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Use of Coal Fly Ash and Other Waste Products in Soil Stabilization and Road Construction-Including Non-Destructive Testing of Roadways

by

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Technical Report Documentation Page

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16. Abstract
An extensive laboratory testing program was performed on subgrade soils stabilized using fly ash and lime kiln dust. The laboratory program included measurements of: compaction curves, small strain elastic moduli, resilient modulus (Mr), Briaud Compaction Device (BCD) modulus, and unconfined compressive strengths of subgrade soils mixed with various amounts of Class C fly ash and lime kiln dust (LKD). The objectives of this study were to (1) quantify changes with time in subgrade modulus and strength from soil stabilization and (2) evaluate potential nondestructive quality control (QC) methods. The amount of improvement in subgrade modulus varied with soil type and soil stabilizer. Increases in Mr values by a factor of five or more were observed in some cases. Relative changes in resilient modulus with time were compared to changes in modulus values measured from small-strain velocity measurements and the BCD (both of which can be applied in the field for QC) with mixed results. In many cases, the trends in modulus change were in good agreement, but in other cases significant differences were observed. Short-term tracking of wave velocity of stabilized soil showed increases of about 20 to 40% (relative to the unstabilized soil) within 1-hr after compaction. Future studies should focus on evaluation of these NDT methods under field conditions.

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FINAL REPORT

Use of Coal Fly Ash and Other Waste Products in Soil Stabilization and Road Construction-Including Non-Destructive Testing of Roadways

Prepared for
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by

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Technical Summary

An extensive laboratory testing program was performed on subgrade soils stabilized using fly ash and lime kiln dust. The laboratory program included measurements of: compaction curves, small strain elastic moduli, resilient modulus, Briaud Compaction Device (BCD) modulus, and unconfined compressive strengths of a high-plasticity clay (CH) subgrade soil and a low-plasticity (CL) subgrade soil mixed with various amounts of Class C fly ash and lime kiln dust (LKD). Variables that were examined in this study included: compaction water content relative to optimum, effect of time on modulus changes, percentage of modifier added to the soil, type of modifier used, and type of subgrade soil. The overall objectives of this research project were to: (1) study effective and economical methods to implement waste materials such as fly ash (FA) and lime kiln dust (LKD) in stabilization of subgrade soils for Missouri pavements, and (2) evaluate innovative non-destructive testing methods to measure the physical and engineering properties of the stabilized soils.

The soils tested in this study were a low plasticity clay (CL) sampled from Atchison County, Missouri and a high plasticity clay (CH) sampled from Putnam County, Missouri. The additives tested in this study were a Class C fly ash from the Labadie Power Plant and lime kiln dust (LKD) supplied by Mississippi Lime. The soil/additive mixtures were tested at laboratories at the University of Missouri (MU) and Missouri University of Science and Technology (MST). Tests performed at MST include: resilient modulus, Briaud modulus, unconfined compressive strength and compaction. Measurements performed at MU include: small-strain elastic moduli (compression and shear) measurements, unconfined compressive strength, and compaction.

With regard to the effect of soil modifiers on soil properties, this study generally showed that significant improvements in soil stiffness can be achieved with the addition of relatively small percentages of modifiers. Resilient modulus values were shown to increase by factors of about 3.5 to 5.5 times the unmodified values with the addition of fly ash to the CL soil. Small-strain modulus measurements of the low-plasticity clay showed similar improvements in modulus with the addition of fly ash. However, measurements of the high-plasticity clay showed little or no improvement in small-strain modulus with the addition of fly ash. The addition of LKD was also shown to significantly increase the stiffness of subgrade soils, although the performance of LKD relative to fly ash was somewhat ambiguous with the resilient modulus tests showing less effect of the LKD (relative to fly ash) and the small-strain elastic modulus results showing a greater effect of LKD on modulus. In both the resilient modulus and small-strain modulus measurements, no strong trend of increasing stiffness with increasing percentage of fly ash was observed.

The addition of soil modifiers also had a significant impact on the unconfined compressive strength. For the CL subgrade, the addition of fly ash nearly doubled the 28-day strength of the soil (from near 30 psi to near 60 psi). As was the case with modulus, increases in the percentage of fly ash did not correspond to large increases in soil strength. For the CH subgrade, the strength increased by a factor of 2 to 2.5. The percentage of fly ash did not greatly affect the 28-day strength of the soil. The addition of LKD had a greater effect on the strength of the CL subgrade as compared to the fly ash, with strength increasing by a factor of 3 or more.

The two potential non-destructive testing methods examined in this study, namely small-strain modulus measurements and BCD modulus measurements, showed mixed results. The relative changes in modulus (modified divided by unmodified values) measured with these devices were compared to the change measured with the resilient modulus test. The BCD device did not show the same trend in modulus change for the fly ash modified soils as was measured with the resilient modulus. However, for the case of LKD added to the CL soil, the agreement in relative modulus increase was reasonably good. The small-strain elastic modulus measurements showed trends in modulus change that were in good agreement with the resilient modulus changes for the fly ash stabilized soil. However, the comparisons for the LKD soil were not as good. The small-strain modulus study also examined the changes in modulus very soon after compaction (1-hr) when quality control measurements would be performed. For the soils and modifiers tested in this study that produced changes in the soil (i.e. excluding the Putnam/fly ash mixture) the 1-hr modulus values ranged from 40% to 90% higher than the unmodified soil. This corresponds to increases in velocity of about 20 to 40%, which are certainly detectable using small-strain velocity measurements in the field (e.g. surface wave measurements). Therefore, it appears that the use of small-strain velocity measurements in the field may be a viable approach for quality control of stabilized soils. However, a field testing program to monitor stabilized subgrades in-situ is needed to verify performance of these techniques.

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The authors would like to express their deepest gratitude to continuing coordination and support by John "JD" Wenzlick, Organizational Performance Engineer of Missouri Department of Transportation, and his assistance over the duration of the project. Financial support to complete this study was provided in part by the Missouri Transportation Institute/Missouri Department of Transportation and by the U.S. Department of Transportation under auspices of University of Transportation Center at the Missouri University of Science and Technology.

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1. INTRODUCTION

The beneficial use of coal fly ash and other waste materials can have an overall economic and environmental benefit. Fossil fuel power plants produce large quantities of coal fly ash each year. This fly ash is mostly disposed of in landfills and ponds, and nationwide, only approximately 40% of coal fly ash is beneficially used. An ideal beneficial use for fly ash and other waste materials is to improve the performance of roadway subgrade and base materials. When mixed with poor-performing soils, the self-cementing properties of Class C fly ash can be used to improve the engineering properties of subgrades, such as stiffness, strength and durability. The increase in subgrade stiffness can result in more economical design of the pavement system. Also fly ash can be added to very soft and wet soils where construction equipment cannot effectively operate to provide a rapid improvement in soil properties and a viable working surface. Lastly, the use of waste materials in pavement construction has the environmental benefit of reducing the need for waste disposal of these materials.

Although there are several benefits to using coal fly ash and other waste materials in soil stabilization there are significant research questions that need to be answered regarding the effective and economical implementation of soil stabilization of Missouri pavements. First, there is a need to measure how much improvement in soil properties can be expected and study the parameters that influence the effectiveness of the soil modification. Secondly, the ultimate quality of modified soil placed in the field will be influenced by several factors. Like conventional compacted soils, there will be an optimal value of water content to achieve the maximum dry density of the soil/additive mixture. However, unlike conventional soil compaction, measurements of water content and density cannot be used alone to assess the subgrade quality. An additional measurement must be performed to verify the changes in material properties from the addition of the soil modifier. There is, therefore, a need to study non-destructive testing methods that can be used in concert with density and water content measurements to assess subgrade quality. Ideally, these measurements could be performed in the laboratory to establish acceptance criteria and in the field to verify the soil properties of the placed materials.

The overall objectives of this joint research project between the Missouri University of Science and Technology (MST) and the University of Missouri (MU) were to: (1) study effective and economical methods to implement waste materials such as fly ash (FA) and lime kiln dust (LKD) in stabilization of subgrade soils for Missouri pavements, and (2) evaluate innovative non-destructive testing methods to measure the physical and engineering properties of the stabilized soils. To achieve these objectives a research plan was proposed which included extensive laboratory studies along with supplemental field studies at an active MoDOT site. Unfortunately, after consultation with MoDOT personnel it was determined that there would not be a viable MoDOT field project to work with during the 1-year duration of this project. Therefore, the revised focus of this study was only on laboratory measurements. In consultation with MoDOT personnel, two field sites, Atchison and Putnam were selected for sampling of subgrade soils (one CL and one CH). After an initial testing of several fly ash materials, two fly ash products, Labadie and LaCygne, were selected for evaluation. It was later decided to substitute one of the fly ash materials (LaCygne) with lime kiln dust (LKD) as the soil modifier.

In this report, results are presented from the laboratory testing program which consisted of monitoring stiffness and strength of the soil/modifier mixtures as a function of time, water content, and soil/additive mix ratios. Resilient modulus and unconfined compressive strength of the soil/additive mixtures are presented and discussed. Also, results from laboratory testing of two potential quality control methods that could be implemented in the field are presented.

2. MATERIALS

2.1. Subgrade Soils Tested

The soils tested for this project were sampled from Atchison County and Putnam County, Missouri. The Atchison soils were collected on State Highway A, in Watson, Missouri, about 1 mile west of junction State Highway BB. The approximate location was at 40^{o}28'38.21''N and 95^{o}38'24.65''. Figure 1 displays the grain size distribution of the Atchison soil and Figure 2 shows its Atterberg limits plotted on a USCS plasticity chart. The Atchison soil is classified as a low-plasticity clay (CL). Table 1 gives the numeric values for the Atterberg limits for 3 sets of tests. Figure 3 displays the grain size distribution of the Putnam soil and Figure 4 shows its Atterberg limits on a USCS plasticity chart. The Putnam soil is classified as high plasticity clay. Table 2 gives the numeric values for the Atterberg limits for 3 sets of tests.

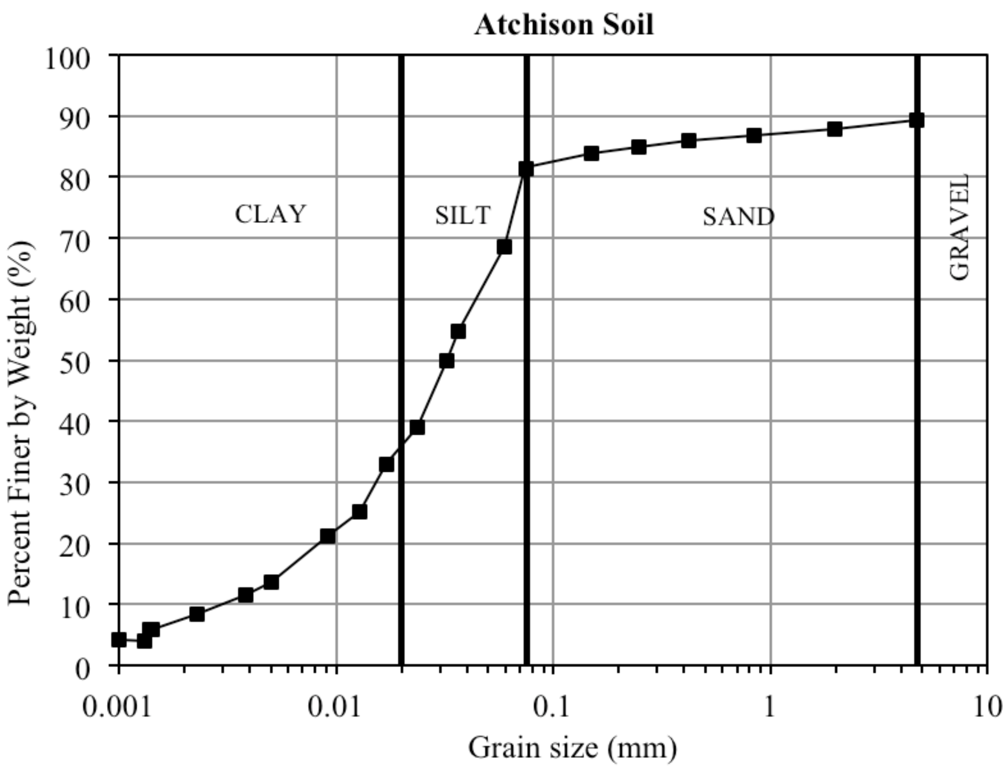

Figure 1 – Grain size distribution curve of the Atchison soil

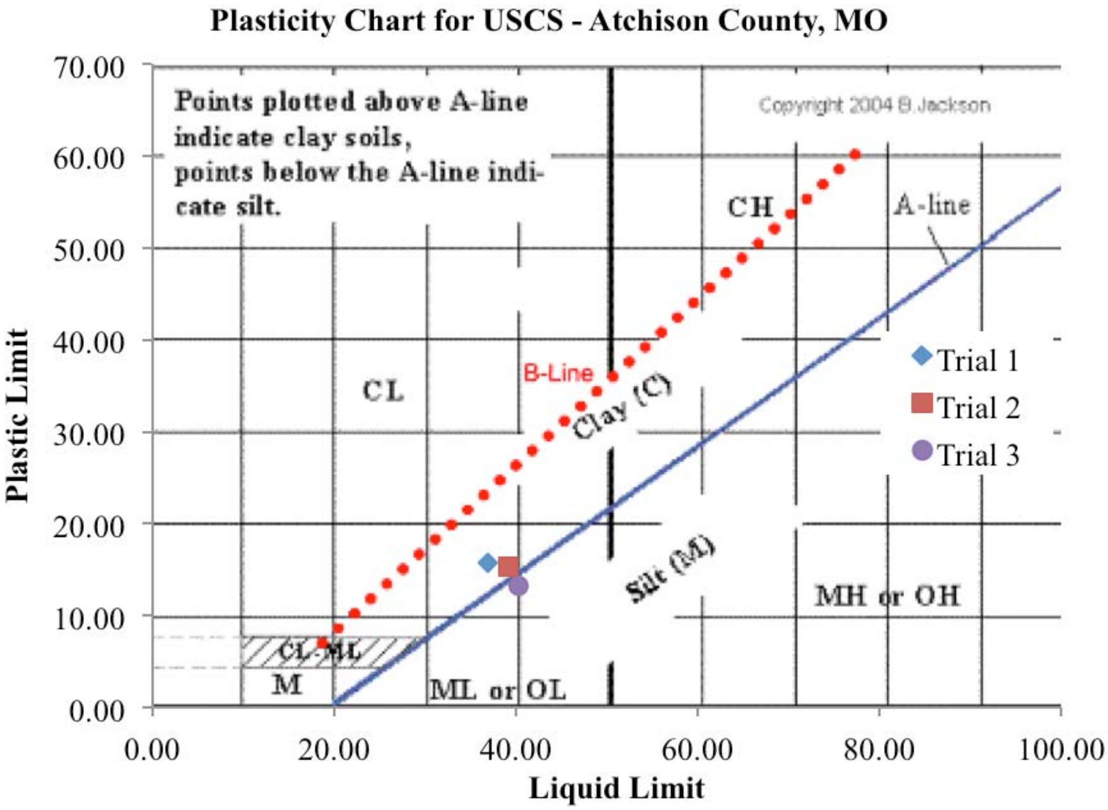

Figure 2 – Atterberg limits on USCS plasticity chart for the Atchison soil

Table 1 – Atterberg limits for the Atchison soil

Trial No.	LL	PL	PI
1	36.95	21.24	15.71
2	39.19	23.81	15.38
3	40.24	26.98	13.26

Table 2 – Atterberg limits for the Putnam soil

Trial No.	LL	PL	PI
1	69.47	31.09	38.37
2	61.21	30.55	30.66
3	59.45	28.15	31.30

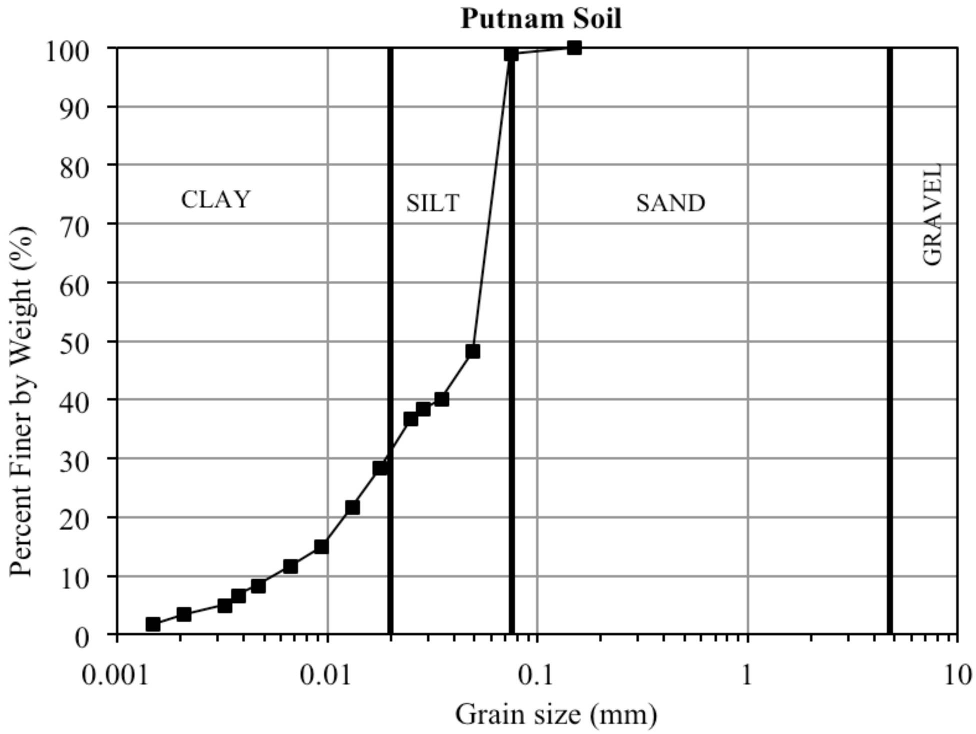

Figure 3 – Grain size distribution curve for the Putnam soil

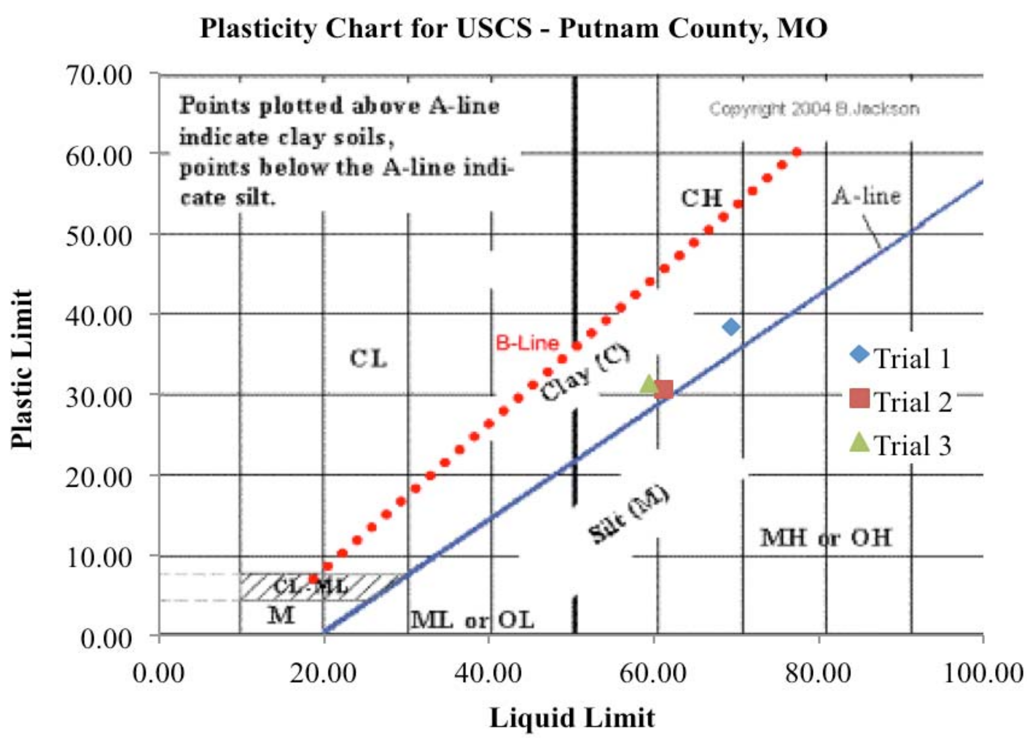

Figure 4 – Atterberg limits on USCS plasticity chart for the Putnam soil

2.2. Additives Used

Labadie Fly Ash

Initially 5 fly ashes were shipped from LaCygne, Nearman, Labadie, Rush Island and Meramec power plants, Missouri. Their physical compositional properties from XRD and SEM-EDS are summarized in Table 3. All fly ashes were derived from combustion of coal and were collected using electro-static precipitators. It is found that all fly ashes have high content of calcium oxide and silicon dioxide. Their CaO-to-SiO_2 ratios ranged from 0.66 to 0.93. The loss on ignition of all the fly ashes was small, with the exception of the Meramec fly ash. Grain size distribution curves of all the fly ashes are presented in Figure 5 and their coefficients of uniformity and curvature were tabulated in Table 4. For Nearman, Rush Island and Labadie fly ashes, they are gap graded and their grain size distribution curves located to the right, which indicated that those three fly ashes were coarser than the other two fly ashes. In general, about 50% of the finer fly ash particles were smaller than 0.075 mm; however, for the coarser fly ashes, only 15% passed the #200 sieve (0.075 mm). The grain size distribution curve of the Atchiosn soil used in this study is also shown in Figure 1. The liquid limit (LL) of the soil and fly ashes are tabulated in Table 4. Set time tests were conducted on the fly ashes and fly ash-soil mixtures with different water contents and different ash-to-soil mix ratios. Based on the laboratory testing, it was decided that the Labadie and LaCygne fly ashes would be used in this project. However, it was later decided to substitute Lime Kiln Dust (LKD) for the LaCygne fly ash.

Table 3 – Percentage of Chemical Compositions in Fly Ash

	Percent of Chemical Compositions (%)				
Chemical Compound	Rush Island (A)	LaCygne (B)	Nearman (C)	Meramec (D)	Labadie (E)
SiO_2	32.26	33.31	30.55	35.42	33.72
Al_2O_3	19.03	20.57	18.78	16.88	21.90
Fe_2O_3	6.24	6.15	7.48	7.97	7.15
CaO	27.94	26.34	28.43	23.21	25.31
MgO	5.55	5.27	5.09	4.87	4.48
SO_3	2.40	1.87	3.33	3.46	2.25
K_2O	0.33	0.43	0.45	0.56	0.41
P_2O_5	1.35	1.27	1.58	1.10	1.20
Ti O_2	1.30	1.59	1.60	1.56	1.30
Na_2O	2.20	1.63	1.50	1.40	1.40
Loss on Ignition	0.26	0.49	0.57	3.05	0.37
Specific Gravity	2.73	2.72	2.72	2.70	2.71
CaO/ SiO_2	0.87	0.79	0.93	0.66	0.75
Classification	C	C	C	C	C

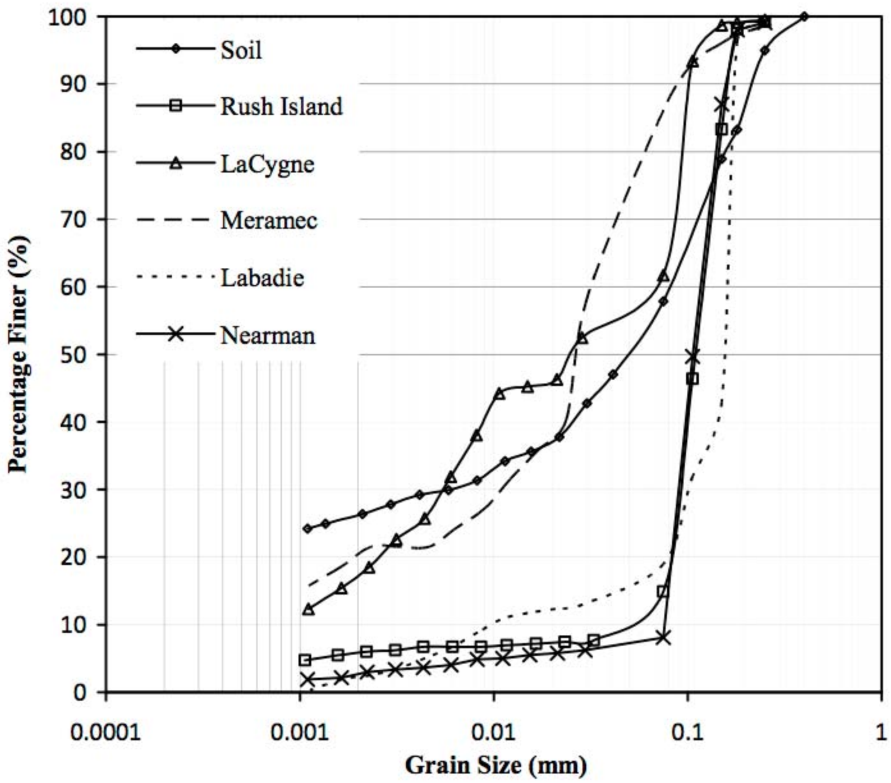

Figure 5 – Grain size distribution of fly ashes and Atchison soil

Table 4 – Index properties of and fly ashes and Atchison soil

	Soil	Rush Island	LaCygne	Meramec	Labadie	Nearman
C_u	3.1	1.2	0.6	5.6	5.9	0.8
C_c	800.0	2.6	77.8	50.0	17.0	1.63
LL	40.0	25.5	23.0	30.2	21.8	20.1

Lime Kiln Dust

Lime kiln dust (LKD) is a byproduct of lime manufacturing and consists primarily of CaO and $CaCO_3$. The LKD used in this study was supplied by Mississippi Lime and goes by the name Code L. The chemical properties of Code L, as listed on the technical data sheet are: 28-38% CaO; 31-38% $CaCO_3$, 5-8% $Ca(OH)_2$, 4-8% SiO_2, and 1.5 – 3% Fe_2O_3, 1-3% Al_2O_3, and 2.5 – 3.5% S.

3. METHODS

3.1. Soil Preparation

The soil preparation procedure was the same for both free-free resonant column (FFRC) and unconfined compressive strength (UCS) testing. The processed soil used was oven-dried overnight at $110^{\circ}C$ and sieved with particles retained on the No. 4 sieve discarded. The soil was mixed with a spatula while a spray bottle gradually added the desired amount of water based on mass of dry solids multiplied by the target water content percentage. Once mixed, the wet soil was placed in a plastic bag and taped shut to temper overnight as shown in Figure 6. Once sufficiently tempered, the water content was taken according to ASTM D2216 and the soil was mixed with the additive (fly ash or LKD) before compaction. The mass of soil additive was determined by multiplying the dry weight of soil by the desired percentage mix of additive. The mixing process is shown in Figures 7 to 9. The soil/additive mixture was mixed by hand to facilitate better distribution of the soil additive throughout the soil.

Figure 6 – Photo of mixed soil tempering in plastic bag

Figure 7 – Soil additive (left) and soil (right) prior to mixing

Figure 8 – Soil and additive combined prior to mixing

Figure 9 – Soil and additive after mixing

3.2. Compaction Procedures

Standard proctor tests were performed by researchers at Missouri Science & Technology on six-inch diameter samples used for the Briaud Compaction Device (BCD) modulus testing. Compaction was also performed on some 4-in samples using the ASTM D698 procedure to verify the consistency of the results. A comparison of values indicated good agreement between four-inch standard proctor mold curves and the curves created with six-inch samples. Using the compaction information provided by MST, samples were prepared wet, dry and near optimum. Early tests were performed using one sample dry of optimum, one near optimum, and one wet of optimum. For later tests, five water contents were selected (approximately 4% dry, 2% dry, "optimum", 2% wet , 4% wet) as targets for the FFRC testing..

To obtain reliable results, FFRC measurements must be performed with samples that have length-to-diameter ratios of approximately two. Therefore, it was not possible to use a standard compaction mold to prepare the samples. Instead, the compaction mold that was used was a 2.9-inch diameter steel mold with a height of 5.2 inches producing a height-to-diameter ratio close to two. Samples were prepared using equivalent energy per volume as the standard proctor test. In addition, a compaction hammer was constructed with a standard proctor mass and height of drop (5.5 lbs and 12 inches respectively) but with a smaller diameter to better replicate the kneading effect of the standard proctor test in a 4-inch mold. This hammer produced better samples with respect to the standard proctor curve than a standard proctor hammer with equivalent energy in a comparative study.

The soil/additive mixture was placed in the mold in three lifts with each lift compacted with fifteen blows in the pattern established by ASTM D698. An overview of the compaction process is shown in Figures 10 and 11. Once compaction was completed, the collar was removed and the excess soil was trimmed with a wire until the top of the sample was uniform and flat, as in the photo in Figure 12. The weight of the mold and sample was then recorded and the specimen was extruded from the mold. The mold used was a split mold but early tests indicated the tendency of the reinforced specimens to crack upon splitting of the mold, so extrusion was used for all resonance testing and unconfined strength specimens. The extrusion process is shown in the photos of Figures 13 and 14.

Figure 10 – Compaction equipment and soil

Figure 11 – Compaction of one layer in the 2.9"-dia. mold

Figure 12 – Trimming of excess soil after compaction

Figure 13 – Compaction mold inserted into extrusion frame

Figure 14 – Sample being extruded

Once extruded, the samples designated for unconfined strength testing were wrapped in plastic, labeled, and placed in a cure room until the designated testing time. The resonance specimens were wrapped with filter paper that had been cut with 0.25" strips across the top and bottom and 0.5" vertical strips alternated with 0.5" spaces to facilitate uniform vacuum around the specimen. An example of the filter paper wrap is shown in Figure 15. End caps were placed on the sample to facilitate attachment of instrumentation and application of vacuum pressure to the specimens.

A rubber membrane with dimensions of 2.5" in diameter, 9" in height and 0.012"thick, encased the specimen, filter paper, and end caps (Figure 16). The membrane was secured to the end caps with rubber O-rings. The final prepared sample is shown in Figure 17.

Figure 15 – Sample with top plate and filter paper added

Figure 16 – Membrane added to sample

Figure 17 – Completed sample with o-rings added to restrain the membrane

3.3. Free-Free Resonance Testing

3.3.1. Background on Free-Free Testing

The free-free resonant column (FFRC) test proposed by Stokoe et al. (1994) allows for fast and economical determination of the small-strain resonant frequency of a cylindrical soil sample under both axial and torsional excitation. The FFRC is a simple apparatus for obtaining stress wave velocities, small-strain compression and shear moduli, and resonant frequencies of samples under low confinement pressures. The test was chosen because it is easy to perform and confining pressures representative of pavement subgrade fall within the workable range for the FFRC test.

In this test, the specimen can be viewed as a rod of finite length that resonates at a specific frequency when excited. The direction of the excitation (longitudinal or torsional), the stiffness of the specimen, and the length of the specimen determine the resonant frequency as governed by wave propagation theory.

The resonant frequency for a longitudinal compression wave is related to the velocity as:

$$V_C = \frac{2\pi L f_c}{\alpha} \tag{3.1}$$

where, V_C is the unconstrained compression wave velocity, L is the length of the specimen, f_c is the resonant frequency, and α is a factor to account for the mass of the end caps attached to the specimen.

A wave excited torsionally propagates through the sample as a shear wave with a particle motion perpendicular to the wave propagation direction. The resonant frequency allows for the back calculation of velocity from:

#

$$V_s = \frac{2\pi L f_s}{\beta} \tag{3.2}$$

where, V_s is the shear wave velocity, f_s is the resonant frequency from the torsional wave, and β accounts for the polar moment of inertia of the end caps.

The presence of accelerometers and vacuum fittings discussed later are also accounted for in the α and β factors. The measured frequencies, f_c and f_s are the first mode resonant frequencies for unconfined compression and shear wave, respectively.

As described above, the measurements to determine V_C and V_s come from measurements of the auto-power spectrum showing frequency versus amplitude. Another type of measurement for compression wave velocity can be performed in the time domain. This allows for the measurement of the time it takes for a compression wave to travel from one end of the sample to the accelerometer on the other end. From this the constrained wave velocity, V_P , can be determined by:

$$V_P = \frac{L}{t^*} \quad (3.3)$$

where L is the length of the specimen and t^* is the net time the wave travels through the sample:

$$t^* = t - \frac{L_C}{V_{AL}} \quad (3.4)$$

where, t is the measured time of travel, L_C is the length (or thickness) of aluminum end caps, and V_{AL} is the constrained wave velocity of aluminum.

Each velocity value can be used to calculate the associated small-strain modulus values from:

$$E_{MAX} = \rho V_C^2 \quad (3.5)$$

$$G_{MAX} = \rho V_S^2 \quad (3.6)$$

$$M_{MAX} = \rho V_P^2 \quad (3.7)$$

where ρ is the mass density of the specimen, E_{MAX} is the small-strain Young's modulus, G_{MAX} is the small strain shear modulus, and M_{MAX} is the small-strain constrained modulus.

3.3.2. FFRC Testing Procedures Used in This Study

Free-free resonance tests were used in this study to monitor the changes in the modified soil with time. An initial baseline measurement was performed for each sample immediately after the specimens were compacted and the membrane was applied. (This time is considered time zero in this study, however, it is about 20 to 40 minutes after water was first introduced in the soil/additive mixture.) Measurements were then taken at approximately 1 hour, 3 hours, 12 hours, 1 day, 3 days, and 7 days (in most cases). One objective of this portion of the work was to evaluate potential non-destructive testing methods that could be performed in the lab and the field for construction quality control of stabilized subgrades. Therefore, the relevant time frame for this application is the first few hours after placement. A second objective was to study how much gain in modulus was achieved for soil placed at optimum or modified wet of optimum with different additives. The application considered here is the modification of soil to develop a viable working platform. For this application the relevant time frame is on the order of days after compaction. For these reasons this portion of the study focused on a time frame out to 3 to 7 days. Longer term measurements out to 28 days or more using other methods.

To perform the FFRC measurement the sample was hung from a frame using two elastic cords and a vacuum pressure of 5 psi was applied through one of the two equally spaced fittings on one endplate, as shown in Figure 18. This vacuum pressure was chosen to simulate the small confining pressures at shallow depths of the subgrade. Two fittings were installed to balance the moment of inertia for the end plate. The opposite end plate was a solid disk of aluminum on which sensors were placed to detect the wave movements. Three accelerometers (Model no. 352C66 from PCB Piezotronics) were glued to the plate, two vertical for shear measurement and one horizontal to measure axial constrained and unconstrained compression waves. The two vertical accelerometers were placed on the same plane with vertical orientation and their output was summed after reversing the polarity of one of the outputs. This summation on the same channel amplifies the torsional response and cancels out bending motions created by the propagated wave.

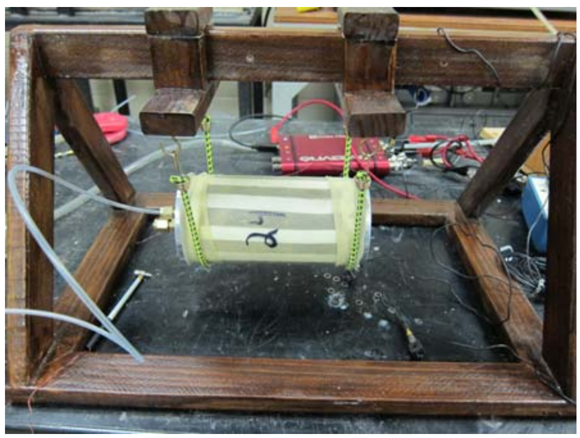

Figure 18 – Sample in free-free resonant column

The glue method to attach the accelerometers was determined to be inefficient because of the excessive time needed to clean the dried glue off of accelerometers and the end plate. Therefore, the end plate was modified with the addition of three tapped holes to allow for attachment of the accelerometers. Two of the holes allowed for the coupling of an aluminum cube (Model no. 080B16 from PCB Piezotronics) made specifically for accelerometers and the center hole was tapped so that the axial accelerometer could be screwed directly into the end plate. The final placement of the accelerometers is shown in Figure 19.

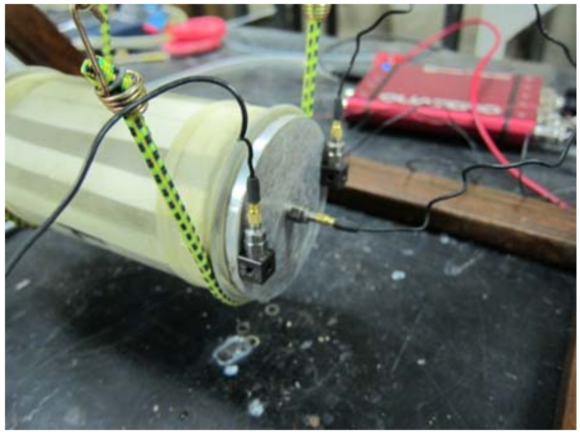

Figure 19 – Accelerometer attached to endplate

Once the accelerometers were attached to the sample and the vacuum pressure reached 5 psi, the measurements were performed. SignalCalc, a software package from Data Physics, was used to record the experiments. The software is designed to work with the Quattro signal analyzer used in this study (model no. DP240). Parameters were input to designate in which domain the measurement was to be taken. When the appropriate file was selected, the sample was struck with an instrumented hammer (Model no. 086D80 from PCB Piezotronics) either axially on the center of the end plate, or vertically to induce shear waves, as shown in Figure 20. The resonant frequency was determined from the first peak of the frequency spectrum (Figure 21) and recorded in a spreadsheet. A spreadsheet was developed using equations 3.1-3.7 to calculate the modulus values for each sample from the measured frequency values. This method allowed for the tracking of the change in velocities and moduli with time.

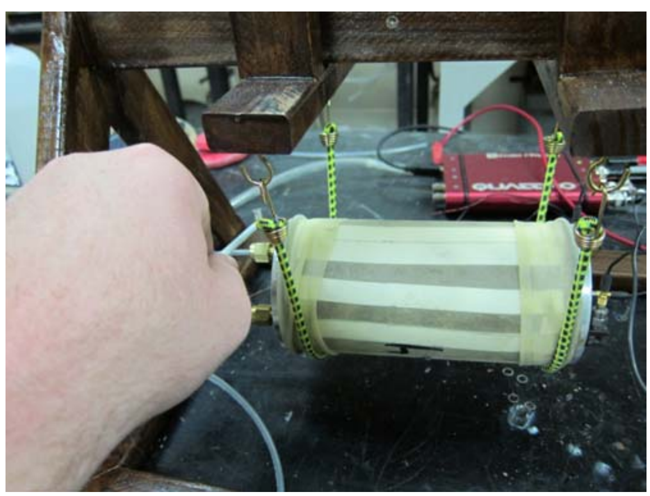

Figure 20 – Downward strike with instrumented hammer to induce shear wave

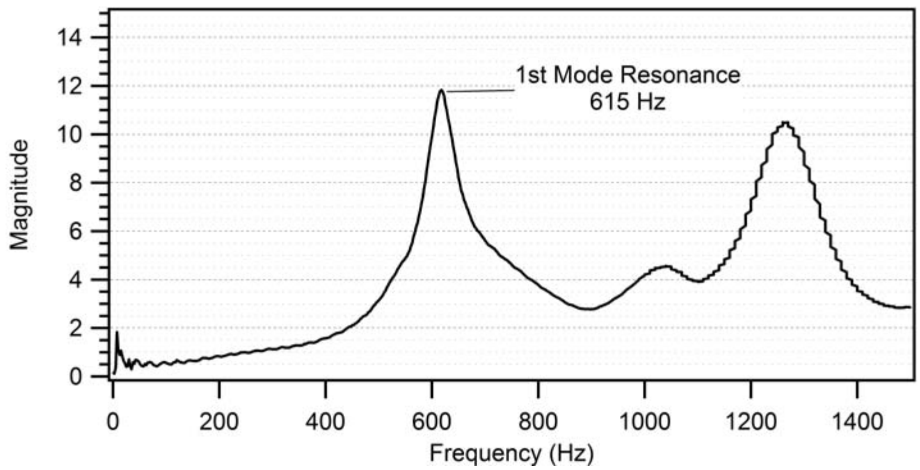

Figure 21 – Frequency response showing first mode resonance peak at 615 Hz for torsional test of Atchison soil with 10% fly ash tested 3-hrs after compaction

In order to measure the constrained modulus, the P-wave velocity was directly measured in the time domain. The sample was struck axially to produce a longitudinal wave in the same way as the unconstrained measurement (Figure 22). In this measurement however the velocity is determined using the difference in time between the initiation of the impulse generated by the hammer and the arrival of the wave at the accelerometer (Figure 23). The velocity was determined using equations 3.3 and 3.4. The velocity was then used to calculate the associated constrained modulus with equation 3.7.

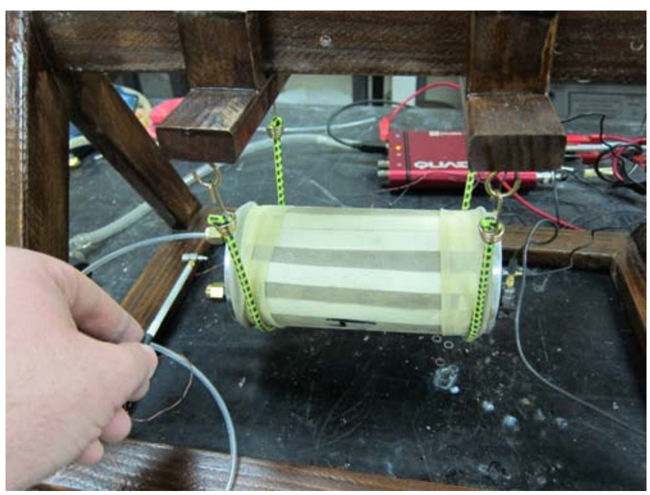
Figure 22 – Instrumented hammer strike to induce axial waves

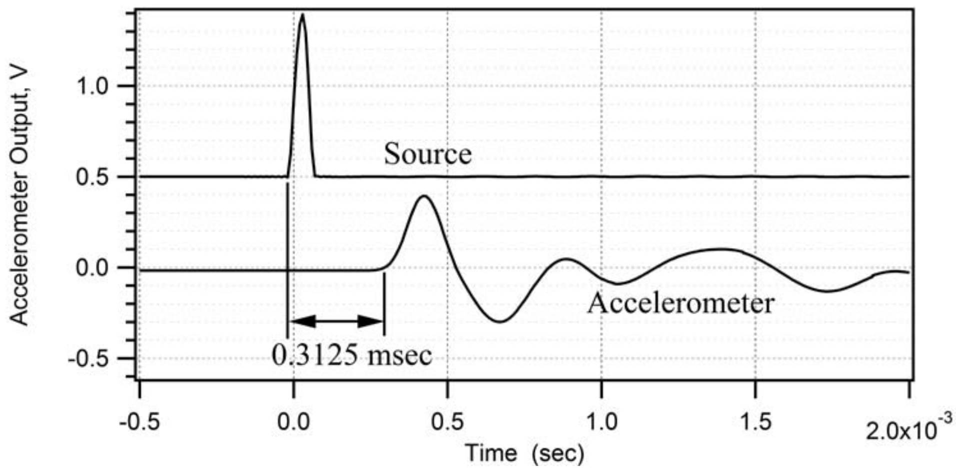

Figure 23 – Time domain measurement of P-wave velocity measurements from testing on Atchison soil mixed with 10% fly ash tested 3 hrs after compaction

After the three measurements were performed, the specimens were held under a confinement pressure of 5 psi to simulate subgrade conditions between readings. Due to equipment limitations, specimens prepared dry of optimum were left attached to vacuum and those wet of optimum were placed in triaxial cells with a confining air pressure of 5 psi. The vacuum showed a tendency to extract significant water from wet specimens over time but not from those prepared dry of optimum. The specimens in the cells were attached to one of the pressure lines that was open to the atmospheric pressure (Figure 24) to allow consolidation under the confining pressure applied to the cell, shown in Figure 25. At each designated testing time the samples were removed from confinement, a vacuum pressure of 5 psi was immediately applied to the samples and the velocity measurements were performed.

It should be emphasized that all of these measurements were performed in the small-strain range where the soil structure is not impacted by repeated measurements. Therefore, this is a truly non-destructive measurement which allows tracking of the soil stiffness with time.

Figure 24 – Specimen after testing placed in pressurized triaxial cell

Figure 25 – Sample confined in pressurized cell

3.4. Unconfined Compression Testing

Unconfined compressive strength tests were also performed on the soil/additive samples. Unlike the FFRC tests, the UCS test is obviously destructive and requires construction of multiple samples to track changes over time. For each soil/additive mixture designated for UCS testing, multiple samples were prepared so that testing could be performed at 1 hour, 1 day, 7 days, 14 days, and 28 days. Do to the excessive number of samples required to perform multiple tests for each soil mixture and time, multiple tests of the same soil mixture and time were performed in only a few cases. Also, the UCS tests were limited to the case of samples prepared near the optimum water content. Soil sample preparation followed the procedures discussed previously.

When all of the specimens were compacted and wrapped in plastic they were taken to the cure room to setup in a 100% humid environment. When tested, the specimen was removed from the room and unwrapped. After being placed in a triaxial cell with no confining pressure or membrane, the specimen was moved onto a load frame, as shown in Figure 26. The UCS measurement was performed using an automated system from GeoTac. The strain rate for the tests was 1% per min. for all specimens. Once broken, the specimen was removed and the water content was measured.

Figure 26 – Load Frame used to perform unconfined compression strength measurements

3.5. Briaud Compaction Device Testing

Several existing devices are capable of determining subgrade and base material soil moduli in the field including, the Falling Weight Deflectometer (FWD), the Lightweight Falling Weight Deflectometer (LFWD), the Geogauge, the Cleg Impact Hammer, and the Plate Load Test (PLT), to name a few. The Briaud Compaction Device (BCD) is another type of such device. The BCD is a simple, small-strain, nondestructive testing apparatus that can be used to evaluate the modulus of compacted soils. The BCD works by applying a small repeatable load to a thin plate in contact with the compacted soil of interest, and recording the resulting stains. A large strain indicates a weaker soil while a small strain indicates a stiffer soil. The load is applied to the plate manually by the operator. This load is recorded by a load cell. The resulting deflections of the thin plate are measured with an assortment of radial and axial strain gages mounted on the thin plate. The acquisition and processing unit within the device then displays the calculated BCD modulus. The software within the device uses correlations determined from field and laboratory tests in order to calculate a low strain modulus, referred to as the BCD modulus. The strain level associated with the BCD is on the order of 10^{-3} (Briaud et al., 2006).

Previous studies have shown that the BCD could be a viable alternative to current practices used for compacted soil quality control/quality assurance (QC/QA) (Li, 2004). Studies have shown that the BCD strongly correlates with other field compaction tests such as the Plate Load Test (Briaud et al., 2006). Current compaction control practices have been in place for decades and consist of determining a maximum dry unit weight in the laboratory then specifying a percentage of that maximum to be achieved in the field. Dry density gives a measurement of how many soil particles are in a specific volume, but other factors such as suction, cementation and confinement have greater influence on the modulus (Briaud et al., 2006). It is well understood that at maximum dry density, a soil has the lowest potential for excessive settlement, highest shear strength, and lowest erosion problems. Less understood, however, is the variation of soil moduli with dry density and moisture content. Studies by Seed et al. (1967) have shown that the Resilient Modulus varies depending on both dry density and moisture content, and varying testing conditions can yield largely varying soil response. Much of the soil compaction monitoring is conducted for pavement subgrades, a situation where moisture contents vary over seasons, and soil modulus is more important than most other soil properties. In this respect, perhaps it is more advantageous to specify field compaction based on a modulus value rather than a target dry density. There are several field testing devices available for field modulus evaluation (Lenke et al., 2003; Li, 2004; Alshibli et al., 2005; Chen et al., 2005; Ampadu and Arthur, 2006; Briaud and Rhee, 2006; Lin et al., 2006). Most are cumbersome, require specialized training, and only loosely correlate values obtained from the device with actual moduli values that can be determined in the laboratory. Unfortunately there does not exist a comprehensive and/or convenient test or method for determining modulus based compaction specifications in the laboratory that can be monitored easily in the field. The BCD was developed as a possible solution to these issues.

The strain response of a soil can be described by many different types of moduli. In addition, the testing conditions, confinement, strain level, and strain rate are all contributing factors to soil moduli (Li, 2004). The modulus defined by the BCD is a stress strain relation corresponding to a strain level of 10^{-3}, stress level of 50kPa, and time of loading of a few seconds. Previous studies have shown that the BCD modulus corresponds well to other modulus defining tests (Rhee, 2008).

The purpose of the BCD laboratory test is to establish a modulus versus moisture content relationship, similar to the dry density versus moisture content relationship established from proctor compaction tests. Once the soil was compacted in the 6 inch split mold, the surface was finished smooth with a straight edge and weighed per standard proctor testing procedures. After the soil and mold were weighed BCD test was conducted in accordance with the BCD User's Manual. This step is shown in Figure 27. The BCD test is designed to complement the proctor compaction test. The BCD has two modes of operation, one for field testing and one for laboratory testing. The two separate modes of operation account for the boundary effects of the proctor mold that would not occur in the field (Li, 2004). It is important that the device is set to the laboratory setting in order to acquire meaningful results (BCD Manual, 2008). To get a good average of the BCD modulus, the manual recommends recording four measurements on the compacted soil. The four measurements should be taken rotating the BCD 90 degrees between each test then averaged to get the BCD modulus (Li, 2004).

Figure 27 – BCD testing on a compacted soil sample in a 6” split mold

3.6. Resilient Modulus Testing

Resilient modulus (Mr) is the cyclic axial stress, S_{cyclic}, (resilient stress) divided by the resilient (recovered) axial strain, ε_r, i.e.

$$M_r = S_{cyclic} / \varepsilon_r.$$

In the AASHTO 307 Standard, a repeated axial cyclic stress of fixed magnitude, load duration (0.1 sec), and cyclic duration (1.0 sec) is applied to a cylindrical test specimen. During testing, the specimen is subjected to a dynamic cyclic stress and a static confining pressure in the triaxial chamber. The total resilient (recoverable) axial deformation response of the specimen is measured and used to calculate the resilient modulus.

The M_r test equipment was in accordance with the AASHTO T 307 for subgrade materials, The Geotechnical Consulting and Testing Systems (GCTS) control system was used to control the MTS 858 closed-loop servo-hydraulic load system, a Humboldt triaxial chamber capable of housing a 2.8 in. diameter specimen was adopted and a GCTS data acquisition system was employed in this study. Load was measured with an external 2200-lb load cell located between the actuator and the chamber piston rod. Deformation was measured using two Schaevitz MHR-250 linear variable differential transducers (LVDTs) mounted externally to the cell. The range of the LVDTs was ± 6.35 mm. Air was used as the confining fluid. Triaxial cell pressure was controlled manually via a pressure regulator, and measured with a pressure transducer linked to the GCTS data acquisition system.

3.6.1. Test Set Up

Mr test specimens were achieved by static compaction. The specimens were fabricated in the following manner. Knowing the target dry densities and moisture contents, and the target compacted volume of the specimen, enough oven-dry material was obtained to produce the five "lifts"; the oven-dry soil and fly ash (lime kiln dust) was placed into a big pan and water was added to bring the material to the OMC plus a small amount to allow for moisture loss. After hand mixing, the material was returned to a large pan, covered, and allowed to cure for at least 15 minutes (usually longer). After curing, a square point scoop was used to systematically translate the calculated amount of moist material from the pan and place it into the designed mold to be compacted as a lift. After compaction of the 5 lifts, the remaining material was used for as-compacted moisture content determination. The soil specimen made from the static compaction method was 2.8-in diameter by 5.6-in height.

The weight, height and diameter of the Mr specimen was measured and a check was performed as to whether the density had reached the 95% compaction level in accordance with the proctor test results. A plain latex membrane was soaked for 16 hours before usage. After making the specimen and curing the sample, specimens were placed in the triaxial cell as shown in Figure 28.

When the specimen had been placed into the triaxial chamber, the cell was transferred to the MTS 858 testing frame and all the drainage valves were kept open. A confining pressure was applied and the two small LVDTs were mounted around the loading piston. A contact stress of 10 percent of the maximum applied axial stress during was maintained, and the loading sequence tabulated in the Table 5 below, was applied. The resilient modulus tests carried out on fly ash treated and untreated subgrade soil strictly followed the ASSHTO Designation T 307-99 (Determining the resilient modulus of soils and aggregate materials).

Table 5 – Testing sequence for the subgrade soil

Sequence No.	σ_3 (psi)	σ_d (psi)	0.9 σ_d (psi)	0.1 σ_d (psi)	No. load applications
0	6	4	3.6	0.4	500
1	6	2	1.8	0.2	100
2	6	4	3.6	0.4	100
3	6	6	5.4	0.6	100
4	6	8	7.2	0.8	100
5	6	10	9.0	1.0	100
6	4	2	1.8	0.2	100
7	4	4	3.6	0.4	100
8	4	6	5.4	0.6	100
9	4	8	7.2	0.8	100
10	4	10	9.0	1.0	100
11	2	2	1.8	0.2	100
12	2	4	3.6	0.4	100
13	2	6	5.4	0.6	100
14	2	8	7.2	0.8	100
15	2	10	9.0	1.0	100

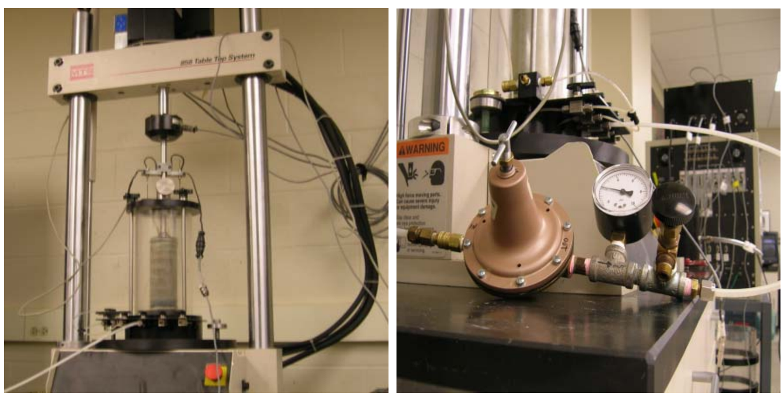

Figure 28 – Resilient modulus test setup

4. RESULTS

4.1. Compaction Results

Standard proctor compaction tests were first carried out to determine the maximum dry unit weight and optimum moisture content. This information is used for construction of samples used in the free-free resonance tests, unconfined compression strength tests, and resilient modulus tests. Figures 29-32 show the compaction curves for Atchison soil with and without additives and Figures 33-38 display the compaction curves for the Putnam soil with and without additives. The amounts of fly ash added in soil were 10%, 15%, and 20% by weight, respectively, while 4% and 8% were selected for LKD.

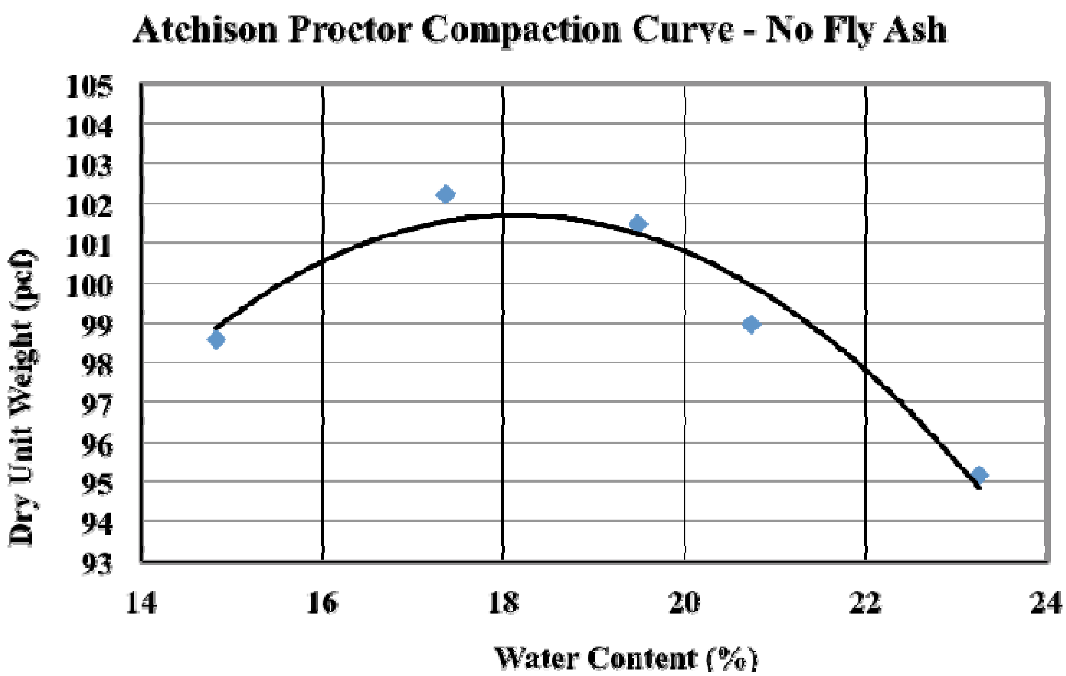

Figure 29 – Proctor compaction curve for Atchison soil with no fly ash

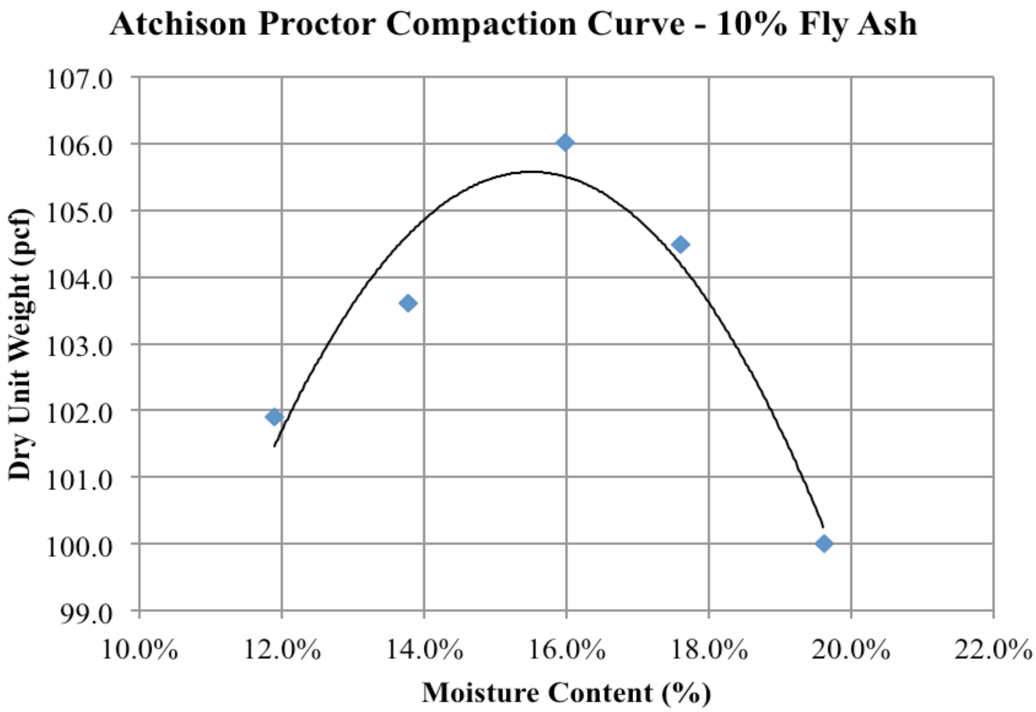

Figure 30 – Proctor compaction curve for Atchison soil with 10% fly ash

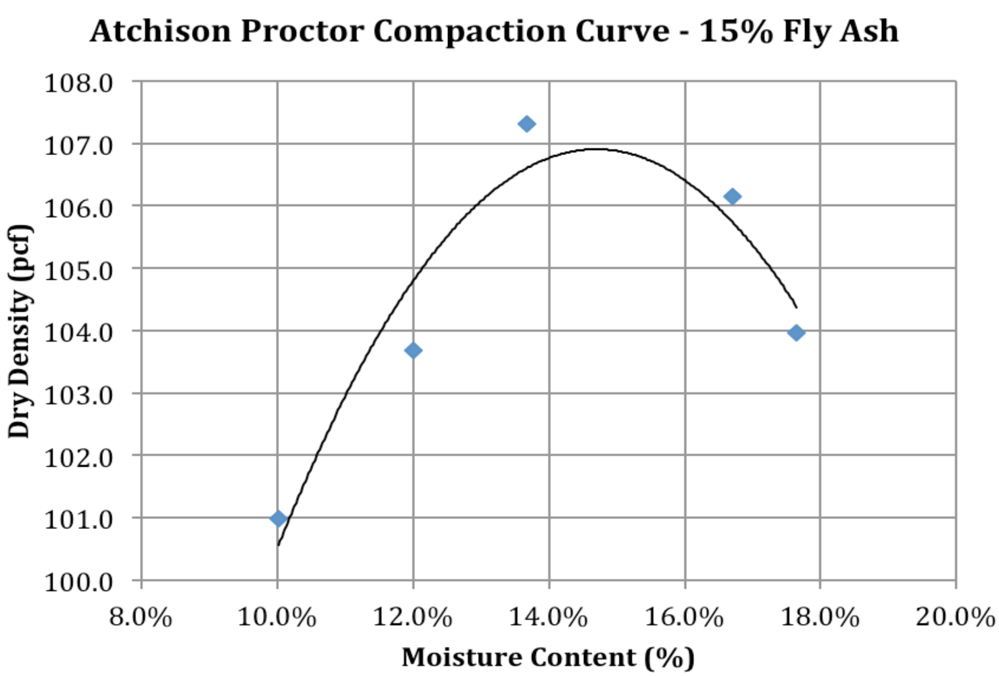

Figure 31 – Proctor compaction curve for Atchison soil with 15% fly ash

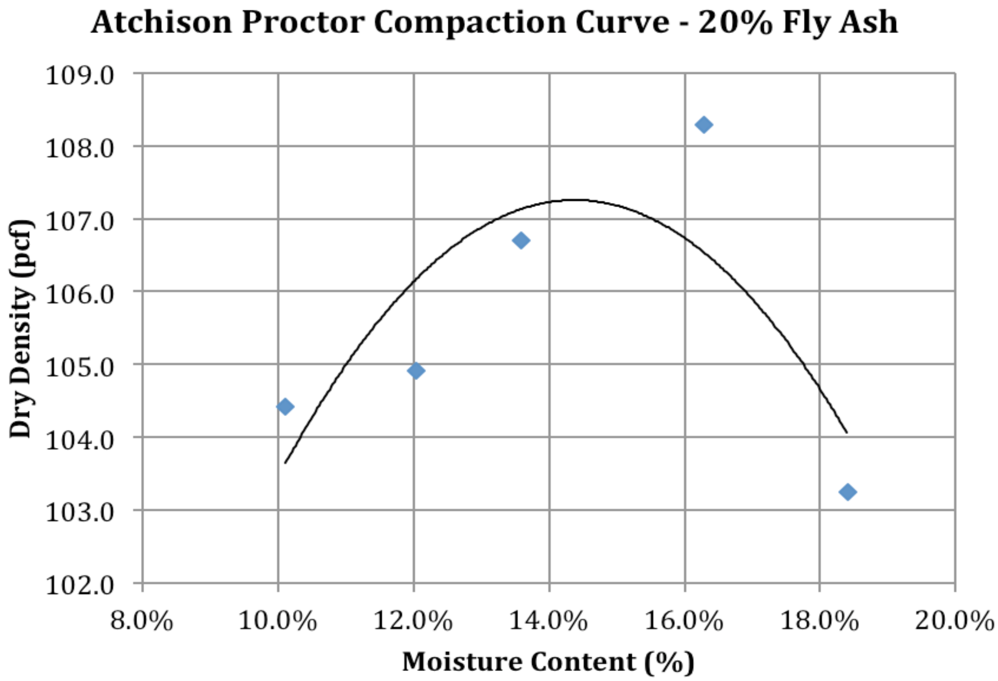

Figure 32 – Proctor compaction curve for Atchison soil with 20% fly ash

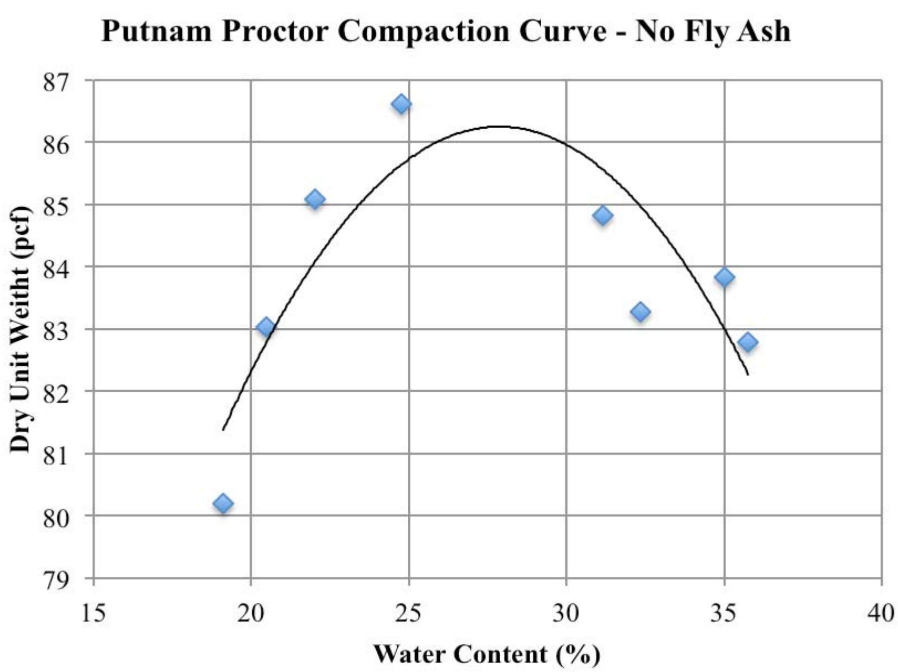

Figure 33 – Proctor compaction curve for Putnam soil with no fly ash

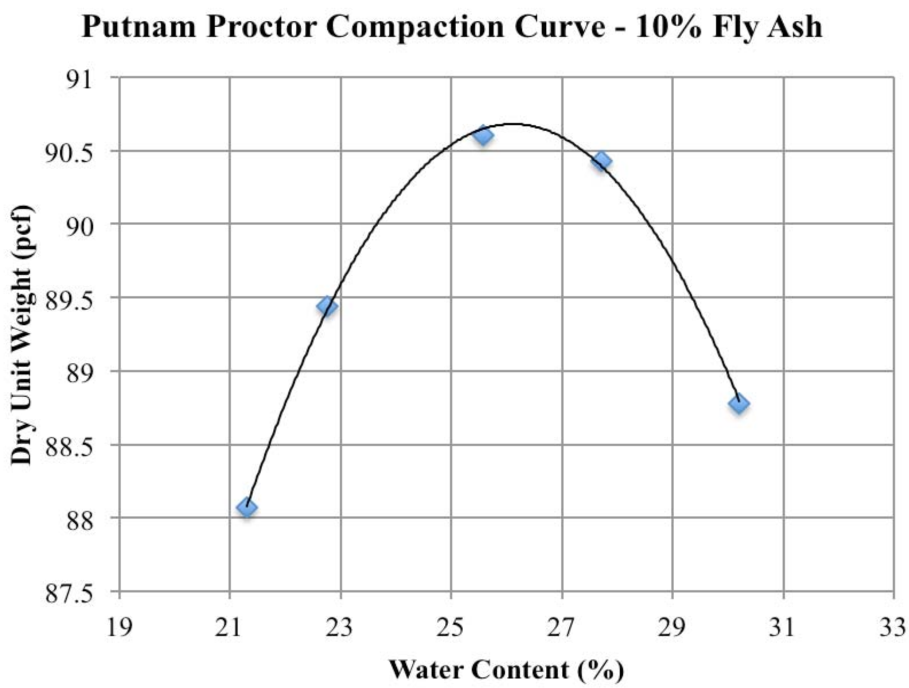

Figure 34 – Proctor compaction curve for Putnam soil with 10% fly ash

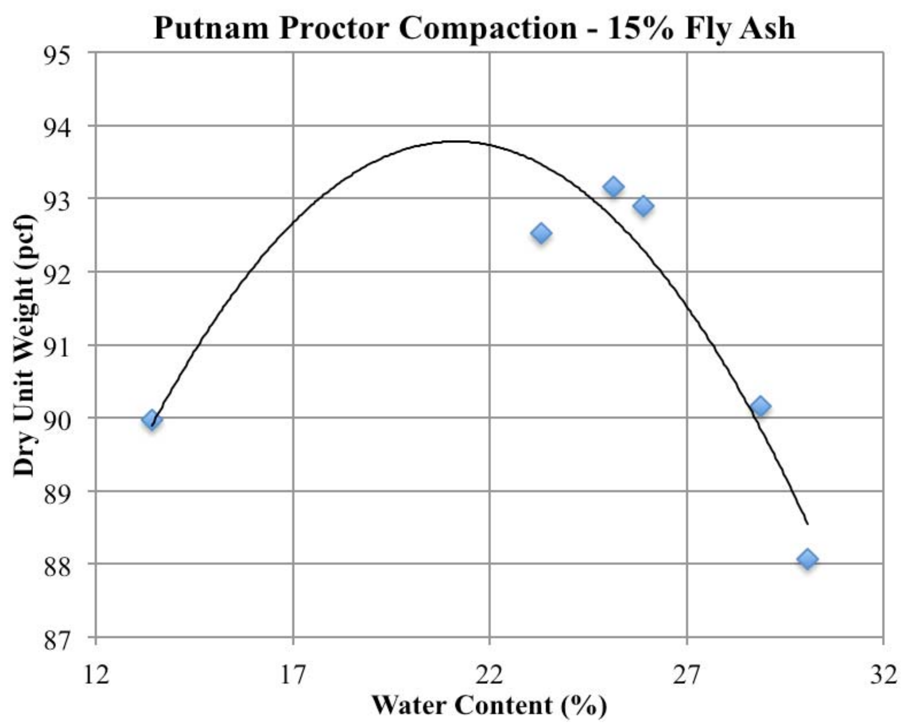

Figure 35 – Proctor compaction curve for Putnam soil with 15% fly ash

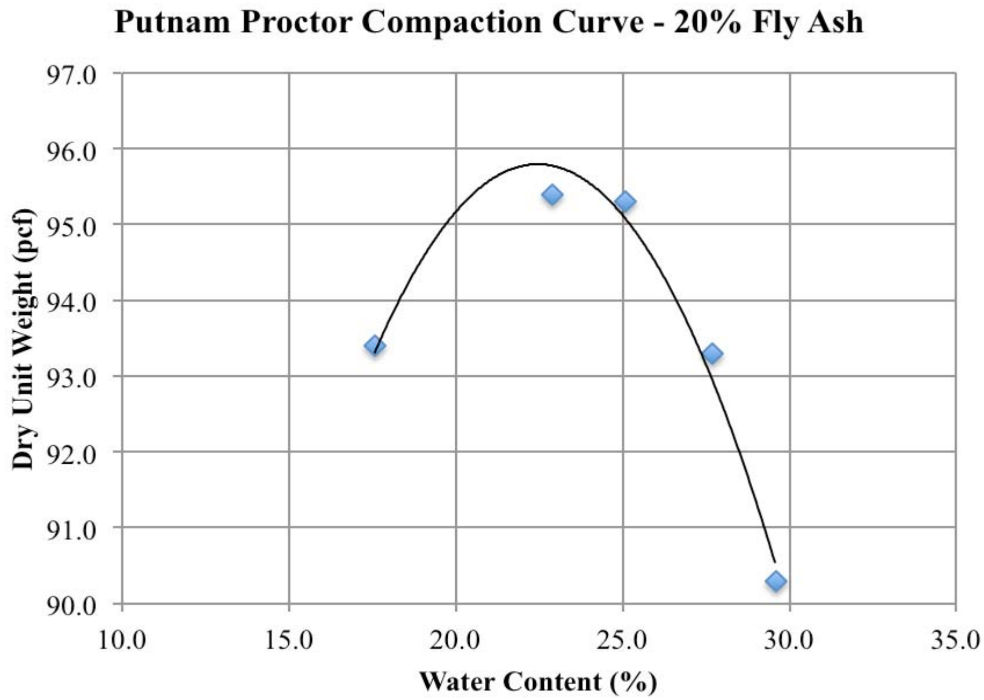

Figure 36 – Proctor compaction curve for Putnam soil with 20% fly ash

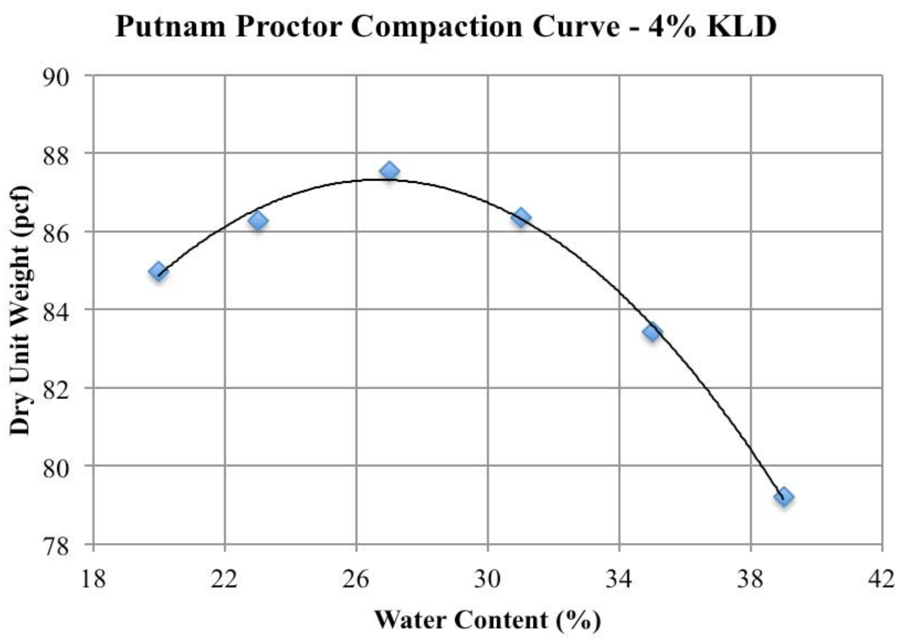

Figure 37 – Proctor compaction curve for Putnam soil with 4% LKD

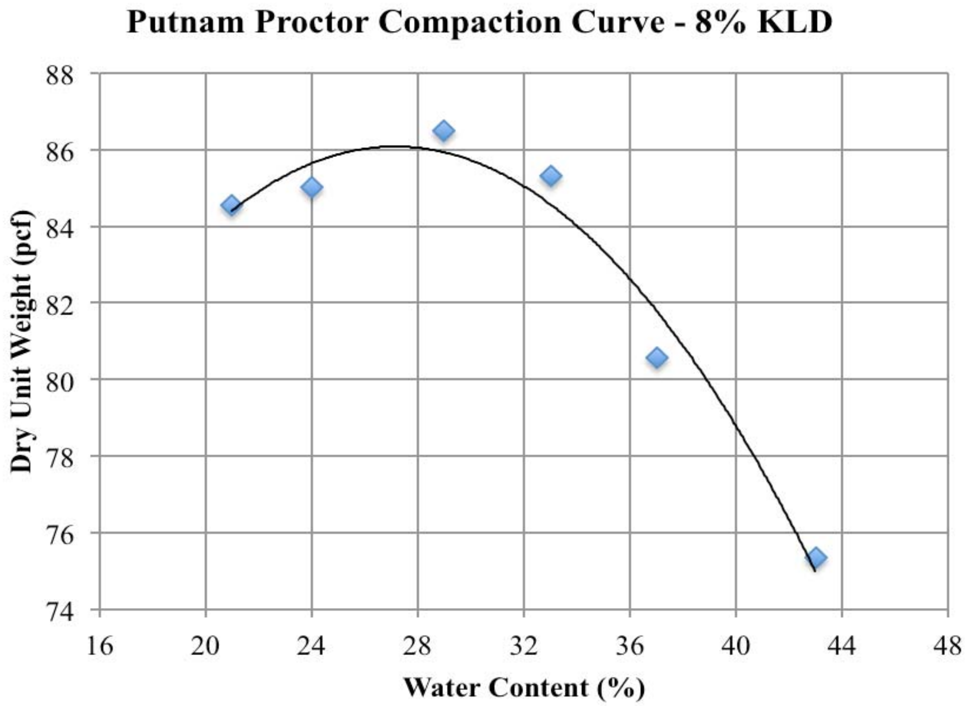

Figure 38 – Proctor compaction curve for Putnam soil with 8% LKD

4.2. Atchison Small-Strain Modulus Results – Time Plots

As discussed above, the free-free resonance test allows for measurement of three elastic constants, namely Young's modulus (E), shear modulus (G), and constrained modulus (M). Also, because the resonance test is non-destructive, it is possible to monitor changes in modulus of a single sample with time. Presented in Section 4.2.1 through 4.2.7 are plots of modulus values versus time for: (1) the Atchison subgrade soil alone, (2) Atchison soil mixed with 10%, 15% and 20% fly ash, and (3) the Atchison soil mixed with 4% and 8% LKD. As shown in Section 4.1, the optimum water content changes significantly with the addition of fly ash to the specimen. Therefore, the target water contents also changed depending on the amount of fly ash or LKD added to the soil. The objective was to prepare samples at optimum, 2% and 4% below optimum, and 2% and 4% above optimum. In some cases the actual water contents differed somewhat from the targeted values.

The objective of this portion of the study was to track changes in the modulus of the soil from immediately after compaction to 7 days after compaction. In several cases, there was a problem with the 7-day reading so the last reading was at 3-days. The very short-term values measured in the hours after mixing and compaction of the soil are needed to assess if field methods such as surface wave velocity measurements could be used as a means of quality control and assessment shortly after placement of the subgrade. The 3-day and 7-day values were selected to simulate the changes in soil properties that could be expected between subgrade modification activities to provide a viable working platform and pavement construction activities. A detailed discussion of the results is presented in Section 5.0

4.2.1. Atchison Subgrade Soil No Additive

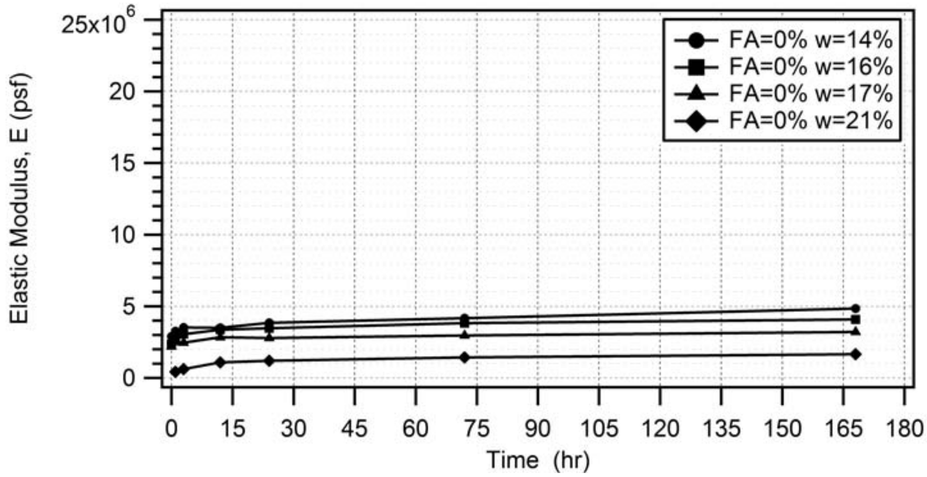

Figure 39 – Change in Young's modulus with time; Atchison soil with no additive

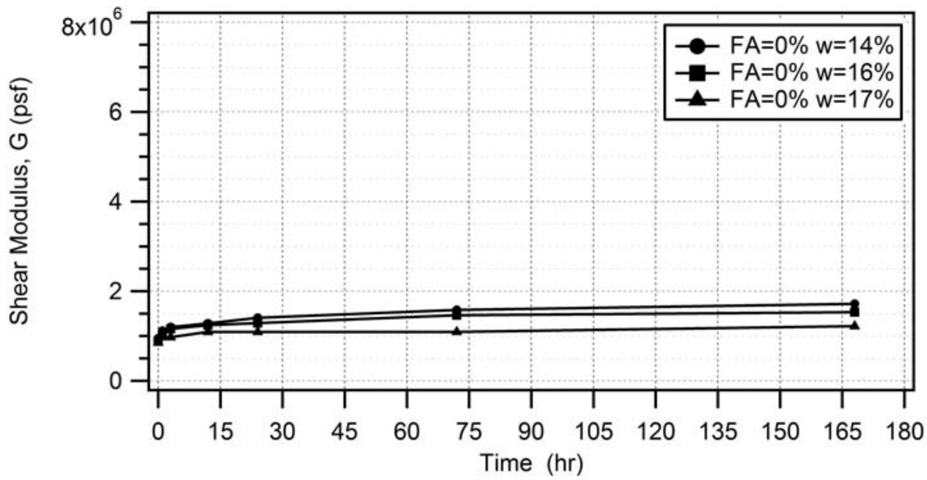

Figure 40 – Change in shear modulus with time; Atchison soil with no additive

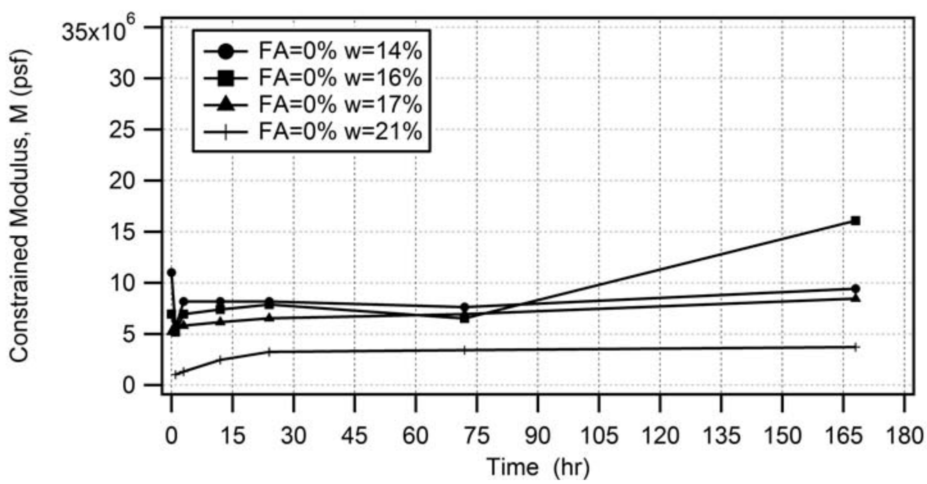

Figure 41 – Change in constrained modulus with time; Atchison soil with no additive

4.2.2. Atchison Subgrade Soil with Fly Ash – Young's Modulus

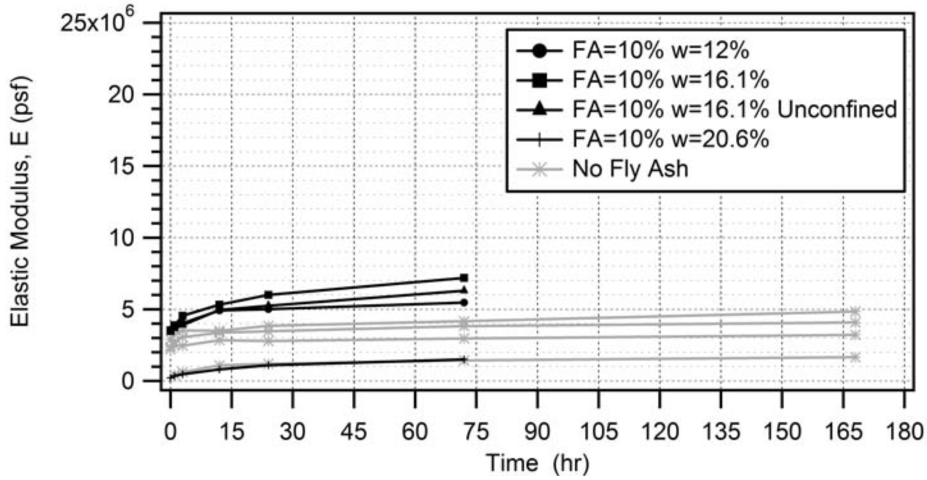

Figure 42 – Change in Young's modulus with time; Atchison soil with 10% FA

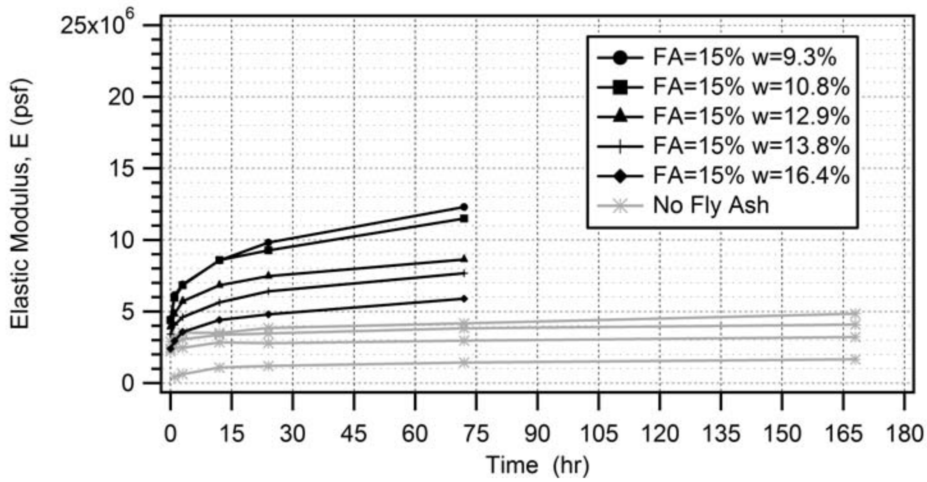

Figure 43 – Change in Young's modulus with time; Atchison soil with 15% FA

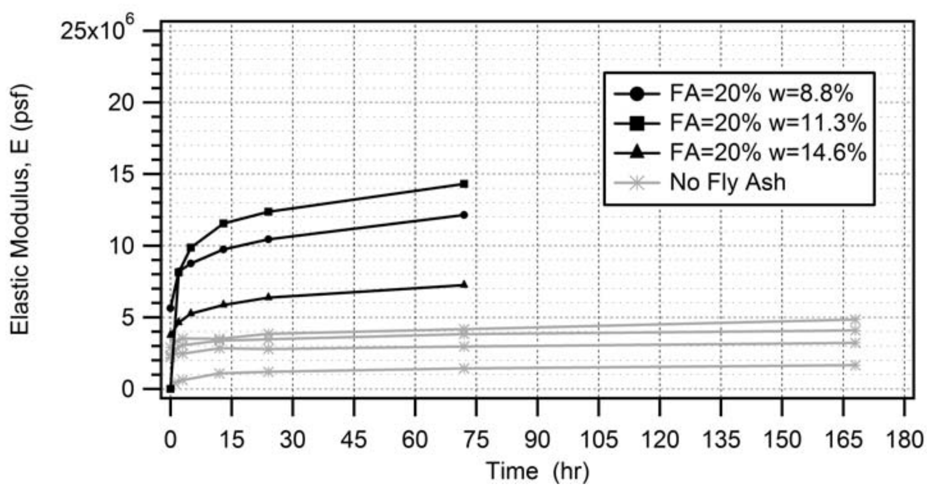

Figure 44 – Change in Young's modulus with time; Atchison soil with 20% FA

4.2.3. Atchison Subgrade Soil with Fly Ash – Shear Modulus

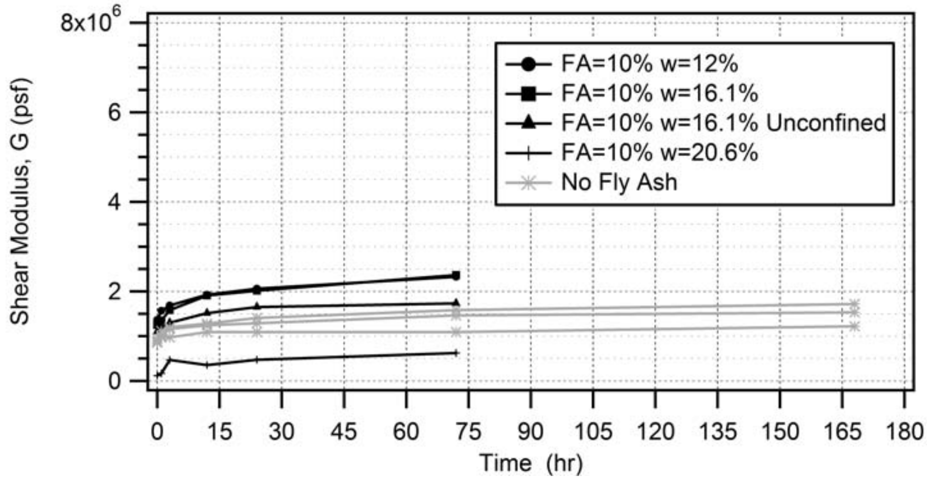

Figure 45 – Change in shear modulus with time; Atchison soil with 10% FA

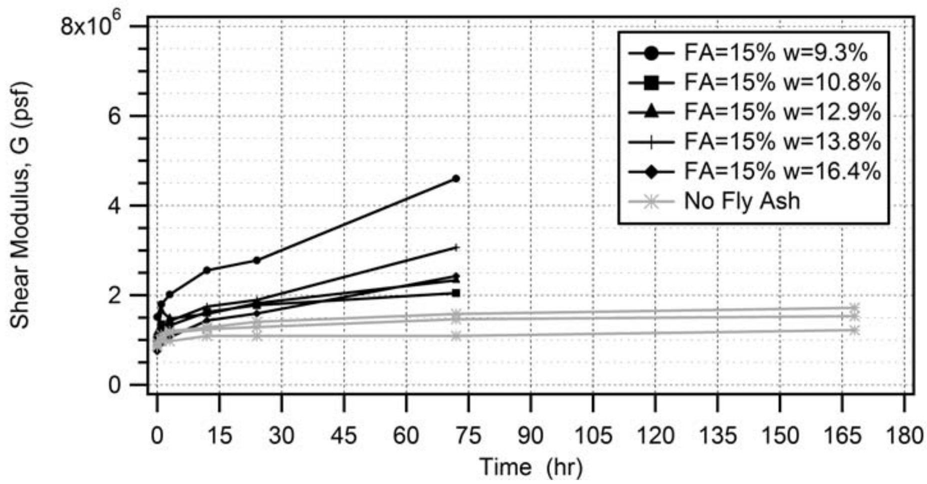

Figure 46 – Change in shear modulus with time; Atchison soil with 15% FA

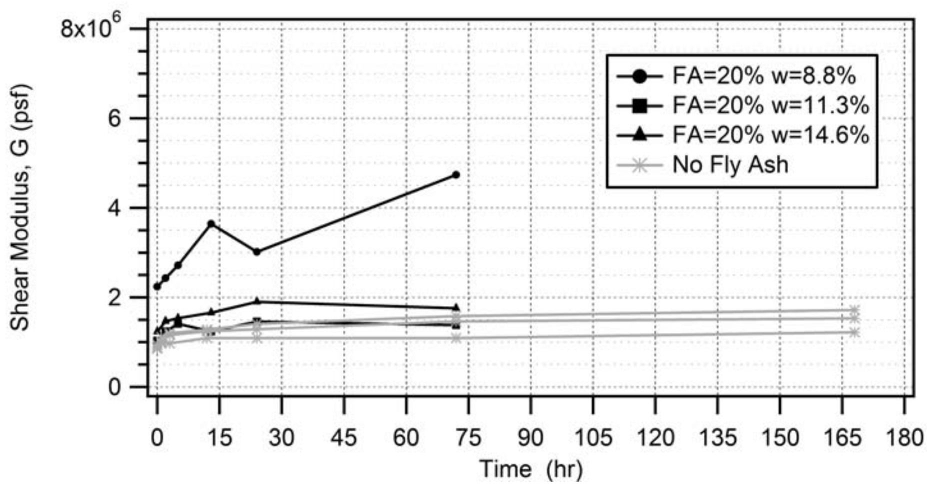

Figure 47 – Change in shear modulus with time; Atchison soil with 20% FA

4.2.4. Atchison Subgrade Soil with Fly Ash – Constrained Modulus

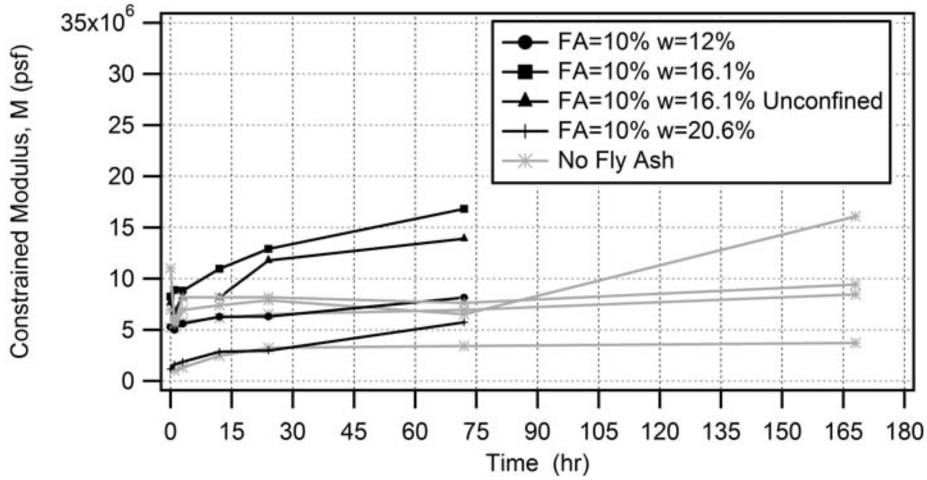

Figure 48 – Change in constrained modulus with time; Atchison soil with 10% FA

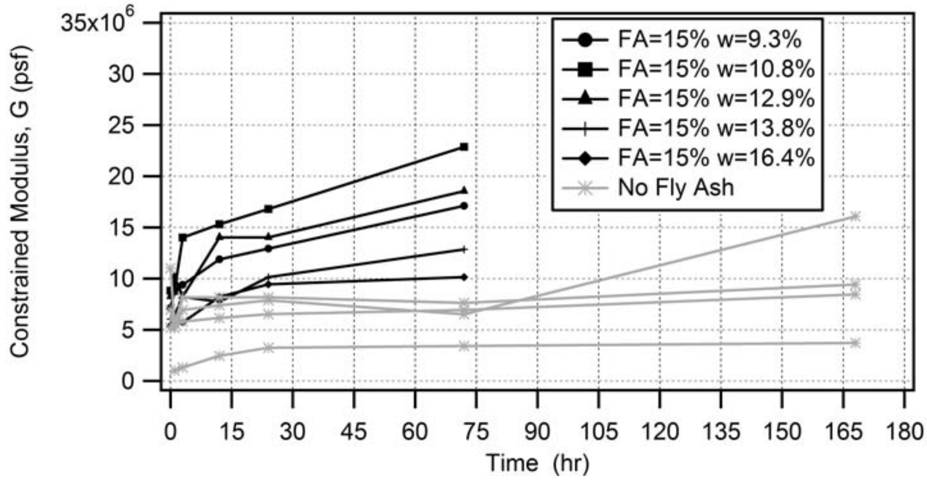

Figure 49 – Change in constrained modulus with time; Atchison soil with 15% FA

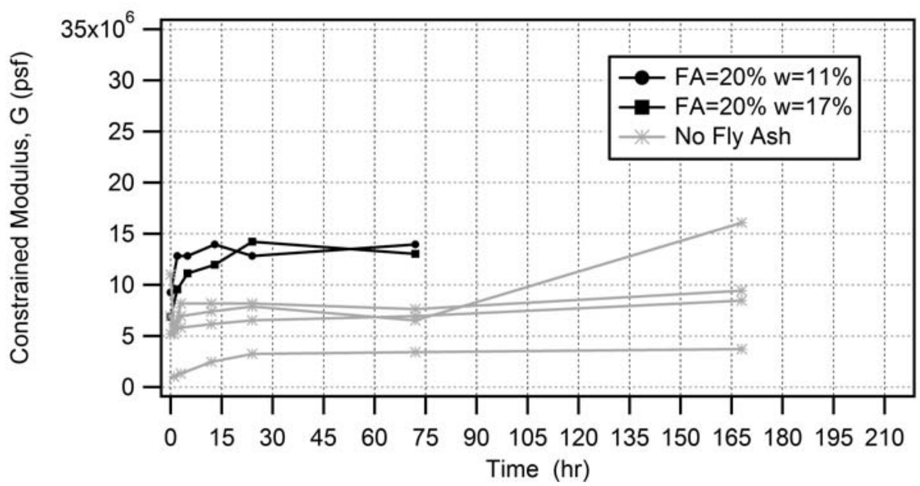

Figure 50 – Change in constrained modulus with time; Atchison soil with 20% FA

4.2.5. Atchison Subgrade Soil with LKD – Young's Modulus

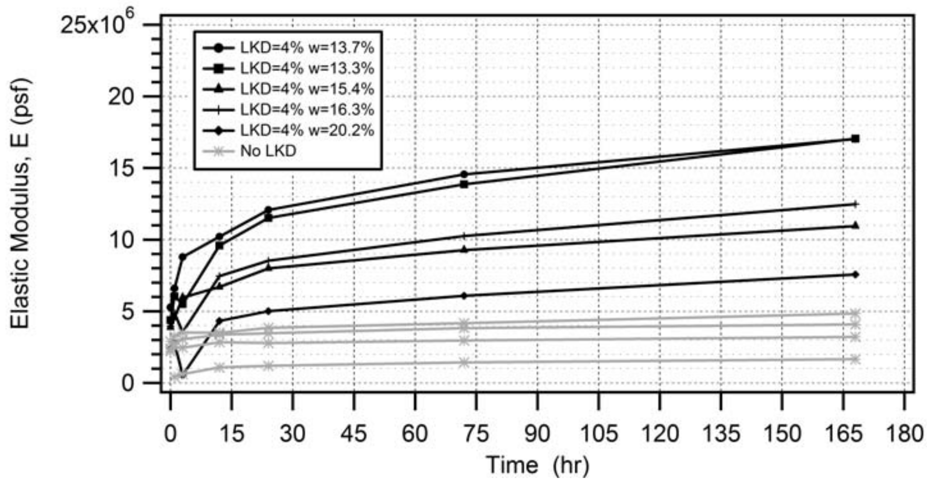

Figure 51 – Change in Young's modulus with time; Atchison soil with 4% LKD

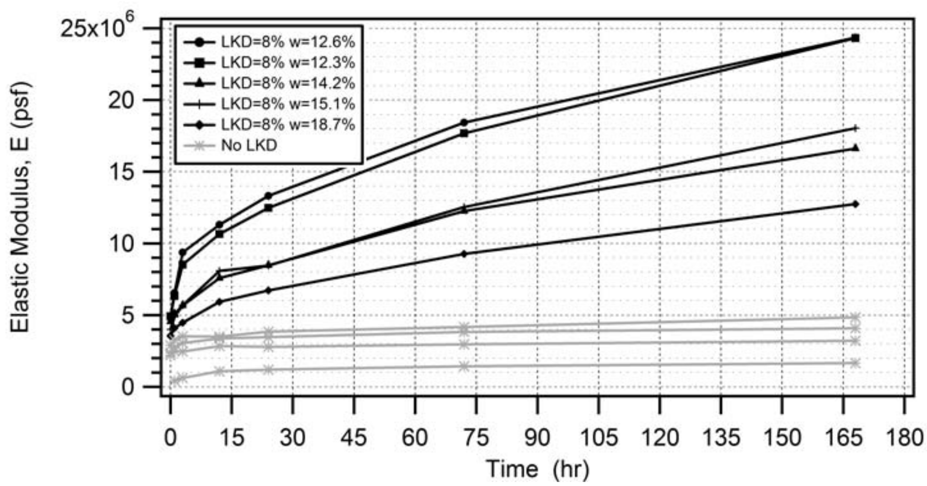

Figure 52 – Change in Young's modulus with time; Atchison soil with 8% LKD

4.2.6. Atchison Subgrade Soil with LKD – Shear Modulus

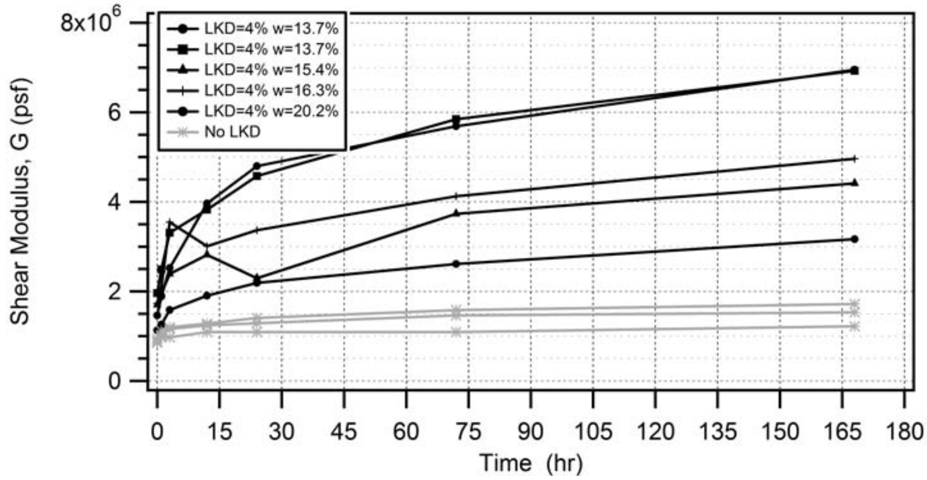

Figure 53 – Change in shear modulus with time; Atchison soil with 4% LKD

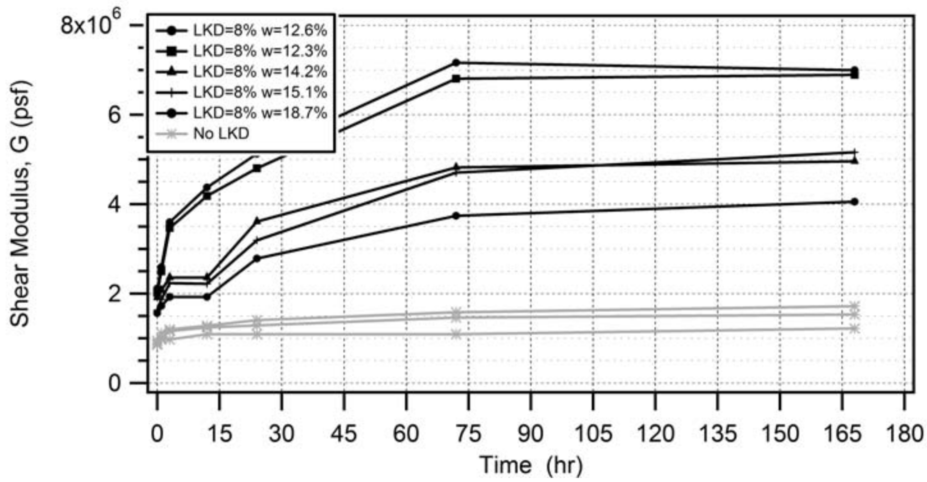

Figure 54 – Change in shear modulus with time; Atchison soil with 8% LKD

4.2.7. Atchison Subgrade Soil with LKD – Constrained Modulus

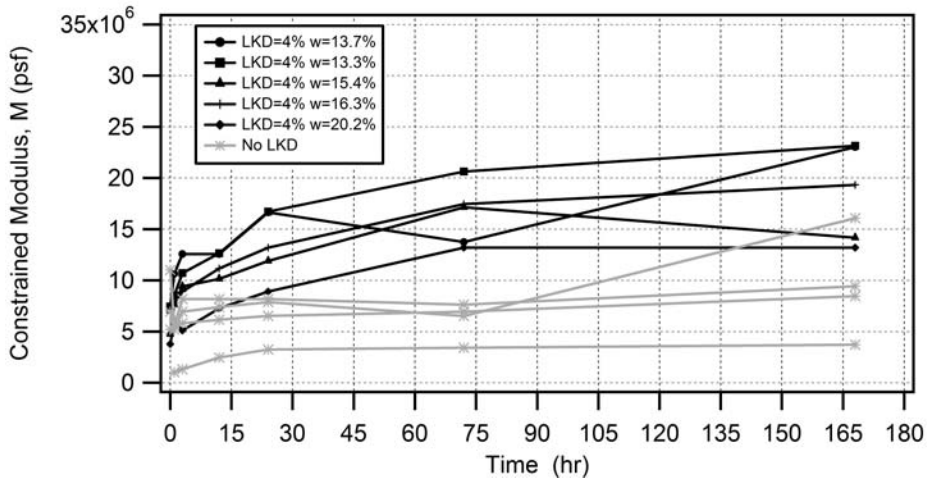

Figure 55 – Change in constrained modulus with time; Atchison soil with 4% LKD

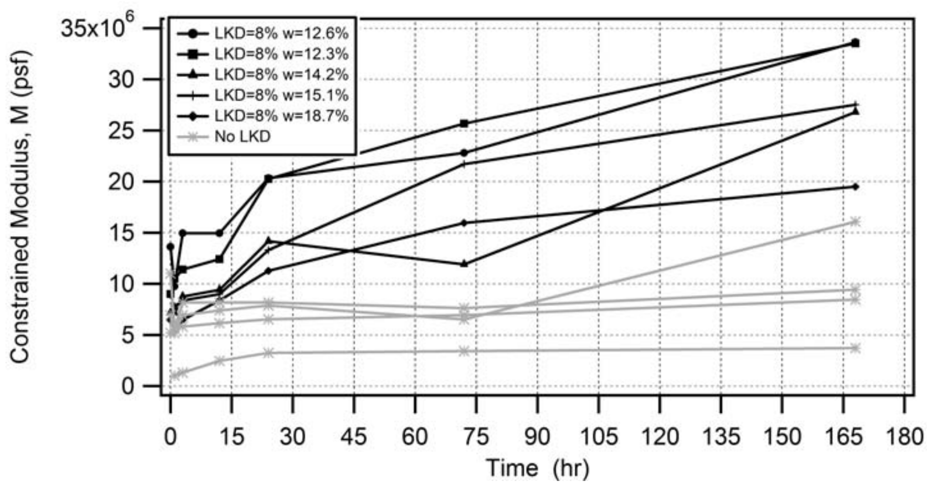

Figure 56 – Change in constrained modulus with time; Atchison soil with 8% LKD

4.3. Atchison Small-Strain Modulus Results – Compaction Plots

The plots shown in Sections 4.3.1 to 4.3.7 present the modulus values from the resonance tests at 0-hr, 1-hr, 1-day, 3-days and 7-days (if available) as a function of water content and plotted along with the soil compaction curve. The shift in the compaction curves to lower optimum water contents with higher levels of fly ash is evident in these plots. The lower modulus values at water contents on the wet side of optimum are also evident in these plots.

4.3.1. Atchison Subgrade Soil with No Additive

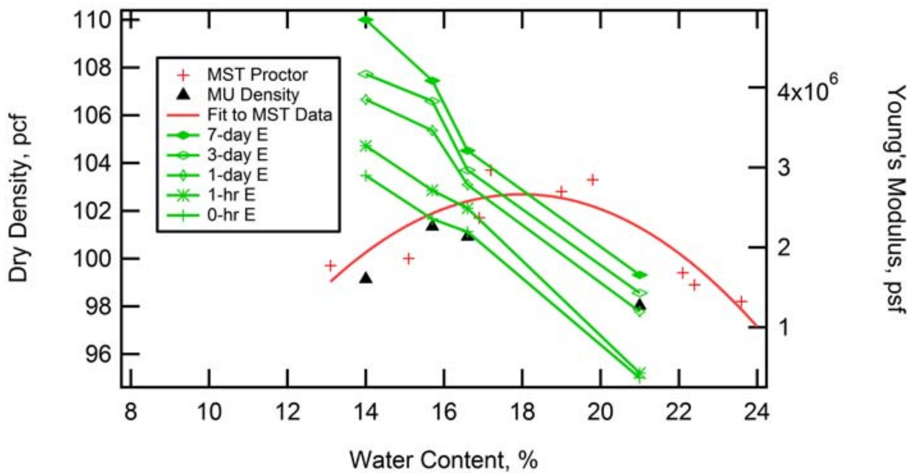

Figure 57 – Change in Young's modulus with water content; no additive

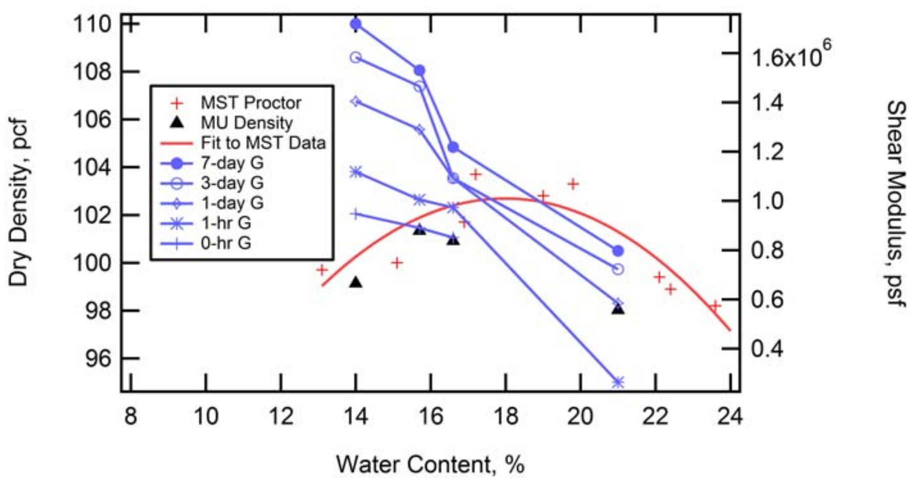

Figure 58 – Change in shear modulus with water content; no additive

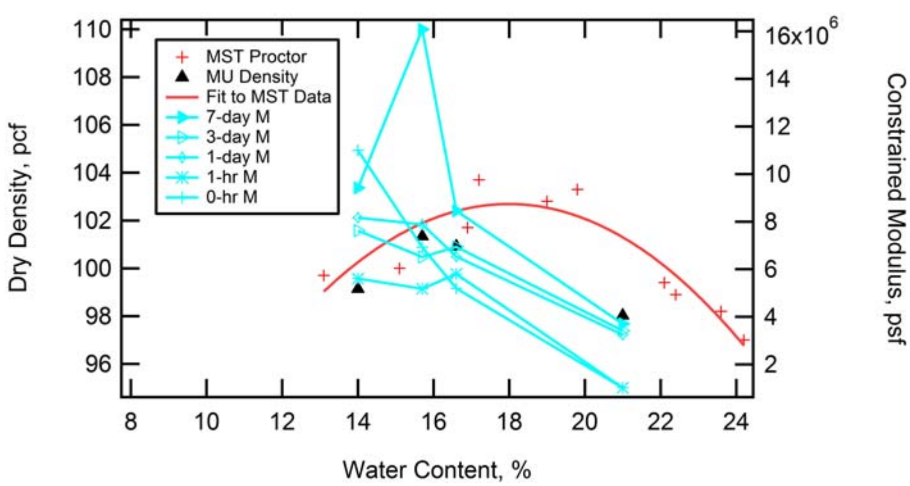

Figure 59 – Change in constrained modulus with water content; no additive

4.3.2. Atchison Subgrade Soil with Fly Ash – Young's Modulus

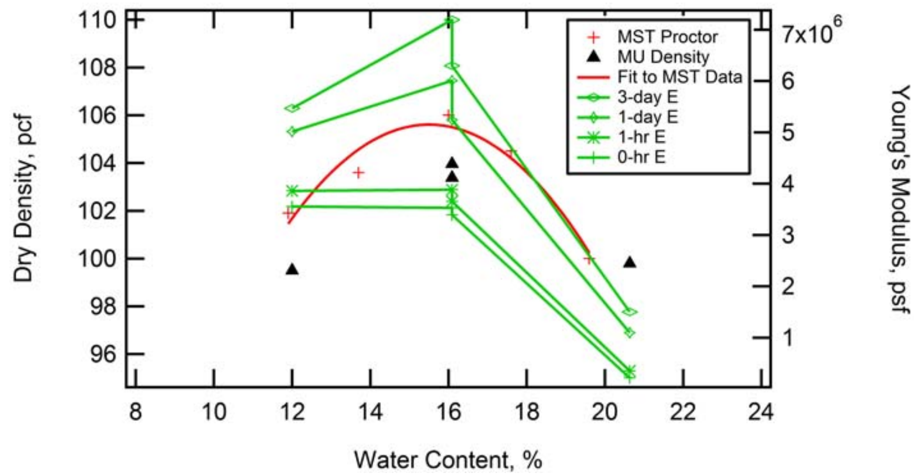

Figure 60 – Change in Young's modulus with water content; 10% Fly Ash

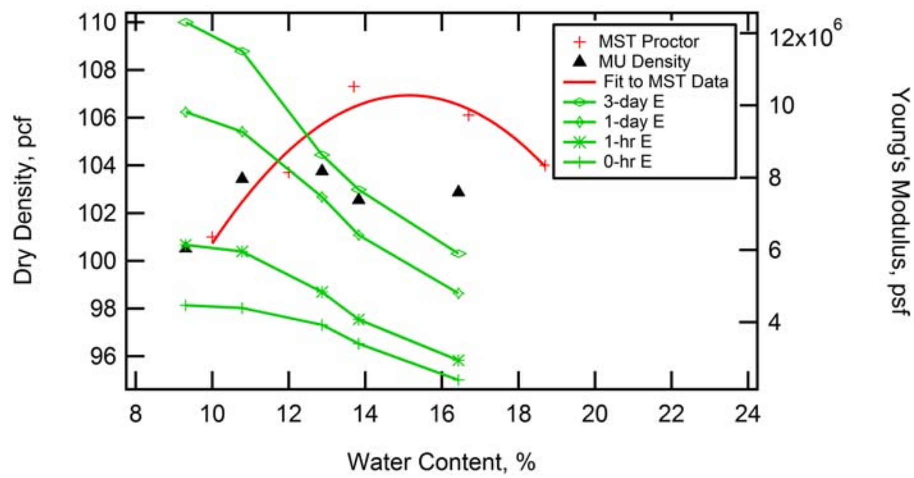

Figure 61 – Change in Young's modulus with water content; 15% Fly Ash

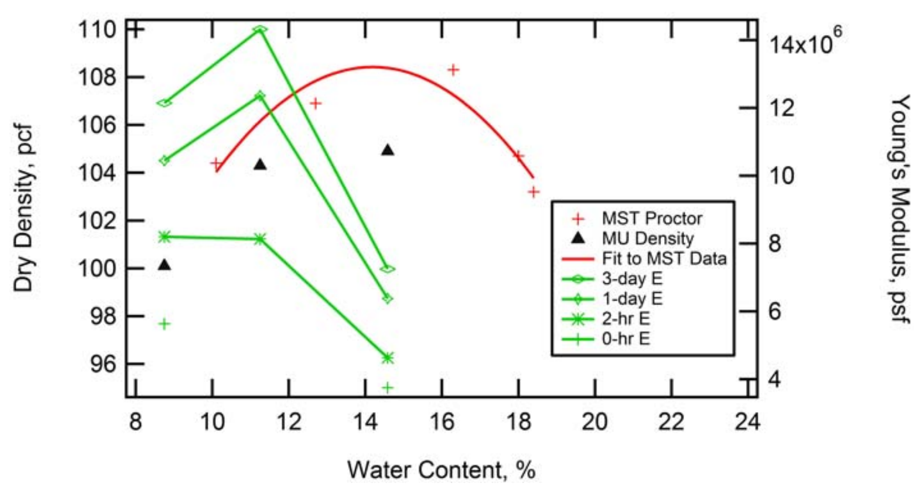

Figure 62 – Change in Young's modulus with water content; 20 % Fly Ash

4.3.3. Atchison Subgrade Soil with Fly Ash – Shear Modulus

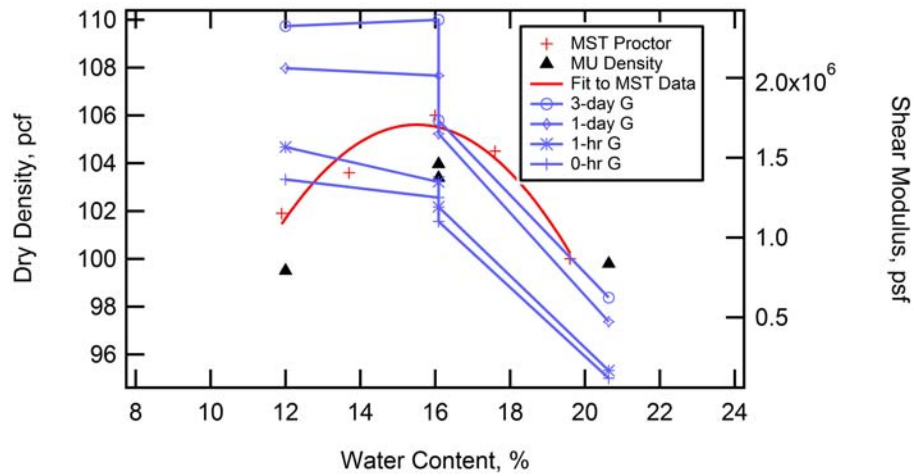

Figure 63 – Change in shear modulus with water content; 10% Fly Ash

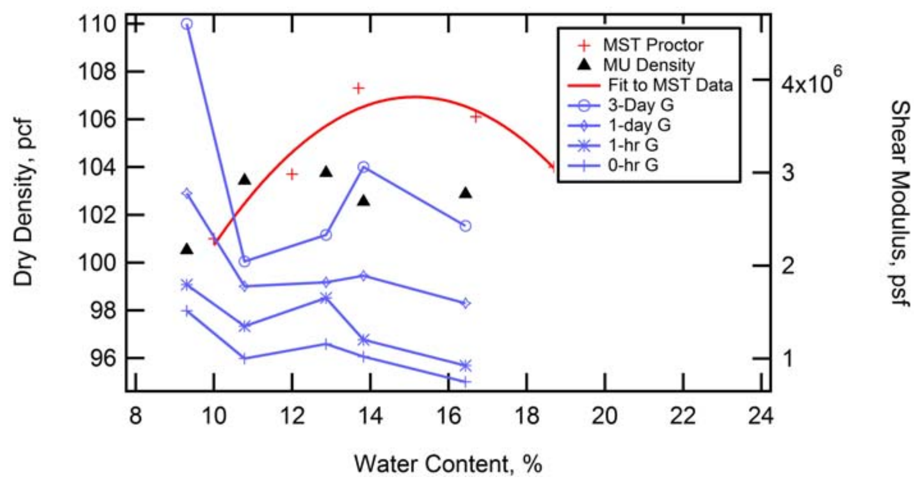

Figure 64 – Change in shear modulus with water content; 15% Fly Ash

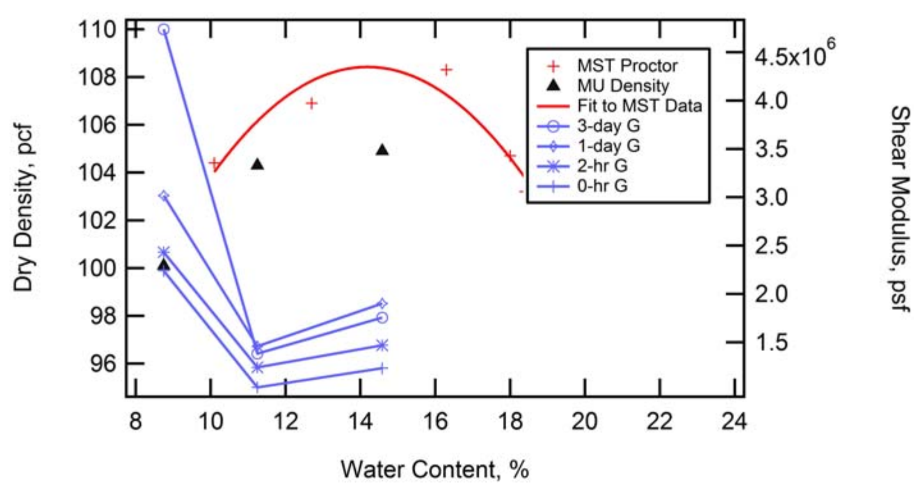

Figure 65 – Change in shear modulus with water content; 20 % Fly Ash

4.3.4. Atchison Subgrade Soil with Fly Ash – Constrained Modulus

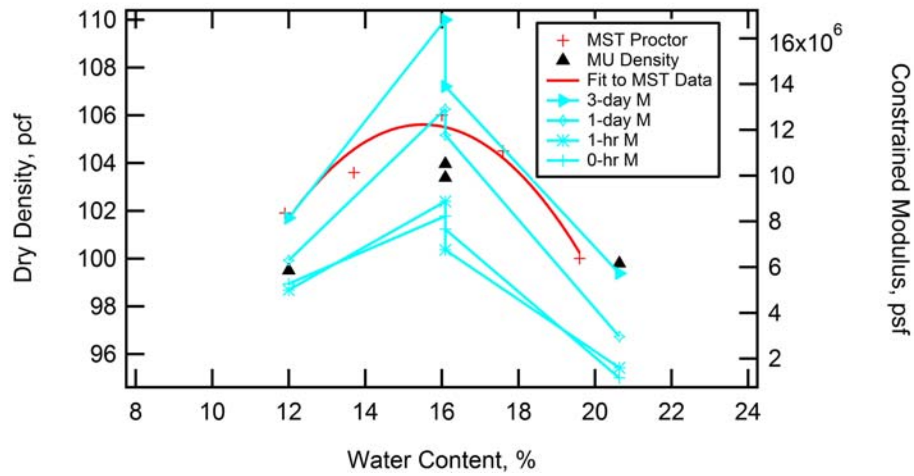

Figure 66 – Change in shear modulus with water content; 10% Fly Ash

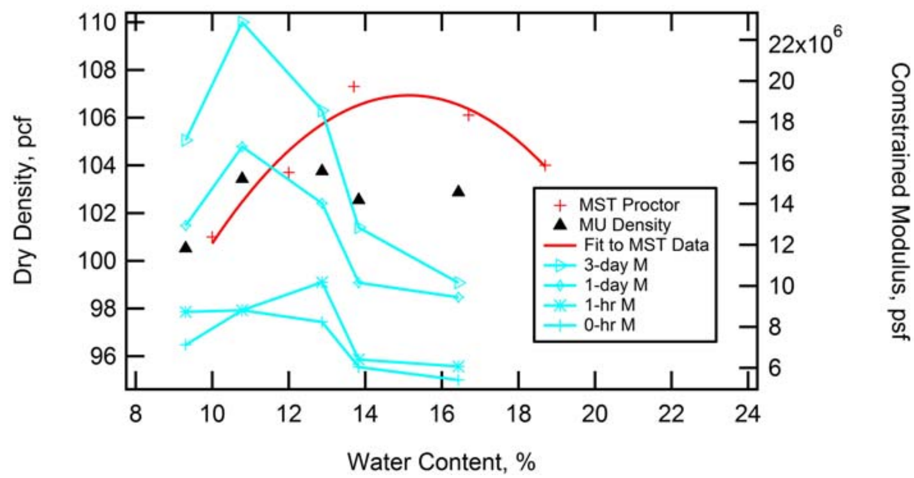

Figure 67 – Change in shear modulus with water content; 15% Fly Ash

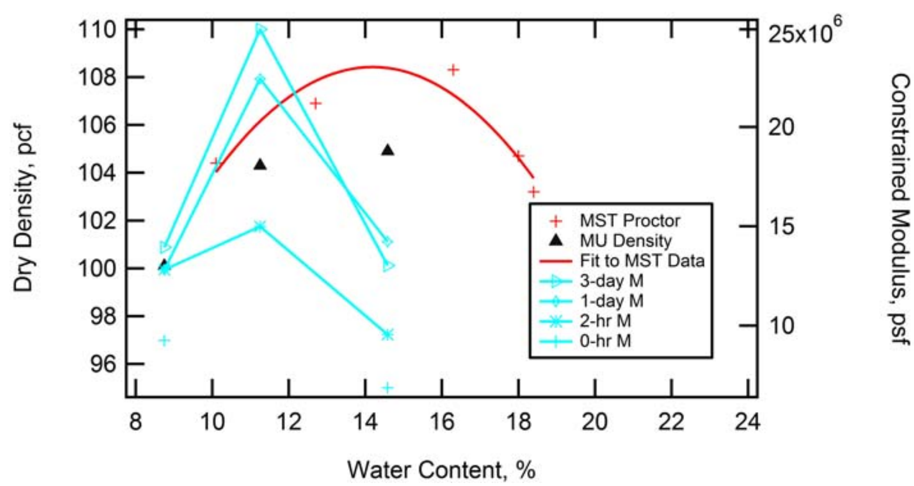

Figure 68 – Change in shear modulus with water content; 20 % Fly Ash

4.3.5. Atchison Subgrade Soil with LKD – Young's Modulus

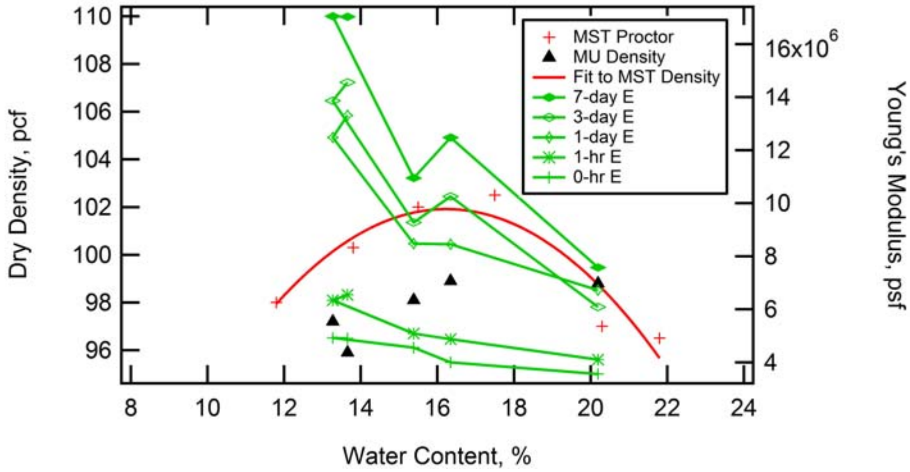

Figure 69 – Change in Young's modulus with water content; 4% LKD

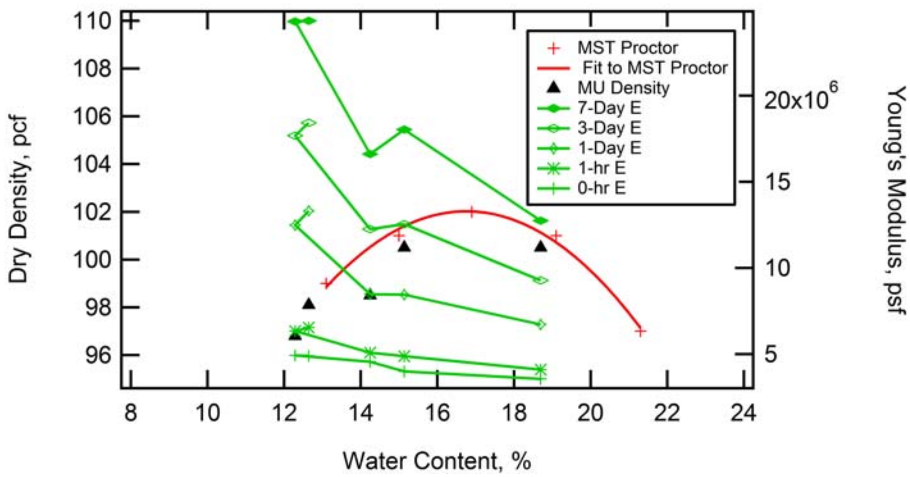

Figure 70 – Change in Young's modulus with water content; 8% LKD

4.3.6. Atchison Subgrade Soil with LKD – Shear Modulus

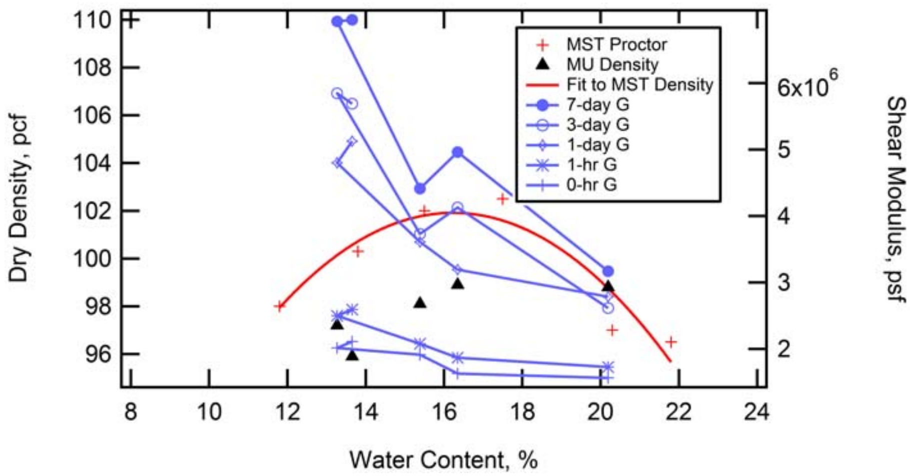

Figure 71 – Change in shear modulus with water content; 4% LKD

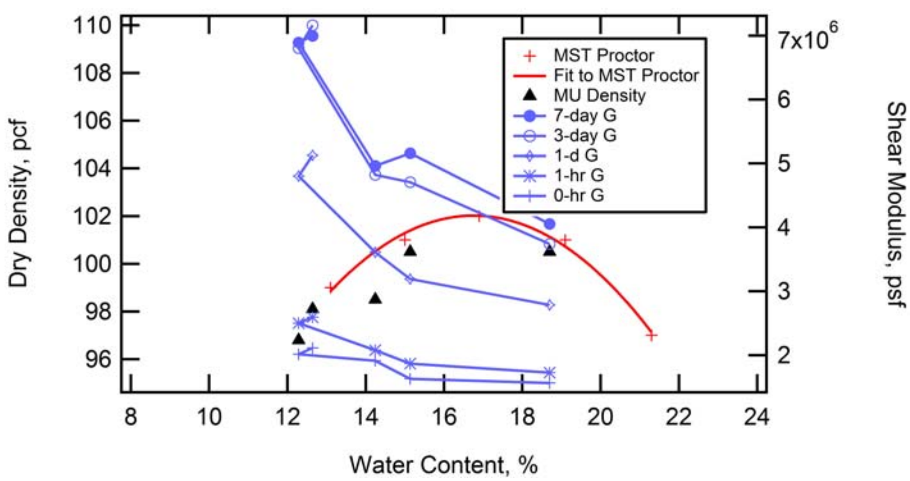

Figure 72 – Change in shear modulus with water content; 8% LKD

4.3.7. Atchison Subgrade Soil with LKD – Constrained Modulus

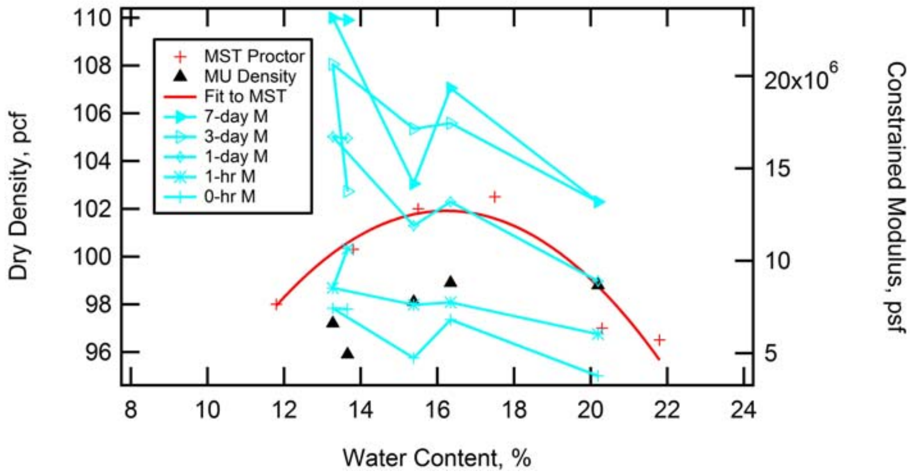

Figure 73 – Change in constrained modulus with water content; 4% LKD

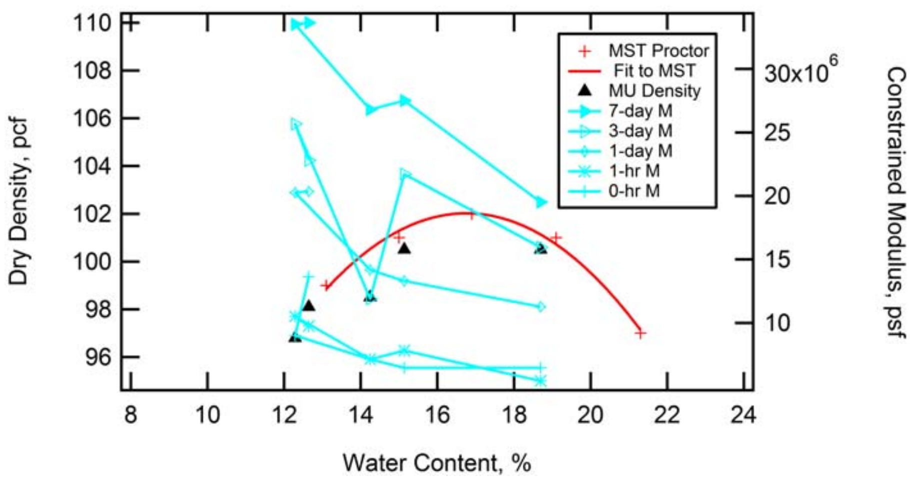

Figure 74 – Change in constrained modulus with water content; 8% LKD

4.4. Putnam Small-Strain Modulus Results – Time Plots

Presented in Section 4.4.1 through 4.4.7 are plots of modulus values versus time for: (1) the Putnam subgrade soil alone, (2) Putnam soil mixed with 10%, 15% and 20% fly ash, and (3) the Putnam soil mixed with 4% and 8% LKD. The Putnam soil differed greatly from the Atchison soil, as discussed above. The optimum water content for the Putnam soil was typically in the range of 20% to 25%, and did not change significantly with the addition of fly ash to the soil. As with the Atchison soil, the objective was to prepare samples at optimum, 2% and 4% below optimum, and 2% and 4% above optimum. However, in preparing these samples, the natural water content of the Putnam soil was not properly accounted for so the actual water contents were typically 2 to 3% higher than the desired values. This resulted in most of the measurements being either near the optimum water content or higher than the optimum water content. Although this was not the desired distribution of water contents, it still provided information on typical applications, namely (1) compacting near optimum and (2) adding fly ash to stabilize a very wet and soft subgrade.

4.4.1. Putnam Subgrade Soil No Additive

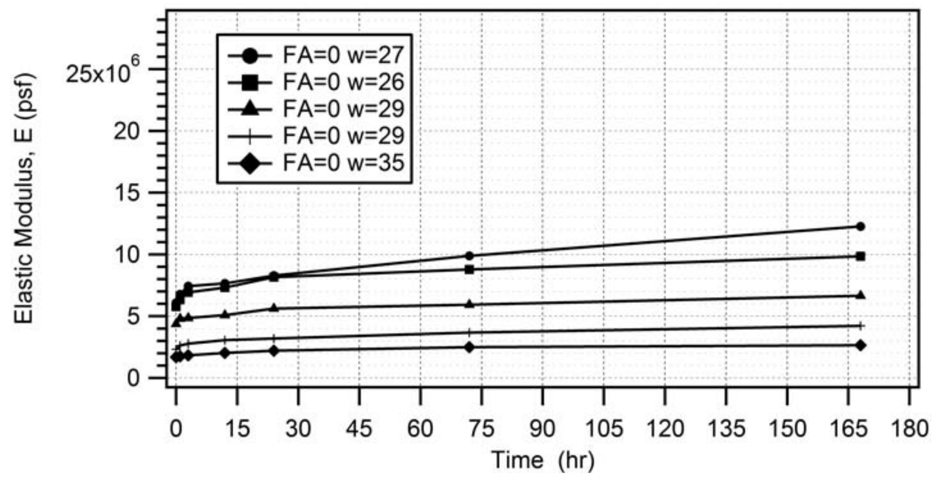

Figure 75 – Change in Young's modulus with time; Putnam soil with no additive

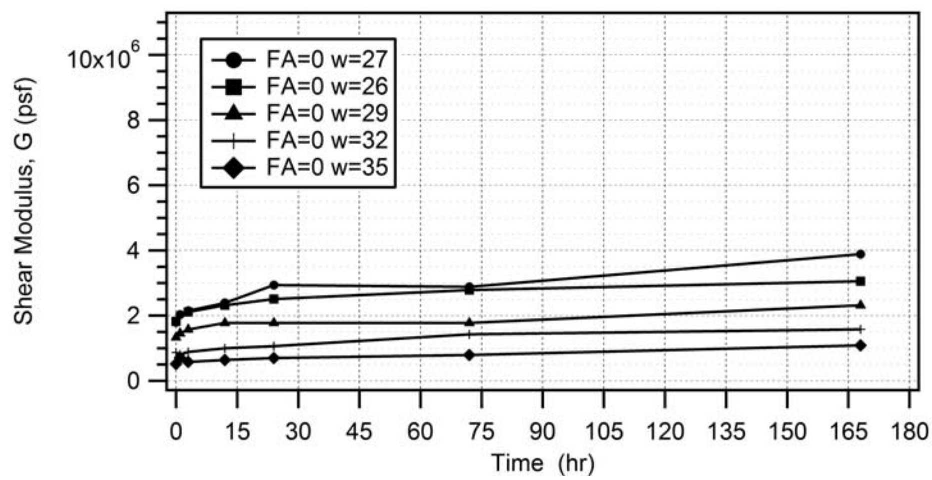

Figure 76 – Change in shear modulus with time; Putnam soil with no additive

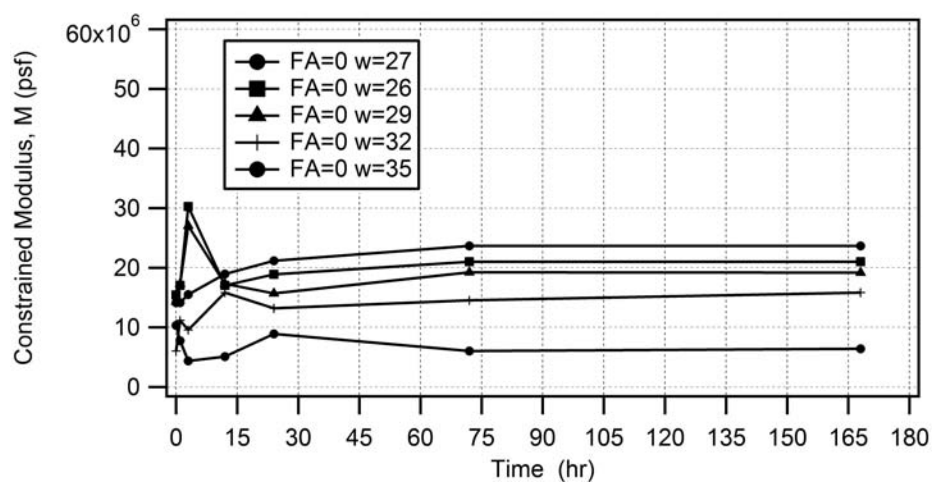

Figure 77 – Change in constrained modulus with time; Putnam soil with no additive

4.4.2. Putnam Subgrade Soil with Fly Ash – Young's Modulus

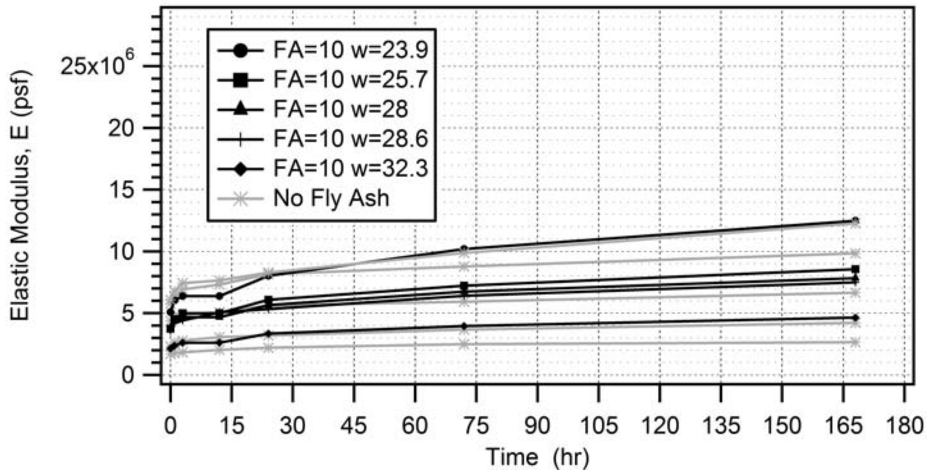

Figure 78 – Change in Young's modulus with time; Putnam soil with 10% FA

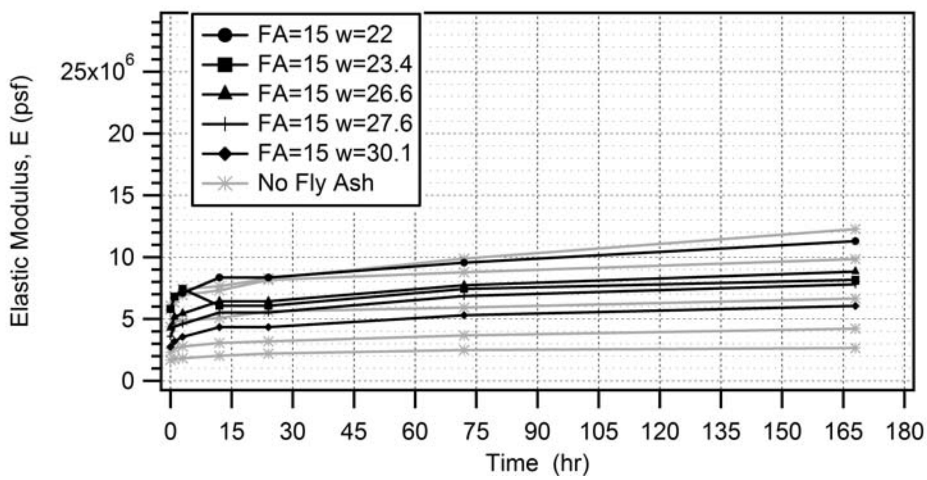

Figure 79 – Change in Young's modulus with time; Putnam soil with 15% FA

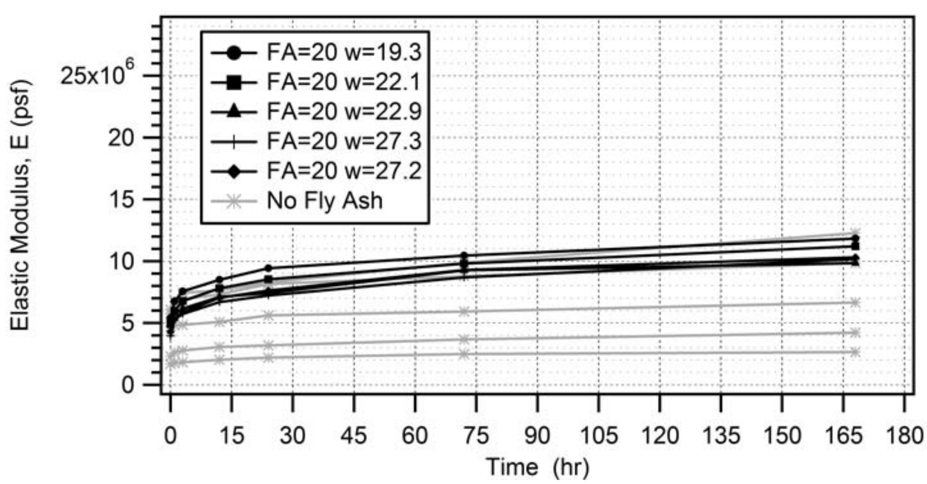

Figure 80 – Change in Young's modulus with time; Putnam soil with 20% FA

4.4.3. Putnam Subgrade Soil with Fly Ash – Shear Modulus

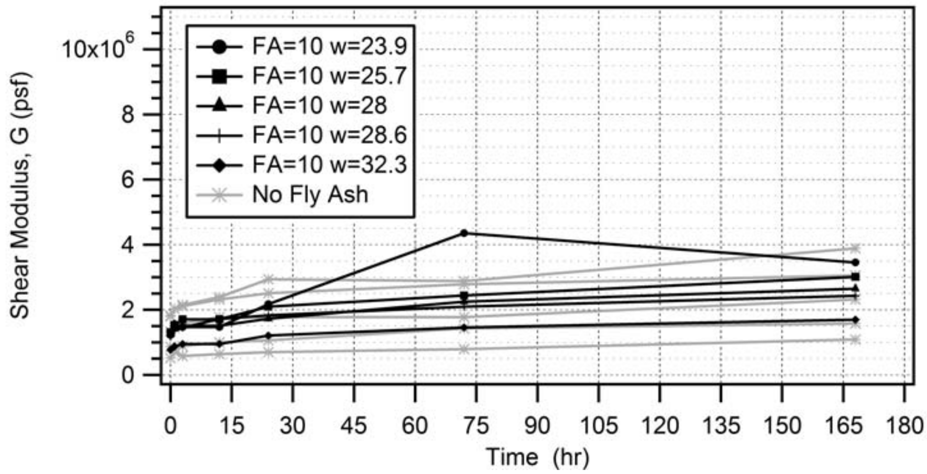

Figure 81 – Change in shear modulus with time; Putnam soil with 10% FA

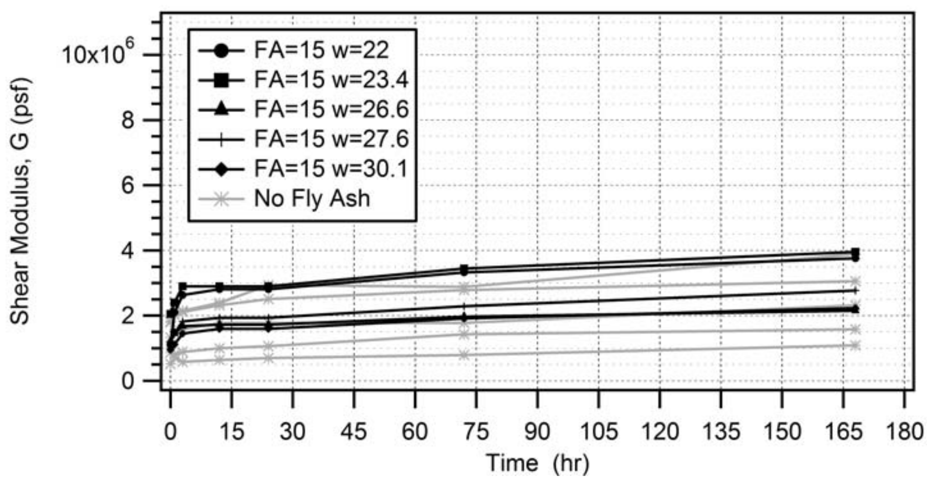

Figure 82 – Change in shear modulus with time; Putnam soil with 15% FA

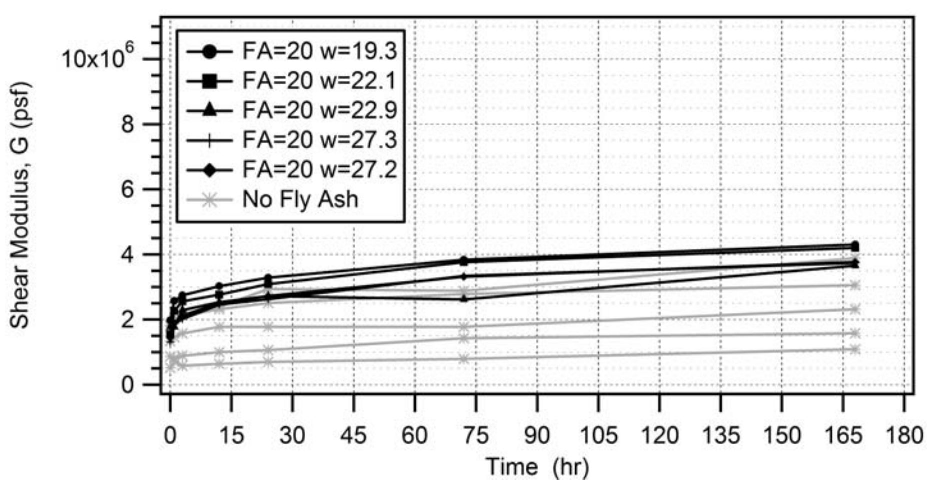

Figure 83 – Change in shear modulus with time; Putnam soil with 20% FA

4.4.4. Putnam Subgrade Soil with Fly Ash – Constrained Modulus

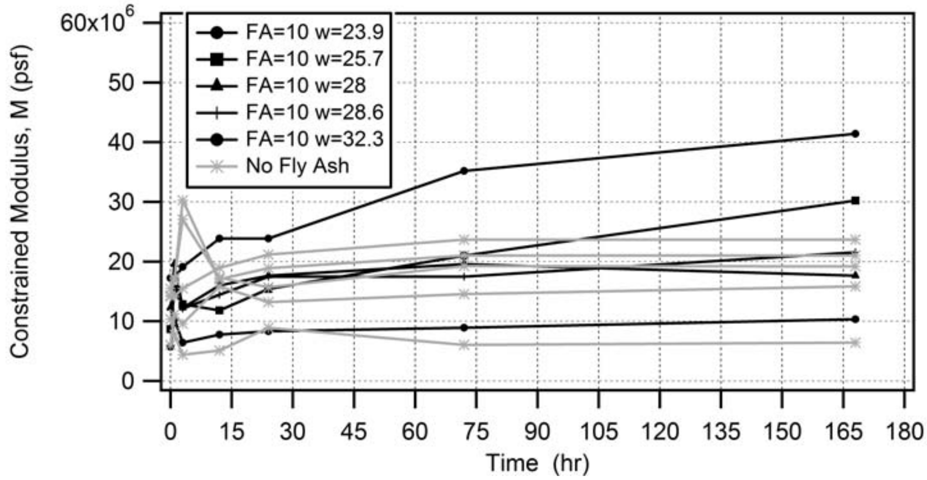

Figure 84 – Change in constrained modulus with time; Putnam soil with 10% FA

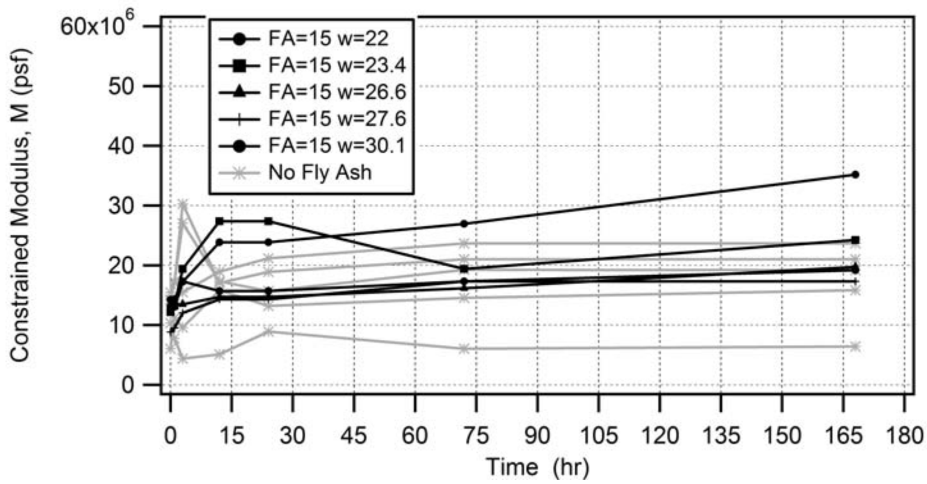

Figure 85 – Change in constrained modulus with time; Putnam soil with 15% FA

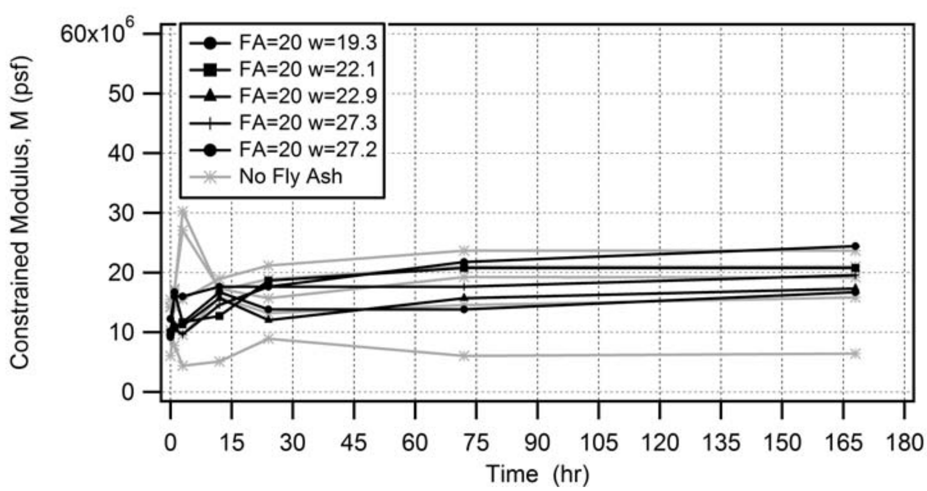

Figure 86 – Change in constrained modulus with time; Putnam soil with 20% FA

4.4.5. Putnam Subgrade Soil with LKD – Young's Modulus

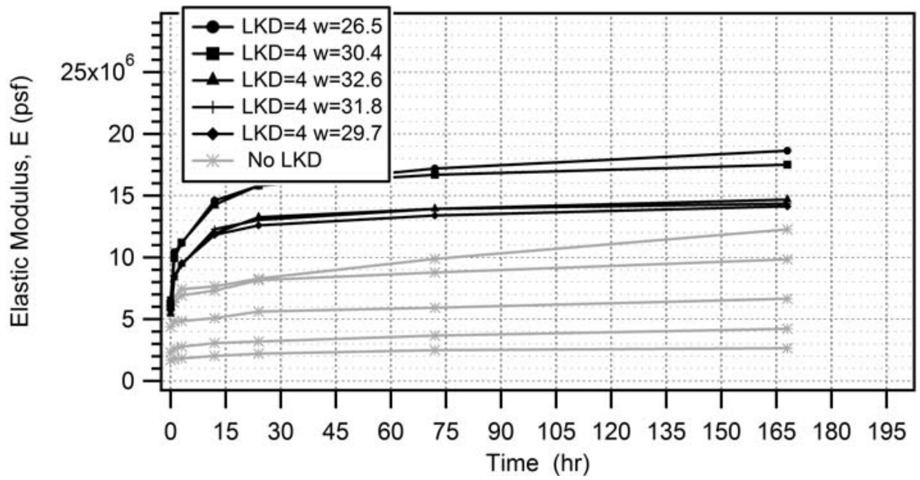

Figure 87 – Change in Young's modulus with time; Putnam soil with 4% LKD

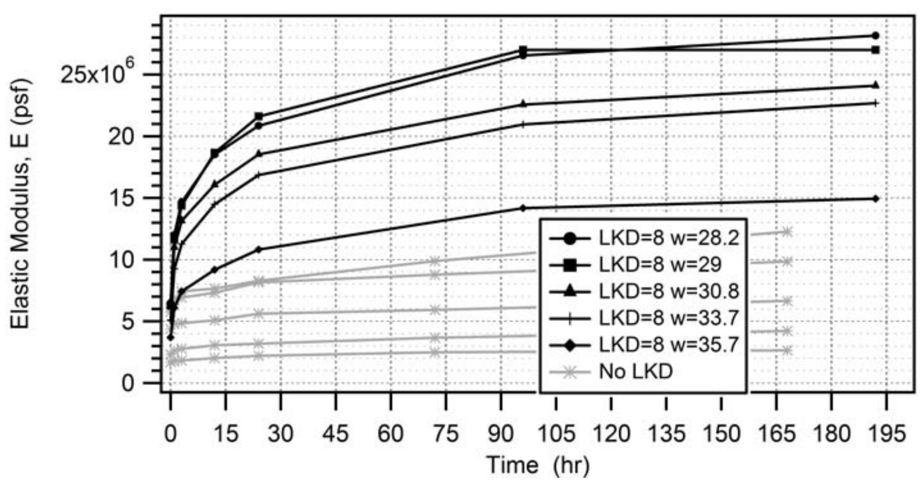

Figure 88 – Change in Young's modulus with time; Putnam soil with 8% LKD

4.4.6. Putnam Subgrade Soil with LKD – Shear Modulus

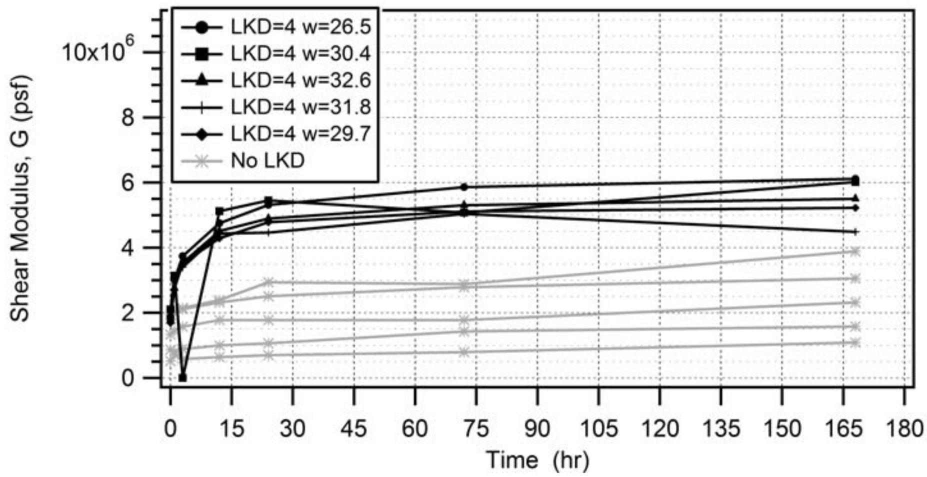

Figure 89 – Change in shear modulus with time; Putnam soil with 4% LKD

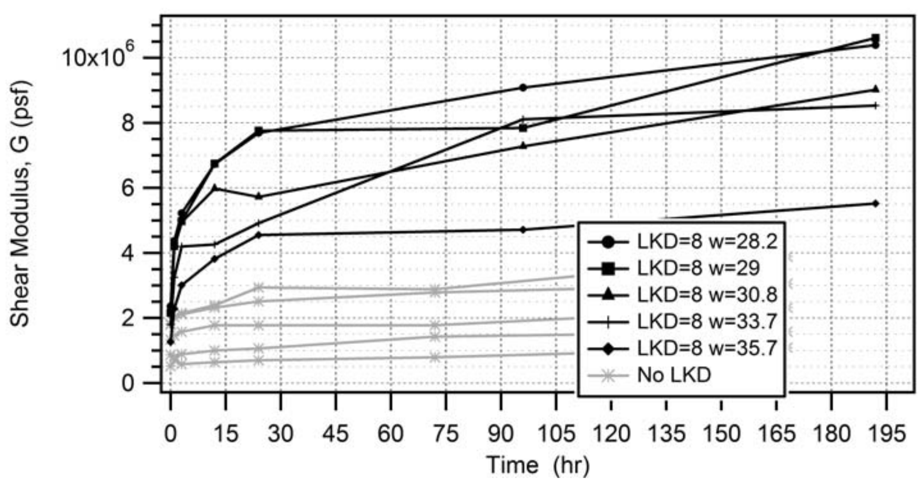

Figure 90 – Change in shear modulus with time; Putnam soil with 8% LKD

4.4.7. Putnam Subgrade Soil with LKD – Constrained Modulus

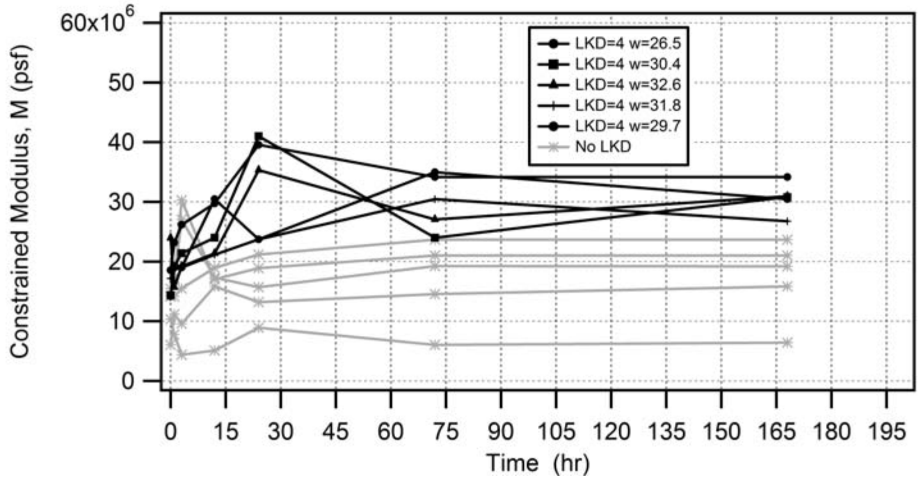

Figure 91 – Change in constrained modulus with time; Putnam soil with 4% LKD

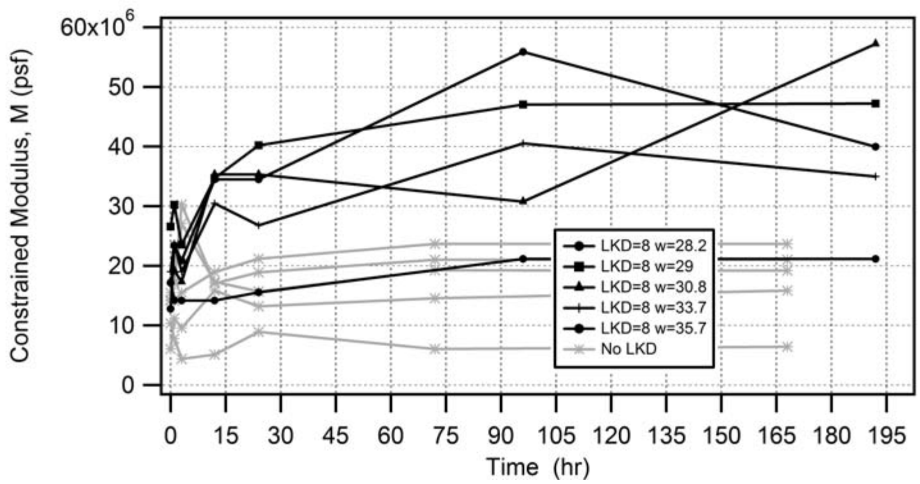

Figure 92 – Change in constrained modulus with time; Putnam soil with 8% LKD

4.5. Putnam Modulus Results – Compaction Plots

The plots shown in Sections 4.5.1 to 4.5.7 present the modulus values from the resonance tests on the Putnam soil at 0-hr, 1-hr, 1-day, 3-days and 7-days (when available) as a function of water content and plotted along with the soil compaction curve. .

4.5.1. Putnam Subgrade Soil with No Additive

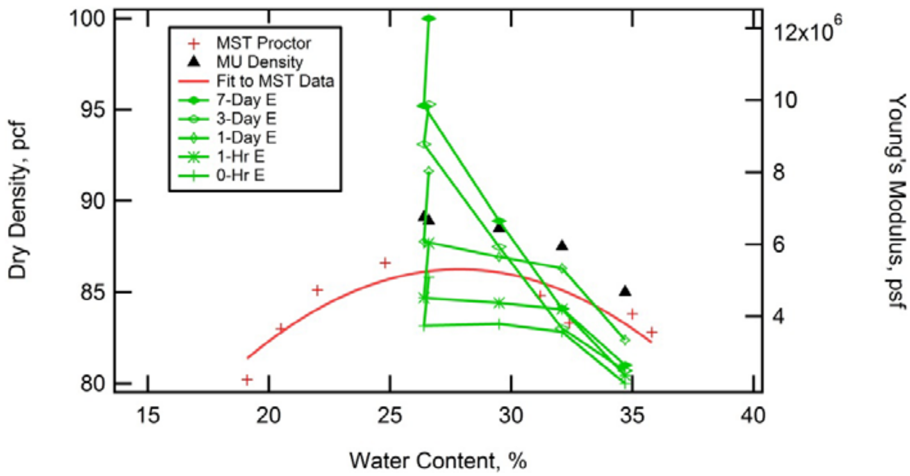

Figure 93 – Change in Young's modulus with water content; no additive

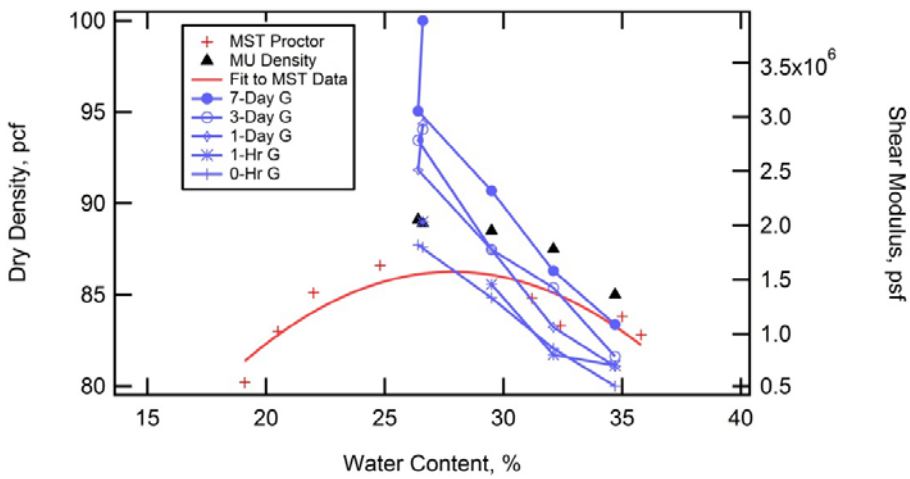

Figure 94 – Change in shear modulus with water content; no additive

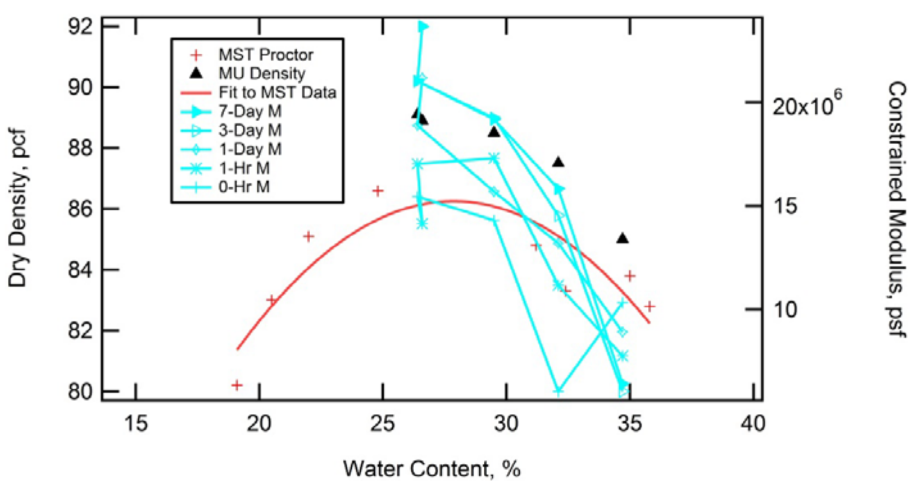

Figure 95 – Change in constrained modulus with water content; no additive

4.5.2. Putnam Subgrade Soil with Fly Ash – Young's Modulus

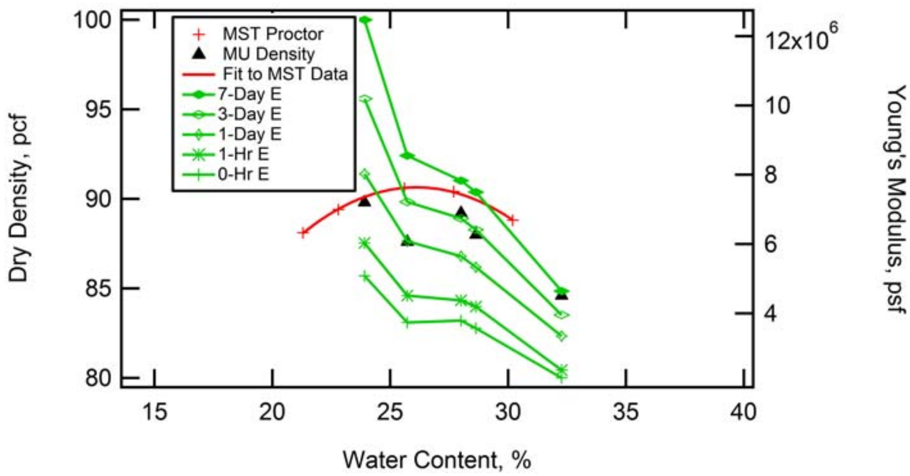

Figure 96 – Change in Young's modulus with water content; 10% Fly Ash

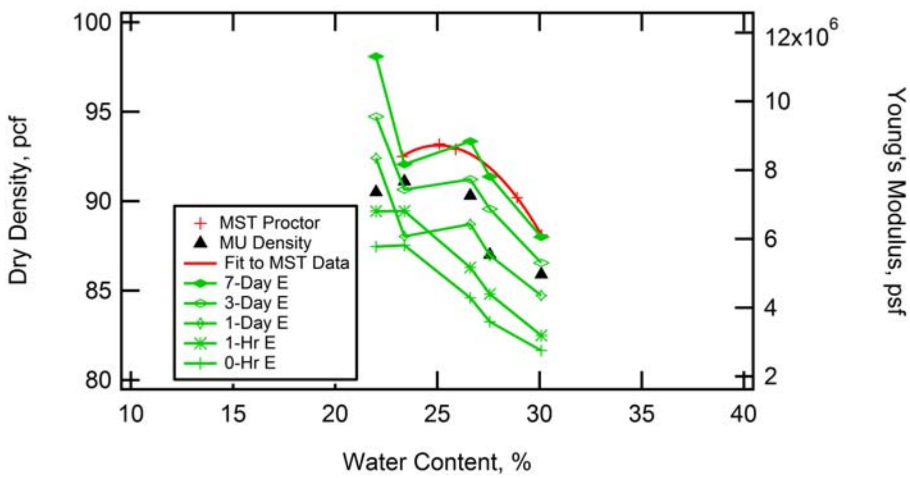

Figure 97 – Change in Young's modulus with water content; 15% Fly Ash

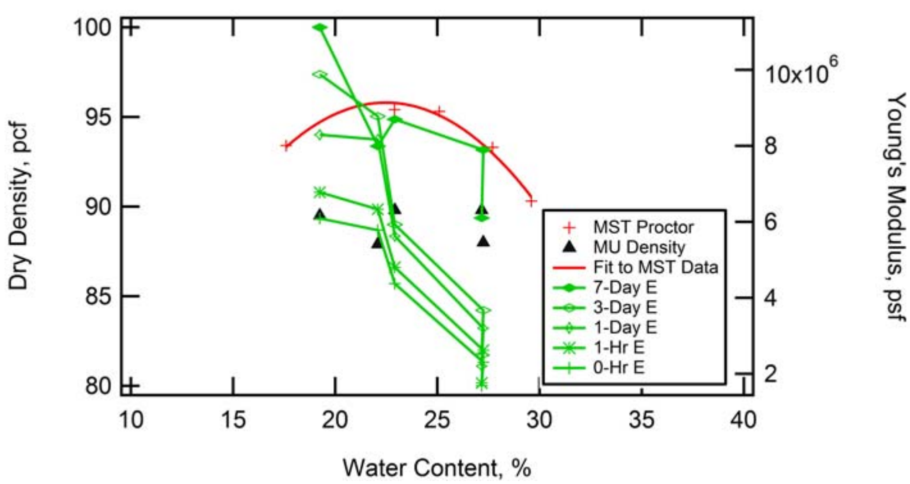

Figure 98 – Change in Young's modulus with water content; 20 % Fly Ash

4.5.3. Putnam Subgrade Soil with Fly Ash – Shear Modulus

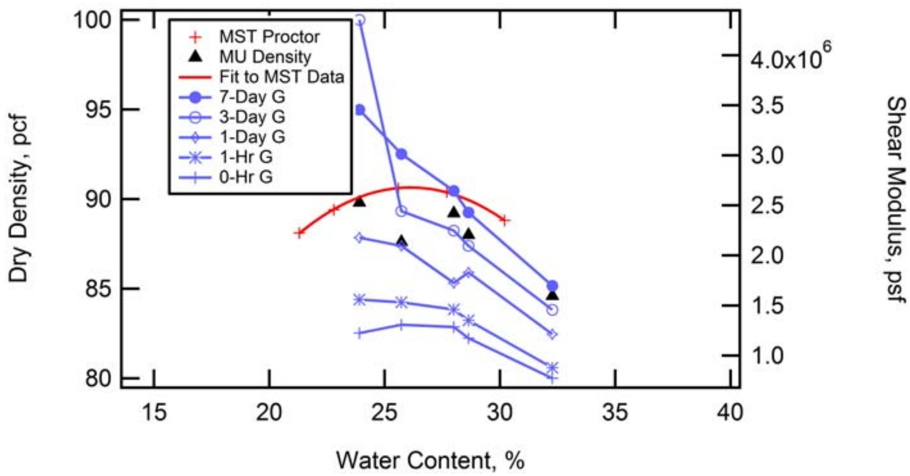

Figure 99 – Change in shear modulus with water content; 10% Fly Ash

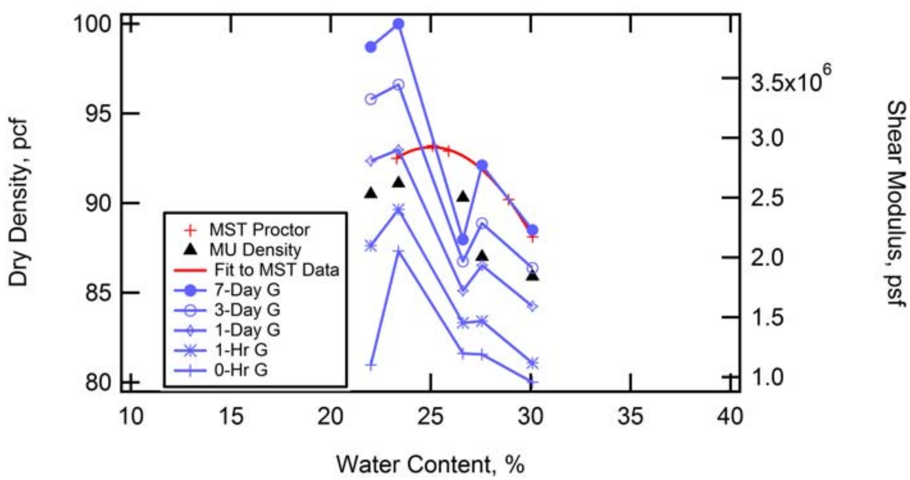

Figure 100 – Change in shear modulus with water content; 15% Fly Ash

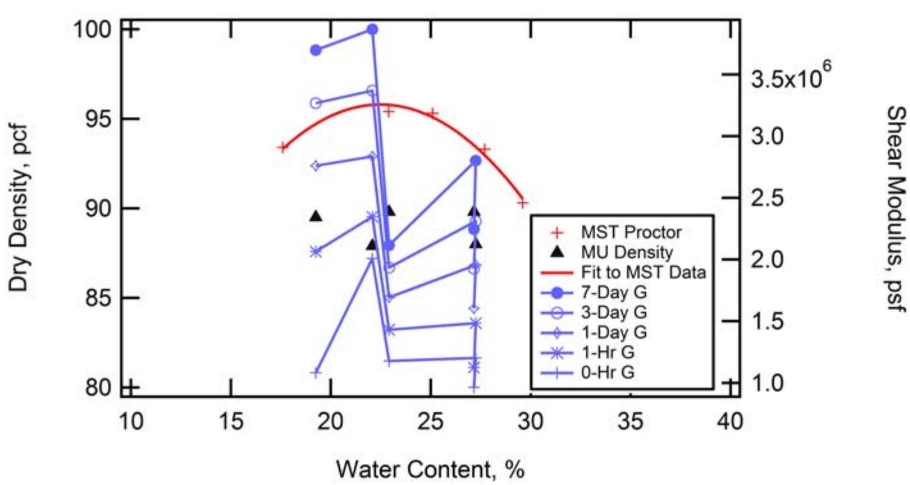

Figure 101 – Change in shear modulus with water content; 20 % Fly Ash

4.5.4. Putnam Subgrade Soil with Fly Ash – Constrained Modulus

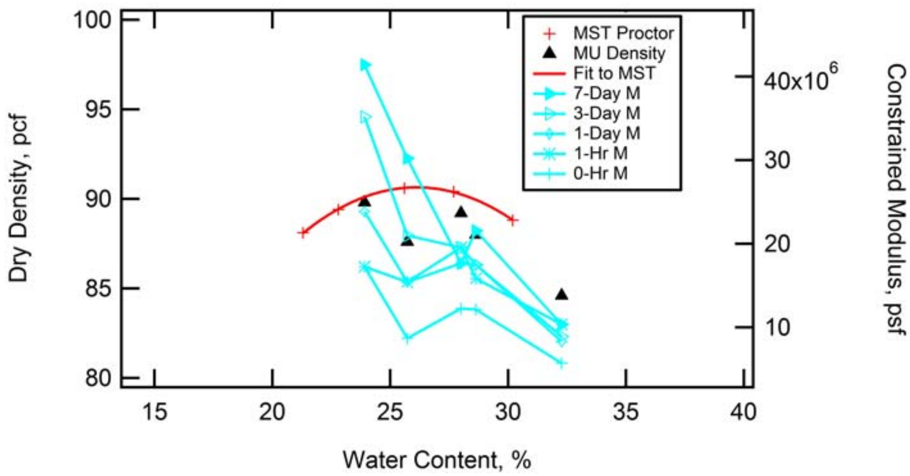

Figure 102 – Change in shear modulus with water content; 10% Fly Ash

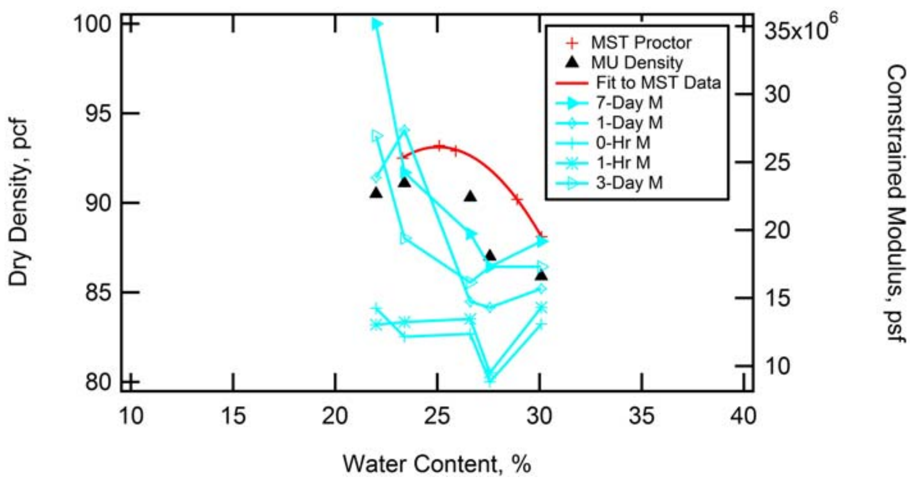

Figure 103 – Change in shear modulus with water content; 15% Fly Ash

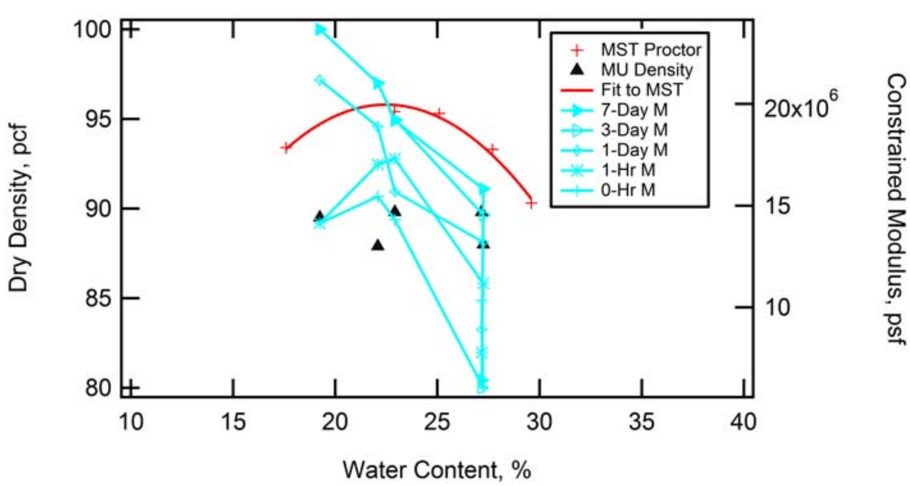

Figure 104 – Change in shear modulus with water content; 20 % Fly Ash

4.5.5. Putnam Subgrade Soil with LKD – Young's Modulus

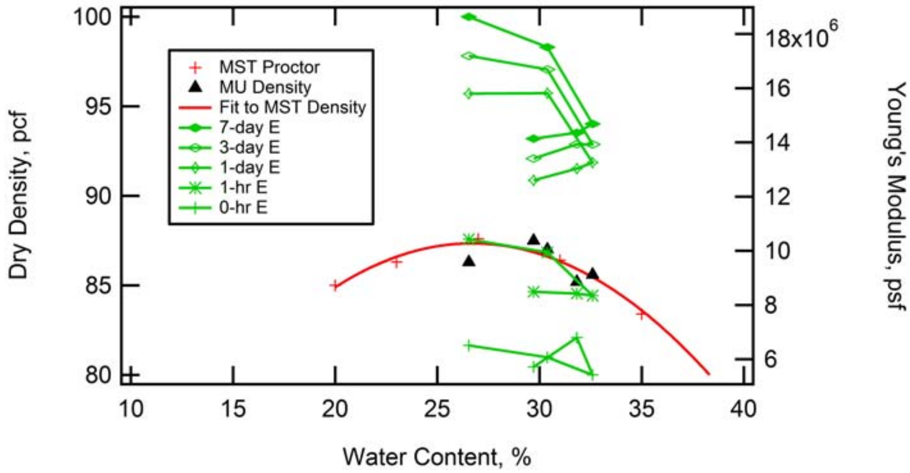

Figure 105 – Change in Young's modulus with water content; 4% LKD

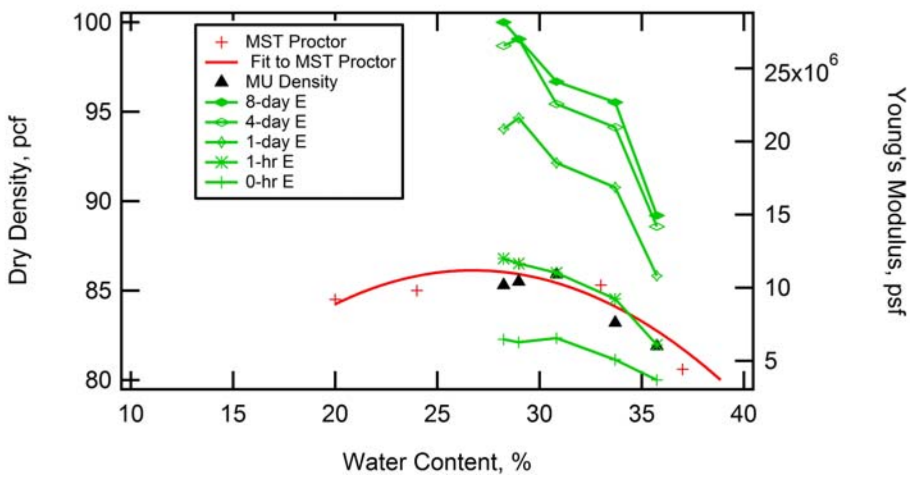

Figure 106 – Change in Young's modulus with water content; 8% LKD

4.5.6. Putnam Subgrade Soil with LKD – Shear Modulus

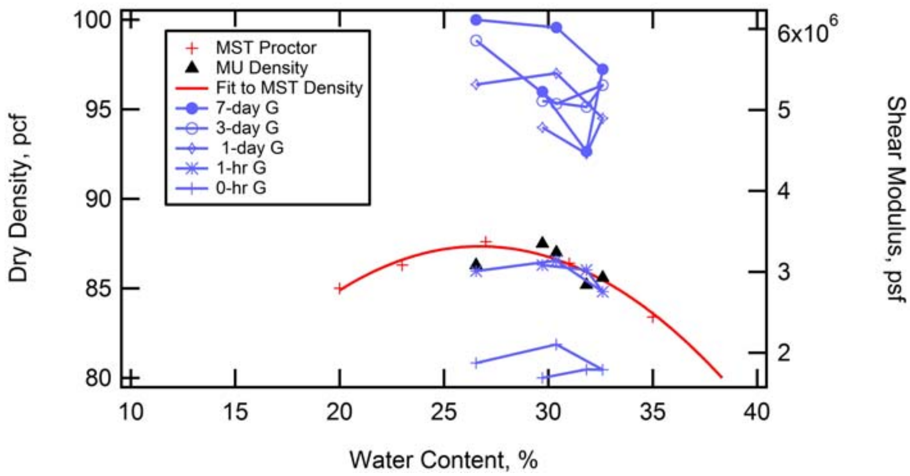

Figure 107 – Change in shear modulus with water content; 4% LKD

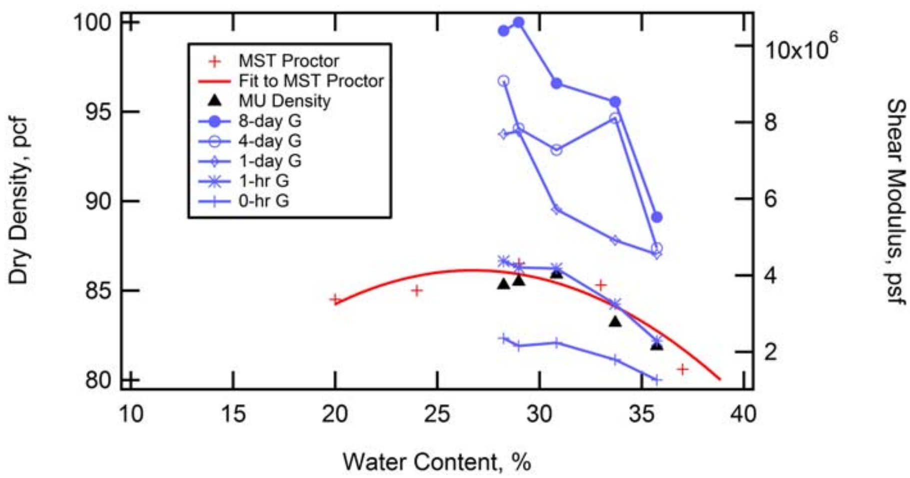

Figure 108 – Change in shear modulus with water content; 8% LKD

4.5.7. Putnam Subgrade Soil with LKD – Constrained Modulus

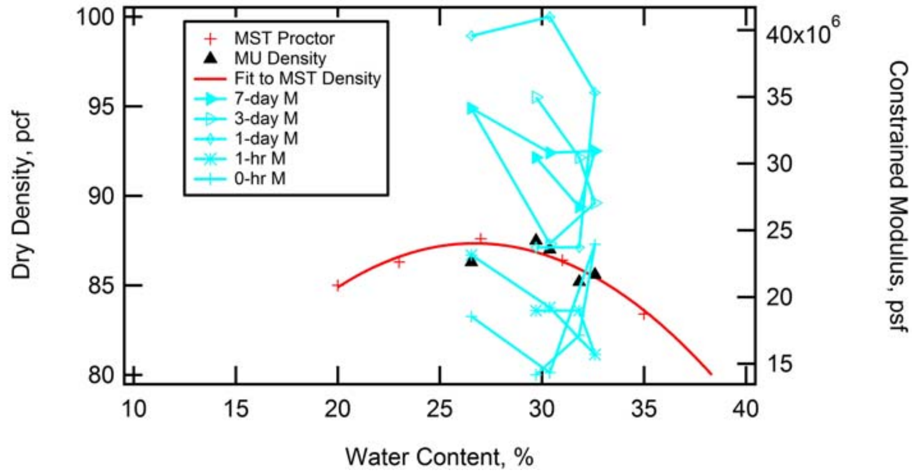

Figure 109 – Change in constrained modulus with water content; 4% LKD

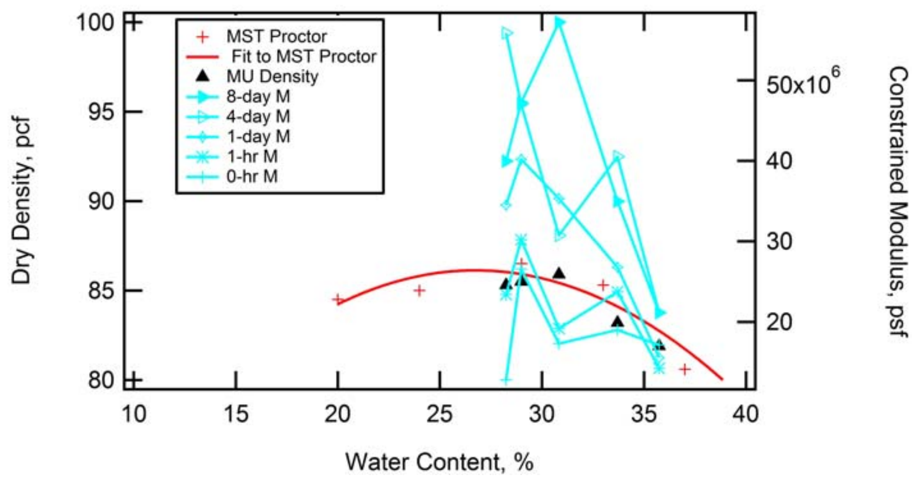

Figure 110 – Change in constrained modulus with water content; 8% LKD

4.6. Atchison Strength Results

Strength testing of the Atchison soil mixtures was performed on samples prepared near optimum (typically <1% dry of optimum). Since this is a destructive test, several samples were prepared at the same water content and were broken: immediately after compaction, 1-day, 3-days, 7-days, 14 days, and 28 days after compaction. Figure 111 shows the changes in the UCS versus time. Multiple strength tests were conducted at 14 days and 28 days using the same soil/fly ash mix. The variability in the results is indicted in the graph. A few samples broke at excessively low applied stresses due to preexisting cracks in the samples. These data have been excluded from the plot.

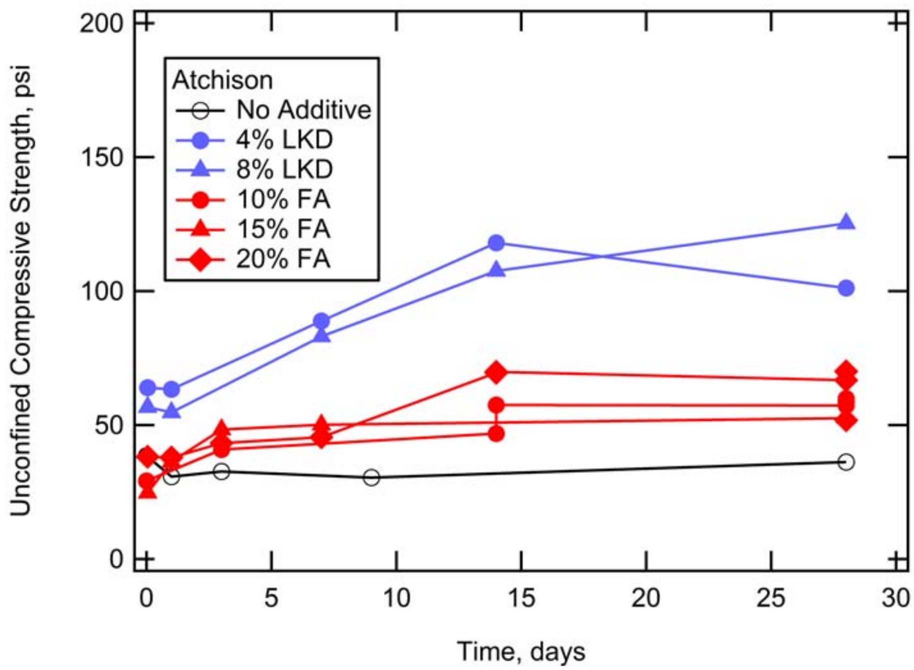

Figure 111 – Change in unconfined compressive strength with time for Atchison soil with various amounts of fly ash and LKD added

4.7. Putnam Strength Results

Unconfined compression strength testing of the Putnam soil with additives was performed on samples prepared near optimum (typically <1% dry of optimum). Since this is a destructive test, several samples were prepared at the same water content and were broken: immediately after compaction, 1-day, 4-days, 7-days, 14 days, and 28 days after compaction. Figure 112 shows the changes in the UCS versus time. The variability in the results is indicted in the graph. A few samples broke at excessively low applied stresses due to preexisting cracks in the samples. These data have been excluded from the plot.

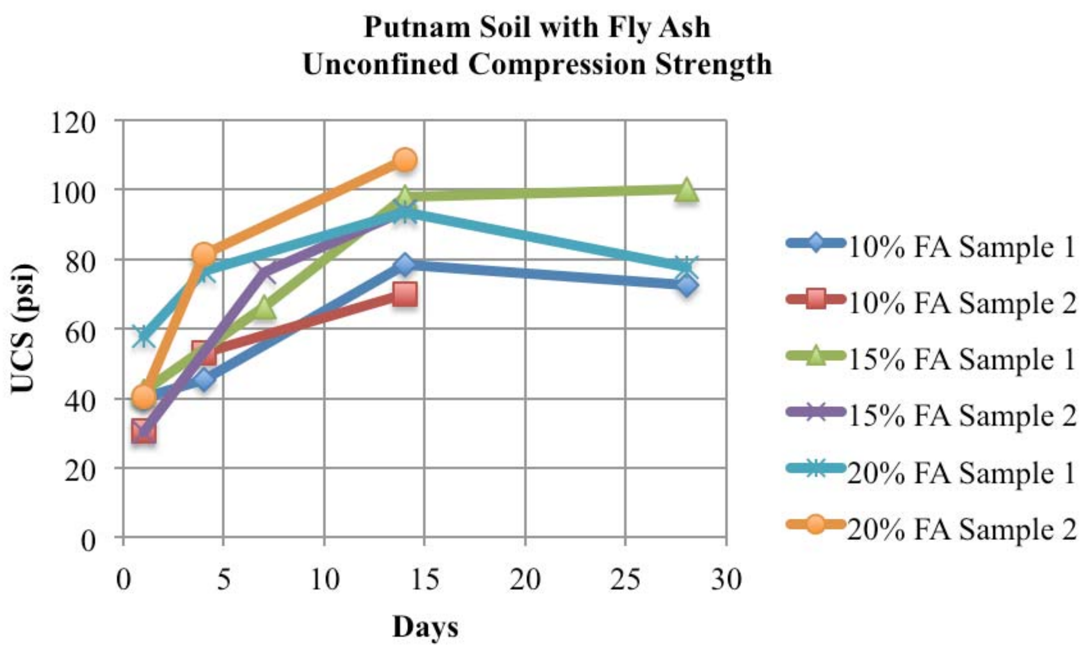

Figure 112 – Change in unconfined compressive strength with time for Putnam soil with various amounts of fly ash added

4.8. Briaud Compaction Device (BCD) Results

Since the Briaud compaction device (BCD) should be directly applied to the surface of 6-inch diameter sample, a 6-inch mold was used to establish the compaction curve. After each specimen was compacted, a BCD reading was taken, denoted as the 0-day measurement. The specimen was then carefully extruded and placed into a customized 6-inch concrete cylinder mold for subsequent measurements (1 day, 7 days, 14 days, and 28 days).

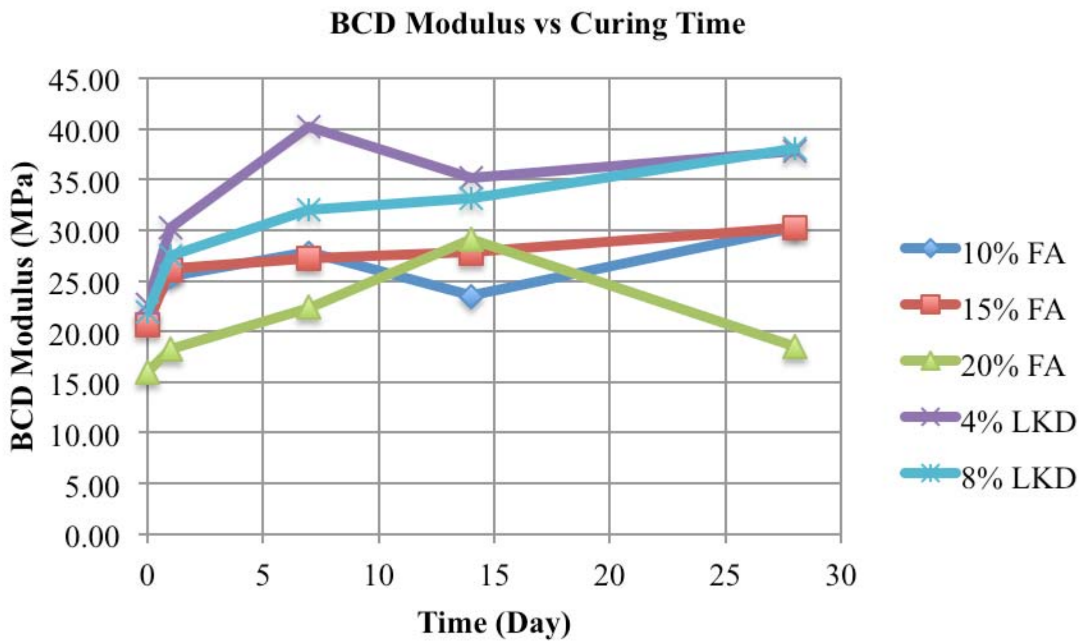

Figure 113 – Change in BCD modulus with time for Atchison soil with various amounts of fly ash and LKD added

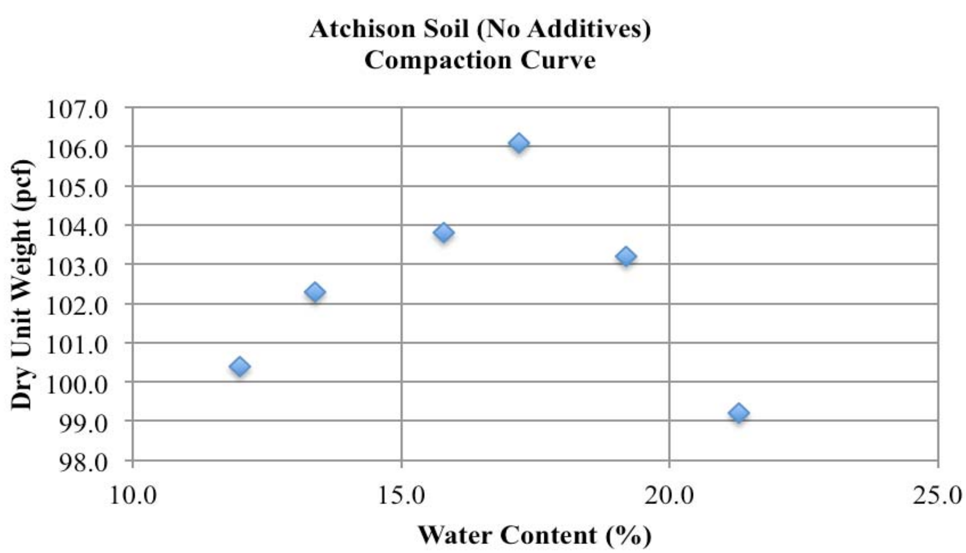

Figure 114 – Proctor compaction curve for Atchison soil with no additives (6-in mold)

4.8.1. BCD Modulus for Atchison Soil with 10% Fly Ash

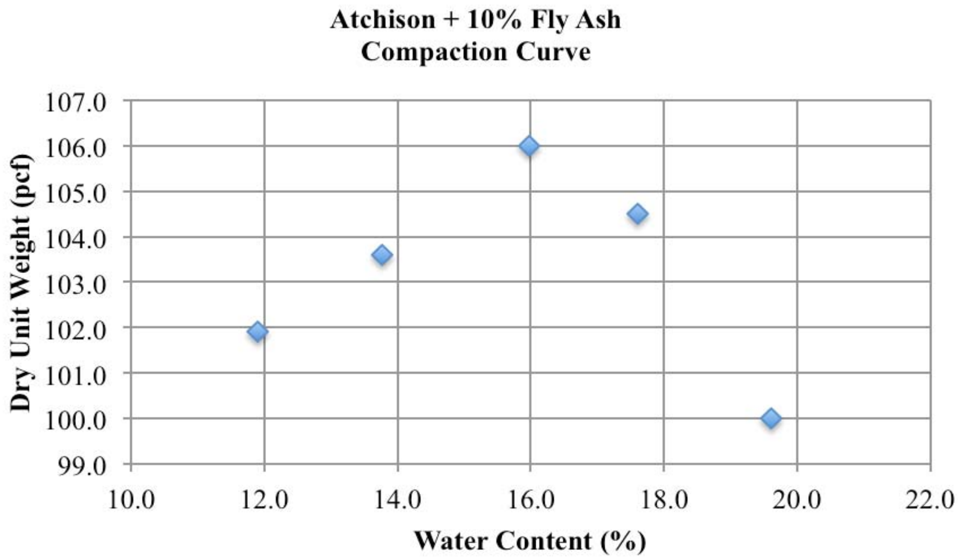

Figure 115 – Proctor compaction curve for Atchison soil with 10% Fly Ash (6-in mold)

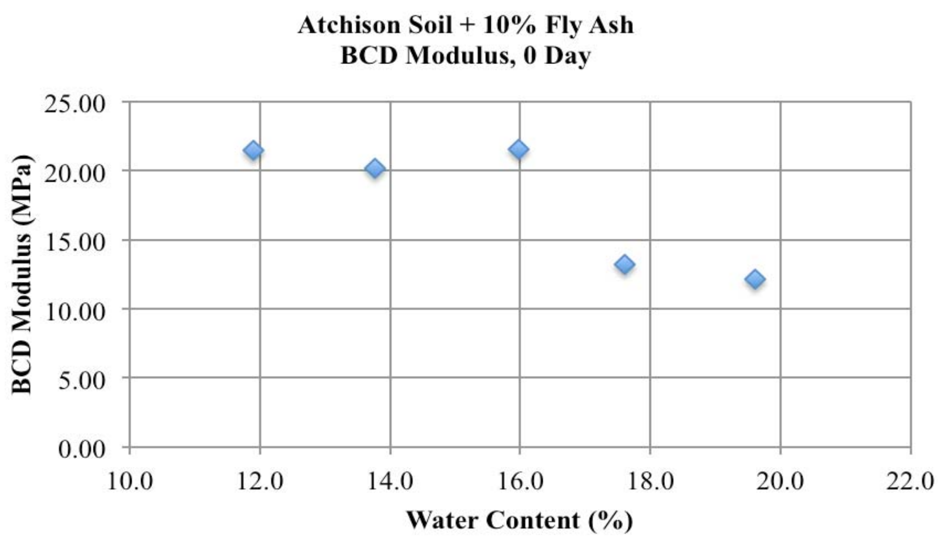

Figure 116 – BCD modulus at various water contents for Atchison soil with 10% fly ash (immediately after compaction)

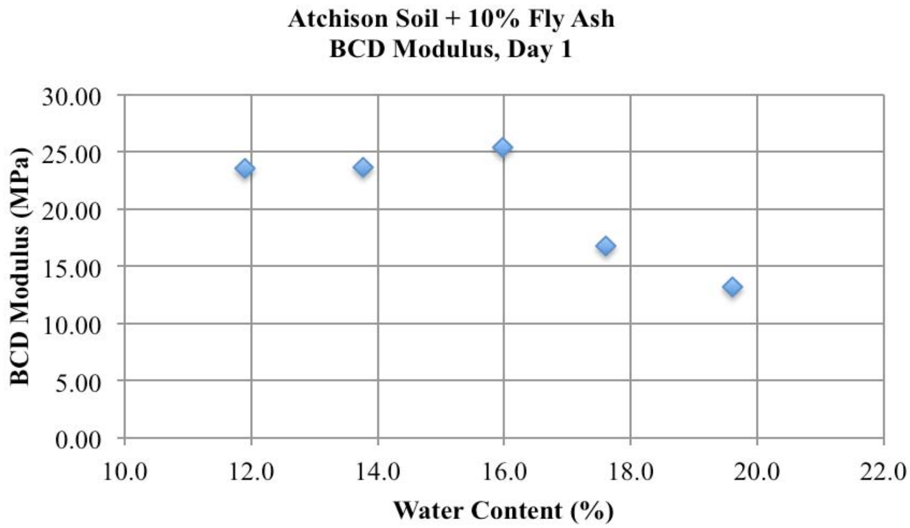

Figure 117 – BCD modulus at various water contents for Atchison soil with 10% fly ash (1 day after compaction)

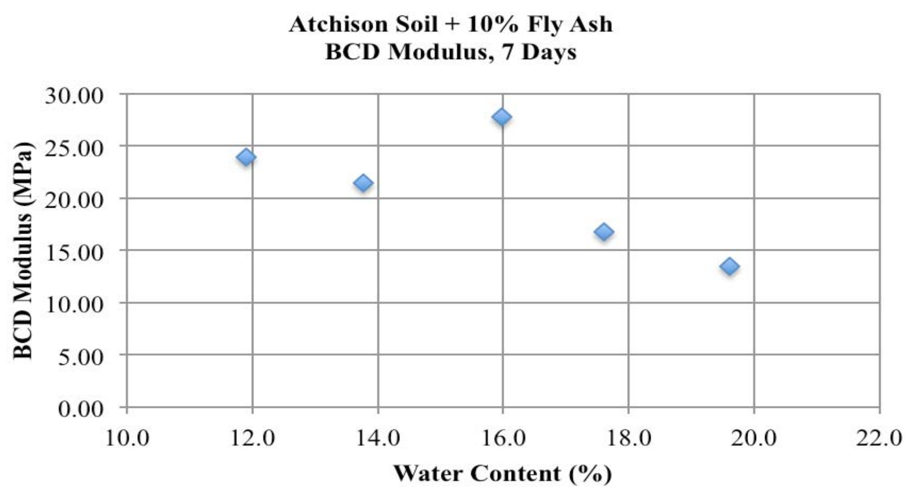

Figure 118 – BCD modulus at various water contents for Atchison soil with 10% fly ash (7 days after compaction)

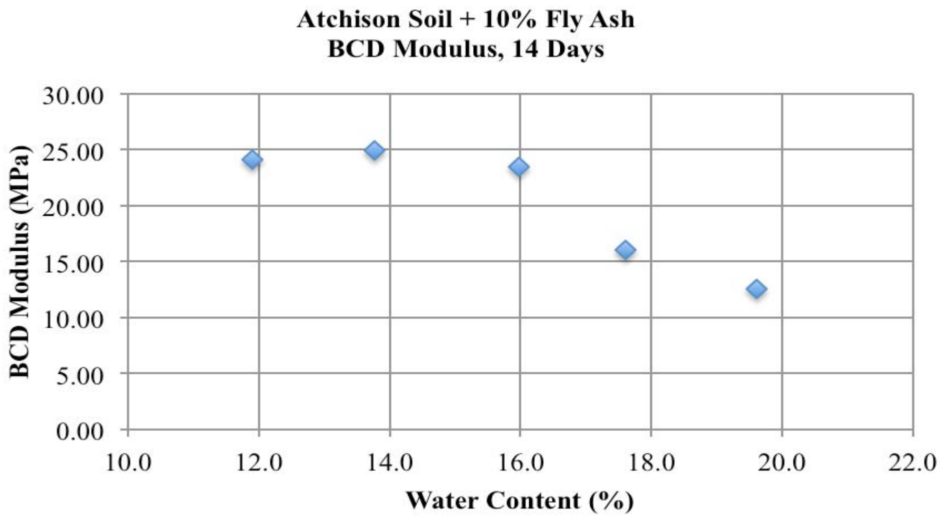

Figure 119 – BCD modulus at various water contents for Atchison soil with 10% fly ash (14 days after compaction)

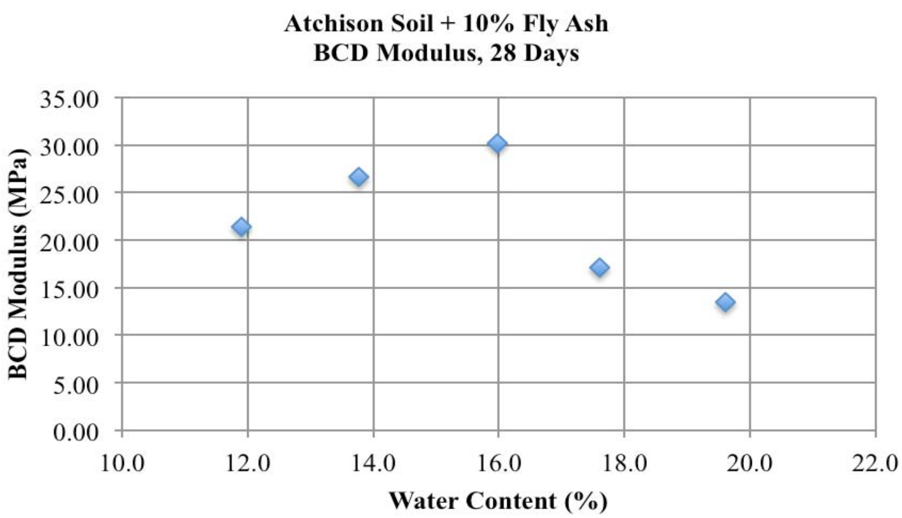

Figure 120 – BCD modulus at various water contents for Atchison soil with 10% fly ash (28 days after compaction)

4.8.2. BCD Modulus for Atchison Soil with 15% Fly Ash

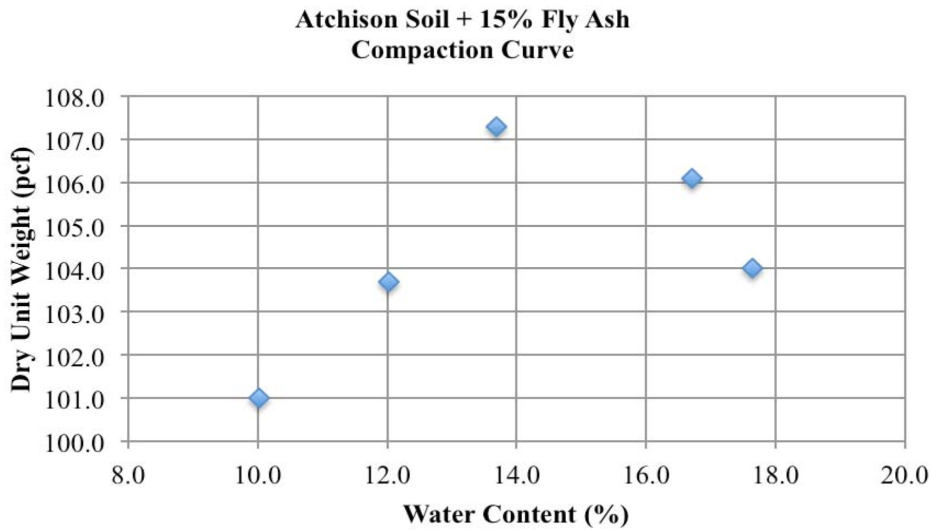

Figure 121 – Proctor compaction curve for Atchison soil with 15% fly ash (6-in mold)

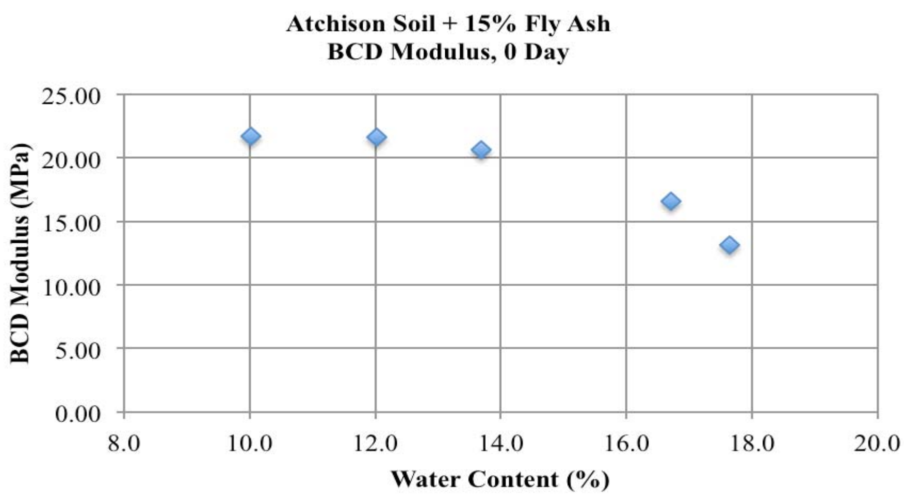

Figure 122 – BCD modulus at various water contents for Atchison soil with 15% fly ash (immediately after compaction)

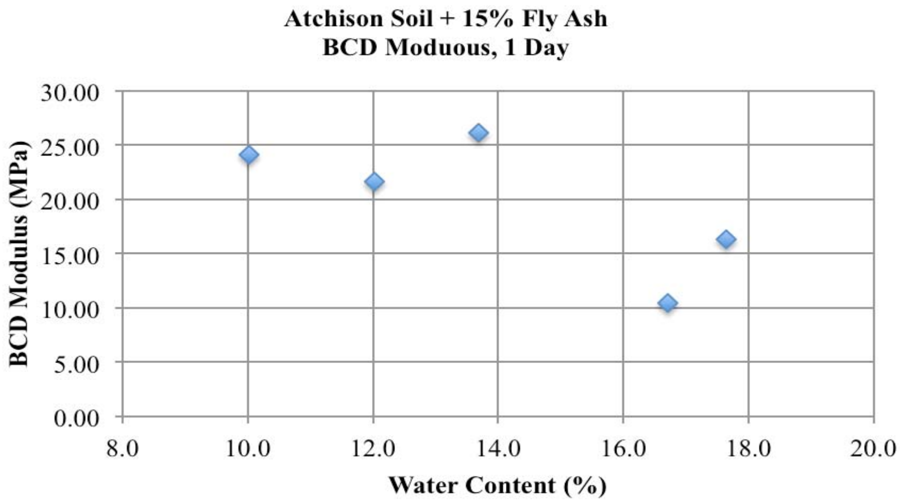

Figure 123 – BCD modulus at various water contents for Atchison soil with 15% fly ash (1 day after compaction)

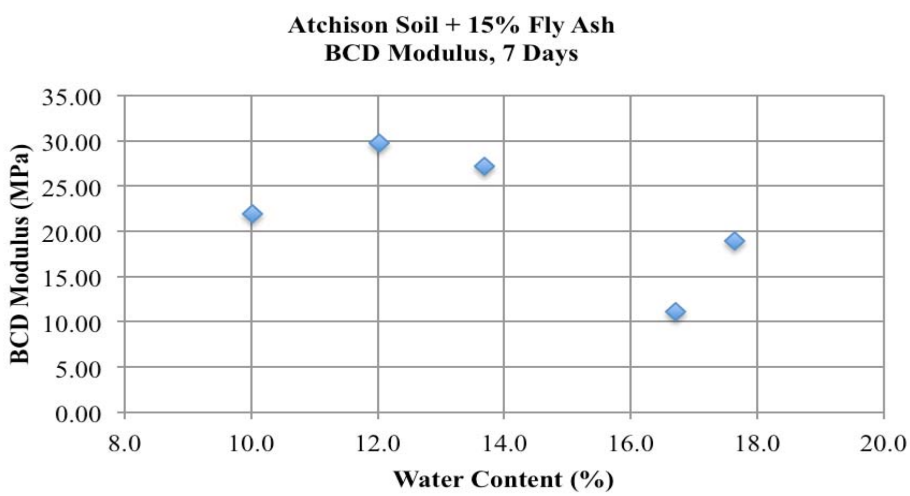

Figure 124 – BCD modulus at various water contents for Atchison soil with 15% fly ash (7 days after compaction)

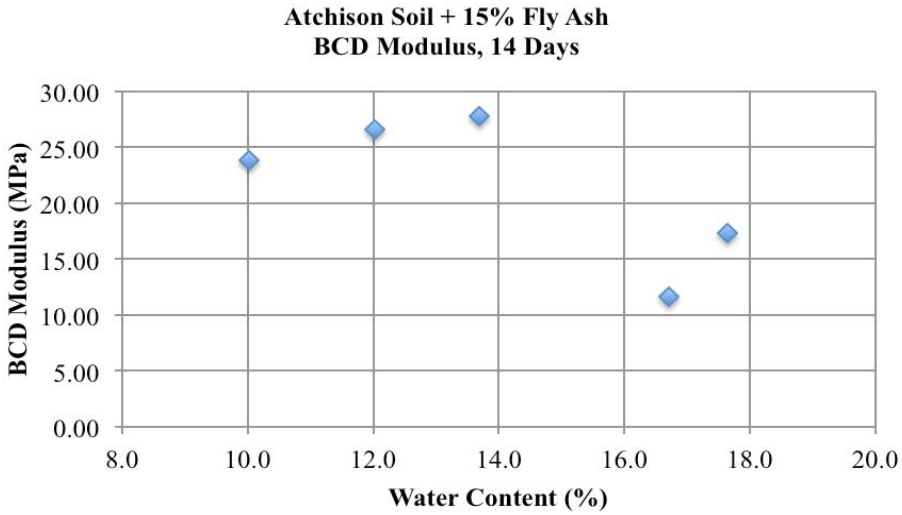

Figure 125 – BCD modulus at various water contents for Atchison soil with 15% fly ash (14 days after compaction)

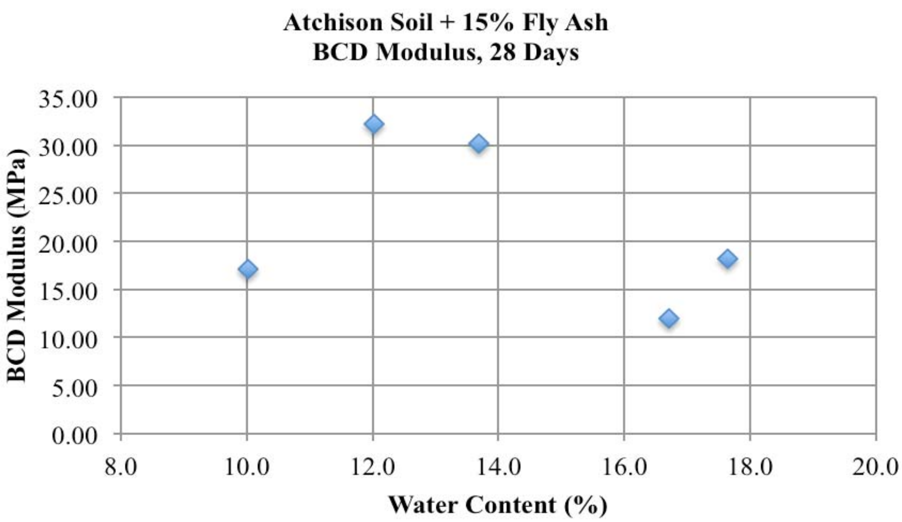

Figure 126 – BCD modulus at various water contents for Atchison soil with 15% fly ash (28 days after compaction)

4.8.3. BCD Modulus for Atchison Soil with 20% Fly Ash

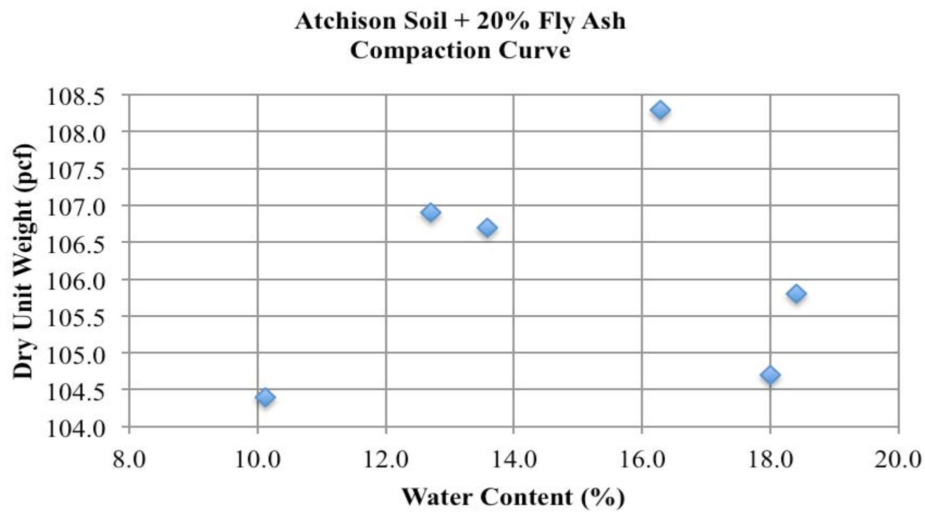

Figure 127 – Proctor compaction curve for Atchison soil with 20% fly ash (6-in mold)

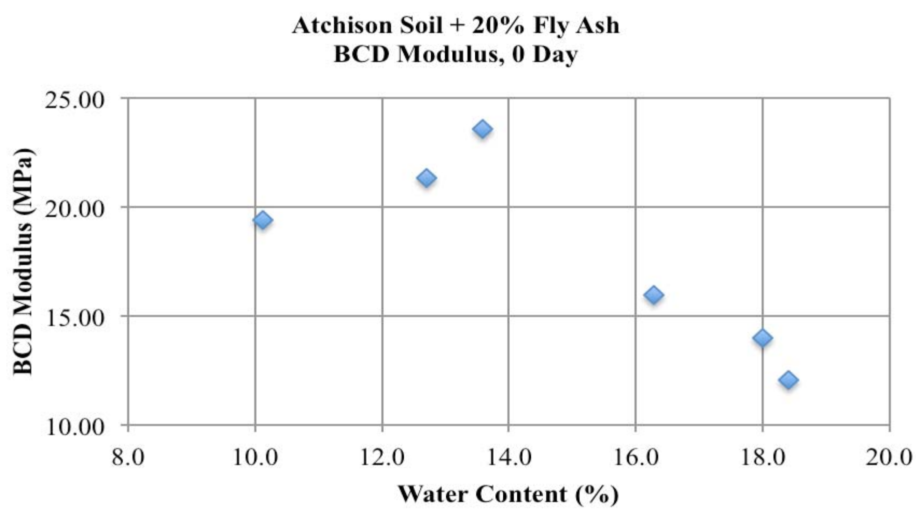

Figure 128 – BCD modulus at various water contents for Atchison soil with 20% fly ash (immediately after compaction)

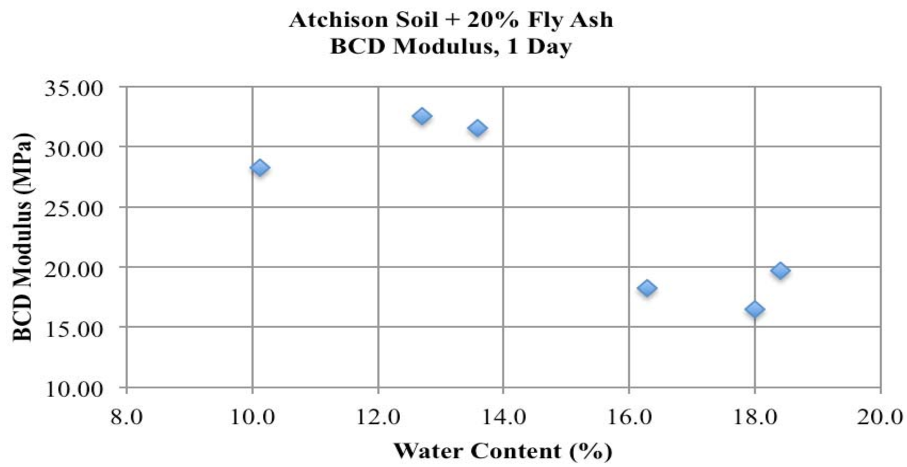

Figure 129 – BCD modulus at various water contents for Atchison soil with 20% fly ash (1 day after compaction)

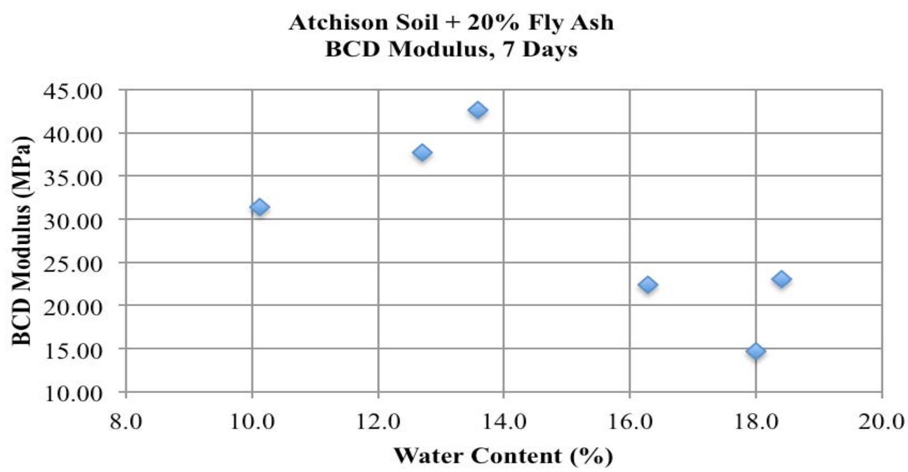

Figure 130 – BCD modulus at various water contents for Atchison soil with 20% fly ash (7 days after compaction)

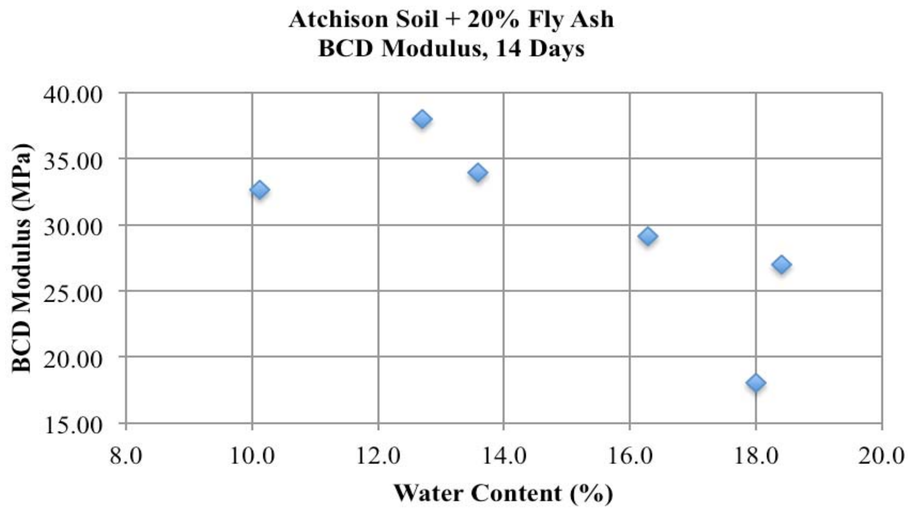

Figure 131 – BCD modulus at various water contents for Atchison soil with 20% fly ash (14 days after compaction)

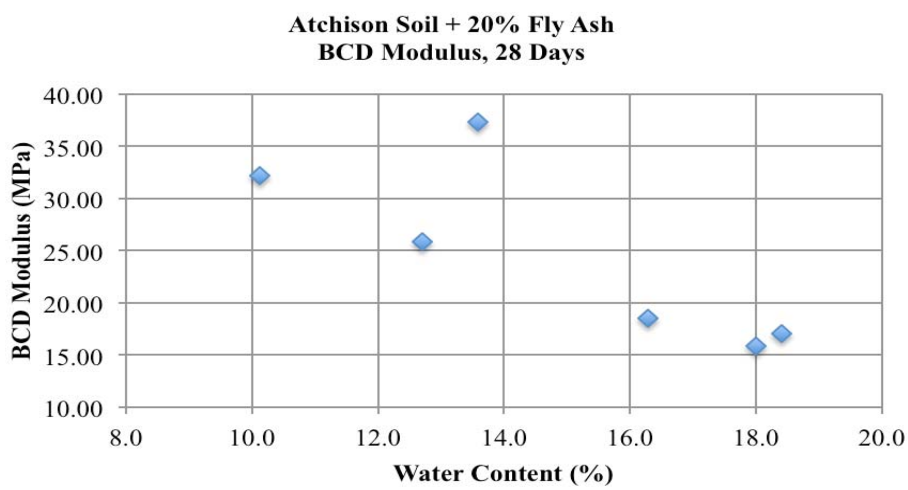

Figure 132 – BCD modulus at various water contents for Atchison soil with 20% fly ash (28 days after compaction)

4.8.4. BCD Modulus for Atchison Soil with 4% LKD

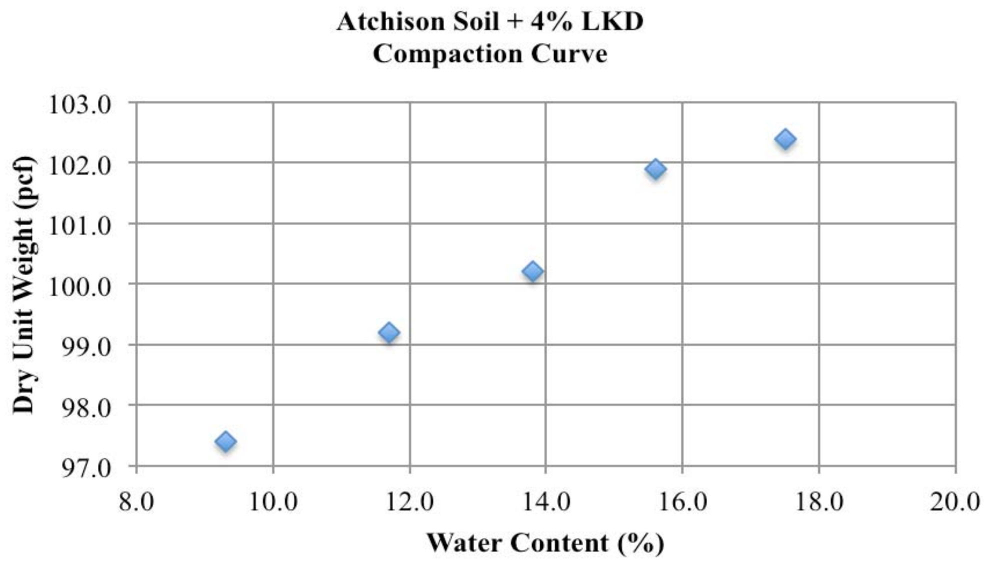

Figure 133 – Proctor compaction curve for Atchison soil with 4% LKD (6-in mold)

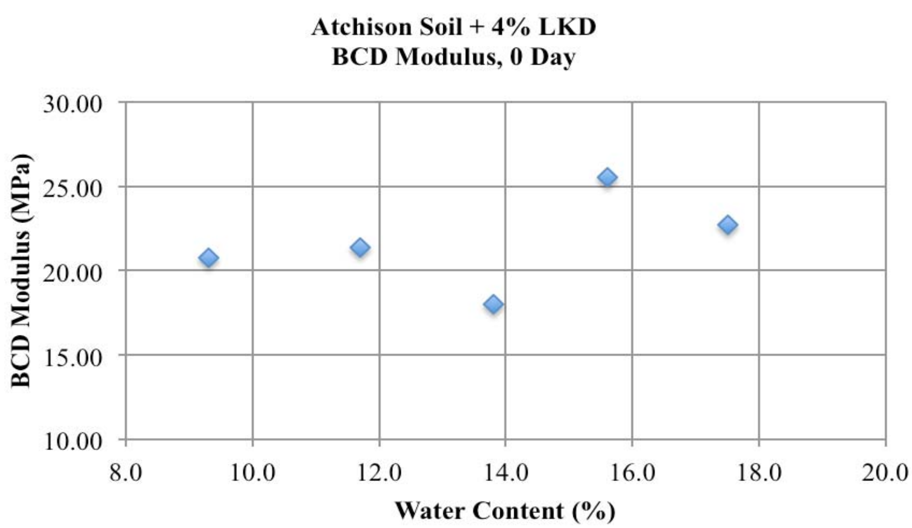

Figure 134 – BCD modulus at various water contents for Atchison soil with 4% LKD (immediately after compaction)

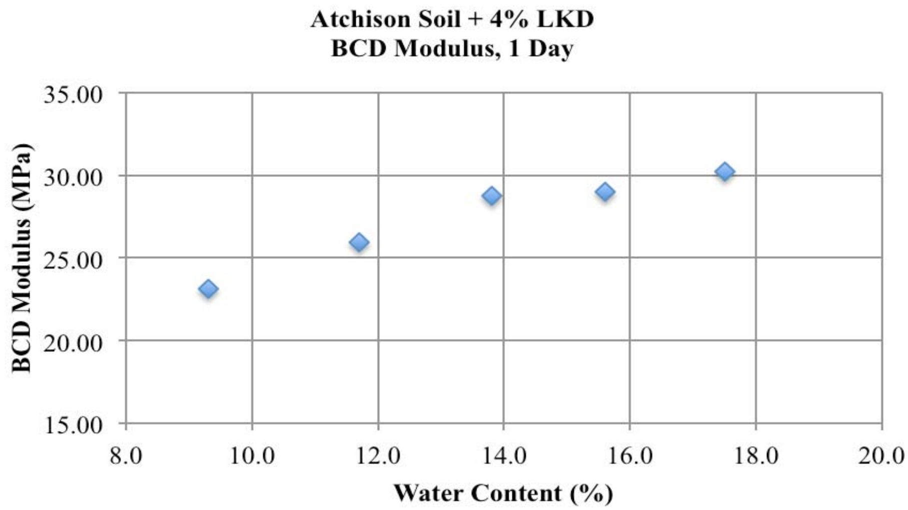

Figure 135 – BCD modulus at various water contents for Atchison soil with 4% LKD (1 Day after compaction)

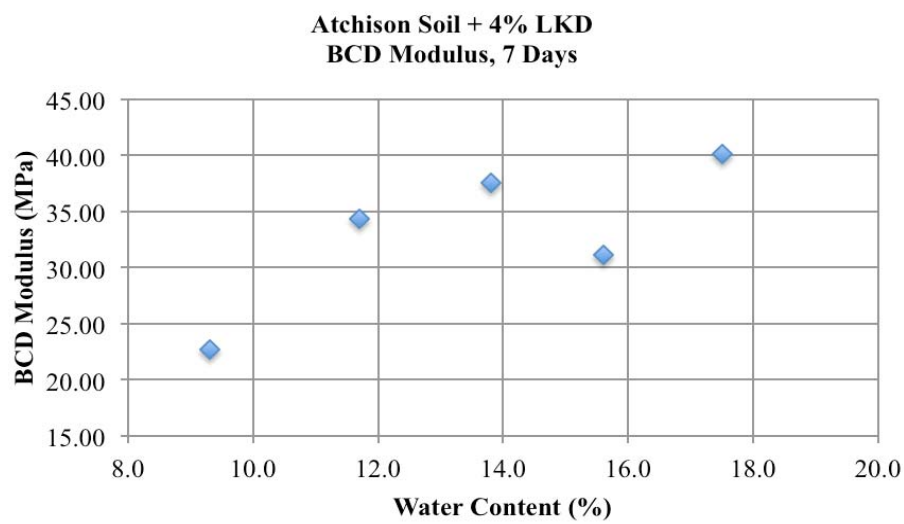

Figure 136 – BCD modulus at various water contents for Atchison soil with 4% LKD (7 days after compaction)

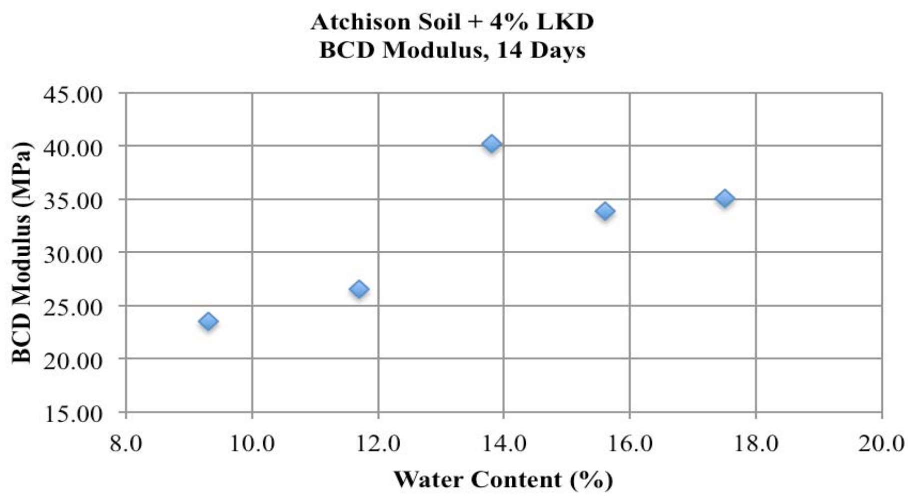

Figure 137 – BCD modulus at various water contents for Atchison soil with 4% LKD (14 Days after compaction)

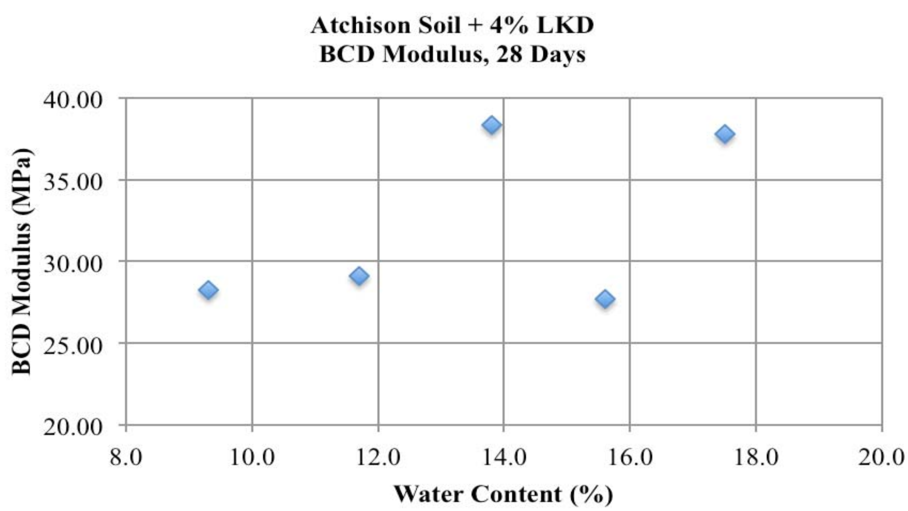

Figure 138 – BCD modulus at various water contents for Atchison soil with 4% LKD (28 Days after compaction)

4.8.5. BCD Modulus for Atchison Soil with 8% LKD

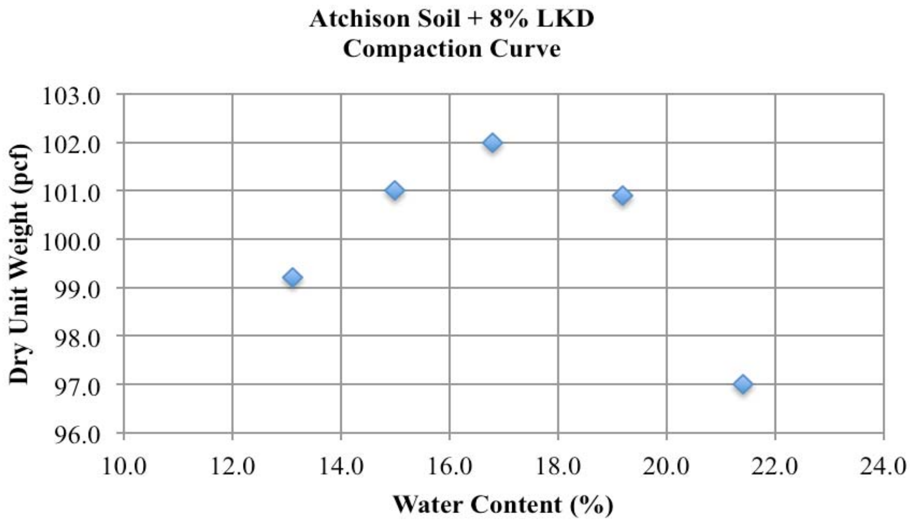

Figure 139 – Proctor compaction for Atchison soil with 8% LKD (6-in mold)

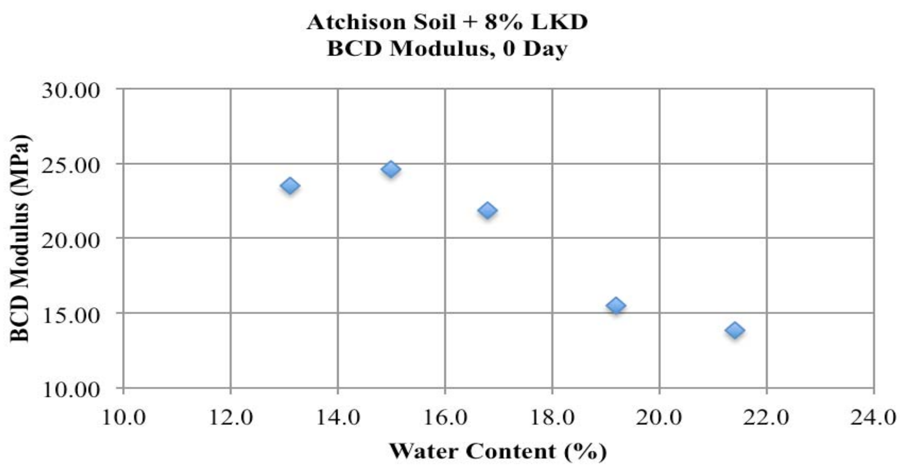

Figure 140 – BCD modulus at various water contents for Atchison soil with 8% LKD (immediately after compaction)

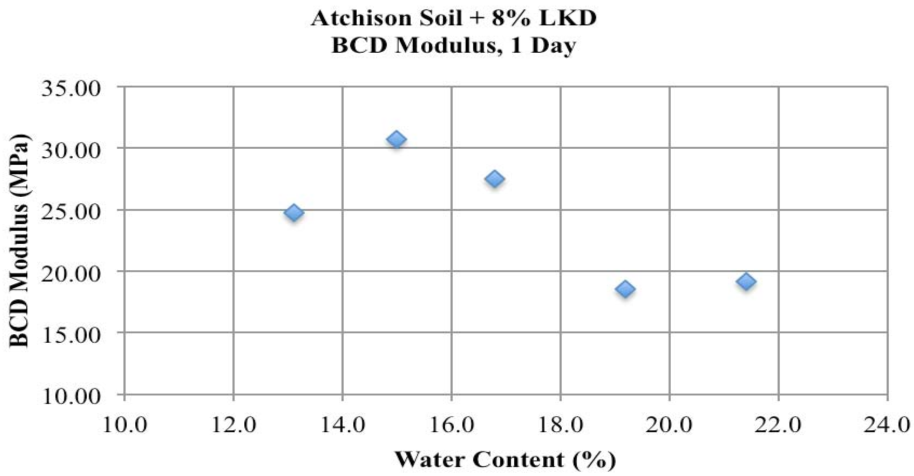

Figure 141 – BCD modulus at various water contents for Atchison soil with 8% LKD (1 Day after compaction)

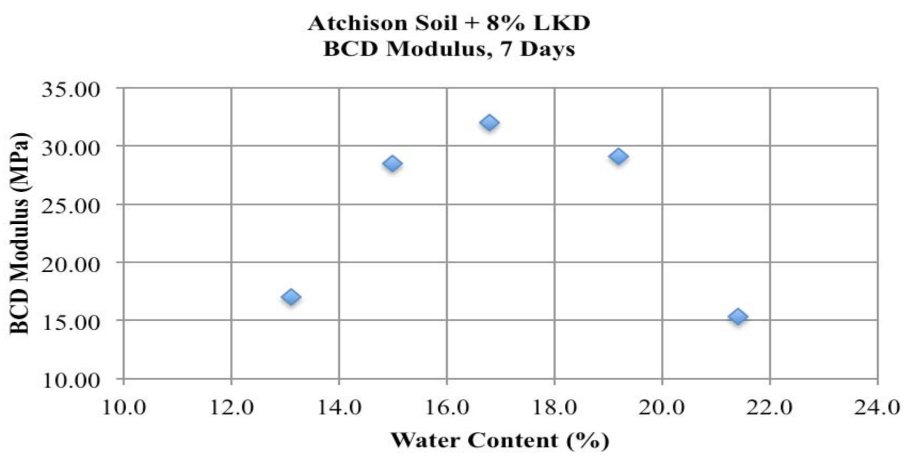

Figure 142 – BCD modulus at various water contents for Atchison soil with 8% LKD (7 Days after compaction)

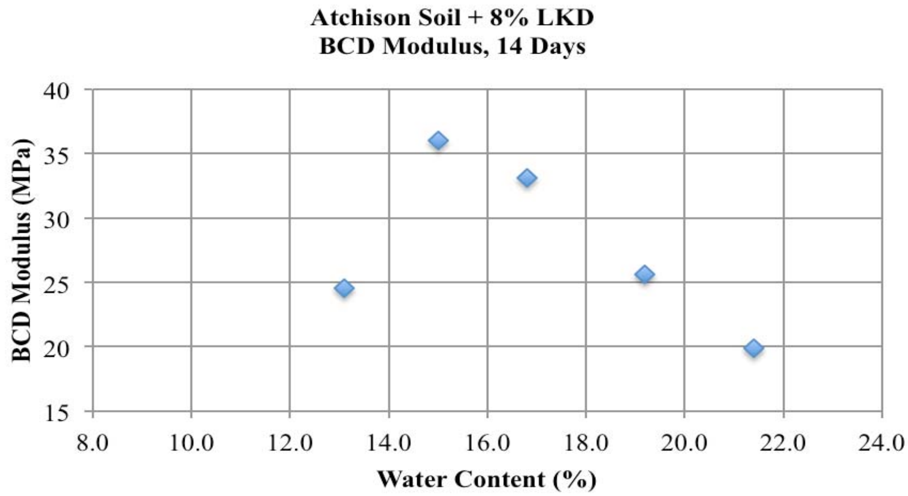

Figure 143 – BCD modulus at various water contents for Atchison soil with 8% LKD (14 days after compaction)

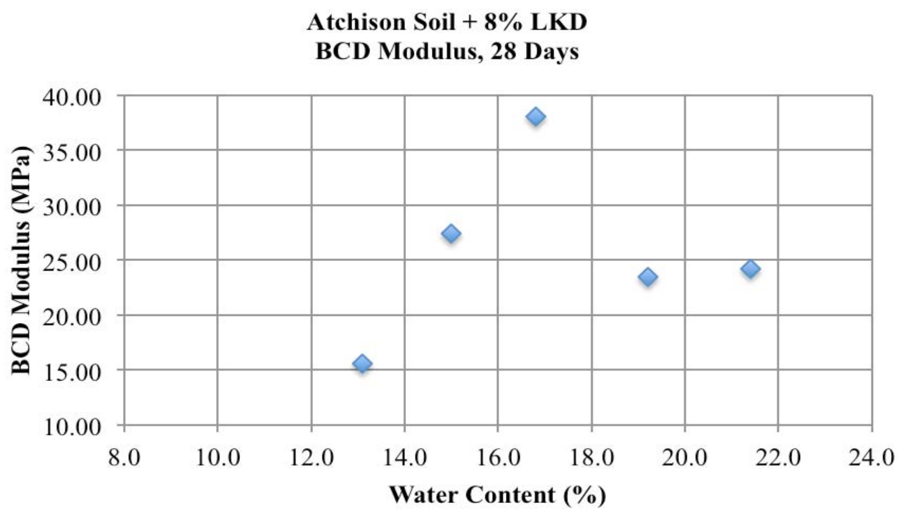

Figure 144 – BCD modulus at various water contents for Atchison soil with 8% LKD (28 days after compaction)

4.9. Resilient Modulus Results

The test results of the fly ash/Atchison soil mixture are shown in the figures below.

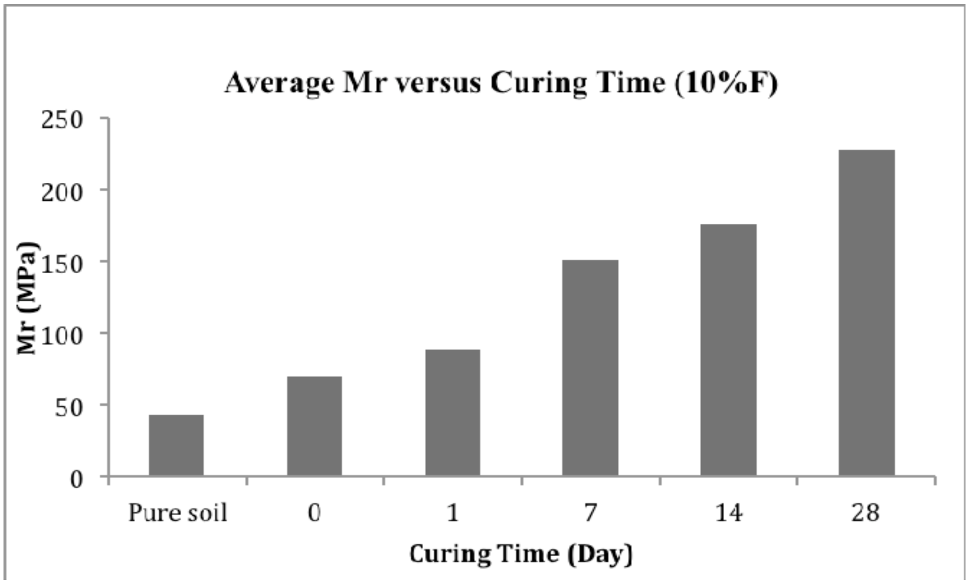

Figure 145 – Average resilient modulus at various curing times for the Atchison soil with 10% fly ash

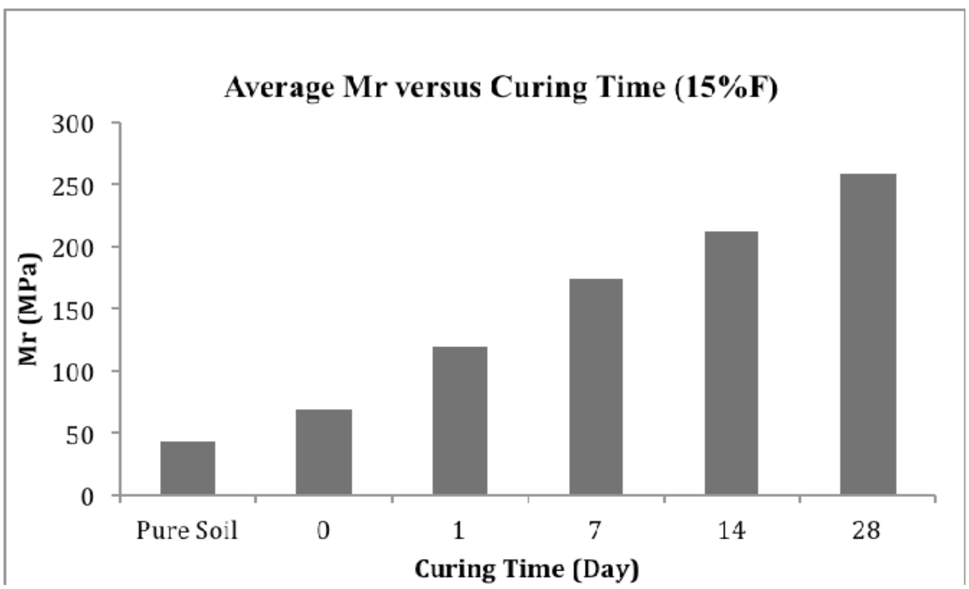

Figure 146 – Average resilient modulus at various curing times for the Atchison soil with 15% fly ash

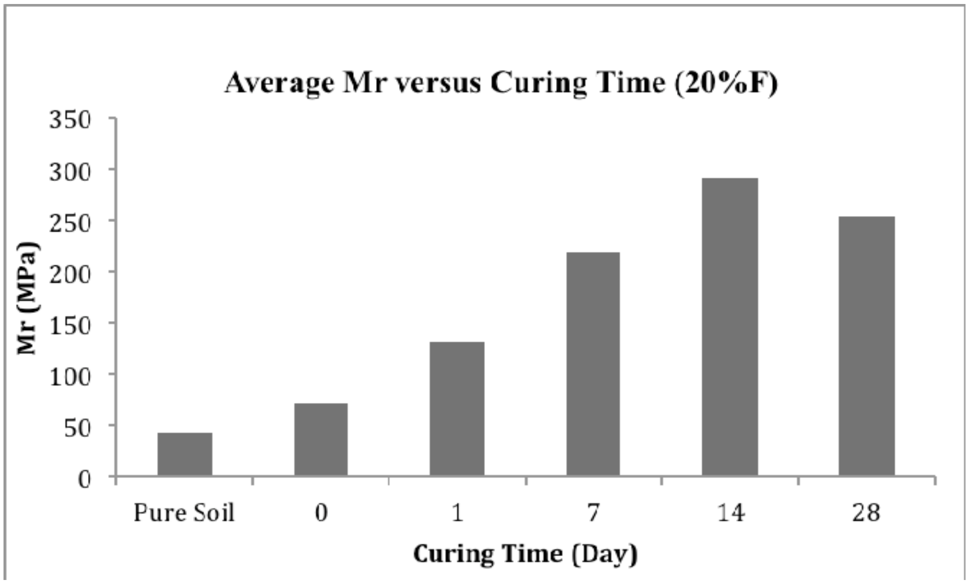

Figure 147 – Average resilient modulus at various curing times for the Atchison soil with 20% fly ash

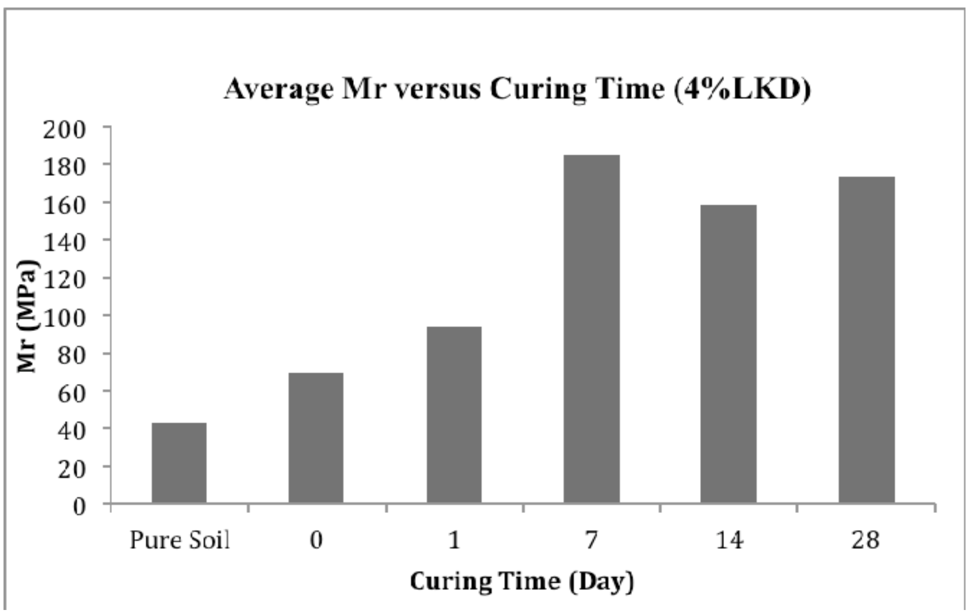

Figure 148 – Average resilient modulus at various curing times for the Atchison soil with 4% LKD

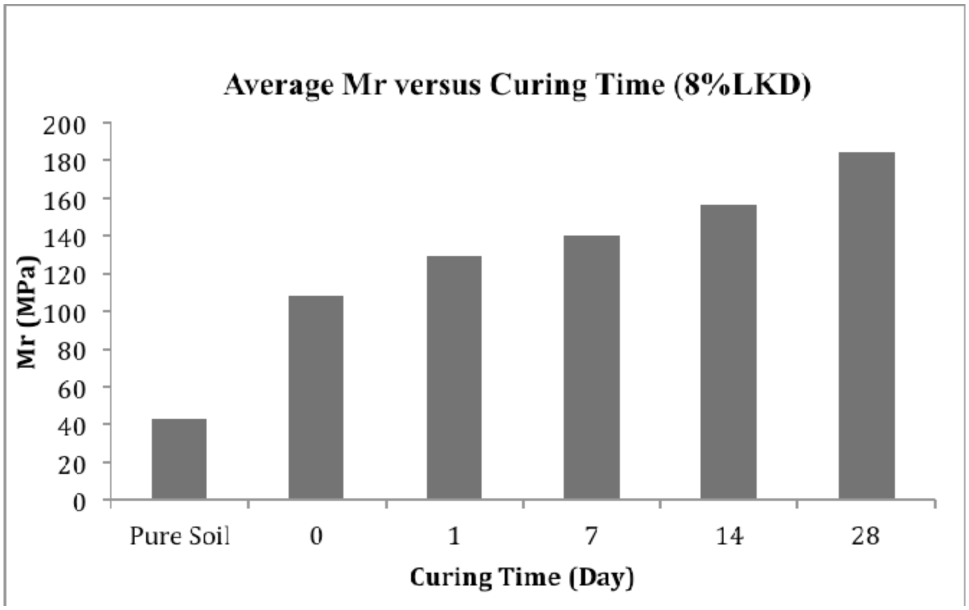

Figure 149 – Average resilient modulus at various curing times for the Atchison soil with 8% LKD

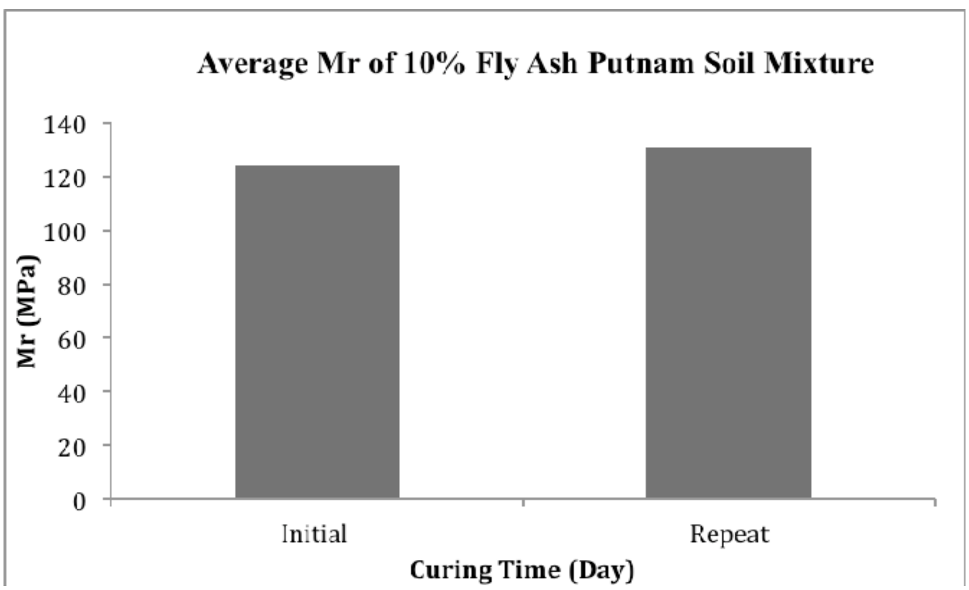

Figure 150 – Variation of resilient modulus in two parallel tests for Putnam soil with 10% fly ash

4.9.1. Resilient Modulus for Atchison Soil with 10% Fly Ash

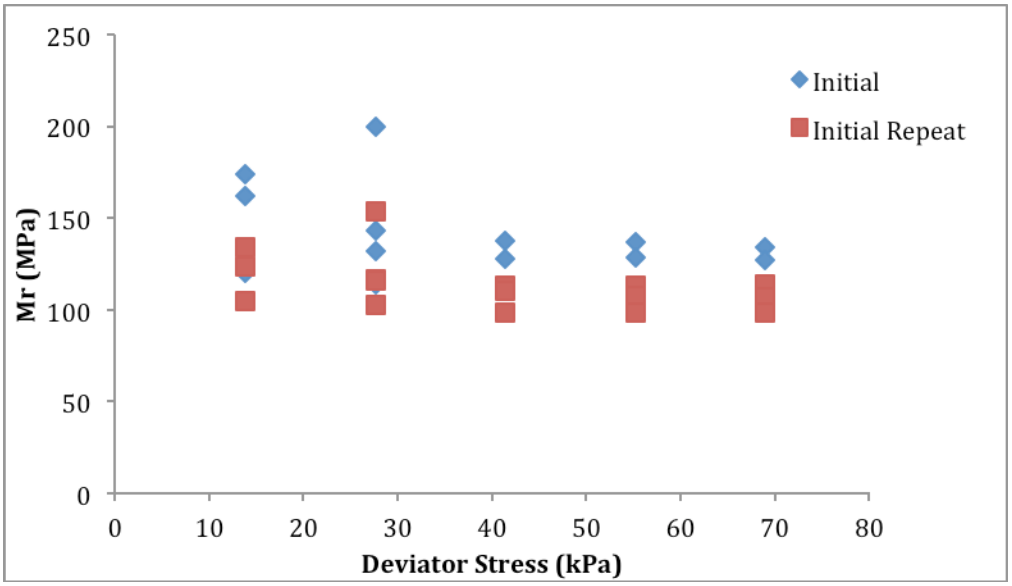

Figure 151 – Variation of resilient modulus in two parallel tests for Putnam soil with 10% fly ash

Resilient modulus of each fly ash soil mixture versus nominal deviator stresses at various curing time periods are plotted below:

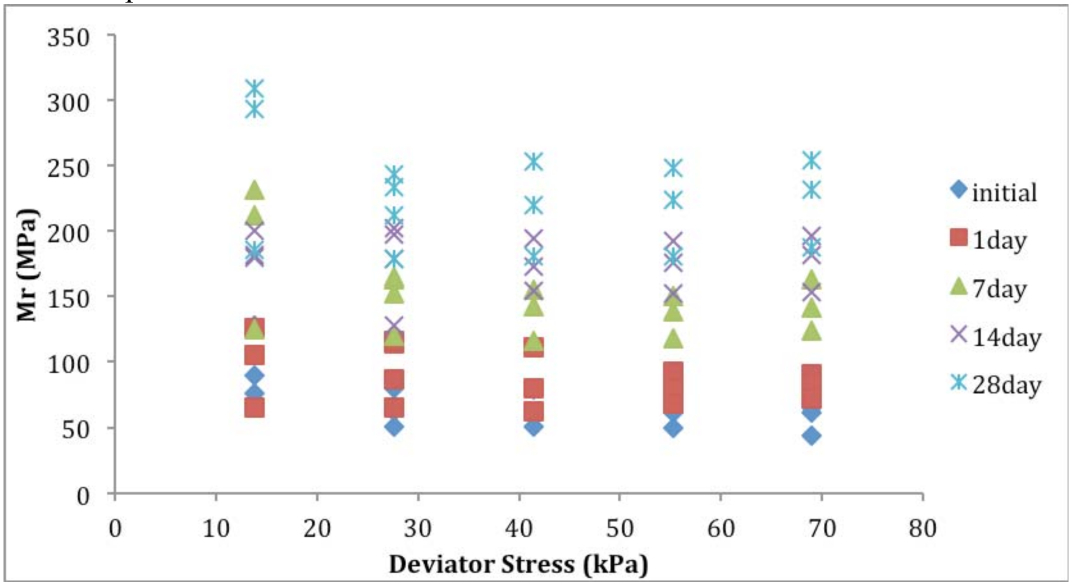

Figure 152 – Resilient modulus versus deviator stress at different curing time period (Atchison soil with 10% fly ash)

Table 6 – Resilient modulus of Atchison soil with 10% fly ash

Sequence	Deviator stress Kpa	Cell Pressure kPa	Pure soil Mpa	initial Mpa	1day Mpa	7day Mpa	14day Mpa	28day Mpa
1	27.6	41.4	45.6	81.0	114.4	165.6	197.4	243.8
2	13.8	41.4	67.3	90.0	125.7	231.3	200.5	309.3
3	27.6	41.4	47.3	80.0	116.2	162.7	201.9	233.3
4	41.4	41.4	40.6	79.0	111.5	155.3	194.3	252.8
5	55.2	41.4	38.7	72.0	93.1	150.1	192.2	248.0
6	68.9	41.4	47.3	65.0	90.5	162.9	196.4	254.6
7	13.8	27.6	48.3	128.0	105.1	211.8	179.4	293.1
8	27.6	27.6	38.5	62.0	86.4	152.8	178.7	212.4
9	41.4	27.6	36.5	61.0	80.1	142.7	173.3	219.5
10	55.2	27.6	38.6	61.0	79.8	138.5	175.7	223.9
11	68.9	27.6	49.3	60.9	82.8	141.5	181.7	232.0
12	13.8	13.8	41.8	75.8	65.2	125.3	181.7	185.4
13	27.6	13.8	33.3	51.0	65.4	119.7	128.4	179.2
14	41.4	13.8	35.1	50.3	62.4	116.5	154.8	181.1
15	55.2	13.8	39.0	49.8	68.4	117.9	152.5	180.5
16	68.9	13.8	40.0	43.6	72.5	124.2	153.5	187.6

4.9.2. Resilient Modulus for Atchison Soil with 15% Fly Ash

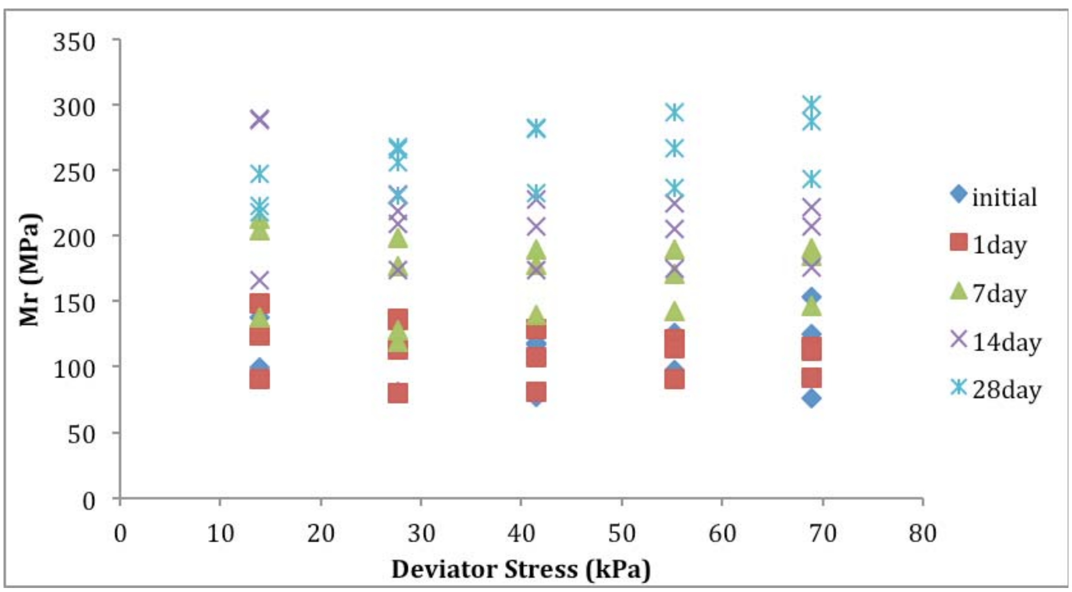

Figure 153 – Resilient modulus versus deviator stress at different curing time period (Atchison soil with 15% fly ash)

Table 7 – Resilient modulus of Atchison soil with 15% fly ash

Sequence	Deviator stress	Cell Pressure	Pure soil	initial	1 day	7day	14day	28day
	Kpa	kPa	Mpa	Mpa	Mpa	Mpa	Mpa	Mpa
1	27.6	41.4	45.6	115.5	135.4	119.1	231.4	266.3
2	13.8	41.4	67.3	123.8	148.9	203.8	288.1	247.7
3	27.6	41.4	47.3	116.7	136.3	198.4	219.3	268.1
4	41.4	41.4	40.6	117.8	128.6	189.8	227.5	282.9
5	55.2	41.4	38.7	126.3	120.7	189.2	224.9	294.6
6	68.9	41.4	47.3	153.7	115.1	190.7	221.9	300.3
7	13.8	27.6	48.3	99.1	123.8	213.4	289.8	222.4
8	27.6	27.6	38.5	115.2	113.4	176.4	209.0	255.8
9	41.4	27.6	36.5	117.6	107.3	178.2	207.2	281.6
10	55.2	27.6	38.6	116.5	114.3	171.2	205.4	266.7
11	68.9	27.6	49.3	125.3	112.7	184.7	207.4	287.7
12	13.8	13.8	41.8	138.2	90.7	137.4	166.2	218.3
13	27.6	13.8	33.3	80.7	80.1	128.1	174.2	230.5
14	41.4	13.8	35.1	77.0	80.7	140.1	174.3	232.2
15	55.2	13.8	39.0	98.0	90.7	142.9	175.2	236.4
16	68.9	13.8	40.0	76.1	92.1	146.6	176.1	243.4

4.9.3. Resilient Modulus for Atchison Soil with 20% Fly Ash

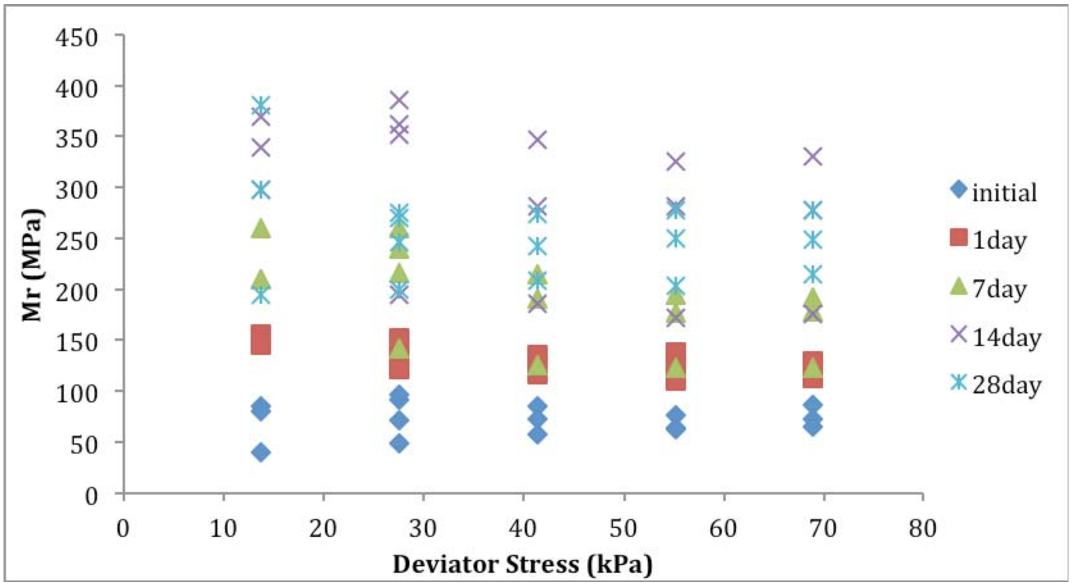

Figure 154 – Resilient modulus versus deviator stress at different curing time period (Atchison soil with 20% fly ash)

Table 8 – Resilient modulus for Atchison soil with 20% fly ash

Sequence	Deviator stress Kpa	Cell Pressure kPa	Pure soil Mpa	initial Mpa	1 day Mpa	7day Mpa	14day Mpa	28day Mpa
1	27.6	41.4	45.6	92.1	146.4	240.4	362.5	275.3
2	13.8	41.4	67.3	85.1	156.2	260.0	370.0	380.9
3	27.6	41.4	47.3	96.4	152.4	259.8	385.8	270.7
4	41.4	41.4	40.6	84.8	135.3	214.4	347.5	274.0
5	55.2	41.4	38.7	64.1	138.1	195.0	325.3	277.4
6	68.9	41.4	47.3	86.3	126.3	192.0	330.6	277.5
7	13.8	27.6	48.3	80.0	150.0	210.0	340.0	298.0
8	27.6	27.6	38.5	70.9	130.0	216.4	351.7	246.9
9	41.4	27.6	36.5	73.2	120.8	191.1	281.2	243.0
10	55.2	27.6	38.6	76.3	120.0	177.1	282.0	249.8
11	68.9	27.6	49.3	73.1	129.2	178.8	277.4	248.6
12	13.8	13.8	41.8	40.2	145.5	209.3	298.5	195.3
13	27.6	13.8	33.3	49.3	121.1	142.4	194.2	200.0
14	41.4	13.8	35.1	57.8	116.3	125.4	186.0	208.8
15	55.2	13.8	39.0	62.0	110.9	122.6	172.2	203.0
16	68.9	13.8	40.0	64.8	112.3	122.8	175.2	214.9

4.9.4. Resilient Modulus for Atchison Soil with 4% LKD

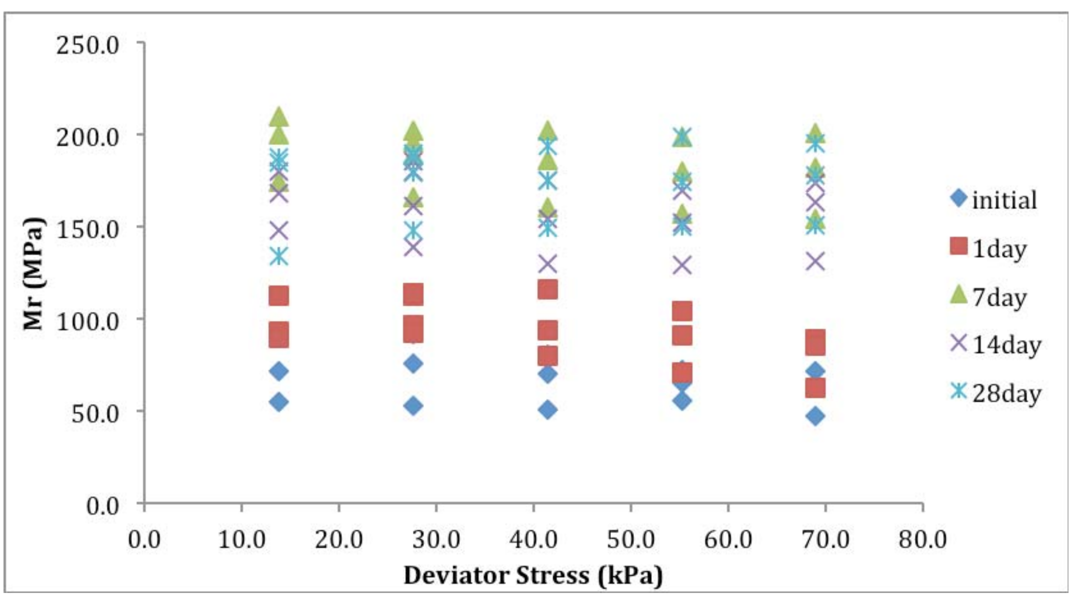

Figure 155 – Resilient modulus versus deviator stress at different curing time period (Atchison soil with 4% LKD)

Table 9 – Resilient modulus of Atchison soil with 4% LKD

Sequence	Deviator stress Kpa	Cell Pressure kPa	Pure soil Mpa	initial Mpa	1day Mpa	7day Mpa	14day Mpa	28 day Mpa
1	27.6	41.4	45.6	91.9	112.9	202.0	185.5	188.4
2	13.8	41.4	67.3	92.0	112.5	210.0	180.0	188.0
3	27.6	41.4	47.3	92.4	113.9	195.9	179.9	189.8
4	41.4	41.4	40.6	81.0	115.9	202.2	175.0	194.1
5	55.2	41.4	38.7	72.5	104.3	199.1	169.8	198.8
6	68.9	41.4	47.3	71.5	89.3	200.6	173.9	195.5
7	13.8	27.6	48.3	72.0	93.3	200.0	168.0	185.0
8	27.6	27.6	38.5	76.0	96.8	189.1	161.1	179.7
9	41.4	27.6	36.5	70.5	94.0	186.0	154.4	175.1
10	55.2	27.6	38.6	65.6	90.9	179.8	152.4	174.6
11	68.9	27.6	49.3	64.7	85.7	181.9	163.4	177.7
12	13.8	13.8	41.8	55.0	90.1	174.5	148.4	134.1
13	27.6	13.8	33.3	53.2	92.8	166.1	138.9	148.4
14	41.4	13.8	35.1	50.9	80.0	160.7	129.8	149.6
15	55.2	13.8	39.0	56.1	71.3	157.3	129.7	150.0
16	68.9	13.8	40.0	47.7	62.7	154.1	131.5	150.9

4.9.5. Resilient Modulus for Atchison Soil with 8% LKD

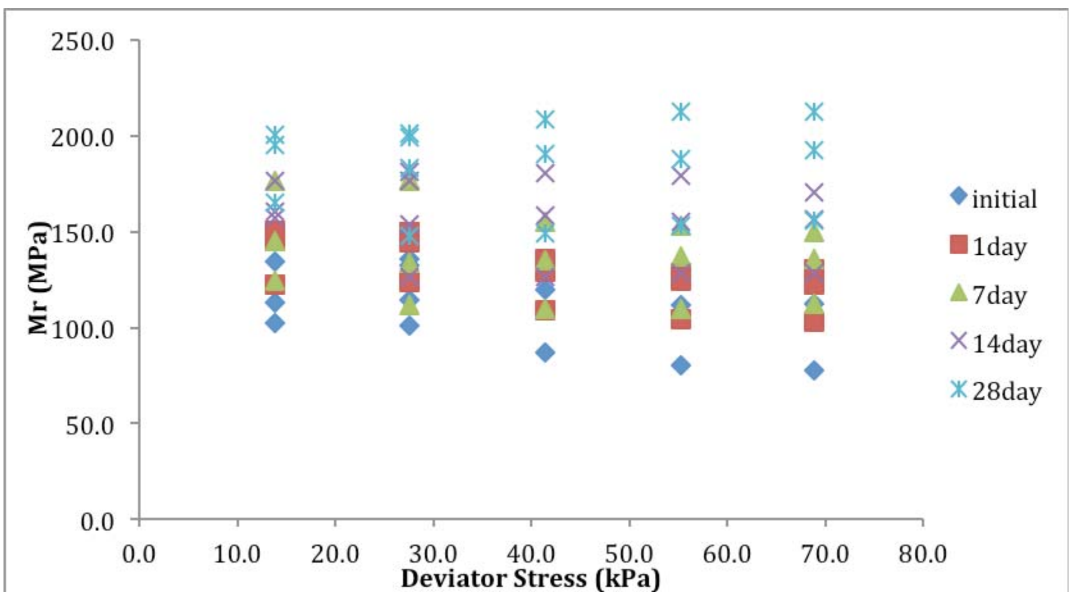

Figure 156 – Resilient modulus versus deviator stress at different curing time period (Atchison soil with 8% LKD)

Table 10 – Resilient modulus for Atchison soil with 8% LKD

Sequence	Deviator stress Kpa	Cell Pressure kPa	Pure soil MPa	initial MPa	1 day MPa	7day MPa	14day MPa	28day MPa
1	27.6	41.4	45.6	132.0	149.4	176.2	176.2	199.1
2	13.8	41.4	67.3	134.0	150.0	176.0	176.1	200.0
3	27.6	41.4	47.3	135.2	149.3	176.9	181.2	201.1
4	41.4	41.4	40.6	119.4	135.5	154.5	180.3	208.5
5	55.2	41.4	38.7	111.1	128.4	153.0	178.9	212.0
6	68.9	41.4	47.3	112.3	130.3	149.7	170.1	212.0
7	13.8	27.6	48.3	112.5	144.5	144.5	160.1	195.0
8	27.6	27.6	38.5	113.8	144.4	133.6	153.3	182.9
9	41.4	27.6	36.5	109.5	128.7	134.8	158.3	190.0
10	55.2	27.6	38.6	104.0	124.0	136.6	154.8	187.5
11	68.9	27.6	49.3	104.4	122.4	135.2	155.9	191.9
12	13.8	13.8	41.8	102.0	122.2	124.2	156.8	164.6
13	27.6	13.8	33.3	100.4	123.3	111.3	125.9	147.8
14	41.4	13.8	35.1	86.4	108.5	109.7	126.4	148.9
15	55.2	13.8	39.0	79.9	103.8	109.6	127.8	152.8
16	68.9	13.8	40.0	77.0	103.0	112.3	128.0	155.8

5. DISCUSSION

5.1. Effect of Soil Additives on Small-Strain Modulus

The results presented in Sections 4.2 to 4.5 include all of the modulus values that were measured from the free-free resonance measurements, namely Young's modulus (E), shear modulus (G), and constrained modulus (M). The trends observed in these moduli values are generally consistent although some discrepancies are evident. There are a few reasons why the changes in modulus values may not be consistent. First, compacted soil is not an isotropic material so the elastic constants that are measured will depend somewhat on the direction of wave propagation. For example, a compression wave is only sensitive to the stresses and structure in the longitudinal direction, while a shear wave is sensitive to stresses and structure in both the longitudinal and transverse directions. These effects are generally small and don't greatly affect the trends in modulus change with time observed in this study. Secondly, measurement of the constrained modulus from the travel time of a compression wave is subject to some subjectivity in identifying the wave arrival times. This is evident in Fig. 18 where the arrival time of the wave at the accelerometer is somewhat ambiguous. In some cases, it is possible that an error occurred during the data collection. For example, the trend in shear modulus values for the 20% fly ash case is much different than the Young's modulus and constrained modulus trends. This is likely due to a problem with the test, such as poor coupling between the end plate and the soil. Based on an examination of the data, it appears that the Young's modulus values provide the most reliable and consistent results in this study. Therefore, to simplify the presentation and discussion of the results, only the values of Young's modulus are presented below.

The addition of fly ash to the Atchison soil had a significant effect on the modulus of the soil. Figure 159 presents a bar graph showing the changes in Young's modulus values for samples compacted near the optimum water content. Figure 160 shows the same data plotted as the ratio of the modified soil modulus to the unmodified case. To develop these graphs, measurement data points that fell within ±2% of optimum and 95% or more of γ_{dmax} were used. When multiple points fell in this range the average value is presented.

The data show fairly small changes in the modulus over the 7-day period for the case of the unmodified Atchison soil. The addition of fly ash had an immediate impact on the small-strain modulus values. The 0-hr values presented in Figure 159 represent measurements that were performed approximately 30 to 40 minutes after the soils were first mixed (accounting for time to compact and setup the sample). The 0-hr modulus values increase from about $2.1\text{x}10^6$ psf to about 3.5 to 3.9 $\text{x}10^6$ psf after the addition of fly ash or LKD. The modified soil continued to show increases in modulus with time. At 3-days, soil with 10% fly ash increased by a factor of about 2.3 compared to the unmodified soil over the same time frame. Addition of 15% fly ash resulted in a similar improvement in 3-day modulus of about 2.3 times the unmodified value. The addition of 20% fly resulted in a slightly larger improvement in modulus with a 3-day modulus that was about 2.5 times the unmodified value. It is interesting to note that doubling the amount of fly ash in the soil had essentially no effect on the 3-day modulus values. This is consistent with what was observed in the strength testing (Figure 111) where the 28 day strengths of the 20% fly ash samples were observed to be essentially the same as the 10% and 15% samples (considering the variability in the measurements).

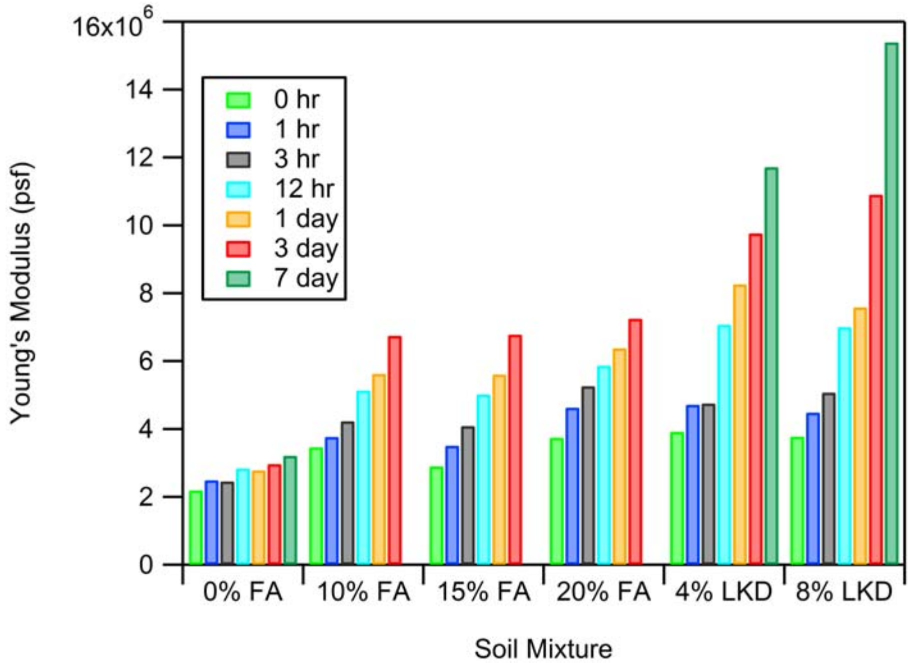

Figure 157 – Change in Young’s modulus of Atchison soil for different soil/additive mixtures compacted near the optimum water content

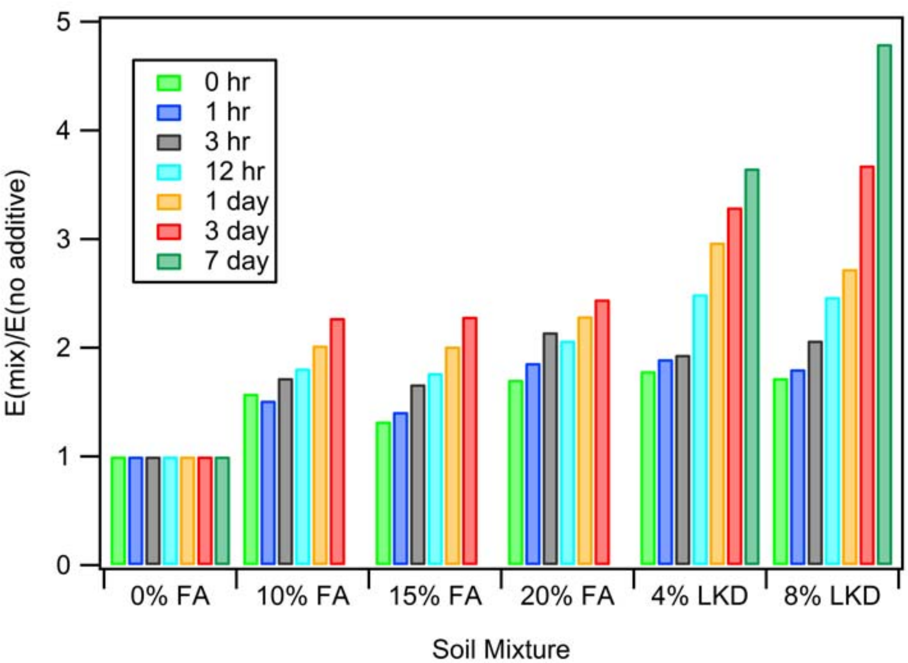

Figure 158 – Ratio of Young’s modulus from modified soils to Young’s modulus of unmodified soil for different soil/additive mixtures of Atchison soil compacted near the optimum water content

The addition of LKD likewise resulted in significant improvements in soil stiffness for the Atchison soil. The immediate increase (0-hr values) in modulus was similar to the fly-ash stabilized soil with an increase of about 70 to 80% for both the 4% and 8% cases. The longer term improvement in modulus, however, was significantly higher than what was achieved with the fly ash. The modulus at 3-days was about 3.3 times the unmodified modulus for the 4% case and 3.7 times for the 8% case. The 7-day values showed continued improvements with ratios of 3.7 and 4.8, respectively for the 4% and 8% LKD.

Unlike the Atchison soil, the Putnam soil showed little improvement in modulus with the addition of the fly ash. In fact, the measured modulus actually decreased slightly. Figure 161 shows the changes in Young's modulus for the Putnam soil with different amounts of fly ash and LKD added. Figure 162 shows the same data presented as the ratio of the modulus values of the modified soil divided by the modulus values of the unmodified soil at the same time. Over the 7-day period the modulus of the compacted Putnam sample with no additive increased by about 77% (as compared to about 45% for the Atchison soil). Surprisingly, all of the fly ash mixtures exhibited lower modulus values at all times than was achieved with the Putnam soil alone (i.e. no additive). The ratios of modulus values at 7-days for the Putnam soil were 0.88, 0.89, and 0.85 for the 10%, 15% and 20% fly-ash mixtures, respectively. Part of the reason for the apparent decrease in modulus has to do with the fact that the samples are not all at the same water content relative to the optimum. The soil without additive was slightly dry of optimum, while the samples with the additive were at or slightly wet of optimum. However, it can still be concluded that the addition of fly ash had essentially no effect on the Putnam soil.

The addition of LKD to the Putnam soil provided a better result. For this case, the 7-day modulus values were 1.9 and 2.9 times the unmodified modulus, respectively. The amount of additive in this case also had a clearly significant effect on the 7-day modulus. It is not apparent why the Putnam soil showed little improvement from the fly ash but moderate improvement from the LKD.

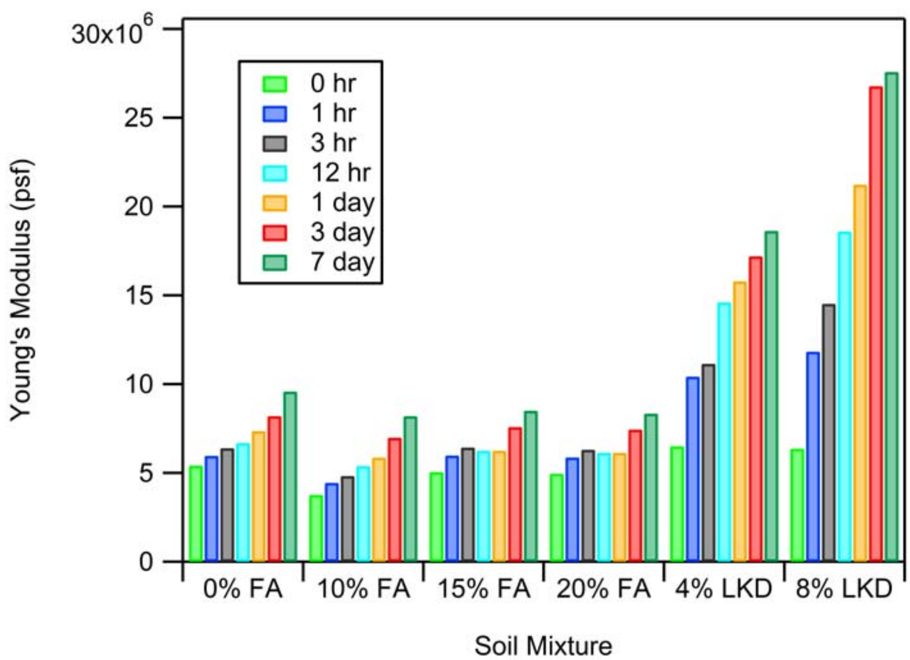

Figure 159 – Change in Young's modulus of Putnam soil for different soil/additive mixtures compacted near the optimum water content

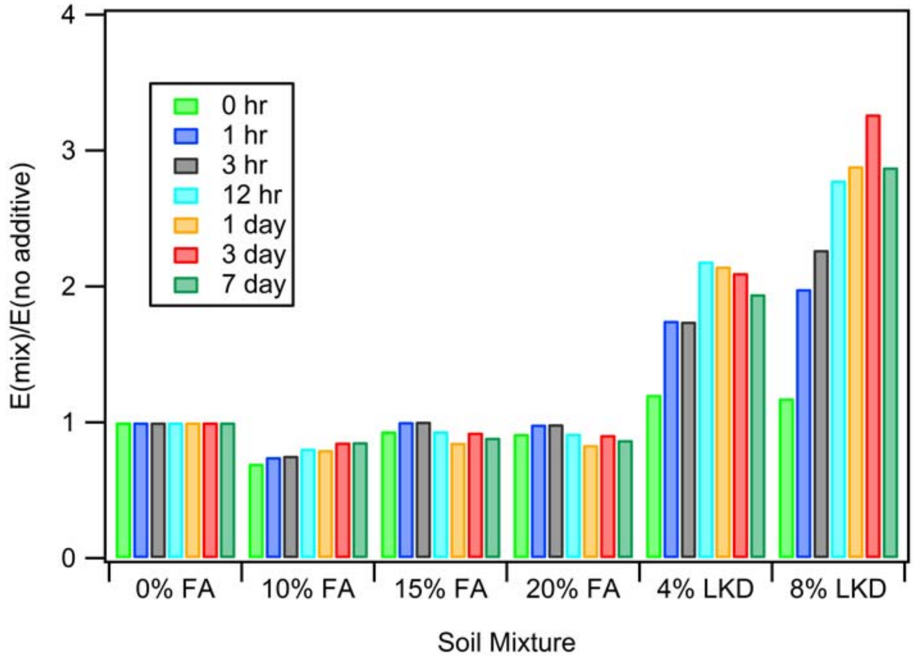

Figure 160 – Ratio of Young's modulus from modified soils to Young's modulus of unmodified soil for different soil/additive mixtures of Putnam soil compacted near the optimum water content

5.2. Effect of Soil Additives on Strength

The results from the strength testing on the Atchison soil are presented in Section 4.6. All strength tests were performed at or near the optimum water content (typically within 1% dry of optimum). The unconfined compression tests on the Atchison soil with no additives remained fairly constant over the 28-day period with values ranging from about 30 psi at 1 day to 36 psi at 28 days. The addition of fly ash to the Atchison soil resulted in a modest increase in UCS. The addition of 20% fly ash showed the largest increase in UCS with an average strength (calculated from 3 tests at 28-day) of 63 psi, or about a 75% increase in strength from the Atchison soil alone. Lower amounts of fly ash resulted in slightly lower strength values, ranging from 52 psi for the 15% case (from a single measurement) and 58 psi for the 10% case (also from a single measurement). The 10% and 15% values fell within the range of values from the 3 tests performed on the 20%-fly ash samples. Therefore, it appears that the percentage of fly ash had little or no effect on ultimate strength values (as was also observed in the modulus measurements).

For the cases with LKD added to the soil, the strength increase was much higher. The 28-day strength for the 4% LKD case was 101 psi and for the 8% case was 125 psi. The ratio of the modified strength to the unmodified soil was 2.8 and 3.5, respectively for the 4% and 8% cases.

5.3. Effect of Soil Additives on Small-Strain Modulus of Soil that is Wet of Optimum

In many cases subgrade soil may be modified under conditions that are well wet of optimum, in order to create a working platform for construction. For this case it is instructive to present the results in terms of the water content of the soil alone, instead of the water content of the soil/additive mixture (as is presented in the figures above). For the case of the Atchison soil, the optimum water content is about 18%. A sample compacted near this optimum water content (slightly on the dry side) yielded a Young's modulus value of about 3.0 x 10^6 psf. To examine the effect of the soil additive on samples that are wet of optimum, Young's modulus values of wet samples are plotted versus the difference between the water content of the soil and the optimum water content (i.e. how wet of optimum the natural soil is), as shown in Fig. 99. For the Atchison soil there were few tests performed at water contents wetter than the optimum water content of the soil alone. For these samples, the measured moduli were about 2 times the modulus that would be obtained from compacting the sample under optimum conditions with no additive. One sample with a natural water content that was about 4% above optimum yielded a lower modulus than would be obtained from the soil compacted at optimum conditions

For the Putnam soil, the natural water content was 25.5% and the modulus of the soil alone compacted at the optimum water content was about 8.7 x 10^6 psf. Many more samples were tested wet of optimum than for the Atchison case due to an error in calculating the amount of water to add to the soil. Figure 100 shows Young's modulus values of wet samples (water content of soil alone > 25.5%) plotted versus the difference between the water content of the soil and the optimum water content. For the Putnam soil, the addition of fly ash to the wet samples did little to increase the modulus of the soil (relative to the unmodified soil compacted at optimum water content). There is clearly a decreasing effectiveness of the fly ash with increasing natural water content. In contrast, the addition of LKD had a dramatic effect on the modulus values at all water contents. The modulus of soil with the addition of 4% LKD was about double the modulus of the unmodified soil compacted at the optimum water content. At 8% LKD, the modulus was up to three times larger. Even soil that was 13% above optimum water content had a higher modulus when 8% LKD was added (as compared to the unmodified soil compacted at optimum water content)

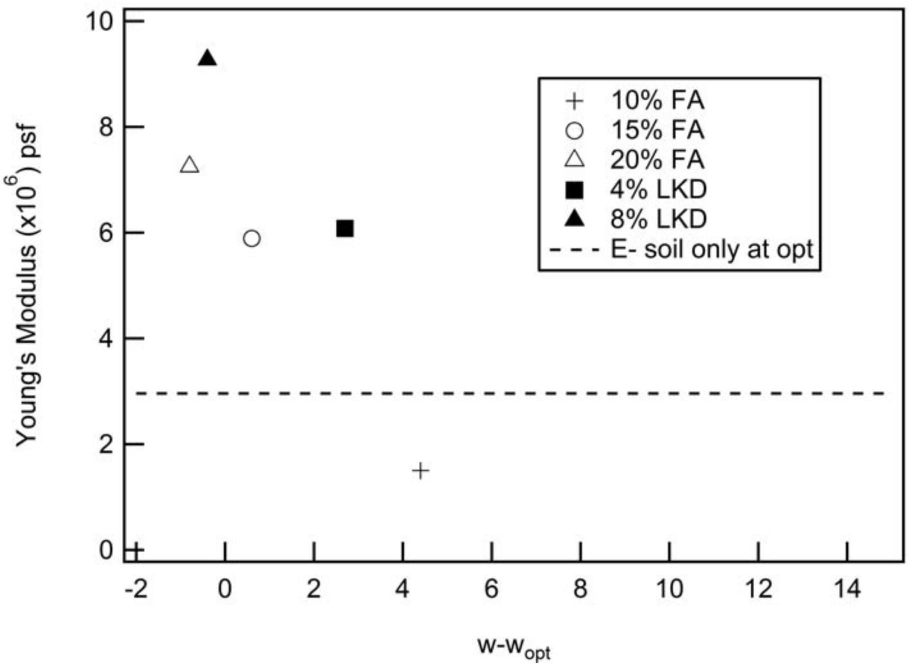

Figure 161 – Young's modulus of modified Atchison soils plotted in terms of the soil water content relative to the optimum water content

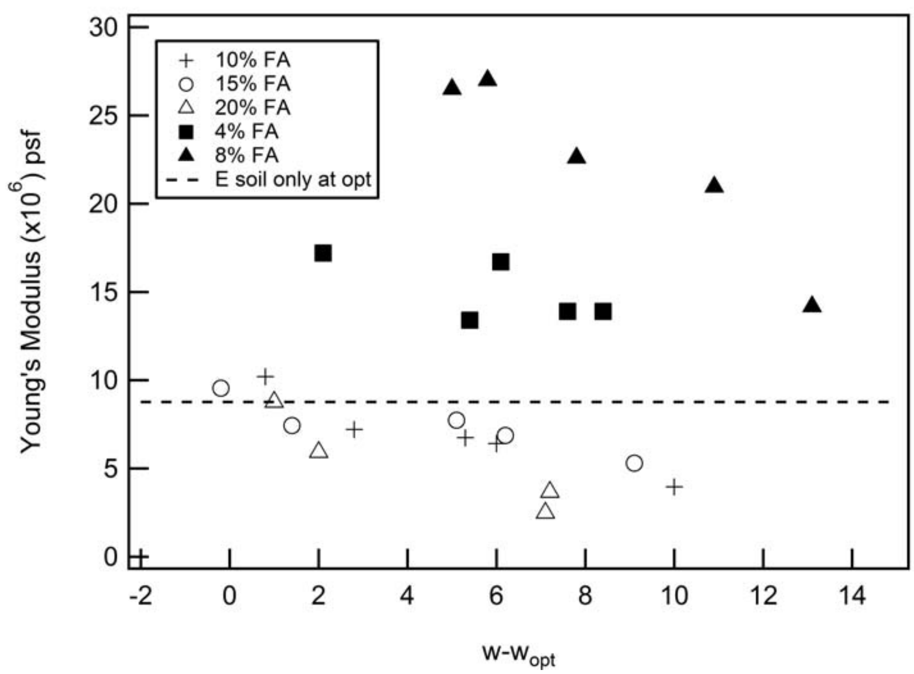

Figure 162 – Young's modulus of modified Putnam soil plotted in terms of the soil water content relative to the optimum water content

5.4. Use of Small-Strain Velocity Measurements for Non-Destructive Quality Control

One of the challenges with using soil modifiers such as fly ash or LKD to improve soil properties is the need to assess the quality of the modified soil after it is placed. With conventional soil compaction, the quality of the subgrade can be assessed with measurements of water content and dry density. However, with modified soils these measurements alone do not indicate the quality of the subgrade. There is a need to develop non-destructive testing (NDT) methods that can be used in the field to assess the quality of the subgrade soon after placement. Ideally, this method could be applied both in the laboratory and the field. One of the objectives of this project was to investigate possible NDT techniques that could be used for this application. Unfortunately, it was not possible to perform the proposed field portion of this study. However, the laboratory measurements provide valuable insight in to the use of velocity measurements as a means of quality control.

Resonance measurements as performed in this study, can be easily performed in the lab on the soil of interest to determine a range of acceptable velocity (or modulus) values that should be achievable in the field. Surface wave measurements can then be performed in the field to non-intrusively and rapidly evaluate the shear wave velocity profile of the modified soil and compare it to the expected values. One of the issues that needs to be studied is how soon after placement of the material can poor quality material be differentiated from good quality material. The modulus tracking experiments performed in this study provide some valuable information in this regard. Figure 101 shows the ratio of Young's modulus values of modified versus unmodified Atchison soil over the first 3 hours after compaction. Figure 102 shows the same plot for the Putnam soil. For the Atchison soil, modulus ratios for the fly ash sample were 1.5, 1.4 and 1.9, respectively for the 10%, 15% and 20% cases. For the LKD, the 1-hr ratios were 1.9 and 1.8 for the 4% and 8% cases. Recalling that these modulus values were calculated from squaring measured velocity values (equation 3.5), the velocity ratios for these cases would be 1.22, 1.18, 1.38 for the 10%, 15%, and 20% fly ash samples and 1.38 and 1.34 for the LKD cases. In other words, soil with fly ash could be differentiated from soil without fly ash by velocity values that were about 20 to 40% higher. Although these results are only for a single soil/fly ash combination, the velocity changes are certainly detectable and are likely greater than the variability of the velocity measurements (although this would need to be evaluated). Based on these data, it appears that velocity could be used to identify soil with modifier and soil without modifier within 1-hr after compaction. However, it is less likely that these measurements would be able to differentiate soils with different percentages of additive, as the changes in velocity would be much smaller.

The Putnam soil did not react well with the fly ash so it is not possible to derive meaningful results from the velocity ratios of the samples with different fly ash percentages. However, for the LKD, the modulus ratios were 1.75 and 2.0 for the 4% and 8% cases. This results in velocity ratios of 1.32 and 1.41. As with the Atchison soil, it seems possible to detect the presence of LKD in the soil but it is not possible to identify the high and low LKD cases.

Based on these results, it seems that velocity measurements would be of some value as a quality control tool. It could possibly be used to identify locations where the soil was not mixed property with the fly ash and/or LKD resulting in low velocity values. The viability of velocity measurements would need to be confirmed in field studies.

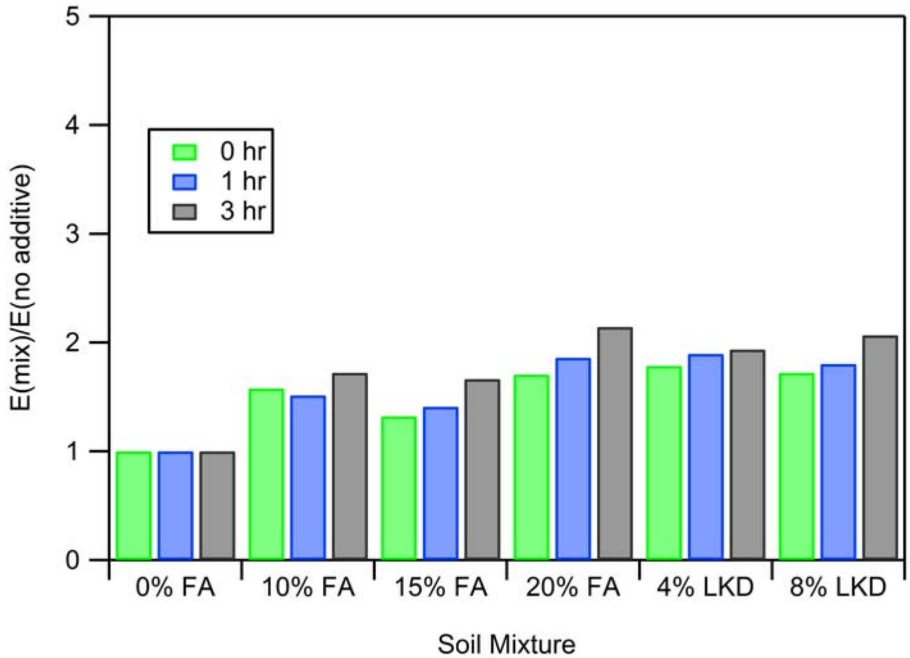

Figure 163 – Ratio of Young's modulus from modified soils to Young's modulus of unmodified soil for different soil/additive mixtures of Atchison soil compacted near the optimum water content and measured over a time span of 3 hours

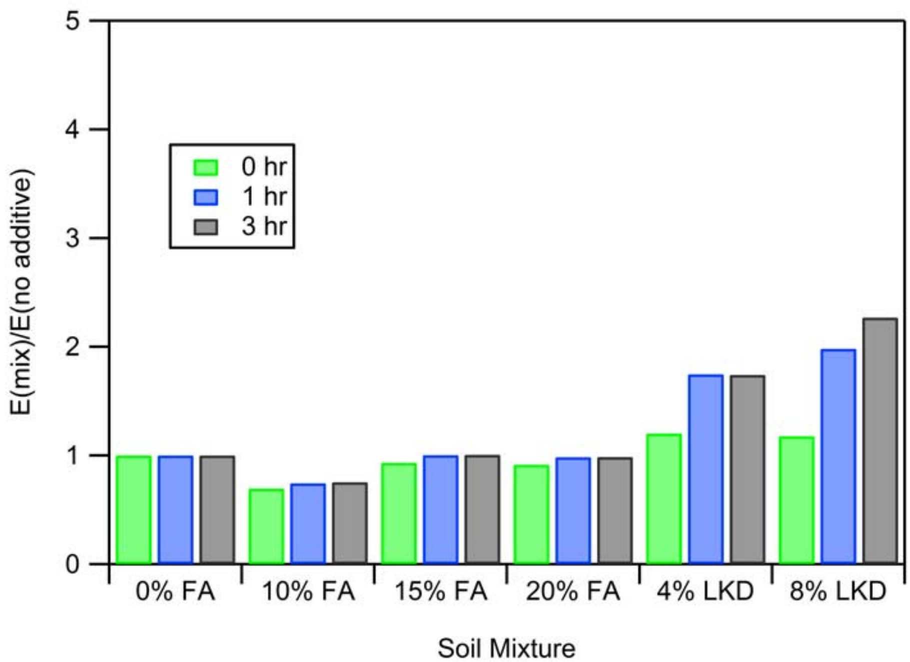

Figure 164 – Ratio of Young's modulus from modified soils to Young's modulus of unmodified soil for different soil/additive mixtures of Putnam soil compacted near the optimum water content and measured over a time span of 3 hours

5.5. Effect of Soil Additives on BCD Modulus

BCD modulus measurements were only performed on the Atchison soil due to time constraints. Figure 167 presents the changes in the measured BCD modulus with time for the different soil additives. From the test results using fly ash as the additive, it is found that the modulus generally gained the most in the first 7 days. Also, increases in the percentage of fly ash did not correspond to increases in the BCD modulus, as indicated by the higher BCD modulus for the 10% mixture than for the 20% mixture. The addition of LKD showed a greater increase in modulus than was observed with the fly ash. A clear trend of increasing modulus with time was observed for the LKD, although little difference was observed between the 4% LKD and 8% LKD cases. Figure 168 shows how the BCD modulus of the modified soil changed relative to the BCD modulus of the soil alone. The 28-day modulus increased by a factor of about 2 for the 10% case. The 15% case showed a decrease in modulus and the 20% case showed only a slight increase. The 1-day and 7-day ratios were also much lower than what was observed from the small-strain modulus measurements and from the resilient modulus measurements, as discussed below. The LKD samples showed modulus values at 28 days that increased by a factor of about 2.2 for both the 4% and 8% cases. The seven-day values increased by a factor of about 2 to 2.4, which is significantly lower than what was observed from the small-strain modulus measurements.

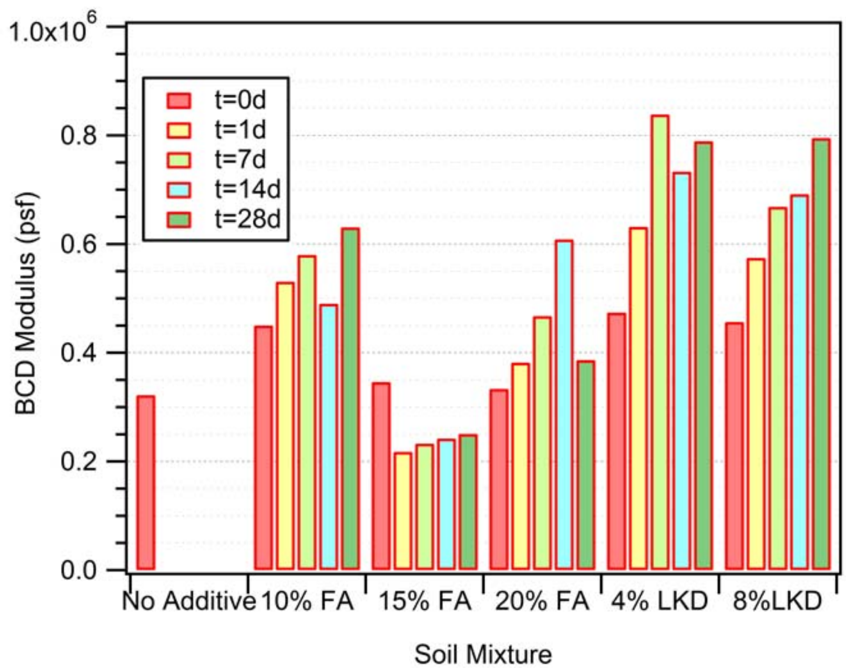

Figure 165 – Change in BCD modulus of Atchison soil for different soil/additive mixtures compacted near the optimum water content

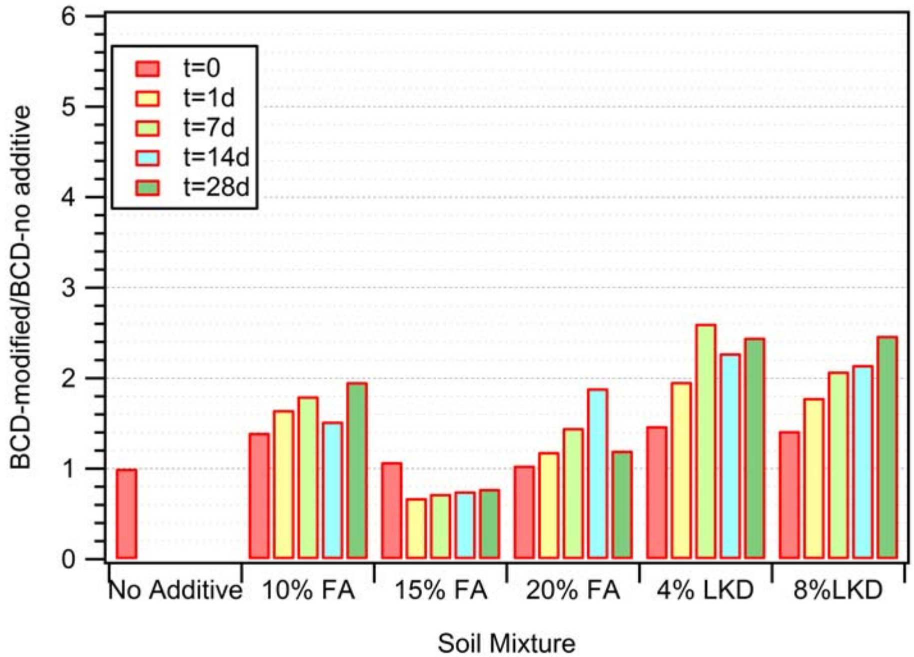

Figure 166 – Ratio of BCD modulus from modified soils to BCD modulus of unmodified soil for different soil/additive mixtures of Atchison soil compacted near the optimum water content

5.6. Effect of Soil Additive on Resilient Modulus

The test results from the resilient modulus measurements show that the soil additives can significantly increase the resilient modulus of the subgrade soil. Figure 169 shows a summary of resilient modulus values for a deviator stress of 13.8 kPa and a confining pressure of 41.4 kPa. (This confining pressure is similar to what was used for the small-strain modulus measurements and allows for comparisons to be made.) The same data is presented as the ratio of resilient modulus of the soil with additive to the soil alone in Figure 170. Based on these measurements, the addition of fly ash resulted in increased values of 28-day modulus by factors of 3.5 to 5.5 over the unmodified case. The addition of LKD resulted in increases by a factor of slightly less than 3 for both the 4% and 8% cases at 28 days.

Comparing Figure 170 to 168, it is apparent that the changes in BCD modulus for the fly ash samples do not follow consistently with the changes in resilient modulus. However, for the LKD case, the modulus ratios measured with the BCD device were similar to what was measured in the resilient modulus test. Comparing the short-term (1-day) values in Figure 170 (resilient modulus) to the 1-day values in Figure 160 (small-strain elastic modulus) for the fly ash modified samples shows good agreement in the ratio of modulus values, with both showing a modulus ratio of about 2. For the LKD samples the 1-day values of small-strain modulus were only slightly higher than the values of resilient modulus, while the 7-day values were much higher.

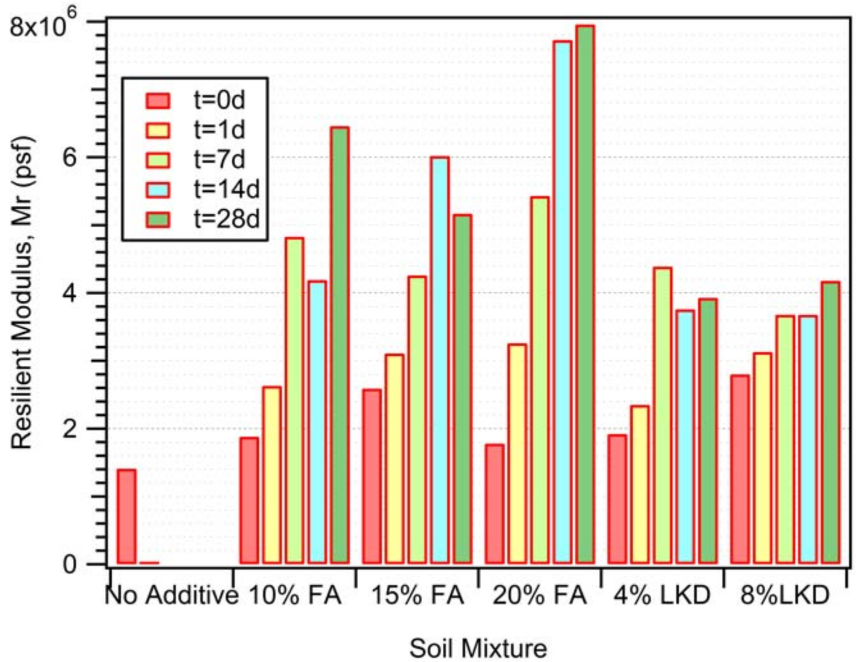

Figure 167 – Change in resilient modulus of Atchison soil for different soil/additive mixtures compacted near the optimum water content (tested with deviator stress of 13.8 kPA and confing pressure of 41.4 kPa)

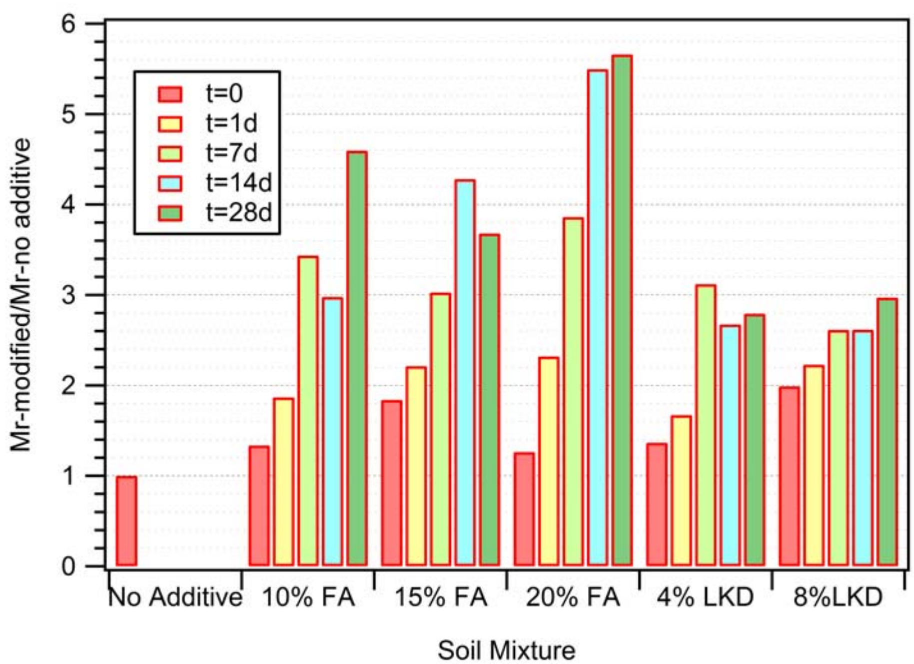

Figure 168 – Ratio of resilient modulus from modified soils to resilient modulus of unmodified soil for different soil/additive mixtures of Atchison soil compacted near the optimum water content (tested with deviator stress of 13.8 kPA and confing pressure of 41.4 kPa)

5.7. Potential for BCD Modulus as a Non-Destructive Quality Control Measure

The BCD is a simple non-destructive testing tool that can determine a modulus for soil compaction control. Other moduli tests can be used for determining a field modulus, but, due to their size and boundary effects, they cannot easily be conducted in a laboratory setting. This drawback limits their usefulness. Without a laboratory value to compare to, only correlations to other lab tests can be used to specify a target field modulus. Correlations are typically soil specific. With the BCD, the operator can conduct a laboratory test to produce a BCD moduli compaction curve (similar to the proctor compaction curve), and then compare BCD moduli values obtained from the field directly to BCD modulus values from the lab test. This is an attractive alternative to soil compaction control using the dry density method because 1.) the BCD directly measures a modulus to determine the compaction state of soils, 2.) the BCD can easily be used in the lab as well as the field so one tool will do it all.

Laboratory testing with the BCD is based on the proctor compaction test standards. Because the BCD is based on the proctor compaction test, no additional lab equipment is required. Conducting BCD tests on the proctor compacted soil is simple, and does not require a great deal of extra time on the technician’s part, allowing two important soil trends to be established: the dry density vs. moisture content compaction curve, and the BCD modulus vs. moisture content compaction curve. When used in parallel, field compaction specifications could be established based on both dry density and modulus, ultimately producing a compacted soil layer that would be both uniformly dense and strong.

The results from this study showed some inconsistency between the properties measured with the BCD and the laboratory resilient modulus values. Although it is not expected that the BCD device would give the same modulus values (due to different loading conditions and strain levels), it was expected that similar trends in the changes in modulus would be observed. For the case of LKD modified soil, the changes (expressed as a ratio of modified to unmodified soil) observed in the BCD modulus and the resilient modulus were quite similar. However, for the case of the fly ash modified soil, the BCD device showed much smaller changes than were observed from the resilient modulus data and the free-free resonance data.

6. CONCLUSIONS

Only two soils and two soil modifiers were tested in this study so it is difficult to draw broad conclusions regarding the effectiveness of soil modification on the engineering properties of Missouri subgrades. However, this study provided some useful information on the magnitude of changes in modulus that can be expected for different soil/additive combinations as well as the effectiveness of potential non-destructive testing methods that can applied in the laboratory and the field for quality control.

With regard to the effect of soil modifiers on soil properties, this study generally showed that significant improvements in soil stiffness can be achieved with the addition of relatively small percentages of modifiers. Resilient modulus values were shown to increase by factors of about 3.5 to 5.5 times the unmodified values with the addition of fly ash to a low plasticity clay (CL) soil. Small-strain modulus measurements of the low-plasticity clay showed similar improvements in modulus with the addition of fly ash. However, measurements of the high-plasticity clay showed little or no improvement in modulus with the addition of fly ash. The addition of LKD was also shown to significantly increase the stiffness of subgrade soils, although the performance of LKD relative to fly ash was somewhat ambiguous. Resilient modulus measurements on LKD modified CL soil showed increases in 28-day modulus values by a factor of about 3 over the unmodified case, which is less than what was observed with the addition of fly ash. However, monitoring of small-strain elastic modulus over the first several days after mixing showed greater increases in modulus with the addition of LKD as compared to the addition of fly ash. Three day values of modulus were increased by a factor of about 3.3 to 3.7 for the low-plasticity clay and 2.0 to 2.9 for the high plasticity clay. In both the resilient modulus and small-strain modulus measurements, the percentage of fly ash added had only a minimal effect on modulus values.

The addition of soil modifiers also had a significant impact on the unconfined compressive strength. For the CL subgrade, the addition of fly ash nearly doubled the 28-day strength of the soil. As was the case with modulus, the percentage of fly ash had a minimal effect on the strength. For the CH subgrade, the strength increased by a factor of 2 to 2.5. The percentage of fly ash did not greatly affect the 28-day strength of the soil. The addition of LKD had a greater effect on the strength of the CL subgrade as compared to the fly ash, with strength increasing by a factor of 3 or more.

Two potential non-destructive testing methods were examined in this study, namely small-strain modulus measurements and BCD modulus measurements. For the case of the fly-ash modified Atchison soil, the relative increase in small-strain modulus values was generally consistent with what was observed in the resilient modulus measurements. The resilient modulus measured at similar confining pressure (41.4 kPa) as the free-free resonance samples and with the smallest deviator stress (13.8 kPa) showed increases in modulus values by factors of 1.9, 2.2, and 2.3 for the 10%, 15% and 20% fly ash mixtures, respectively, 1-day after compaction. For the free-free specimens, the modulus at 1-day increased by factors of 2.0, 2.0 and 2.3 for the 10%, 15% and 20% fly ash mixtures, respectively. It should be noted that it is expected that the actual values of the resilient modulus values will be significantly lower than the small-strain values due to soil nonlinearity. However, the consistency between the measured change in modulus values in this case supports the viability of using small-strain velocity measurements in the field as a means of quality assurance. However, comparisons in modulus change with the addition of LKD were not as strong, with resilient modulus values increasing by factors of 1.7 and 2.2, while the small-strain modulus increased by factors of 2.9 and 2.7, respectively for the 4% and 8% mixtures. The BCD modulus changes did not agree well with the changes in resilient modulus for the case of fly ash added to the CL subgrade. However, for the case of LKD added to the CL soil, the agreement in relative modulus increase was reasonable. Based on these results, it is not possible to definitively conclude that either method is a viable NDT technique for monitoring stabilized subgrades. A field testing program to monitor in-situ stabilized subgrades is needed to verify performance of these techniques.

Lastly, the small-strain modulus study examined the changes in modulus very soon after compaction (1-hr) when quality control measurements would be performed. For the soils and modifiers tested in this study that produced changes in the soil (i.e. excluding the Putnam/fly ash mixtures) the 1-hr modulus values ranged from 40% to 90% higher than the unmodified soil. This corresponds to increases in velocity of about 18 to 38%. These changes in velocity are certainly detectable, although a detailed study of variability and field verification would need to be performed to confirm the feasibility of this approach.

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