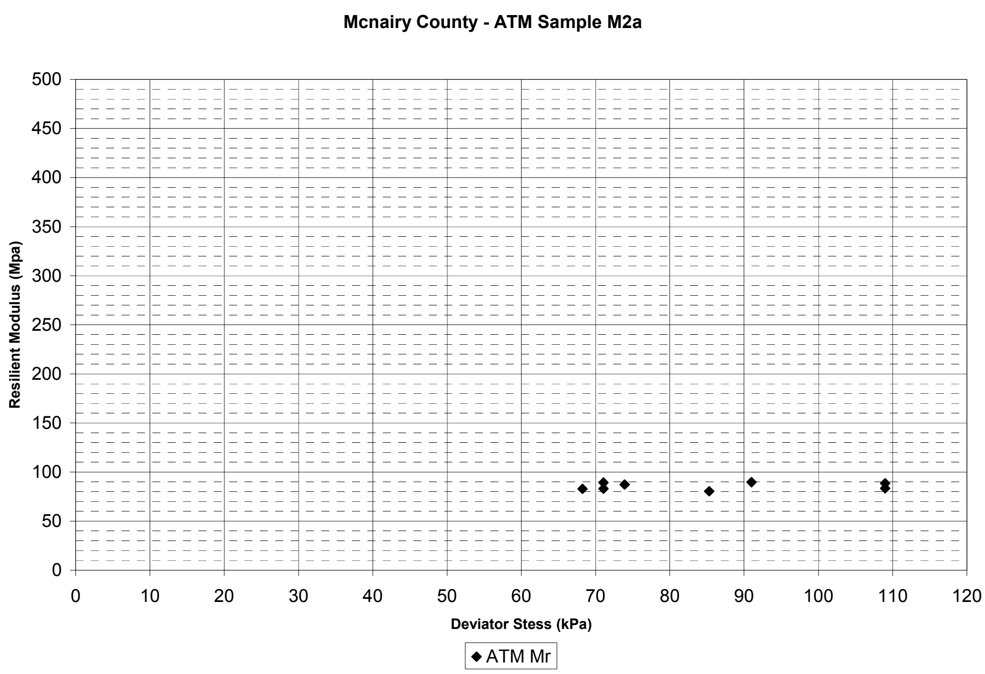
Blount County - ATM Sample B4



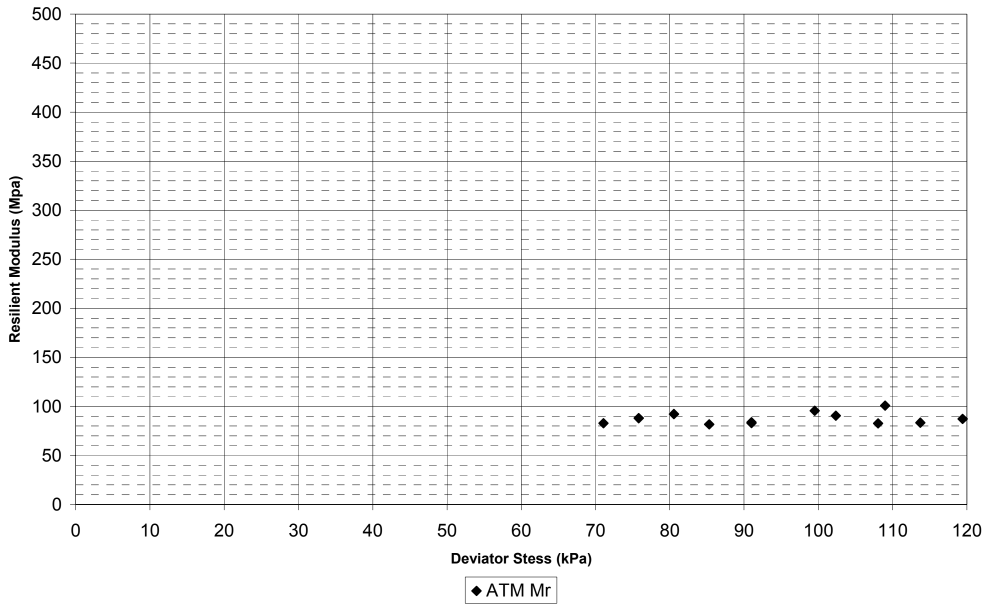
Mcnairy County - ATM Sample M1



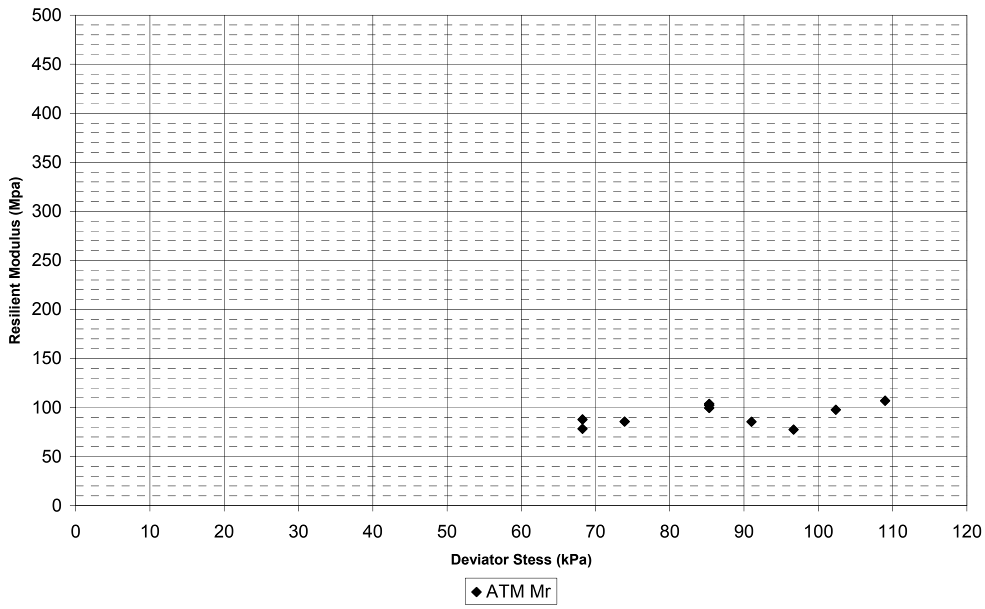

Mcnairy County - ATM Sample M2
Resilient Modulus (Mpa)
500
450
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Deviator Stess (kPa)
ATM Mr

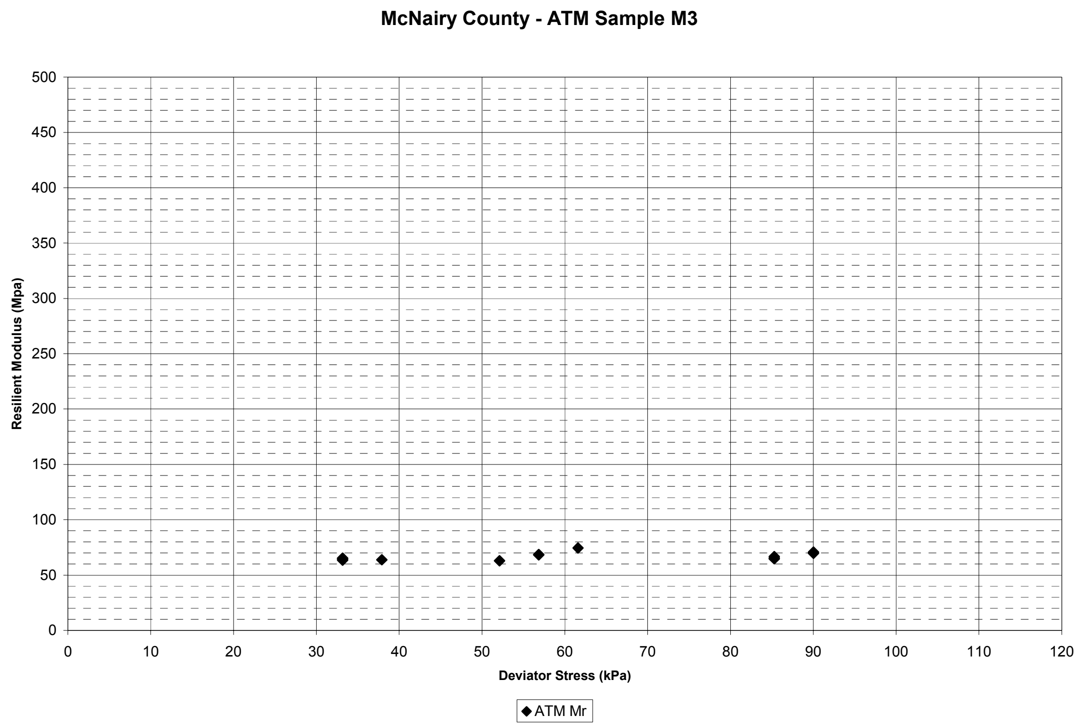

Mcnairy County - ATM Sample M2a
Resilient Modulus (Mpa)
500
450
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Deviator Stess (kPa)
ATM Mr

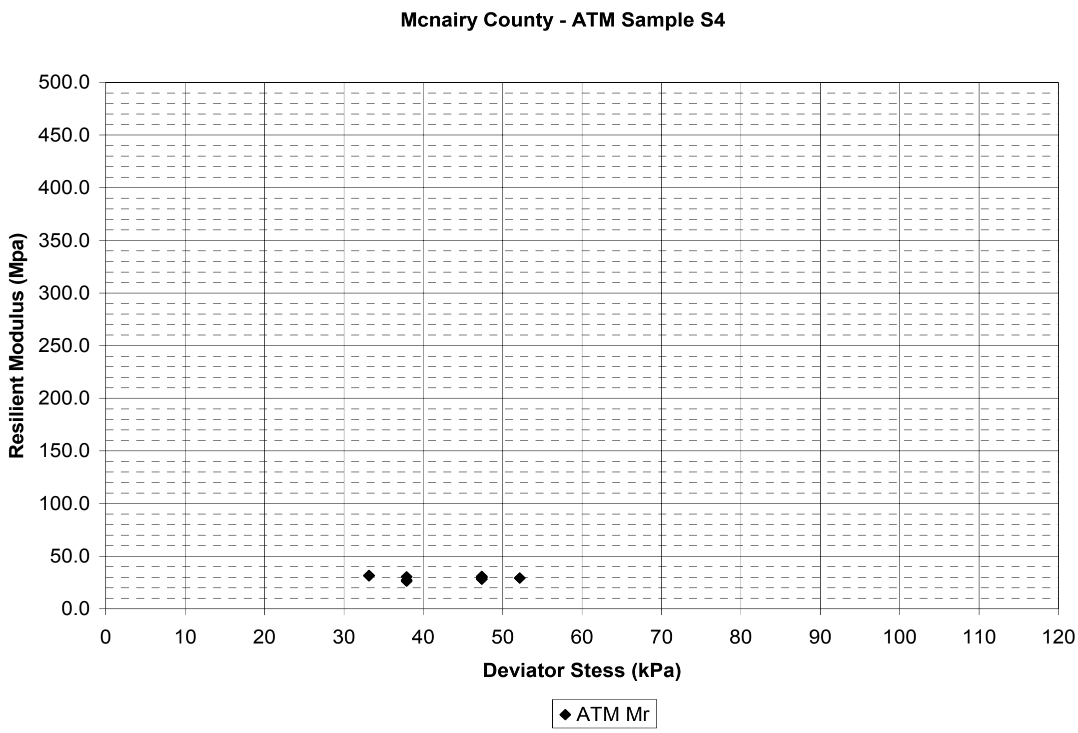
Mcnairy County - ATM Sample M2b



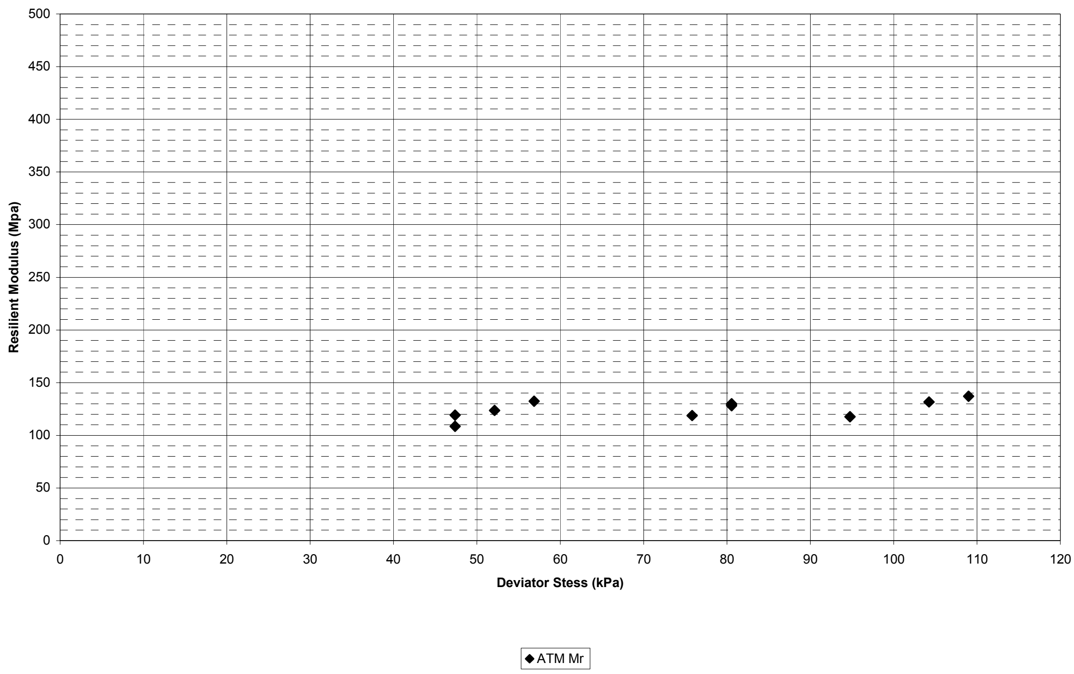
Mcnairy County - ATM Sample M2c



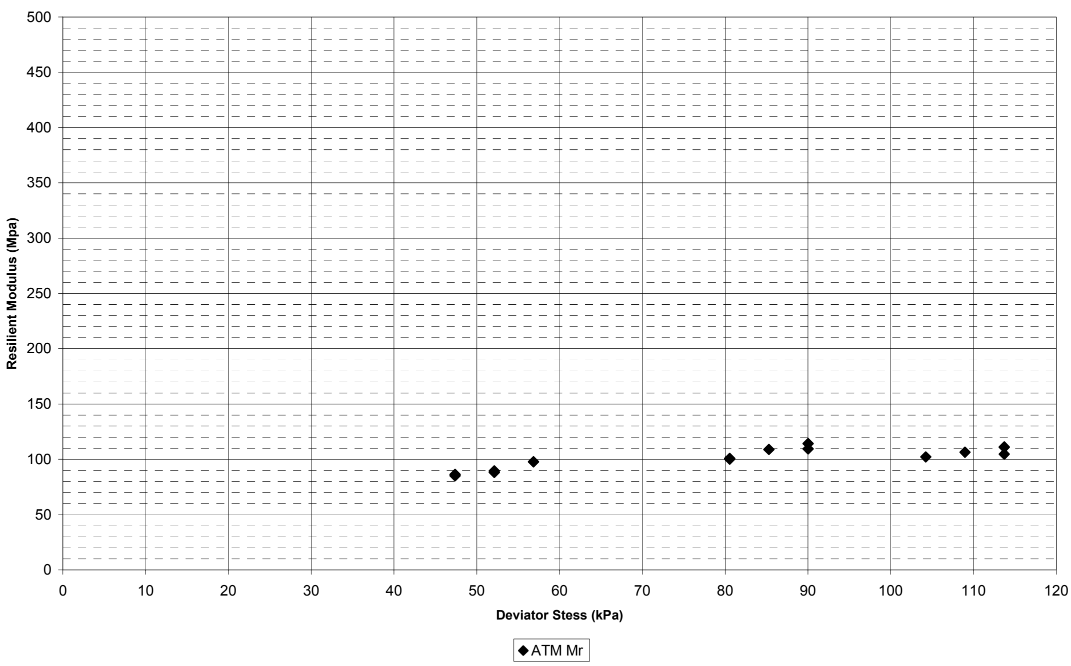

McNairy County - ATM Sample M3
Resilient Modulus (Mpa)
Deviator Stress (kPa)
ATM Mr

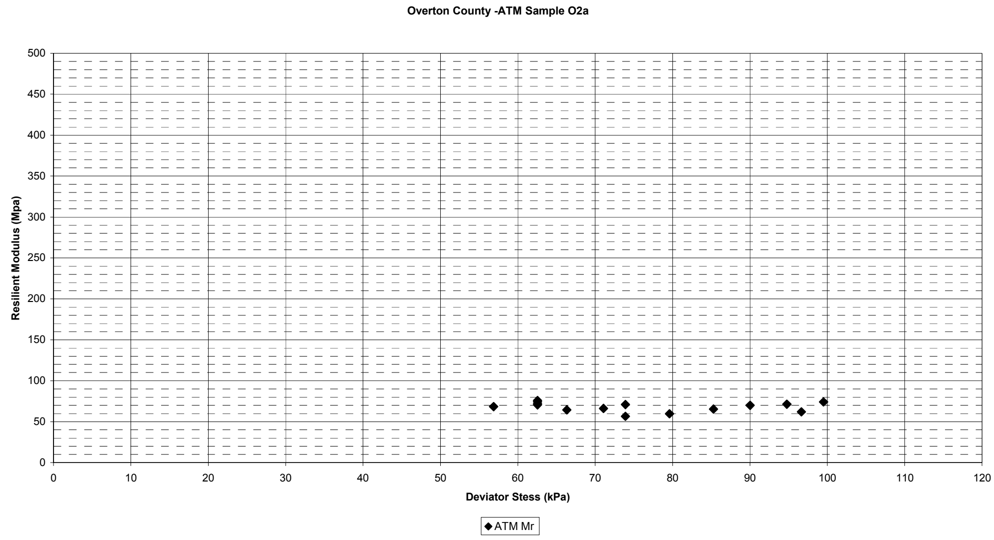

Mcnairy County - ATM Sample S4
Resilient Modulus (Mpa)
Deviator Stess (kPa)
ATM Mr

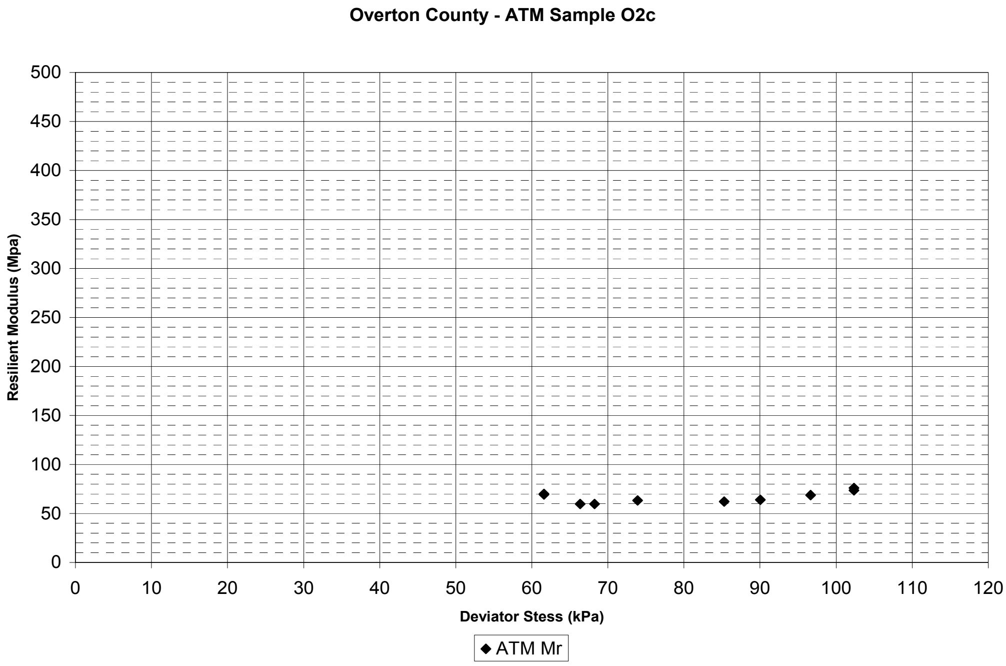
Overton County - ATM Sample O1



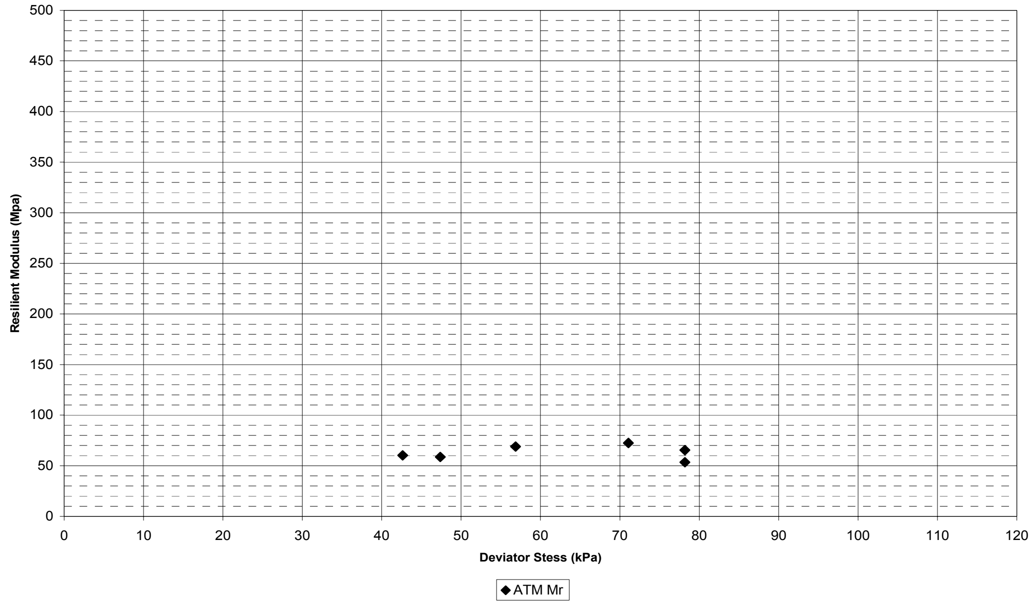
Overton County - ATM Sample O2



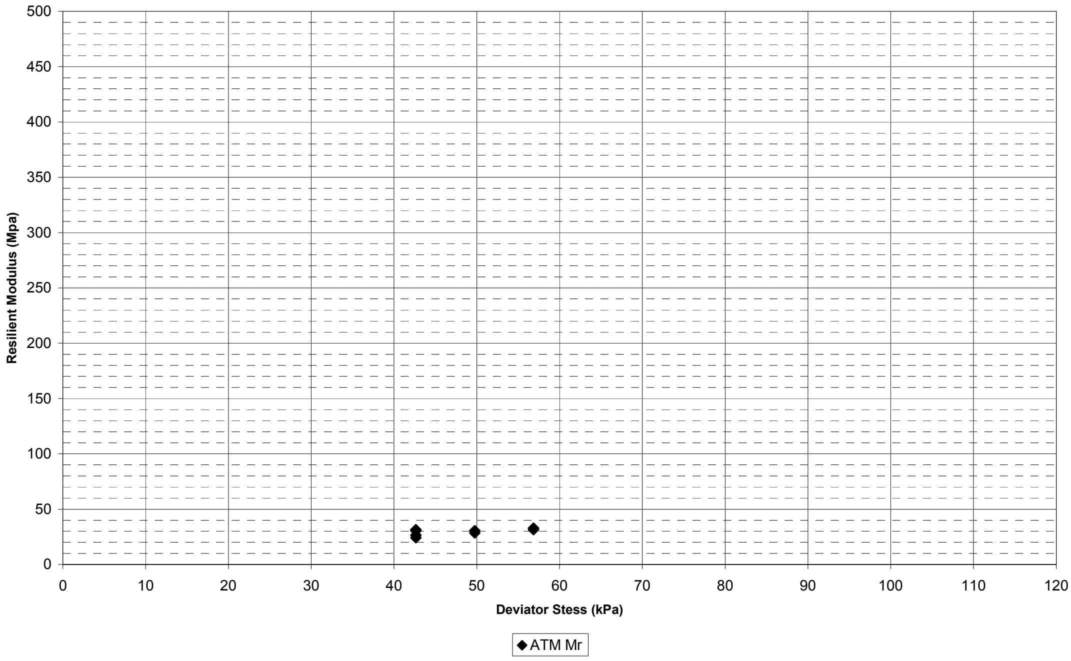

Overton County -ATM Sample O2a
Resilient Modulus (Mpa)
500
450
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Deviator Stess (kPa)
ATM Mr

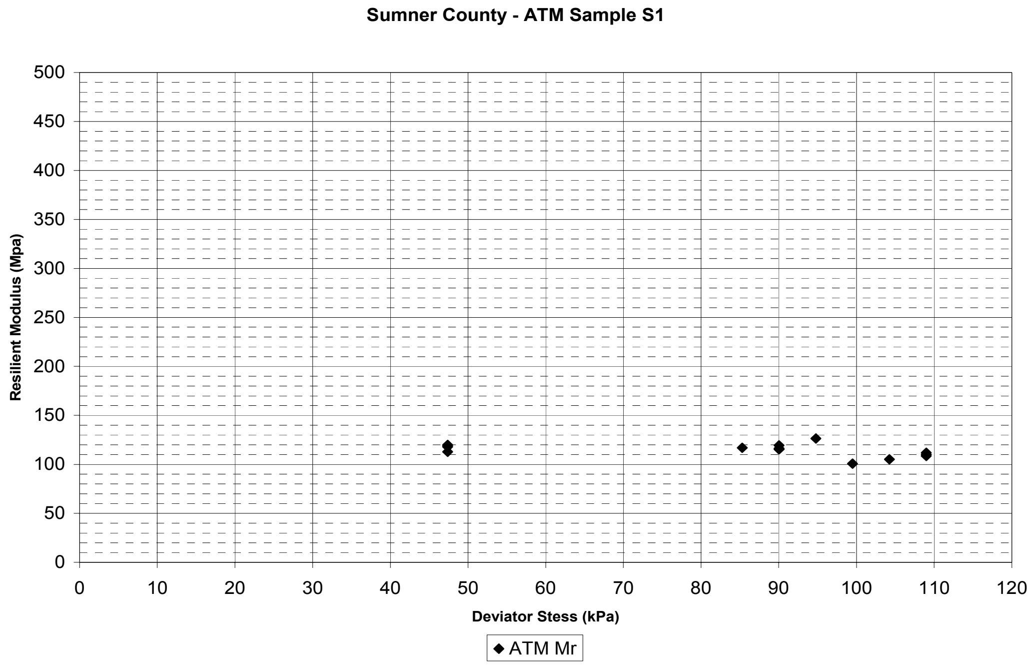

Overton County - ATM Sample O2c
Resilient Modulus (Mpa)
500
450
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
110
120
Deviator Stess (kPa)
ATM Mr

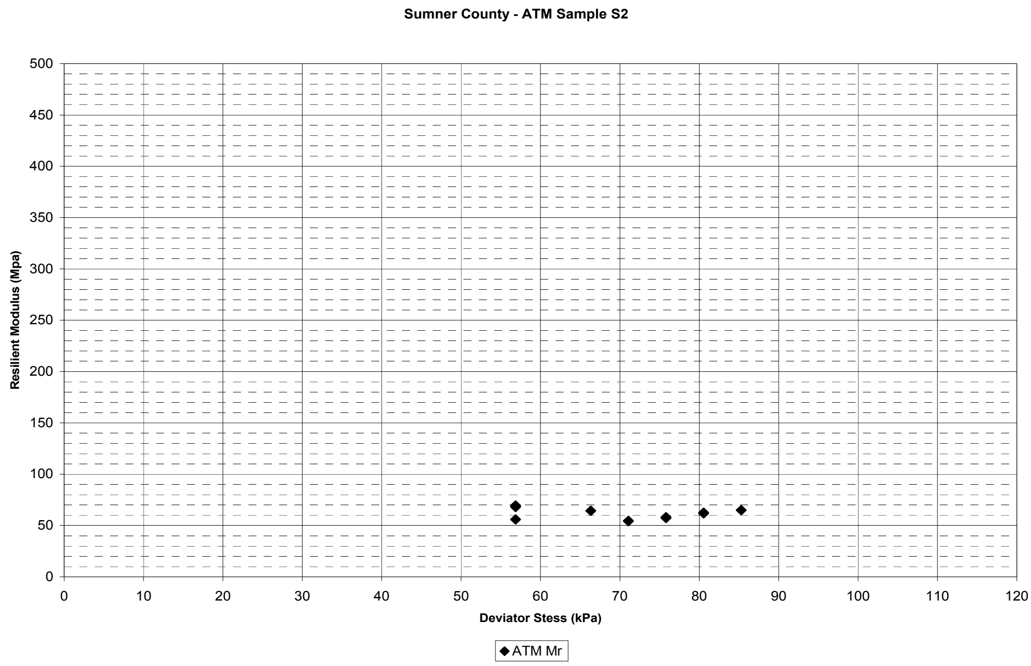
Overton County - ATM Sample O3



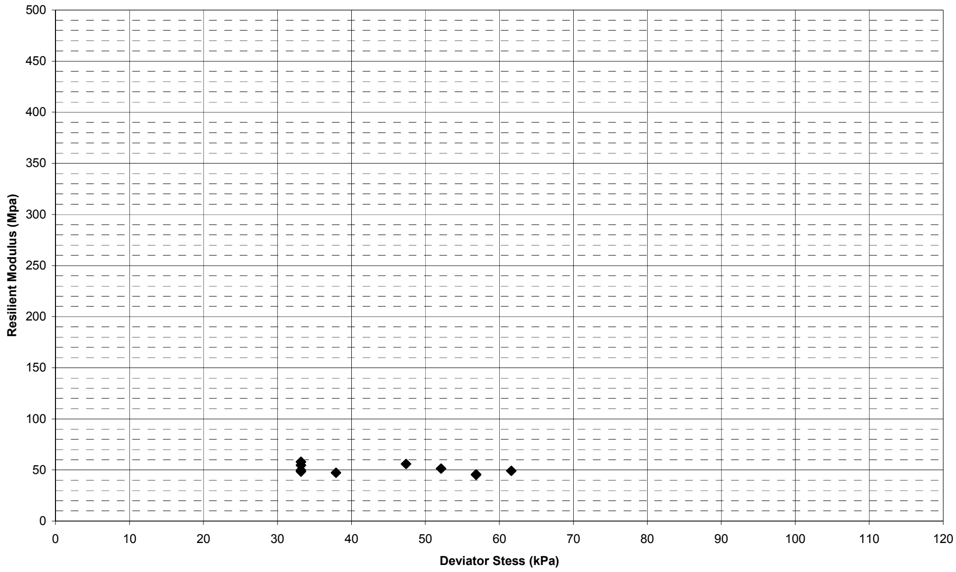
Overton County - ATM Sample O4



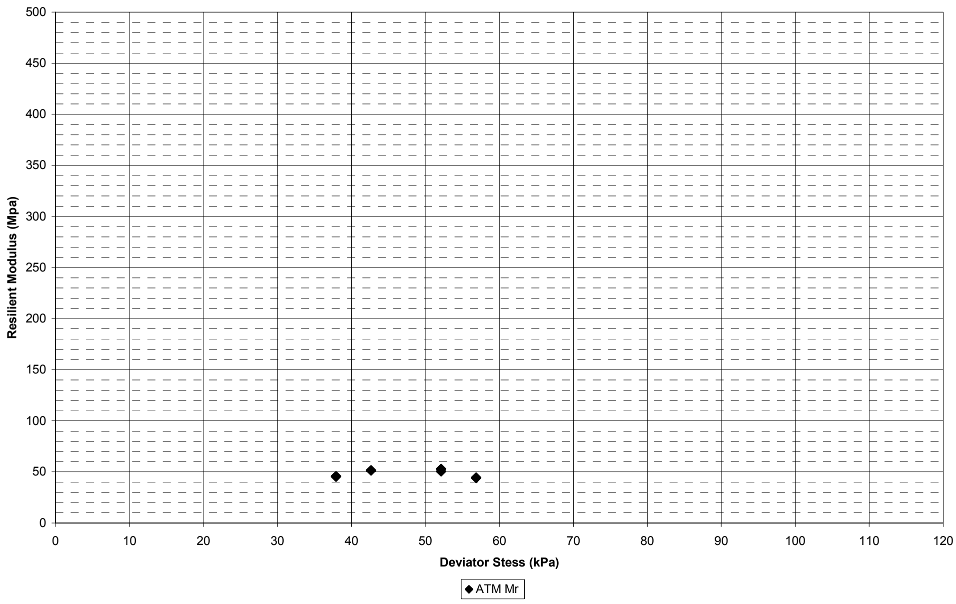

Sumner County - ATM Sample S1
Resilient Modulus (Mpa)
0
50
100
150
200
250
300
350
400
450
500
0
10
20
30
40
50
60
70
80
90
100
110
120
Deviator Stess (kPa)
ATM Mr


Sumner County - ATM Sample S2
Resilient Modulus (Mpa)
0
50
100
150
200
250
300
350
400
450
500
0
10
20
30
40
50
60
70
80
90
100
110
120
Deviator Stess (kPa)
ATM Mr

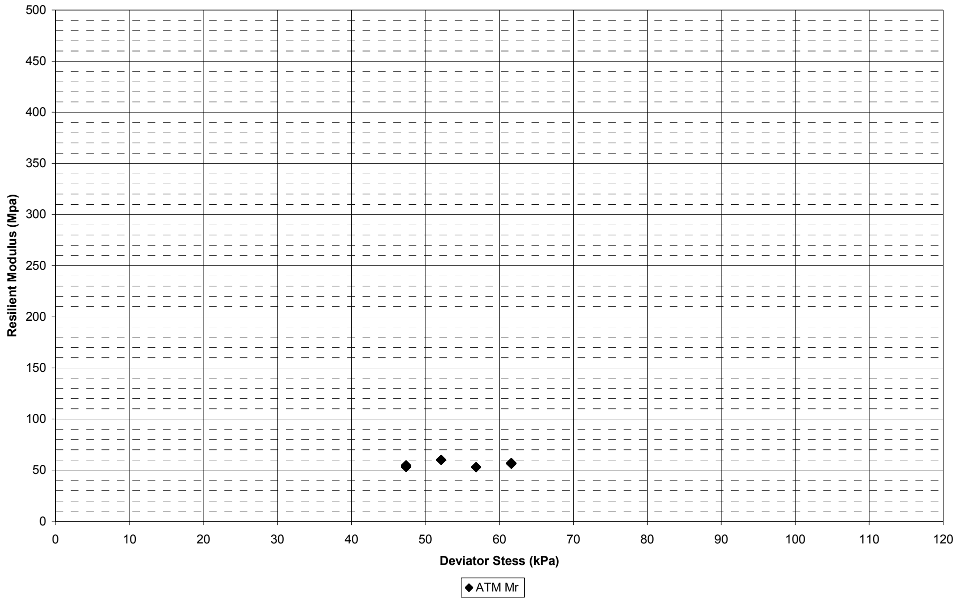
Sumner County - ATM Sample S2A



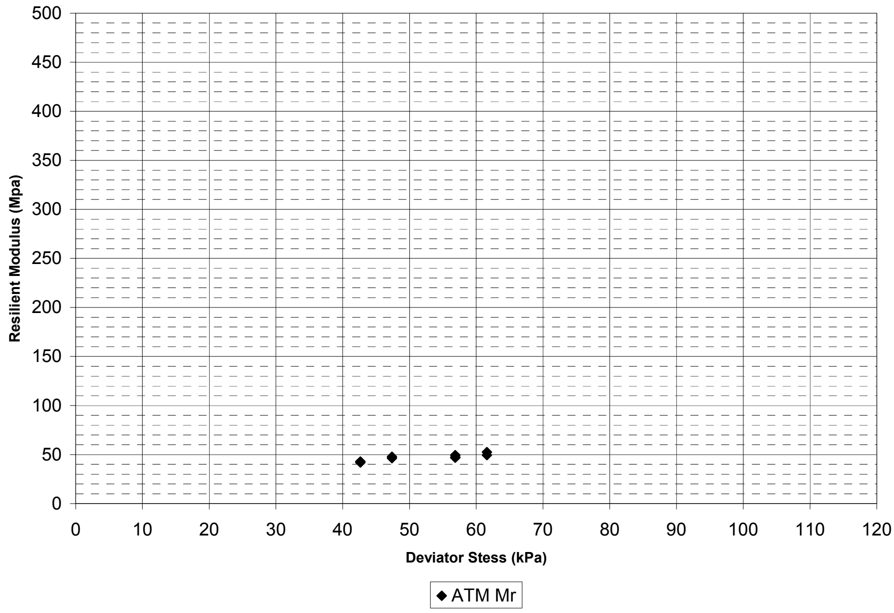
Sumner County - ATM Sample S2b



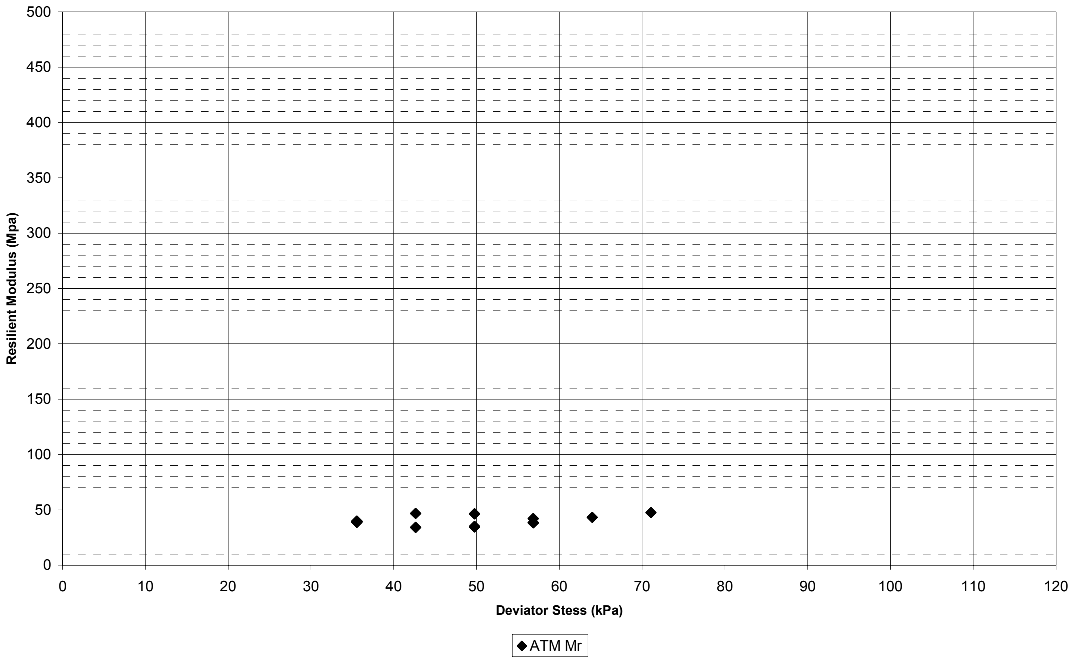
Sumner County - ATM Sample S2c



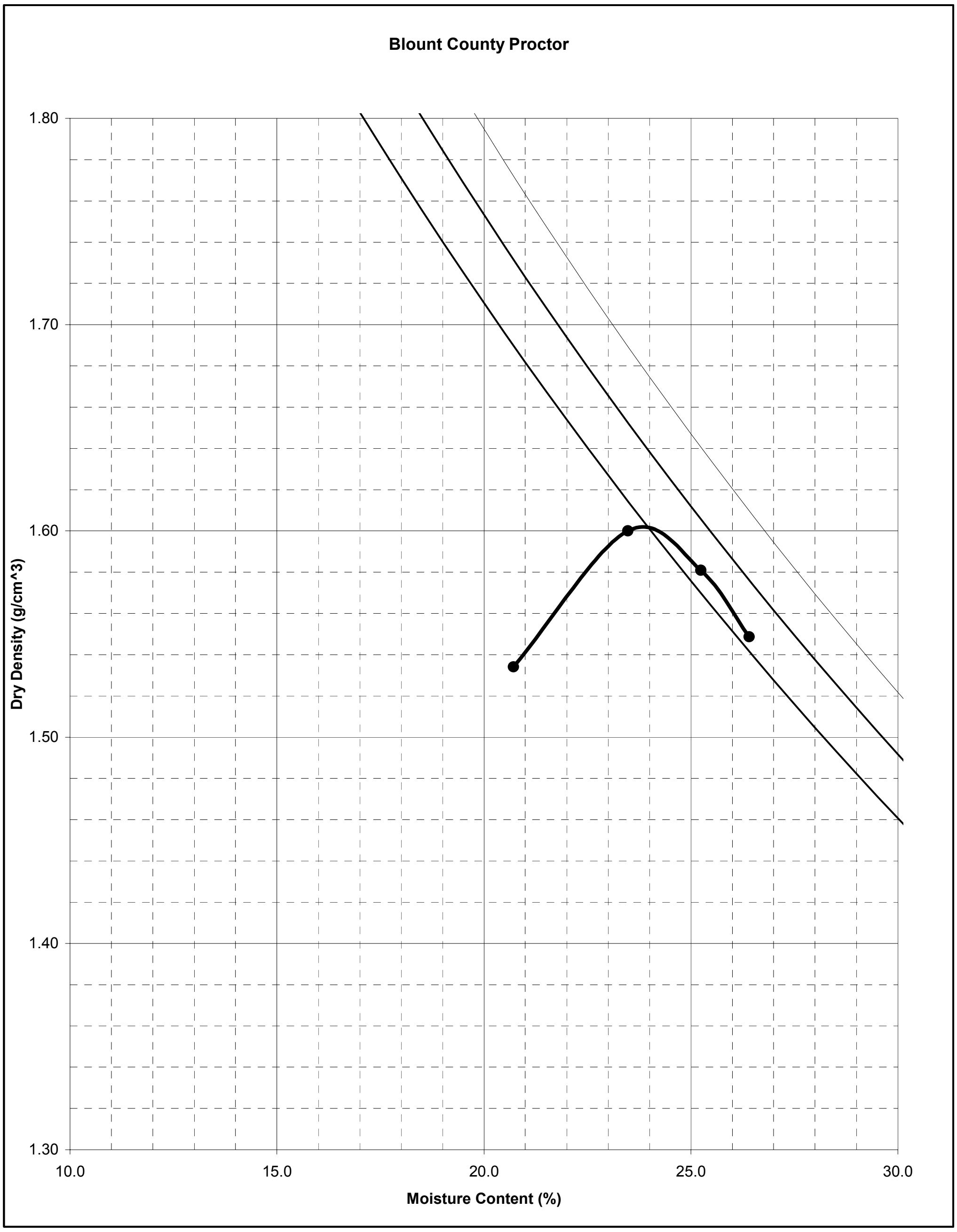
Sumner County - ATM Sample S3

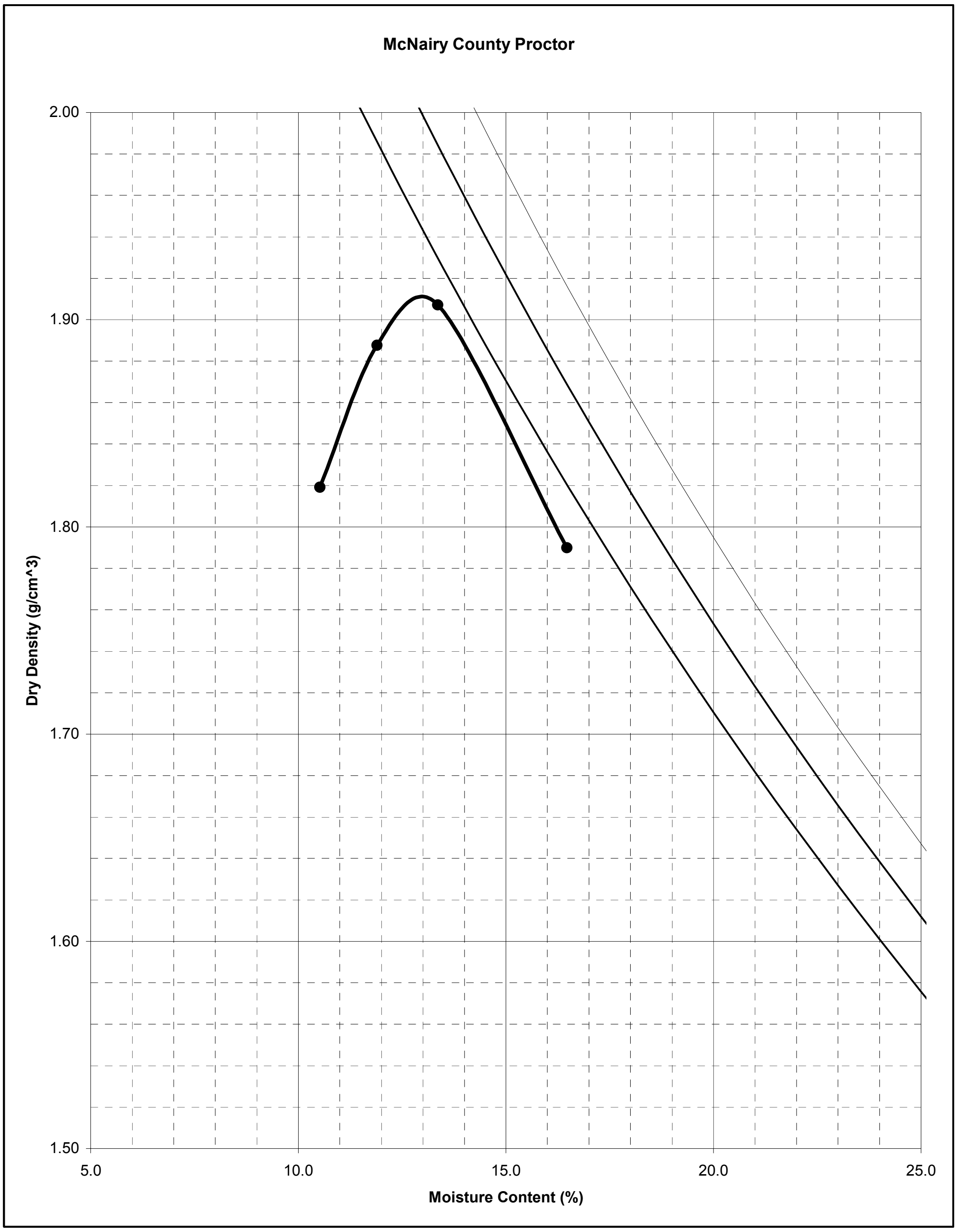


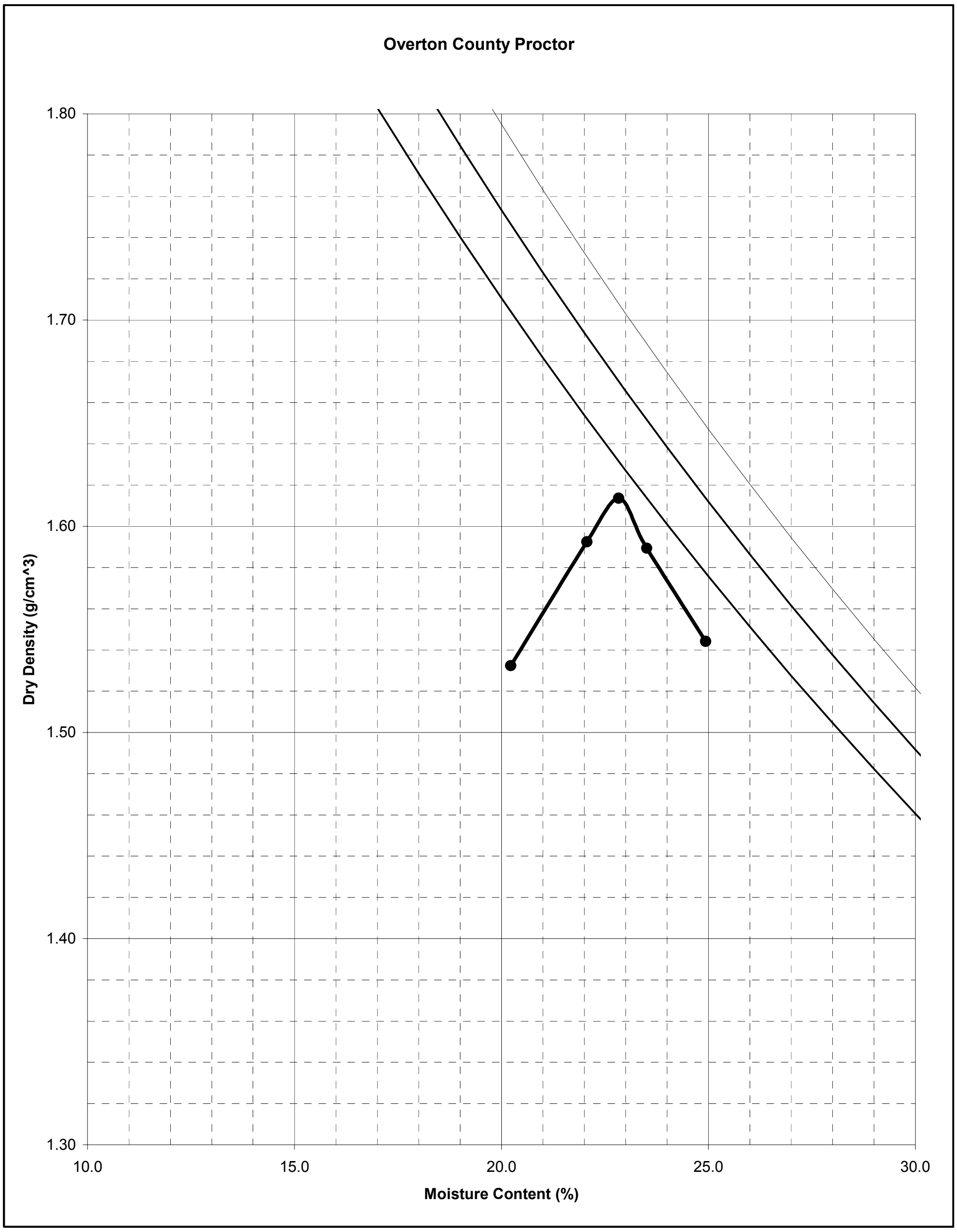
Sumner County - ATM Sample S4

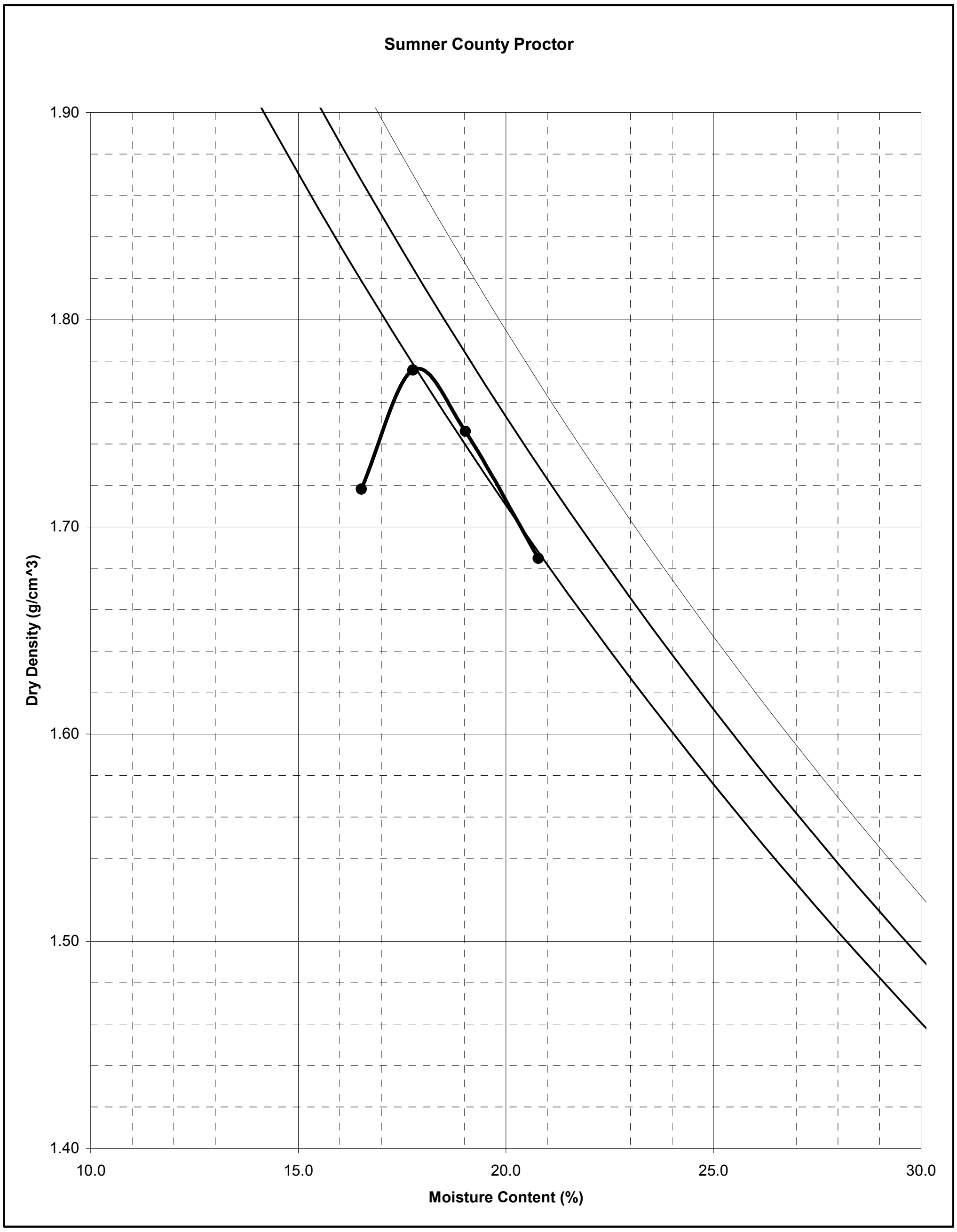


Appendix D Moisture – Density Curves


Blount County Proctor
1.80
1.70
1.60
1.50
1.40
1.30
Dry Density (g/cm^3)
10.0
15.0
20.0
25.0
30.0
Moisture Content (%)


McNairy County Proctor
2.00
1.90
1.80
1.70
1.60
1.50
Dry Density (g/cm^3)
5.0
10.0
15.0
20.0
25.0
Moisture Content (%)


Overton County Proctor
1.80
1.70
1.60
1.50
1.40
1.30
Dry Density (g/cm^3)
10.0
15.0
20.0
25.0
30.0
Moisture Content (%)


Sumner County Proctor
1.90
1.80
1.70
1.60
1.50
1.40
Dry Density (g/cm^3)
10.0
15.0
20.0
25.0
30.0
Moisture Content (%)

Vita

Jonathan Michael Smolen was born on December 23, 1976 in Mesa, Arizona. He graduated Park County High School in Livingston, Montana in the spring of 1995 and began attending the University of Tennessee in the fall of 1995. In the summer of 2001 graduated from the University of Tennessee with a Bachelor of Science Degree in Civil Engineering. Jonathan Michael Smolen began graduate school at the University of Tennessee in fall of 2001 for the purposes of obtaining a Master of Science Degree in Geotechnical Engineering.