EFFECT OF CLIMATIC CHANGES ON SUBGRADE STIFFNESS

by

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For my mom Lucila and my aunt Socorro. Thanks for being with me ALWAYS.

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ABSTRACT

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There is consistent research evidence that shows improvement of the engineering properties of subgrade soils treated with lime or cement. However, limited information is available on the effect of climatic changes on the subgrade stiffness. The thesis studies the effects of changes in soil moisture content and temperature on the resilient modulus of treated and untreated subgrades in Indiana. Two types of soils were tested: A-6 and A-7-6, from two locations in Indiana: Hartford City and Bloomington, respectively. When existing standards ASTM D559/559-15 and ASTM D560/560-16 for wetting/drying (WD) and freezing/thawing (FT) processes, respectively, were followed, the treated and untreated samples failed through the process of preparation due to the stringent procedures in the standards. Appropriate test conditions were investigated, as part of the research, to develop new protocols more appropriate to the field conditions in Indiana. Two new test protocols were developed and successfully applied to the treated soils. A total of 26 resilient modulus, M_R, tests were conducted following the standard AASHTO T307-99. The M_R results showed that the repeated action of WD and FT cycles reduced the stiffness of the chemically-treated soils down to values similar to or lower than those of the untreated soils. However, when the amount of chemical was doubled, with respect to the optimum, the M_R of the treated soils improved over that of the untreated soils, even after the wetting-drying cycles.

1. INTRODUCTION

1.1 Problem Statement and Motivation

The pavement structure must support appropriately the traffic loads during its service life. This is achieved by designing the thickness and stiffness of each pavement layer. The resilient modulus, M_R, is a stiffness measurement used for the subgrade and is defined as the ratio of the applied deviatoric stress to the axial recoverable strain. It can be determined in the laboratory by following the standard AASHTO T307-99 that prescribes combinations of loading and confinement, i.e. the samples are tested at three confinement stresses σ_3: 2, 4, and 6psi (13.8, 27.6, and 41.4kPa) and five deviatoric stresses σ_d: 2, 4, 6, 8, and 10psi (13.8, 27.6, 41.4, 55.2, and 69kPa). Although there are typical M_R values in the literature based on the type of soil, the range of values is quite large, and thus it is necessary knowing the stiffness for any specific soil. The main factors that influence the M_R values are the number of stress applications, soil type and thixotropy, level of stresses, matrix suction, compaction method, type of admixture, optimum moisture content, maximum dry density, and water content (Woojin, 1993).

Moreover, to meet the pavement design life requirements, low bearing capacity soils such as A-6 and A-7-6 are mixed with chemical agents to improve their engineering properties. In Indiana, the most common admixtures used are Lime Kiln Dust (LKD), Quick Lime (QL), and Portland Cement (PC). The main objective in the Mechanistic-Empirical Pavement Design Guide (MEPDG) is to assign pavement support layers that meet performance criteria, to optimize the pavement design (Sandoval et al., 2018). To that end, the design input parameters of the subgrade (M_R) must reflect the actual field conditions, which should include any improvements achieved.

The actual stiffness, and overall behavior of subgrade soils, may differ from those obtained in the laboratory, as they may be subjected to conditions quite different, such as changes (cycles) of temperature, e.g. freezing-thawing (FT), and changes (cycles) of moisture, e.g. wetting-drying (WD). The investigation of the effects of FT and WD cycles on the resilient modulus of treated and untreated subgrades is the major objective of this study.

1.2 Research Objective and Scope of the Work

The first stage of the project consisted in investigating subgrade stabilization alternatives by exploring engineering properties, namely fines content, plasticity index, unconfined compression strength and resilient modulus of subgrades, untreated, and treated with lime and cement. Details of the laboratory test results and discussions can be found in “Subgrade Stabilization Alternatives” (Sandoval et al., 2018).

As mentioned, the main objective of this study is to evaluate improved subgrades, in Indiana, subjected to climatic changes (FT and WD cycles). The most predominant subgrade soils in Indiana, classified as A-6 and A-7-6 were mixed with three commonly used admixtures, namely: Lime Kiln Dust (LKD), Quick Lime (QL), and Portland Cement (PC). Remolded soil samples, untreated and mixed with the chemicals, were compacted at optimum moisture content and at the 100% of the Standard Proctor. The specimens were cured for 7 days and then, subjected to FT and WD cycles, before conducting resilient modulus, M_R, tests in the laboratory. For a type of soil, additional specimens were prepared to evaluate the effect of overdosing (the chemical treatment was doubled). Two or three identical samples were tested to verify the repeatability of the results. After 7-days curing, the specimens were subjected to twelve WD and FT cycles following the standards ASTM D559/559M-15 and ASTM D560/560M-16, respectively. Then, the M_R tests were conducted following AASHTO T307-99 for Type 2 Material, i.e., fine-grained soils.

The objectives of the research are:

1. Determine the changes of stiffness of chemically-treated soils due to changes of moisture content applying cycles of wetting and drying, WD.
2. Quantify the effects of overdosing on the M_R of specimens exposed to changes of moisture content.
3. Determine the changes of stiffness of chemically-treated soils due to changes of temperature applying cycles of freezing and thawing, FT.

The soils used were the same as those in the research “Subgrade Stabilization Alternatives” by Sandoval et al., 2018, where an extensive testing program was completed on untreated and treated soils. The reason for using the same soils was to be able to compare the changes of stiffness without cycles and after WD or FT cycles.

1.3 Outline

This thesis is organized in six chapters. The background is included in Chapter 2. Chapter 3 presents the classification and description of the soils and soils admixtures used in the tests. Chapter 4 describes the protocol used and the M_R results for the WD tests. Similarly, Chapter 5 explains the protocol used and the M_R test results for the FT tests. Lastly, Chapter 6 presents the conclusions and recommendations. Table A. 1 lists the tests conducted in this research. The letters “A, B, C, and D”, in the numbering of figures and tables, stand for Appendices A, B, C, and D, respectively. The Appendices, attached to this report are: Appendix A shows the experimental program, Appendix B presents the tests results related with the chemical treatment, and the Appendixes C and D include all the M_R results after WD and FT cycles, respectively.

2. BACKGROUND

Laboratory resilient modulus, M_R, tests were conducted in this research to determine the change in stiffness of LKD, PC, and QL treated soil specimens after repeated wetting/drying (WD) and freezing/thawing (FT) cycles.

2.1 Standard Procedure for the Experimental Program

The American Association of State Highway and Transportation Officials, AASHTO, developed the standard method to measure the resilient modulus of subgrades. First, “T-274: Resilient Modulus of Subgrade Soils” was adopted in 1982, but it was discontinued in 1990. Afterwards, “T-292: Resilient Modulus of Subgrade Soils and Untreated Base/Subbase Materials” was adopted in 1991 and discontinued in 2003. Within this period, from 1992 to 1997, “T-294: Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils – SHTP Protocol P46” was used. Then, “T-307: Determining the Resilient Modulus of Soils and Aggregate Materials” was adopted in 1999, which is still in use.

To study the durability of the compacted soils mixed with cement under WD and FT cycles, the American Society for Testing and Materials (ASTM) developed the standards D559/D559M-15 and D560/D560M-16, respectively. D559/D559M-15 was first approved in 2003, withdrawn in July 2012, and reinstated in November 2015. Regarding the standard D560/D560M-16, it was originally approved in 1987, and the current approved edition was issued in November 2016.

2.1.1 AASHTO T307-99 to Determine the Resilient Modulus (Active)

In the standard, the specimens are subjected to different cyclic axial stresses under different confining stresses. When applying an axial cyclic stress, a load duration of 0.1s and a cycle duration of 1.0 to 3.0s are used.

The standard considers two types of materials for the subgrade: Type 1, that includes all untreated soils that meet the criteria of less than 70 percent passing the 2.00-mm (No. 10) sieve and less than

20 percent passing the 75-µm (No. 200) sieve, with a plasticity index of 10 or less; and Type 2, that includes all the untreated soils not meeting the criteria for material Type 1. For Type 1 materials, or compacted specimens of Type 2 materials, the specimen's diameter should be at least five times the maximum particle size, and the length, at least twice the diameter. In this research, the standard for Type 2 material was used based on the index properties of the soils (discussed in Chapter 3). Samples with 3" diameter and 6" height were used.

The standard requires a conditioning stage, prior to the M_R test, that consists of a minimum of 500 repetitions of a load under an axial stress of 4psi (27.6 kPa). If the sample is still decreasing in height at the end of the conditioning period, the stress cycling shall be continued up to 1,000 repetitions, as highlighted later in Table 4-4. As shown in the table, the M_R test includes three different confinement stresses, σ_3: 2 psi (13.8 kPa), 4 psi (27.6 kPa) and 6 psi (41.4 kPa); and five different deviatoric stresses, σ_d: 2 psi (13.8 kPa), 4 psi (27.6 kPa), 6 psi (41.4 kPa), 8 psi (55.2 kPa) and 10 psi (69 kPa). The reported resilient modulus, M_R, corresponds to the average of that measured during the last five cycles of each load sequence.

2.1.2 ASTM D559/D559M-15 Standard Test Method for Wetting and Drying (WD) Compacted Soil-Cement Mixtures

The D559/D559M-15 test method is used to determine the resistance of compacted soil-cement specimens to WD cycles. The samples must be compacted to their maximum density at optimum water content using the compaction procedure described in the standard D558-11. After compaction, the specimens are placed in a moist room and protected from free water for a period of seven days. The temperature in the moist room must be 73.5^{o}F (23^{o}C) and the relative humidity, 100%. At the end of this period, the samples are submerged in potable water at room temperature for a period of 5 hours, then placed in an oven at 160°F (71°C) for 42 hours. This process constitutes one cycle of WD, and it must be repeated twelve times. After the twelve WD cycles, the M_R tests are conducted.

2.1.3 ASTM D560/D560M-16 Standard Test Method for Freezing/Thawing (FT) Compacted Soil-Cement Mixtures

This test method is used to determine the resistance of compacted soil-cement specimens to FT cycles. The samples must be compacted following the standard ASTM D558-11. After compaction, the specimens are placed in a moist-controlled room and protected from free water for a period of seven days. The temperature in the moist room must be 73.5°F (23°C) and the relative humidity, 100%. Then, the samples are placed on an absorptive material over a carrier and placed in a freezing cabinet at a constant temperature not warmer than −10°F (−23°C) for 24 hours. After that, the samples must be removed and placed in the moist room for 23 hours. Free water is allowed in the procedure. This process constitutes one cycle of FT, and it must be repeated twelve times. After the twelve FT, the M_R tests are conducted.

2.2 Some Previous Studies on Subgrade Stiffness

The American Association of State Highway and Transportation Officials (AASHTO), through the Guide for the Design of Pavement Structures in 1986, introduced the resilient modulus, M_R, a soil property related to the soil stiffness that is used to predict the performance of the pavement structure. To determine the M_R, the testing procedure should include two steps: a conditioning stage and after that, the repeated loading to measure the recoverable strains, thus, it is calculated from the deviator stress and resilient deformation averaged over the last five load cycles. The M_R can be affected by several factors, namely: number of stress applications, thixotropy, level of stresses, matrix suction, method of compaction, compaction water content and dry density, and type of admixture used for treatment purposes, if any (Woojin, 1993). In this chapter, previous studies on the subgrade resilient modulus of untreated and treated soils, as well as of treated soils subjected to Wetting/Drying (WD) and Freezing/Thawing (FT) cycles, are presented.

2.2.1 Resilient Modulus of Untreated Soils

Elliott (1987) conducted resilient modulus tests following the standard AASTHO T274-82. In an attempt to simplify the test, the author evaluated the effect of confining pressure, deviatoric stress, number of stress cycles, and compaction method on the stiffness of cohesive soils in Arkansas. In this standard method, the cycle load duration varies from 1 to 3 seconds and the test procedure requires three confining stresses: 0psi (0kPa), 3psi (20.7kPa), 6psi (41.4kPa), and five deviatoric stresses 1psi (6.7kPa), 2psi (13.8kPa), 4psi (27.6kPa), 8psi (55.2kPa), 10 psi (67kPa) with 200 repetitions at each confining pressure. The author defined a 3psi (20.7kPa) confining pressure and 8psi (55.2kPa) deviatoric stress as representative values for the actual field conditions in Arkansas. The author found that the type of compaction and the reduction in the number of cycles, from 200 to 50, did not have any significant effect on the M_R results. It was found that, with these adjustments, the testing time could be shortened from 100 to 2 minutes, and so the complexity of the test could be reduced.

Woojin (1993) evaluated the resilient modulus of in-service subgrades in Indiana using untreated and treated compacted samples to develop correlations and simplify the testing program. Correlations between M_R and the stress required to cause 1% strain in unconfined compression tests ($S_{u1.0\%}$), and simplified procedures (reduced number of stress combinations) to obtain the M_R, were developed. In the study, for untreated compacted samples, the resilient modulus from laboratory test ranged between 1.5 to 26ksi (10.3 to 179.26MPa), for a deviatoric stress of 6psi (41.4kPa), and three different confining stresses, 0, 3, 6psi (0, 20.7, 41.4kPa). For illustration purposes, Figure 2-1 shows results of the M_R tests conducted by Woojin (1993) on cohesive soils at different moisture contents.

Mao (1995) performed resilient modulus tests on subgrade plastic soils (A-4 and A-6) in Ohio. Untreated samples were compacted in the laboratory to evaluate the M_R, using AASHTO T274-82. The tests were done for different moisture contents, above and below the optimum. The M_R values ranged between 2.2ksi (15MPa) and 7.3ksi (50MPa). It was found that the M_R values decreased with increasing deviatoric stresses and moisture content.

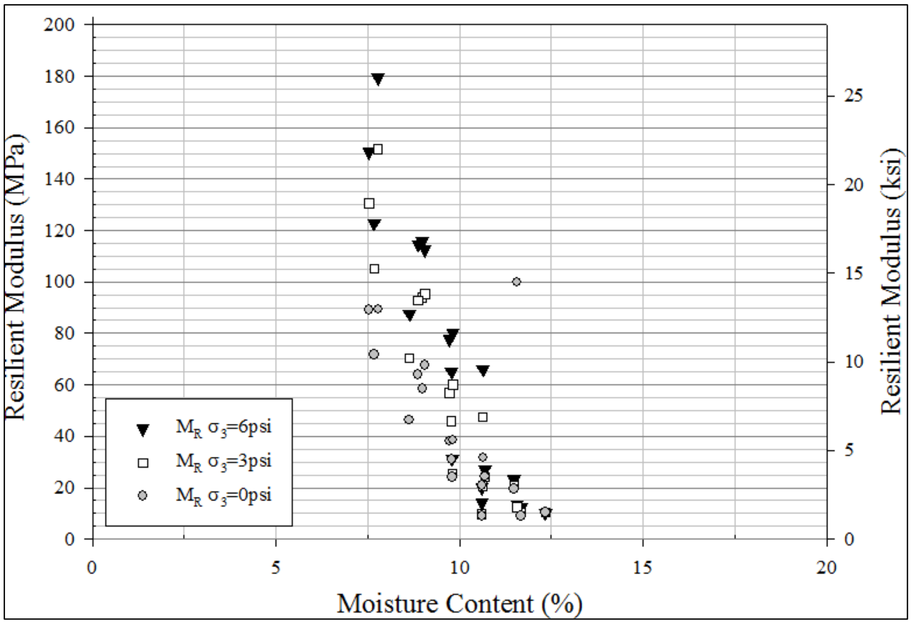


Figure 2-1. Resilient Modulus of Untreated Cohesive Soils vs. Moisture Content in Indiana. (Adapted from Woojin, 1993)

Hopkins (2002) performed resilient modulus tests on undisturbed untreated and treated subgrades around Kentucky. Cohesive soils (A-6 and A-7-6) were tested following the AASHTO T-294-92 standard. The M_R values ranged between 8.7 to 18.8ksi (60 to 130MPa). The authors highlighted that the M_R values decreased with the increase of the deviatoric stresses but increased with the increase of the confining stresses.

Baladi et al. (2009) estimated the subgrade stiffness of sandy and clayey (A-6, A-7-5 and A-7-6) soils in Michigan. Disturbed and undisturbed samples were collected. After sample preparation in the laboratory, M_R tests were conducted following a modified AASHTO T307-99 procedure. The load-unload period was changed from 0.1 to 0.5s. All test samples were conditioned for 500 loading cycles and constant confining pressure of 7.5 psi (52 kPa) was used. To simulate field conditions, the M_R for axial cyclic stress of 10 psi (69 kPa) was used in all the analyses. The authors concluded that for soils without any treatment, at any given confinement stress, the M_R was around 37ksi (255 MPa). They explained that the reason of the high M_R values, compared to typical fine-grain soils, was because most of the tests were conducted on soil samples that were on the dry side.

Figure 2-2 compiles the subgrade M_R values in Indiana and surrounding states, from the references discussed above. As shown in the figure, for cohesive soils, M_R values of the untreated soil ranged from 1.5 to 26.1ksi (10 to180 MPa). It is also seen that there is a marked trend for the soils in Ohio and Kentucky of the M_R values to be lower for larger deviatoric stresses (σ_d), i.e. 24.6ksi (170MPa) for σ_d of 2psi (13.8kpa), 15.9ksi (110 MPa) for 4psi (27.6kPa), 13ksi (90MPa) for 6, 8, and 10psi (41.4, 55.1, and 68.9kPa). The range of M_R values is larger in Michigan, with values from 2.9 to 44.2ksi (20 to 305MPa) for σ_d 10 and 15psi (68.9 to 103.4kpa). In Indiana, the M_R values range from 1.5 to 26.1ksi (10 to 180 MPa) for the three confining stresses investigated, 0, 3, and 6psi (0, 20.7, 41.4kPa).

Recently, in Indiana, Ji et al., (2014) conducted M_R tests on undisturbed untreated samples, to evaluate the subgrade M_R and its implementation in the Mechanistic-Empirical Design Guide (MEPDG). The soils used were A-4, A-6, and A-7-6, and the average of M_R values from the laboratory tests ranged from 5.8 to 9ksi (40 to 62MPa). In the first stage of the research project that includes this thesis, Sandoval et al., 2018, studied subgrade stabilization alternatives, where M_R tests were conducted on clayey soils classified as A-6 and A-7-6. The untreated specimens compacted in the laboratory at 95% of the Standard Proctor, presented M_R values between 4.4 to 17.4ksi (30 to 120MPa), when following the AASHTO T307-99 standard. The test results from the recent studies are also included in Figure 2-2.

In summary, typical M_R values for untreated soils in Indiana range between 4.4 to 17.4ksi (30 and 120MPa) for different confining and deviatoric stresses. However, soils with high moisture content, plasticity and compressibility, and low stiffness may need to be chemically-modified or stabilized. Modification is a short-term treatment that improves the construction platform, while stabilization is used to increase the soil long-term engineering properties. Given that, the research discussed in this thesis is concerned with the subgrade stiffness after treatment, especially how it changes after WD and FT cylces.

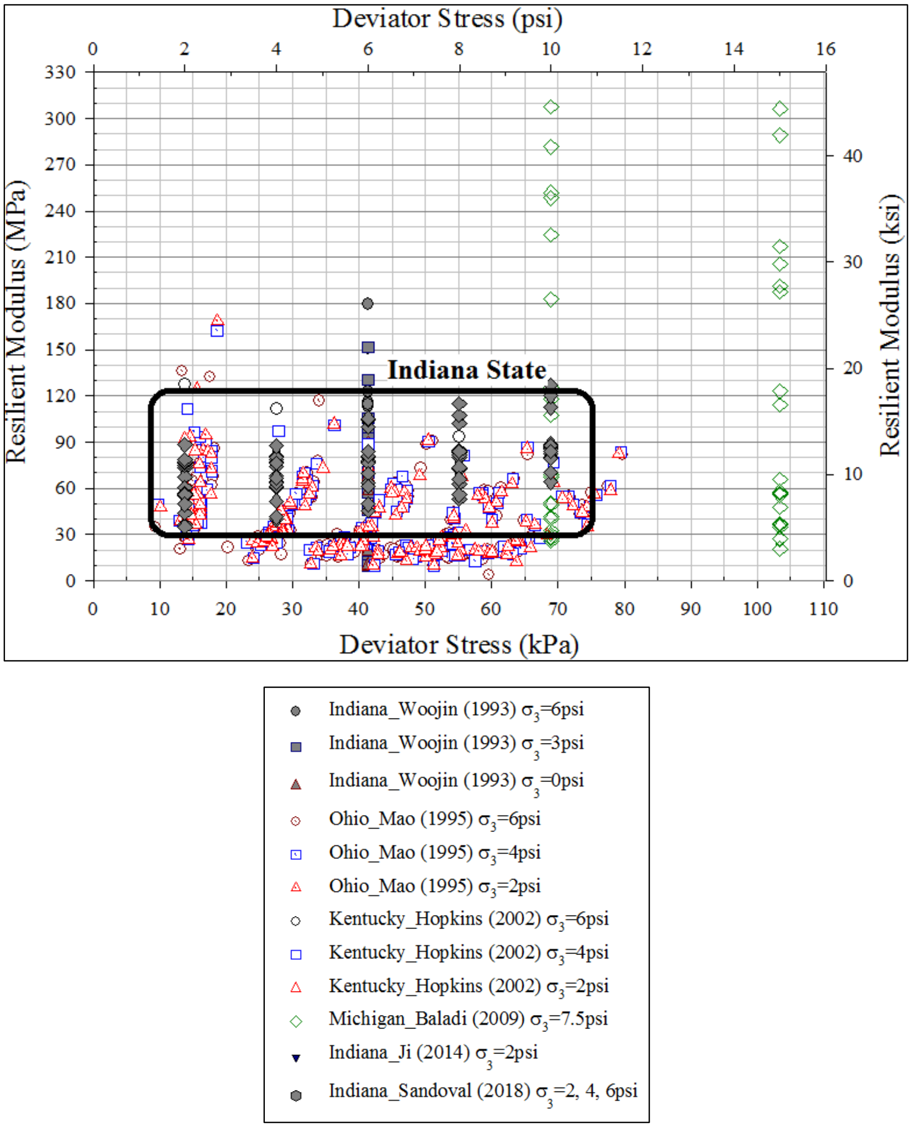


Figure 2-2. Resilient Modulus of Untreated Subgrades in Indiana and Surrounding States from Previous Studies

2.2.2 Resilient Modulus of Treated Soils

Some of the most common admixtures used to improve the subgrade soils are lime (LKD or QL), fly ash, and Portland cement. Solanki et al. (2009) conducted M_R laboratory tests to study the stiffness of stabilized subgrades in Oklahoma. The soils (A-4, A-6, A-7-6) were mixed with 3% Lime Kiln Dust (LKD) or 5% Portland cement. Resilient modulus tests were conducted on untreated and treated soils after 28-days curing period. As shown in Figure 2-3 (green and blue arrows), the subgrade stiffness improved, with an increase of 400 and 900% (compared to the untreated soil), for cement and lime, respectively.

Sandoval et al., 2018, explored the engineering properties of the treated and untreated subgrades in Indiana and evaluated the change in the subgrade stiffness. They investigated A-7-6 and A-6 soils mixed with lime (mainly LKD), cement, and a combination of lime and cement. The increase in the soil stiffness for treated samples was in general larger for mixtures with cement than with lime. The maximum rate of increase after 28-days curing period was around 130%, as shown in Figure 2-3, red arrow.

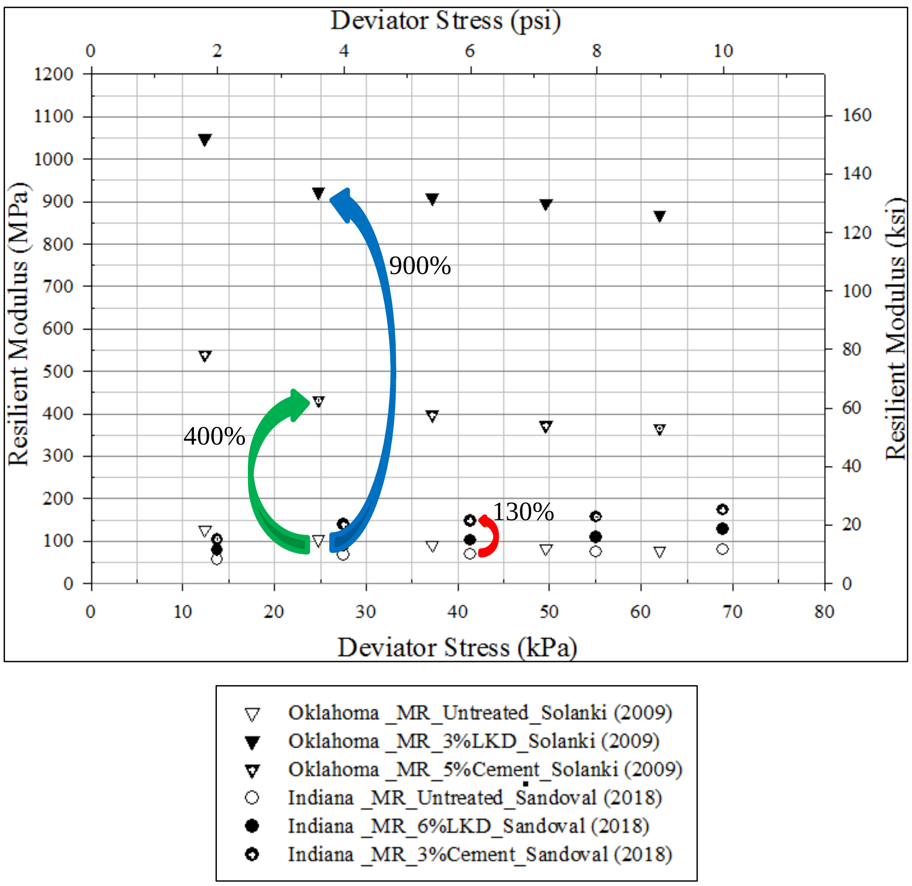


Figure 2-3. Resilient Modulus of Treated Samples. 28-days Curing. (Adapted from Solanki et al., 2009 and Sandoval et al., 2018)

2.2.3 Resilient Modulus of Soils Affected by Changes in Moisture Content – Wetting /Drying

Even though the increase in the soil stiffness with treatment is evident, as shown in the preceding section, the effectiveness of the treatment has not been ascertained when the soil is subjected to extreme weather conditions. Depending on the season throughout the year, the soil may be exposed to changes in moisture content or temperature. These changes should be considered to evaluate the actual subgrade stiffness. Elliott (1987) stated that "reliable procedures for predicting moisture and freeze/thaw cycles are not available", but few authors have investigated the degradation of the treated and untreated subgrade due to the weather changes.

Laboratory procedures, to study the effects of moisture changes on the subgrade stiffness have been proposed. Khoury and Zaman (2004) analyzed the correlation between resilient modulus, moisture variation, and soil suction for subgrade soils in Oklahoma. The authors introduced a new wetting process by injecting water to the specimens and then drying by placing the specimens into a membrane in an oven at 41^{o}C (105^{o}F). After that, M_R tests were conducted. The study indicated that the M_R values are influenced by the initial moisture content. The M_R values were higher after the drying cycle than after the wetting cycle. A significant conclusion from this study was that the moisture gradients in a sample did not have an influence on the M_R.

Solanki et al. (2014) studied the effect of wet-dry (WD) cycles on the stiffness of stabilized A-7-6 soils in Oklahoma, mixed with 6% hydrated lime, 10% class C fly ash (CFA), and 10% cement kiln dust (CKD). After 7 days of curing, compacted samples were subjected to WD cycles (ASTM D559/559M-15) and then tested for their M_R (AASHTO T 307-99). Both the original and stabilized soil specimens showed a significant reduction in M_R values due to the WD cycles, and the specimens failed during the second WD cycle. For example, a specimen mixed with 6% lime presented a reduction of its M_R value of around 80% after WD cycles, as shown in Figure 2-4.

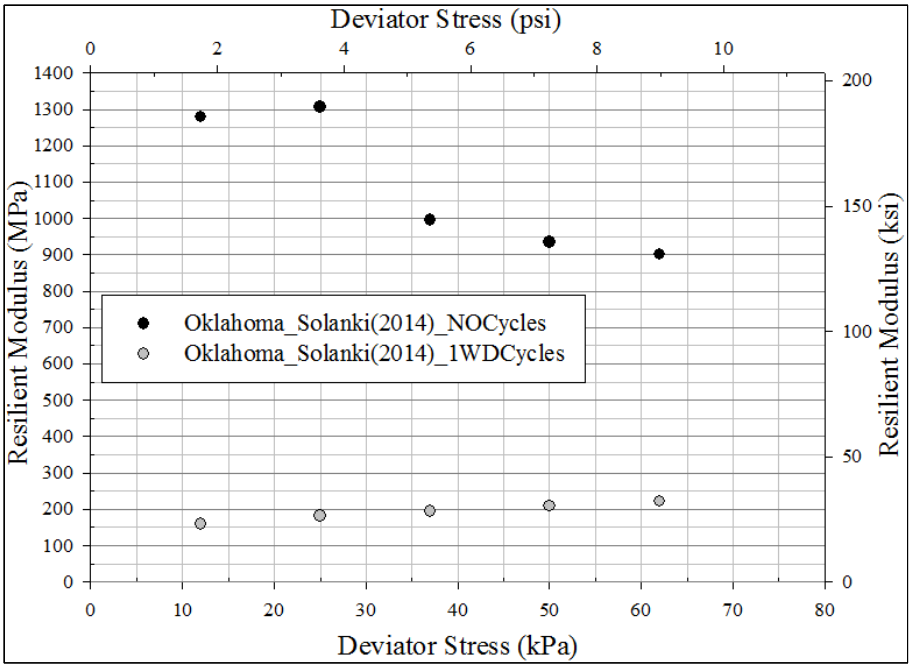
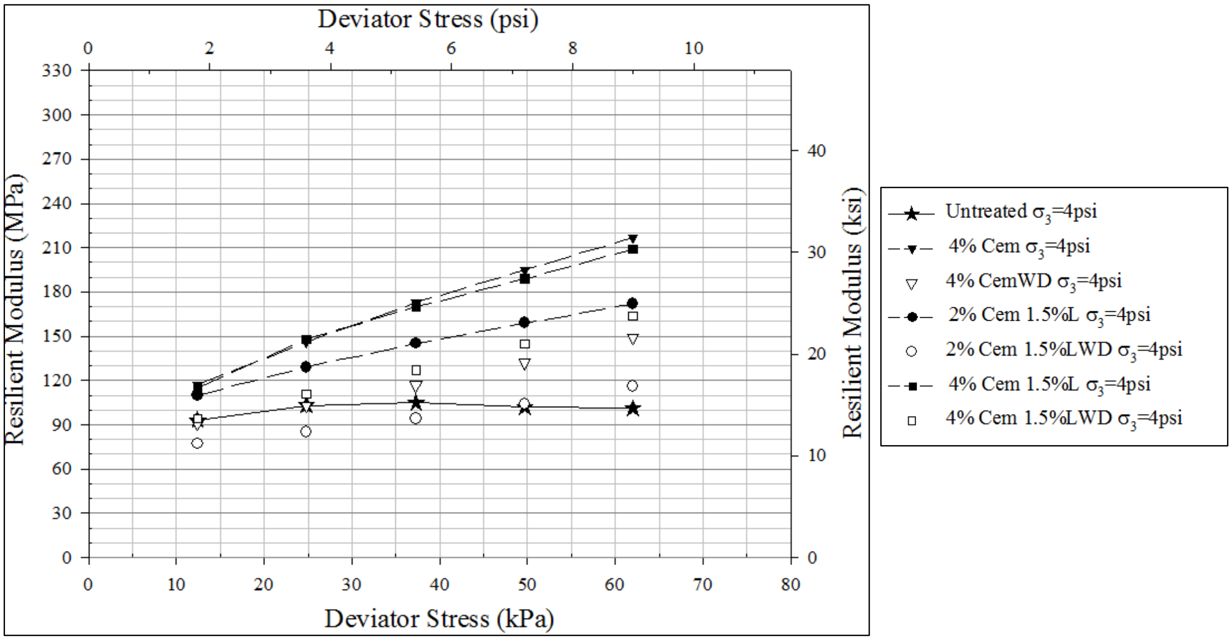


Figure 2-4. Resilient Modulus After one WD Cycle for (6% lime) Treated Samples (Adapted from Solanki et al., 2014)

Rasul et al. (2017) studied the deterioration of treated soils under WD cycles. The performance of subgrades improved with lime and cement was determined by measuring the resilient modulus. After 25 WD cycles, following the ASTM D559/559M-15 standard, a decrease of the resilient modulus of the subgrade was found. Figure 2-5 shows the decrease in stiffness (around 30% below treatment with no cycles) after the WD cycles. The solid line corresponds to the untreated sample and the black and white points represent the treated samples without and after WD cycles, respectively.



Cem: Cement, L: Lime, WD: After Wetting/Drying cycles

Figure 2-5. Resilient Modulus After 25 WD Cycles (Adapted from Rasul, 2017)

2.2.4 Resilient Modulus of Soils Affected by Changes in Temperature - Freezing/Thawing

Another factor that affects the M_R is the change in the soil temperature. Dempsey and Thompson (1971) described the use of a theoretical heat-transfer model to develop field quantitative data in Illinois. The authors used 30-years climatic data (maximum and minimum daily air temperature, percentage of possible sunshine, and average daily wind velocity) to define a Freezing/Thawing (FT) test protocol using statistical analyses. Using the freeze/thaw cycle shown in Figure 2-6, the cooling rate, freezing temperatures and the duration of the freezing temperature were defined. The authors compared field data with the procedures for freezing/thawing (FT) in the standard ASTM D560/560M-16, and found that: cooling rates in the standard are higher than in the field, the twelve freezing/thawing cycles defined in the standard exceed the cycles presented at the locations investigated, the duration of freezing was longer than 24 hours, which is the time prescribed in the standard, and the freezing temperature around the State, that averaged 26°F (-3.3°C), was higher than the required in the standard -10°F (-23.3°C). They concluded that the standard procedure was so stringent and did not simulate the actual field conditions in Illinois.

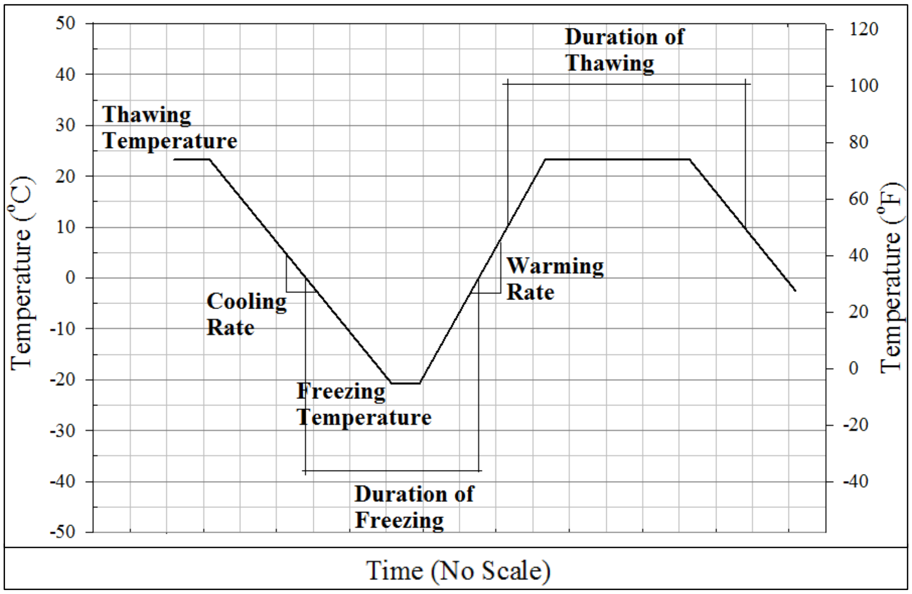


Figure 2-6. Idealized Freeze-Thaw Cycle (Adapted from Dempsey and Thompson, 1971)

Woojin (1993) conducted M_R tests on untreated samples after 0, 1, 2, and 3 FT cycles in a closed system that promoted 1D freezing. The author defined a freeze/thaw cycle based on the findings from Dempsey and Thompson (1971), thawing the specimens 32 hours at 42°F (6°C), 10 hours of cooling (0.326 °F/hr), freezing 32 hours at 28°F (-2°C), and 10 hours of warming (0.534 °F/hr). After that, the M_R test was performed on compacted samples with standard Proctor in the laboratory. The author found that untreated clays subjected to FT cycles showed volume changes, ranging between 12.2% and 26%. After one FT cycle, the soil stiffness was reduced by 30% to 50%, at a deviatoric stress smaller than 6psi (41.4kPa).

Simonsen et al. (2002) tested untreated clayey samples from New Hampshire, at eight temperatures: 68, 41, 32.9, 31.1, 28.4, 23, 14, and -4°F (20, 5, 0.5, -0.5, -2, -5, -10, and -20°C), after one full freeze-thaw cycle. 2.8” in diameter and 6” in height samples were compacted at optimum moisture content in the laboratory. Afterwards, the specimens were frozen and thawed inside a triaxial cell in a closed system (nor “in” or “out-flow” of moisture). Then, the M_R test was conducted following the standard AASHTO T294-92, i.e. using a 0.1s pulse and a 0.9s rest period, the specimens were preloaded by 200 repetitions, then four confining stresses, 2, 4, 6, 10psi (14, 28, 42, 69 kPa), and nine deviatoric stresses, 2, 4, 6, 15, 20, 30, 32, 49, 65, 81, 97, 130psi (14, 28, 42, 104, 138, 207, 220, 340, 450, 560, 670, 897kPa) were applied. The higher deviatoric stresses were considered for sample temperatures below zero Celsius degrees. The authors found that all the soils presented a reduction in M_R after the thawing stage, as shown in Figure 2-7. The specimen stiffness decreased by 20–50% after one FT cycle.

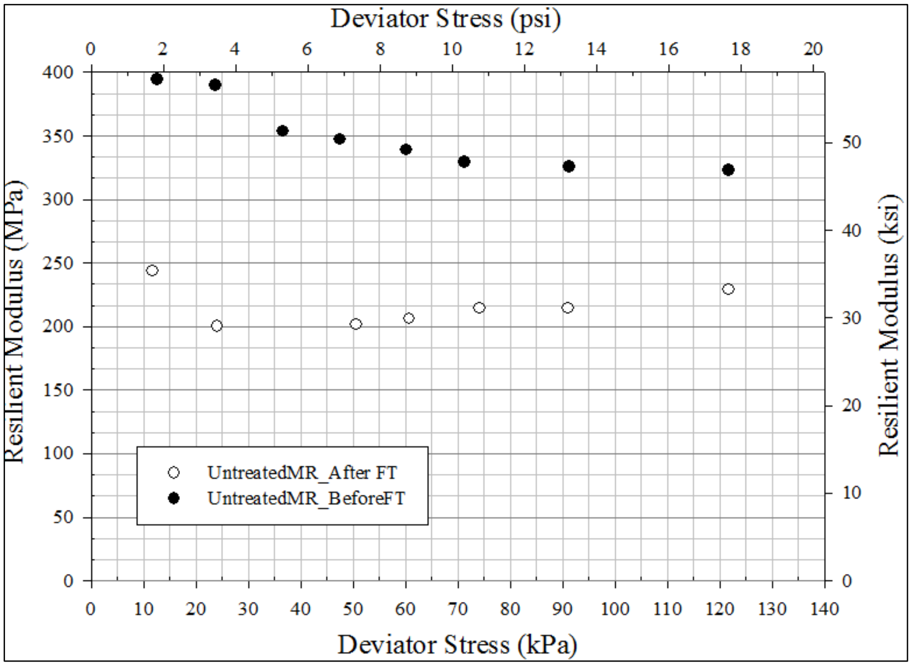


Figure 2-7. Resilient Modulus After one FT Cycle (Adapted from Simonsen et al., 2002)

In more recent studies, Solanki et al., (2013) evaluated the durability of the treated subgrades when the samples were subjected to FT cycles following the standard ASTM D560/560M-16. The soils were treated with hydrated lime, class C fly ash (CFA), and cement kiln dust (CKD). After 7-days curing, the samples were subjected to 0, 1, 4, 8, and 12 FT cycles and the M_R test was conducted following the AASHTO T307-99. As expected, it was found that both, untreated and treated specimens, experienced a reduction in M_R values due to the application of FT cycles. Also, the greater the number of cycles, the lower M_R, as shown in Figure 2-8. It is also seen in the figure, that most of the soils mixed with 10% CKD had an increased capacity to endure FT.

Becker et al., (2014), studied the FT performance of stabilized pavement with Portland cement (PC) and fly ash (FA) in Boone, Iowa. Field tests such as Falling Weight Deflectometer (FWD) and Dynamic Cone Penetrometer (DCP) were performed before (October 2012) and after (April 2013) one season of FT. The authors compared FWD (elastic modulus) values during October

2012 and April 2013 measurements, as shown in Figure 2-9. The results indicated that sections with cement stabilization provided the highest stiffness values. The authors concluded that all soils experienced a significant decrease (on average 2 to 9 times compared with October measurements) of the FWD modulus during spring-thaw. They highlighted the importance of stabilizing the subgrade to endure the freeze-thaw effects.

Bandara et al. (2015), at the Cold Regions Conference, presented a study regarding the durability of stabilized subgrades submitted to FT cycles. Soils classified as A-6 were mixed with Cement Kiln Dust (CKD) or Lime Kiln Dust (LKD). After 1, 3, 7, and 12 FT cycles, unconfined compression tests were conducted. The authors mentioned that the laboratory tests following the ASTM D560/560M-16 standard were harsher than field conditions. The authors found a reduction of strength with FT cycles, as shown in Figure 2-10.

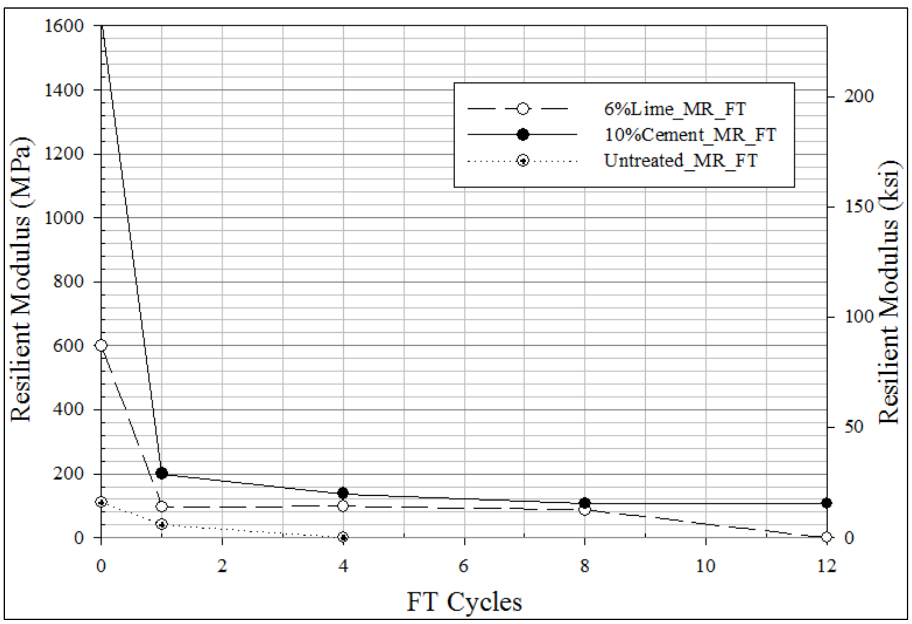
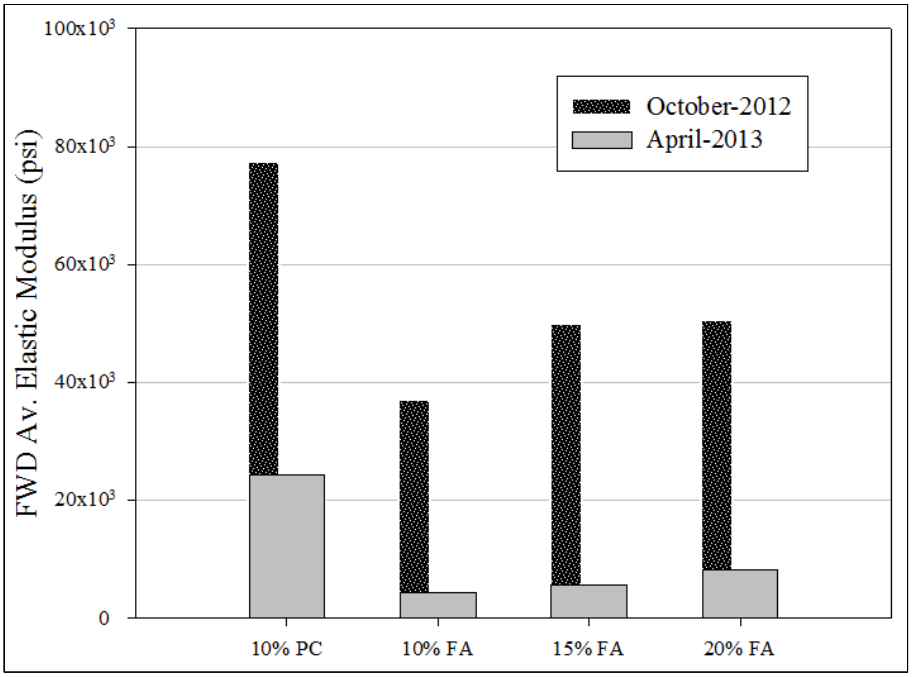


Figure 2-8. Resilient Modulus After FT Cycles (Adapted from Solanki et al., 2013)



PC: Portland Cement, FA: Fly Ash

Figure 2-9. Average FWD Elastic Modulus After a FT Season (Adapted from Becker et al., 2014)

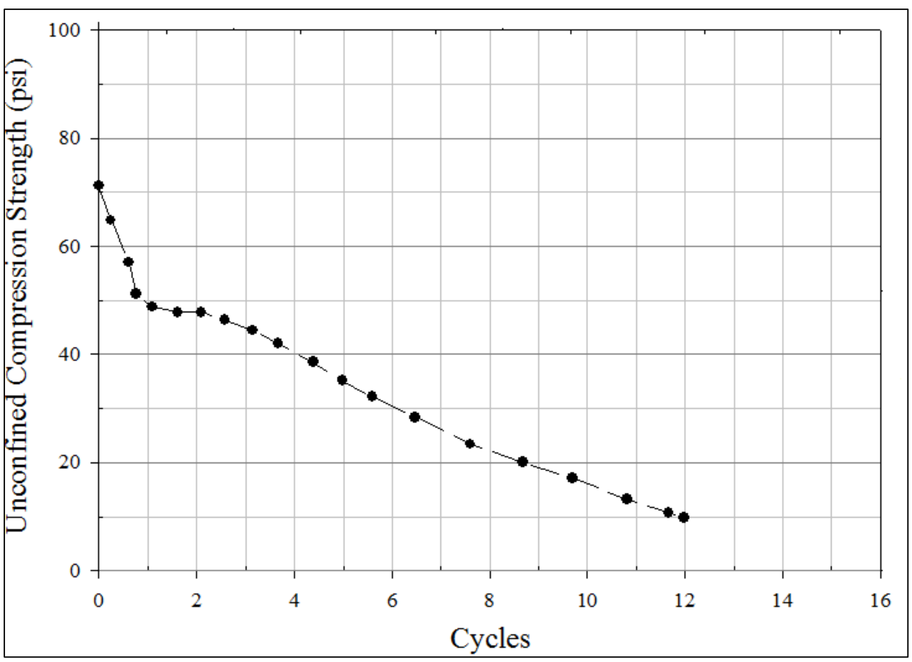


Figure 2-10. UCS Under FT Cycles for CKD-soil Mixture (Adapted from Bandara, 2015)

In summary, the data available in the literature, while still limited, seem to indicate that Wetting/Drying (WD) and Freezing/Thawing (FT) cycles, following the ASTM standards D559/559M-15 and D560/560M-16, respectively, both cause a reduction of the resilient modulus of the treated or untreated subgrade soil.

3. SOILS CHARACTERIZATION AND CHEMICAL TREATMENT

The soils used for the tests, as will be discussed in more detail later, were collected at different locations in Indiana and are representative of the materials found in the State. However, it can be argued that the results are applicable, or at least can be of interest, to the Midwest states located at the same or higher latitude than Indiana. The reason for this is the similar geologic origin of the soils in the area. The large majority of the soil deposits in the Midwest are of glacial origin, with the exception of the lake deposits around the Great Lakes and alluvial deposits around rivers. Two main glaciations during the Pleistocene define the geological setting of the area: the more recent Winconsinian glaciation (30,000 to 11,600 years ago) and the Illinoian glaciation (300,000 to 130,000 years ago). The ice sheet reached the South of Indiana and the started to retreat about 18,000 years ago, leaving behind extensive soil deposits that characterize the current geological setting.

3.1 Samples Location and Index Properties of Untreated Soils

Four sampling sites from two locations in Indiana were selected as soil sources. The places are Hartford City (HC) and Bloomington (BM). At the latter, three samples with differences in plasticity were selected, namely BM1, BM2 and BM3. Hartford City (Blackford County) is in the northeast of Indiana, and Bloomington (Monroe County) in the southern region of the state, as shown in Figure 3-1.

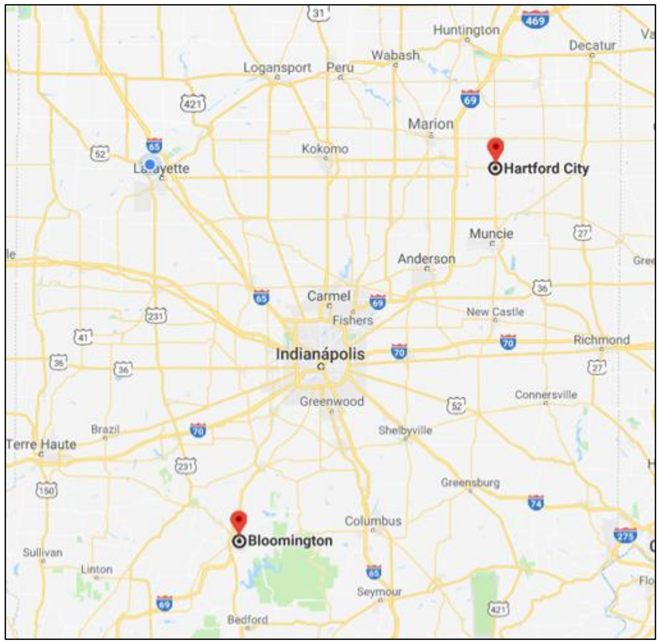


Figure 3-1. Location of the Sampling Sites – Indiana

In this chapter, classification, pH, and proctor test results are used to characterize the subgrade soils and to determine the optimum amount of treatment. For classification purposes, grain size distribution and plasticity tests were performed following the standard AASHTO T-88 and AASHTO T-89/T-90, respectively. The results are shown in Table 3-1, and they indicate that the soil from HC is classified as A-6, while BM soils are classified as A-7-6. Loss on Ignition (LOI) tests following AASHTO T-267 were also conducted, and the results are shown in Table 3-2. The soils have organic matter content below 6% which is the maximum value accepted for soils that can be chemically-treated.

Table 3-1. Soil Classification Tests

Site	LL (%)	PL (%)	PI (%)	Passing # 200	AASHTO Class.
Hartford City	26.00	11.60	14.40	-	A-6
	37.20	14.20	23.00	88.20	A-6
Bloomington # 1	41.20	17.30	23.90	88.40	A-7-6
Bloomington # 2	66.00	20.80	45.20	93.50	A-7-6
Bloomington # 3	58.60	21.00	37.60	-	A-7-6

Table 3-2. Loss on Ignition Test Results

Site	Organic Matter Content (%)	Calcium Carbonate Content (%)
Hartford City	2.0	18.7
	2.0	20.5
Bloomington # 1	3.9	2.0
	2.6	3.6
Bloomington # 2	2.3	12.9
	2.1	12.8

3.2 Optimum Amount of Treatment

HC, BM1, and BM2 soils were treated with Lime Kiln Dust (LKD) and/or Portland cement. For BM3, the effect of treatment with cement, LKD and QL was investigated for verification and overdosing purposes (see Table 3-1). The optimum amounts of treatment were obtained following the recommendations provided in the INDOT manual: “Design Procedures for Soil Modification or Stabilization, 2015”, as discussed below. The compaction curves for the mixtures of soils with different treatments used in this research can be seen in Figures B.1 to B.3 for HC, BM1, and BM2, respectively.

3.2.1 Treatment with Lime Kiln Dust (LKD)

Lime kiln dust (LKD) is a byproduct of lime production which contains lime, alumina, and silica. When LKD is mixed with a clayey soil, three reactions are involved: cation exchange, pozzolanic, and carbonation. Consequently, the pH and electrolyte concentration are increased as shown in Figure 3-2, where hydrogen (H^+) is removed from the soil cation exchange and replaced with cation Calcium (Ca^{+2}) and/or magnesium (Mg^{+2}).

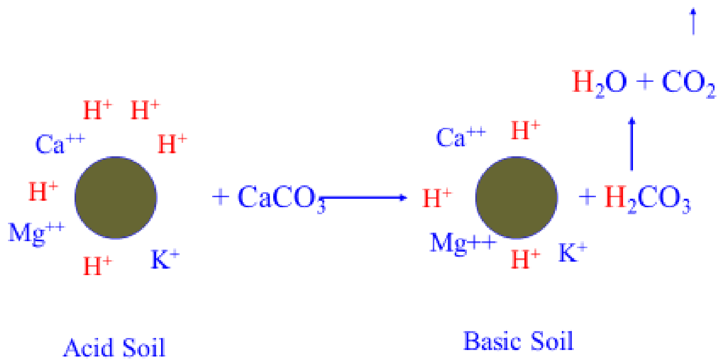


Figure 3-2. Chemical Reaction of Clay Mixed with Lime

Following the requirements in the Design Procedures for Soil Modification or Stabilization, 2015, two criteria must be met to determine the minimum amount of LKD to be used for the stabilization: i) a minimum pH of 12.4 following Eades and Grim pH test; and, ii) an increase in the unconfined compression strength of 50psi (344.7kPa) after curing for 48 hours at 70°F (21ºC) in a moisture room, following AASHTO T-208.

Eades and Grim pH tests are shown in Figure 3-3. In the figure, the pH for the soils investigated is given for different LKD contents. As seen in the plot, the amount of LKD required is 6% for HC and BM1, and 5% for BM2. Regarding BM3, it was desired to use the same amount of LKD than that for BM2, i.e., 5%. Thus, the pH for BM3+5% LKD was verified to be larger than 12.4. With those amounts of LKD, unconfined compression tests were performed to determine the increase in strength. Figures B.4 to B.6 show results of unconfined compression strength tests for the optimum LKD content after 48 hours of curing, for HC, BM1, and BM2, respectively. As seen in the figures, the increase in unconfined compression strength after 48 hours was larger than 50psi (344.7kPa) in all the cases.

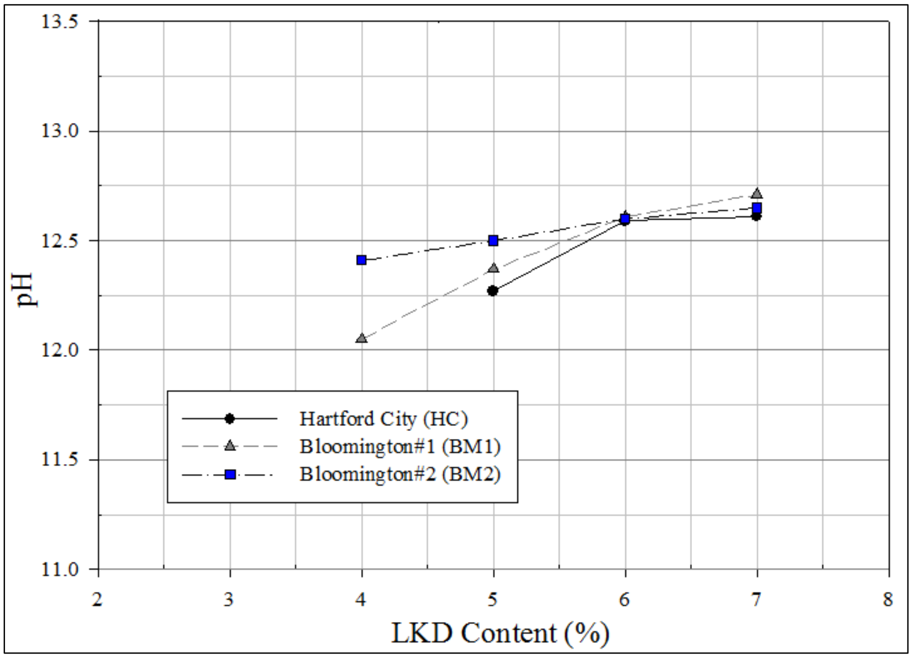


Figure 3-3. Results of Eades and Grim pH Tests for the Four Soils Treated (Adapted from Sandoval et. al., 2018)

3.2.2 Treatment with Cement

Mixing clayey soils with cement entails three stages: flocculation of clay particles, pozzolanic reaction and hardening of the cement particles. The pozzolanic and hardening reactions are responsible of the improvement of the subgrade stiffness. This treatment's response is influenced by the cation associated with the clay and the type of clay mineral. Cement hydration leads to a rise in pH of the pore water, then the pozzolanic reaction is guaranteed as shown in Figure 3-4.

To determine the optimum amount of cement for stabilization, only the strength criterion must be satisfied. In this case, an increase in the unconfined compression strength of 100psi (689.5kPa), after curing for 48 hours at 70°F (21°C) in the moisture room, is required. Results of unconfined compression strength tests, for the optimum amount of cement, are shown in Figures B.4 to B.6 for HC, BM1, and BM2, respectively. Results from those samples that did not reach the strength criterion with smaller amount of cement (3%) are shown in Figure B. 7. This only occurred for the highly plastic soil, BM2.

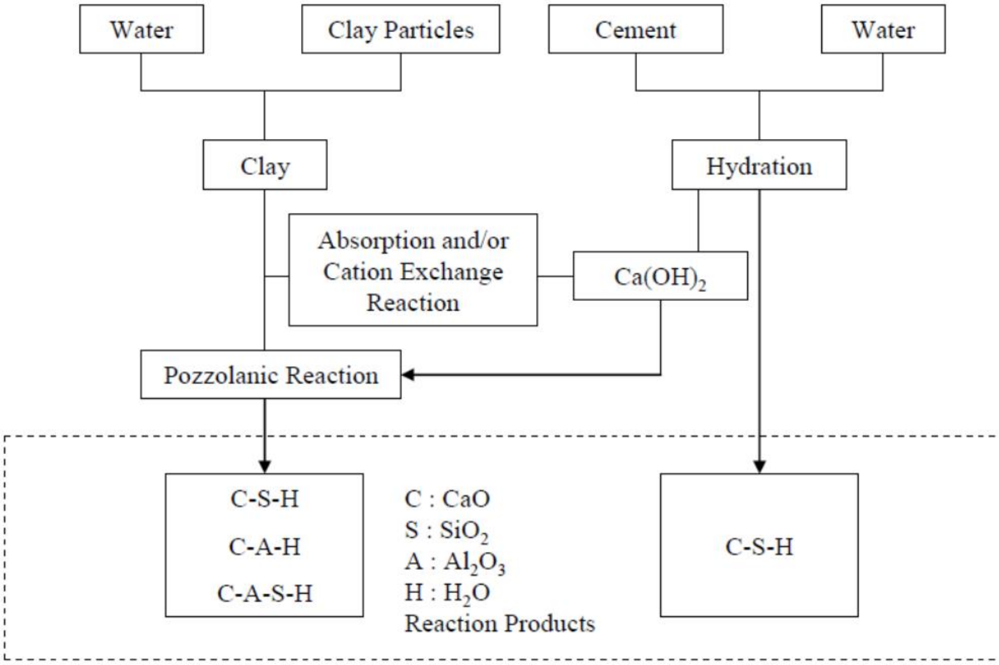


Figure 3-4. Chemical Reaction between Clay and Cement

A summary of the maximum unit weight and optimum moisture content are included in Table 3-3, for the four samples. The table also shows the optimum amount of treatment. As seen in the table, the optimum amount of treatment varies between 5% and 6% for LKD, and between 3% and 5% for cement.

Table 3-3. Summary of Optimum Amount of Treatment, Maximum Unit Weight and Optimum Moisture Content for the Treated Soils

Site	Optimum LKD			Optimum Cement		
	Amount (%)	γ_d (pcf)	OMC (%)	Amount (%)	γ_d (pcf)	OMC (%)
Hartford City	6	115.4	16.5	3	121.1	12.3
Bloomington # 1	6	103.6	20.8	3	107.3	19.6
Bloomington # 2	5	98.6	26.3	5	101.1	25.7
Bloomington # 3	5	101.1	23.1	-	-	-

OMC: Optimum moisture content

4. EFFECT OF CHANGES IN MOISTURE CONTENT ON RESILIENT MODULUS

The subgrades in Indiana are exposed to changes in moisture content throughout the seasons, which may degrade the stiffness of the natural or treated subgrade. To evaluate this degradation, the American Society for Testing and Materials (ASTM) has proposed the Standard D559/D559M-15 to determine the resistance of compacted specimens treated with cement, subjected to repeated wetting and drying cycles. Although no standard procedure has yet been developed by ASTM or AASHTO for lime-soil mixture (Dempsey, B. and Thompson, M., 1971), in this study, the ASTM D559/559M-15 was used for both admixtures of Lime Kiln Dust (LKD) lime and Portland Cement. In this research, 3" diameter and 6" height remolded samples of soil mixed with cement or LKD were compacted at 100% of the Standard Proctor energy, to conduct resilient modulus, M_R, tests, following the standard AASHTO T307-99 for Type 2 Material, i.e., fine-grained soils. Fine-grained soils with low and high plasticity (A-6 and A-7-6, shown in Table 3-1), from Hartford City and Bloomington were used for this analysis.

4.1 Procedure Following the ASTM Standard D559/D559M-15

After compaction, the specimens were cured in the moisture room for 7 days. Later, the samples were exposed to twelve wetting/drying (WD) cycles following the Standard D559/D559M-15. Each cycle of WD consisted of submerging the sample in tap water at room temperature for 5 hours, and later oven drying it at 160^{o}F (71^{o}C) for 42 hours. Figure 4-1 shows the wetting stage (part a) at 73^{o}F (23^{o}C), and oven drying (part b) at 160^{o}F (71^{o}C) for a Bloomington#1 (BM1) sample.

(a) Submerging – 73°F (23°C) (5 hours) (b) Oven Drying – 160°F (71°C) (42 hours)

Figure 4-1. BM1 Specimen Following the Standard ASTM D559/D559M

However, by following strictly the standard, the treated samples failed after the first three cycles, mostly during the wetting stage, as shown in Figure 4-2. The specimens exhibited cracks in the plane of compaction (Figure 4-2 a) and in a plane perpendicular to it (Figure 4-2 b). In an attempt to prevent the failure of the samples and to simulate better the field conditions, the samples were confined with a perforated PVC pipe that allowed water flow into the specimen, as shown in Figure 4-3. The wetting/drying procedure was done following the standard ASTM D559/D559M-15, i.e., by submerging and oven drying the samples. However, the samples again failed around the fifth cycle, under the extreme temperature changes required by the standard, as shown in Figure 4-4.

(a) Plane of compaction (b) Perpendicular to plane of compaction

Figure 4-2. Samples Collapsed After Following the Standard ASTM D559/D559M (3^{rd} Cycle)

(a) Submerging – 73°F (23°C) (5 hours) (b) Oven Drying – 160°F (71°C) (42 hours)

Figure 4-3. Samples Confined with a Perforated PVC Pipe, Under Wetting and Drying Cycles

Figure 4-4. Collapse of a Confined Sample (5^{th} cycle)

4.2 Modified Protocol Test for Wetting and Drying

The subgrade's temperature in Indiana vary through the seasons; however, these variations are not as extreme as required by the standard ASTM D559/D559M-15. The actual temperatures that the subgrade in Indiana would experience were obtained from the Indiana State Climate Office (iClimate) at Purdue University, which uses information included in the National Centers for Environmental Information (NOAA). Table 4-1 lists the latitude and longitude of each station, and Figure 4-5 shows the eight climatic stations around the state where there are reports of daily readings at different depths, for 10 years, from January 2008 to December 2017. For more details, see Appendix C where there are daily temperature data at 4 inches depth from each station in Figures C.1 to C.8.

The temperature data was separated between the North and South of Indiana, given that the average temperatures are quite different. Figures 4-6 and 4-7 include the maximum yearly soil temperatures at 4 inches depth for each climatic station, for the North and South, respectively. The figures show that in the northern Indiana, the soil temperature ranged from 80°F (27°C) to 110°F (43°C), while in the southern they ranged between 90°F (32°C) and 110°F (43°C). According to the INDOT Design Manual (2013), subgrades in Indiana are located around 12 to 16 inches depth. Consequently, data readings around the entire state at different depths were used to estimate the subgrade temperature, as shown in Figure 4-8. The figure shows the maximum soil temperature at different depths around the state and the highest subgrade temperature at 12 inches depth, in the past 10 years, was around 87.5°F (31°C).

Table 4-1. Location of Climatic Stations in Indiana State (Data from iClimate)

Name	City/Town	County	Latitude	Longitude
ACRE	WEST LAFAYETTE	TIPPECANOE	40.550	-86.917
DPAC	MUNCIE	RANDOLPH	40.250	-85.150
NEPAC	COLUMBIA	WHITLEY	41.100	-85.383
PPAC	WANATAH	LAPORTE	41.450	-86.930
TPAC	LAFAYETTE	TIPPECANOE	40.298	-86.903
SEPAC	BUTLERVILLE	JENNINGS	39.033	-85.517
SIPAC	HOOSIER NATIONAL FOREST	DUBOIS	38.450	-86.700
SWPAC	VINCENNES	KNOX	38.733	-87.483

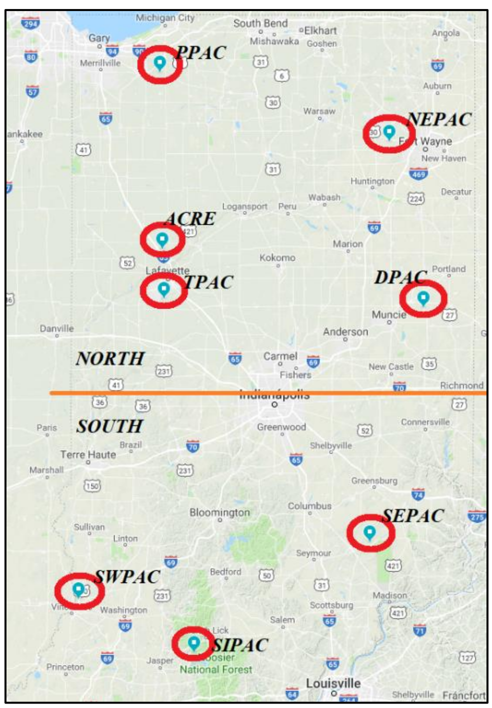
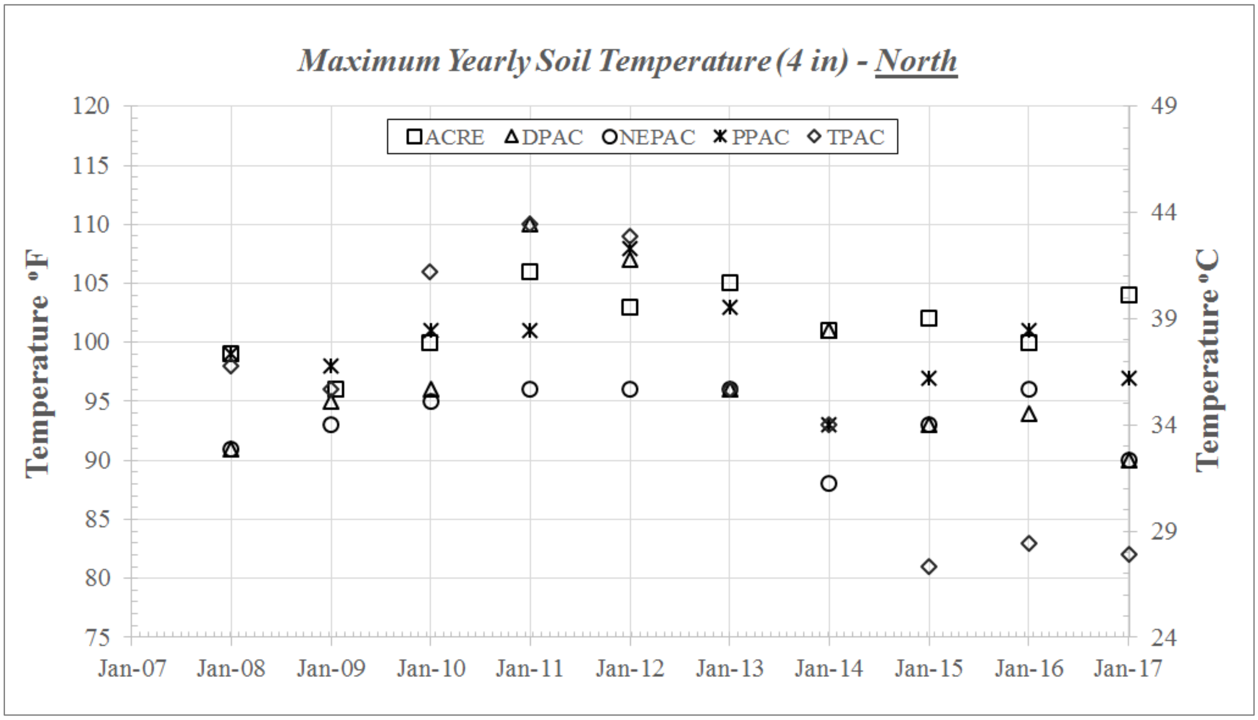
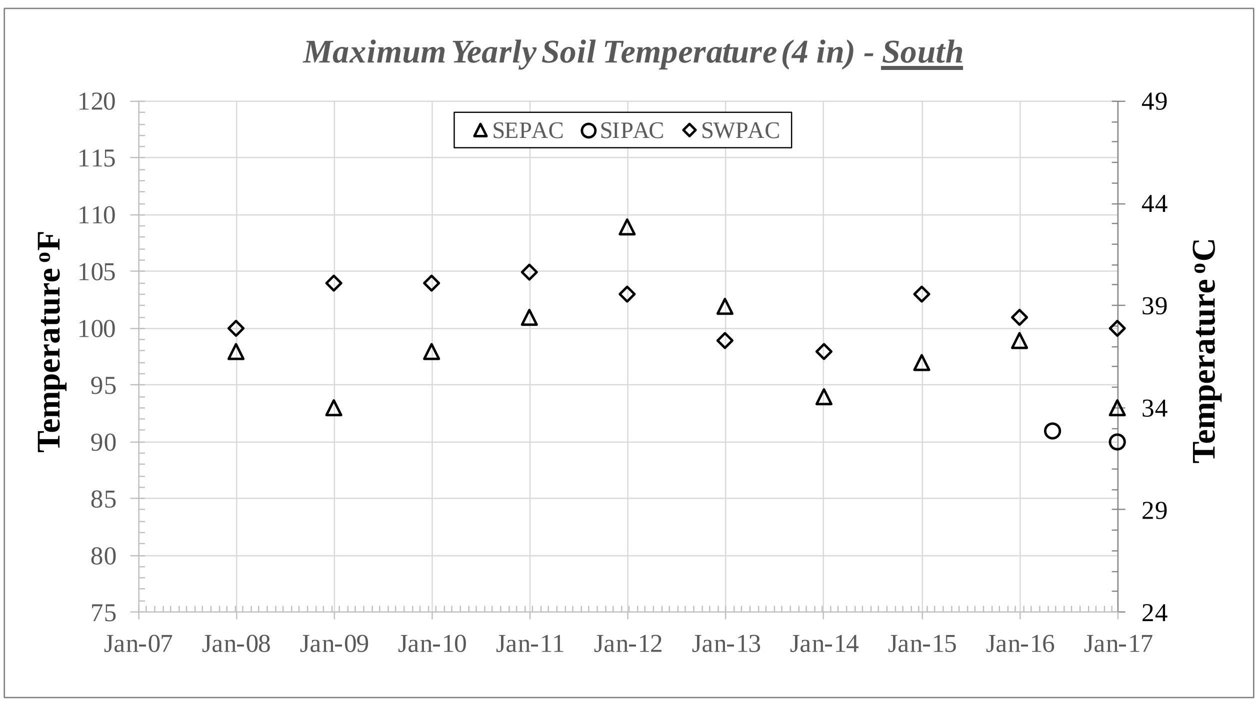


Figure 4-5. Climatic Stations in Indiana State (Google Maps)



Data from iClimate

Figure 4-6. Maximum Yearly Soil Temperature at 4 inches depth (10 years readings) – North



Data from iClimate

Figure 4-7. Maximum Yearly Soil Temperature at 4 inches depth (10 years readings) – South

These findings were discussed with the Study Advisory Committee (SAC) on September 2018. The following test protocol was proposed, which is thought to be a closer representation of the conditions in the field: for the wetting stage, place the specimens in the moisture room for two days with water coming from the bottom (without immersion); for the drying stage, two days at room temperature (without placing the samples into the oven), as shown in Figure 4-9. For repeatability purposes, three samples for each type of mixture were tested. The samples were subjected to twelve wetting-drying cycles, which lasted around two months.

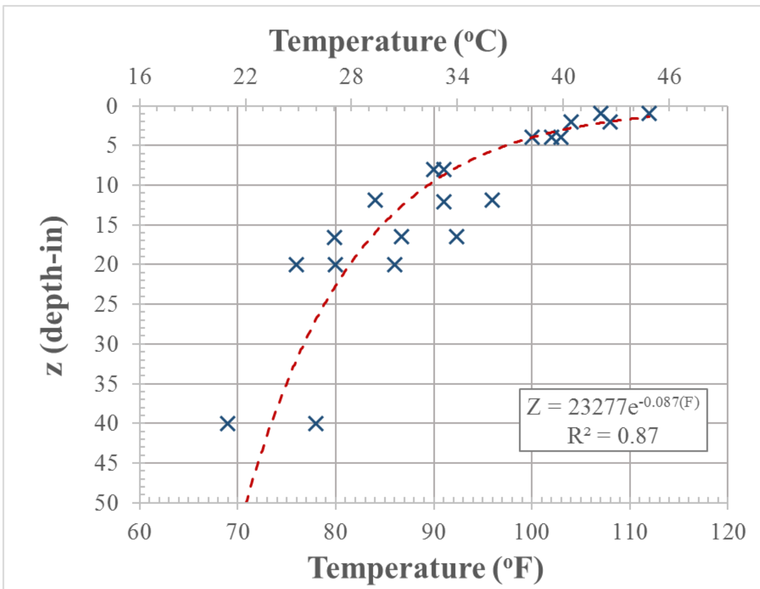
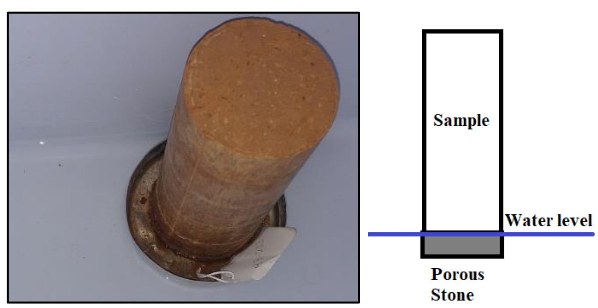


Figure 4-8. Maximum Soil Temperature at Different Depths Around the State

(a) Drying Stage (2 days) – BM1 and HC



(b) Wetting Stage (2 days) – BM1

Figure 4-9. Modified WD Process BM1 and HC, LKD Treated Soils

The types and amount of optimum chemical treatment for the specimens were presented in Chapter 3, for Hartford City (HC), Bloomington#1 (BM1), Bloomington#2 (BM2), and Bloomington#3

(BM3) soils. Table 4-2 lists the optimum amount of LKD, cement, and Quick Lime (QL) for the soils tested. The wetting/drying (WD) procedure was conducted on HC, BM1, and BM2 soils mixed with LKD and cement following the proposed protocol. For verification purposes, samples of BM3 were mixed with QL. The index properties of these soils were discussed in Chapter 3. As shown in Table 4-3, thirteen (13) M_R tests were conducted, following the standard AASHTO T307-99 for Type 2 Material, i.e., fine-grained soils. Eight tests were run at the INDOT lab in Indianapolis, given that the device in West Lafayette was not operational. After the equipment was again available, five tests were done at the INDOT lab in West Lafayette.

As highlighted in Table 4-2, it was possible to accomplish the twelve WD cycles for mixtures with LKD for HC and BM1 as shown in Figures 4-10 and 4-11, respectively. In contrast, the highly plastic clayey soils, BM2 and BM3, failed during the first WD cycles following the modified protocol test as shown in Figure 4-12. Regarding the mixtures with cement, the twelve WD cycles were accomplished only for BM1 (see Figure 4-13), while samples of BM2 and HC failed for this admixture (see Figure 4-14). Highly plastic soil does not support the WD cycles even when mixed with lime or cement. Sandoval et al., 2018 found acceptable M_R results for the highly plastic soil (BM3) mixed with double amount of treatment. Thus, the highly plastic soil (BM3) mixed with double amount of treatment of QL and cement were exposed to WD cycles, as shown in Figures 4-15 and 4-16, respectively.

From these finding, and from the acceptable results presented by Sandoval et al., 2018, when overdosing a highly plastic soil (BM3), samples with double treatment of QL and cement were tested, as shown in Figures 4-15 and 4-16, respectively. All these figures show the samples throughout the WD process, from the 1st to the 12th cycles. The M_R results for overdosed samples are discussed later in Section 4.4.

Table 4-2 Optimum Amount of Treatment

	Amount (%)		
Site	LKD	Cement	QL
Hartford City	6	3	--
Bloomington #1	6	3	--
Bloomington #2	5	5	--
Bloomington #3	--	--	5
	Successful 12 WD cycles		
LKD :	Lime Kiln Dust		
QL:	Quick Lime		
--:	Collapsed specimen		

Table 4-3. Amount of M_R Tests Conducted for Hartford City and Bloomington#1

Type of sample		Amount M_R
Hartford City	Untreated	2
	LKD Lime	3
Bloomington#1	Untreated	3
	LKD Lime	3
	Cement	2
Total		13

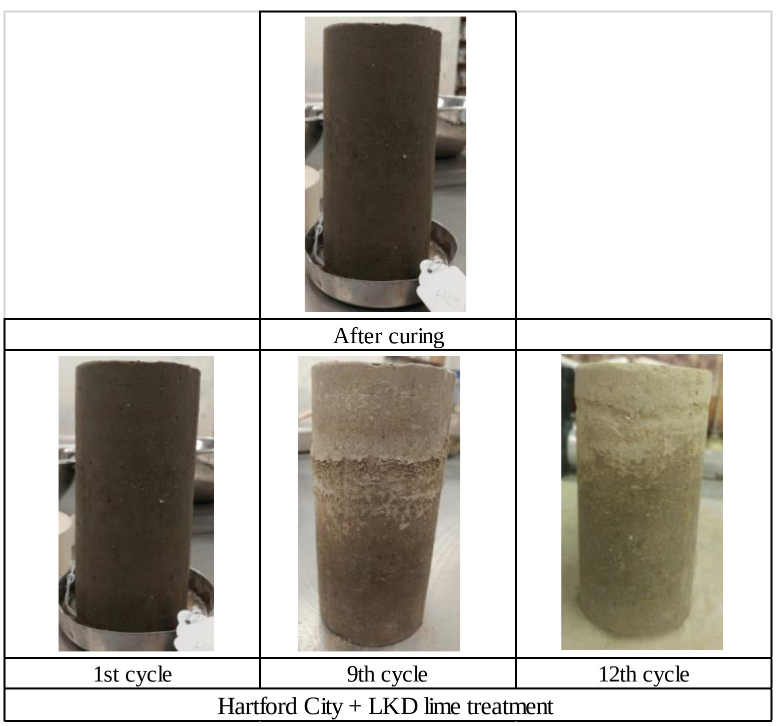


Figure 4-10. HC Samples Treated with LKD During WD Cycles. Modified Protocol

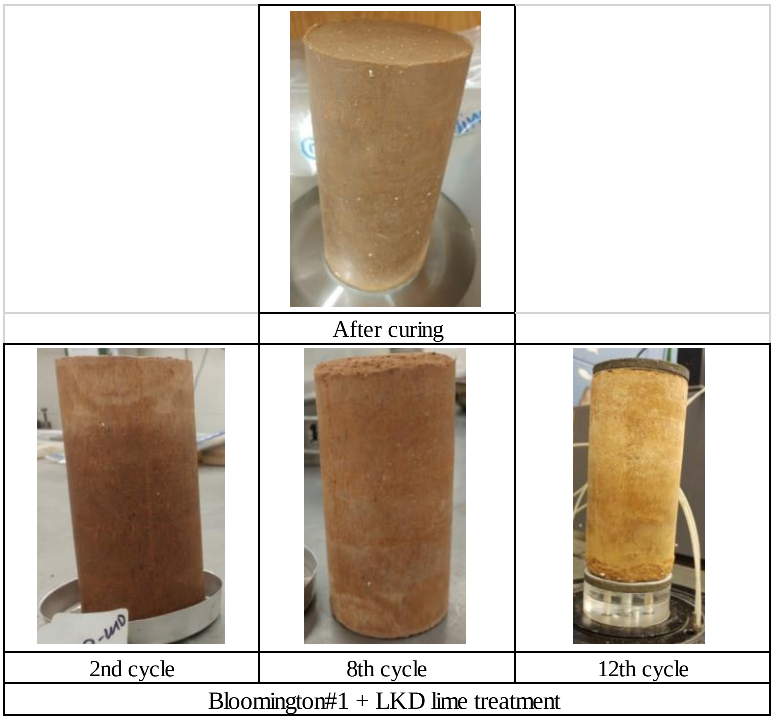


Figure 4-11. BM1 Samples Treated with LKD During WD Cycles. Modified Protocol

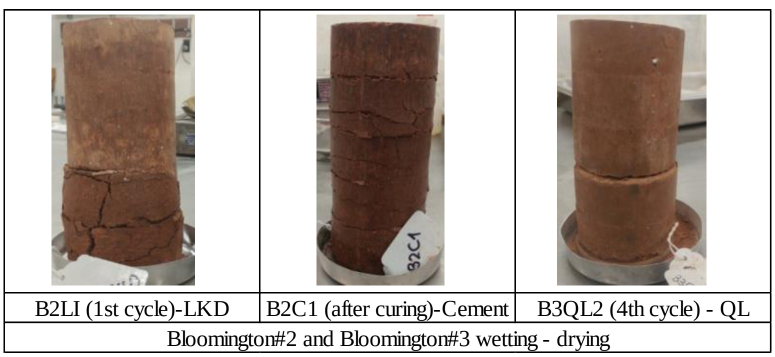


Figure 4-12. Collapsed Samples During WD Cycles BM2 with LKD, Cement and QL. Modified Protocol

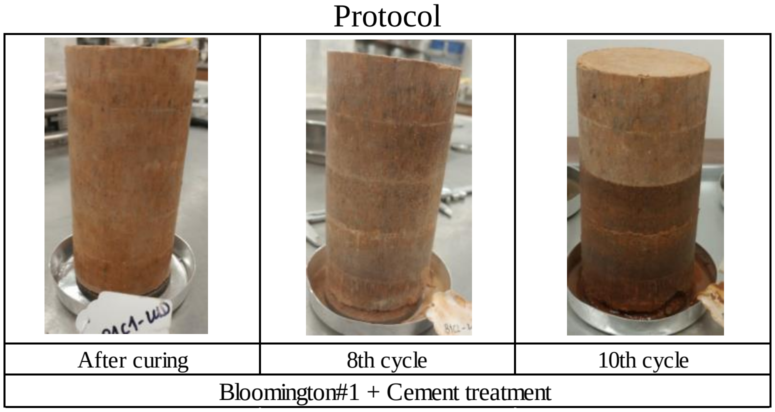


Figure 4-13. BM1 Samples Treated with Cement During WD Cycles. Modified Protocol

		
HCC3 (9th cycle)	HCC1 (11th cycle)	HCC1 (12th cycle)
Hartford City wetting - drying		

Figure 4-14. Collapsed Samples During WD Cycles HC with Cement. Modified Protocol

		
	After curing	
		
4th cycle	10th cycle	12th cycle
Bloomington#3 + double QL treatment		

Figure 4-15. BM3 Samples Treated with Double Amount of QL During WD Cycles. Modified Protocol

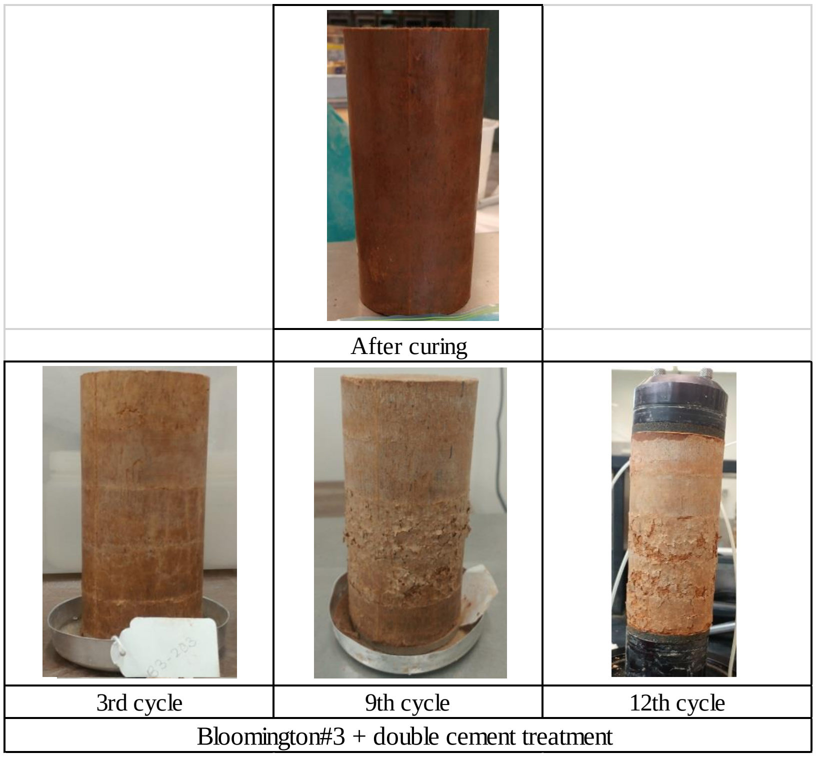


Figure 4-16. BM3 Samples Treated with Double Amount of Cement During WD Cycles. Modified Protocol

4.3 Results of Resilient Modulus Tests for the Optimum Amount of Treatment After Wetting and Drying

The resilient modulus tests were conducted, following the standard AASHTO T307-99, at the INDOT facilities in West Lafayette and in Indianapolis, where a Triaxial Cell Model 3600 (GEOCOMP Corporation) was available, as shown in Figure 4-17.

The equipment shown in Figure 4-18 contains a controller that sends to and receives commands from a Linear Electro-Mechanical Actuator (LEMA) to produce the cyclic loading. The machine also processes signals coming from the transducers and controls the confining pressure in the test cell. An external air pressure supply of 500 kPa (72.5 psi) is needed for the Electro Pneumatic controller.

After the specimen is ready (compaction, 7-days curing period, and WD or FT cycles), a porous stone and paper filter are placed on the base of the triaxial chamber. Subsequently, the specimen is placed on the paper filter carefully, with a paper filter and porous stone on the top and with the sample cap. Then, the membrane is placed and sealed on the top and bottom with O-rings, as shown in Figure 4-17. The chamber is installed and secured with the tie rods, and the LVDTs positioned. The assembly is placed on the machine under the axial loading device. Afterwards, the air pressure supply is connected to the triaxial chamber and a confining pressure of 6psi (41.4kPa) is applied. Then, the conditioning stage (500 load repetitions) and the loading sequence (100 load repetitions) are performed, as described in Table 4-4. The vertical recovered deformation is recorded to calculate the M_R.

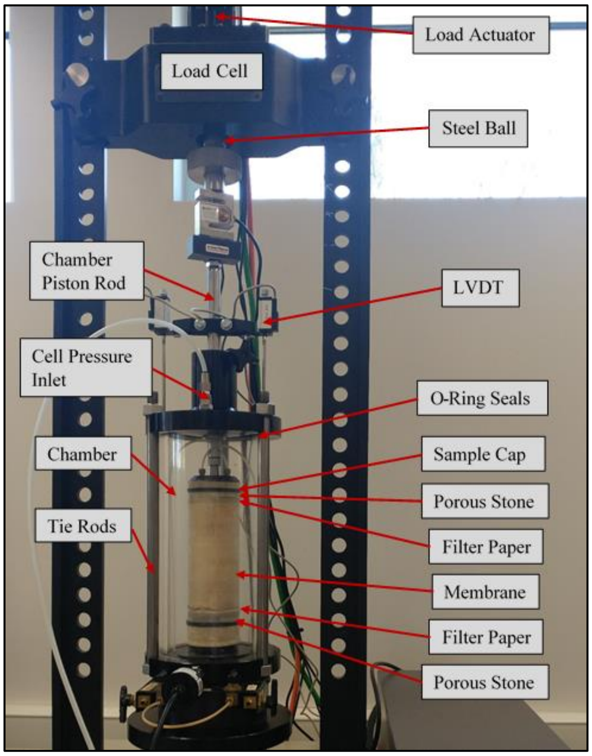


Figure 4-17. Triaxial Pressure Chamber Model 3600 (INDOT Laboratory)

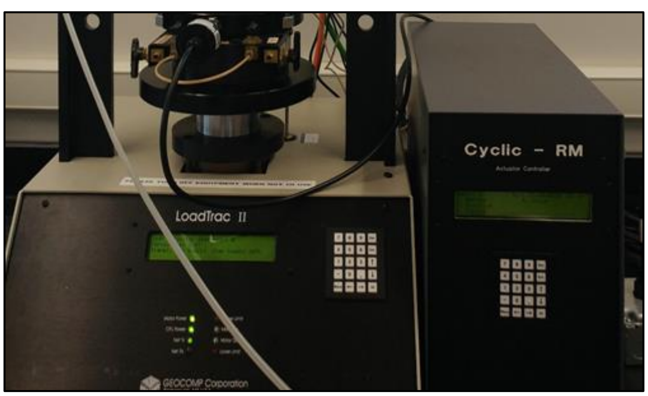


Figure 4-18. LoadTrac-II/Cyclic-RM and Load Frame (INDOT laboratory)

Table 4-4. Testing Sequence for M_R Test - Cohesive Soils

Sequence No.	Confining Pressure		Max. Axial Stress		No. of Load Applications
	kPa	psi	kPa	psi	
0	41.4	6	27.6	4	500–1000
1	41.4	6	13.8	2	100
2	41.4	6	27.6	4	100
3	41.4	6	41.4	6	100
4	41.4	6	55.2	8	100
5	41.4	6	68.9	10	100
6	27.6	4	13.8	2	100
7	27.6	4	27.6	4	100
8	27.6	4	41.4	6	100
9	27.6	4	55.2	8	100
10	27.6	4	68.9	10	100
11	13.8	2	13.8	2	100
12	13.8	2	27.6	4	100
13	13.8	2	41.4	6	100
14	13.8	2	55.2	8	100
15	13.8	2	68.9	10	100

Equation 1 is suggested by GEOCOMP to obtain the resilient modulus.

$$M_R = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\sigma_d}{p_a}\right)^{k_3} \qquad \text{Equation 1}$$

Where:

$$p_a = atmospheric\ pressure$$

$$k_1, k_2, k_3 : Non - linear\ elastic\ constants\ and\ coefficients$$

Table C. 1, in Appendix C, lists all the results obtained for the M_R tests for WD analysis, and Figures C. 9 to C. 17 show all the M_R tests results at optimum amount of treatment for HC and BM1 soils after the WD cycles. For comparison purposes, the M_R results for treated and untreated samples compacted at 95% of the Standard Proctor at 28 days curing (Sandoval et al., 2018) are also shown in the figures.

Only results of M_R tests for the intermediate confinement stress, σ_3 = 4psi (27.6kPa), for the five deviatoric stresses 2, 4, 6, 8, and 10 psi (13.8, 27.6, 41.4, 55.2, and 69kPa) are discussed in this session, given that there are no remarkable differences for the different confinement stresses (Sandoval et al., 2018). Figures 4-19 to 4-21 show the M_R test results for HC mixed with LKD, BM1 with LKD, and BM1 with cement, respectively. For comparison purposes, the plots include gray and black solid lines that represent the untreated and treated specimens compacted at 95% of the Standard Proctor, respectively. The black dashed line corresponds to the untreated samples compacted at 100% of the Standard Proctor and the color lines (three samples for repeatability - green, red, and blue) correspond to the treated samples compacted at 100% of the Standard Proctor, after the twelve WD cycles. The figures show an increase in the stiffness of the treated samples after 28-days curing, as shown by the gray and black solid lines in the plots. However, after twelve WD cycles (2 months), the specimens presented signs of degradation that affected the stiffness of the treated soil.

Table 4-6, at the end of this chapter, shows M_R values for σ_3=4psi (27.6kPa) and σ_d=6, 8 and 10psi (41.4, 55.1, and 68.9kPa) for optimum amount of treatment. The change in stiffness with respect to the untreated soil, compacted at 100% of the Standard Proctor, is also provided in Table 4-6 (a), while Table 4-6 (b) shows the change in stiffness with respect to the treated soil, compacted at 95% of the Standard Proctor without any WD cycle. The following discussion includes the results shown in Figures 4-19 to 4-21 and listed in Table 4-6.

Regarding Hartford City (HC) treated with LKD, Figure 4-19 shows that the increase in M_R on the treated samples is affected by the changes in moisture content. The figure shows the degradation in the treated subgrade stiffness after the twelve WD cycles, with resilient modulus values very close to those of the untreated specimens. However, there is still, on average, around a 20% gain in M_R for this type of soil after the WD process, compared to the untreated specimens without any WD cycles. Regarding Bloomington#1 (BM1) treated with LKD, as shown in Figure 4-20, a larger stiffness degradation is seen, and the values of the M_R after the WD cycles are even lower than those of the untreated samples, with final values around 30% below the untreated soil. For Bloomington#1 (BM1) mixed with cement, Figure 4-21 shows that the treated samples had a reduction of the stiffness of at least 50% (on average) below the untreated sample. As seen in Table 4-6, after the WD cycles, the stiffness degradation is bigger for samples mixed with cement than with LKD admixtures during the moisture changes.

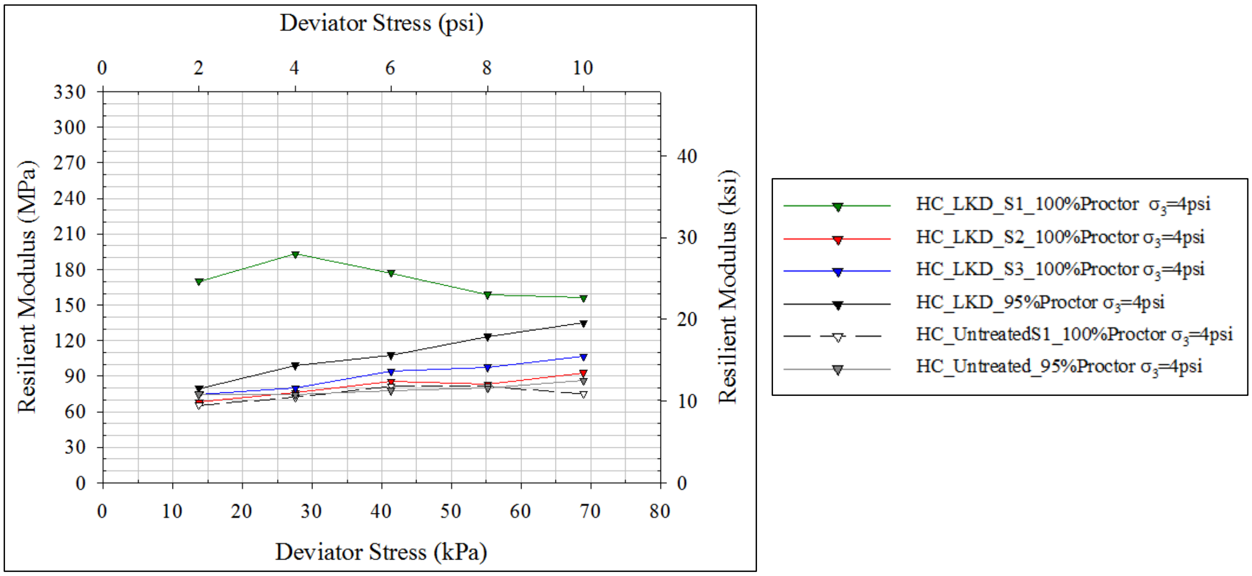


Figure 4-19. Resilient Modulus for HC Soil-optimum Treatment with LKD, After 12 Wetting/Drying Cycles

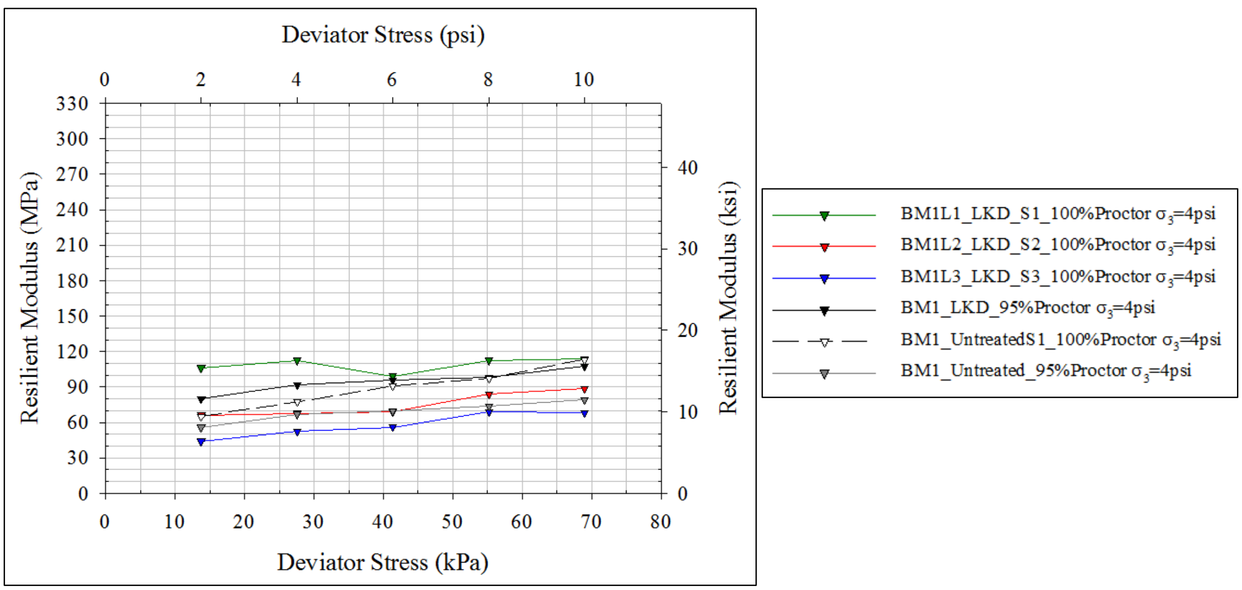


Figure 4-20. Resilient Modulus for BM1 Soil-Optimum Treatment with LKD, After 12 Wetting/Drying Cycles

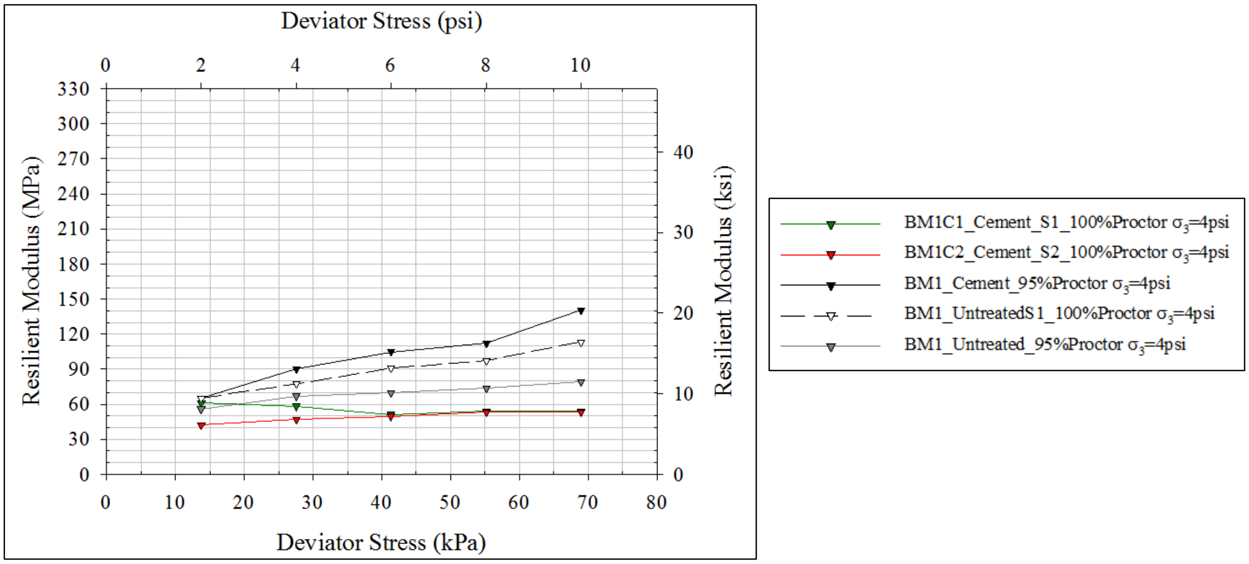


Figure 4-21. Resilient Modulus for BM1 Soil-optimum Treatment with Cement, After 12 Wetting/Drying Cycles

4.4 Overdosed Treatment with Quick Lime and Cement for Soils with High Plasticity (Bloomington#3, BM3) for Wetting and Drying

The lack of confinement of the samples during the tests is thought to cause damage in tension of the specimens, particularly during the drying cycles, as discussed previously in Section 4.2. This behavior is sensitive to plasticity and thus soils with high plasticity are affected the most. As shown in Figure 4-22, high plasticity clayey soils, BM2 and BM3, underwent significant cracking at the beginning of the WD cycles, which produced the collapse of the specimens. The figure shows a sample of Bloomington#3 (BM3) treated with the optimum amount of Quick Lime (QL), under the WD cycles, which failed during the drying stage in the 4th cycle. In an attempt to explore the effects of increasing the chemical treatment, one of the highly plastic soils, Bloomington#3 (BM3), was prepared with overdosed amount of chemical content. As defined by Sandoval et al., 2018, overdosing consisted in doubling the optimum amount of treatment found by following the INDOT Design Procedures for Soil Modification or Stabilization (2015). As shown in Table 3-1 in Chapter 3, BM3 soil has properties very similar to those of BM2. After the twelve WD cycles on the overdosed samples, eleven (11) M_R tests were conducted in the INDOT laboratory in West Lafayette, following the standard AASHTO T307-99, as listed in Table 4-5.

Figure 4-22. Collapse of a High Plasticity QL Treated Sample During Wetting/Drying Cycles

Table 4-5 Amount of M_R for Bloomington#3

Type of sample		Amount M_R
Bloomington#3 (100%_Proctor)	Untreated	3
	QL	3
	Cement	3
Bloomington#3 (95%_Proctor)	QL	2
Total		11

Table 4-6 shows M_R values for σ_3=4psi (27.6kPa) and σ_d=6, 8 and 10psi (41.4, 55.1, and 68.9kPa) for overdosed samples. The change in stiffness with respect to the untreated soil, compacted at 100% of the Standard Proctor, is also provided in Table 4-6 (a), while Table 4-6 (b) shows the change in stiffness with respect to the treated soil, compacted at 95% of the Standard Proctor without any WD cycle. Figures 4-23 and 4-24 show results of the M_R tests for samples of Bloomington#3 soil treated with overdosed QL and cement, respectively. For comparison purposes, M_R values for the intermediate confining stress are presented. In the figure, the black dashed line corresponds to the untreated samples compacted at 100% of the Standard Proctor, the black solid line corresponds to the treated sample compacted at 95% Proctor with no cycles, and the color lines represent the overdosed treated specimens (three for repeatability – green, red, and blue) compacted at 100% of the Standard Proctor, after the twelve WD cycles.

Figure 4-23 shows that the QL overdosed treated samples not only survived the WD cycles, but also showed an increase in the stiffness at the end of the WD process by 55%, on average, compared to the untreated soil compacted at 100% of the Standard Proctor. As seen in Figure 4-24, the soil stiffness of BM3 samples overdosed with cement was reduced below the value of the untreated sample by 20%, on average, i.e., overdosing with cement did not produce as good results as those obtained with overdosing with QL. However, this degradation is not as harsh as that observed in treated samples with cement for optimum amount of treatment. In the appendices, Figures C.18 to C.23 show the M_R tests results for overdosed BM3 soils and Table C. 1 lists the values.

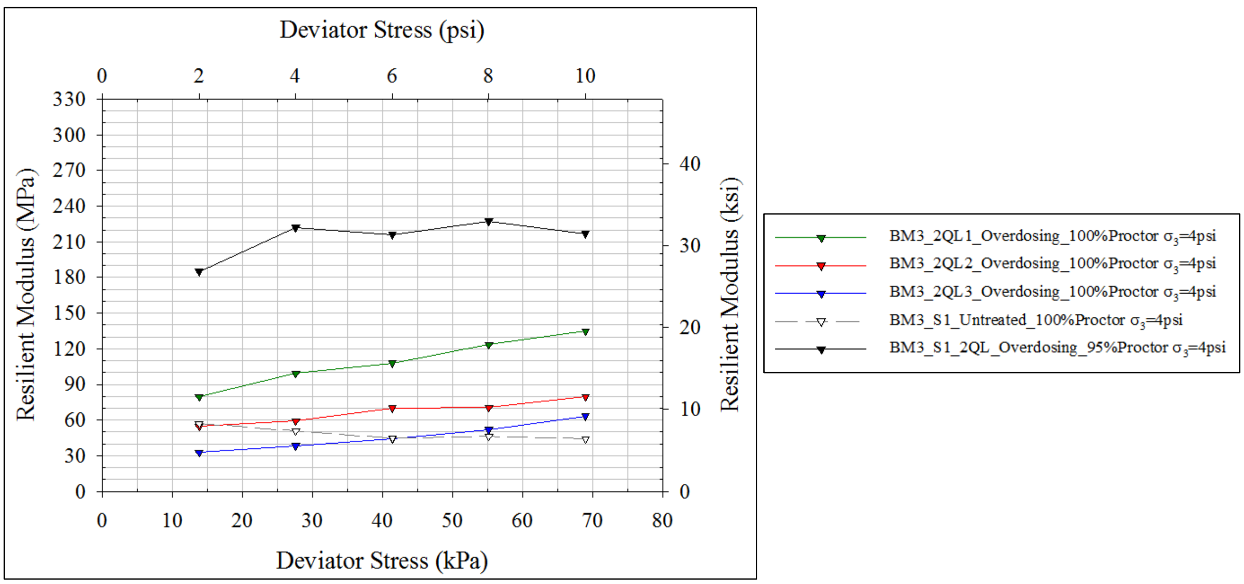


Figure 4-23. Resilient Modulus for BM3 Overdosed with QL, After 12 Wetting/Drying Cycles

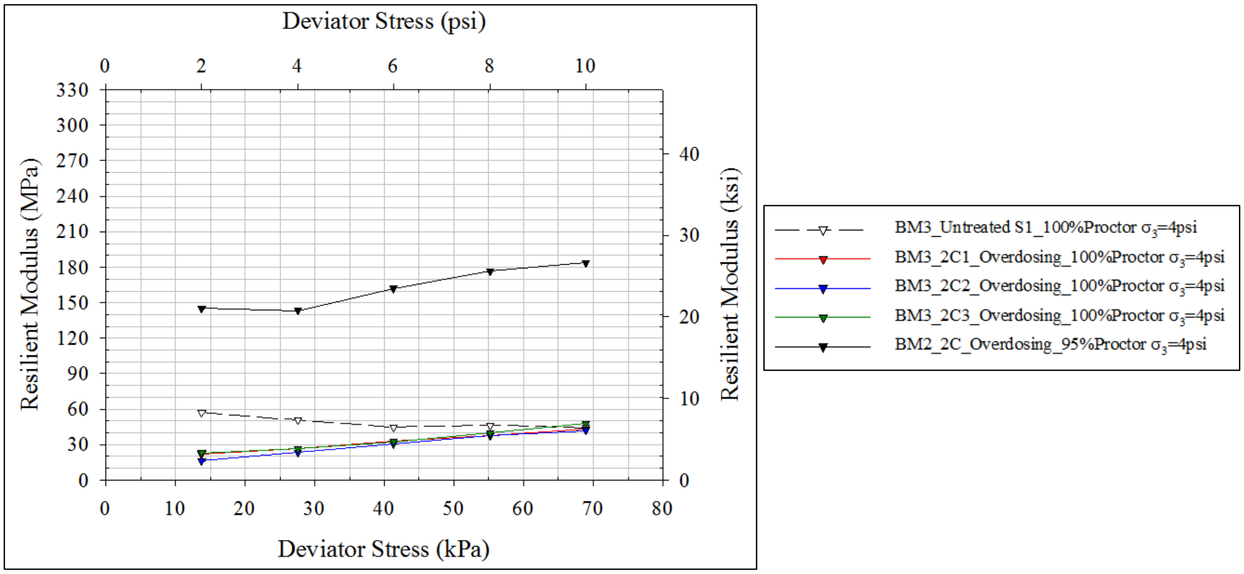


Figure 4-24. Resilient Modulus for BM3 Overdosed with Cement, After 12 Wetting/Drying Cycles

Table 4-6 (a) Comparison Between Resilient Modulus (M_R) for Untreated Soil and Treated Soils After WD Cycles, for Optimum and Overdosing Treatments

Site	Untreated			Optimum LKD						Optimum Cement					
	Deviatoric Stress, σ_d (psi)			Deviatoric Stress, σ_d (psi)						Deviatoric Stress, σ_d (psi)					
	6	8	10	6		8		10		6		8		10	
	Resilient Modulus, M_R (ksi)			Resilient Modulus After Cycles, MR (ksi)						Resilient Modulus After Cycles, MR (ksi)					
				M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)
BM1	13.17	14.09	16.42	10.01	-25	12.15	-14	12.86	-22	7.43	-44	7.85	-45	7.87	-53
				8.14	-39	9.97	-30	9.92	-40	7.20	-46	7.75	-46	7.71	-54
HC	11.83	11.78	10.86	12.37	5	12.04	3	13.47	25	---	---	---	---	---	---
				13.62	16	14.15	21	15.47	43	---	---	---	---	---	---

Site	Untreated			Double Quick Lime						Double Cement					
	Deviatoric Stress, σ_d (psi)			Deviatoric Stress, σ_d (psi)						Deviatoric Stress, σ_d (psi)					
	6	8	10	6		8		10		6		8		10	
	Resilient Modulus, M_R (ksi)			Resilient Modulus After Cycles, MR (ksi)						Resilient Modulus After Cycles, MR (ksi)					
				M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)
BM3	6.49	6.73	6.42	8.84	37	9.63	44	10.92	71	4.79	-27	5.44	-20	6.22	-4
				10.21	58	10.22	52	11.56	81	4.47	-32	5.50	-19	6.09	-6

(b) Comparison Between Resilient Modulus (M_R) for Treated Soil without Cycles and After WD Cycles, for Optimum and Overdosing Treatments

Site	Treated			Optimum LKD						Optimum Cement					
	Deviatoric Stress, σ_d (psi)			Deviatoric Stress, σ_d (psi)						Deviatoric Stress, σ_d (psi)					
	6	8	10	6		8		10		6		8		10	
	Resilient Modulus, M_R (ksi)			Resilient Modulus After Cycles, MR (ksi)						Resilient Modulus After Cycles, MR (ksi)					
				M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)
BM1	13.90	14.20	15.60	10.01	-29	12.15	-15	12.86	-18	7.43	-52	7.85	-52	7.87	-62
				8.14	-42	9.97	-30	9.92	-37	7.20	-53	7.75	-53	7.71	-63
HC	15.63	17.91	19.56	12.37	-21	12.04	-33	13.47	-32	---	---	---	---	---	---
				13.62	-13	14.15	-22	15.47	-21	---	---	---	---	---	---

Site	Treated			Double Quick Lime						Double Cement					
	Deviatoric Stress, σ_d (psi)			Deviatoric Stress, σ_d (psi)						Deviatoric Stress, σ_d (psi)					
	6	8	10	6		8		10		6		8		10	
	Resilient Modulus, M_R (ksi)			Resilient Modulus After Cycles, MR (ksi)						Resilient Modulus After Cycles, MR (ksi)					
				M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)
BM3	29.87	36.57	33.35	8.84	-71	9.63	-74	10.92	-68	4.79	-80	5.44	-79	6.22	-77
				10.21	-66	10.22	-73	11.56	-66	4.47	-81	5.50	-79	6.09	-78

5. EFFECT OF CHANGES IN TEMPERATURE ON RESILIENT MODULUS

The soils in Indiana are exposed not only to changes in moisture content but also to changes in temperature throughout the seasons. During the winter and spring seasons, the low temperatures may cause frozen-heave within the soils. Throughout freezing, ice-segregation, which is the formation of ice lenses, is produced and after thawing the soils become weak (Chamberlain, 1981). These cyclic temperature changes may degrade the stiffness of the natural and treated subgrades. To evaluate any detrimental effects that changes in temperature may have on the resilient modulus, M_R, of the treated subgrade, a laboratory testing campaign was performed. The soil used for all the tests was Bloomington#1 (BM1), which was mixed with Lime Kiln Dust (LKD) or Portland cement. The same types and amount of chemical treatment presented in Chapter 3 were considered. For Bloomington#1 (BM1) the optimum amount of cement used was 3% and for LKD it was 6%.

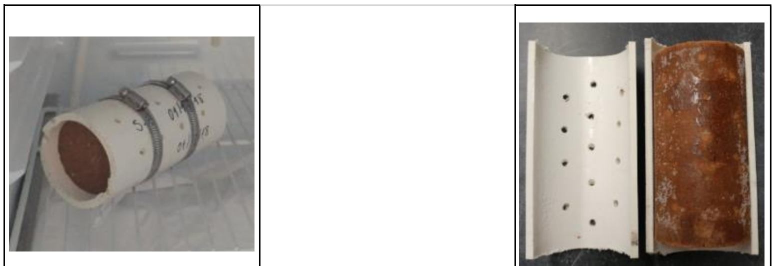
The M_R tests were conducted, following the standard AASHTO T307-99, at the INDOT facilities in Indianapolis, following the methodology described in Chapter 4.

5.1 Procedure Following the ASTM Standard D560/D560M-16

To evaluate the subgrade stiffness degradation due to temperature changes, freezing/thawing (FT) tests were first done following the American Society for Testing and Materials, ASTM, Standard D560/D560M-16, as shown in Figure 5-1. This standard is used to determine the resistance of compacted soil-cement treated specimens to repeated freezing and thawing cycles. Although no standard procedure has yet been developed for lime-soil mixtures (Dempsey and Thompson, 1971), the ASTM D560/560M-16 was used for both admixtures of LKD lime and cement. 3” diameter and 6” height remolded samples were compacted at 100% of the Standard Proctor.

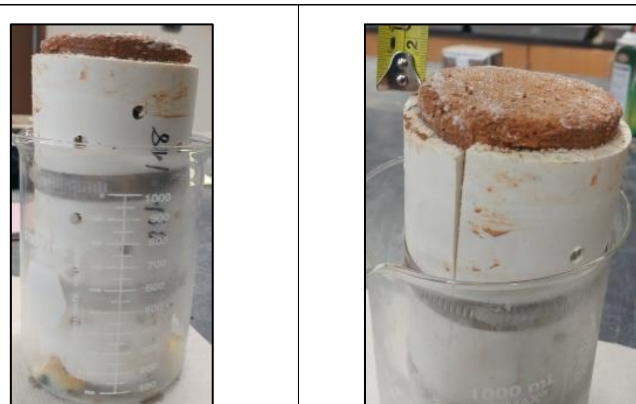
After compaction, the soil mixed with Lime Kiln Dust (LKD) or cement was cured in the moisture room for 7 days. Later, the samples were exposed to twelve freezing/thawing (FT) cycles. Each cycle consisted of placing the soil sample on a saturated pad inside the freezer at -9.5^{o}F (-23^{o}C) for 24 hours, and then inside the moisture room at 73.5^{o}F (23^{o}C) for 23 hours.

To simulate better the field conditions, the specimens were confined with a perforated PVC pipe, as shown in Figure 5-1. However, as shown in Figure 5-2 (a) and (b), by following strictly the Standard D560/D560M-16, the treated sample presented premature failure due to excessive deformations, around 20%, during the twelve FT cycles. It was also found by Woojin L.,1993 that after FT cycles, the samples changed their volume around 12 to 26%.



BM1+LKD FT cycles (ASTM D560/D560M)

Figure 5-1. BM1 Confined Samples Treated with LKD During Freezing and Thawing Cycles Following the Standard D560/D560M-16 - Optimum Amount of Treatment – 1st Cycle



(a) During FT cycles (b) After 12 FT cycles

Figure 5-2. BM1 LKD Lime Treated Sample Confined with a Drilled PVC Pipe, Under Twelve FT Cycles, Following the Standard ASTM D560/D560M-16 – 12th Cycle

To investigate the sample deformations after the FT cycles, when following the ASTM standard, finite elements analyses were performed. The software ABAQUS was used where a coupled temperature/displacement analysis, assuming a lineal-elastic material, was employed. Even though elasticity may be viewed as a very restrictive assumption, the analyses were conducted to have an estimate of the strains and stresses produced in the sample during the FT process (see Appendix D for further information). As shown in Figure 5-3, the maximum tensile stresses in the sample are about 8.7 and 36.2psi (60kPa and 250kPa), depending on the interface considered between the soil and the pipe, i.e. frictional (rollers) or fixed (pins), respectively. Value of the tensile strength of compacted clays vary with the authors; for example, Towner (1987) proposed a conservative value for the tensile strength of clays in the range of 4.4 to 43.5psi (30 to 300kPa), while Wang (2013), for specimens with dry density 1.65 g/cm^3 and moisture content 20%, suggested tensile stresses between 5psi and 5.8psi (35kPa and 40kPa). Also, Stirling (2015), for clayey soils subjected to climatic loading and water content around 20%, proposed values around 4.4psi (30kPa). A conservative value for the tensile strength of clays could be between 5.8 and 14.5 psi (40 and 100kPa). Consequently, the tensile stresses obtained with the numerical model are large enough to overcome the soil strength, especially when confinement may induce friction/tensile stresses at the perimeter of the specimen. As a result, it was decided to perform the FT laboratory tests on unconfined samples.

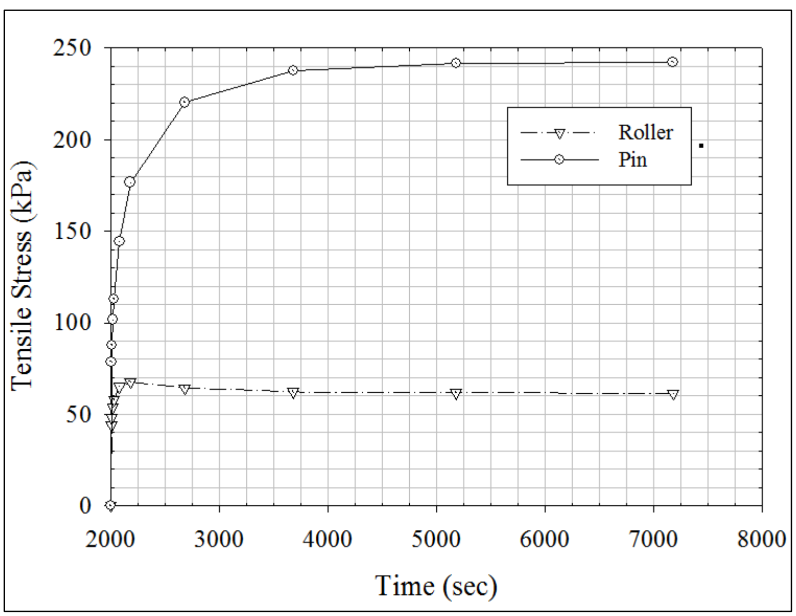
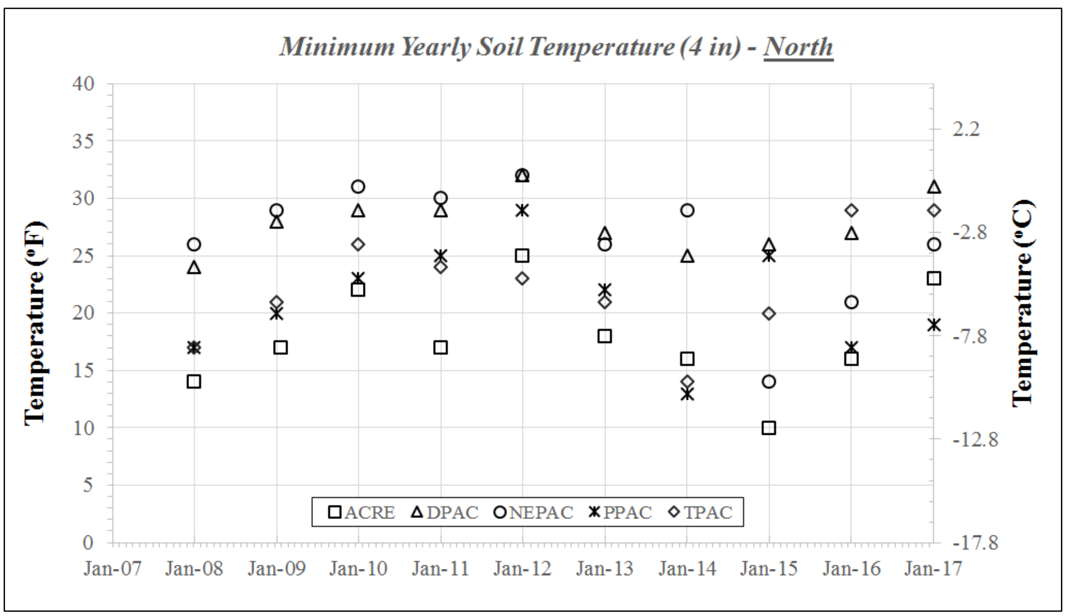


Figure 5-3. Results of FEM. Tensile Stresses in the Specimen Following the ASTM Standard

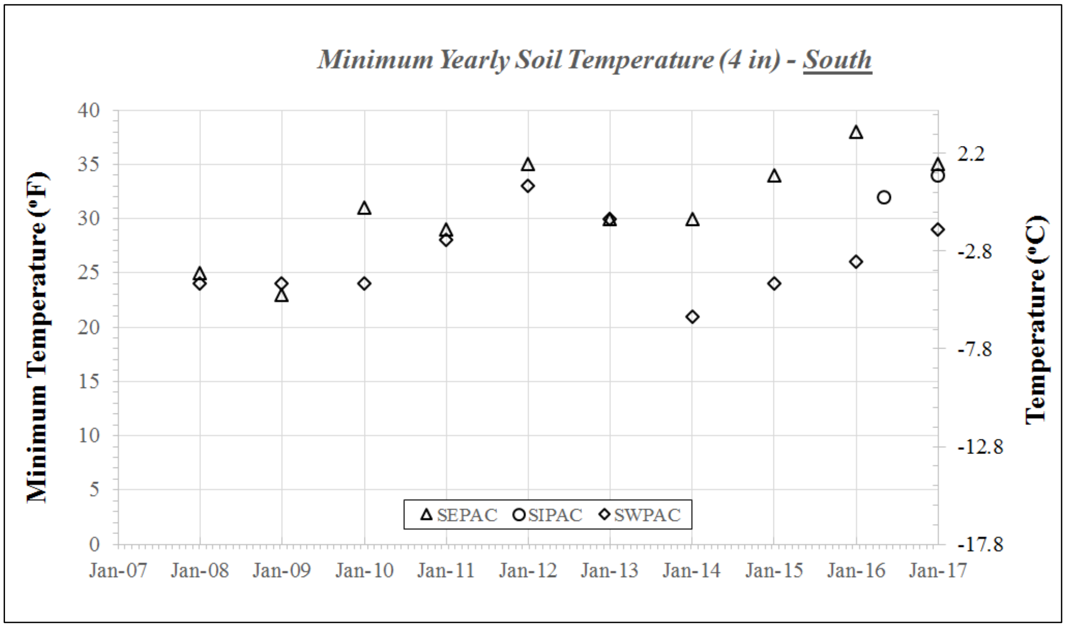
5.2 Modified Protocol Test for Freezing and Thawing

The subgrade's temperatures in Indiana are not as extreme as those in the ASTM D560/D560M-16 standard. Figure 4-5, in the previous chapter, shows the location of the eight climatic stations around the State, where there are records of daily temperature readings, at different depths, for the last ten years. Figures 5-4 and 5-5 plot the minimum yearly soil temperatures at 4 inches depth for the North and South of the State, respectively (see Appendix C for additional information). The figures show that in northern Indiana, the minimum soil temperature ranges from 14°F (-10°C) to 32°F (0°C), while in southern Indiana, between 21°F (-6°C) and 38°F (3°C). The subgrade is located around 12 inches depth, so the existing data was used to estimate the minimum temperature at that depth, with the lowest values around the State, as shown in Figure 5-6. The minimum subgrade temperature at 12 inches depth is around 28.4°F (-2°C). Notice that the minimum temperature is seen in the North of the State, and as shown in Figure 5-5, it is 14°F (-10°C). This extreme temperature was used for the tests as a conservative value with a cooling rate around 1°C/hr and duration of freezing of 24 hours.



Data from iClimate

Figure 5-4. Minimum Yearly Soil Temperature at 4 inches Depth (10 years readings) – North



Data from iClimate

Figure 5-5. Minimum Yearly Soil Temperature at 4 inches Depth (10 years readings) – South

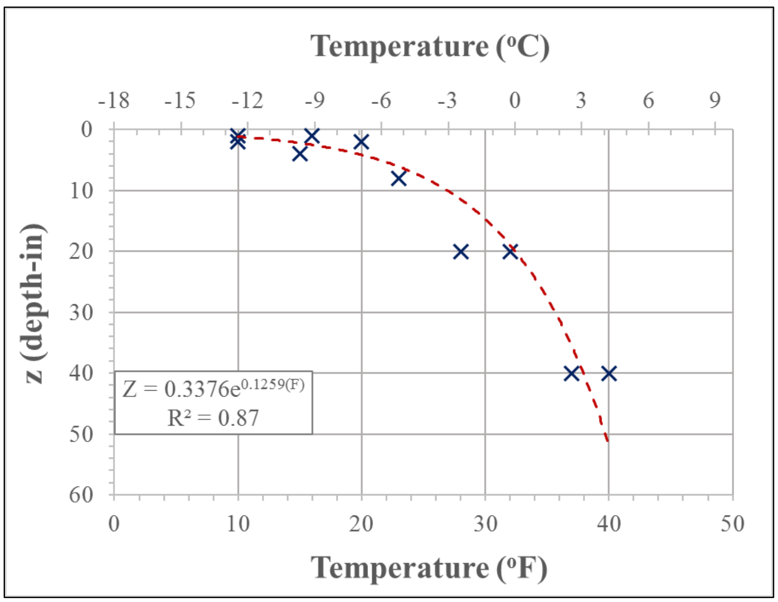


Figure 5-6. Minimum Soil Temperature at Different Depths

These findings were discussed with the Study Advisory Committee (SAC) on September 2018, when the following protocol was adopted: for the freezing stage, place the specimens with no confinement in the freezer for twenty-four hours at 14ºF (-10ºC); afterwards, place the samples in the moisture room at 73ºF (23ºC) for twenty-four hours, for the thawing period. All the samples are subjected to twelve freezing/thawing cycles, which requires about one month. Figures 5-7 and

5-8 show the stages of freezing and thawing for a Bloomington#1 (BM1) specimen treated with optimum amount of treatment with LKD and cement, respectively.

		
1st cycle_Thawing	2nd cycle_Freezing	10th cycle_Thawing
BM1+LKD 1st FT cycle (Adjusted protocol)		

Figure 5-7. Bloomington#1 Sample Treated with LKD During FT Cycles Following the Modified Protocol - Optimum Amount of Treatment

		
8th cycle_Freezing		11th cycle_Freezing
BM1+Cement FT cycles (Adjusted protocol)		

Figure 5-8. Bloomington#1 Sample Treated with Cement During FT Cycles Following the Modified Protocol - Optimum Amount of Treatment

5.3 Results of Resilient Modulus Tests for the Optimum Amount of Treatment for Freezing and Thawing

Freezing and thawing cycles were performed using Bloomington#1 (BM1) soil mixed with LKD lime and cement. Afterwards, M_R tests were conducted following the standard AASHTO T307-99 for Type 2 Material, i.e., fine-grained soils. Two tests were run at the INDOT laboratory in Indianapolis, given that the device in West Lafayette was not operational at the time.

All the results can be found in Appendix D, where Table D. 1 lists all the values obtained from the M_R tests, and Figures D.4 to D.9 are plots of all the M_R test results. For comparison purposes, only results of M_R tests for σ_3 = 4psi (27.6kPa) are shown and discussed below.

Figures 5-9 and 5-10 show the M_R test results for BM1 mixed with LKD and cement, respectively. For comparison purposes, the figures include values of untreated and treated samples with and without FT cycles. The gray and black solid lines represent the untreated and LKD treated specimens compacted at 95% of the Standard Proctor, without any FT cycles, respectively. The black dashed line corresponds to the untreated sample compacted at 100% of the Standard Proctor. The blue line in Figure 5-9 and the red line in Figure 5-10 correspond to the LKD and cement treated specimens, respectively, compacted at 100% of the Standard Proctor, after twelve FT cycles. As mentioned previously, the increase in the stiffness of the treated samples with respect to the untreated (without any FT cycles) is evident. However, after twelve freezing/thawing (FT) cycles, the stiffness of the treated sample is greatly diminished. For Bloomington#1 (BM1) soil treated with LKD (Figure 5-9), the resilient modulus decreases down to values very close to those of the untreated specimens compacted at 100% of the Standard Proctor. Mixtures with cement (Figure 5-10) exhibit a slightly larger degradation of stiffness after the twelve FT cycles, but still with values close to the untreated sample. Similar to what was found for samples submitted to WD cycles, the admixtures with LKD display larger M_R after the FT cycles than cement-treated samples. Table 5-1 shows M_R values for σ_3=4psi (27.6kPa) and σ_d=6, 8 and 10psi (41.4, 55.1, and 68.9kPa). The change in stiffness with respect to the untreated soil, compacted at 100% of the Standard Proctor, is also provided in Table 5-1 (a), while Table 5-1 (b) shows the change in stiffness with respect to the treated soil, compacted at 95% of the Standard Proctor without any FT cycle.

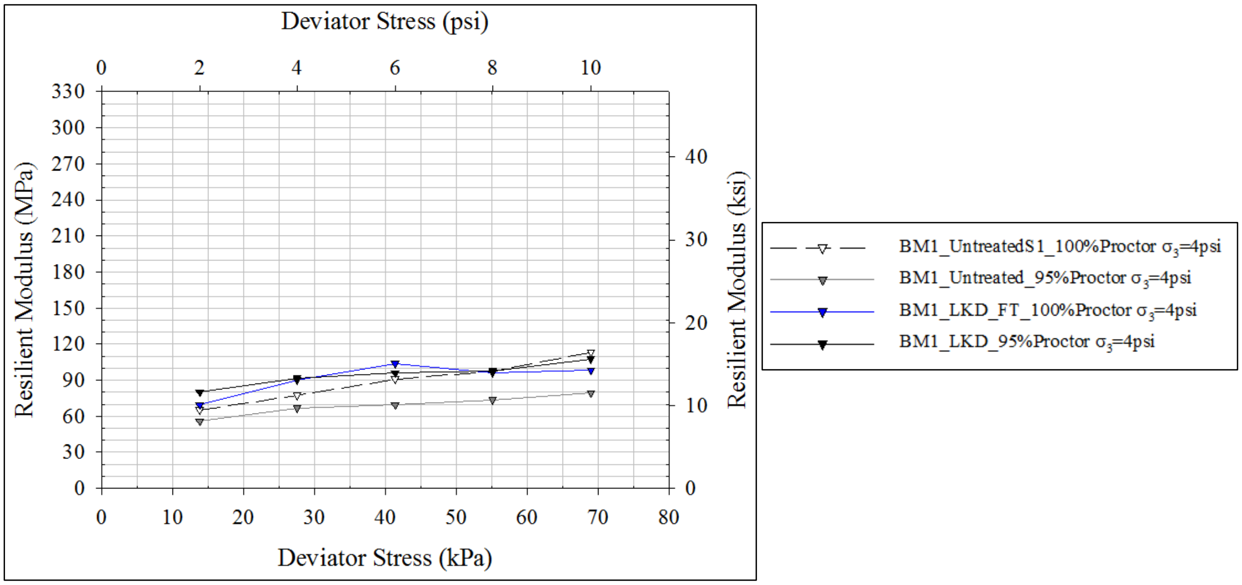


Figure 5-9. Resilient Modulus for BM1 Soil-Optimum Treatment with LKD, After 12 Freezing/Thawing Cycles

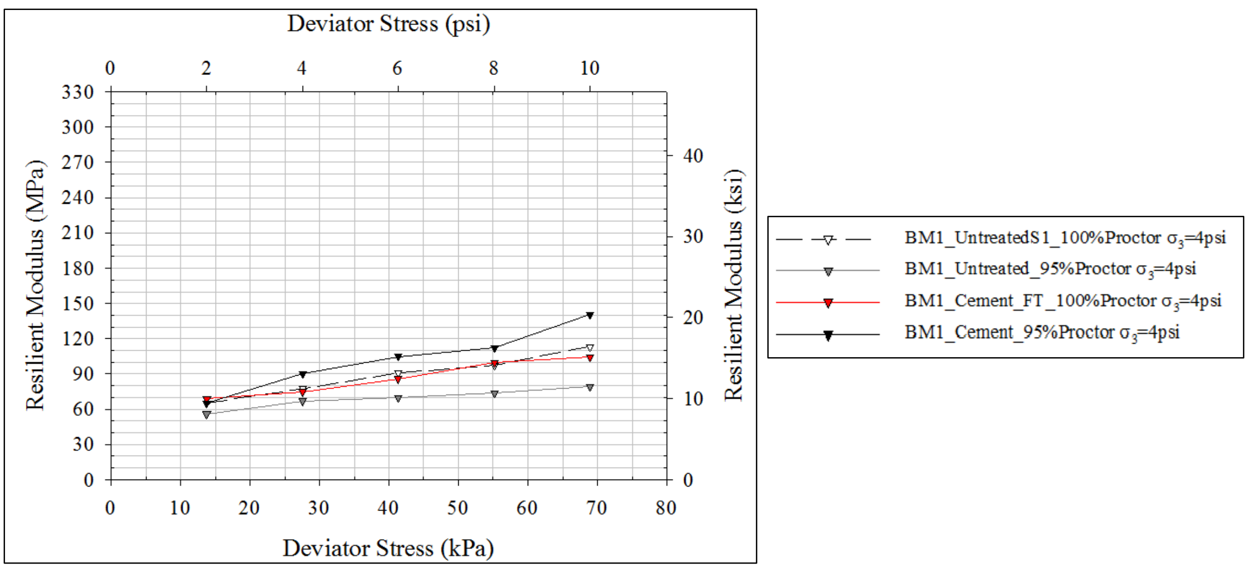


Figure 5-10. Resilient Modulus for BM1 Soil-Optimum Treatment with Cement, After 12 Freezing/Thawing Cycles

Table 5-1 (a) Comparison Between Resilient Modulus (M_R) For Untreated Soil and Treated Soils After FT cycles, for Optimum Treatment

Site	Untreated			Optimum LKD						Optimum Cement					
	Deviatoric Stress, σ_d (psi)			Deviatoric Stress, σ_d (psi)						Deviatoric Stress, σ_d (psi)					
	6	8	10	6		8		10		6		8		10	
	Resilient Modulus, M_R (ksi)			Resilient Modulus After Cycles, MR (ksi)						Resilient Modulus After Cycles, MR (ksi)					
				M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)
BM1	90.82	97.14	113.22	15.04	15	13.96	-1	14.26	-14	12.44	-6	14.41	3	15.11	-8

(b) Comparison Between Resilient Modulus (M_R) For Treated Soil without Cycles and After FT cycles, for Optimum Treatment

Site	Treated			Optimum LKD						Optimum Cement					
	Deviatoric Stress, σ_d (psi)			Deviatoric Stress, σ_d (psi)						Deviatoric Stress, σ_d (psi)					
	6	8	10	6		8		10		6		8		10	
	Resilient Modulus, M_R (ksi)			Resilient Modulus After Cycles, MR (ksi)						Resilient Modulus After Cycles, MR (ksi)					
				M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)	M_R	Ch. (%)
BM1	13.90	14.20	15.60	15.04	9	13.96	-2	14.26	-9	12.44	-19	14.41	-12	15.11	-26

6. CONCLUSIONS

In pavement structures supported by low bearing capacity soils such as A-6 and A-7-6, it is common practice in Indiana to mix the natural soil used for the subgrade with a chemical agent (e.g., LKD, QL or PC) to improve its engineering properties. While the chemical treatment usually improves the mechanical properties of the soil, climatic factors should be considered, since moisture and temperature changes may cause a significant effect on the subgrade stiffness. To accurately forecast pavement performance, it is important to assess the wetting/drying, WD, and freezing/thawing, FT, effects that the subgrade soils will experience during their service life.

An experimental program was conducted to evaluate the subgrade stiffness of A-6 and A-7-6 treated soils. The program included resilient modulus tests of samples compacted in the laboratory at 100% of the Standard Proctor. The A-6 soil was obtained from Hartford City (HC) in Blackford County, while the A-7-6 soils were collected from Bloomington (BM1, BM2, BM3) in Monroe County. The experimental program included a total of 26 resilient modulus, M_R, tests conducted after twelve WD and FT cycles. Optimum and double of the optimum amount (overdosing) of treatment were used for the samples subjected to WD cycles, while FT cycles were applied only to the specimens compacted at optimum amount of treatment. For the soils investigated, the optimum amount of treatment used was between 5% and 6% for LKD and between 3% and 5% for cement. For overdosing purposes, the amount of treatment was doubled.

Although the treated soils presented an increase of stiffness and overdosing produced a larger increase in M_R, with respect to that of the untreated soil (Sandoval et al., 2018), the effect of moisture and temperature changes on the M_R was quite detrimental. From the laboratory results, the following conclusions were made:

1. Following strictly the standard ASTM D559/D559M-15 for wetting and drying (WD) cycles, at the optimum treatment, the treated specimens failed during the wetting stage in the first three to five cycles. A test protocol was proposed for the wetting and drying process: place the specimens in the moisture room for two days with water coming from the bottom (without immersion); afterwards, two days at room temperature (without

placing the samples into the oven). The samples were subjected to twelve wetting-drying cycles. After that, thirteen (13) M_R tests were conducted. The WD cycles resulted in a significant decrease of the resilient modulus of the treated soils, down to values similar to those of the untreated soils. Soil specimens (eleven) overdosed with quick lime, after the twelve WD cycles, had an increase of the stiffness of 55%, on average, while those overdosed with cement had a reduction of stiffness down to about 20% below the untreated soil. The repeated action of WD cycles degrades the stiffness of the treated soil.

2. Following strictly the Standard D560/D560M-16, to determine the resistance of compacted treated specimens, subjected to repeated freezing and thawing, FT, cycles, treated soil specimens presented premature failure due to excessive deformations. The following protocol was adopted: the specimens were placed in the freezer for twenty-four hours at 14°F (-10°C); afterwards, the samples were placed in the moisture room at 73°F (23°C) for twenty-four hours. The samples were subjected to twelve freezing/thawing cycles and then, M_R tests were conducted. The FT tests resulted in a reduction of the stiffness of the treated soils to values similar or smaller than those of the untreated soils, with slightly larger reductions with cement treatment. In accordance with Dempsey and Thompson (1971), more realistic and rational FT durability testing procedures should be developed for stabilized subgrades. Statistical analysis of climatic data should be considered to determine the actual seasonal characteristics of the site. Also, the actual field conditions that include type of soil and admixture, confinement, type of compaction, density and moisture content must be studied.

The research shows that chemical treatment of clayey subgrade soils improves the engineering behavior of the soils. When the treated soils were subjected to cycles of wetting and drying (WD) or to cycles of freezing and thawing (FT), the gain in stiffness achieved with the chemical treatment was lost. While the benefits with the treatment are consistent, the reduction found with the WD and FT cycles, are not. Field observations have shown that the treatment and the improved soil properties remain even after years of construction (Jung et al., 2009). The reasons for this unexpected behavior are unclear but may be due to the lack of confinement of the specimens or to differences between laboratory and field tests. Further research is needed to understand this issue. What the research has clearly shown are the benefits of overdosing. Overdosing improves the resilient modulus of the soil, even under the harsh conditions in the laboratory during the cycles of WD (FT tests on overdosed specimens were not conducted, but it is expected to have similar benefits as those mentioned for WD). Clearly, overdosing carries an increase of cost of construction and calls for more stringent field monitoring to make sure that the quality and uniformity of the treatment are as expected. However, these costs may be easily offset with a much longer life of the treatment. What is recommended is an implementation of this research. A section of a new pavement construction could be built with overdosing and its performance monitored to determine its benefits, both during the short and long term.

APPENDIX A. EXPERIMENTAL PROGRAM

The tests conducted are listed in Table A. 1.

Table A. 1 Experimental Program for All the Soils and Treatments

<table>
<tr><th rowspan="2">Soil</th><th rowspan="2">Condition</th><th colspan="2">Resilient Modulus</th></tr>
<tr><th>FT Cycles</th><th>WD Cycles</th></tr>
<tr><td rowspan="3">Hartford City (A-6)</td><td>Untreated</td><td colspan="2">X</td></tr>
<tr><td>Soil + LKD</td><td></td><td>X</td></tr>
<tr><td>Soil + Cement</td><td></td><td></td></tr>
<tr><td rowspan="3">Bloomington # 1 (A-7-6)</td><td>Untreated</td><td colspan="2">X</td></tr>
<tr><td>Soil + LKD</td><td>X</td><td>X</td></tr>
<tr><td>Soil + Cement</td><td>X</td><td>X</td></tr>
<tr><td rowspan="3">Bloomington # 2 (A-7-6)</td><td>Untreated</td><td></td><td></td></tr>
<tr><td>Soil + LKD</td><td></td><td></td></tr>
<tr><td>Soil + Cement</td><td></td><td></td></tr>
<tr><td rowspan="3">Bloomington # 3 (A-7-6)</td><td>Untreated</td><td colspan="2">X</td></tr>
<tr><td>Soil + QL</td><td></td><td>X[-]</td></tr>
<tr><td>Soil + Cement</td><td></td><td>X[-]</td></tr>
<tr><td colspan="4">[-]: Overdosing</td></tr>
<tr><td colspan="4">WD & FT Cycles: 100% of the Standard Proctor</td></tr>
</table>

APPENDIX B. CHEMICAL TREATMENT

Figure B. 1 to Figure B. 3 show the compaction curves for untreated and treated soils, for HC, BM1, and BM2, respectively.

Figure B. 4 to B. 6 show results of the unconfined compression strength tests with the optimum amount of treatment for HC, BM1, and BM2 soils, respectively. Figure B. 7 shows results of mixtures of BM2 + cement that did not reach the strength requirements.

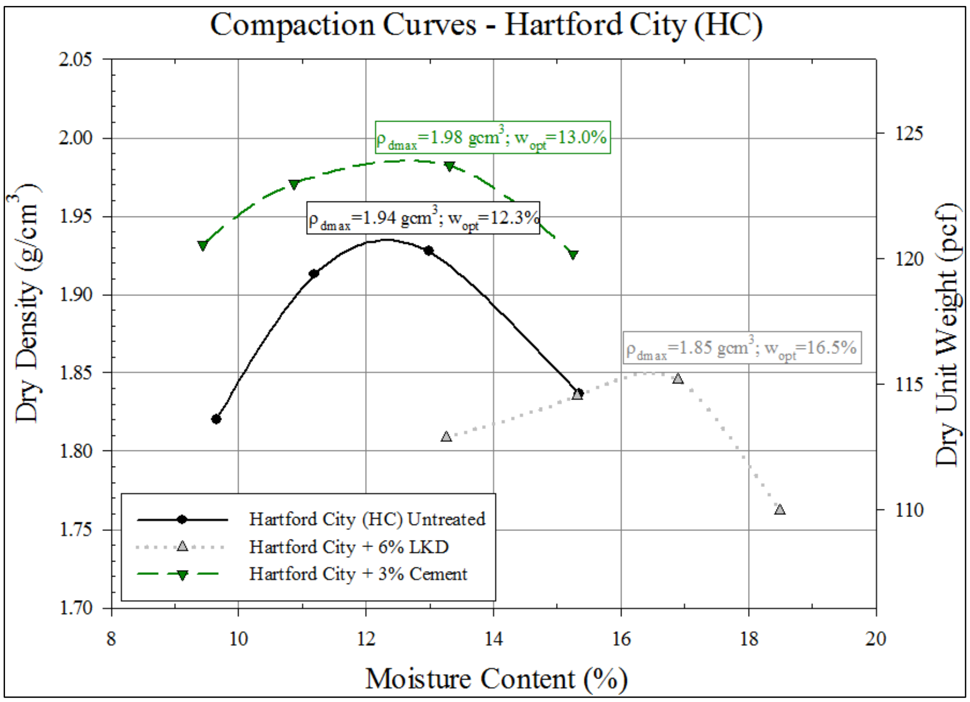


Figure B. 1. Compaction Curves for Untreated Soil and Soil with Optimum Amount of Treatment. Hartford City (HC), A-6 Soil

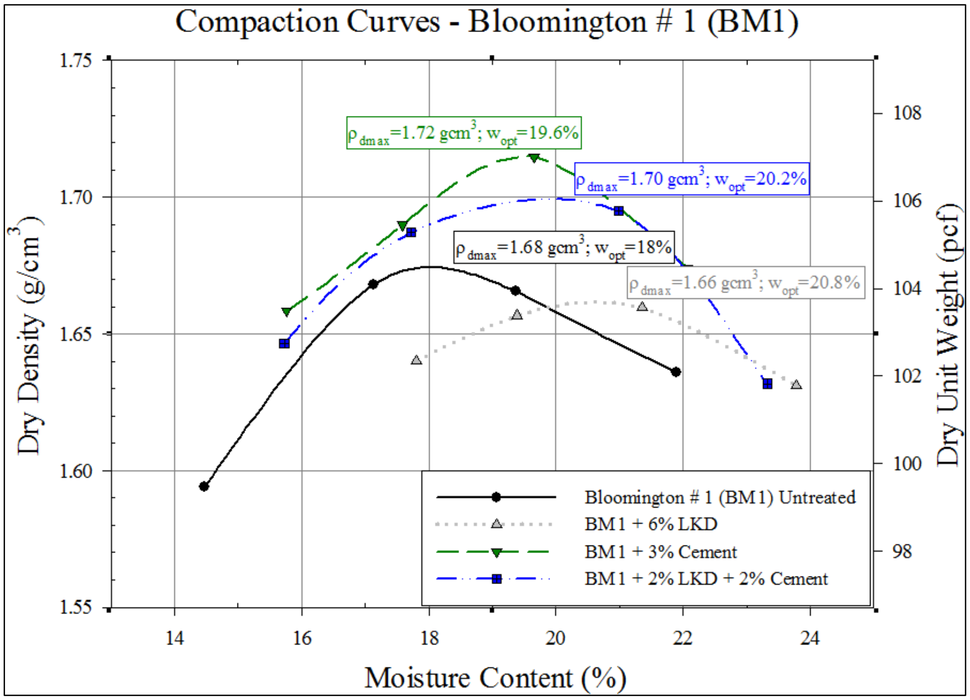


Figure B. 2. Compaction Curves for Untreated Soil and Soil with Optimum Amount of Treatment. Bloomington #1 (BM1), A-7-6 Soil

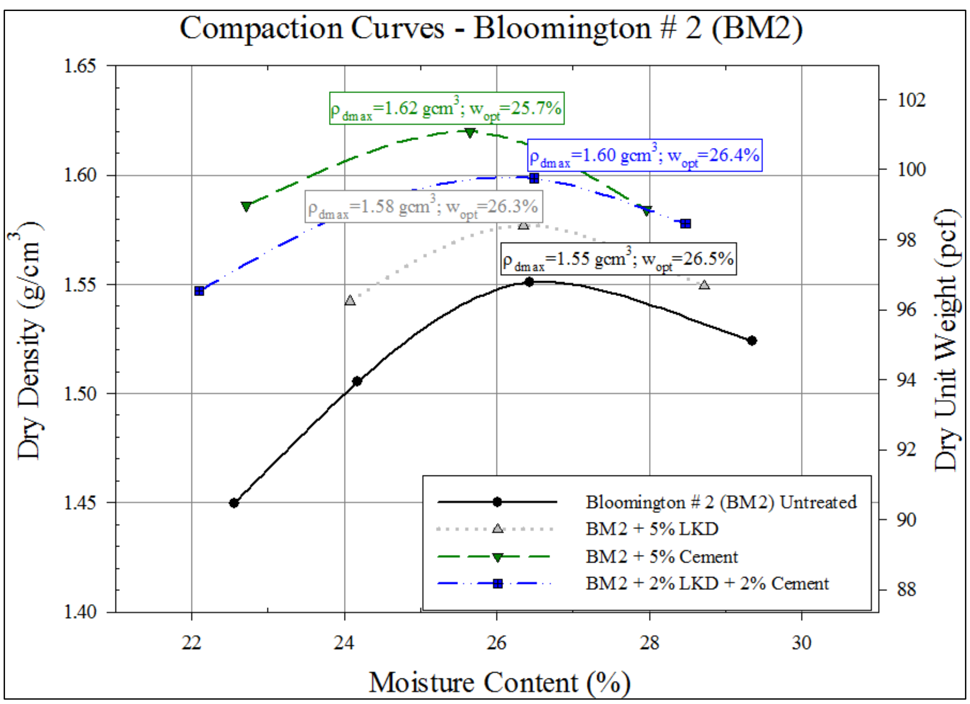


Figure B. 3. Compaction Curves for Untreated Soil and Soil with Optimum Amount of Treatment. Bloomington #2 (BM2), A-7-6 Soil

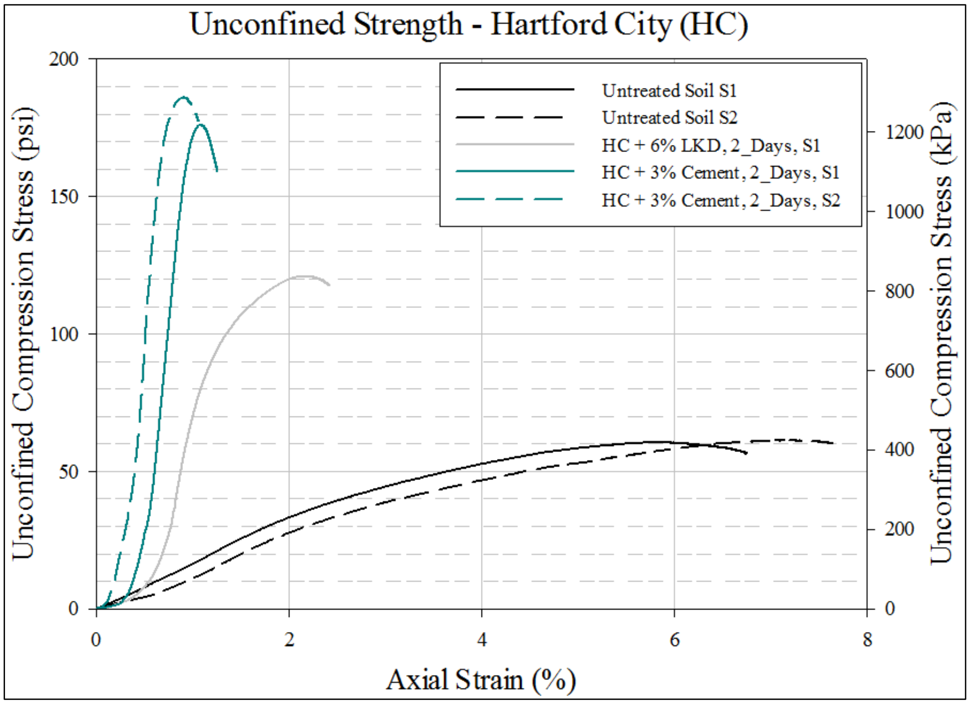


Figure B. 4. Unconfined Compression Strength for Untreated Soil and Soil with Optimum Amount of Treatment After 48 Hours Curing. Hartford City (HC)

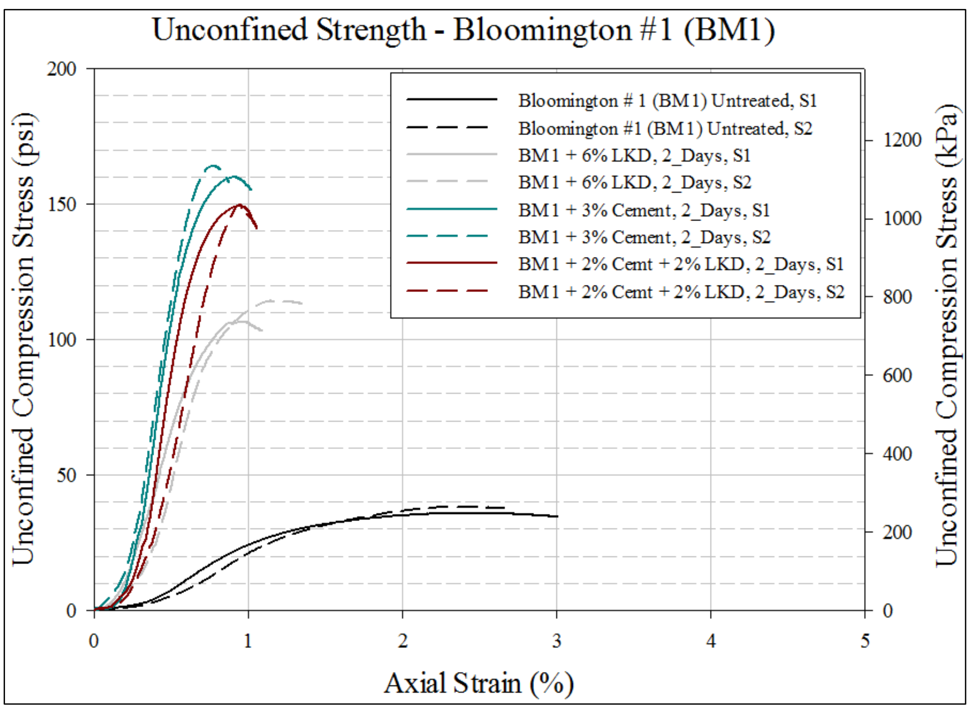


Figure B. 5. Unconfined Compression Strength for Untreated Soil and Soil with Optimum Amount of Treatment After 48-hours Curing. Bloomington #1 (BM1)

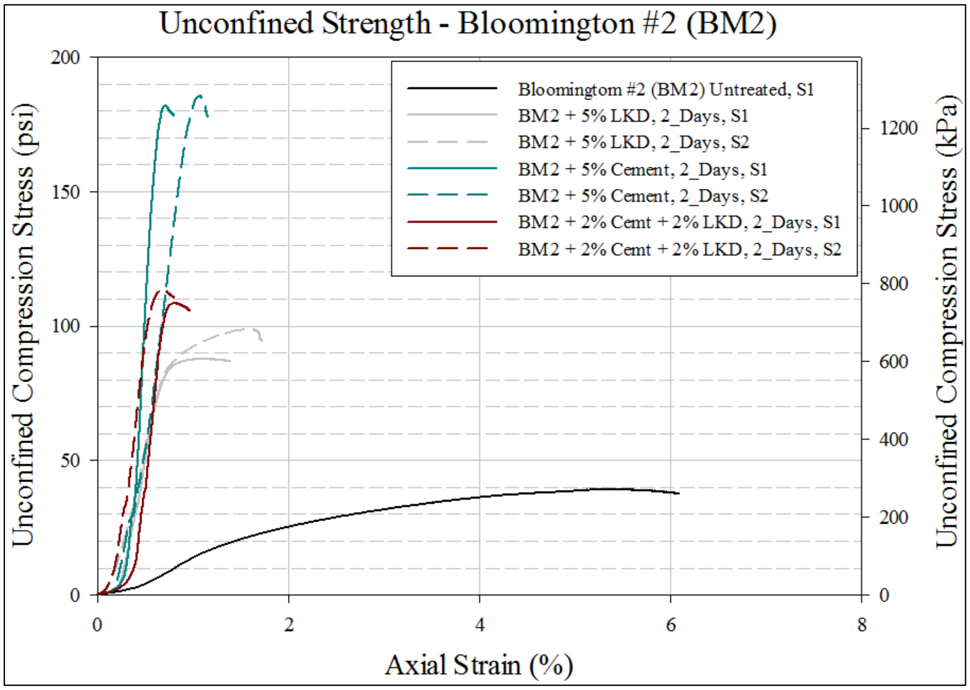


Figure B. 6. Unconfined Compression Strength for Untreated Soil and Soil with Optimum Amount of Treatment After 48-hours Curing. Bloomington #2 (BM2)

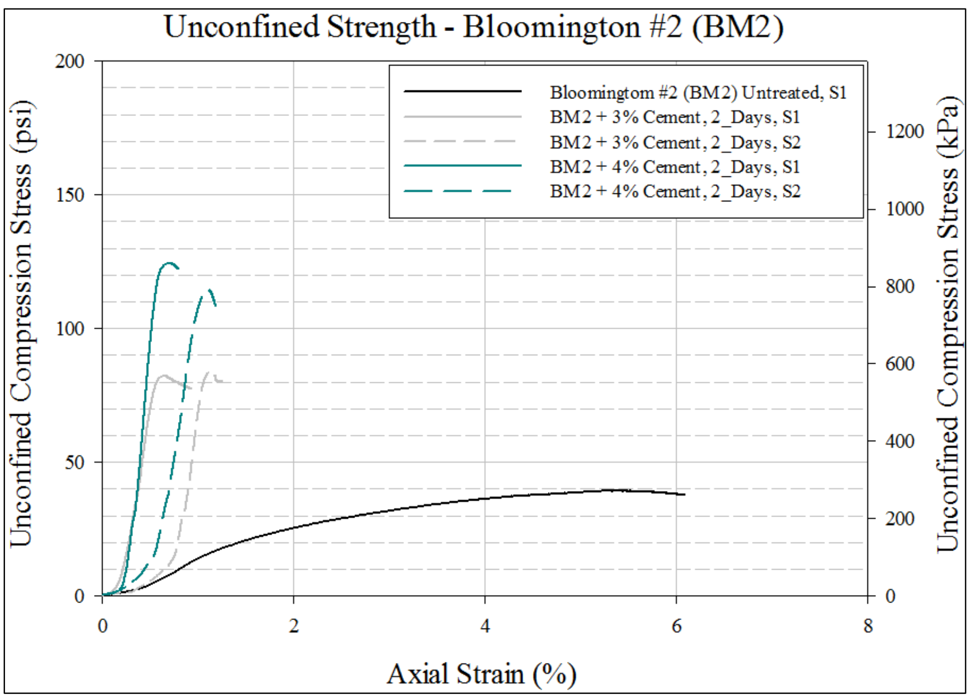


Figure B. 7. Unconfined Compression Strength for Untreated Soil and Soil with Amount of Cement Smaller than Optimum After 48-hours Curing. Bloomington #2 (BM2)

APPENDIX C. RESILIENT MODULUS AFFECTED BY CHANGES IN MOISTURE CONTENT

Figure C. 1 to Figure C. 8 present the daily extreme temperature readings for each station, during a 10-year period.

Results of the resilient modulus tests for specimens of HC LKD treated samples and BM1 specimens treated with LKD and cement are shown in Figure C. 9 to Figure C. 17. Results of the resilient modulus tests for BM3 soil treated with overdosed QL are shown in Figure C. 18 to Figure C. 20, and BM3 soil treated with overdosed cement are shown in Figure C. 21 to Figure C. 23.

Table C. 1 shows M_R values for all the soils and samples, i.e., untreated and treated with LKD, cement, or QL, for optimum and overdosed amount of treatment.

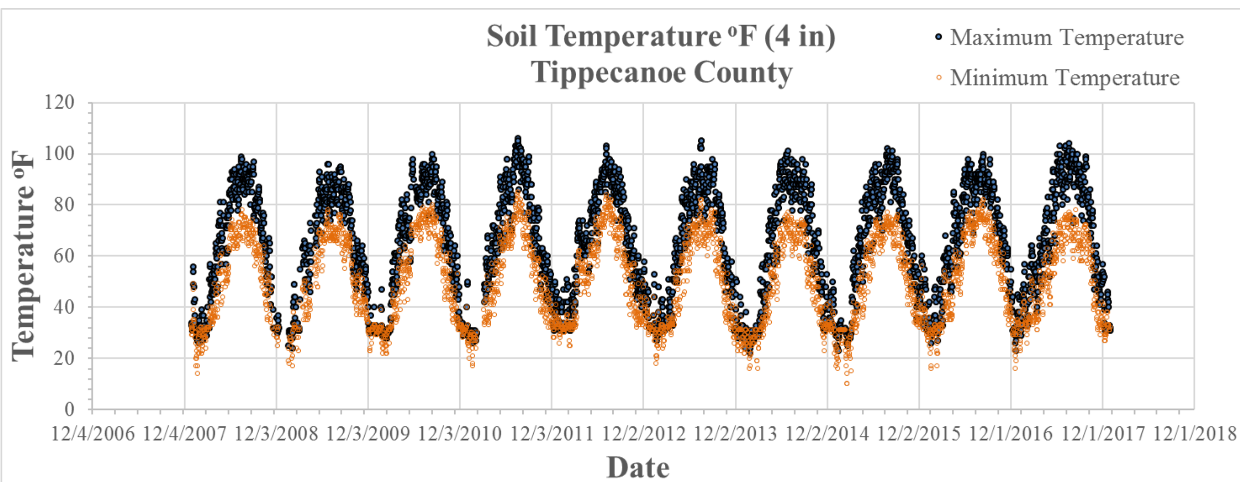


Figure C. 1. Daily Temperature Readings at 4” Depth ACRE (iClimate)

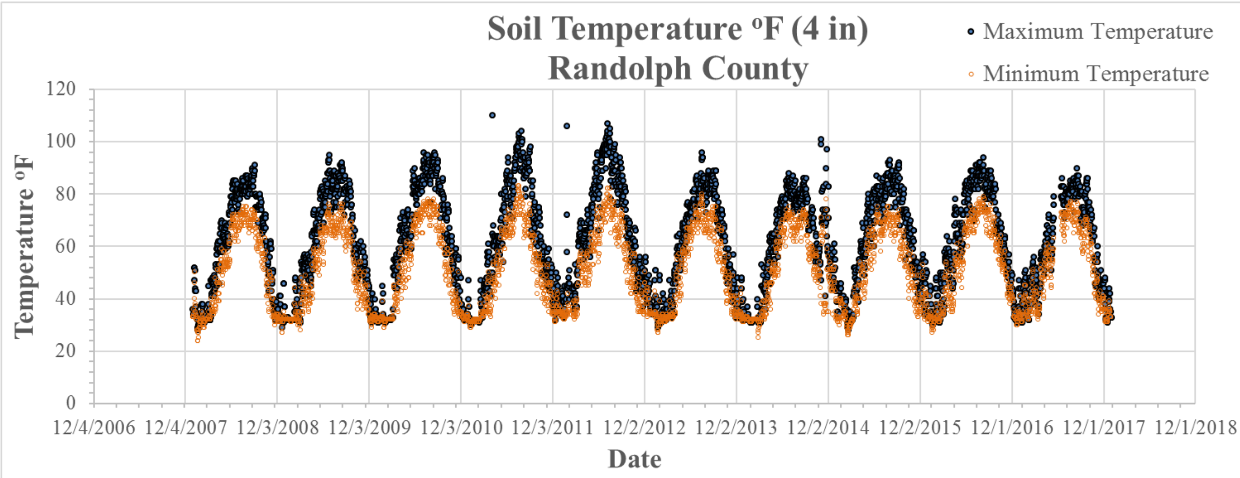


Figure C. 2. Daily Temperature Readings at 4" Depth DPAC (iClimate)

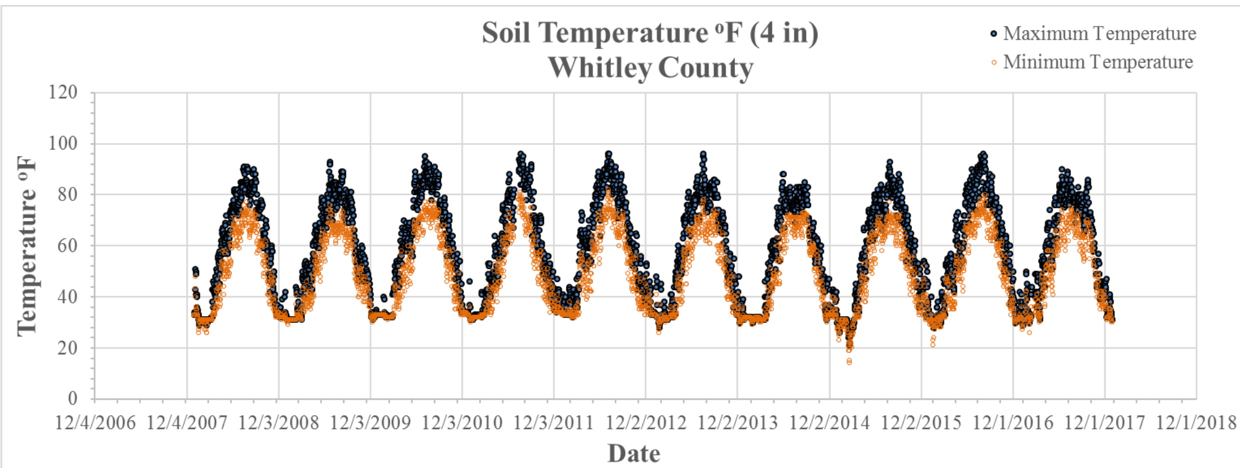


Figure C. 3. Daily Temperature Readings at 4" Depth NPAC (iClimate)

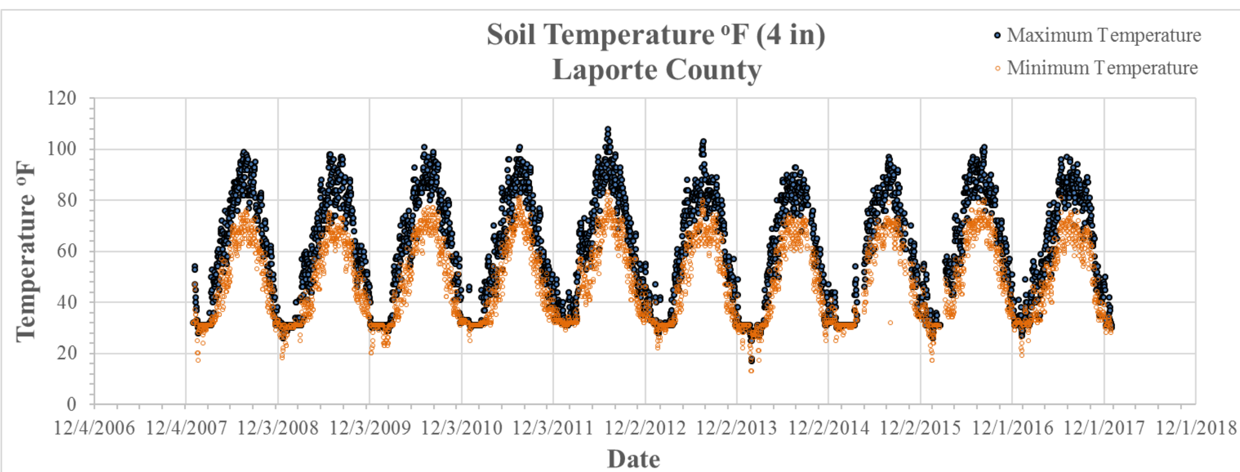


Figure C. 4. Daily Temperature Readings at 4" Depth PPAC (iClimate)

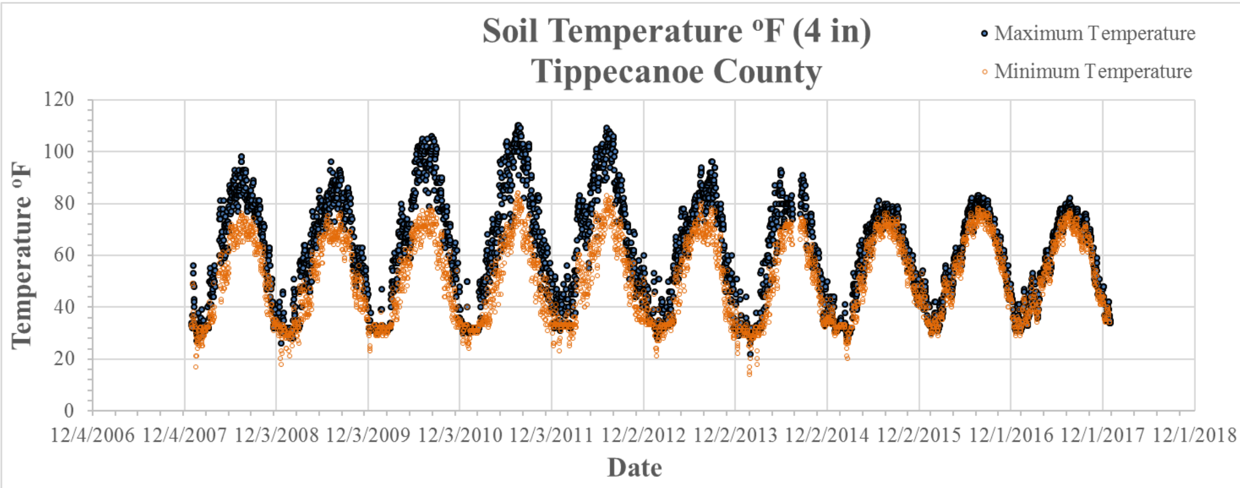


Figure C. 5. Daily Temperature Readings at 4" Depth TPAC (iClimate)

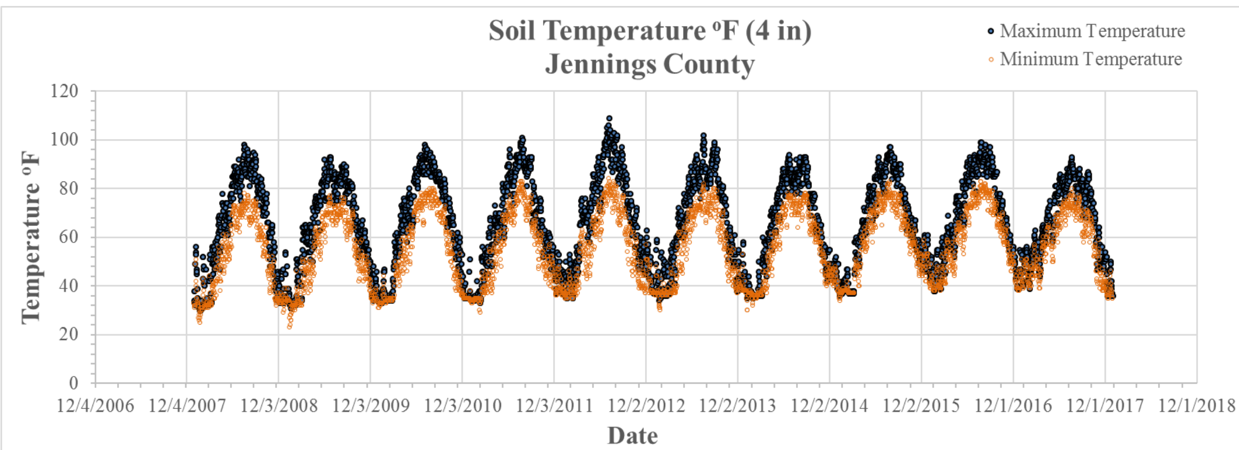


Figure C. 6. Daily Temperature Readings at 4" Depth SEPAC (iClimate)

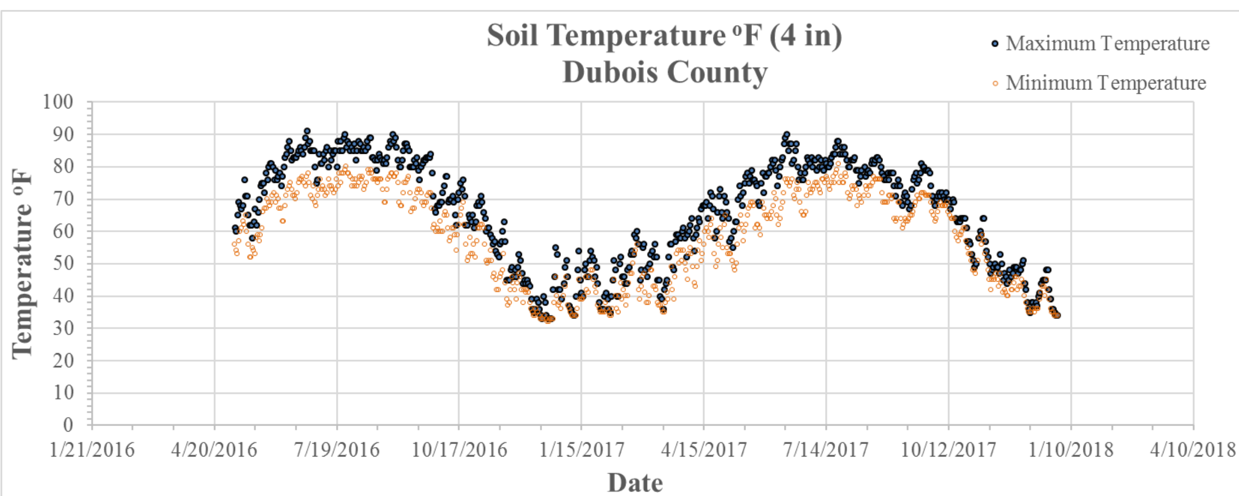


Figure C. 7. Daily Temperature Readings at 4" Depth SIPAC (iClimate)

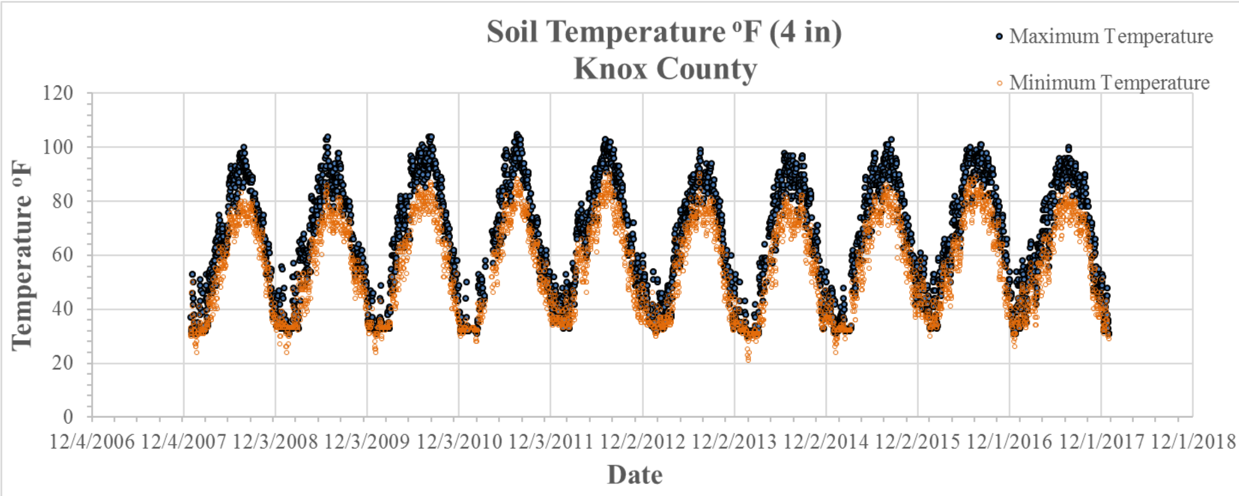


Figure C. 8. Daily Temperature Readings at 4” Depth SWPAC (iClimate)

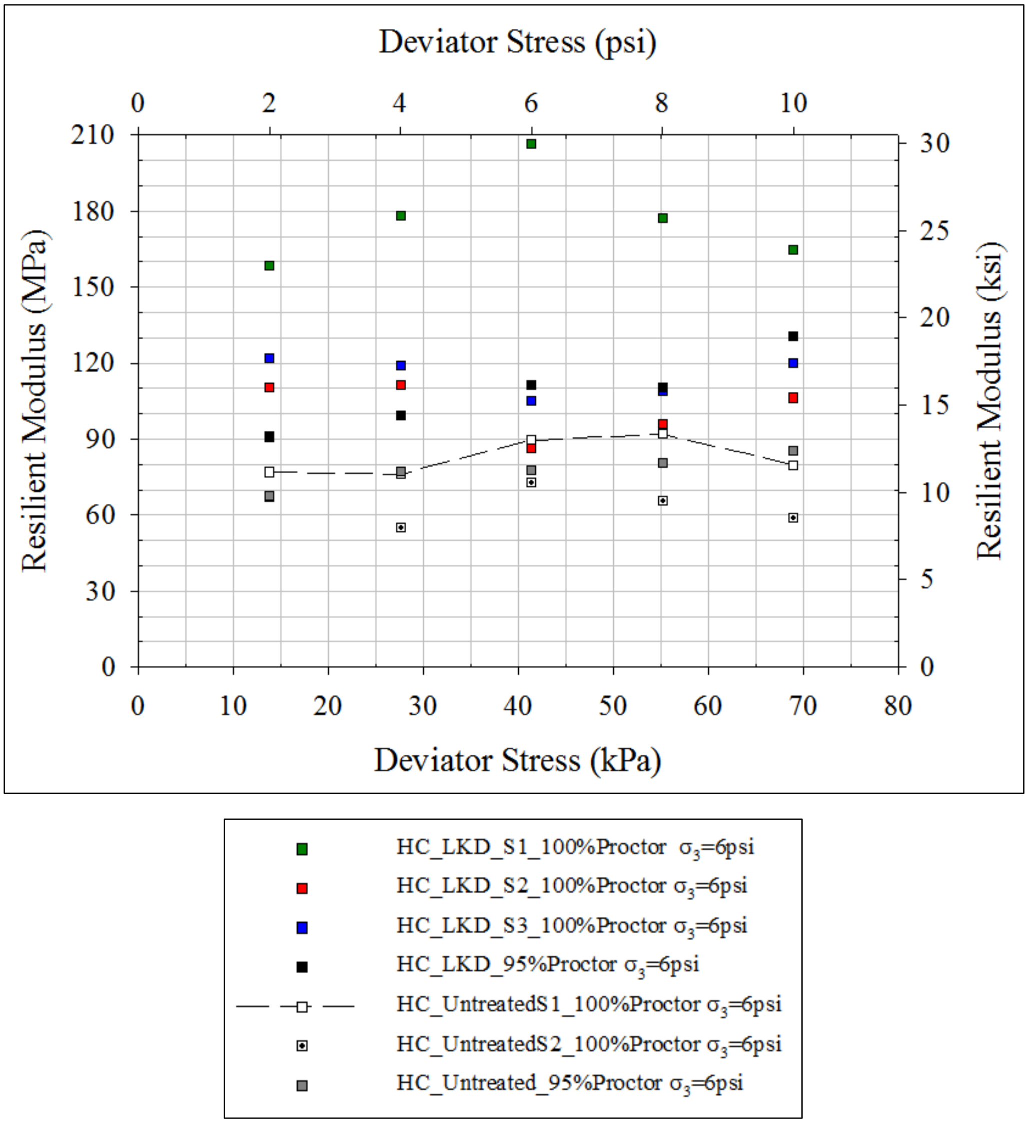


Figure C. 9. Resilient Modulus for Untreated Soil and Soil Treated with Optimum Amount of LKD, After Twelve Wetting-Drying Cycles. Confinement Stress 6 psi. Hartford City (HC)

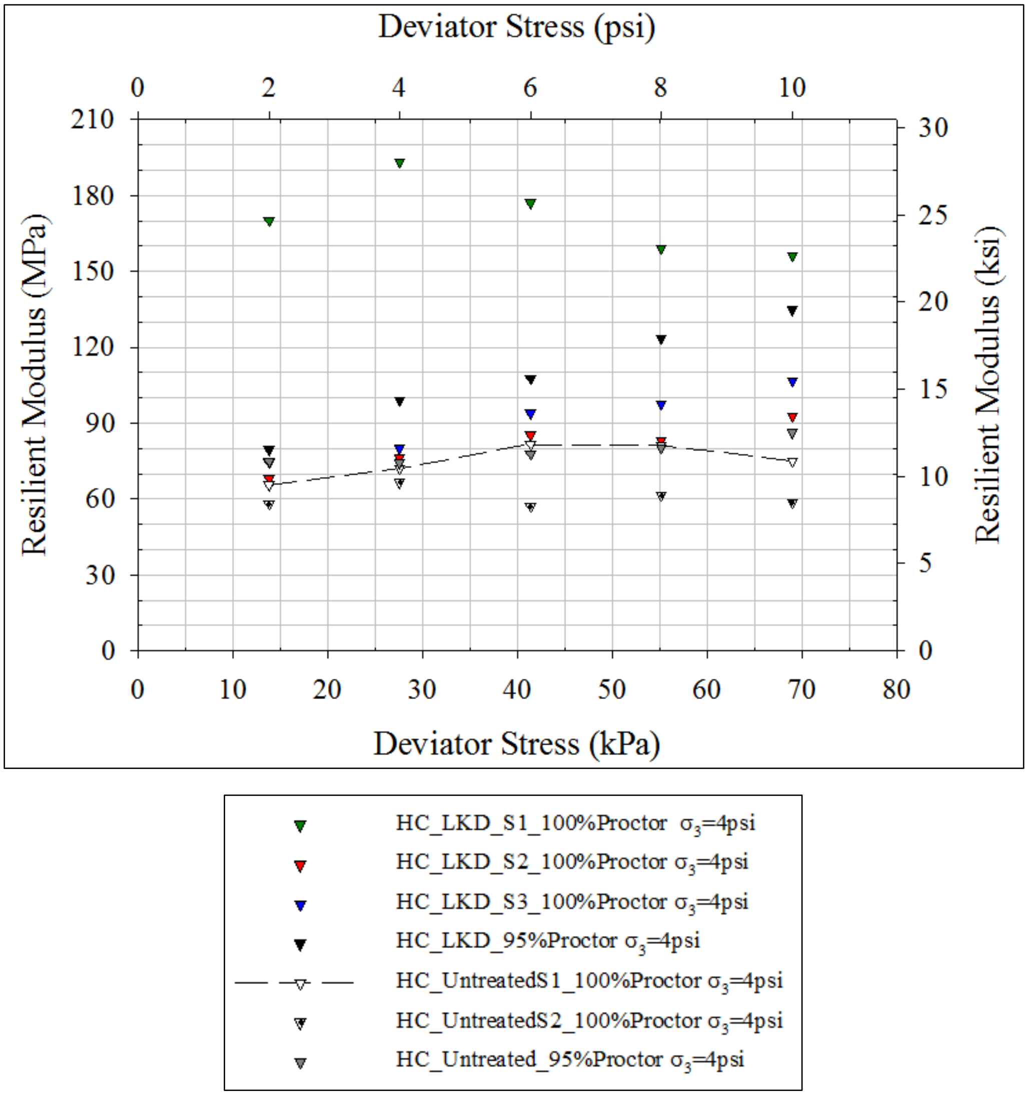


Figure C. 10. Resilient Modulus for Untreated Soil and Soil Treated with Optimum Amount of LKD, After Twelve Wetting-Drying Cycles. Confinement Stress 4 psi. Hartford City (HC)

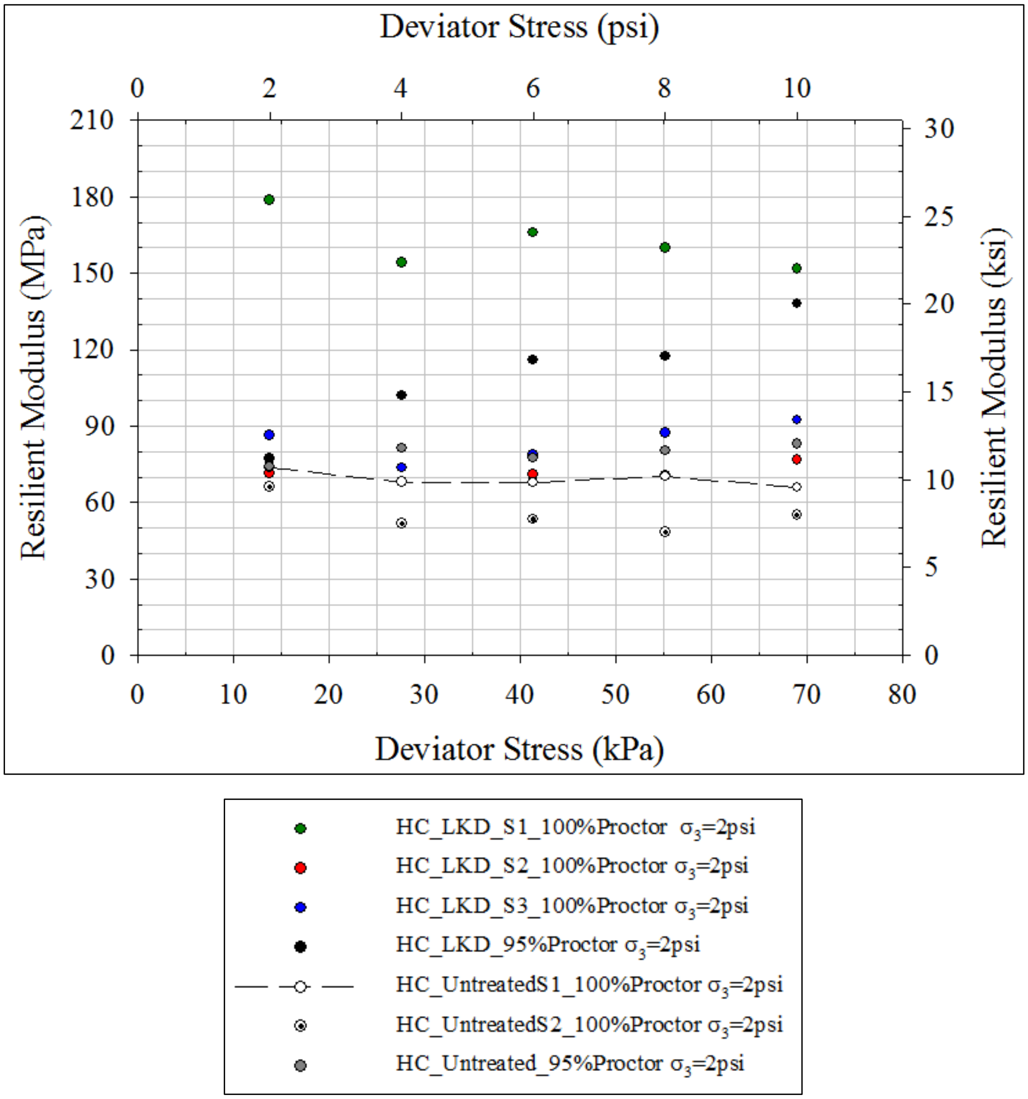


Figure C. 11. Resilient Modulus for Untreated Soil and Soil Treated with Optimum Amount of LKD, After Twelve Wetting-Drying Cycles. Confinement Stress 2 psi. Hartford City (HC)

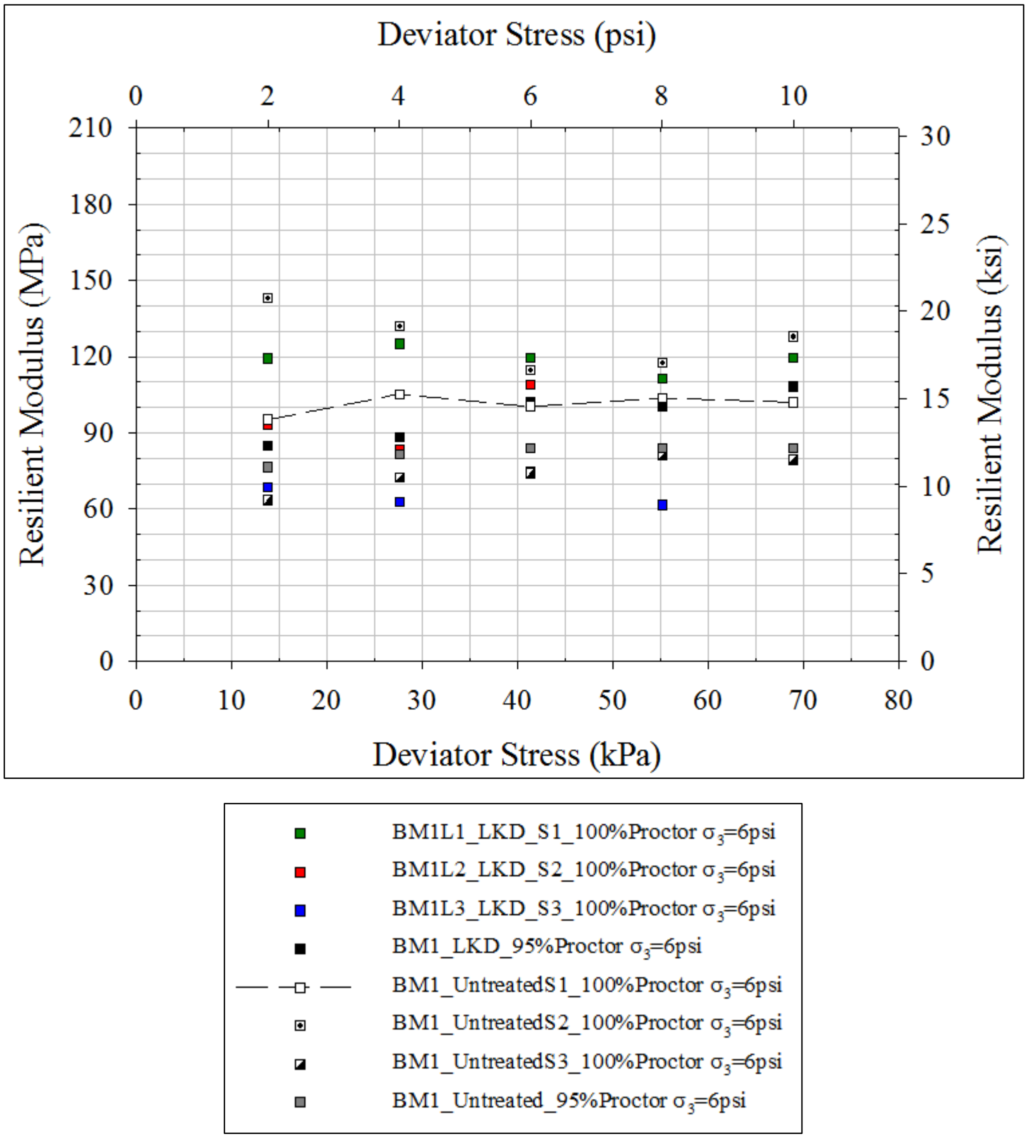


Figure C. 12. Resilient Modulus for Untreated Soil and Soil Treated with Optimum Amount of LKD, After Twelve Wetting-Drying Cycles. Confinement Stress 6 psi. Bloomington#1 (BM1)

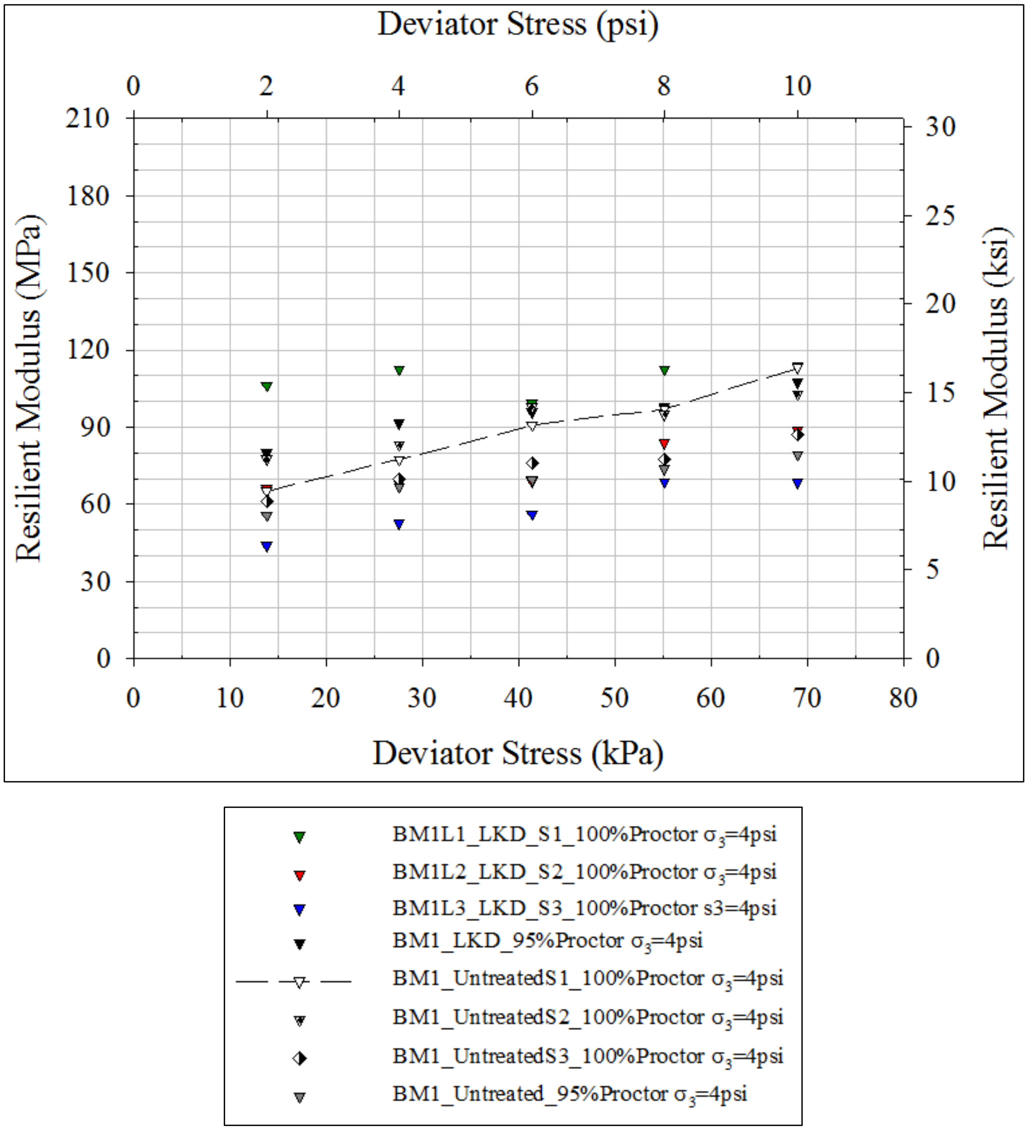


Figure C. 13. Resilient Modulus for Untreated Soil and Soil Treated with Optimum Amount of LKD, After Twelve Wetting-Drying Cycles. Confinement Stress 4 psi. Bloomington#1 (BM1)

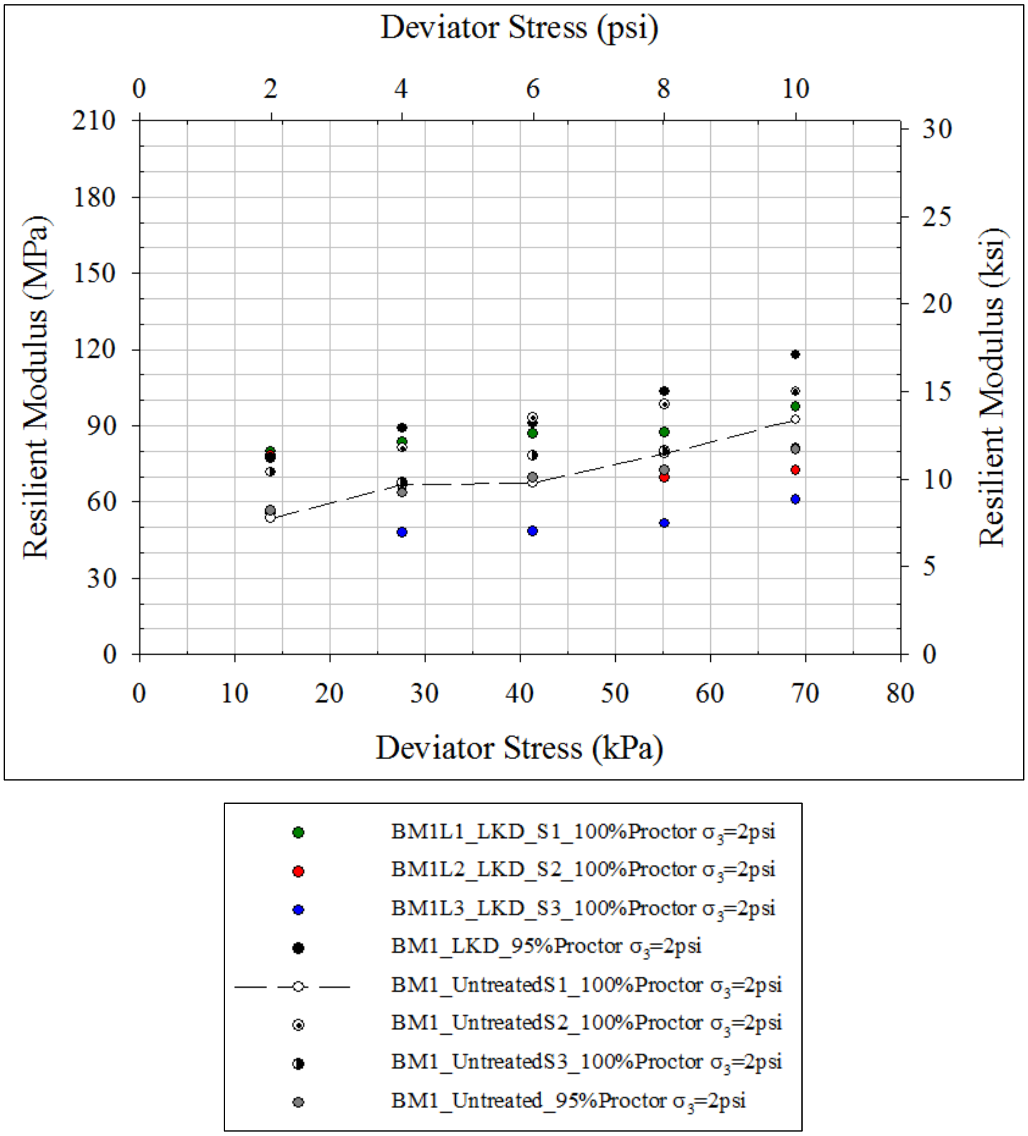


Figure C. 14. Resilient Modulus for Untreated Soil and Soil Treated with Optimum Amount of LKD, After Twelve Wetting-Drying Cycles. Confinement Stress 2 psi. Bloomington#1 (BM1)

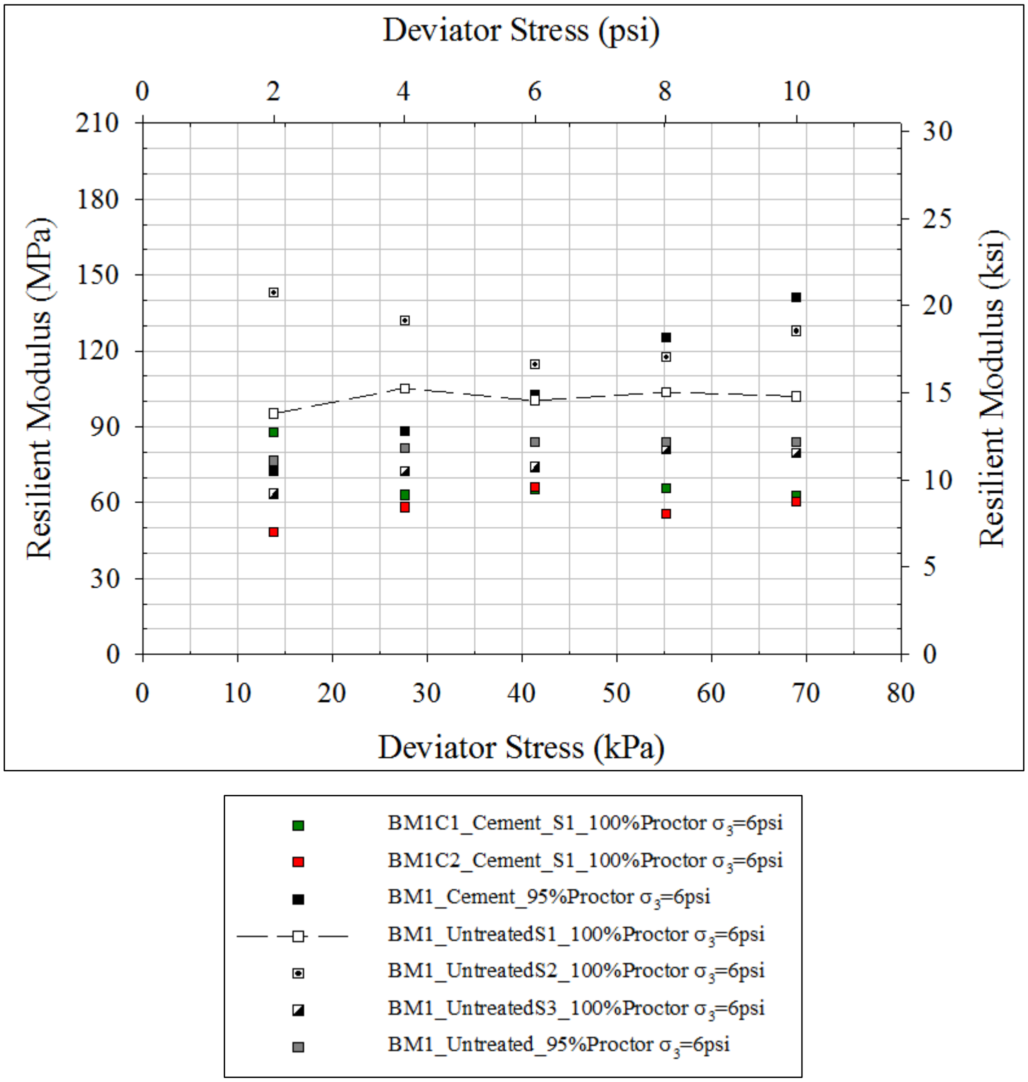


Figure C. 15. Resilient Modulus for Untreated Soil and Soil Treated with Optimum Amount of Cement, After Twelve Wetting-Drying Cycles. Confinement Stress 6 psi. Bloomington#1 (BM1)

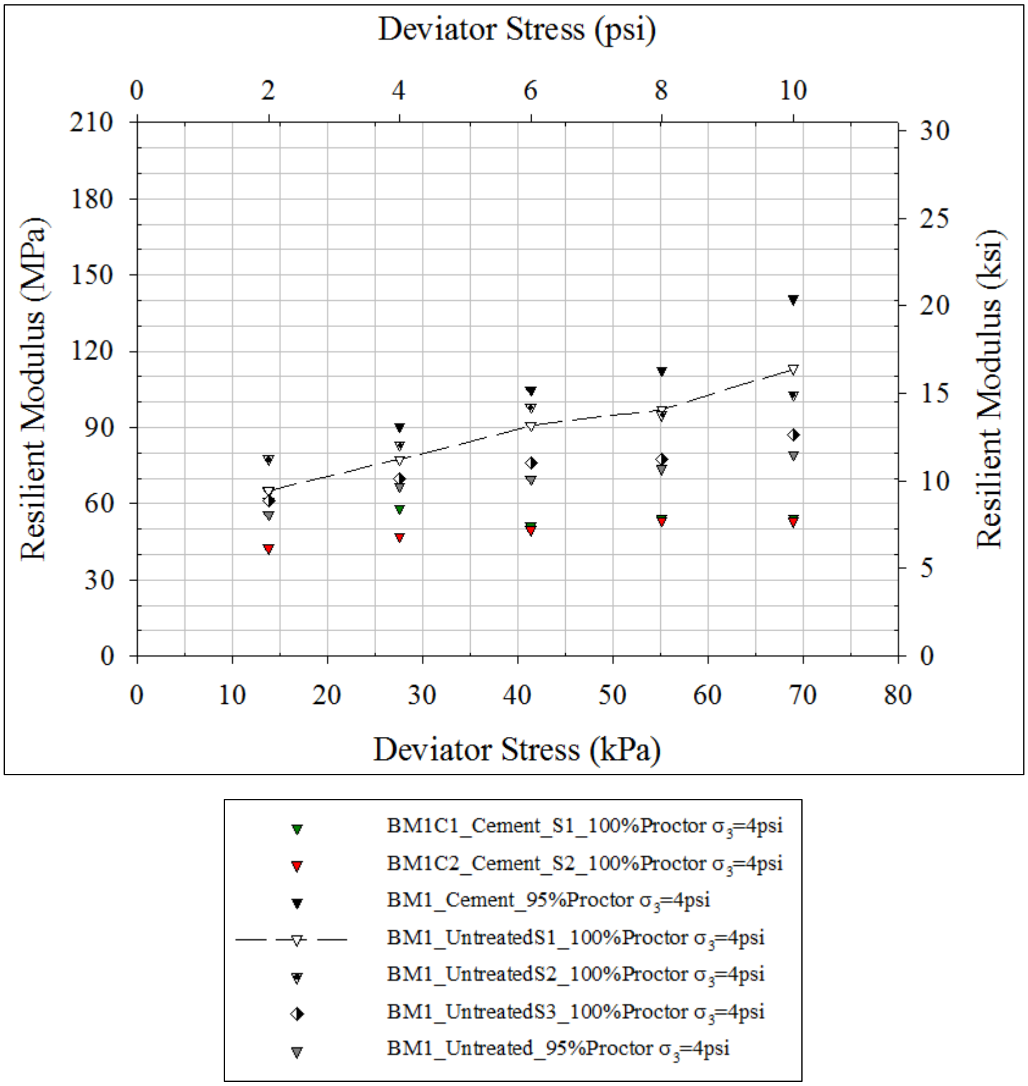


Figure C. 16. Resilient Modulus for Untreated Soil and Soil Treated with Optimum Amount of Cement, After Twelve Wetting-Drying Cycles. Confinement Stress 4 psi. Bloomington#1 (BM1)

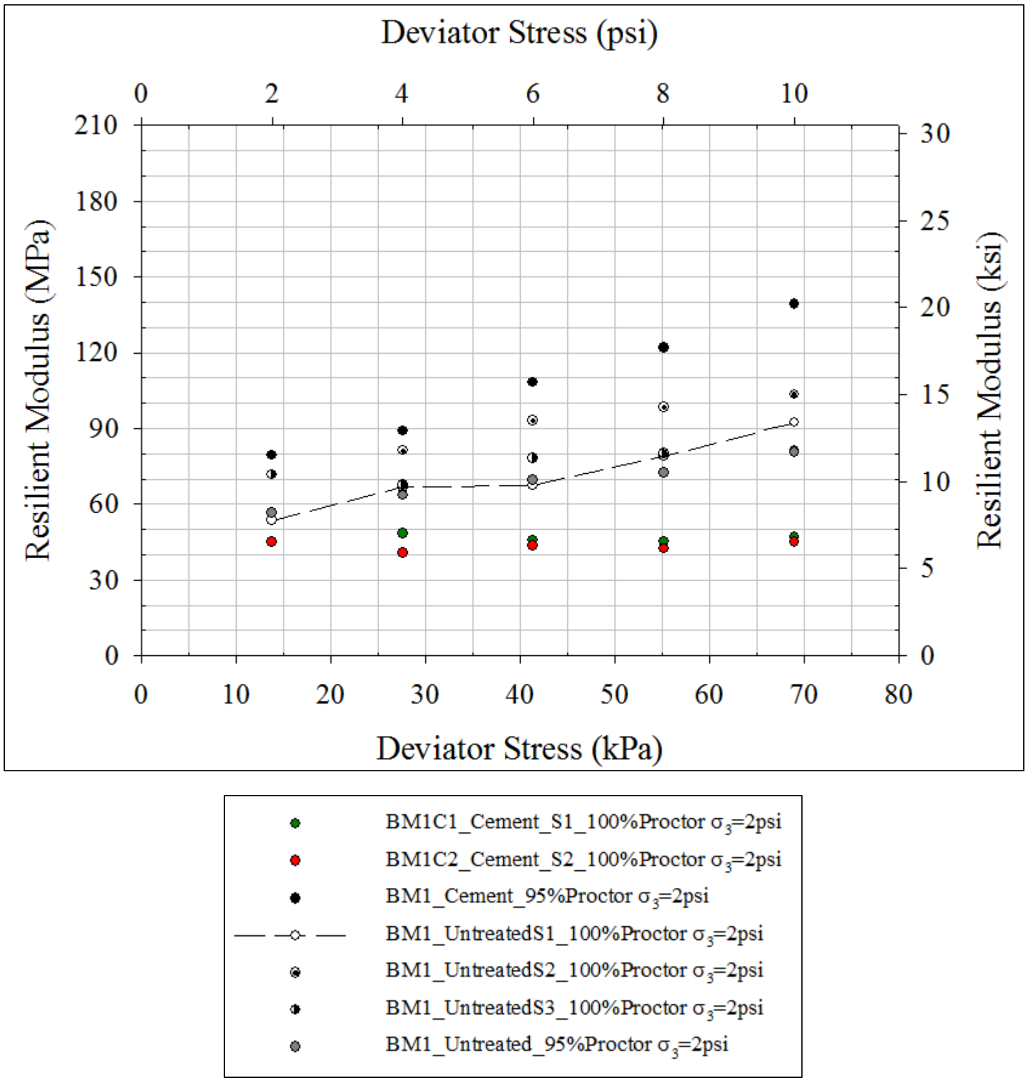


Figure C. 17. Resilient Modulus for Untreated Soil and Soil Treated with Optimum Amount of Cement, After Twelve Wetting-Drying Cycles. Confinement Stress 2 psi. Bloomington#1 (BM1)

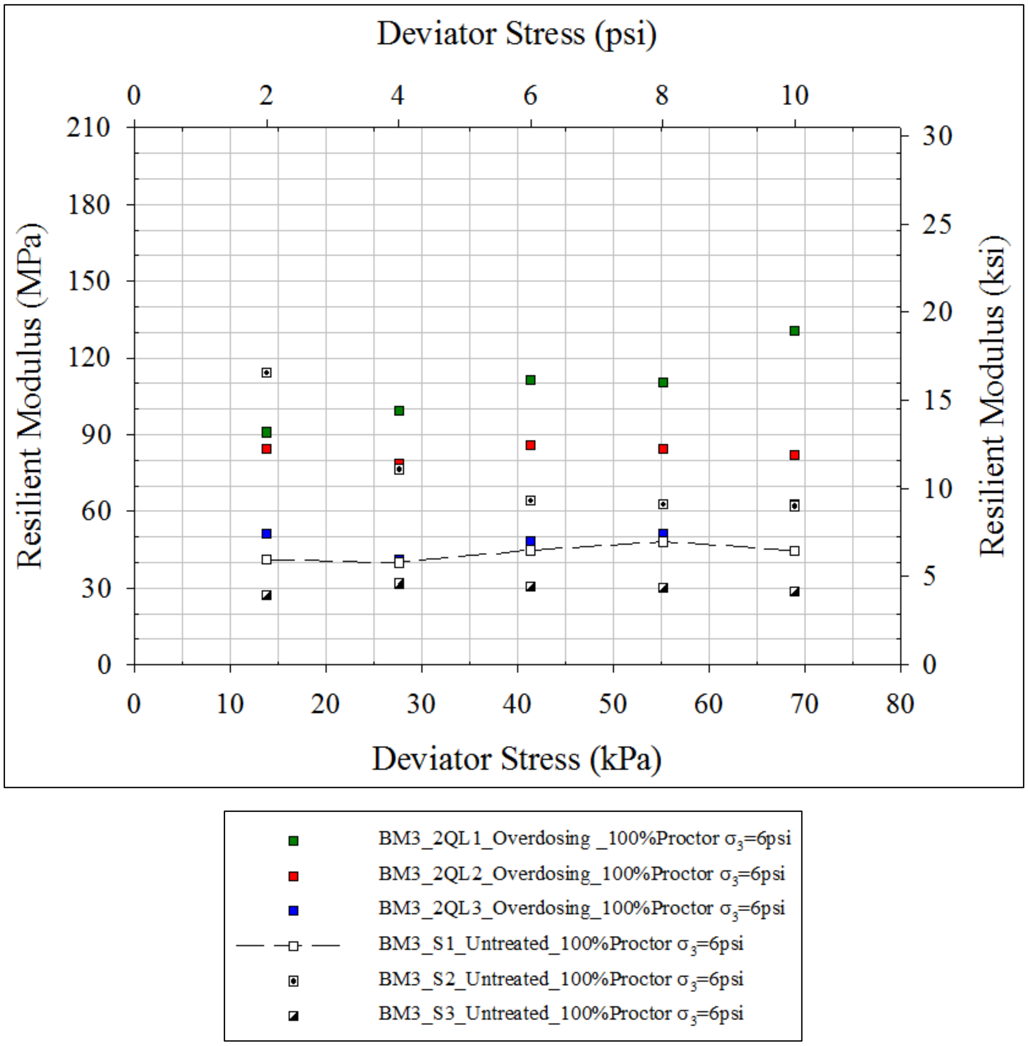


Figure C. 18. Resilient Modulus for Untreated Soil and Soil Treated with Double Amount of QL After Twelve Wetting-Drying Cycles. Confinement Stress 6 psi. Bloomington#3 (BM3)

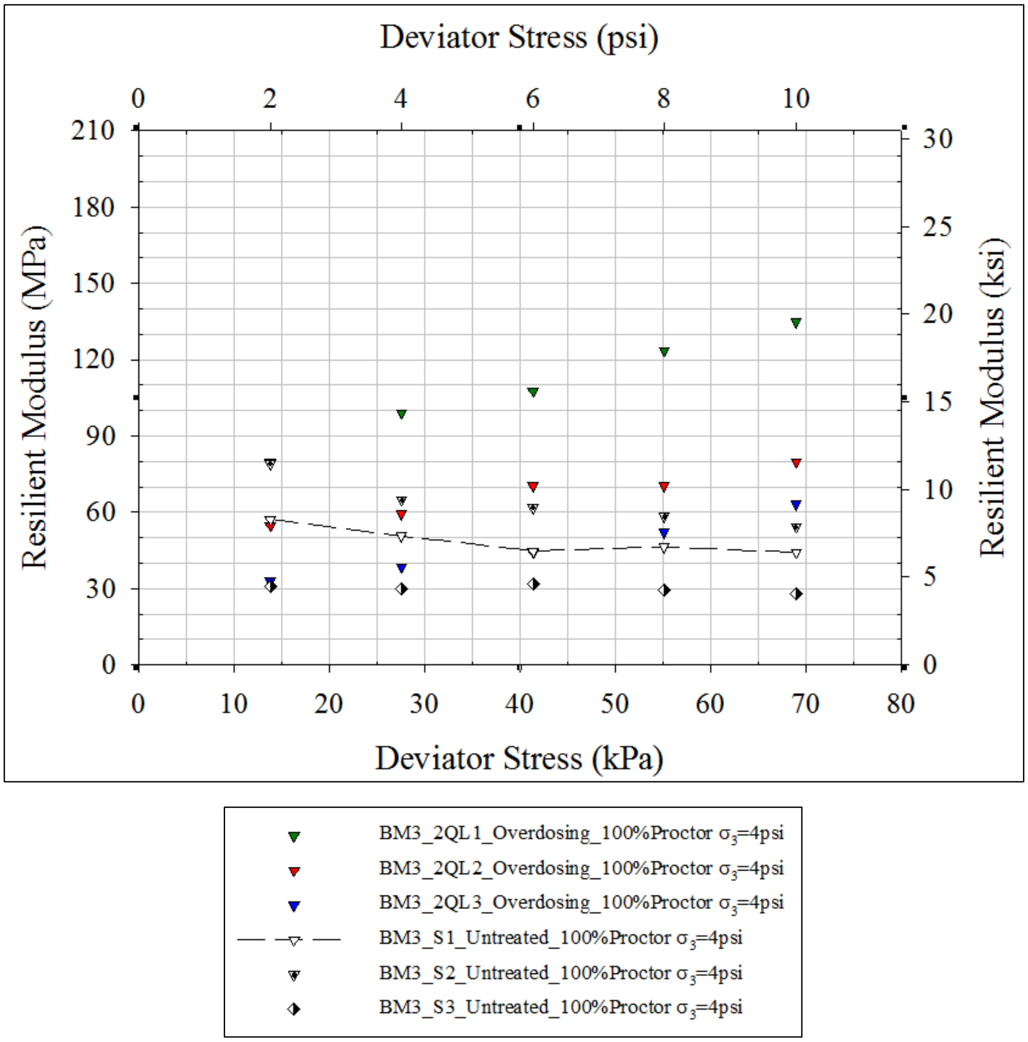


Figure C. 19. Resilient Modulus for Untreated Soil and Soil Treated with Double Amount of QL After Twelve Wetting-Drying Cycles. Confinement Stress 4 psi. Bloomington#3 (BM3)

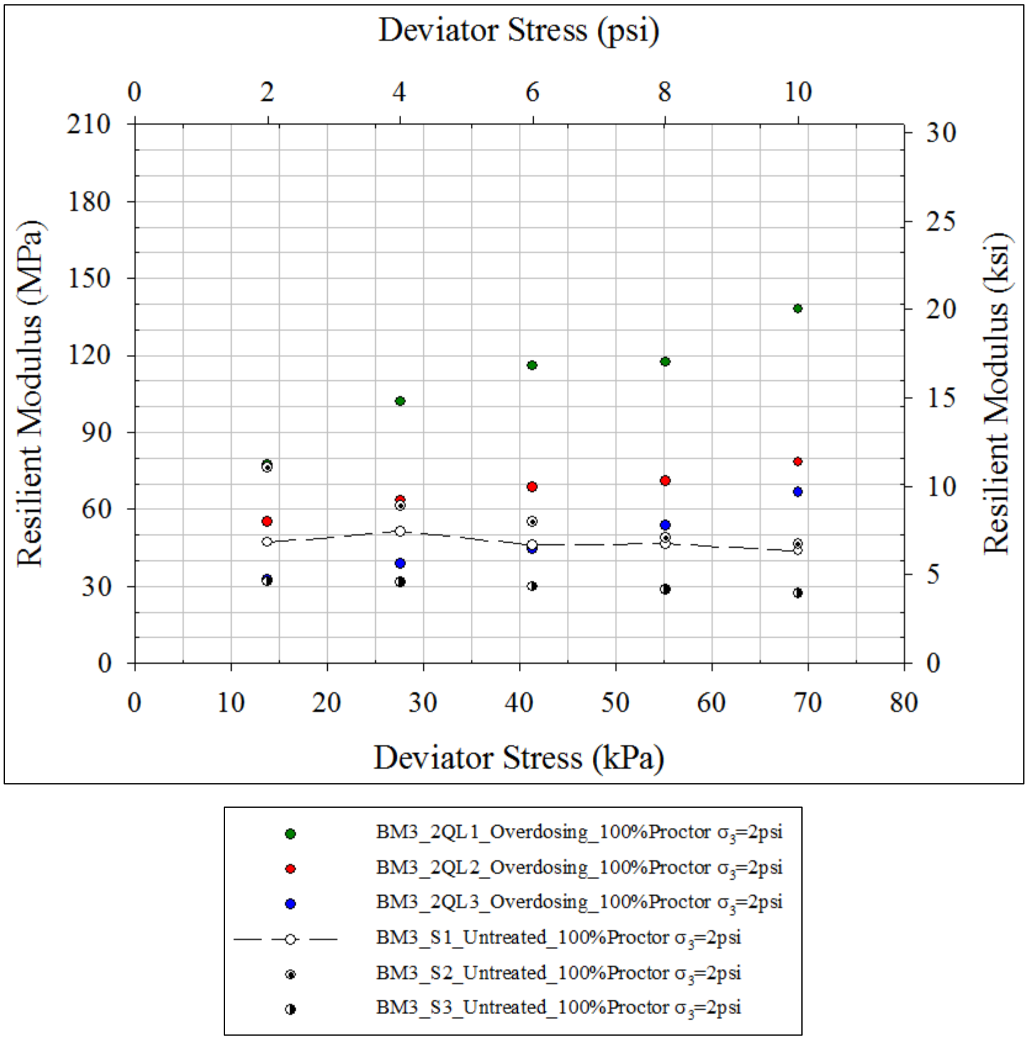


Figure C. 20. Resilient Modulus for Untreated Soil and Soil Treated with Double Amount of QL After Twelve Wetting-Drying Cycles. Confinement Stress 2 psi. Bloomington#3 (BM3)

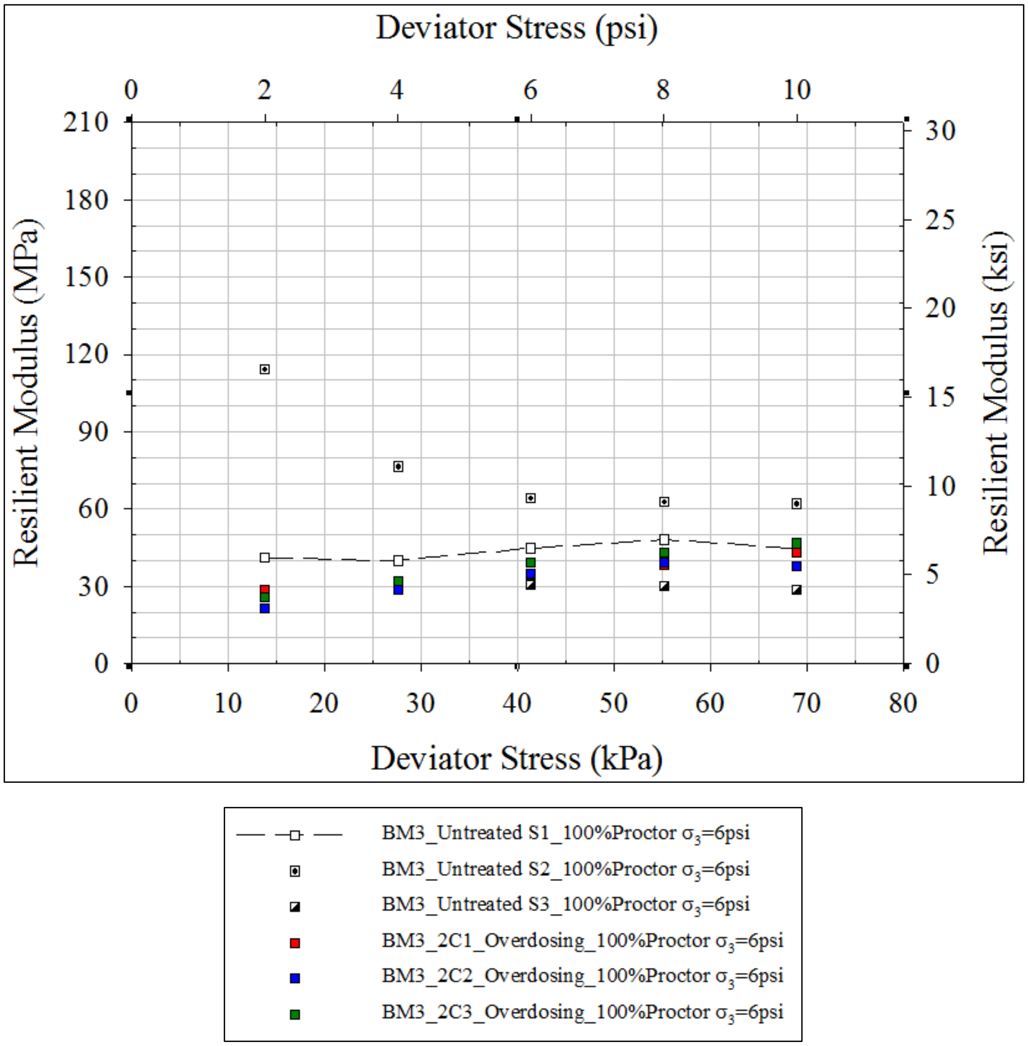


Figure C. 21. Resilient Modulus for Untreated Soil and Soil Treated with Double Amount of Cement After Twelve Wetting-Drying Cycles. Confinement Stress 6 psi. Bloomington#3 (BM3)

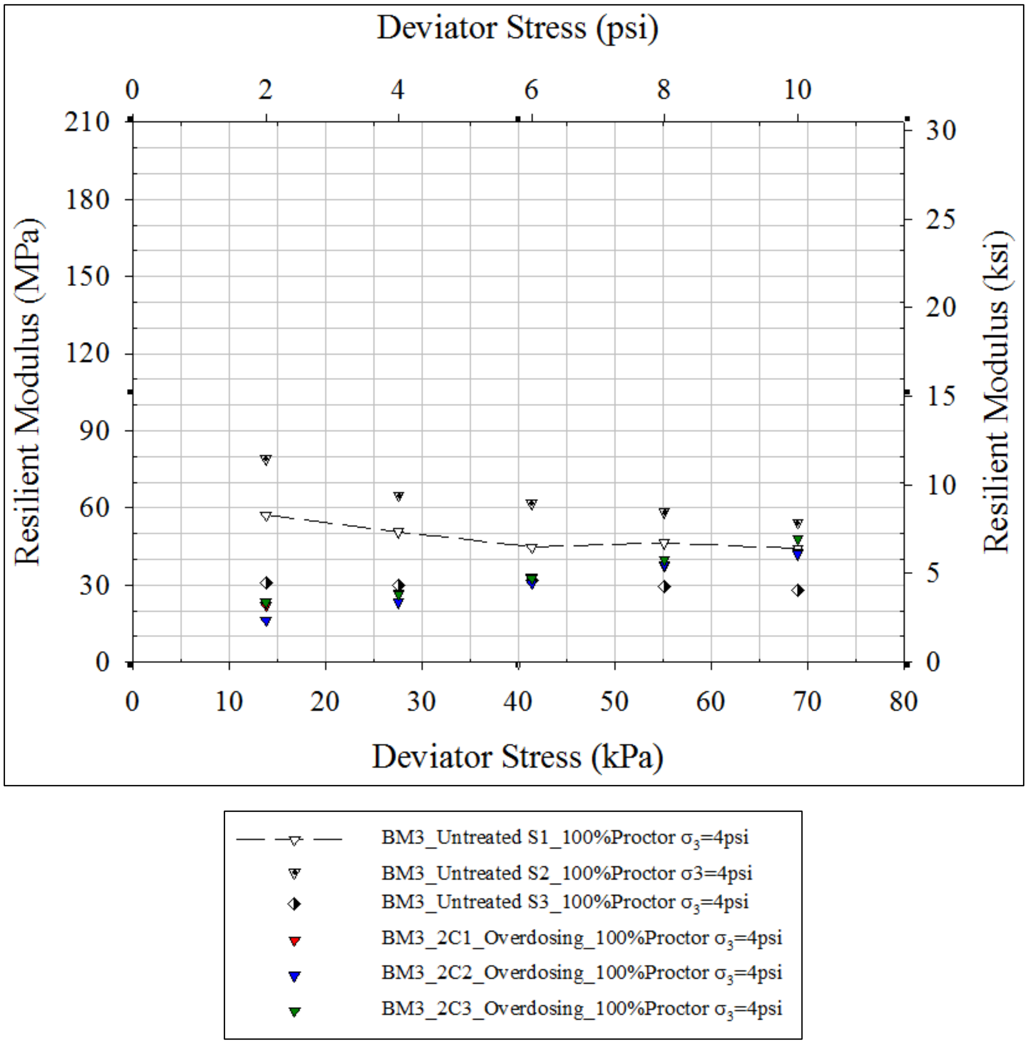


Figure C. 22. Resilient Modulus for Untreated Soil and Soil Treated with Double Amount of Cement After Twelve Wetting-Drying Cycles. Confinement Stress 4 psi. Bloomington#3 (BM3)

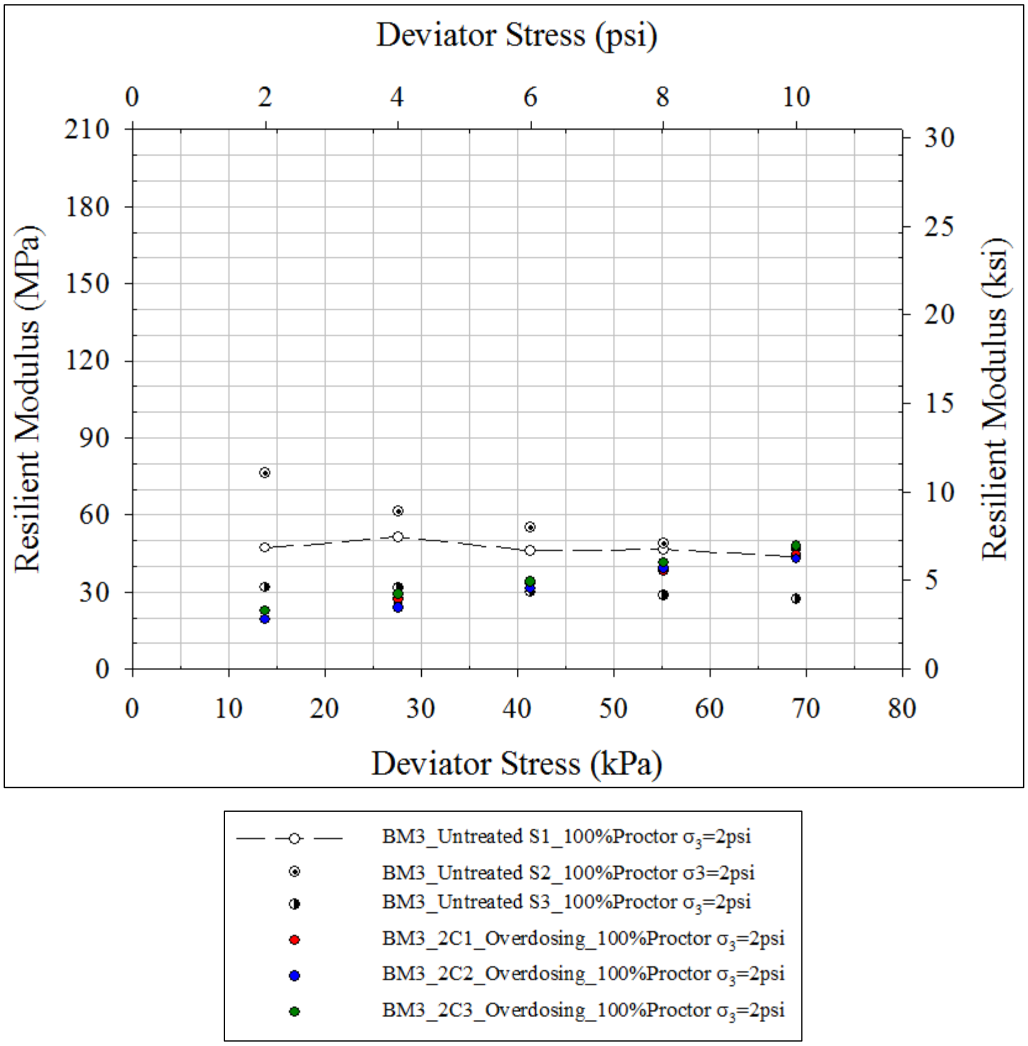


Figure C. 23. Resilient Modulus for Untreated Soil and Soil Treated with Double Amount of Cement After Twelve Wetting-Drying Cycles. Confinement Stress 2 psi. Bloomington#3 (BM3)

Table C. 1. Results for M_R Tests on Untreated Soil and Soil Treated with LKD or Cement for HC, BM1, BM3 Soils

Sample	Curing (Days) / WD-Cycles	M_R (ksi) at Different Confinement and Deviatoric Stresses														
		Confinement Stress, σ_3 = 2 psi					Confinement Stress, σ_3 = 4 psi					Confinement Stress, σ_3 = 6 psi				
		Deviatoric Stress, σ_d (psi)					Deviatoric Stress, σ_d (psi)					Deviatoric Stress, σ_d (psi)				
		2	4	6	8	10	2	4	6	8	10	2	4	6	8	10
BM1 Untreated, S1	7/12	7.77	9.68	9.78	11.4	13.4	9.46	11.2	13.2	14.1	16.4	13.8	15.3	14.6	15	14.8
BM1 Untreated, S2	7/12	10.4	11.8	13.5	14.3	15	11.2	12	14.2	13.8	14.9	20.8	19.2	16.6	17.1	18.6
BM1 Untreated, S3	7/12	10.4	9.81	11.3	11.6	11.8	8.85	10.1	11.1	11.3	12.6	9.22	10.5	10.7	11.8	11.6
BM1 + 6% LKD, S1	7/12	11.6	12.1	12.6	12.7	14.1	15.4	16.3	14.4	16.3	16.5	17.3	18.1	17.3	16.2	17.4
BM1 + 6% LKD, S2	7/12	11.4	9.8	10.1	10.1	10.5	9.62	9.86	10	12.2	12.9	13.5	12.1	15.8	12.1	14.8
BM1 + 6% LKD, S3	7/12	8.02	6.96	7.02	7.48	8.84	6.39	7.63	8.14	9.97	9.92	9.93	9.11	10.9	8.93	11.5
BM1 + 3% Cement, S1	7/12	7.75	7.01	6.65	6.55	6.79	8.85	8.45	7.43	7.85	7.87	12.7	9.15	9.49	9.55	9.09
BM1 + 3% Cement, S2	7/12	6.53	5.91	6.33	6.15	6.52	6.17	6.82	7.2	7.75	7.71	7	8.44	9.58	8.06	8.78
HC Untreated, S1	7/12	10.7	9.86	9.83	10.2	9.55	9.51	10.5	11.8	11.8	10.9	11.2	11	13	13.4	11.6
HC Untreated, S2	7/12	9.61	7.51	7.76	7.02	7.98	8.42	9.67	8.29	8.91	8.52	9.74	8	10.6	9.55	8.57
HC + 6% LKD, S1	7/12	25.9	22.4	24.1	23.2	22	24.7	28	25.7	23.1	22.7	23	25.9	30	25.7	23.9
HC + 6% LKD, S2	7/12	10.4	9.86	10.3	10.2	11.1	9.89	11	12.4	12	13.5	16	16.2	12.6	14	15.4
HC + 6% LKD, S3	7/12	12.5	10.7	11.4	12.7	13.4	10.8	11.6	13.6	14.1	15.5	17.7	17.3	15.2	15.9	17.4
BM3 Untreated, S1	7/12	6.84	7.45	6.69	6.76	6.35	8.28	7.36	6.49	6.73	6.42	5.96	5.8	6.5	6.99	6.47
BM3 Untreated, S2	7/12	11.1	8.88	7.99	7.1	6.74	11.5	9.4	8.97	8.45	7.87	16.6	11.1	9.31	9.09	9.02
BM3 Untreated, S3	7/12	4.61	4.58	4.34	4.17	3.94	4.45	4.37	4.63	4.26	4.08	3.94	4.62	4.42	4.34	4.14
BM3 + 10% QL, S1	7/12	6.69	7.87	9.22	9.98	11	7.26	7.29	8.84	9.63	10.9	10.5	9.35	9.87	10.4	11.1
BM3 + 10% QL, S2	7/12	7.98	9.2	9.95	10.3	11.4	7.95	8.61	10.2	10.2	11.6	12.2	11.4	12.5	12.2	11.9
BM3 + 10% QL, S3	7/12	4.72	5.62	6.45	7.8	9.66	4.78	5.56	6.42	7.55	9.17	7.43	5.98	7.03	7.4	9.13
BM3 + 6% Cement, S1	7/12	3.29	3.96	4.85	5.55	6.47	3.21	3.86	4.79	5.44	6.22	4.16	4.64	5.02	5.57	6.29
BM3 + 6% Cement, S2	7/12	2.8	3.46	4.54	5.68	6.23	2.38	3.37	4.47	5.5	6.09	3.1	4.16	5.07	5.7	5.46
BM3 + 6% Cement, S3	7/12	3.28	4.21	4.92	6.02	6.94	3.36	3.82	4.72	5.78	6.96	3.73	4.66	5.67	6.27	6.77

1 psi ≈ 6.89 kPa; 1 ksi ≈ 6.89 MPa

	Overdosing (double amount of treatment)

APPENDIX D. RESILIENT MODULUS AFFECTED BY CHANGES IN TEMPERATURE

Figure D. 1 shows the model geometry and mesh used for the analyses.

Figure D. 2 and Figure D. 3 show the strains in the sample, after twelve FT cycles, for pin and roller boundaries, respectively.

Results of the resilient modulus tests, after twelve FT cycles, for BM1 specimens treated with LKD are shown in Figure D. 4 to Figure D. 6. For BM1 treated with cement, the results are shown in Figure D. 7 to Figure D. 9. Table D. 1 lists the M_R values for the specimens, i.e., untreated and treated.

Figure D. 1. Model Geometry and Mesh

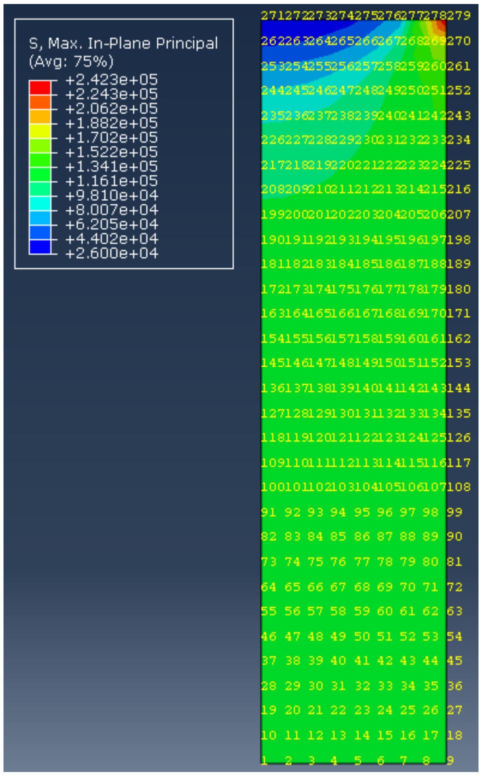


Figure D. 2. Strains in a BM1 Sample Treated with LKD – Fixed (pinned) Boundary

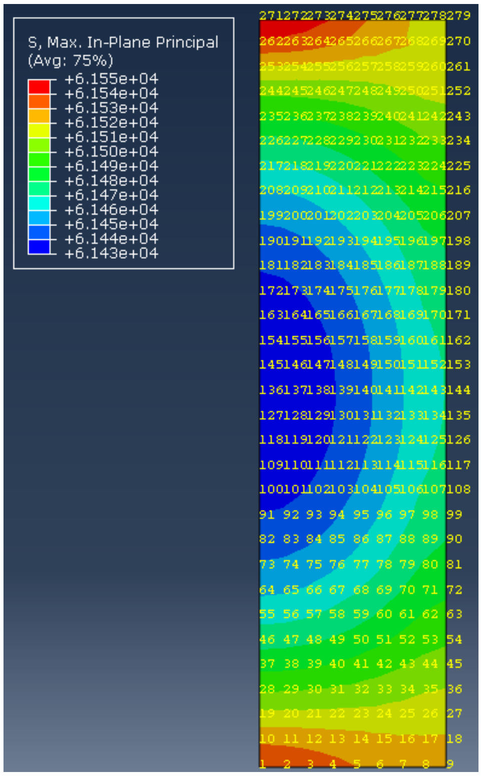


Figure D. 3. Strains in a BM1 Sample Treated with LKD – Roller Boundary

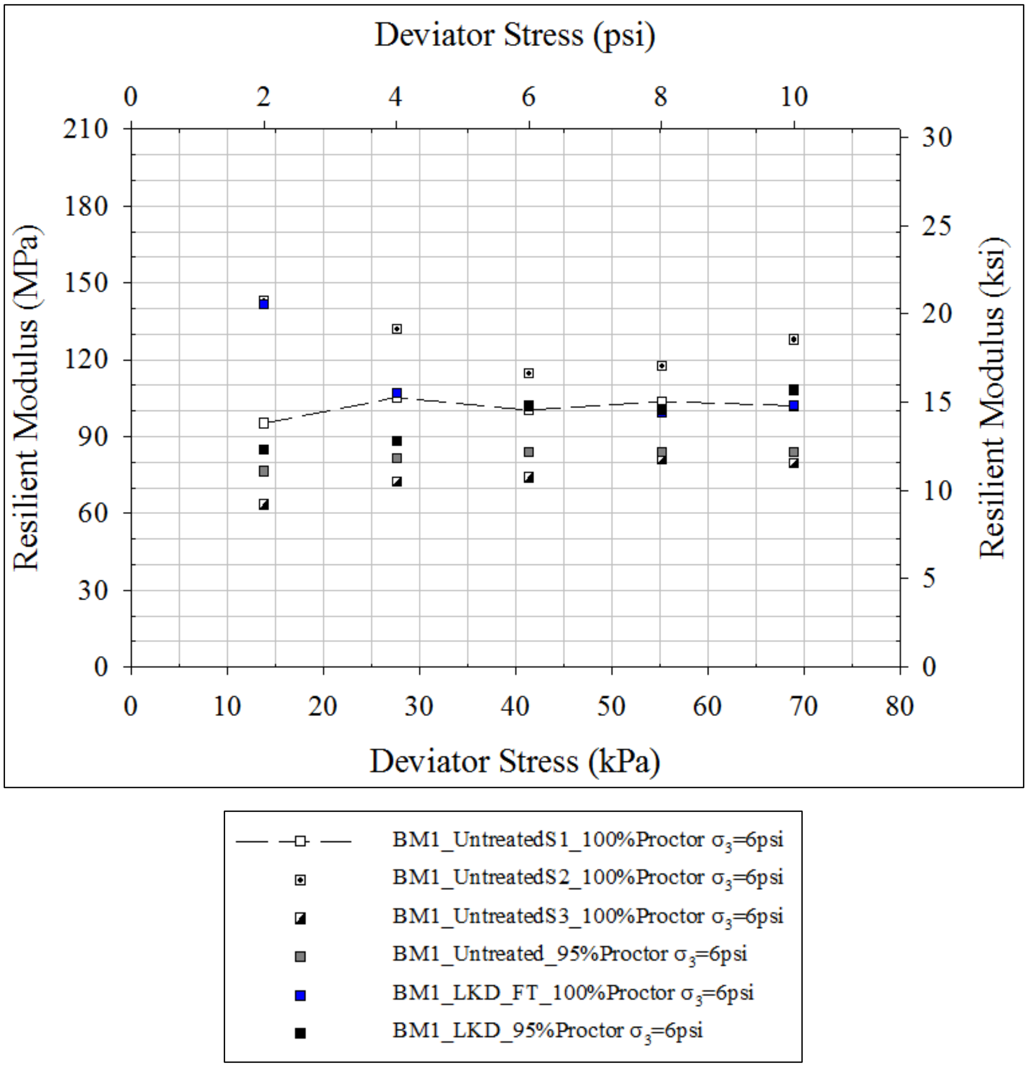


Figure D. 4. Resilient Modulus for Untreated BM1 Soil and BM1 Soil Treated with Optimum Amount of LKD, After Twelve FT Cycles. Confinement Stress 6 psi.

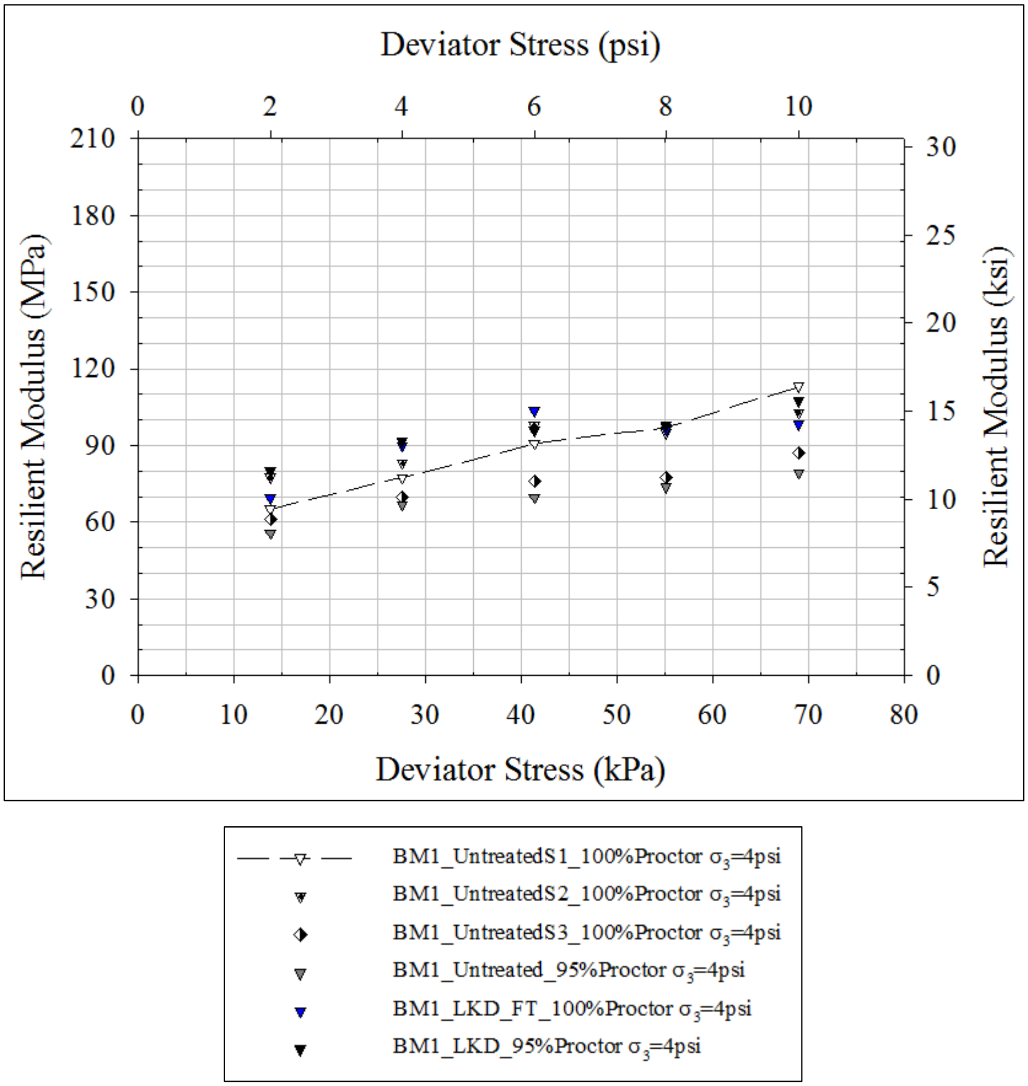


Figure D. 5. Resilient Modulus for Untreated BM1 Soil and BM1 Soil Treated with Optimum Amount of LKD, After Twelve FT Cycles. Confinement Stress 4 psi.

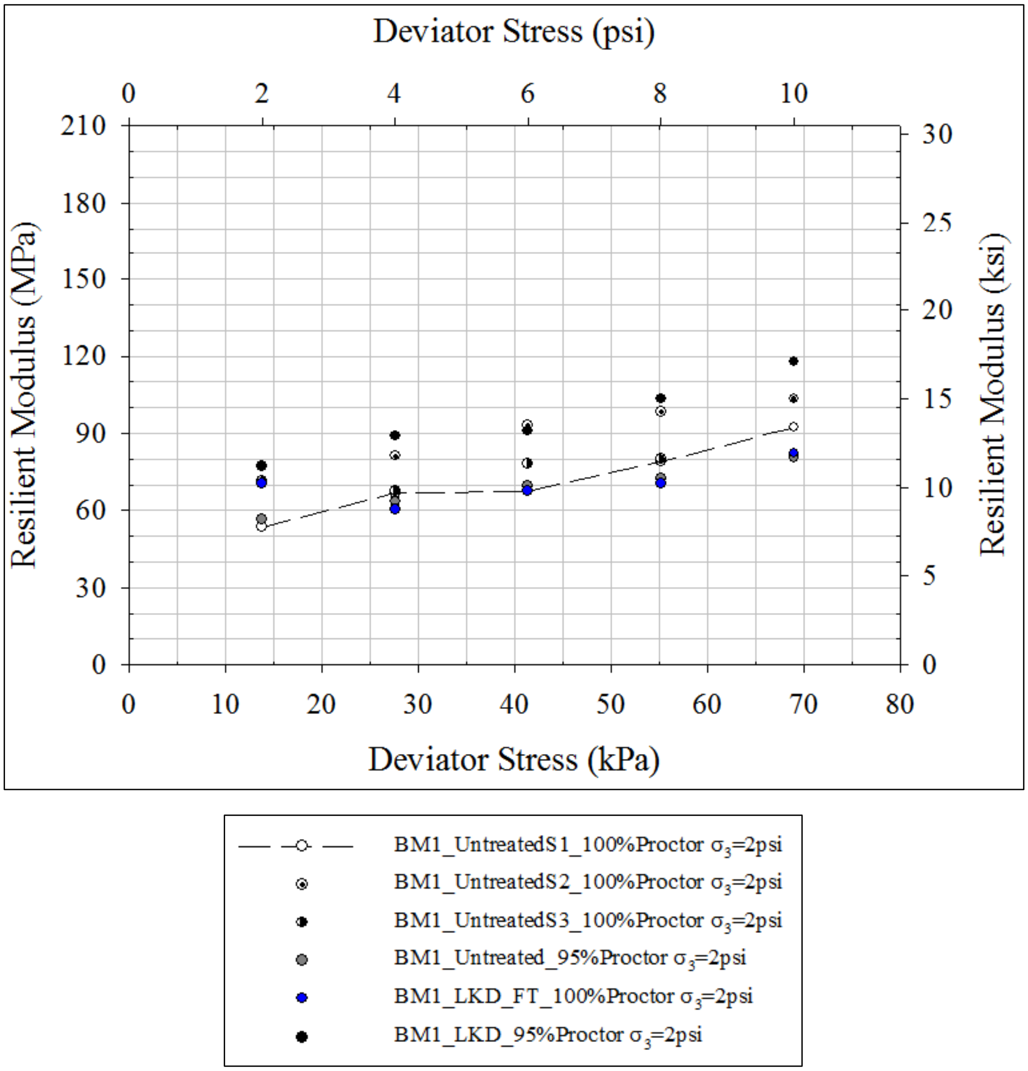


Figure D. 6. Resilient Modulus for Untreated BM1 Soil and BM1 Soil Treated with Optimum Amount of LKD, After Twelve FT Cycles. Confinement Stress 2 psi.

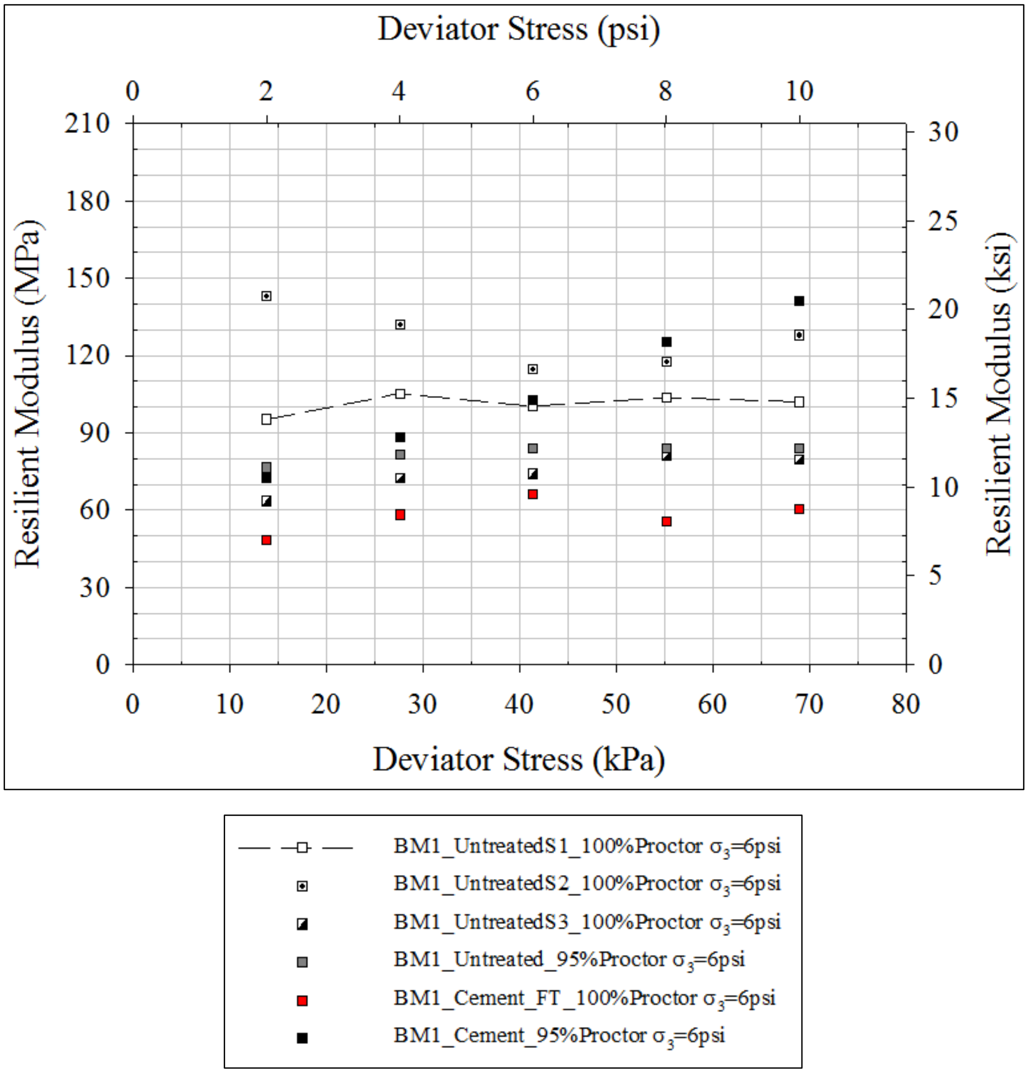


Figure D. 7. Resilient Modulus for Untreated BM1 Soil and BM1 Soil Treated with Optimum Amount of Cement, After Twelve FT Cycles. Confinement Stress 6 psi.

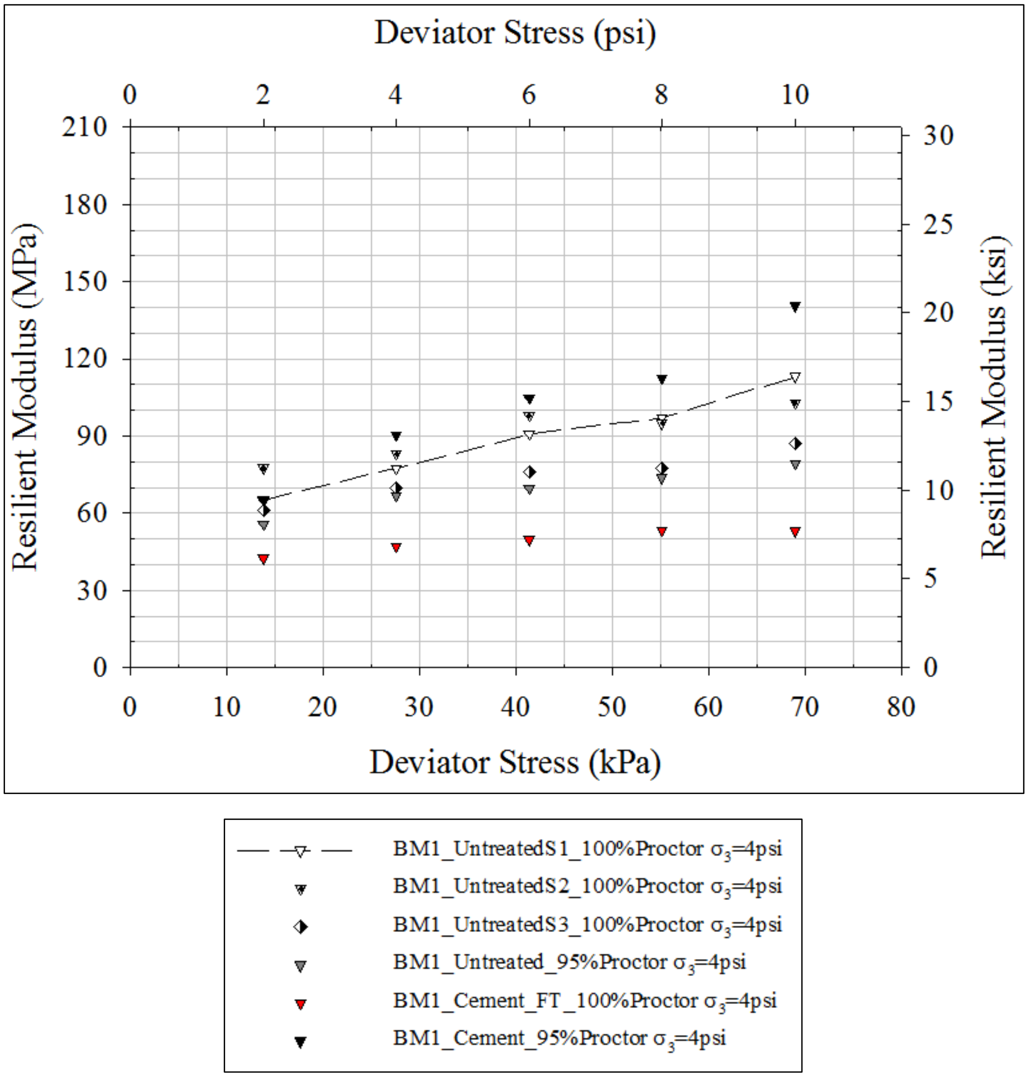


Figure D. 8. Resilient Modulus for Untreated BM1 Soil and BM1 Soil Treated with Optimum Amount of Cement, After Twelve FT Cycles. Confinement Stress 4 psi.

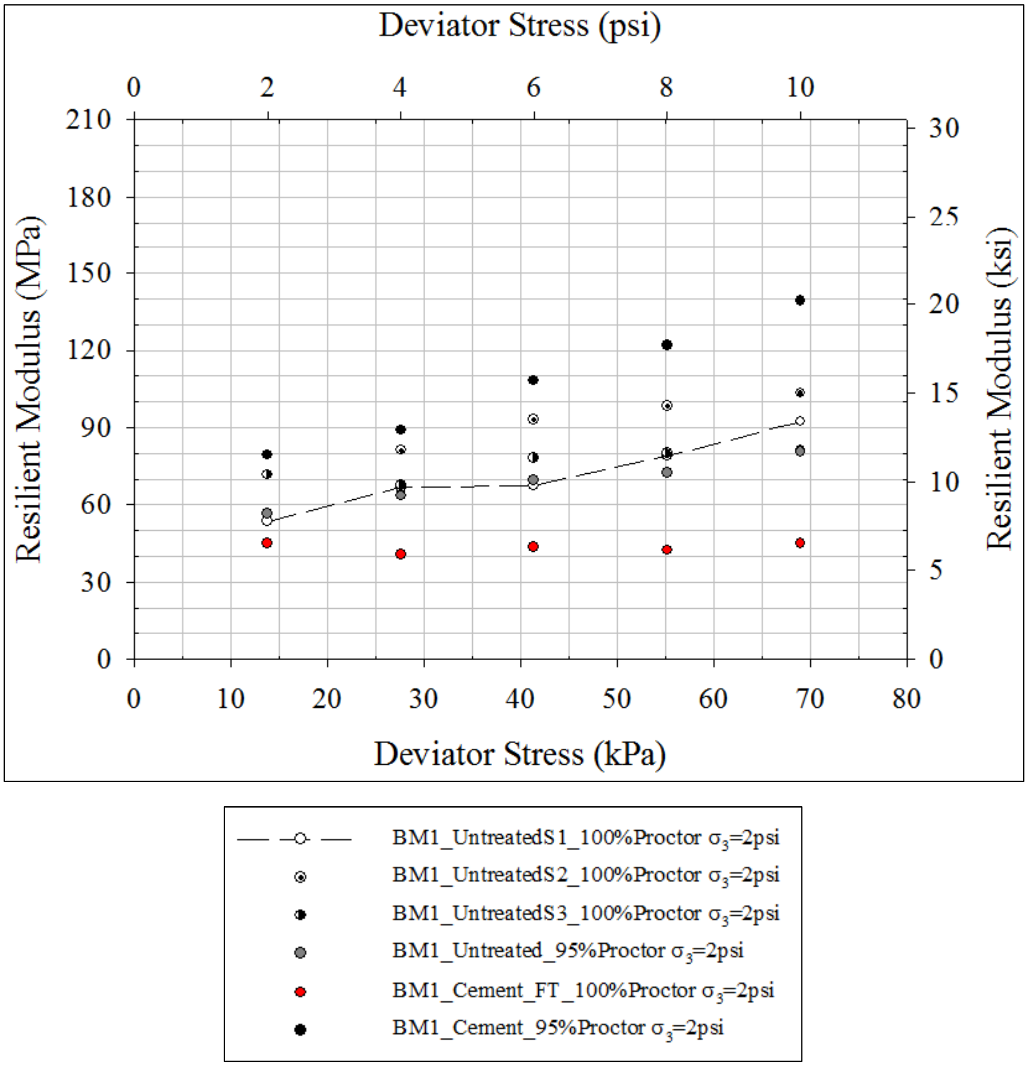


Figure D. 9. Resilient Modulus for Untreated BM1 Soil and BM1 Soil Treated with Optimum Amount of Cement, After Twelve FT Cycles. Confinement Stress 2 psi.

Table D. 1. Results for M_R Tests on Untreated Soil and Soil Treated with LKD or Cement for BM1 Soil

Sample	Curing (Days) / FT-Cycles	M_R (ksi) at Different Confinement and Deviatoric Stresses														
		Confinement Stress, σ_3 = 2 psi					Confinement Stress, σ_3 = 4 psi					Confinement Stress, σ_3 = 6 psi				
		Deviatoric Stress, σ_d (psi)					Deviatoric Stress, σ_d (psi)					Deviatoric Stress, σ_d (psi)				
		2	4	6	8	10	2	4	6	8	10	2	4	6	8	10
BM1 Untreated, S1	7/12	7.77	9.68	9.78	11.4	13.4	9.46	11.2	13.2	14.1	16.4	13.8	15.3	14.6	15	14.8
BM1 Untreated, S2	7/12	10.4	11.8	13.5	14.3	15	11.2	12	14.2	13.8	14.9	20.8	19.2	16.6	17.1	18.6
BM1 Untreated, S3	7/12	10.4	9.81	11.3	11.6	11.8	8.85	10.1	11.1	11.3	12.6	9.22	10.5	10.7	11.8	11.6
BM1 + 6% LKD, S1	7/12	10.2	8.75	9.81	10.2	11.9	10.1	13.1	15	14	14.3	20.5	15.5	14.8	14.4	14.8
BM1 + 3% Cement, S1	7/12	6.53	5.91	6.33	6.15	6.52	6.17	6.82	7.2	7.75	7.71	7	8.44	9.58	8.06	8.78

1 psi ≈ 6.89 kPa; 1 ksi ≈ 6.89 MPa

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