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Subgrade Stabilization Alternatives

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16. Abstract

Recent research has shown that the subgrade soil type and its engineering properties govern the performance of the pavement, especially for clayey soils. However, current application of the PavementME in Indiana does not fully account for the changes of type of soil and stiffness that may arise with treatment. This research addresses this issue by exploring engineering properties, namely fines content, plasticity index, unconfined compression strength and resilient modulus of subgrade stabilization alternatives. The effects of changes in moisture content and temperature on the stiffness of treated subgrades are also studied. Three A-7-6 soils and one A-6 soil mixed with lime kiln dust (LKD) and/or Portland cement (PC); and one A-7-6 soil mixed with quick lime (QL) are investigated. An increase in the soils grain size and a decrease in the plasticity is observed with all chemical treatments; however, the change in soil type is only evident when the optimum amount of treatment is doubled. An increase in the soil's stiffness is always seen for treated soils, in some cases by a factor of two. Test conditions are investigated to develop new appropriate protocols that represent field conditions for changes in moisture and temperature. The MR results show that the action of wetting-drying and freezing-thawing cycles reduces the stiffness of the treated soils, at optimum treatment, down to values similar to, or lower than, those of the untreated soils. When the amount of chemical is doubled, the treated soils' MR improves over that of the untreated soils, even after the wetting-drying cycles.

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EXECUTIVE SUMMARY

Introduction

In 2009, INDOT adopted the *Mechanistic-Empirical Pavement Design Guide* method (MEPDG or PavementME after 2012). The main design objective in the PavementME is to optimize pavement design by assigning pavement support layers that meet the performance criteria. One of the issues of this method is that it requires the input of design parameters that reflect the actual conditions of the subgrade in the field. Current application of the PavementME in Indiana neglects the changes in the nature of the soils that occur with chemical treatment. If accounted for in the PavementME, such changes would decrease the susceptibility of the soil to moisture and temperature variations.

This study addresses this issue by exploring engineering properties, namely fines content, plasticity index, unconfined compression strength, and resilient modulus of subgrade stabilization alternatives. The effects of changes in moisture content and temperature on the subgrade's stiffness is also considered.

This research focuses on treatment with Lime Kiln Dust (LKD), Portland cement (PC), or a combination of LKD and cement. Treatment with Quick Lime (QL) is also investigated. The soils targeted are A-6 and A-7-6, which have low bearing capacity and are sensitive to changes in moisture content; thus, they are often treated with a chemical agent.

Findings

- The A-6 soil was obtained from Hartford City (HC) in Blackford County, while the A-7-6 soils were collected from Fort Wayne (FW) in Allen County, and from Bloomington (BM1, BM2, BM3) in Monroe County. For these soils, the LL ranged between 26.0% and 66.0%, while the PI was between 14.4% and 45.2%.
- For the soils investigated, the optimum amount of treatment ranged between 5% and 6% for LKD, between 3% and 5% for cement, and between 2% LKD + 2% cement when both chemicals were used.
- The plasticity index decreased with treatment for all the soils, but there was not a clear trend regarding which treatment had a larger effect on the soils' plasticity. Curing time had no major effect on the soils' plasticity. The largest reduction in PI occurred before 28 days of curing. The soil grain size always increased with treatment. Although with the optimum amount of treatment the plasticity decreased (up to 20%) and the grain size increased (up to 37% with respect to the untreated soil), the type of soil did not change for most of the soils investigated (i.e., the soil remained as A-6 or A-7-6).
- After 28 days of curing, the increase in strength with respect to the untreated soil ranged from 123% for HC + LKD to 613% for BM2 + cement. For most soils, the largest unconfined compression strength was observed on mixtures with cement. The increase in strength with curing time of the soil mixtures with LKD or cement did not depend on soil plasticity, as soils with relative similar plasticity (BM1 vs. FW) had different strengths.
- All treated soils exhibited an increase of the resilient modulus, M_R, with respect to that of the untreated soil. At the optimum amount of treatment, the M_R was larger for mixtures with cement than with LKD. The M_R of the treated soils increased with the increase of the deviatoric stress. Such effect was more remarkable for samples containing cement. There was no clear trend between M_R and curing time.
- When the optimum amount of treatment was doubled (overdosing), the decrease in plasticity and fines content was more remarkable than using the optimum amount of treatment. The type of soil always changed, transforming a fine-grained soil into a granular soil (e.g., from A-6 to A-2-4).
- Overdosing produced a larger increase in the unconfined compression strength of the soil compared to the optimum treatment. The strength obtained from overdosing could be twice the strength of optimum treatment. Overdosing produced a larger increase in soil stiffness compared with the optimum treatment.
- Considering realistic conditions for natural and treated subgrades, calculations using the PavementME could result in an increase in the IRI or in a larger design life of the pavement. This would result in a reduction of the cost of the pavement, as a smaller pavement thickness would be required for the same design life. The improvement is clear when the treatment is doubled (overdosed), especially with cement.
- When strictly following the standard ASTM D559/D559M for wetting and drying (WD) cycles at the optimum amount of treatment, the treated specimens failed during the wetting stage in the first three to five cycles. A modified test protocol was proposed for the WD process. The samples were subjected to twelve wetting-drying cycles. After that, M_R tests were conducted. The WD cycles resulted in a significant decrease of the resilient modulus of the treated soils to values similar to those of the untreated soils. After the twelve WD cycles, soil specimens overdosed with quick lime had an increase in stiffness of 55% on average, while those overdosed with cement had a reduction of stiffness down to about 20% compared to the untreated soil without WD cycles.
- Strictly following the Standard D560/D560M to determine the stiffness of compacted treated specimens subjected to repeated freezing and thawing (FT) cycles, treated soil specimens presented premature failure due to excessive deformations. A modified test protocol was adopted. 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 without FT cycles.

Implementation

The research clearly showed the benefits of overdosing (i.e., of doubling the amount of chemicals). Overdosing changed the type of soil from clayey to granular, and improved the resilient modulus of the soil, even under the harsh conditions in the laboratory during the cycles of WD, especially for soils with lower plasticity. Clearly, overdosing increases the 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 pavement structure, with less maintenance, or even with a less thick structure. It is recommended to implement this research. A section of a new pavement construction should be built using overdosing and its performance monitored to verify the discussed changes and their benefits, during both the short and long term.

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1. INTRODUCTION

In 2009, INDOT adopted the Mechanistic-Empirical Pavement Design Guide (MEPDG) method, a new design guide based on the Federal Highway Administration (FHWA) Long Term Pavement Performance (LTPP). The main objective of design in the MEPDG (called PavementME after 2012) has changed compared to that of the American Association of State Highway and Transportation Officials (AASHTO) 1993 Design Guide, which is to assign pavement support layers that meet the performance criteria to optimize the pavement design.

With the implementation of this new design approach, difficulties have been encountered to pass the INDOT performance criteria: pavement roughness (International Roughness Index, IRI) for hot mixed asphalt (HMA), and faulting and IRI for concrete pavement, when low bearing capacity soils such as A-6 or A-7-6 are considered for the subgrade. This is an issue of major importance for both the asphalt and concrete pavement industries, which have asked INDOT for alternatives for the pavement structure to meet the design life requirements.

One of the issues of the PavementME is that the method requires the input of design parameters that reflect the actual conditions of the subgrade in the field, to better predict pavement performance over time. This is based on different criteria such as roughness, rutting, faulting and fatigue cracks. Recent research (El Howayek et al., 2016) has shown that the type and the engineering properties of the soil used for the subgrade govern, to a great extent, the performance of the pavement, which in the PavementME is determined mostly by the Enhanced Integrated Climatic Model (EICM). The research has shown that: (1) For clayey soils such as A-7-6 soils, the overall deformation of the pavement structure is controlled by the subgrade (80% of total deformation). (2) For the climatic conditions existing in Indiana, the location of the water table does not affect the value that the PavementME uses for the subgrade resilient modulus. (3) The gravimetric water content is the most influential parameter on the EICM because it is directly related to the optimum degree of saturation of the subgrade soil. (4) Current practice appears to produce a double reduction of the subgrade modulus used for pavement design, since the resilient modulus values provided as input into the PavementME already account for the site conditions but are then further reduced by the EICM module.

Current application of the PavementME in Indiana neglects the changes in the nature of the soils that arise with treatment, i.e., an A-7-6 soil treated with Lime Kiln Dust (LKD) or Portland cement continues to be modeled as an A-7-6 soil even though there is some evidence, albeit not systematic, that treatment could change the type of soil, e.g., from A-7-6 to A-6 or even to A-4 (Jung & Bobet, 2008; Jung et al., 2009), which, if accounted for in the PavementME, would decrease the susceptibility of the subgrade to moisture changes in comparison with the untreated soil. The current application also neglects, to a large extent, the stiffness improvement with treatment (Jung & Bobet, 2008; Jung et al., 2009). With the adoption of the PavementME, it is possible to consider in the input parameters the actual properties of the stabilized soil subgrade, and thus the PavementME method opens the possibility for design engineers to be innovative in utilizing the stabilized pavement layers to reduce the cost of the pavement surface or increase its design life. The pavement design should not be based on the type of the original soil but rather on its modulus and other engineering properties of the actual (treated/improved) materials. This research addresses that issue by exploring engineering properties, namely fines content, plasticity index, unconfined compression strength and resilient modulus of the subgrade stabilization alternatives. Also, the effect of changes in moisture content and temperature on the subgrade's stiffness is considered. Thus, pavement engineers can design the pavement structure accordingly, and achieve the desired level of performance for the target pavement life. Hence, this research has the following objectives:

1. Quantify the changes of the type of soil that occur with chemical treatment and, more specifically, determine the changes in fines content and plasticity index.
2. Quantify the changes in subgrade resilient modulus with chemical treatment.
3. Investigate the evolution of the properties of a chemically-treated soil with time.
4. Quantify the changes in resilient modulus of the soil with overdosing the treatment.
5. Determine the sensitivity of a chemically treated soil with changes of moisture content and temperature.

The objectives are accomplished through a number of tasks to evaluate the changes of engineering properties that occur with treatment of typical soils found in Indiana. The research focuses on treatment with Lime Kiln Dust (LKD), Portland cement, or a combination of LKD and cement. Also, treatment with Quick Lime was investigated for verification purposes. The soils targeted are A-6 and A-7-6, which have low bearing capacity, are sensitive to changes of moisture content, and are thus often treated with a chemical agent. The Appendices, attached to this report, include all the results from the tests performed. Letters in the numbering of figures and tables stand for the corresponding Appendix. Table A.1 lists the tests performed in this research. In some of the cases, two or three identical tests were conducted to verify the repeatability of the results. All the samples used for the tests had particle sizes smaller than 2.0 mm (passing sieve #10). The experimental program included a total of 20 compaction tests, 4 Eades and Grim pH tests, 8 Loss on Ignition (LOI) tests, 50 Atterberg limits, 16 grain size analysis, 117 unconfined compression tests, and 63 resilient modulus tests.

2. SAMPLES LOCATION AND INDEX PROPERTIES OF UNTREATED SOILS

Three different locations in Indiana were selected to soil sources: Hartford City (HC), Fort Wayne (FW) and Bloomington (BM). For the latter, three soils with important differences in plasticity were investigated, which are identified in this report as Bloomington #1 (BM1), Bloomington #2 (BM2), and Bloomington #3 (BM3). BM3 was used for verification purposes. Thus, the research included samples from five different sites in Indiana. Hartford City is in the northeast of the state in Blackford County; Fort Wayne is in the northeast of Indiana, in Allen County; and Bloomington is located in the southern region of Indiana in the Monroe County. Figure 2.1 shows the location of the sampling sites.

Classification tests, namely grain size distribution and plasticity, were performed on all soils following the standards AASHTO T-88 and AASHTO T-89/T-90, respectively. The results are shown in Table 2.1 and indicate that the soil from Hartford City is classified as A-6, while the other soils are classified as A-7-6. Loss on Ignition (LOI) tests following AASHTO T-267 were also carried out, and the results are shown in Table B.1 in the Appendices. All the soils have organic matter content below the maximum accepted for soils that can be chemically treated (below 6%).

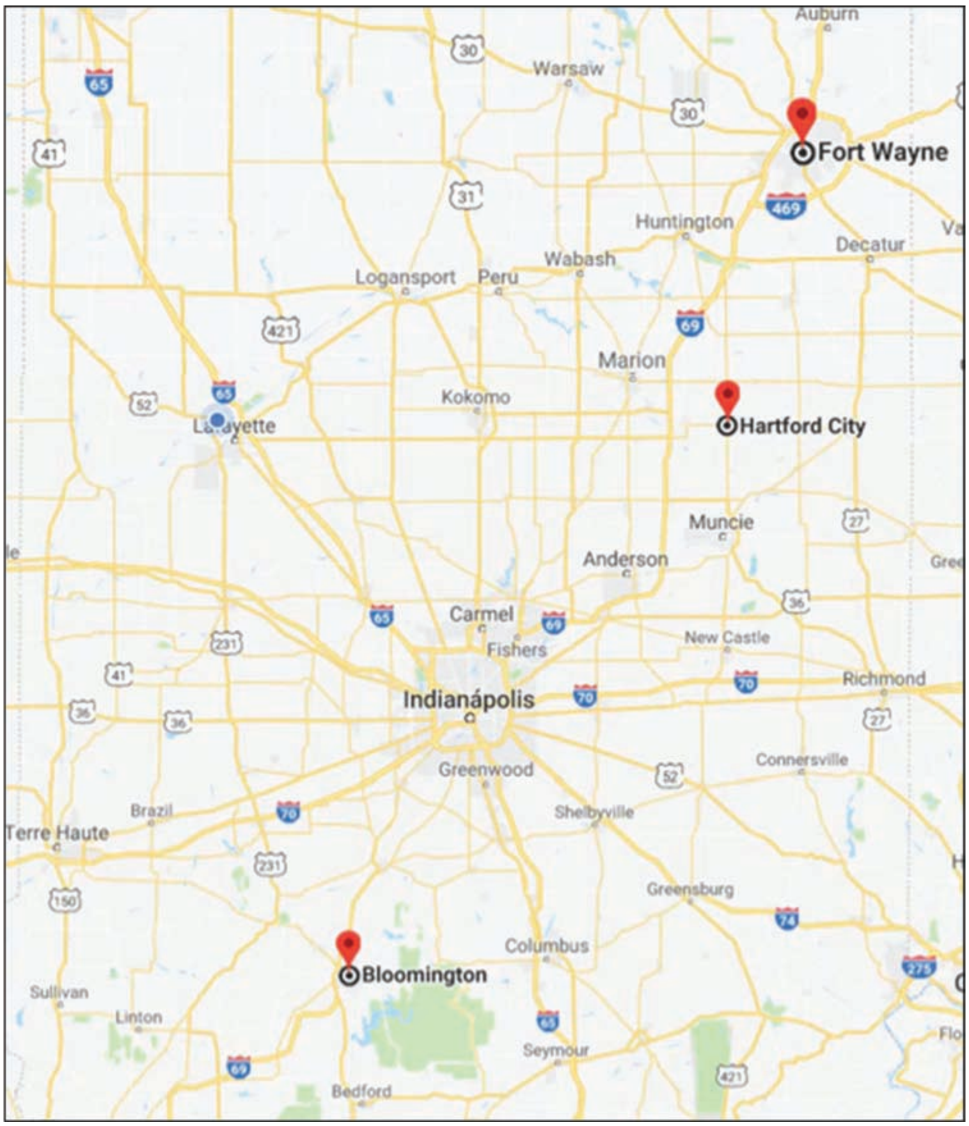


Figure 2.1 Location of the sampling sites. Indiana.

TABLE 2.1
Results of classification tests for the five soils

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
Fort Wayne	43.00	14.10	28.90	82.00	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

3. OPTIMUM AMOUNT OF TREATMENT

Four soils, HC, BM1, BM2, and FW were treated with Lime Kiln Dust (LKD), cement, or equal amounts of LKD and cement, when possible. Results of treatment with quick lime (QL) and LKD were compared for the same soil (BM3), for verification purposes. 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. Compaction curves for the Standard Proctor energy were prepared for all untreated and treated soils. The Standard Proctor test, following AASHTO T-99, was performed on the untreated soils. To minimize the amount of soil used for compaction, Harvard Miniature tests were performed for the treated soils, after extensive calibration to determine the number of layers and tamps per layer, such that the same results as the Standard Proctor tests were obtained. The compaction curves for the mixtures of soils with different treatments can be seen in Figures C.1 to C.5 for HC, BM1, FW, BM2, and BM3, respectively. Results for maximum unit weight and optimum moisture content for all the soils and treatments are included in Table 3.1, which also shows the optimum amount of treatments.

3.1 Treatment with Lime Kiln Dust (LKD)

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: (1) a minimum pH of 12.4 following Eades and Grim pH test; and (2) an increase in the unconfined compression strength of 50 psi (344.7 kPa) after curing for 48 hours at 70°F (21°C) in a moisture room, following AASHTO T-208.

First, the pH tests were carried out, and the results are shown in Figure C.6. As seen in the figure, the amount of LKD required is 6% for HC and BM1, and 5% for FW and BM2. Regarding BM3 soil, it was desired using the same amount of LKD than that for BM2, i.e., 5%, then the pH for mixtures 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 C.7 to C.10 show results of unconfined compression strength tests for the optimum LKD content after 48 hours of curing, for HC, BM1, FW, and BM2, respectively. As seen in the figures, the increase in unconfined compression strength after 48 hours was larger than 50 psi in all the cases.

3.2 Treatment with Cement

The pozzolanic reaction is guaranteed when using cement with any soil, and so a minimum pH must not be reached. Thus, 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 100 psi (689.5 kPa), after curing for 48 hours at 70°F (21°C) in the moisture room, is required. Mixtures with 3% cement were initially prepared; if the strength criterion was not reached, the amount of cement was increased by 1% and samples for unconfined compression tests were prepared and tested. Results of unconfined compression strength tests, for the optimum amount of cement, are shown in Figures C.7 to C.10 for HC, BM1, FW, and BM2, respectively. Results from those samples that did not reach the strength criterion with 3% cement are shown in Figure C.11. This only occurred for the highly plastic soils of Bloomington #2.

3.3 Treatment with LKD Lime and Cement

To determine the optimum amount of LKD and cement (together) needed for stabilization, only the strength criterion must be satisfied. In this case, an increase in the unconfined compression strength of 75 psi (517.1 kPa), after curing for 48 hours at 70°F (21°C) in the moisture room, is required. The samples were compacted using the same amount of LKD and cement. Mixtures with 2% LKD and 2% cement were initially prepared, and the strength criterion was checked. When the minimum strength was not reached, the amounts of treatment were increased to 3% LKD and 3% cement. Figures C.8 and C.10 show, respectively, the unconfined compression strength results for BM1 and BM2 mixed with the optimum amount of LKD and cement. Two soils were not tested: FW because the amount of soil was limited and so it was not possible to make the specimens required; and HC because the amount of cement required, for treatment with cement only, was 3% and the treatment with 2% LKD and 2% cement was not successful. It was decided that the mixture of cement and LKD was not economically competitive compared with the treatment with cement

TABLE 3.1
Summary of optimum amount of treatment, maximum unit weight and optimum moisture content for the four soils treated

Site	Optimum LKD			Optimum Cement			Optimum Cement + LKD			Optimum Cement + LKD		
	Amount (%)	γ_d (pcf)	OMC (%)	Amount (%)	γ_d (pcf)	OMC (%)	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	2 + 2	106.1	20.2	—	—	—
Fort Wayne	5	113.6	15.6	3	117.9	14.8	—	—	—	—	—	—
Bloomington #2	5	98.6	26.3	5	101.1	25.7	2 + 2	99.8	26.4	—	—	—
Bloomington #3	5	101.1	23.1	—	—	—	—	—	—	5	101.8	22.7

Note: OMC = optimum moisture content.

or LKD only. Figure C.12 shows the results of the mixtures of HC with 2% + 2% LKD that did not reach the required strength.

Table 3.1 shows a summary of the results discussed in Sections 3.1 to 3.3. As seen in the table, the optimum amount of treatment varies between 5% and 6% for LKD, between 3% and 5% for cement, and is 2% LKD + 2% cement. It is also seen in Table 3.1 that the optimum amount of cement for the soil with the largest plasticity (BM2) is large compared to the other soils (5% vs. 3%).

4. EFFECT OF TREATMENT ON PLASTICITY AND GRAIN SIZE DISTRIBUTION

The effect of treatment on the soil's plasticity and grain size distribution was evaluated. The investigation was performed because changes in the type of soil would be beneficial for the PavementME. Atterberg limits and grain size analysis were performed following the standards AASHTO T-89/T-90 and AASHTO T-88, respectively. The tests were conducted on natural soils and on samples treated with Lime Kiln Dust (LKD), cement and cement + LKD.

To assess the effect of the age of the treatment on the soil's plasticity, Atterberg limits were carried out on samples cured at different times. For mixtures with LKD, samples at 2, 7, 28, and 90 days were tested. For mixtures with cement, and LKD + cement, the curing periods were 2, 7, and 28 days. For a small number of samples, Atterberg limits were performed at longer times. Results of the Atterberg limits at different times and for different treatments are shown in Figures D.1 to D.3 for HC soils, in Figures D.4 to D.7 for BM1, in Figures D.8 to D.10 for FW, and in Figures D.11 to D.14 for BM2.

The effect of treatment on the soil's plasticity is relatively similar for all the mixtures. The liquid limit (LL) either increased somewhat during the first 7 days and later decreased with time to values very close to those of the untreated soil, or slightly decreased somewhat with treatment from the beginning. Regarding the plastic limit (PL), there was always an increase with treatment, larger than the increase in LL, if any was observed. The larger increase in PL triggered a decrease in the plasticity index (PI) of the soil. As seen in Figure 4.1 and in more detail in Figures D.1 to D.14 in the Appendices, the major reduction in plasticity is seen before 28 days, even though some additional decrease is observed for longer times.

The comparison of the effect of different treatments (LKD, cement or LKD + cement) can be summarized as follows: (1) For BM1 soil (6% LKD, 3% cement, 2% LKD + 2% cement), the largest decrease in plasticity is with LKD, followed by cement, while the smallest decrease occurs with mixtures with LKD + cement; (2) For FW (5% LKD and 3% cement), the decrease in PI is relatively the same in both cases; (3) For BM2 (5% LKD, 5% cement, 2% LKD + 2% cement), the largest decrease in PI is seen for mixtures with cement, with a smaller decrease in PI for mixtures with LKD or LKD + cement. As seen in Figure D.3, the effect of type of treatment on plasticity for HC cannot be determined, as the untreated soil used for mixtures with LKD had different initial plasticity than that mixed with cement, even though in both cases the soils are classified as A-6. The larger decrease in plasticity occurred in BM2 + cement, which was reduced by 20% (from 45.2% to 25.2%) after 50 days of treatment. The smallest effect on PI was seen for BM1, which decreased 1.3% (from 24% to 22.7%) after 70 days of treatment with 2% cement + 2% LKD.

To determine the grain size distribution, moist samples of treated or untreated soils were washed through # 200 sieve prior to the sieve analysis. The effect of time on grain size was not evaluated, given that all the tests were performed at ages between 75 and 190 days from treatment. Figures D.15 to D.18 show curves of grain size distribution for samples HC, BM1, FW, and BM2, respectively. There is not a clear trend for the effect of treatment on the grain size distribution. Even though there is always some increase in the grain size for soils mixed at the optimum amount of treatment, the changes show no clear trend, i.e., the changes are important for some soils and almost negligible for others, and it is not clear if the changes are more pronounced with LKD, cement or LKD + cement. The larger increase in particle size was for HC + cement at 190-days curing, which reduced the passing # 200 from 88.2% to 55.4% (37% reduction). The smaller increase in size was for BM1 + LKD at 170-days curing, which

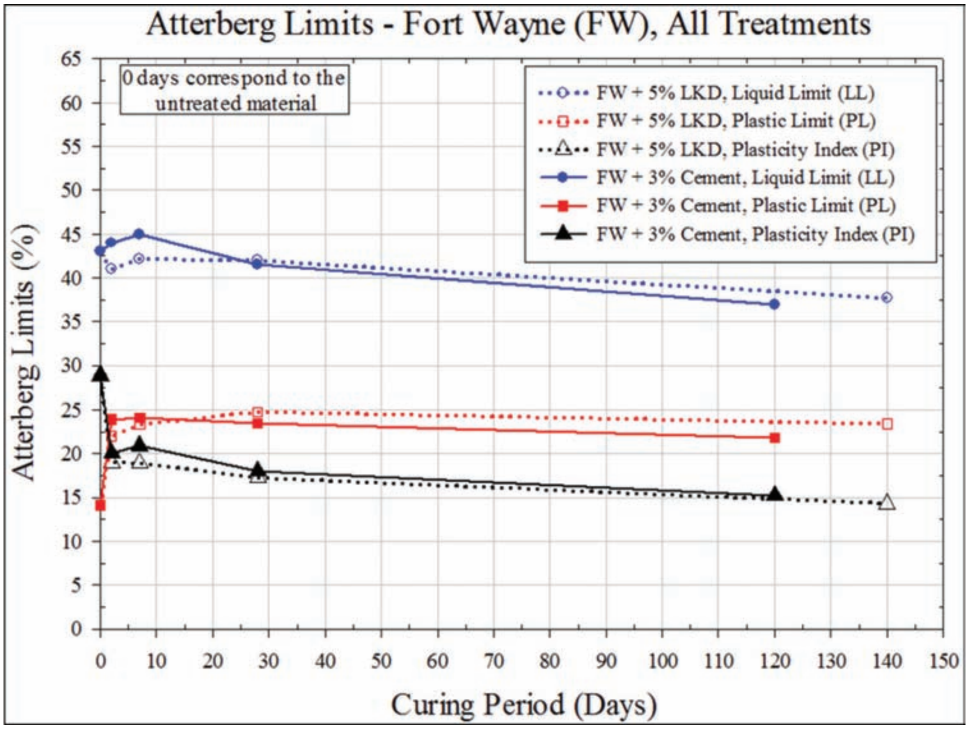


Figure 4.1 Atterberg limits for untreated and treated soils with optimum amounts of LKD or cement at different curing periods. Fort Wayne (FW).

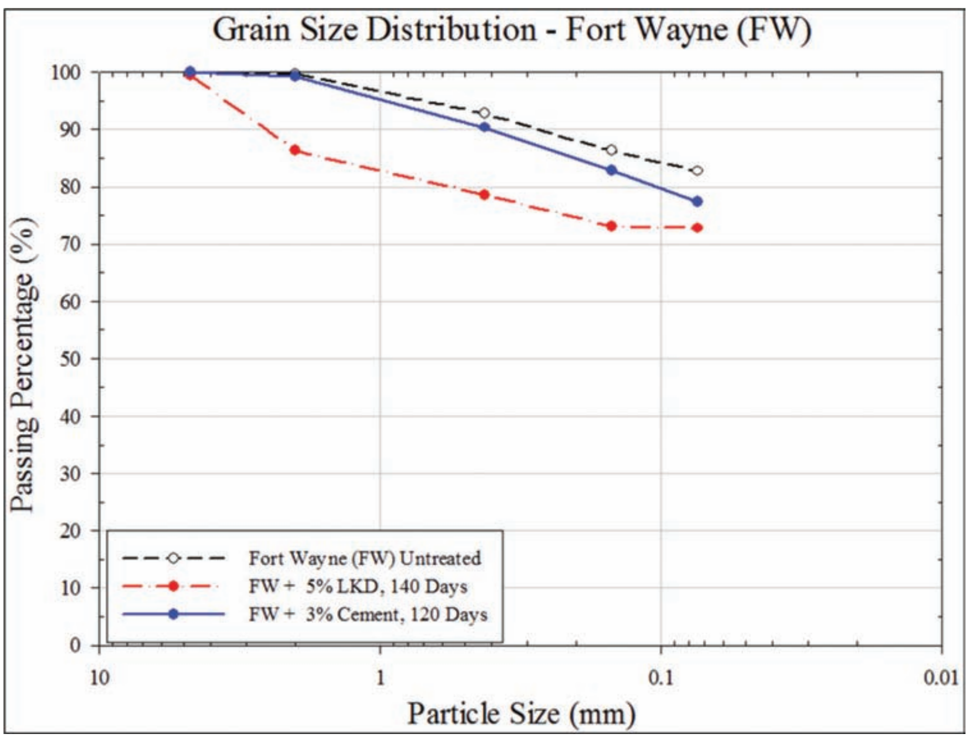


Figure 4.2 Grain size distribution for untreated and treated soils with optimum amounts of LKD or cement. Fort Wayne (FW).

reduced the passing # 200 from 88.4% to 83.6% (5.4% reduction).

Even though the plasticity decreased, and the grain size increased for all the soils investigated (Figures D.1 to D.18), the changes were not enough to change the type of soil, and only one soil, FW, changed from A-7-6 to A-6. For illustration purposes, Figures 4.1 and 4.2 show, respectively, the Atterberg limits and grain size distribution, for the FW soil treated with LKD or cement.

5. EFFECT OF TREATMENT ON THE UNCONFINED COMPRESSION STRENGTH

The unconfined compression strength, after 48 hours curing, is used as a criterion to define the optimum amount of treatment. In this research, samples for unconfined compression strength, using the optimum amount of treatment and compacted at the same densities, were prepared to be tested at different times; more exactly, at the same age at which the Atterberg limits were obtained. That is, unconfined compression tests were performed at 2, 7, 28, and 90 days after sample preparation for mixtures with Lime Kiln Dust (LKD), and at 2, 7, and 28 days for mixtures with cement or LKD + cement. The unconfined compression tests were conducted to evaluate if there is any trend in the increase in strength with time. Results of unconfined compression tests for different ages and treatments are shown in Figures E.1 and E.2 for HC soil, in Figures E.3 to E.5 for BM1, in Figures E.6 and E.7 for FW, and in Figures E.8 to E.10 for BM2 soil. As expected, the unconfined compression strength of the soils increases with the treatment with LKD, cement or LKD + cement. Table 5.1 shows, for the four soils, the strength for each untreated soil as well as for each treatment after 28-days curing. The table also shows the strength gained as a percentage of the initial (untreated) strength. As seen in Table 5.1, the larger increase in strength, with respect to the untreated soil, occurred for BM2 + cement (40/276 to 285/1965 psi/kPa, i.e., 613%), and the smaller increase in strength for HC + LKD (60/414 to 134/924 psi/kPa, i.e., 123%).

To illustrate the variation in strength with time, Figure 5.1 compares the increase in unconfined compression strength after 2-days curing with the increase in unconfined strength after 28-days curing for the BM1

TABLE 5.1
Comparison between unconfined compression strength for untreated and treated soil after 28-days curing, for the four soils investigated and for all treatments

Site	q_u Untreated (psi/kPa)	Optimum LKD		Optimum Cement		Optimum Cement + LKD	
		q_u (psi/kPa)	Incr. (%)	q_u (psi/kPa)	Incr. (%)	q_u (psi/kPa)	Incr. (%)
Hartford City (HC)	60/414	134/924	123	235/1620	292	—	—
Bloomington #1 (BM1)	38/262	180/1241	374	185/1276	387	184/1269	384
Fort Wayne (FW)	56/386	190/1310	239	292/2013	421	—	—
Bloomington #2 (BM2)	40/276	89/614	123	285/1965	613	121/834	203

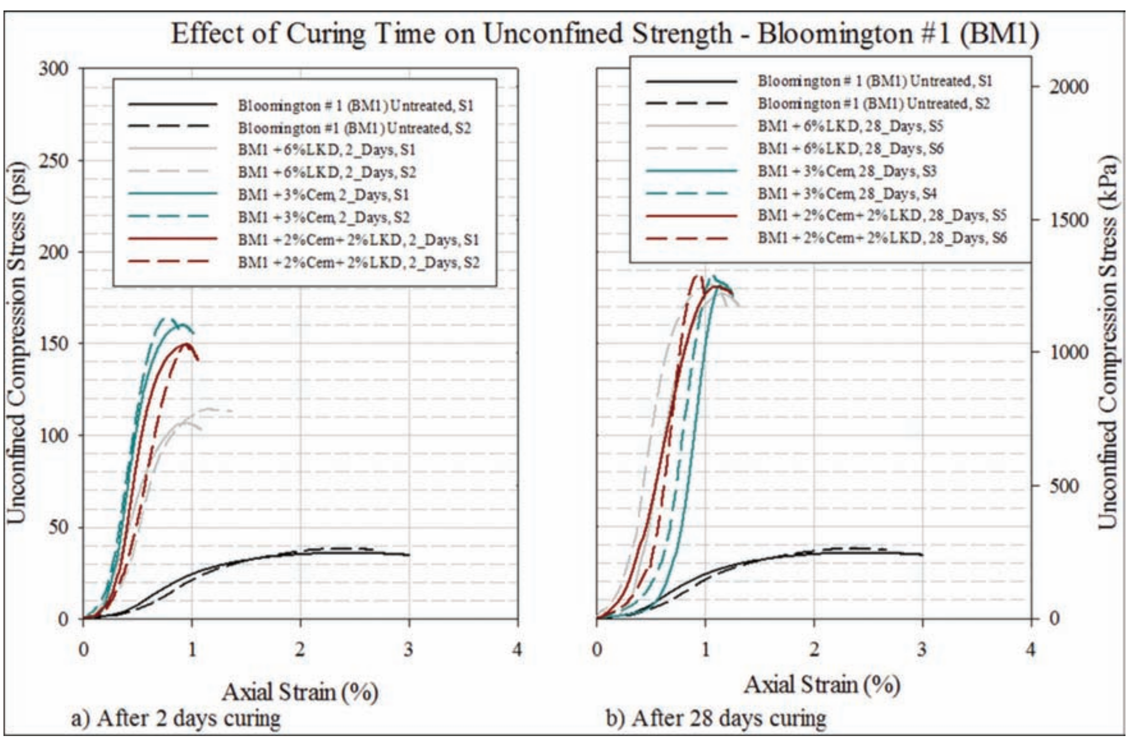


Figure 5.1 Unconfined compression strength for untreated soil and for soil with optimum amount of treatment after 2- and 28-days curing. Bloomington #1 (BM1).

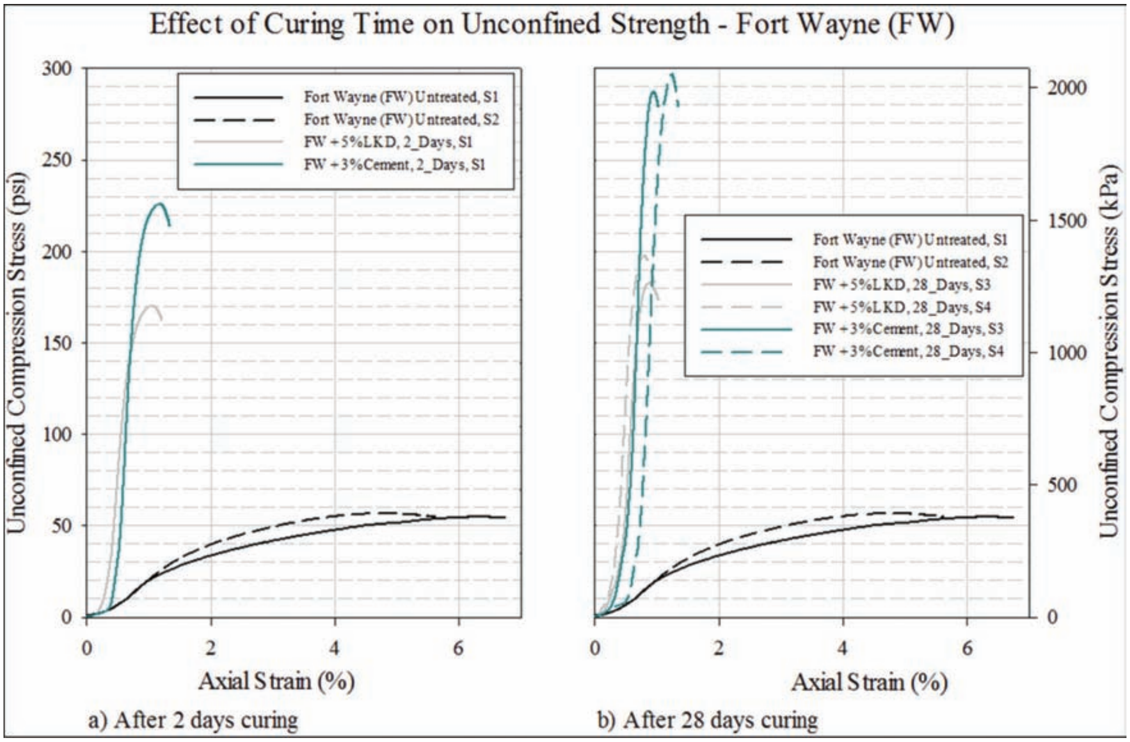


Figure 5.2 Unconfined compression strength for untreated soil and for soil with optimum amount of treatment after 2- and 28-days curing. Fort Wayne (FW).

soil treated with LKD, cement and cement + LKD. As seen in the figure, the mixture with LKD had the larger increase in strength between 2 and 28 days (≅69/476 psi/kPa), followed by the mixture with cement + LKD (≅34/234 psi/kPa), while the mixture with cement had the smallest increase in strength (≅23/159 psi/kPa). This behavior is opposite to that seen for the other three soils, where in general a larger effect of the curing time on the strength is seen for mixtures with cement (see Figures E.1 to E.10 in the Appendices). For illustration purposes, Figure 5.2 shows the same comparison for the FW soil. In this case, the larger increase in the unconfined strength with time is seen for mixtures with cement (≅66/455 psi/kPa), while the soil with LKD only increased its strength about 20/138 psi/kPa, between 2- and 28-days curing. It must be noted that soils BM1 and FW had relatively similar plasticity and both are classified as A-7-6 (see Table 2.1), so the differences in the effect of time on the increase in shear strength cannot be associated to the plasticity of the soil, but perhaps to other characteristics such as mineralogy, etc.

Finally, Figures 5.1 and 5.2, and in more detail Figures E.1 to E.10 in the appendices, show an increase of stiffness of the soil with treatment and a decrease of the strain at which the peak strength is reached.

6. EFFECT OF OPTIMUM AMOUNT OF TREATMENT ON THE RESILIENT MODULUS

One of the main motivations for this research was the evaluation of the change in stiffness of fine-grained soils (A-6 and A-7-6) when treated with Lime Kiln Dust (LKD), cement or combinations of LKD + cement. The reason for this is that current application of the PavementME in Indiana does not use the actual (improved) stiffness of the treated soils.

Remolded samples of soil compacted at 95% of the Standard Proctor energy were prepared to conduct resilient modulus tests, following AASHTO T 307-99 (American Association of State and Highway Transportation Officials, 2007) for Type 2 Material, i.e., fine-grained soils. The effect of curing time on the soils' stiffness was also evaluated in a manner similar to what was done for plasticity, granulometry and strength. For mixtures with LKD, samples at 7-, 28-, and 90-days of age were tested. For soils mixed with LKD or LKD + cement, the curing periods were 7 and 28 days. For HC + LKD, a sample was also tested after 2 days of curing. 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) and 6 psi (41.4 kPa), 8 psi (55.2 kPa) and 10 psi (69 kPa) were used. In total, 31 M_R tests on soils with optimum amount of treatment were conducted. For comparison purposes, and for the FW soil only, a sample was tested with 1% of LKD below the optimum. Table F.1 shows all the results from the M_R tests.

As seen in the Appendices, in Table F.1 and in Figures F.1 to F.10, for the same soil and test conditions, smaller or larger values of M_R are obtained for any of the confinement stresses (σ_3 = 2, psi = 13.8 kPa,

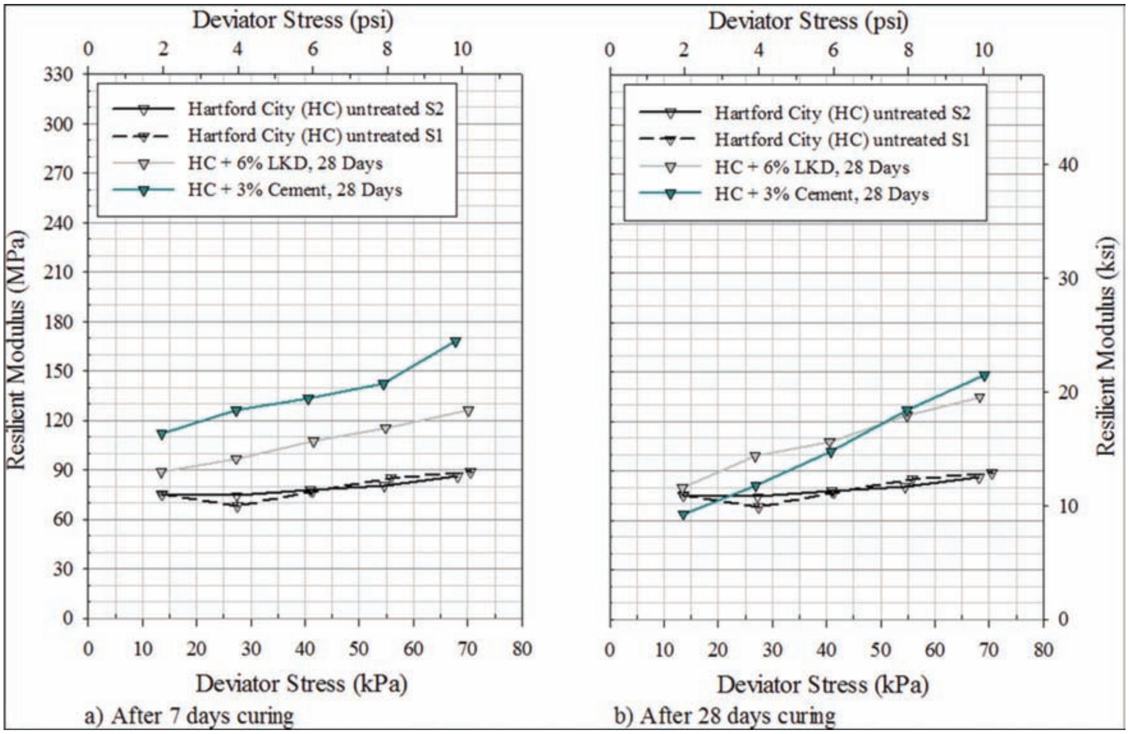


Figure 6.1 Resilient modulus for untreated soil and for soil with optimum amount of treatment after 7- and 28-days curing. Hartford City (HC).

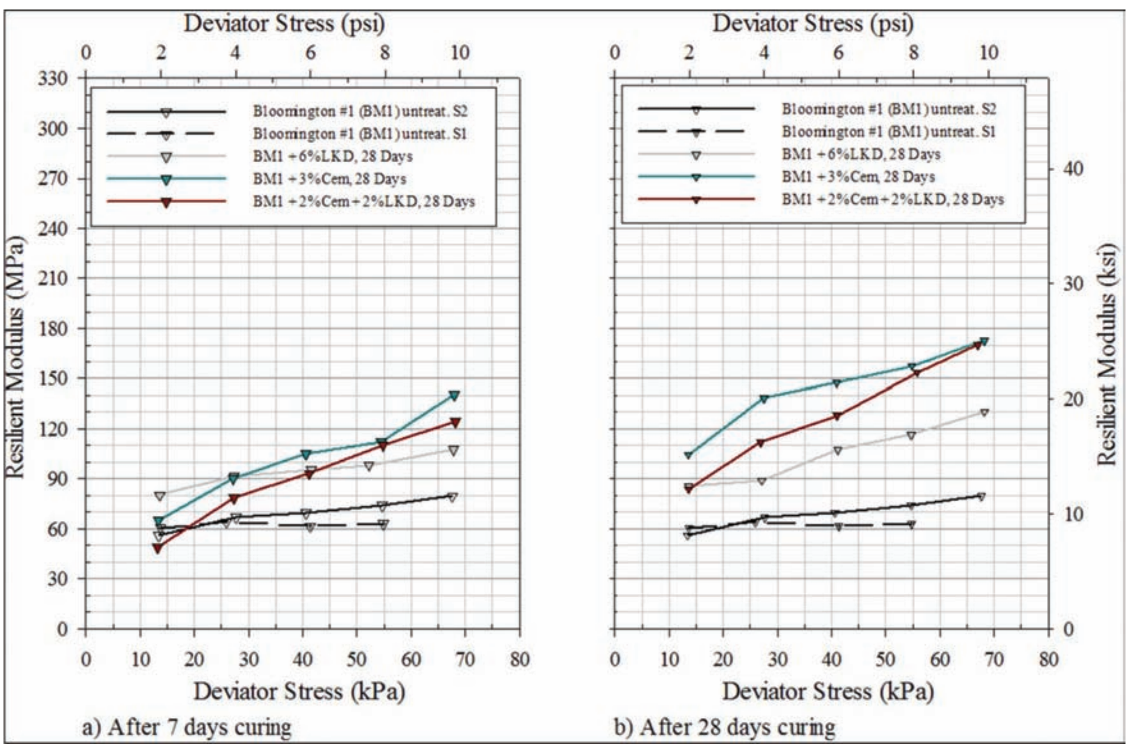


Figure 6.2 Resilient modulus for untreated soil and for soil with optimum amount of treatment after 7- and 28-days curing. Bloomington #1 (BM1).

4 psi = 27.6 kPa, or 6 psi = 41.4 kPa); so there does not seem to be a clear effect of confinement on M_R. In the following, only the intermediate confinement stress (4 psi = 27.6 kPa) is included for discussion. Figures 6.1 to 6.4 show results of M_R values for untreated and treated soils (with LKD, cement and cement + LKD)

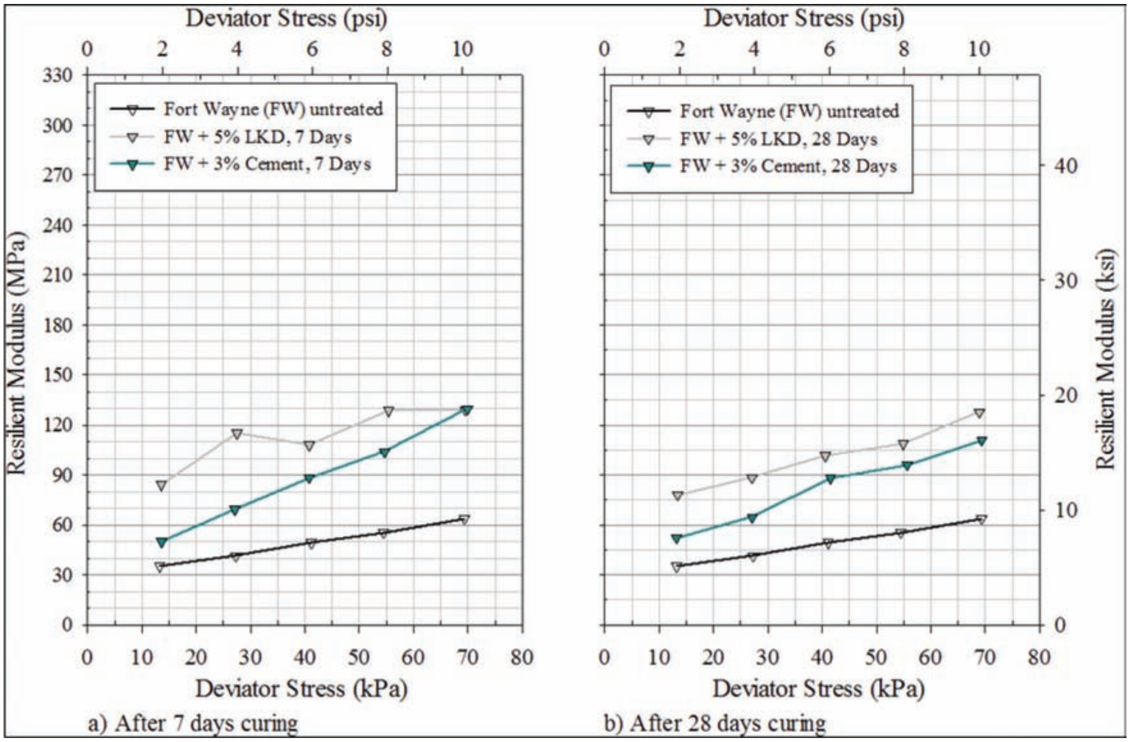


Figure 6.3 Resilient modulus for untreated soil and for soil with optimum amount of treatment after 7- and 28-days curing. Fort Wayne (FW).

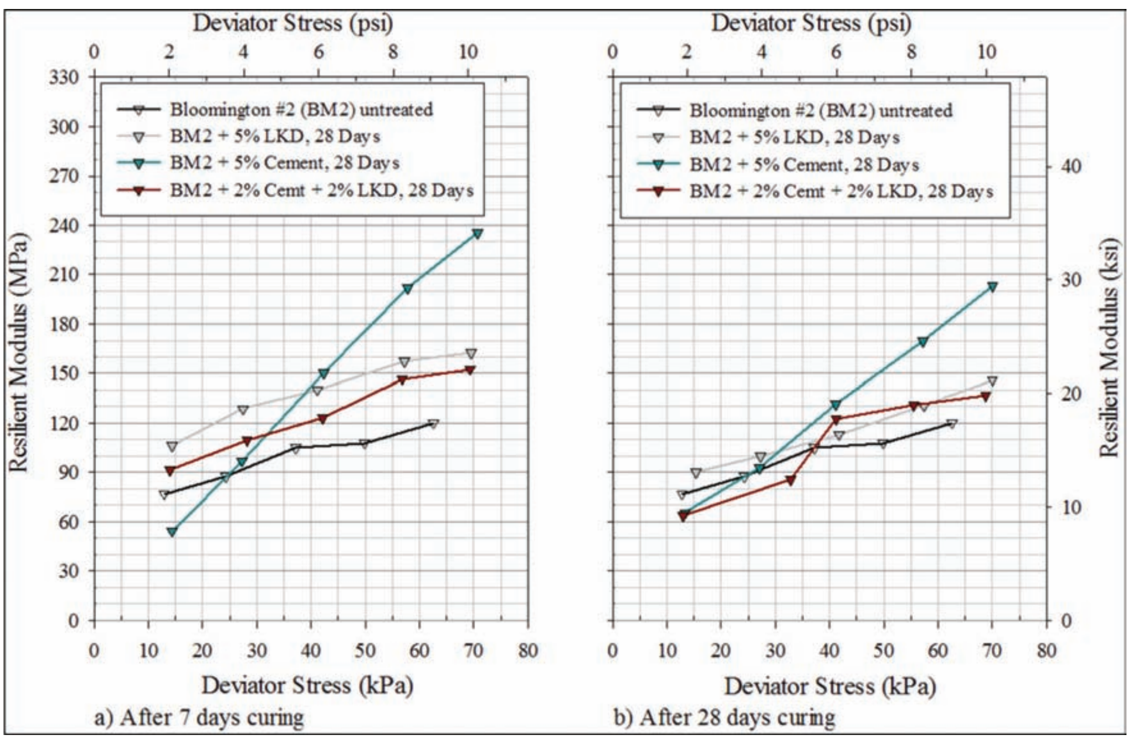


Figure 6.4 Resilient modulus for untreated soil and for soil with optimum amount of treatment after 7- and 28-days curing. Bloomington #2 (BM2).

after 7- and 28-days curing for HC, BM1, FW, and BM2 soils, respectively. The following comments can be made:

There is a clear increase in the stiffness of the soil when mixed with any treatment, especially for larger deviatoric stresses $\sigma_d \geq 4$ psi (27.6 kPa). The increase is, in general, more remarkable for samples containing cement and gets larger with the amount of cement (see BM2 with 5% cement in Figure 6.4). The increase in stiffness with deviatoric stress is less noticeable for untreated soils.

There is not a clear trend on the effect of curing time (7 versus 28 days) for soils mixed with LKD, cement or cement + LKD. For some samples, the M_R values for 7 days are a little larger than for 28 days (e.g., HC + cement in Figure 6.1, BM2 with all the treatments in Figure 6.4), while for other samples, M_R values for 7 days are smaller than for 28 days (e.g., HC + LKD in Figure 6.1, BM1 with all the treatments in Figure 6.2). These differences however fall within experimental error or soil variability and so no large differences between the results at 7 and 28 days are obtained. It is important to note, however, that for 90-days curing, both HC and BM1 soils mixed with LKD, showed an important increase in stiffness for all confinements and deviatoric stresses, (see Table F.1 and Figures F.1 and F.3 in the appendices). This is expected since pozzolanic reactions continue over time, and so the longer the time lapse after preparation, the larger the effects of the treatment. Note however that the results indicate, again as expected, that the largest increase in stiffness occurs shortly after treatment, while the improvement is gradual over time.

For the optimum amount of treatment, M_R values are in general larger for mixtures with cement than with LKD. M_R values for mixtures with cement + LKD tend to fall within the two treatments. For discussion purposes, Table 6.1 shows M_R values for $\sigma_3 = 4$ psi and $\sigma_d = 6$, 8, and 10 psi. The increase in stiffness with respect to untreated soil is also provided. As seen in the table, the increase in stiffness ranges between 8% for BM2 + LKD, at $\sigma_d = 6$ psi and 28-days curing, and 132% for FW + LKD at $\sigma_d = 8$ psi and 7-days curing. It is also seen that there is at least one treatment for each soil (LKD, cement or cement + LKD) that at least doubles (increase in stiffness of about 100%) the stiffness of the untreated soil. This is an important finding that could be considered when designing the pavement structure.

It must be noted that the increase in M_R with treatment, with respect to the natural soil, is smaller compared to the increase in the unconfined compression strength, which, at 28-days curing, ranged between 123% and 613%, as shown in Table 5.1. The effect of time and type of treatment on the unconfined compression strength is also different than that for the resilient modulus. For example, the important increase in unconfined strength for FW + cement, much larger than for FW + LKD, does not occur in terms of stiffness, where larger values of M_R were obtained for mixtures with LKD.

TABLE 6.1
Comparison between resilient modulus (M_R) for untreated soil and after 7- and 28-days curing, for the four soils and all the treatments

Site	Untreated			Optimum LKD						Optimum Cement						Optimum Cement + LKD					
	Deviatoric Stress, σ_d (psi)			Deviatoric Stress, σ_d (psi)						Deviatoric Stress, σ_d (psi)						Deviatoric Stress, σ_d (psi)					
	6	8	10	6		8		10		6		8		10		6		8		10	
	Resilient Modulus, M_R (ksi)			Resilient Modulus at 7- and 28-Days Curing Period, M_R (ksi)						Resilient Modulus at 7- and 28-Days Curing Period, M_R (ksi)						Resilient Modulus at 7- and 28-Days Curing Period, M_R (ksi)					
				7/28	Inc. (%)	7/28	Inc. (%)	7/28	Inc. (%)	7/28	Inc. (%)	7/28	Inc. (%)	7/28	Inc. (%)	7/28	Inc. (%)	7/28	Inc. (%)	7/28	Inc. (%)
HC	11.2	12	12.7	15.6	39	16.8	40	18.3	44	19.3	72	20.6	72	24.4	92						
				15.6	40	17.9	49	19.6	54	14.8	32	18.4	54	21.5	69						
BM1	9.5	9.9	11.5	13.9	46	14.2	43	15.6	35	15.2	60	16.3	64	20.4	77	13.5	42	16	61	18	56
				15.6	64	16.9	70	18.9	64	21.4	125	22.8	130	25.1	117	18.5	95	22.3	124	24.7	113
FW	77.2	88.1	19.3	15.7	120	18.7	132	18.7	102	12.8	79	15.1	87	18.8	103						
				14.8	107	15.8	95	18.6	100	12.8	79	14	73	16.1	74						
BM2	15.2	15.6	17.4	20.3	34	22.8	46	23.6	35	21.8	43	29.3	87	34.1	96	17.9	17	21.2	36	22.1	26
				16.4	8	18.9	21	21.2	21	19	25	24.6	57	29.5	69	17.8	17	19	21	19.8	14

7. EFFECT OF OVERDOSING THE TREATMENT ON PLASTICITY, GRAIN SIZE, SHEAR STRENGTH AND RESILIENT MODULUS

The effects of overdosing, (increasing the amount of treatment beyond optimum) on plasticity, grain size, unconfined compression strength and resilient modulus was investigated by conducting additional tests for one A-6 soil (HC) and one A-7-6 soil (BM2). The treatment was doubled, compared to the optimum, for mixtures with Lime Kiln Dust (LKD) and cement. Samples for unconfined compression and Atterberg limits tests were cured for 28 and 90 (or 120) days; for the resilient modulus tests the samples were cured for 28 (or 35) days; and for the grain size distribution the curing period was 150 (or 180) days.

Results of all the tests conducted on both soils (HC, BM2) are shown in the Appendices. Figures G.1 and G.2 show compaction curves; Figures G.3 to G.6, Atterberg limits; Figures G.7 and G.8, grain size distribution; Figures G.9 to G.12, unconfined compression strength; and Figures G.13 to G.16, resilient modulus. For comparison purposes, results of the same tests with the optimum amount of treatment are also included in the figures.

7.1 Effect of Overdosing on Plasticity and Grain Size Distribution

Atterberg limits and grain size analysis were performed on samples with overdosed LKD and cement, following the standards AASHTO T-89/T-90 and AASHTO T-88, respectively. As done for untreated and treated samples with the optimum amount of treatment for the grain size distribution, moist samples were washed through # 200 sieve prior to the sieve analysis. These tests were performed on samples cured at 150, 180, or 190 days. The Atterberg limits were conducted on samples cured for 28 and 90 (or 120) days. Results of the Atterberg limits tests can be seen in Figures G.3 and G.4 for HC soil; and in Figures G.5 and G.6 for BM2 soil. For the grain size distribution, the results are shown in Figures G.7 and G.8 for HC and BM2, respectively. For illustration purposes, Figure 7.1 shows Atterberg limits and grain size distribution curves for BM2 soil mixed with overdosed cement and LKD. As it can be seen in the figure, there is an important decrease in the liquid limit and an important increase in the plastic limit, which triggers a considerable reduction in the plasticity index. This is somewhat different from what was seen with the optimum amount of treatment, where the liquid limit was similar or increased a little with treatment, and the reduction in plasticity index was less noticeable. The decrease in fines content in Figure 7.1 is also evident. As expected, the decrease in plasticity and fines content is larger compared to that obtained with the optimum amount of treatment. As a result, the type of soil is changed in all cases. For the BM2 soil shown in Figure 7.1, the A-7-6 soil changed to A-7-5 and A-5 for treatment with LKD and cement, respectively. For the

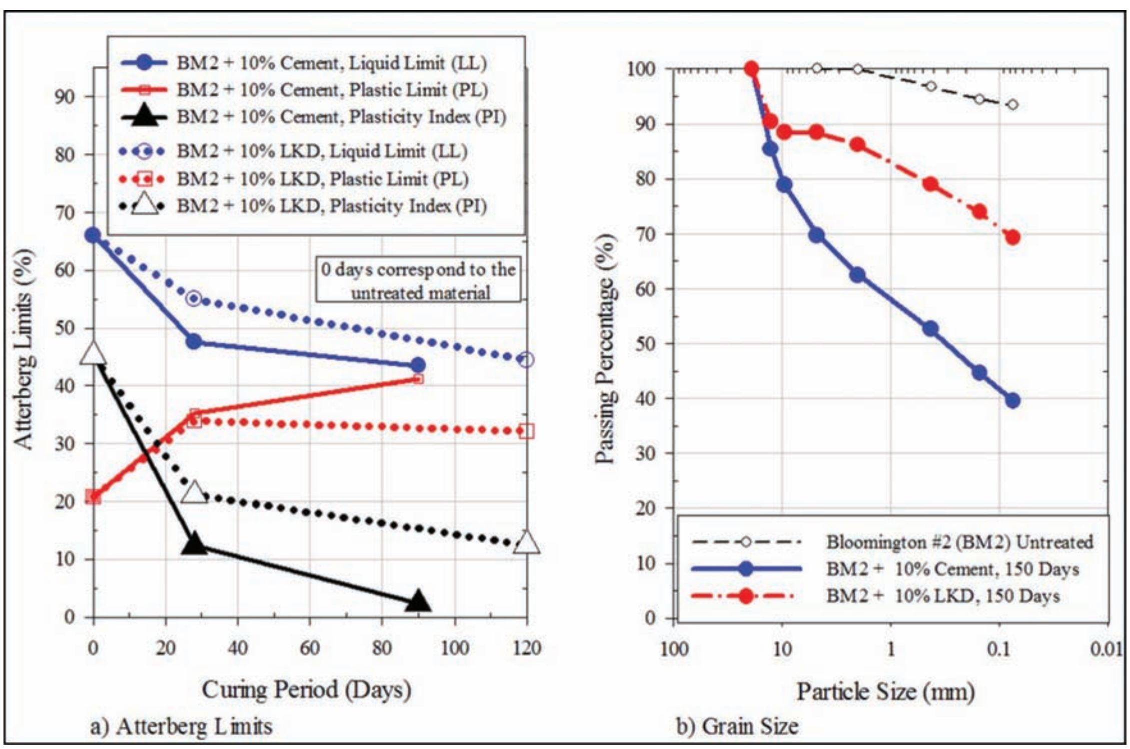


Figure 7.1 Atterberg limits and grain size distribution for treated soils with overdosed LKD and cement. Bloomington #2 (BM2).

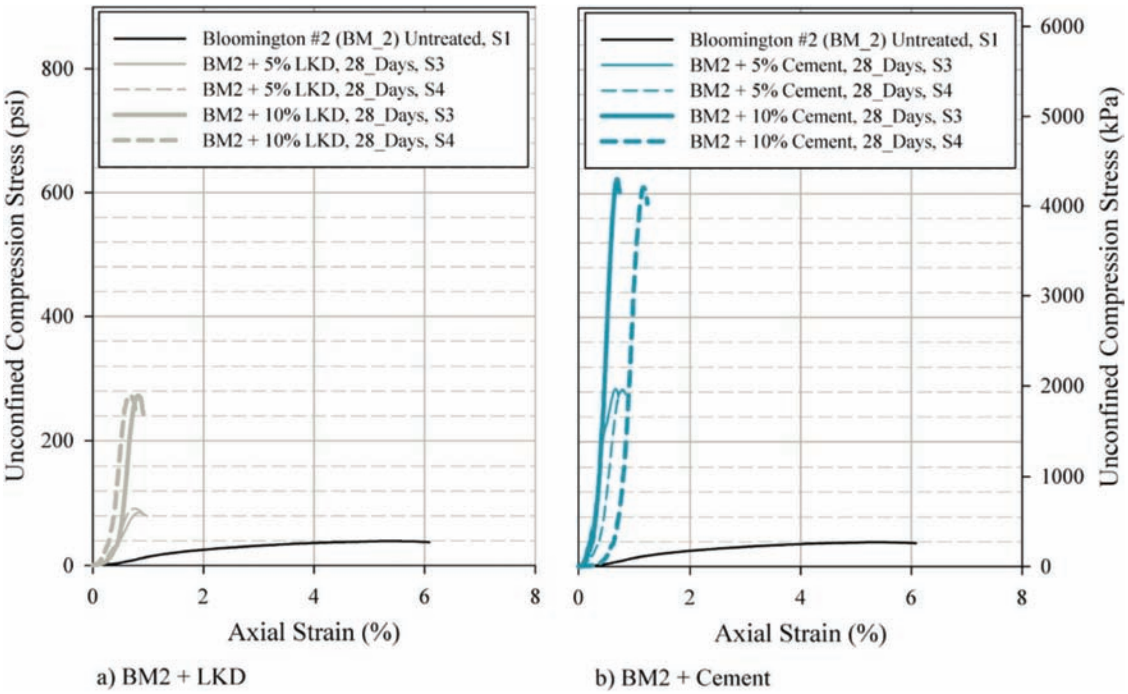


Figure 7.2 Unconfined compression strength for untreated soil and soil treated with optimum and overdosed LKD (left) and cement (right). Bloomington #2 (BM2) after 28-days curing.

HC (see results in Appendix G), the A-6 soil changed to A-4 and A-2-4, for treatment with LKD and cement, respectively. Thus, the overdosed treatment produced a change in the type of soil, which did not occur with the optimum amount of treatment shown in Chapter 4. For the two soils investigated, the overdosing with cement had a better effect changing the type of soil.

7.2 Effect of Overdosing on the Unconfined Compression Strength

Unconfined compression tests following the standard AASHTO T-208 were run for both soils and with overdosed treatments (LKD and cement) at different ages (28 and 90 days). Results are shown in the Appendices, in Figures G.9 and G.10 for HC, and in Figures G.11 and G.12 for BM2. For illustration purposes, Figure 7.2 compares the increase in strength after 28-days curing for BM2 soil treated with overdosed LKD (left) and cement (right). Results of untreated samples and samples with optimum amount of treatment are also included. As expected, the unconfined compression strength increased with the increase in the amount of treatment. Figure 7.2 also shows that the treatment with cement had a larger effect on the increase in strength, compared with the LKD.

7.3 Effect of Overdosing on the Resilient Modulus

Resilient modulus tests following the standard AASHTO T 307-99 (American Association of State and Highway Transportation Officials, 2007) were conducted for both soils and overdosed treatments (LKD and cement) after 28- or 35-days curing. Results are shown in the Appendices, in Figures G.13 to G.16, for both HC and BM2 soils. Table G.1 shows all the results from the M_R tests. For illustration purposes, Figure 7.3 compares the increase in stiffness for BM2 under the intermediate confinement stress, σ_3 = 27.6 kPa (4 psi) and Table 7.1 shows M_R values for σ_3 = 4 psi and σ_d = 6, 8, and 10 psi. Results of untreated samples and samples with optimum amount of treatment are also included. As seen in the figure, the increase in stiffness is more remarkable for the smallest deviatoric stress (σ_d = 13.8 kPa = 2 psi). As the deviatoric stress increases, the differences between stiffness obtained with overdosed and optimum amount of treatment decrease and are almost negligible for the largest deviatoric stress (σ_d = 69 kPa = 10 psi). Similar to what was observed for the Atterberg limits, grain size, and unconfined compression strength, a better effect on stiffness is obtained with cement than for LKD, for both the optimum and overdosed treatments.

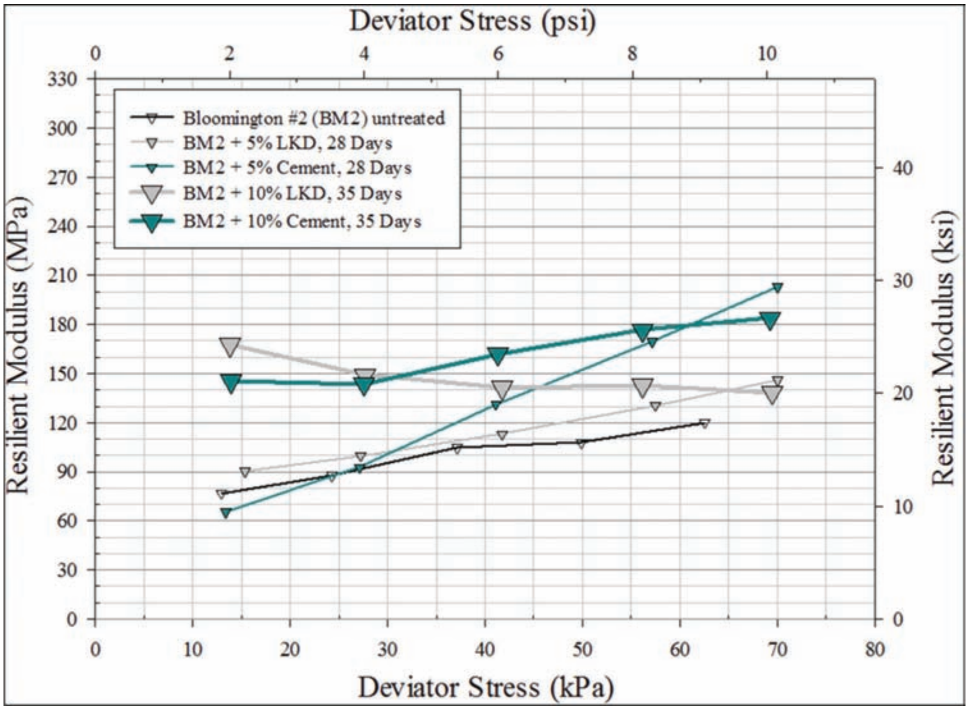


Figure 7.3 Resilient modulus for untreated soil and soil treated with optimum and overdosed LKD and cement. Bloomington #2 (BM2) after 28- and 35-days curing.

TABLE 7.1
Resilient Modulus (M_R) for LKD or cement overdosed HC and BM2 soils, 35-days curing

	Untreated			Overdosing LKD						Overdosing 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 at 35-Days Curing Period, M_R (ksi)						Resilient Modulus at 35-Days Curing Period, M_R (ksi)					
Site	Resilient Modulus, M_R (ksi)			35	Inc. (%)	35	Inc. (%)	35	Inc. (%)	35	Inc. (%)	35	Inc. (%)	35	Inc. (%)
HC	11.1	12.3	12.9	18.0	61.9	19.5	57.9	21.9	70.4	23.6	112.5	26.9	117.6	32.1	149.7
BM2	15.2	15.6	17.4	20.5	35.0	20.7	32.4	20.1	15.1	23.5	54.7	25.6	64.0	26.7	52.9

8. DIFFERENCE IN PLASTICITY, UNCONFINED COMPRESSION STRENGTH AND RESILIENT MODULUS BETWEEN LKD AND QUICK LIME

The effects of using two types of lime with differences in reactivity and chemical composition were investigated. As described in Chapters 1 to 7, most of the tests in this research were conducted using LKD, because most of the improvement of the subgrades in Indiana has been conducted using LKD. However, quick lime (QL) has also been used. Thus, it was suggested in the Study Advisory Committee (SAC) Meeting on March 2018, to conduct additional tests to compare results obtained for soils treated with LKD and with QL. For the comparison, Bloomington #3 (BM3) soil was used. As shown in Table 8.1, this soil has properties similar to those of BM2. This soil (BM3) was selected because there was not enough BM2 soil to conduct the additional experimental campaign. Samples for Atterberg limits tests were cured for 7 and 75 days; for unconfined compression strength, the samples were cured for 60 days; and for the resilient modulus tests, the curing period was 28 days.

The results for all the Atterberg limits tests are shown in Appendix H. For illustration purposes, Table 8.1 compares the Atterberg limits at 75 days for the two types of lime used (LKD and QL). As seen in the table, the QL has a larger effect on the reduction of the soil plasticity. The percentage in decrease in plasticity is approximately 65% when using QL, while it is only about 7% when using LKD. For the BM3 soil, using QL changes the soil from A-7-6 to A-7-5, and it is very

TABLE 8.1
Comparison of Atterberg limits BM3 mixed with LKD vs. QL

Untreated	Lime Kiln Dust (LKD)		Quick Lime (QL)	
Liquid Limit (%)	**Liquid Limit 75 Days (%)**	**Decrease (%)**	**Liquid Limit 75 Days (%)**	**Decrease (%)**
58.7	63	7.3	47.5	19.1
Plastic Limit (%)	**Plastic Limit 75 Days (%)**	**Increase (%)**	**Plastic Limit 75 Days (%)**	**Increase (%)**
21	28.1	33.8	34.2	62.9
Plasticity Index (%)	**Plasticity Index 75 Days (%)**	**Decrease (%)**	**Plasticity Index 75 Days (%)**	**Decrease (%)**
37.7	34.9	7.4	13.3	64.7

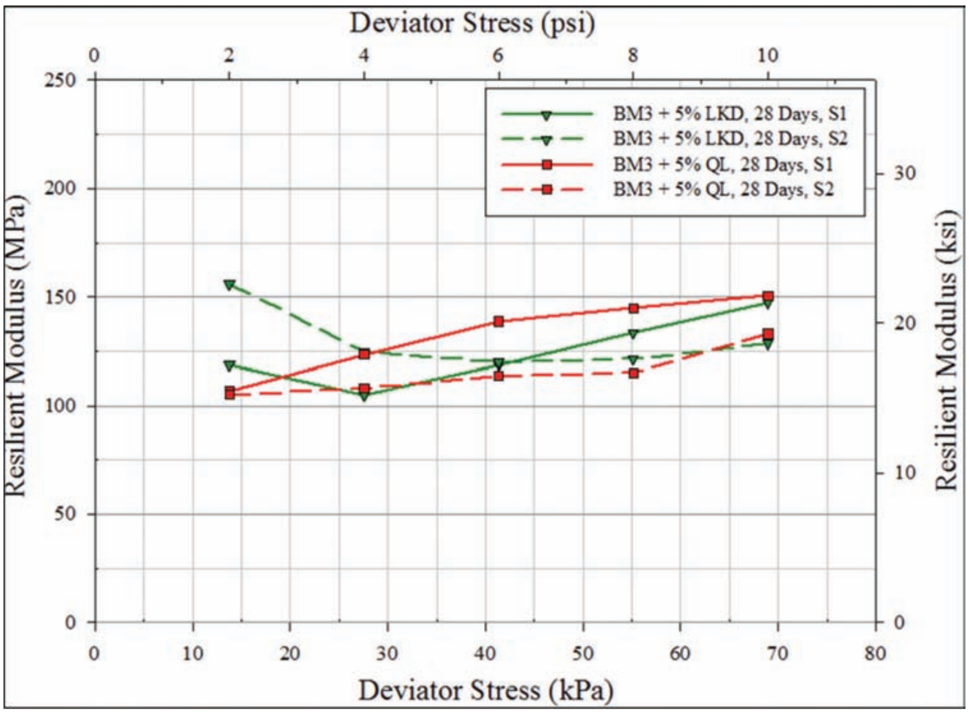


Figure 8.1 Resilient modulus for soil treated with optimum amount of LKD and QL after 28-days curing. Results for σ_d = 4 psi (27.6 kPa). Bloomington #3 (BM3).

close to changing it to A-5. For the samples treated with LKD, even though the plasticity decreases, the soil BM3 remains as A-7-6.

The results for the unconfined compression strength at 60 days are shown in Figure H.2 in the Appendices. The results show that, for the same age of the samples, there is a larger increase in unconfined compression strength for samples treated with QL than with LKD.

Figure H.3 in the Appendices shows results of resilient modulus tests for BM3 samples treated with LKD and QL. The figure includes two samples for each type of lime, the three confinement and the five deviatoric stresses required by the Standard AASHTO T 307-99 (American Association of State and Highway Transportation Officials, 2007). For illustration purposes, Figure 8.1 shows results for the intermediate confinement stress, σ_3 = 27.6 kPa (4 psi). As seen in the figure, unlike to what was observed with the Atterberg limits and unconfined compression strength, there is not a remarkable difference in the resilient modulus, when using LKD or QL. For the smallest deviatoric stress, σ_d = 13.8 kPa (2 psi), samples treated with LKD have larger stiffness. However, for the other deviatoric stresses, σ_d = 27.6 to 69 kPa (4 to 10 psi), results are very similar, and the differences fall within the experimental error.

9. EFFECT OF TREATMENT ON PAVEMENT PERFORMANCE USING THE MEPDG

For treated subgrades, current application of the PavementME in Indiana neglects the changes of the nature of the soil that can arise with treatment, i.e., A-6 or A-7-6 soils continue to be modeled as A-6 or A-7-6 soil, although there is some evidence that changes in the type of soil could occur (Jung & Bobet, 2008; Jung et al., 2009). The current application also neglects, to a great extent, the increase in stiffness with treatment.

For natural subgrades, the current application of PavementME in Indiana also appears to produce a double reduction in its stiffness, as the M_R values provided as input to PavementME are reduced to account for the site conditions, and a reference value, much smaller than typical values found in the literature for fine-grained soils, is assigned. Additionally, a further reduction in M_R is performed within the Enhanced Integrated Climatic Model (EICM) to account for the moisture conditions at the site. Comparisons of pavement performance were made by including more realistic properties of the untreated and treated subgrade in the PavementME. For the comparisons, the pavement structure used corresponds to that of the Fort Wayne I-469 project.

The characteristics of the pavement structure are listed below, as suggested by El Howayek et al. (2016).

- Design life: 20 years
- Pavement: Flexible-HMA
- Reliability level: 90%
- Climate station data: Fort Wayne, IN
- Water table depth: 2-ft
- Pavement structure: see Table 9.1

9.1 Comparison Using the Optimum Amount of Treatment

The properties for the subgrade are those obtained in the laboratory tests conducted on Fort Wayne (FW) soil in this research. Note that the FW soil had, in general, the smallest values of M_R for the untreated and treated samples. Five different scenarios were considered. In Scenario 1, the M_R values for treated and untreated subgrade given in Table 9.1, as recommended by INDOT, were used. In such Scenario, the LL, PI and fines content obtained for the FW soil were used for both the untreated and treated subgrade; that is 43%, 29%, and 83%, respectively. For Scenario 2, the initial M_R value of the natural subgrade was changed from 3.25 ksi to the values of the FW untreated, i.e., 7.5 ksi, while the other properties were kept as in Scenario 1. In Scenario 3, the initial M_R value for the treated subgrade was changed to 15.5 ksi, the average value obtained in the laboratory for FW + LKD at 28 days, while the other properties were as in Scenario 1. In Scenario 4, the type of soil, LL, PI and fines content for the treated subgrade (layer 4 in Table 9.1) were updated based on this research, for FW + LKD at 28 days (i.e., A-6, 38%, 14.5%, and 73%, respectively). Finally, in Scenario 5, all the changes in Scenarios 2, 3, and 4 were included. Results of IRI for the different scenarios are shown in Table 9.2. The failure year for the threshold IRI (160 in/mi) is also included. In the table, the changes in properties with respect to Scenario 1 are shown in red text.

As seen in Table 9.2, if realistic conditions for the stiffness and type of subgrade are considered (Scenario 5), the IRI is decreased by ≈ 5 in/mi, with an increased design life of ≈ 1.5 years, or by 8%. The best improvement for the other scenarios (2 to 4) is obtained when the stiffness of the subgrade corresponds to a more realistic value (Scenario 2). In this case, the IRI decreased by ≈ 3.5 in/mi, or the design life increased by ≈ 1 year (5%). It must be mentioned again that the cases analyzed corresponded to the soil that had the smallest increase in stiffness with treatment. If the other soils were considered, larger decreases in IRI, or increase in design life, would had been obtained.

TABLE 9.1
Pavement structure used for the MEPDG (adapted from El Howayek et al., 2016)

Layer	Layer Type	Material Type	Thickness (in)	M_R (ksi)
1	Flexible	Asphalt Concrete	1.5	—
2	Flexible	Asphalt Concrete	2.5	—
3	Flexible	Asphalt Concrete	10	—
4	Subgrade	A-7-6 (treated)	14	9
5	Subgrade	A-7-6 (untreated)	Semi-infinite	3.25

Note: 1 ksi ≈ 6.89 MPa.

9.2 Comparison Using the Overdosed Amount of Treatment

In this section the new properties obtained for the A-6 (HC) and A-7-6 (BM2) soil after overdosing with LKD and cement were included in the PavementME. Only Scenario 5 was evaluated, that is, considering realistic properties in terms of type of soil, plasticity, fines content, and stiffness, for both the untreated and the treated subgrade. Tables 9.3 and 9.4 show the

TABLE 9.2
Parametric analysis with PavementME for FW (A-7-6) soil

	Soil Properties Untreated Subgrade (Layer 5)					Soil Properties Treated Subgrade (Layer 4)						
Scenario	Class	LL (%)	PI (%)	Fines (%)	M_R (ksi)	Class	LL (%)	PI (%)	Fines (%)	M_R (ksi)	IRI at Reliability 19 Years (in/mi)	Failure Year
1	A-7-6	43	29	82	3.25	A-7-6	43	29	82	9	158.6	19.3
2	A-7-6	43	29	82	7.5	A-7-6	43	29	82	9	155.2	20.3
3	A-7-6	43	29	82	3.25	A-7-6	43	29	82	15.5	157.8	19.6
4	A-7-6	43	29	82	3.25	A-6	38	15	73	9	157.6	19.6
5	A-7-6	43	29	82	7.5	A-6	38	15	73	15.5	153.6	20.8

Note: 1 ksi ≈ 6.89 MPa.

TABLE 9.3
Parametric analysis with PavementME for HC (A-6) soil

	Soil Properties Untreated Subgrade (Layer 5)					Soil Properties Treated Subgrade (Layer 4)						
Scenario	Class	LL (%)	PI (%)	Fines (%)	M_R (ksi)	Class	LL (%)	PI (%)	Fines (%)	M_R (ksi)	IRI at reliability 19 years (in/mi)	Failure Year
1	A-6	37	15	88	3.25	A-6	37	15	88	9	157.1	19.8
5 (12% LKD)	A-6	37	15	88	11.5	A-4	32	2.6	50	23	149.8	22
5 (6% Cement)	A-6	37	15	88	11.5	A-2-4	32	5	28	26	147.8	22.7

Note: 1 ksi ≈ 6.89 MPa.

TABLE 9.4
Parametric analysis with PavementME for BM2 (A-7-6) soil

	Soil Properties Untreated Subgrade (Layer 5)					Soil Properties Treated Subgrade (Layer 4)						
Scenario	Class	LL (%)	PI (%)	Fines (%)	M_R (ksi)	Class	LL (%)	PI (%)	Fines (%)	M_R (ksi)	IRI at Reliability 19 Years (in/mi)	Failure Year
1	A-7-6	66	45	94	3.25	A-7-6	66	45	94	9	158.1	19.5
5 (10% LKD)	A-7-6	66	45	94	14	A-7-5	45	12	69	21	151	21.5
5 (10% Cement)	A-7-6	66	45	94	14	A-5	44	2.3	40	23	149.7	21.9

Note: 1 ksi ≈ 6.89 MPa.

results of the design for HC and BM2, respectively. As seen in the tables, when overdosing the treatment, the decrease in IRI or increase in design life is more remarkable, compared to the optimum amount of treatment, especially when using cement. For HC, the decrease in IRI and increase in pavement life are respectively 7.3 in/mi and 2.2 years for treatment with LKD; or 9.3 in/mi and 2.9 years for treatment with cement. For BM2 soil, IRI decreases 7.1 in/mi and the design life increases 2 years for treatment- with LKD; or 8.4 in/mi and 2.4 years when using cement.

The results shown in Table 9.2 to Table 9.4 demonstrate the importance of considering realistic conditions for natural and treated subgrades. These would result in a larger design life or in a reduction of the cost of the pavement, as a smaller pavement thickness would be required for the same design life. The improvement is more remarkable when the treatment is overdosed.

10. EFFECT OF CHANGES IN MOISTURE CONTENT ON RESILIENT MODULUS

The effect of changes in moisture content on subgrade resilient modulus was investigated by wetting and drying soil treated samples. The soils 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 ASTM D559/D559M (2015) to determine the resistance of compacted specimens treated with cement, subjected to repeated wetting and drying cycles. In this research, 3″ diameter and 6″ height remolded samples of soil mixed with cement or Lime Kiln Dust (LKD) were compacted at 100% of the Standard Proctor energy, to conduct Resilient Modulus (M_R) tests, following the AASHTO T 307-99 (American Association of State and Highway Transportation Officials, 2007) for Type 2 Material, i.e., fine-grained soils. Fine-grained soils with low and high plasticity (A-6 and A-7-6, see Table 2.1) from Hartford City and Bloomington were used for this analysis.

10.1 Procedure Following the Standard ASTM D559/D559M

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 ASTM D559/D559M (2015). 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°F (71°C) for 42 hours. Figure 10.1 shows the wetting stage (part a) at 73°F (23°C), and oven drying (part b) at 160°F (71°C) for a Bloomington #1 (BM1) sample.

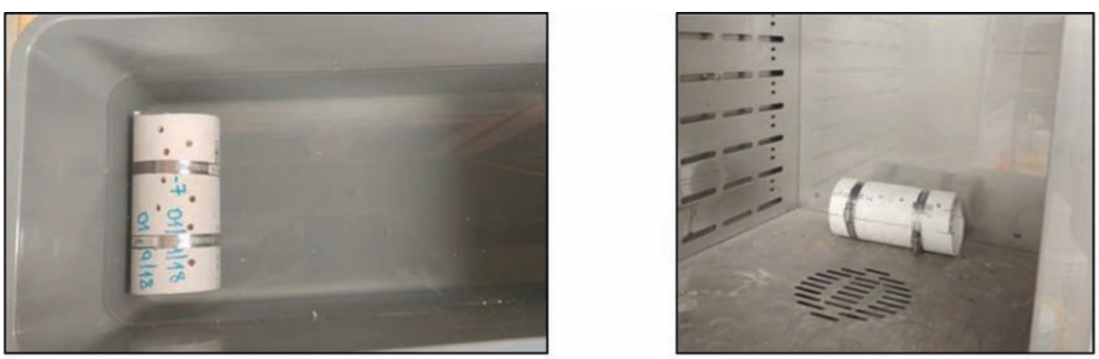
However, by following strictly the standard, the treated samples failed after the first three cycles, mostly during the wetting stage, as shown in Figure 10.2. The specimens exhibited cracks in the plane of compaction

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

Figure 10.1 BM1 Specimen following the standard ASTM D559/D559M (2015).

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

Figure 10.2 Samples collapsed after following the standard ASTM D559/D559M (third cycle).



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

Figure 10.3 Samples confined with a perforated PVC pipe, under wetting and drying cycles.

(Figure 10.2 (a)) and in a plane perpendicular to it (Figure 10.2 (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 10.3. The wetting/drying procedure was done again following the standard ASTM D559/D559M (2015), 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 (see Figure 10.4).

10.2 Modified Protocol Test

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 (2015). 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 10.1 lists the latitude and longitude, and Figure 10.5 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 I (Figures I.2 to I.9).

The temperature data was separated between the north and south of Indiana, given that the average temperatures are quite different. Figures 10.6 and 10.7 include the maximum yearly soil temperatures at a 4-inch depth for each climatic station, for the north and south, respectively. The figures show that in the north of Indiana, the soil temperature ranges from 80°F (27°C) to 110°F (43°C), while in the south they range between 90°F (32°C) and 110°F (43°C). According to the *INDOT Design Manual* (INDOT, 2013), subgrades in Indiana are located around a 12- to 16- inch depth. Consequently, data readings around the entire state at different

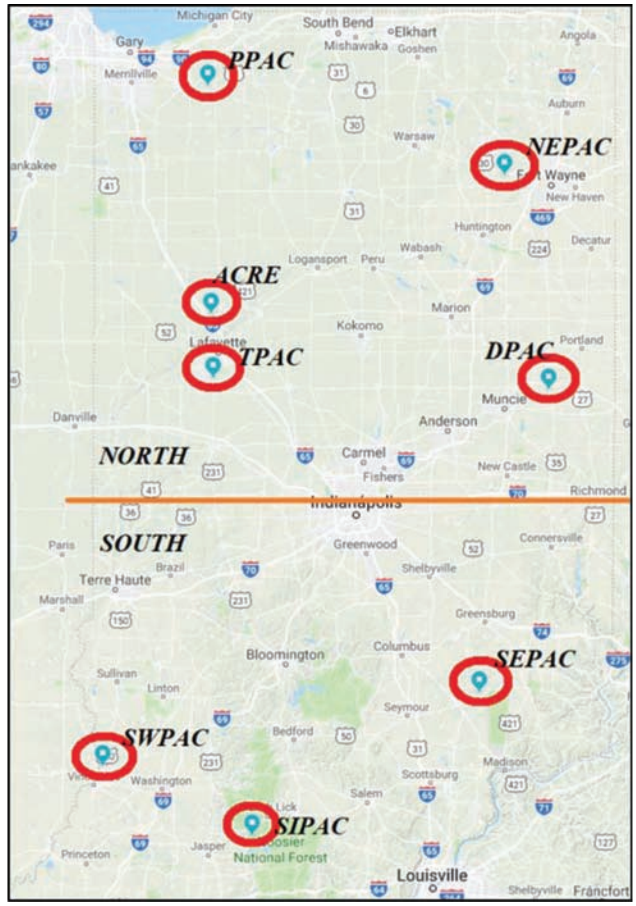
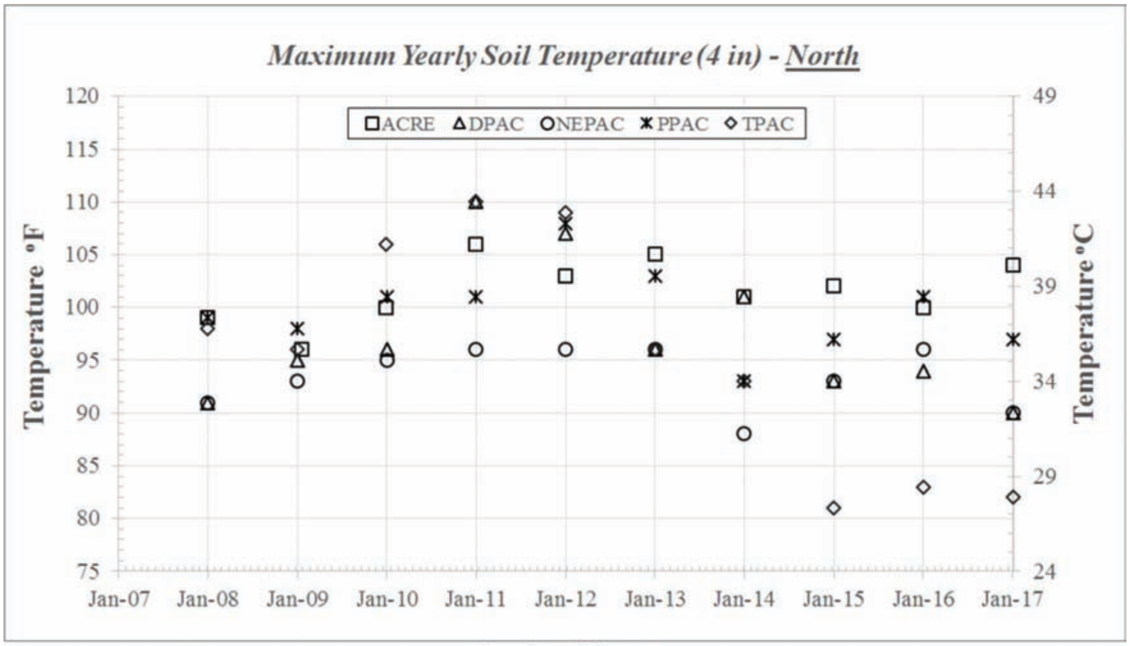


Figure 10.5 Climatic stations in Indiana (Google Maps).

Figure 10.4 Collapse of a confined sample (fifth cycle).

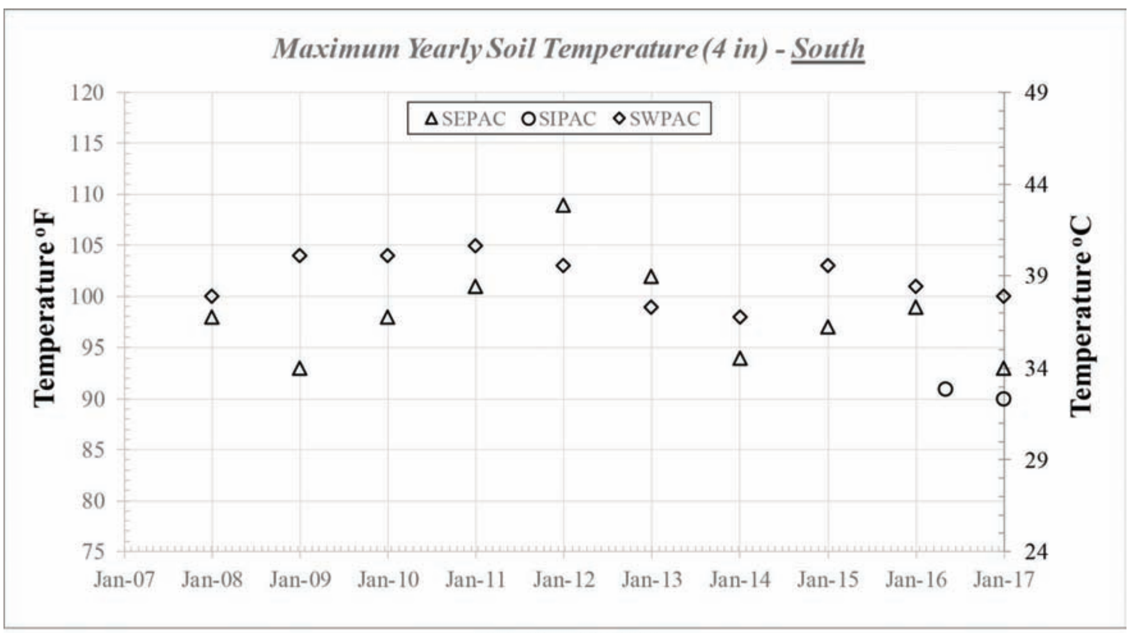
TABLE 10.1
Location of climatic stations in Indiana State (data from iClimate)

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



Data from iClimate

Figure 10.6 Maximum yearly soil temperature at a 4-inch depth (10 years of readings)—north.



Data from iClimate

Figure 10.7 Maximum yearly soil temperature at a 4-inch depth (10 years of readings)—south.

depths were used to estimate the subgrade temperature, as shown in Figure 10.8. The figure shows that the highest subgrade temperature at a 12-inch depth is around 87.5°F (31°C).

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 10.9. 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.

The types and amount of optimum chemical treatment, following the INDOT requirements in *Design Procedures for Soil Modification or Stabilization* (INDOT, 2015) for the M_R tests were presented in Chapter 3, for Hartford City, Bloomington #1, Bloomington #2, and Fort Wayne soils. Table 10.3 lists the optimum amount of LKD, cement, and Quick Lime (QL) for the soils tested. The wetting/drying procedure was conducted on Hartford City (HC), Bloomington #1 (BM1), and Bloomington #2 (BM2) soils mixed with LKD and cement. For verification purposes, samples of Bloomington #3 (BM3) were mixed with QL. The index properties of these soils were discussed in Chapter 2. As shown in Table 10.2, thirteen (13) M_R tests were conducted, following the standard AASHTO T 307-99 (American Association of State and Highway Transportation Officials, 2007) 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 10.3, it was possible to accomplish the twelve wetting/drying cycles for mixtures with LKD for HC and BM1. In contrast, the highly plastic clayey soils, BM2, failed during the first wetting/drying cycle following the modified protocol test. The mixtures of BM3 with QL also failed during the first three wetting/drying cycles. Regarding the mixtures with cement, the twelve WD cycles were accomplished only for BM1, while samples for BM2 and HC failed for this admixture. From these finding, and from the acceptable results shown in Chapter 7 when overdosing a highly plastic soil (BM3), samples with overdosed QL and cement were tested. The M_R results for overdosed samples are discussed in section 10.4.

10.3 Results of Resilient Modulus Tests for the Optimum Amount of Treatment

As specified in the standard AASHTO T 307-99 (American Association of State and Highway Transportation Officials, 2007) for Type 2 Material, three different confinement stresses (σ_3 = 2, 4, and 6 psi) were used for each resilient modulus (M_R) test. Table I.1, in Appendix I, lists all the results obtained for the M_R tests for WD analysis, Figures I.17 to I.25 show all the M_R tests results for optimum amount of treatment for HC and BM1 soils. For comparison purposes, the M_R results for treated and untreated samples compacted at 95% of the Standard Proctor at 28-days curing (discussed in Chapter 6) are also shown in the figures.

Only results of M_R tests for intermediate confinement stress, $\sigma_3 = 4$ psi (27.6 kPa) for the five deviatoric stresses are discussed in this session, given that, as mentioned in Chapter 6, there are no remarkable differences for the different confinement stresses. Figures 10.10 to 10.12 show the M_R test results for HC with LKD, BM1 with LKD, and BM1 with cement, respectively. For comparison purposes, the plots include the gray and black solid lines that represent the untreated and treated specimens compacted at 95% of the Standard Proctor. The black dashed line corresponds to the untreated samples compacted at 100% of the Standard Proctor and the color lines (three samples for repeatability) correspond to the treated samples compacted at 100% of the Standard Proctor, after the twelve wetting/drying (WD) cycles. As discussed in Chapter 6, 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 wetting/drying (WD) cycles (2 months), the specimens presented signs of degradation that affected the stiffness of the treated soil.

Table 10.5 shows M_R values for $\sigma_3 = 4$ psi and σ_d = 6, 8, and 10 psi. The change in stiffness with respect to untreated soil, compacted at 100% of the Standard Proctor, is also provided. The following discussion includes the results shown in Figures 10.10 to 10.12 and listed in the Table 10.5.

Regarding Hartford City (HC) treated with LKD, Figure 10.10 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 for this type of soil after the WD process, compared to the untreated specimens without any WD cycle. Regarding Bloomington #1 (BM1) treated with LKD, (Figure 10.11), 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 10.12), the treated samples had a reduction of the stiffness of at least 50% (on average) below the untreated sample. As seen in Table 10.5, after WD cycles, the stiffness degradation is bigger for samples mixed with cement which means a better response for LKD admixtures during the moisture changes in the specimens.

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

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. This behavior is sensitive to plasticity and thus soils with high plasticity are affected the most. As one can see in Figure 10.13, high plasticity clayey soils, BM2 and BM3, underwent significant cracking at the beginning of the WD cycles, that 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 discussed in Chapter 7, overdosing consisted in doubling the optimum amount of treatment found by following the *Design Procedures for Soil Modification or Stabilization* (INDOT, 2015). As shown in Table 8.1 BM3 soil has properties very similar to those of BM2. After the twelve WD cycles in overdosed samples, eleven (11) M_R tests were conducted in the INDOT laboratory in West Lafayette, following the standard AASHTO T 307-99 (American Association of State and Highway Transportation Officials, 2007) for Type 2 Material, i.e., fine-grained soils, as shown in Table 10.4.

Table 10.5 shows M_R values for σ_3 = 4 psi and σ_d = 6, 8, and 10 psi. The change in stiffness with respect to untreated soil is also presented. Figure 10.14 and 10.15 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 intermediate confining stress are presented. In the figure, the black dashed line corresponds to the untreated samples compacted at 100% of the Standard Proctor and the color lines represent the overdosed treated specimens (three for repeatability) compacted at 100% of the Standard Proctor, after the twelve wetting/drying (WD) cycles.

Figure 10.14 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 10.15, the soil stiffness of BM3 samples overdosed with cement was reduced below the value for the untreated sample by 20% on average, i.e., overdosing with cement did not produce as good results as those obtained 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 I.26 to I.31 show the M_R tests results for overdosed BM3 soils and Table I.1 lists these values.

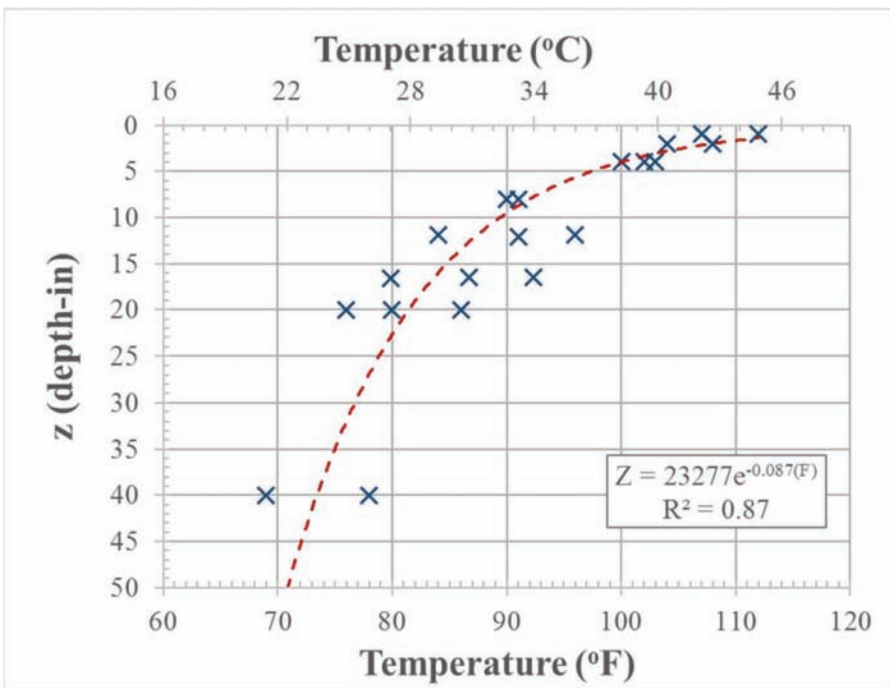


Figure 10.8 Maximum soil temperature at different depths around the state.

(a) Drying stage (2 days)—BM1 and HC (b) Wetting stage (2 days)—BM1

Figure 10.9 Modified WD process BM1 and HC, LKD treated soils.

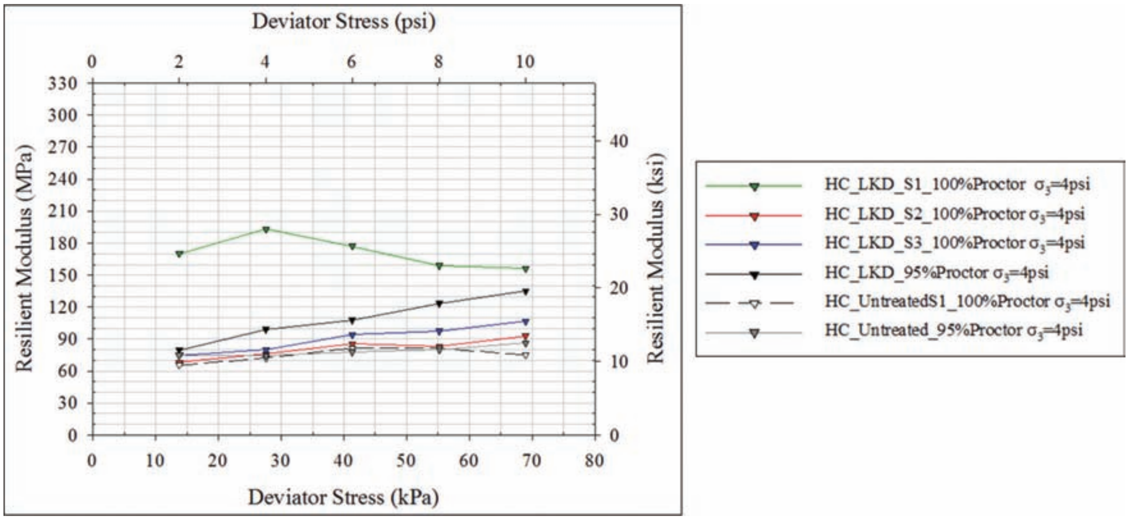


Figure 10.10 Resilient modulus for HC soil-optimum treatment with LKD, after 12 wetting/drying cycles.

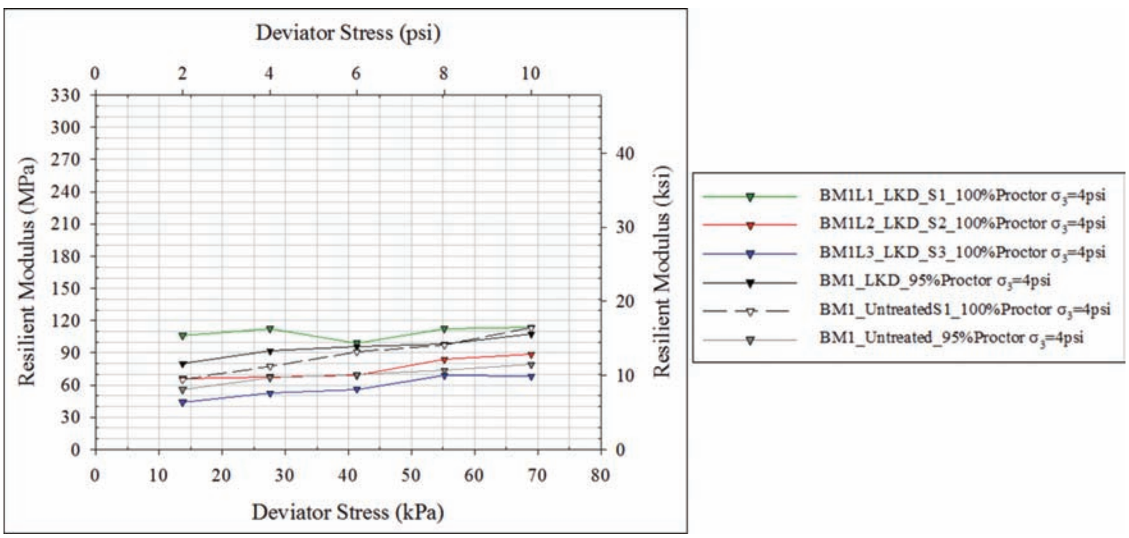


Figure 10.11 Resilient modulus for BM1 soil-optimum treatment with LKD, after 12 wetting/drying cycles.

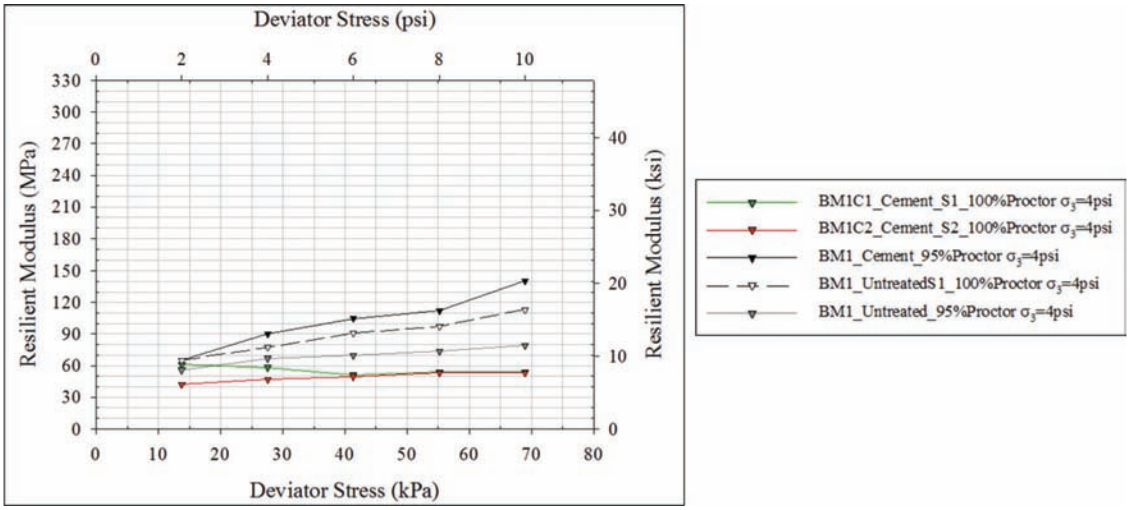


Figure 10.12 Resilient modulus for BM1 soil-optimum treatment with cement, after 12 wetting/drying cycles.

Figure 10.13 Collapse of a high plasticity QL treated sample during wetting/drying cycles.

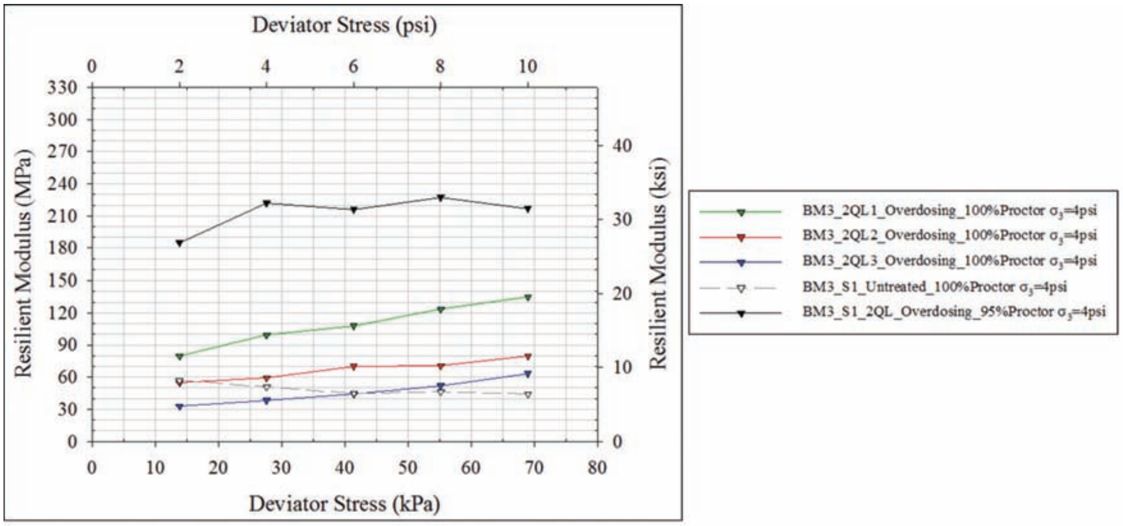


Figure 10.14 Resilient modulus for BM3 overdosed with QL, after 12 wetting/drying cycles.

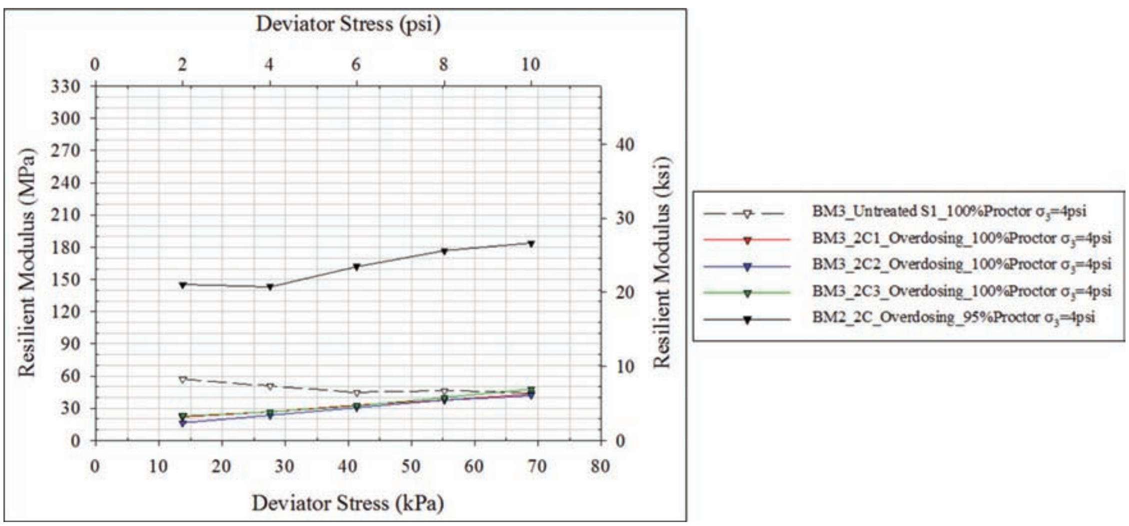


Figure 10.15 Resilient modulus for BM3 overdosed with cement, after 12 wetting/drying cycles.

TABLE 10.2
Amount of M_R tests 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

TABLE 10.3
Optimum amount of treatment for the treated soils

	Amount (%)		
Site	**LKD**	**Cement**	**QL**
Hartford City	6	3	—
Bloomington #1	6	3	—
Bloomington #2	5	5	—
Bloomington #3	—	—	5
	Successful 12 WD cycles		

Note: LKD = Lime Kiln Dust
QL = Quick Lime
→ = Collapsed specimen

TABLE 10.4
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 10.5
Comparison between resilient modulus (M_R) for untreated soil and treated soils after WD cycles, for optimum and overdosing treatments

	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 After Cycles, MR (ksi)						Resilient Modulus After Cycles, MR (ksi)					
Site	Resilient Modulus, M_R (ksi)			M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)
BM1	90.82	97.14	113.22	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	81.55	81.25	74.91	12.37	5	12.04	3	13.47	25	—	—	—	—	—	—
				13.62	16	14.15	21	15.47	43	—	—	—	—	—	—

	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 After Cycles, MR (ksi)						Resilient Modulus After Cycles, MR (ksi)					
Site	Resilient Modulus, M_R (ksi)			M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)
BM3	44.74	46.37	44.30	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

	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 After Cycles, MR (ksi)						Resilient Modulus After Cycles, MR (ksi)					
Site	Resilient Modulus, M_R (ksi)			M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)
BM1	90.82	97.14	113.22	15.04	15	13.96	-1	14.26	-14	7.20	-46	7.75	-46	7.71	-54

11. EFFECT OF CHANGES IN TEMPERATURE ON RESILIENT MODULUS

The effect of changes in temperature on subgrade resilient modulus was investigated by freezing and thawing treated soils. 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 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%.

11.1 Procedure Following the Standard ASTM D560/D560M

To evaluate the subgrade stiffness degradation due to temperature changes, the freezing/thawing (FT) tests were first done following the American Society for Testing and Materials, Standard ASTM D560/D560M (American Society for Testing and Materials, 2016). This standard is used to determine the resistance of compacted soil-cement treated specimens to repeated freezing and thawing cycles. Remolded samples with 3″ diameters and 6″ heights 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°F (-23°C) for 24 hours, and then inside the moisture room at 73.5°F (23°C) for 23 hours.

To simulate better the field conditions, the specimens were confined with a perforated PVC pipe, as shown in Figure 11.1 (a). However, as shown in Figure 11.1 (b) and (c), by following strictly the Standard ASTM D560/D560M (American Society for Testing and Materials, 2016), the treated sample presented premature failure due to excessive deformations, around 20%, during the twelve FT cycles.

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 elastic 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 J for further information). As shown in Figure 11.2, the maximum tensile stresses in the sample are about 60 kPa and 250 kPa depending on the interface considered between the soil and the pipe, i.e., frictional (rollers) or fixed (pins), respectively. The range of values for the tensile strength of compacted clays varies with the authors; for example, Towner (1987) proposed a conservative value for the tensile strength of clays in the range of 30 to 300 kPa, while Zhang et al. (2013), for specimens with dry density 1.65 g/cm^3 and moisture content 20%, suggested tensile stresses between 35 kPa and 40 kPa. Also, Stirling et al. (2015), for clayey soils subjected to climatic loading and water content around 20%, proposed values around 30 kPa. A conservative

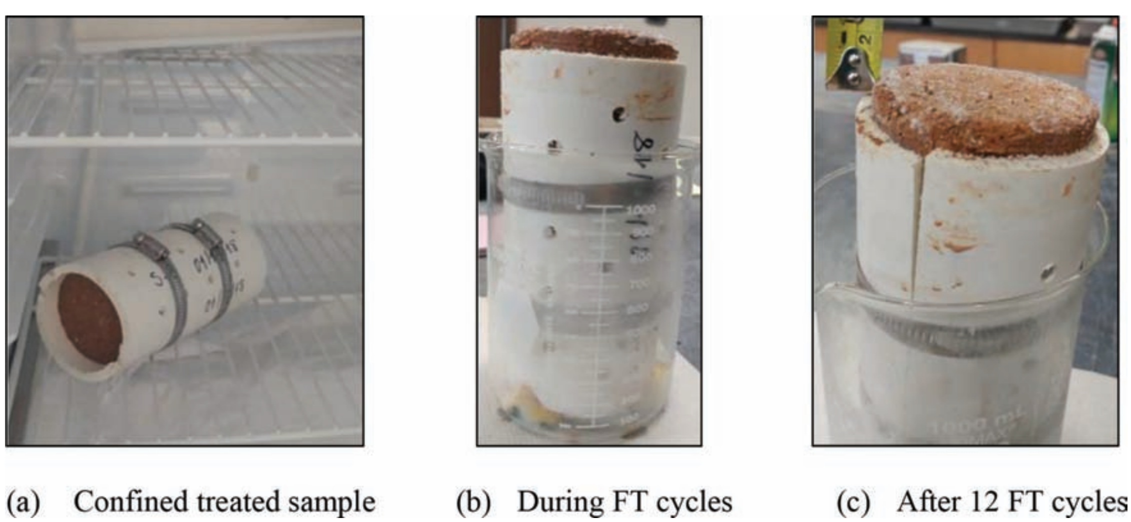


Figure 11.1 BM1 LKD lime treated sample confined with a drilled PVC pipe, under twelve FT cycles, following the standard ASTM D560/D560M (American Society for Testing and Materials, 2016).

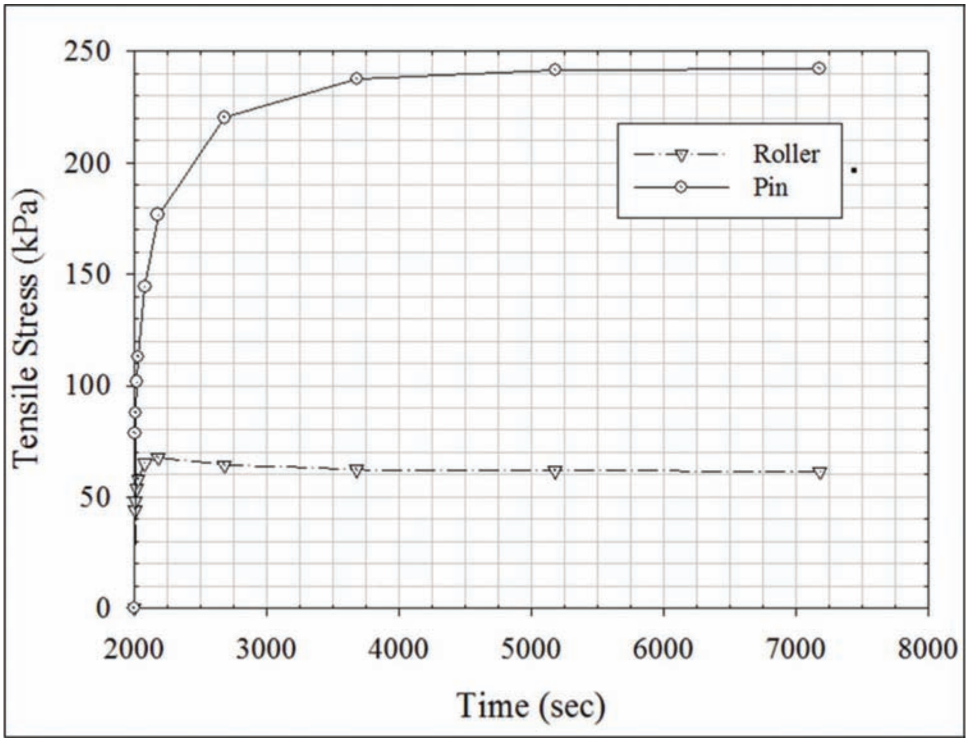


Figure 11.2 Results of FEM. Tensile stresses in the specimen following the ASTM standard.

value for the tensile strength of clays could be between 40 and 100 kPa. Consequently, the tensile stresses obtained with the numerical model are large enough to overcome the soil strength, especially when confinement is provided. As a result, it was decided to perform the FT tests on unconfined samples.

11.2 Modified Protocol Test

The subgrade's temperatures in Indiana are not as extreme as those in the ASTM D560/D560M standard (American Society for Testing and Materials, 2016). Figure 10.5 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. Figure 11.3 and 11.4 plot the minimum yearly soil temperatures at a 4-inch depth for the north and south of the state, respectively (see Appendix I for additional information). The figures show that in the north of Indiana, the minimum soil temperature ranges from 14°F (-10°C) to 32°F (0°C), while in the south between 21°F (-6°C) and 38°F (3°C). The subgrade is located around a 12-inch depth, so the existing data was used to estimate the minimum temperature at that depth, as shown in Figure 11.5. The minimum subgrade temperature at a 12-inch 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 Figures 11.4, it is 10°F (-12°C). This extreme temperature was used for the tests.

These findings were discussed with the Study Advisory Committee (SAC) on September 2018, when the following protocol was adopted: for the freezing stage, the specimens are placed with no confinement in the freezer for twenty-four hours at 10°F (-12°C), afterwards, the samples are placed in the moisture room at 73°F (23°C) for twenty-four hours, for the thawing period. All the samples are subjected to twelve freezing/thawing cycles, which requires about one month. Figure 11.6 shows the stages of freezing (part a) and thawing (part b) for a Bloomington #1 (BM1) specimen treated with optimum amount of treatment with LKD.

11.3 Results of Resilient Modulus Tests for the Optimum Amount of Treatment

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 T 307-99 (American Association of State and Highway Transportation Officials, 2007) 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 J, where Table J.1 lists all the values obtained from the M_R tests, and Figures J.8 to J.13 are plots of all the M_R test results. For comparison purposes, only results of M_R tests for σ_3 = 4 psi (27.6 kPa) are shown and discussed below.

Figures 11.7 and 11.8 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

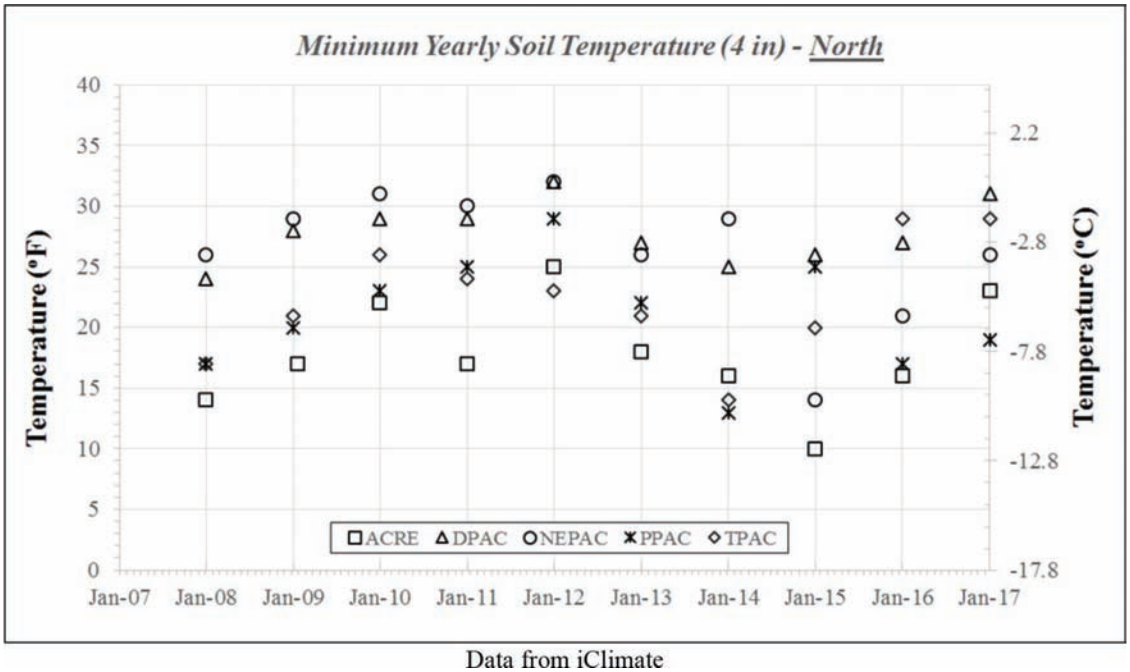


Figure 11.3 Minimum yearly soil temperature at a 4-inch depth (10-years readings)—north.

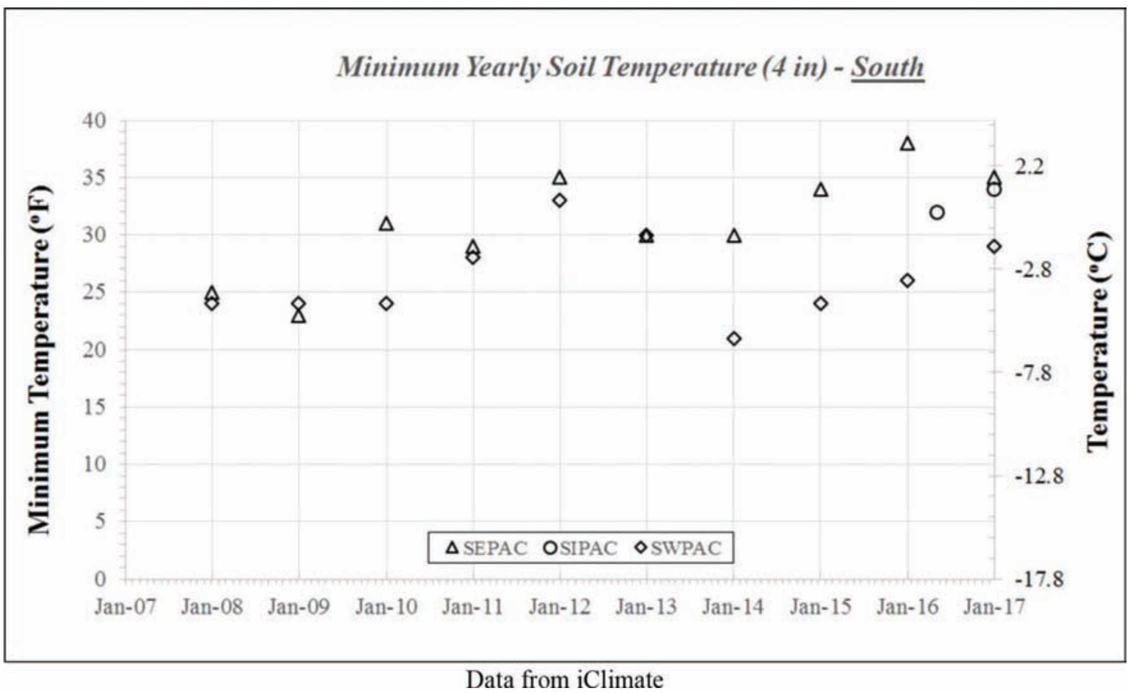


Figure 11.4 Minimum yearly soil temperature at a 4-inch depth (10-years readings)—south.

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 11.7) and the red line (in Figure 11.8) correspond to the LKD and cement treated specimens, respectively, compacted at 100% of the Standard Proctor, after twelve FT cycles. The increase in the stiffness of the treated samples with respect to the untreated (without any FT cycles) is evident. This is consistent with the findings in Chapter 6. However, after twelve freezing/thawing (FT) cycles, the stiffness of the treated sample is

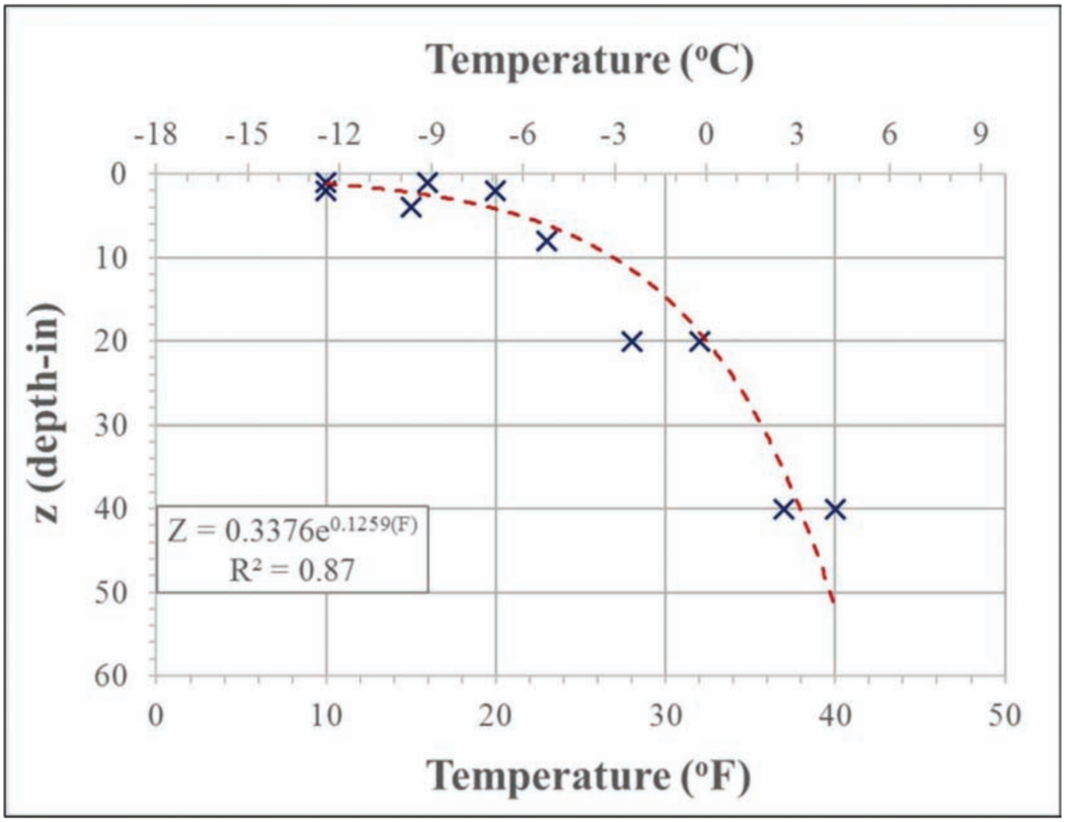


Figure 11.5 Minimum soil temperature at different depths.

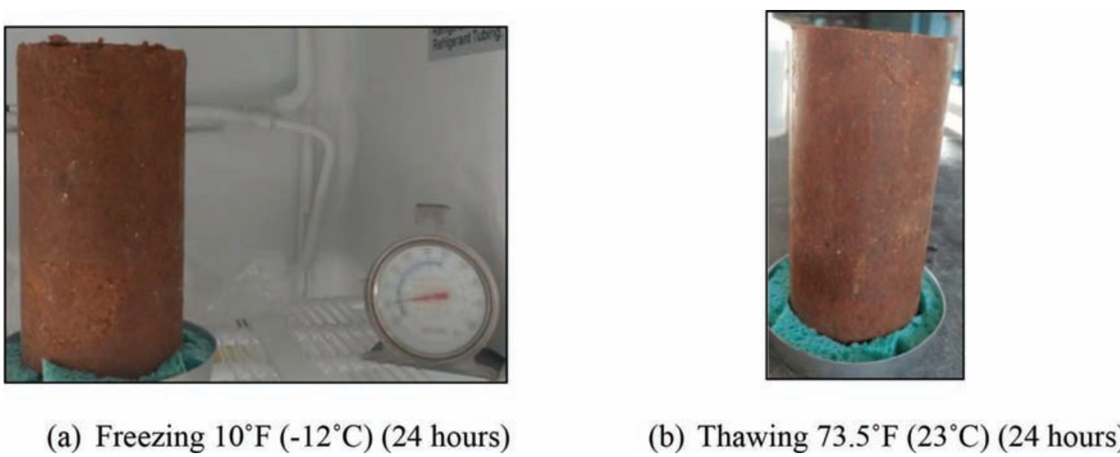


Figure 11.6 BM1 LKD treated specimen following the standard ASTM D560/D560M (American Society for Testing and Materials, 2016).

greatly diminished. For Bloomington #1 (BM1) soil treated with LKD (Figure 11.7), 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 11.8) exhibit a larger degradation of stiffness after the twelve FT cycles, with a reduction of around 40% (on average) with respect to the untreated sample. As found for samples submitted to WD cycles, the admixtures with LKD display larger M_R after the FT cycles. Table 11.1 shows M_R values for σ_3 = 4 psi and σ_d = 6, 8, and 10 psi.

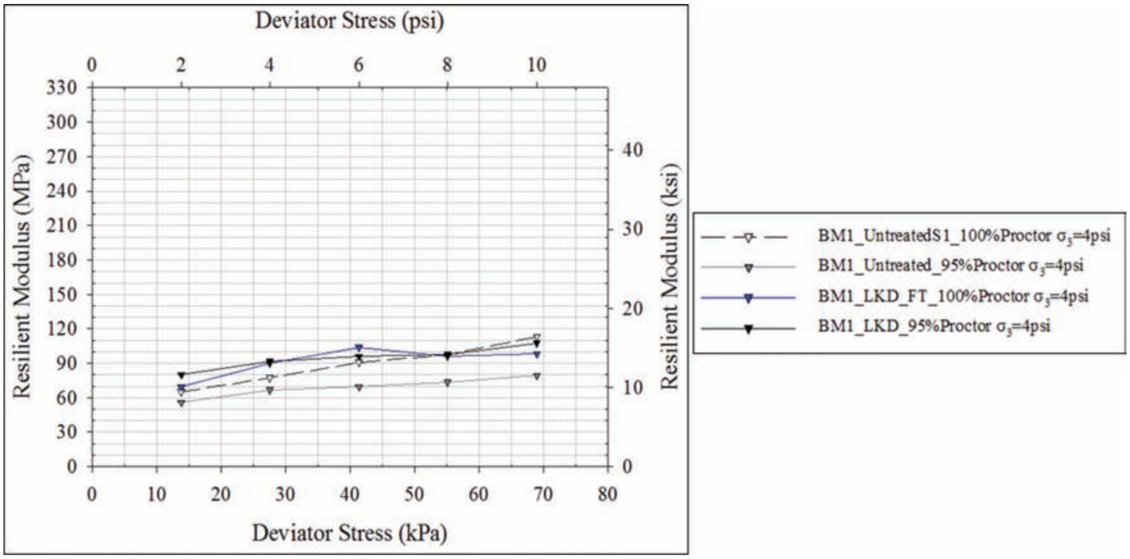


Figure 11.7 Resilient modulus for BM1 soil-optimum treatment with LKD, after 12 freezing/thawing cycles.

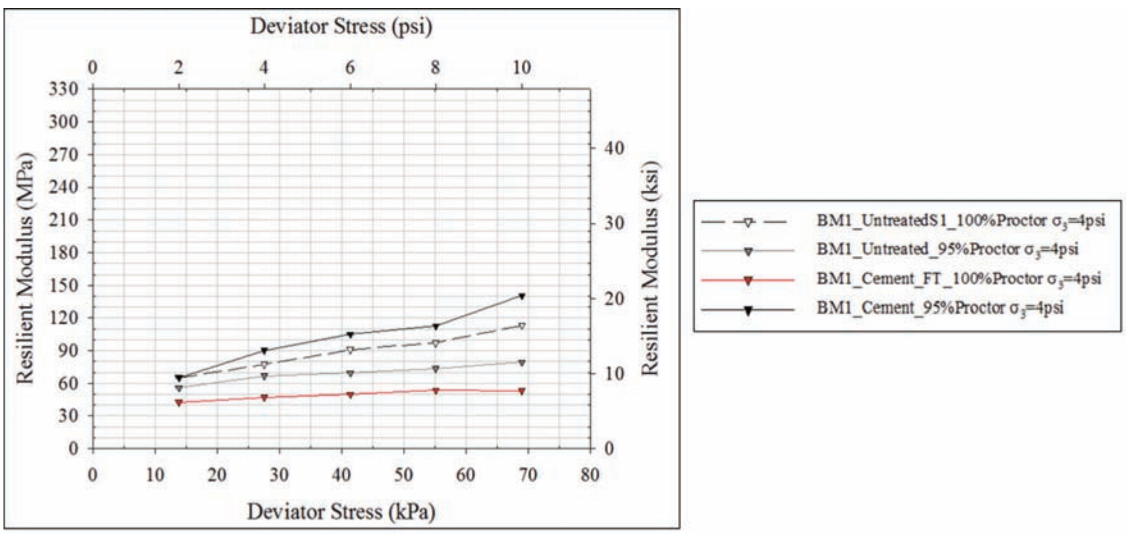


Figure 11.8 Resilient modulus for BM1 soil-optimum treatment with cement, after 12 freezing/thawing cycles.

TABLE 11.1
Comparison between resilient modulus (M_R) for untreated soil and treated soils after FT cycles, for optimum treatment

	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 After Cycles, MR (ksi)						Resilient Modulus After Cycles, MR (ksi)					
Site	Resilient Modulus, M_R (ksi)			M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)	M_R	Inc. (%)
BM1	90.82	97.14	113.22	15.04	15	13.96	-1	14.26	-14	7.20	-46	7.75	-46	7.71	-54

12. SUMMARY AND CONCLUSIONS

For pavement structures placed over fine-grained plastic soils (A-6 or A-7-6), it is a common practice in Indiana to improve the natural subgrade with a chemical agent (e.g., LKD, QL or cement). However, for the pavement design, current practice may underestimate the changes in the nature of the soils that arise with treatment (i.e., an A-7-6 soil treated with LKD or cement continues to be modeled as an A-7-6 soil. Nevertheless, there is some evidence, albeit not systematic, that treatment could change the type of soil (e.g., Jung & Bobet, 2008; Jung et al., 2009). The current practice may also underestimate the stiffness improvement with treatment.

In 2009, INDOT adopted the *Mechanistic-Empirical Pavement Design Guide* (MEPDG) method, a new design guide based on the FHWA *Long Term Pavement Performance* (LTPP). The main objective of design in the MEPDG, called PavementME after 2012, is changed totally compared to that of the 1993 *AASHTO Guide for Design of Pavement Structures*. The main objective is to design pavement support layers to meet the performance criteria and make the pavement design more economical. With the adoption of the PavementME, it is possible to consider in the input parameters the actual properties of the stabilized soil subgrade, and thus the PavementME method opens the possibility for design engineers to be very innovative in utilizing the stabilized pavement layers to reduce the cost of the pavement surface or increase its design life. Therefore, the pavement designer may not need to use the type and properties of the original soil, but rather the type, modulus and other engineering properties of the treated soil.

An extensive laboratory experimental program was conducted to evaluate the engineering properties (fines content, plasticity index, shear strength and resilient modulus) of one A-6 soil and four A-7-6 soils. The A-6 soil was obtained from Hartford City (HC) in Blackford County, while the A-7-6 soils were collected from Fort Wayne (FW) in Allen County, and from Bloomington (BM1, BM2, BM3) in Monroe County. For these soils, the LL ranged between 26.0% and 66.0%, while the PI was between 14.4% and 45.2%. The experimental program included a total of 20 compaction tests, 4 Eades and Grim pH tests, 8 Loss on Ignition (LOI) tests, 50 Atterberg limits, 16 grain size analysis, 117 unconfined compression tests, and 63 resilient modulus tests, as shown in Table 12.1. The tests were conducted at different curing periods, from 2 to 190 days, but mostly at 2, 7, and 28 days. The optimum and a double of the optimum (overdosing) amount of treatment were used for the tests.

From the laboratory results, the following conclusions were reached:

1. For the soils investigated, the optimum amount of treatment ranged between 5% and 6% for LKD, between 3% and 5% for cement, and 2% LKD + 2% cement when both chemicals were used.
2. The plasticity index decreased with treatment for all the soils, but there was not a clear trend regarding which treatment had a larger effect on the soils' plasticity, i.e., for some soils a larger reduction was seen for mixtures with LKD and for others with mixtures with cement. The reduction in plasticity was caused by an important increase in the plastic limit with a small increase or even decrease in the liquid limit. Curing time had no major effect on the soils' plasticity. The largest reduction in PI occurred before 28 days of curing. The grain size always increased with treatment. However, there was no trend regarding what treatment produced better results. With the optimum amount of treatment, although the plasticity decreased (up to 20%) and the grain size increased (up to 37% with respect to the untreated soil), the type of soil did not change, i.e., soils were still A-6 or A-7-6 after treatment with the optimum amount of LKD, cement or cement + LKD.
3. The unconfined compression strength of treated soils, at the optimum chemical content, was larger than that of the natural soil. After 28-days curing, the increase in strength, with respect to the untreated soil, ranged between 123% for HC + LKD, to 613% for BM2 + cement. For most soils, the largest unconfined compression strength was observed for mixtures with cement. The increase in strength with time of the soil mixtures with LKD or cement did not depend on soil plasticity, as soils with relative similar plasticity (BM1 vs. FW) had different strengths.
4. All treated soils exhibited an increase of the resilient modulus, M_R, with respect to that of the untreated soil. At the optimum amount of treatment, the resilient modulus was larger for mixtures with cement than with LKD. The M_R of the treated soils increased with the increase of the deviatoric stress. Such effect was more remarkable for samples containing cement. There was no clear trend of M_R and curing time.
5. When the optimum amount of treatment was doubled (overdosing), the decrease in plasticity and fines content

TABLE 12.1
Number of tests with optimum amount of treatment and overdosing: aging and climatic analyses

Test	Optimum Amount of Treatment: Aging	Optimum Amount of Treatment: BM3 (QL vs. LKD)	Optimum Amount of Treatment: WD/FT	Overdosing (Double): Aging	Overdosing (Double): WD Overdosing	Total
Compaction	14	2	—	4	—	20
Atterberg Limits	36	6	—	8	—	50
Grain Size	12	—	—	4	—	16
Unconfined Compression	97	4	—	16	—	117
Resilient Modulus	31	4	13	4	11	63

was more remarkable than using the optimum amount of treatment. The type of soil always changed, transforming a fine-grained soil into a granular soil (e.g., from A-6 to A-2-4).

6. Overdosing (i.e., double the amount the optimum chemical treatment) produced a larger increase in the unconfined compression strength of the soil compared to the optimum treatment. The strength obtained with overdosing could be double than using optimum treatment. Overdosing produced a larger increase in soil stiffness, compared with the optimum treatment.
7. Considering realistic conditions for natural and treated subgrades in the PavementME produces an increase in the IRI or in a larger design life. This would result in a reduction of the cost of the pavement, as a smaller pavement thickness would be required for the same design life. The improvement is more evident when the treatment is overdosed, especially with cement.
8. Following strictly the standard ASTM D559/D559M (2015) 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 overdosed with quick lime, after the twelve WD cycles, had an increase of the stiffness by 55%, on average, while those overdosed with cement had a reduction of stiffness down to about 20% below the untreated soil.
9. Following strictly the Standard ASTM D560/D560M (American Society for Testing and Materials, 2016), 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.

The research shows that chemical treatment of clayey subgrade soils improves the engineering behavior of the soils. The improvement, in terms of plasticity and gran size distribution, may not be sufficient to change the type of soil, but increases the stiffness (resilient modulus) and strength (unconfined compression strength) of the soil. 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 attained with the chemical treatment was lost. While the benefits obtained with the treatment are consistent with what is expected, 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 is the benefits of overdosing. Overdosing changes the type of soil, from clayey to granular, and 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.

13. RECOMMENDATIONS

The results of this research are a first step to make the current pavement design in Indiana more efficient, according to the field conditions of the subgrade. However, as listed below, additional research and activities can be conducted such that the state of stresses in the field and the wetting/drying and freezing/thawing processes during the seasons can be better represented in the experimental campaign.

1. Propose a test protocol to provide representative vertical and horizontal effective stresses to the samples during the curing process. In this research some confinement was provided to some samples by restricting the radial deformation. However, a better representation should be tried by providing known values of radial and vertical stresses, with different magnitude among them.
2. Conduct an experimental campaign for samples with overdosed treatment exposed to cycles of freezing/thawing. Such tests were not performed in this research where only samples with the optimum amount of treatment were tested.
3. Investigate additional soils with different plasticity exposed to cycles of wetting/drying, when treatment is overdosed. Even though in this research it was shown that soils with high plasticity lost all the stiffness gained with the treatment, and soils with a lower plasticity keep some increase in stiffness, compared to the untreated condition, this behavior should be verified for different soils, when a more realistic state of stresses during curing (as discussed in 1) is used.

14. IMPLEMENTATION

The research clearly showed the benefits of overdosing, i.e., of doubling the amount of chemical. Overdosing changes the type of soil, from clayey to granular, and improves the resilient modulus of the soil, even under the harsh conditions in the laboratory during the cycles of WD, especially for soils with lower plasticity. 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 pavement structure, with less maintenance, or even with a less thick structure. It is recommended an implementation of this research. A section of a new pavement construction should be built using overdosing, and its performance monitored to verify the discussed changes and their benefits, both during the short and long term.

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APPENDICES

Appendix A. Introduction

Appendix B. Location and index properties of untreated soils

Appendix C. Optimum amount of treatment

Appendix D. Effect of optimum amount of treatment on plasticity and grain size distribution

Appendix E. Effect of optimum amount of treatment on plasticity and grain size distribution

Appendix F. Effect of optimum amount of treatment on resilient modulus

Appendix G. Effect of overdosing the treatment on plasticity, grain size, shear strength and resilient modulus

Appendix H. Difference in Plasticity, Unconfined Compression Strength and Resilient Modulus Between LKD and Quick Lime

Appendix I. Effect of Moisture on Resilient Modulus

Appendix J. Effect of Changes of Temperature on Resilient Modulus

APPENDIX A. INTRODUCTION

The tests conducted are listed in Table A.1

Table A.1 Experimental program for all the soils, treatments, and curing periods

Soil	Condition	Comp.	Atterberg Limits					Grain Size Distribution		Unconfined Compression				Resilient Modulus					
			Curing Period (Days)					Curing Period (Days)		Curing Period (Days)				Curing Period (Days)					
			0/2	7	28	90	>90	0	>90	0/2	7	28	90	0/2	7	28	FT Cycles	WD Cycles	90
Hartford City (A-6)	Untreated	X	X					X		X				X			X		
	Soil[b] LKD	X	X	X	X	X			X	X	X	X	X	X	X	X		X	X
	Soil[b] Cement	X	X	X	X		X		X	X	X	X		X	X	X			
Bloomington #1 (A-7-6)	Untreated	X	X					X		X				X			X		
	Soil[b] LKD	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X
	Soil[b] Cement	X	X	X	X		X		X	X	X	X		X	X	X	X	X	
	Soil[b] LKD[b] Cement	X	X	X	X	X[a]				X	X	X		X	X	X			
Fort Wayne (A-7-6)	Untreated	X	X					X		X				X					
	Soil[b] LKD	X	X	X	X		X		X	X	X	X	X	X	X	X			X
	Soil[b] Cement	X	X	X	X		X		X	X	X	X		X	X	X			
Bloomington #2 (A-7-6)	Untreated	X	X					X		X				X					

	Soil[b] LKD	X	X	X	X	X	X		X	X	X	X		X	X	X			
	Soil[b] Cement	X	X	X	X[b]				X	X	X	X		X	X	X			
	Soil[b] LKD[b] Cement	X	X	X	X[b]					X	X	X		X	X	X			
Bloomington #3 (A-7-6)	Untreated	X	X					X									X		
	Soil[b] QL	X								X						X[c]		X[c]	
	Soil[b] Cement	X								X						X[c]		X[c]	

[a] This test was performed at 70 days
[b] These tests were performed at 50 days
[c] Overdosing
WD & FT Cycles: 100% of the Standard Proctor

APPENDIX B. LOCATION AND INDEX PROPERTIES OF UNTREATED SOILS

Table B.1 lists the results for loss on ignition tests conducted on the four soils. The tests were performed following AASHTO T-267.

Table B.1 Results of loss on ignition tests for all soils

Number	Site	Organic Matter Content (%)	Calcium Carbonate Content (%)
1	Hartford City	2	18.7
		2	20.5
2	Bloomington #1	3.9	2
		2.6	3.6
3	Fort Wayne	2.3	6
		2.4	6.2
4	Bloomington #2	2.3	12.9
		2.1	12.8

APPENDIX C. OPTIMUM AMOUNT OF TREATMENT

Figures C.1 to C.5 show the compaction curves for untreated and treated soils, for HC, BM1, FW, and BM2, respectively. Standard Proctor compaction tests following AASHTO T-99 were performed for untreated soils. Specimens for soils mixed with Lime Kiln Dust (LKD), cement or cement + LKD were prepared using the Harvard Miniature device. An extensive calibration between the Proctor and the Harvard Miniature tests was done to achieve the same compaction. This was done by changing the number of layers and tamping energy to prepare the smaller samples.

Results of Eades and Grim pH tests are shown in Figure C.6. In the figure, the pH for the four soils investigated is given for different LKD contents. Figures C.7 to C.10 show results of the unconfined compression strength tests with the optimum amount of treatment for HC, BM1, FW and BM2 soils, respectively. Figures C.11 and C.12 show results of mixtures of BM2 + cement and HC with LKD + cement that did not reach the strength requirements.

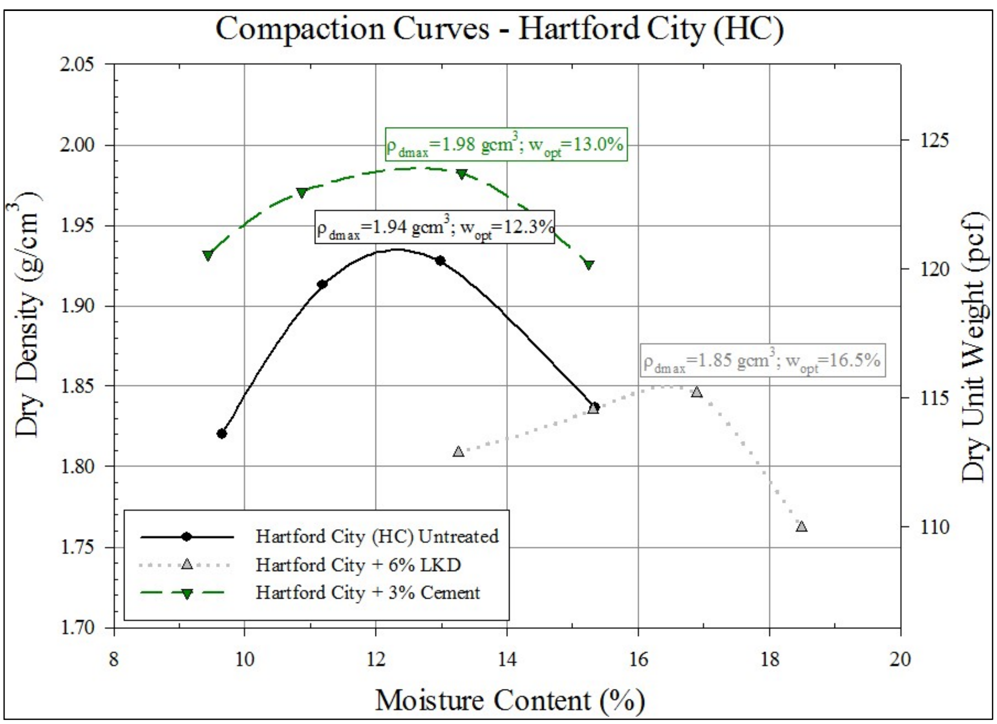


Figure C.1 Compaction curves for untreated soil and soil with optimum amount of treatment. Hartford City (HC), A-6 soil.

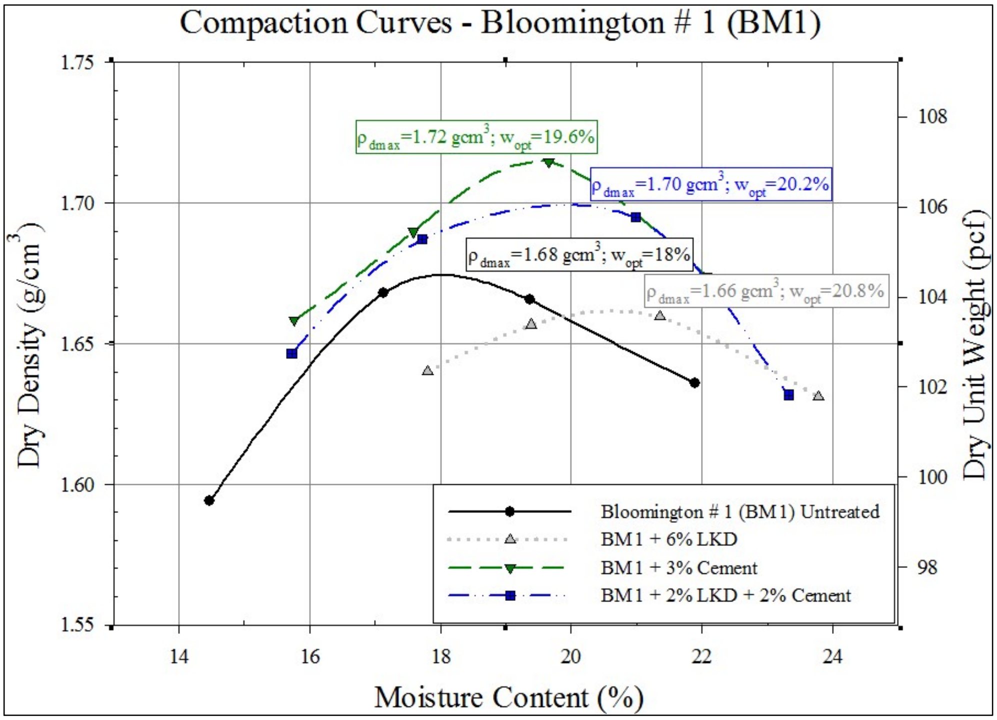


Figure C.2 Compaction curves for untreated soil and soil with optimum amount of treatment. Bloomington #1 (BM1), A-7-6 soil.

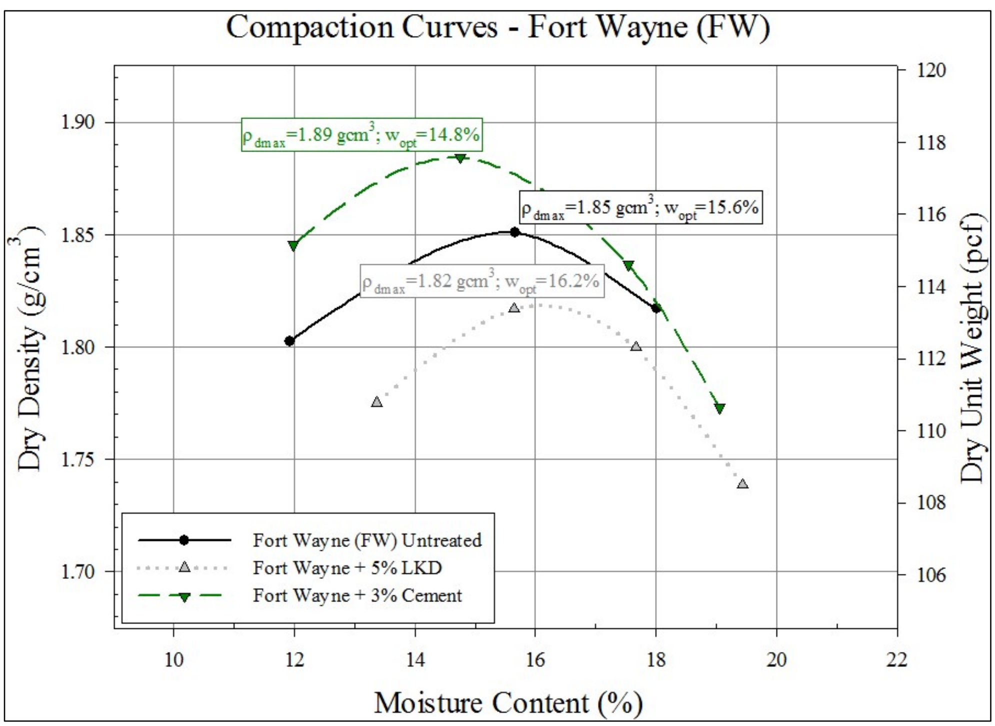


Figure C.3 Compaction curves for untreated soil and soil with optimum amount of treatment. Fort Wayne (FW), A-7-6 soil.

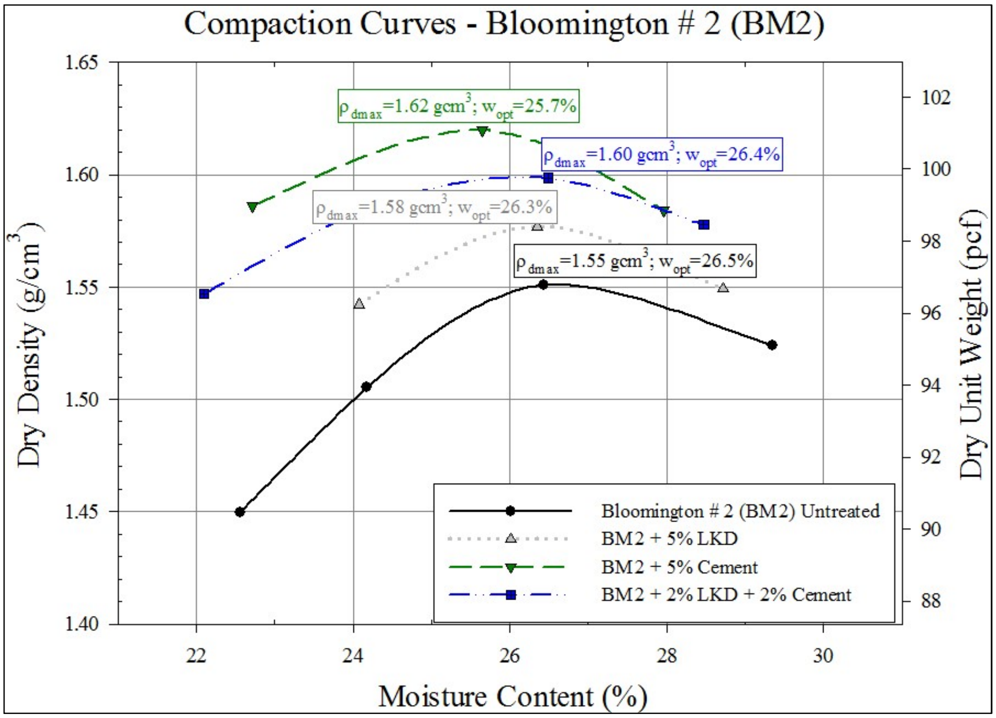


Figure C.4 Compaction curves for untreated soil and soil with optimum amount of treatment. Bloomington #2 (BM2), A-7-6 soil.

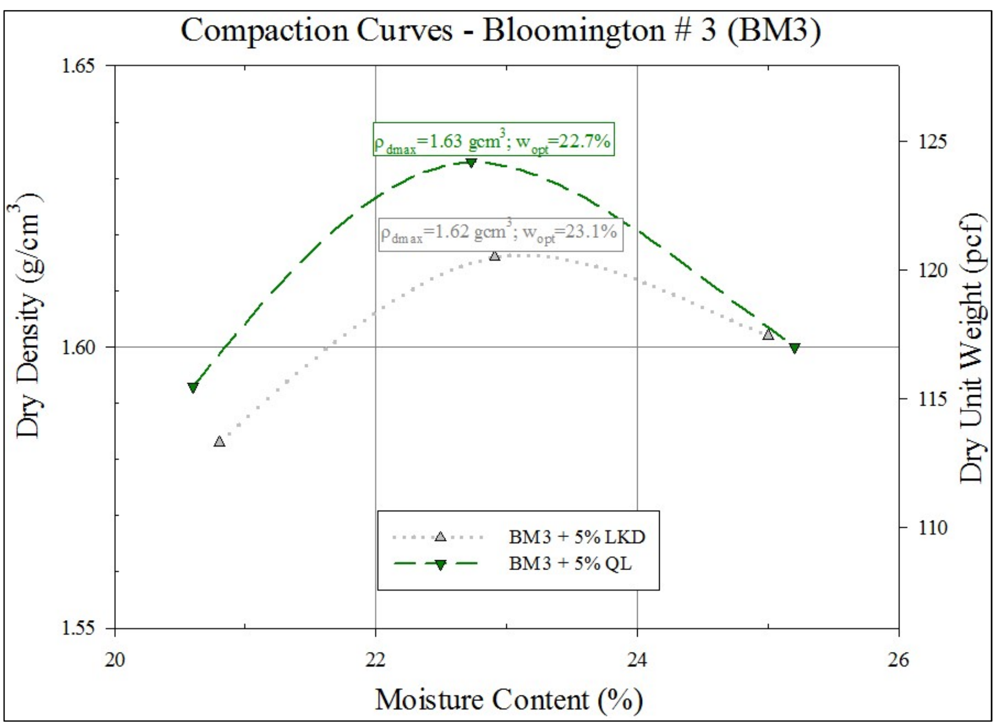


Figure C.5 Compaction curves for soil with optimum amount of treatment. Bloomington #3 (BM3), A-7-6 soil.

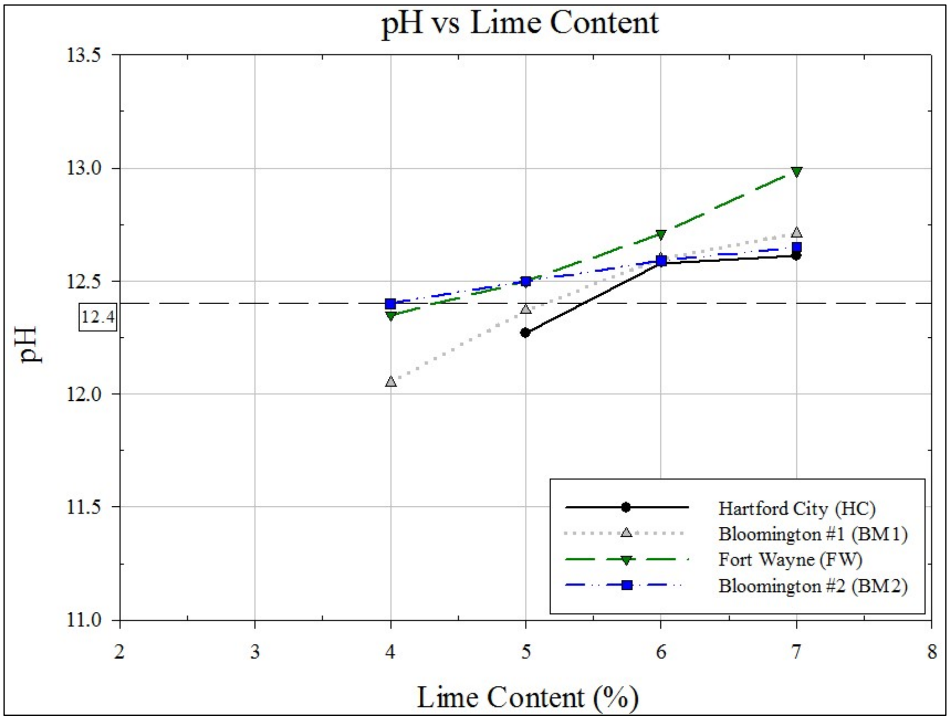


Figure C.6 Results of Eades and Grim pH tests for the four soils treated.

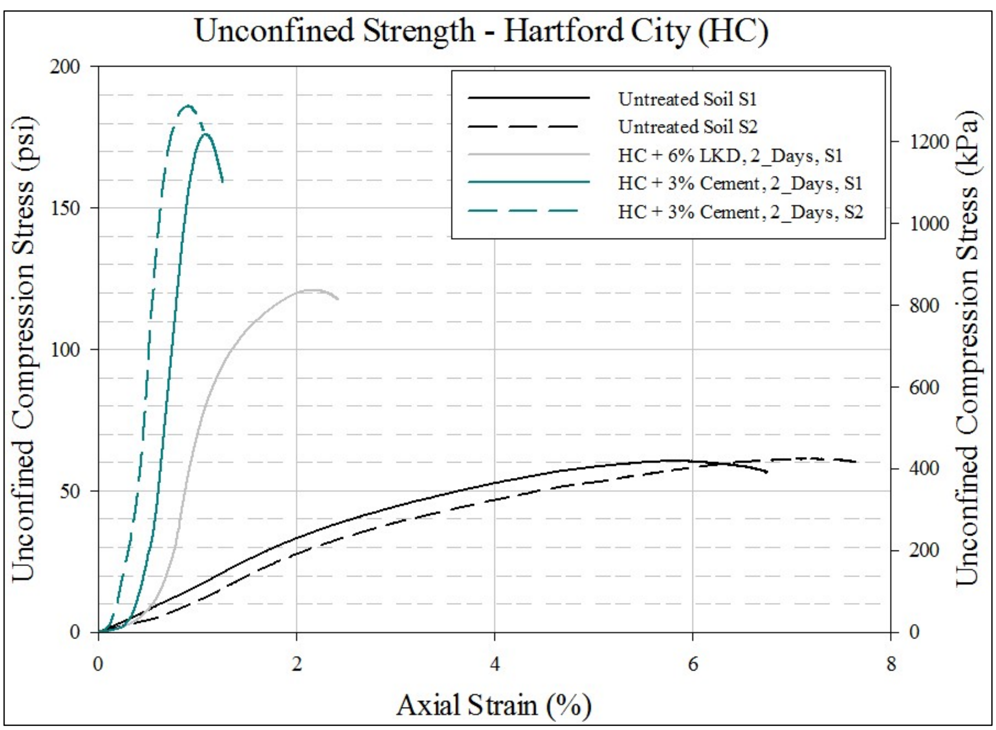


Figure C.7 Unconfined compression strength for untreated soil and soil with optimum amount of treatment after 48 hours curing. Hartford City (HC).

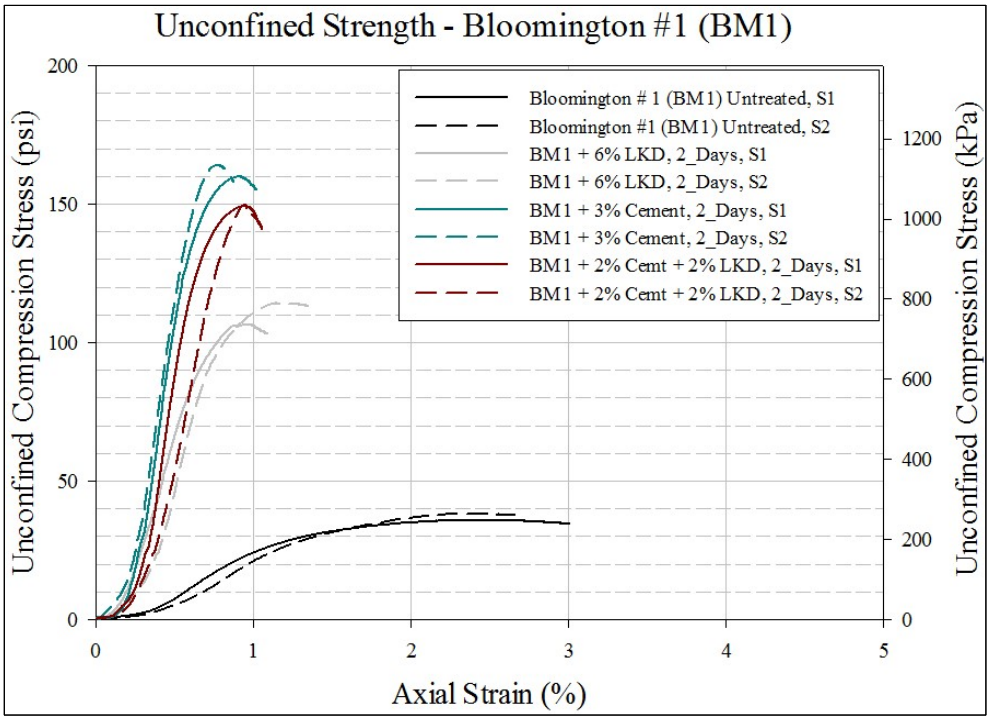


Figure C.8 Unconfined compression strength for untreated soil and soil with optimum amount of treatment after 48 hours curing. Bloomington #1 (BM1).

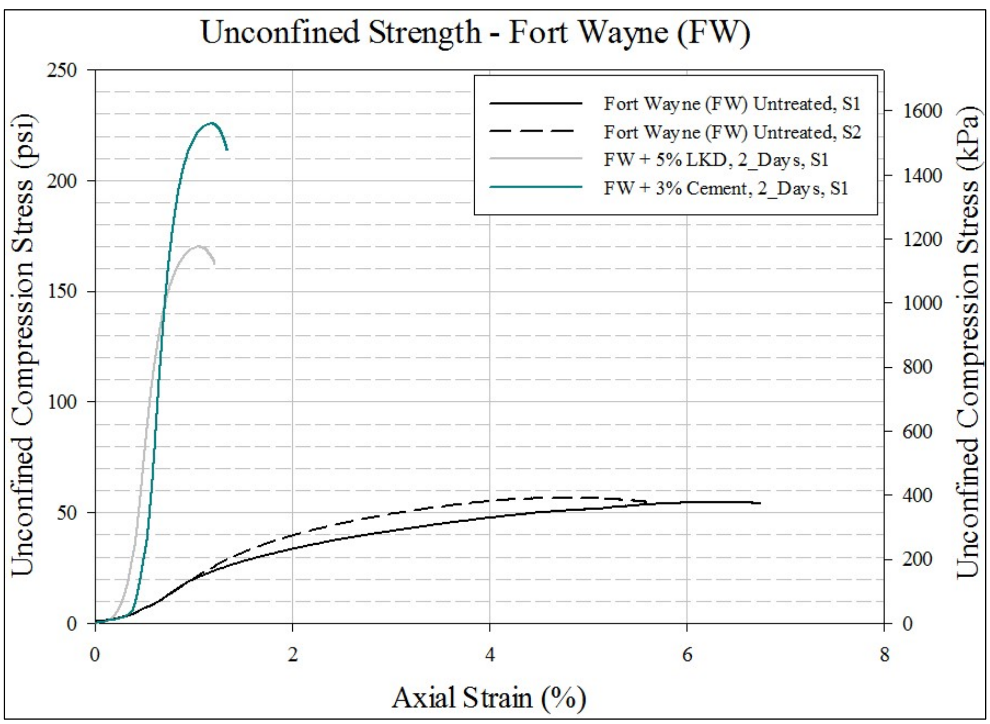


Figure C.9 Unconfined compression strength for untreated soil and soil with optimum amount of treatment after 48 hours curing. Fort Wayne (FW).

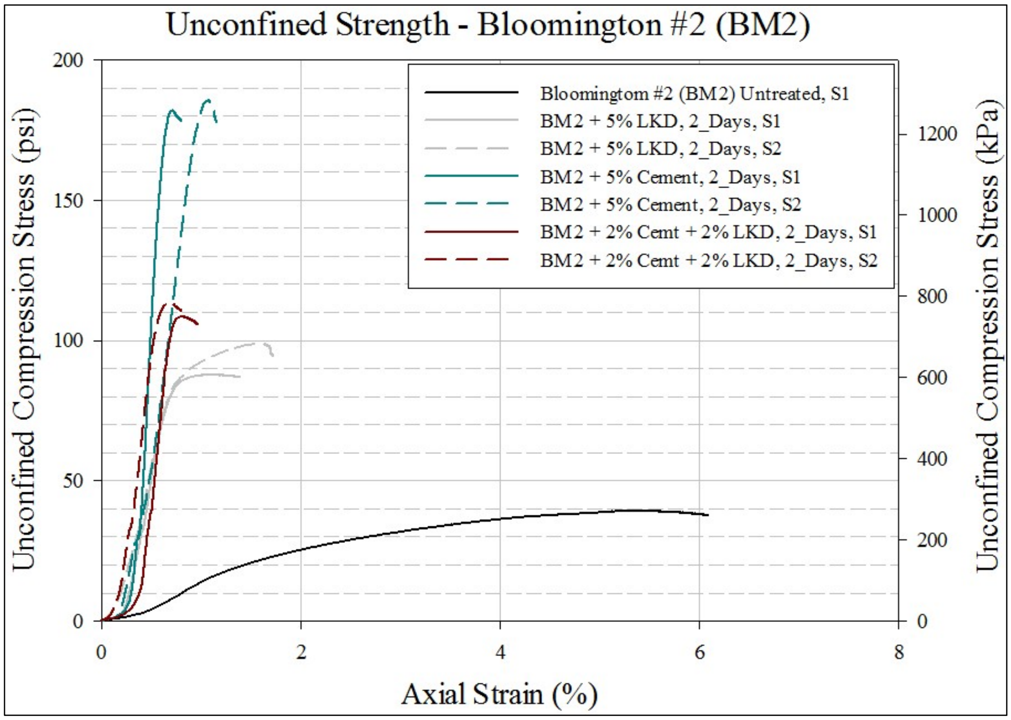


Figure C.10 Unconfined compression strength for untreated soil and soil with optimum amount of treatment after 48 hours curing. Bloomington #2 (BM2).

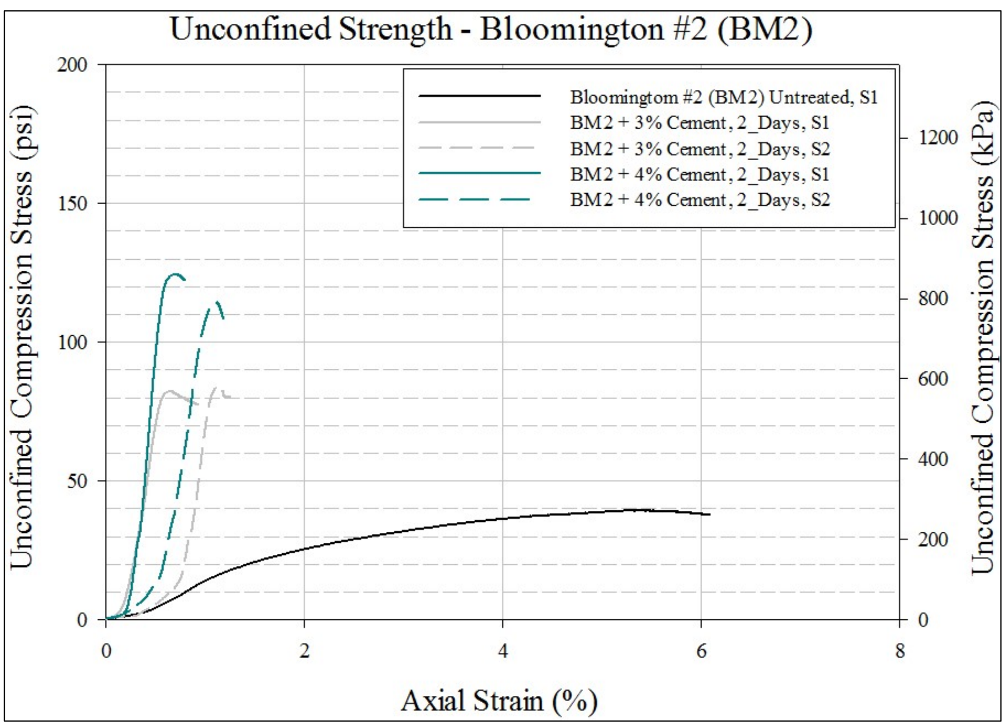


Figure C.11 Unconfined compression strength for untreated soil and soil with amount of cement smaller than optimum after 48 hours curing. Bloomington #2 (BM2).

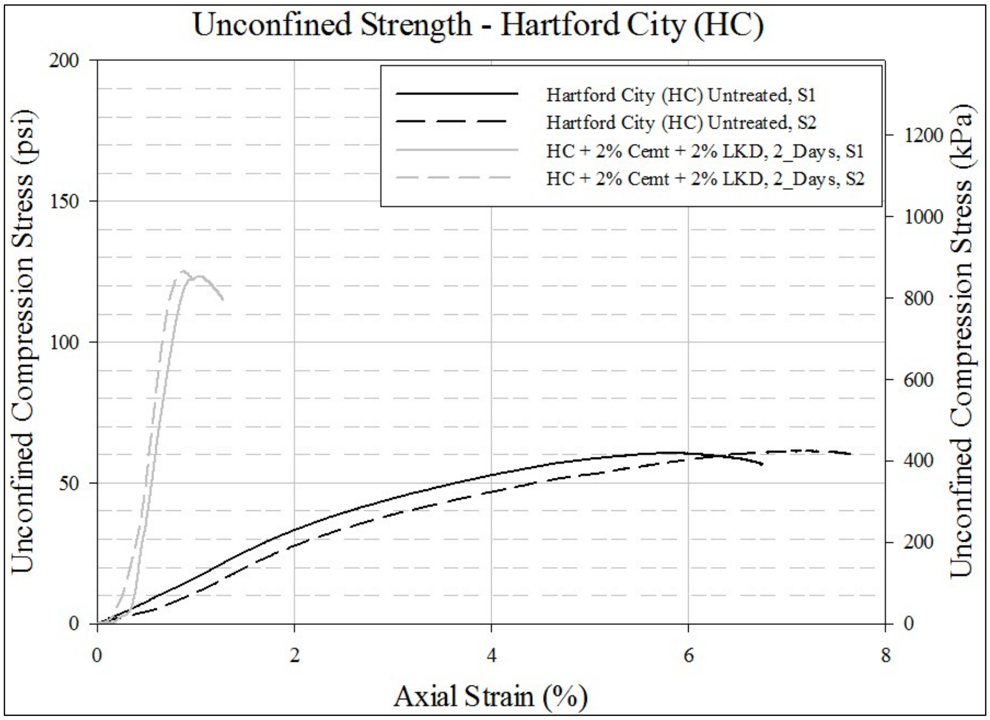


Figure C.12 Unconfined compression strength for untreated soil and soil with amount of cement + LKD smaller than optimum after 48 hours curing. Hartford City (HC).

APPENDIX D. EFFECT OF OPTIMUM AMOUNT OF TREATMENT ON PLASTICITY AND GRAIN SIZE DISTRIBUTION

The Atterberg limits were conducted on soil Passing #40, following AASHTO T-89/T-90. Results of the Atterberg limits, for different ages and treatment, are shown in Figures D.1 to D.3 for samples from HC; in Figures D.4 to D.7 for BM1; in Figures D.8 to D.10 for FW; and in Figures D.11 to D.14 for BM2.

To obtain the grain size distribution, moist samples were first washed through the #200 sieve, and the sieve analysis was performed following AASHTO T-88. Tests were performed for specimens cured between 75 and 190 days. Figures D.15 to D.18 show the grain size distribution for HC, BM1, FW, and BM2 soils, respectively.

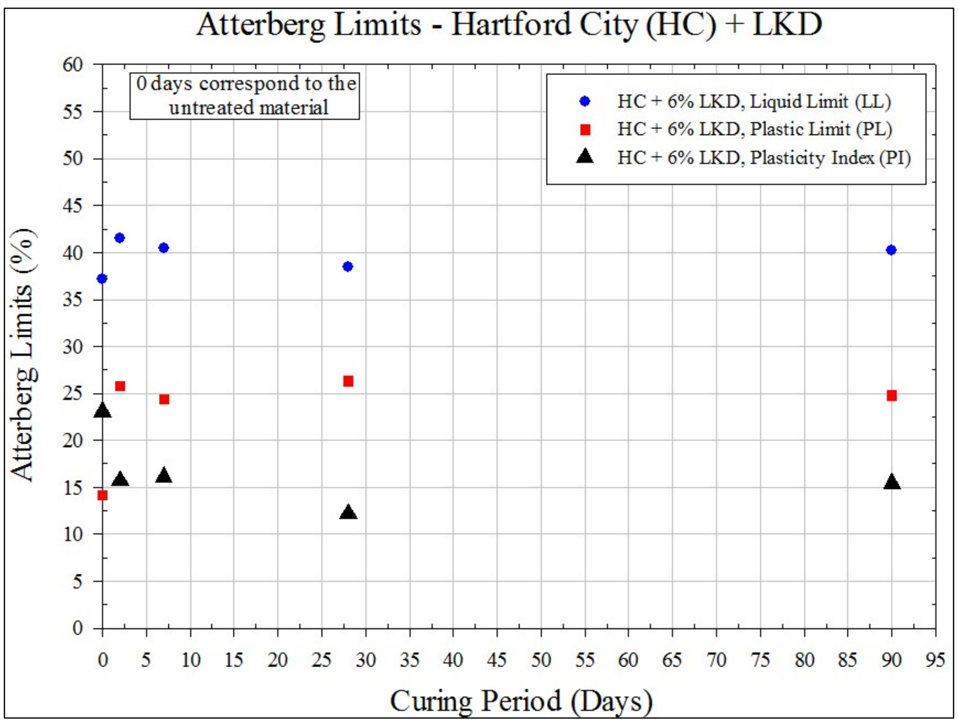


Figure D.1 Atterberg limits for untreated soil and soil treated with optimum amount of LKD for different curing periods. Hartford City (HC).

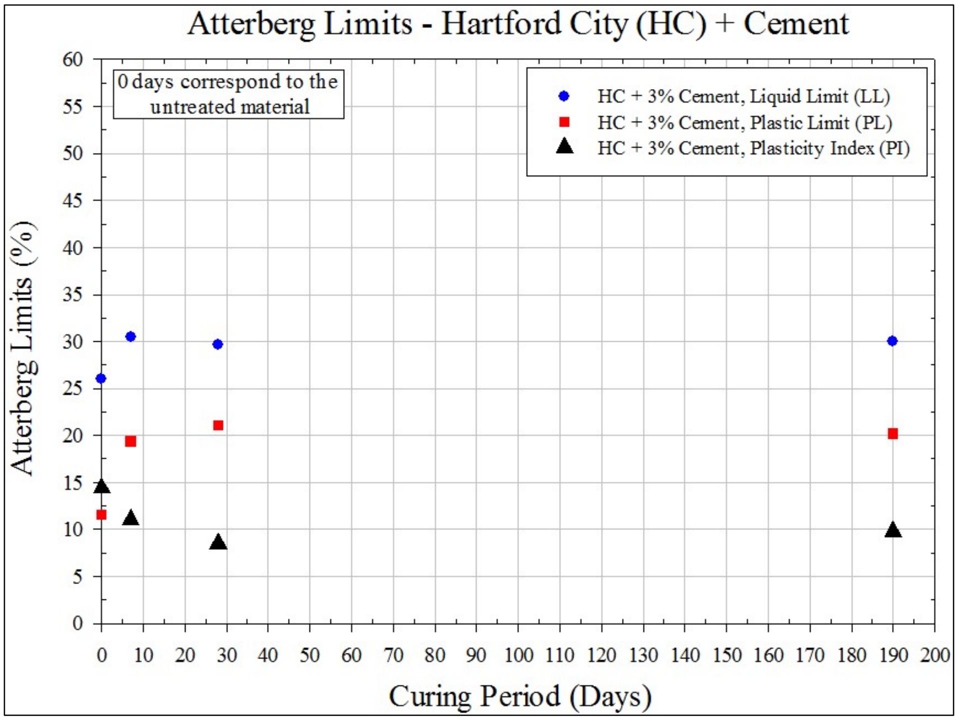


Figure D.2 Atterberg limits for untreated soil and soil treated with optimum amount of cement for different curing periods. Hartford City (HC).

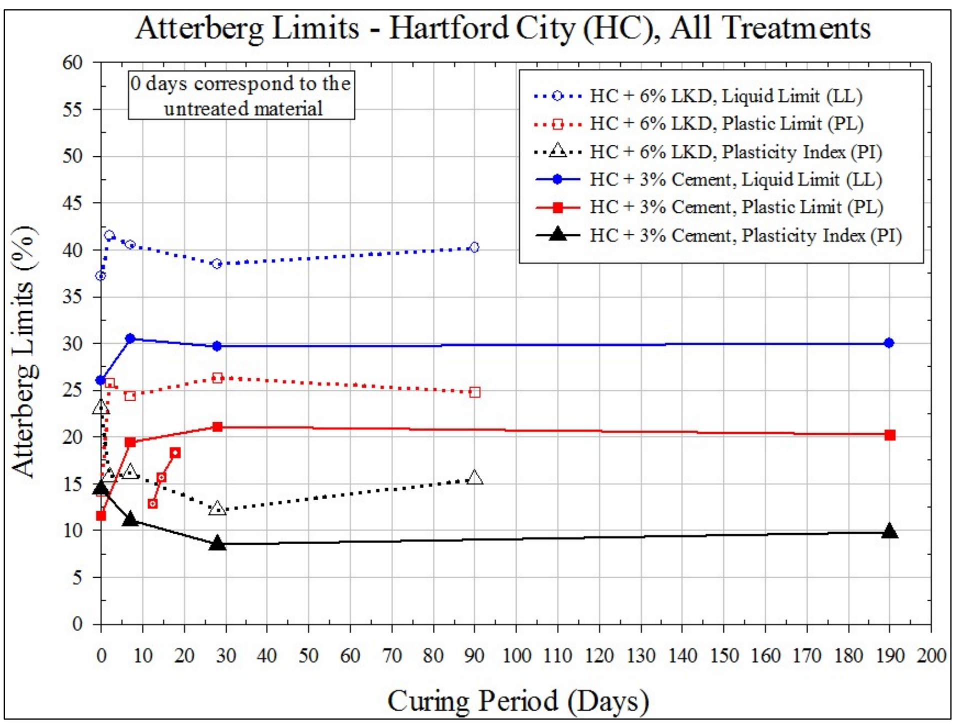


Figure D.3 Atterberg limits for untreated soil and soil treated with optimum amounts of LKD or cement for different curing periods. Hartford City (HC).

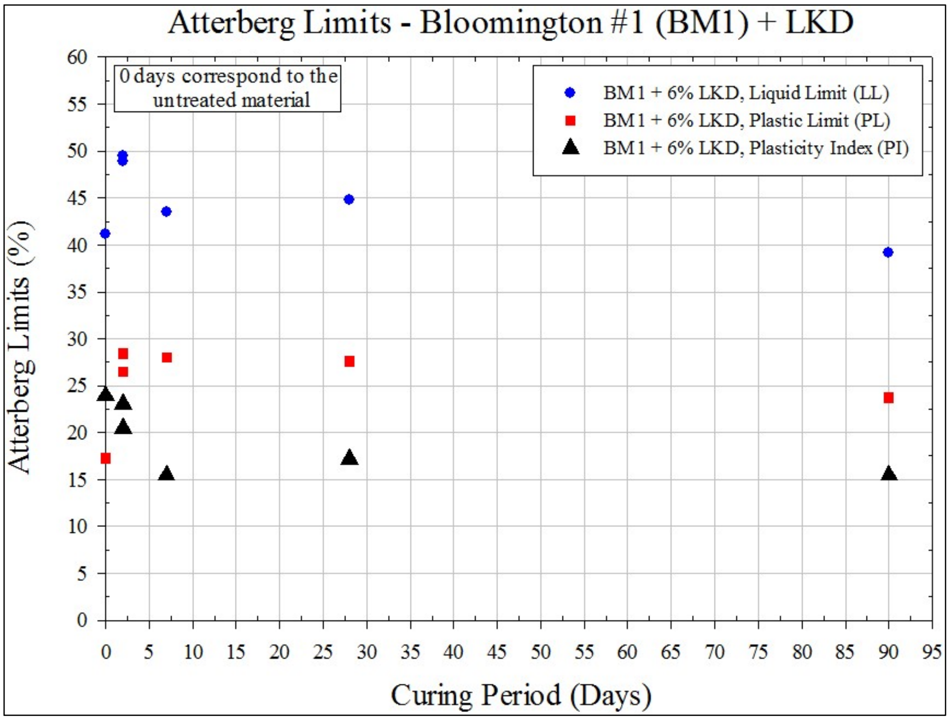


Figure D.4 Atterberg limits for untreated soil and soil treated with optimum amount of LKD for different curing periods. Bloomington #1 (BM1).

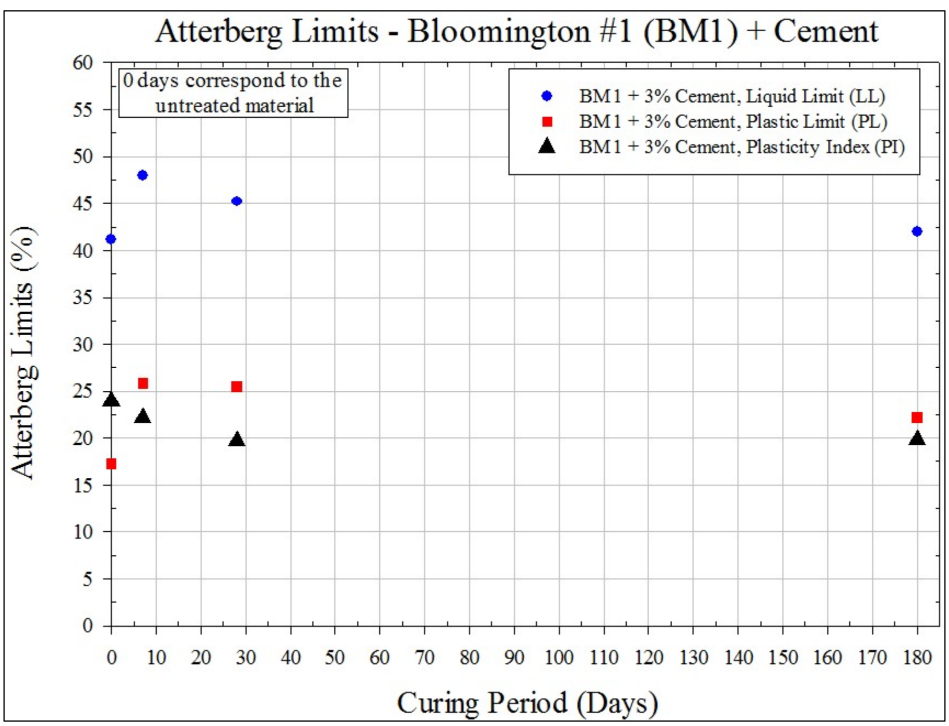


Figure D.5 Atterberg limits for untreated soil and soil treated with optimum amount of cement for different curing periods. Bloomington #1 (BM1).

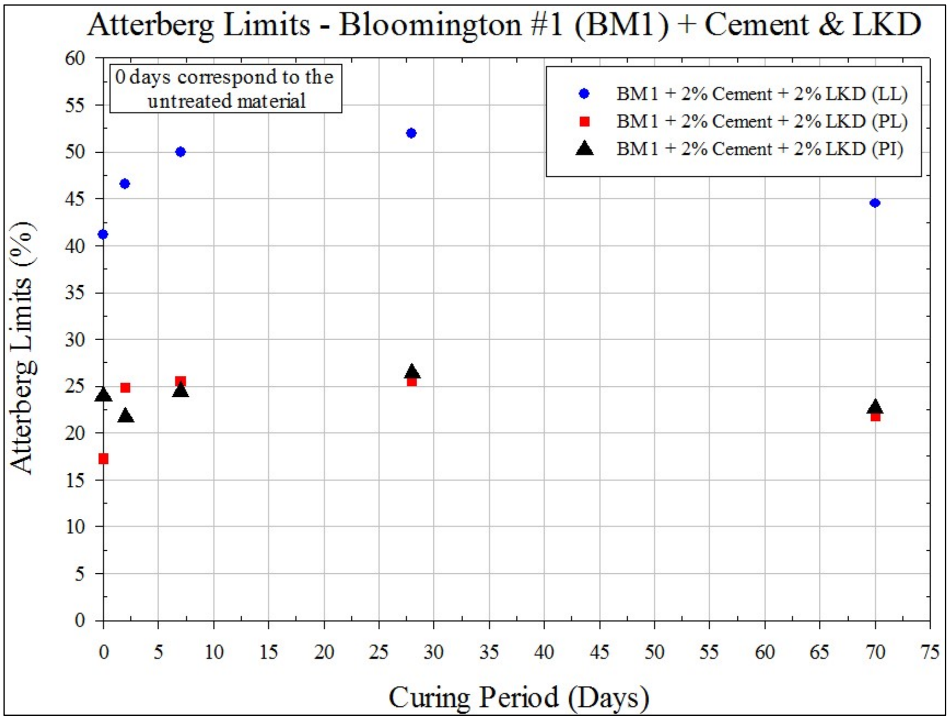


Figure D.6 Atterberg limits for untreated soil and soil treated with optimum amount of cement + LKD for different curing periods. Bloomington #1 (BM1).

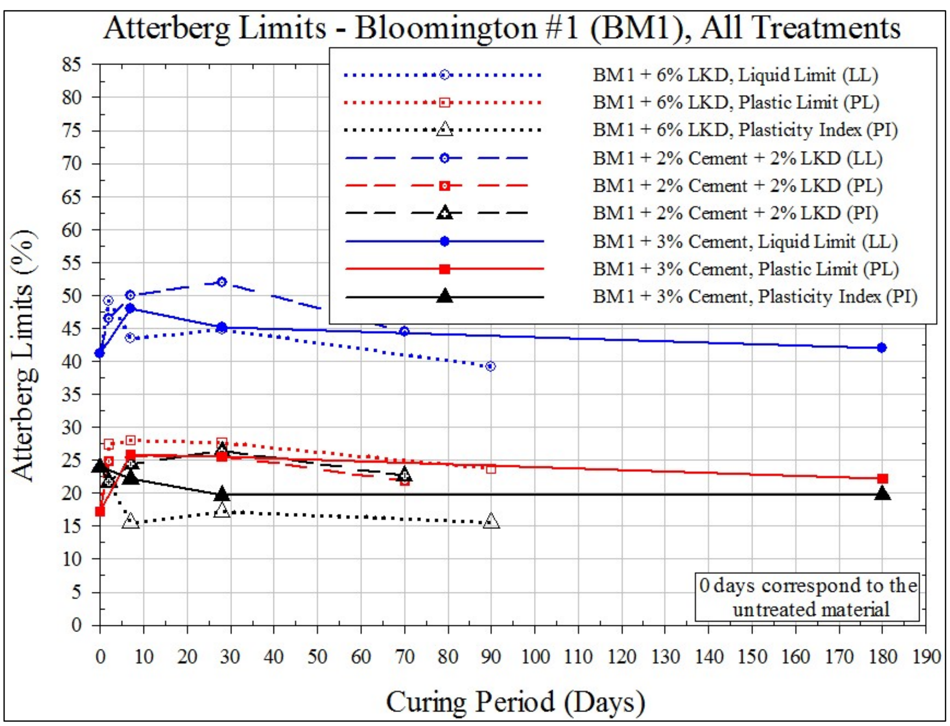


Figure D.7 Atterberg limits for untreated soil and soil treated with optimum amount of LKD, cement, or cement + LKD for different curing periods. Bloomington #1 (BM1).

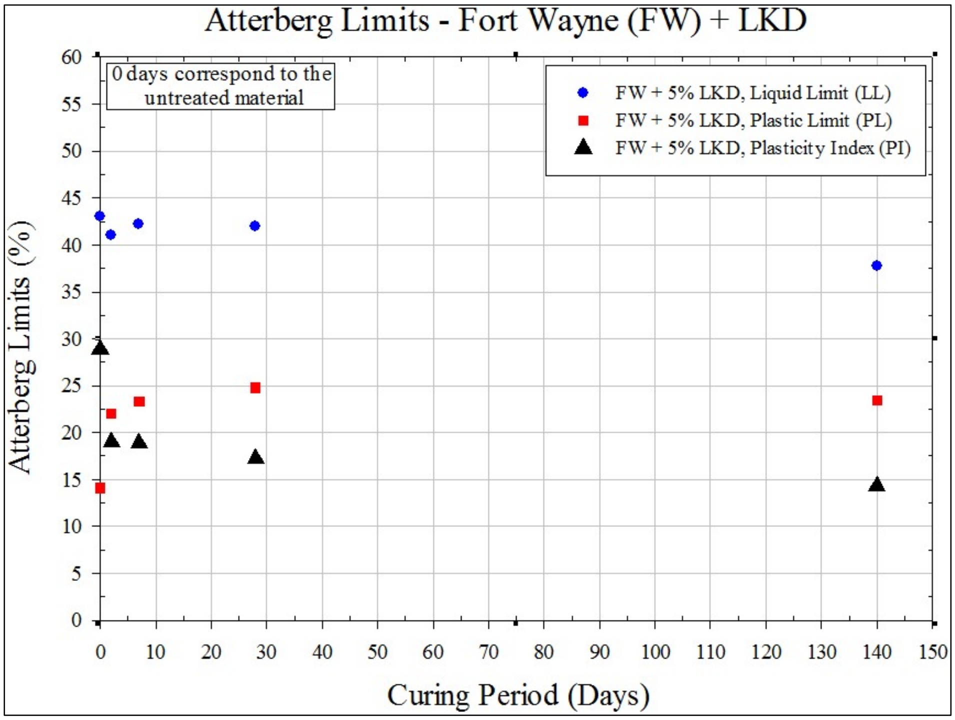


Figure D.8 Atterberg limits for untreated soil and soil treated with optimum amount of LKD for different curing periods. Fort Wayne (FW).

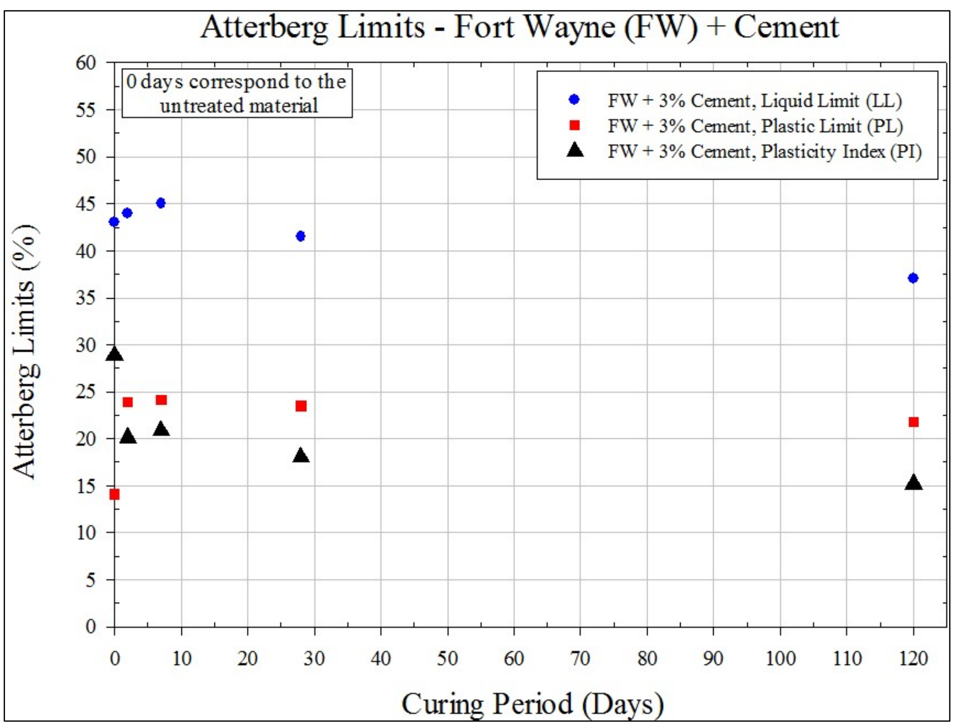


Figure D.9 Atterberg limits for untreated soil and soil treated with optimum amount of cement for different curing periods. Fort Wayne (FW).

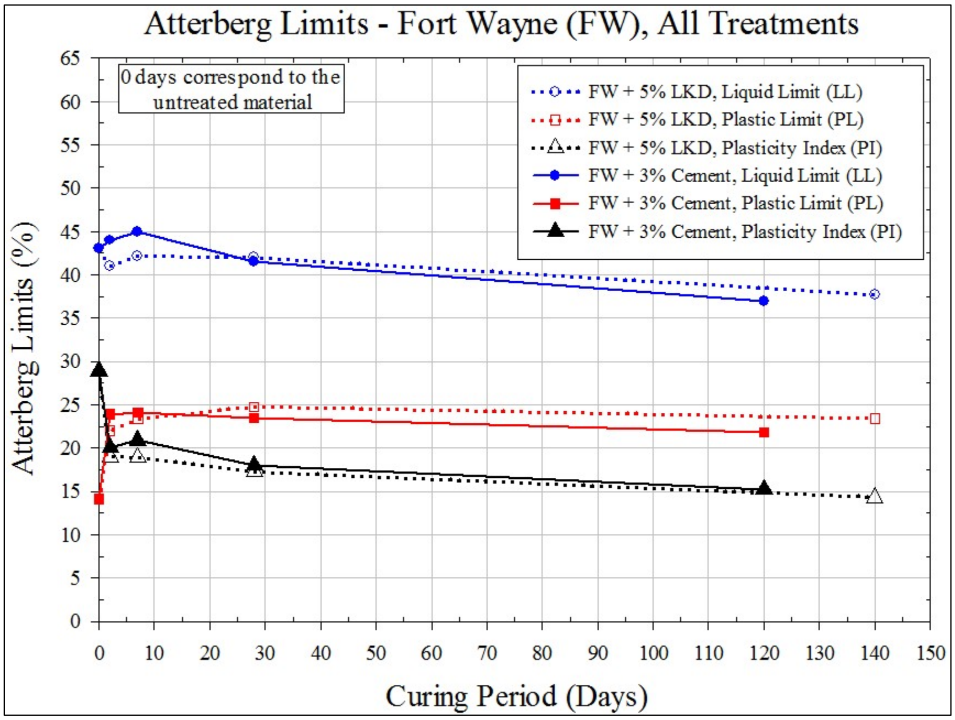


Figure D.10 Atterberg limits for untreated soil and soil treated with optimum amount of LKD or cement, for different curing periods. Fort Wayne (FW).

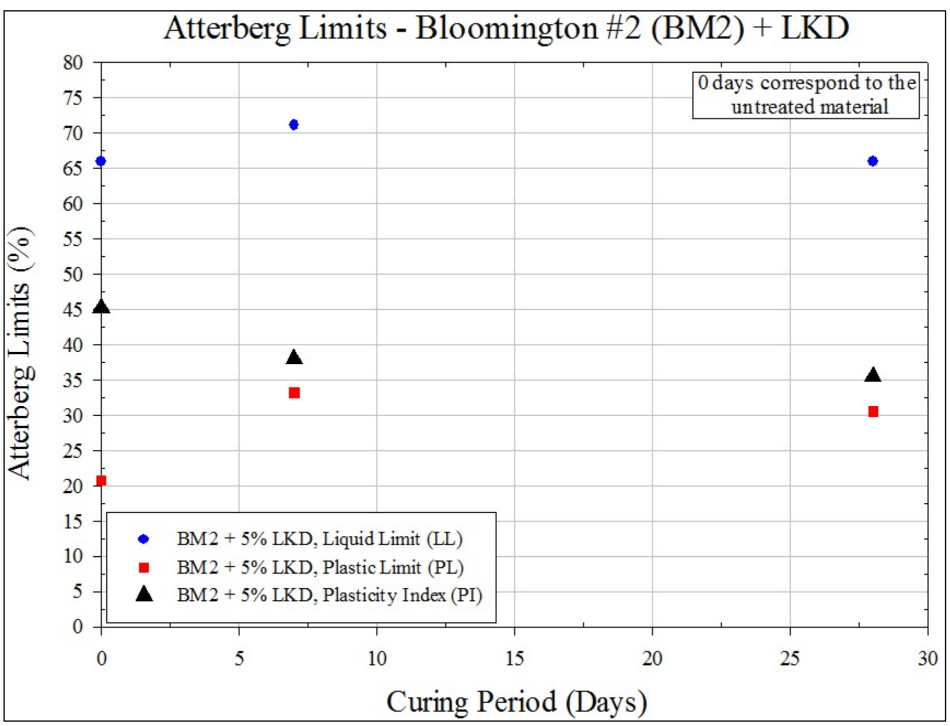


Figure D.11 Atterberg limits for untreated soil and soil treated with optimum amount of LKD for different curing periods. Bloomington #2 (BM2).

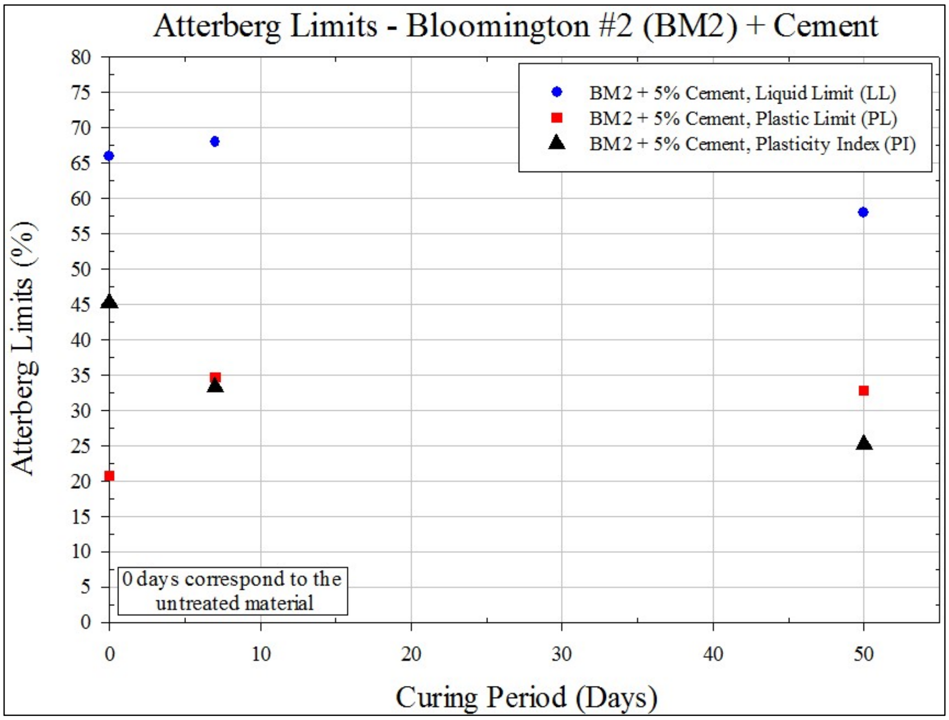


Figure D.12 Atterberg limits for untreated soil and soil treated with optimum amount of cement, for different curing periods. Bloomington #2 (BM2).

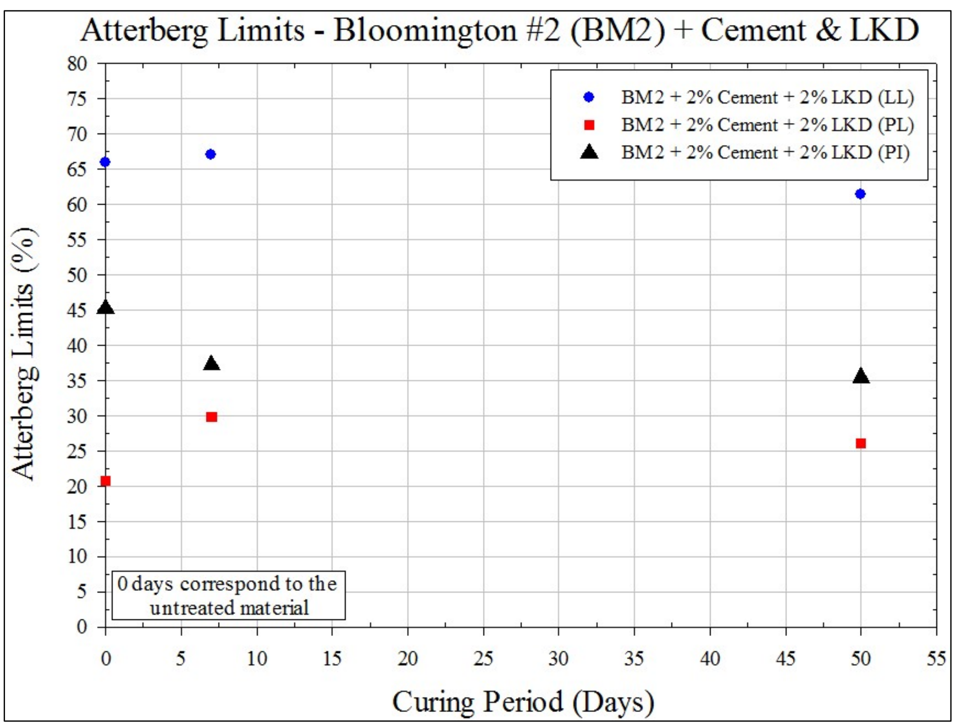


Figure D.13 Atterberg limits for untreated soil and soil treated with optimum amount of cement + LKD for different curing periods. Bloomington #2 (BM2).

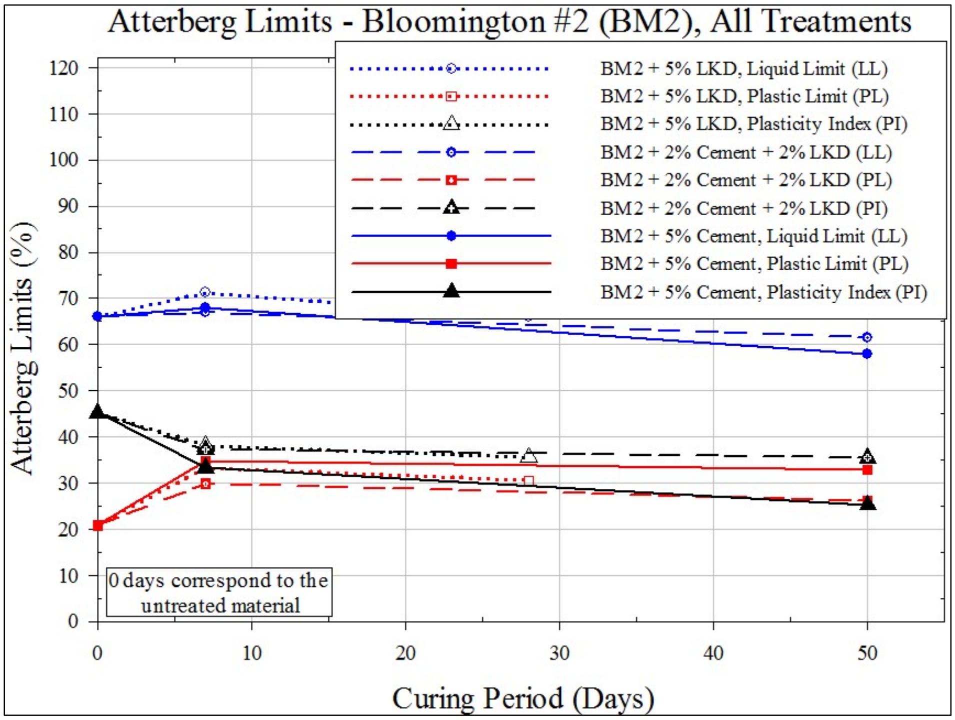


Figure D.14 Atterberg limits for untreated soil and soil treated with optimum amount of LKD, cement, or cement + LKD for different curing periods. Bloomington #2 (BM2).

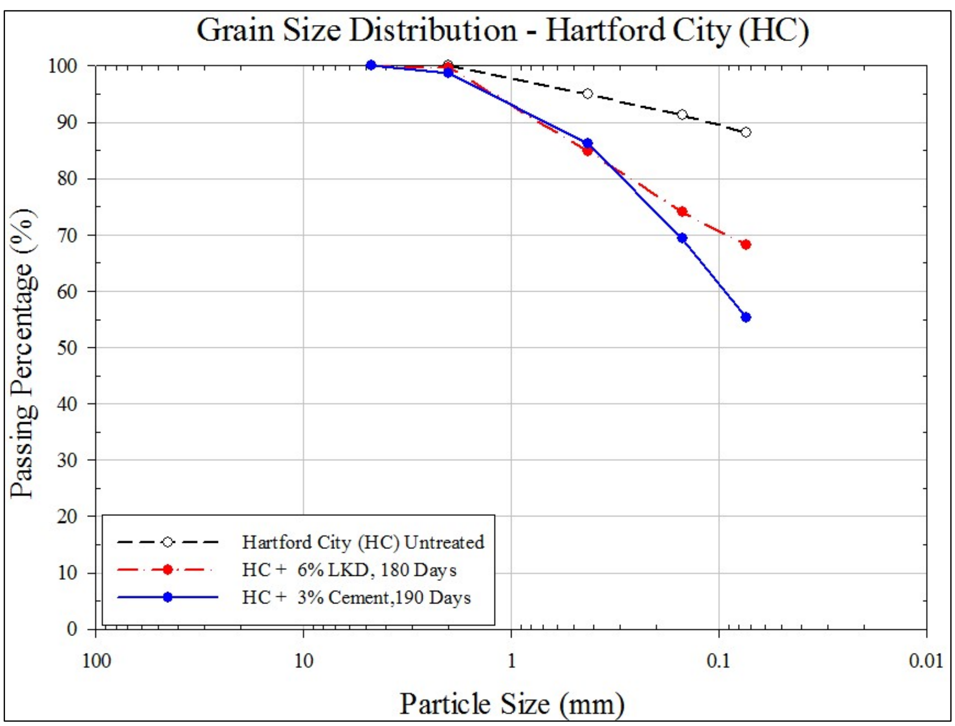


Figure D.15 Grain size distribution for untreated soil and soil treated with optimum amount of LKD or cement. Hartford City (HC).

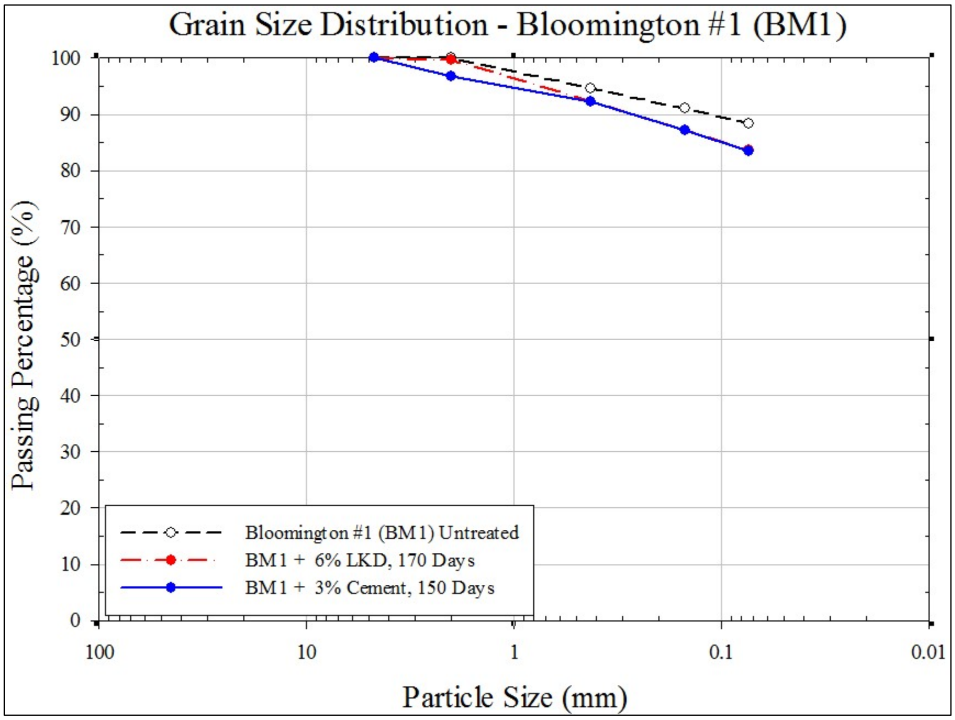


Figure D.16 Grain size distribution for untreated soil and soil treated with optimum amount of LKD or cement. Bloomington #1 (BM1).

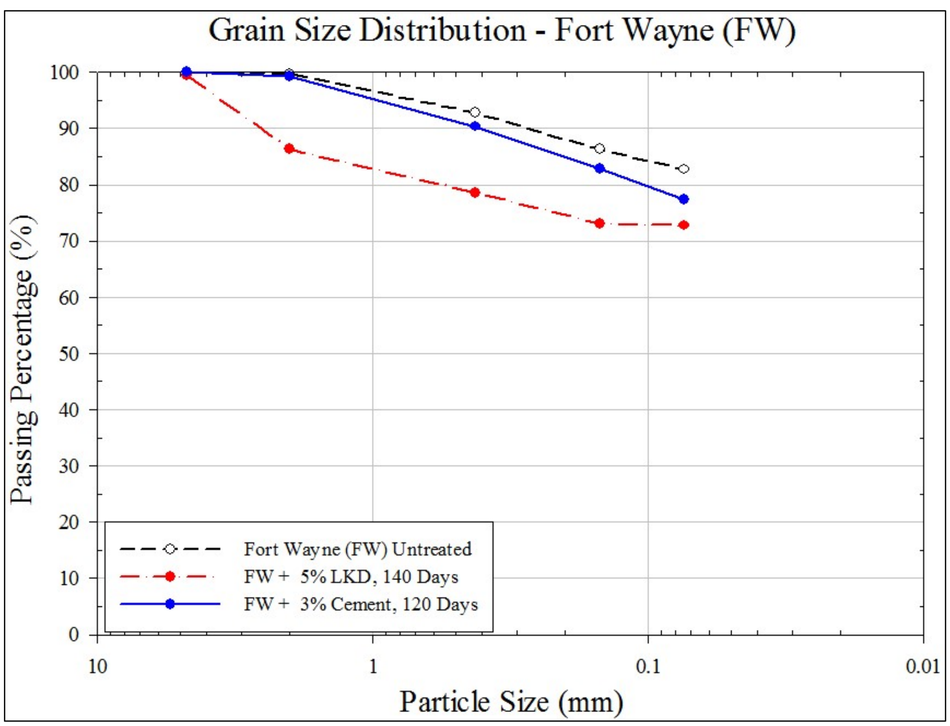


Figure D.17 Grain size distribution for untreated soil and soil treated with optimum amount of LKD or cement. Fort Wayne (FW).

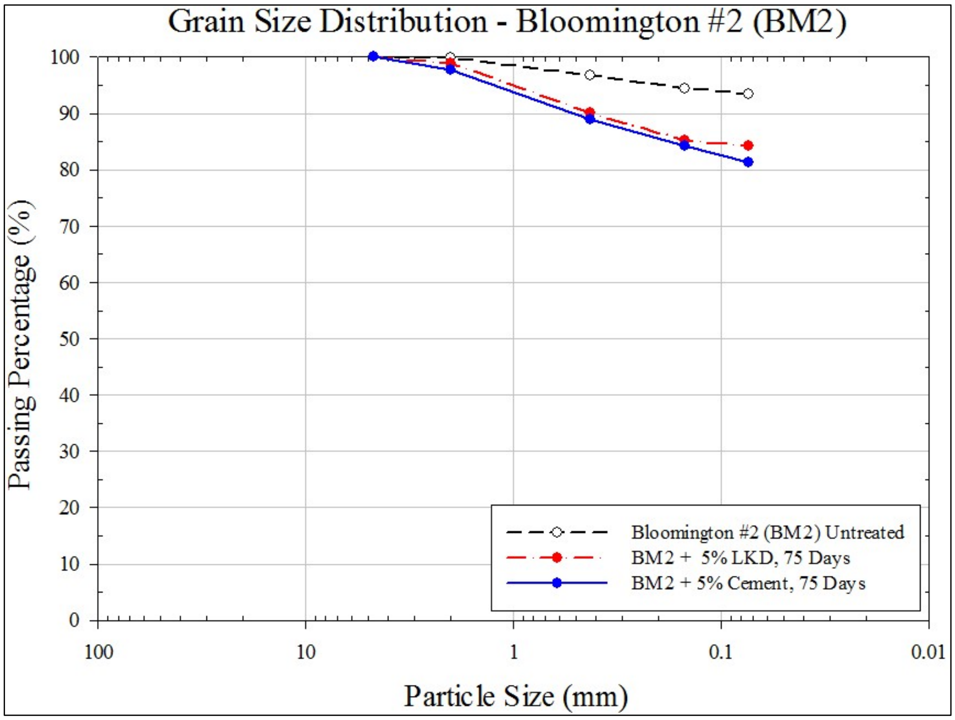


Figure D.18 Grain size distribution for untreated soil and soil treated with optimum amount of LKD or cement. Bloomington #2 (BM2).

APPENDIX E. EFFECT OF OPTIMUM AMOUNT OF TREATMENT ON UNCONFINED COMPRESSION STRENGTH

Samples for unconfined compression tests (following AASHTO T-208) were prepared and tested at 2, 7, 28, and 90 days for mixtures with LKD, and at 2, 7, and 28 days for mixtures with cement or LKD + cement. The samples had 33 mm of diameter and 71 mm of height. The test results are shown in Figures E.1 and E.2 for HC samples; in Figures E.3 to E.5 for BM1; in Figures E.6 and E.7 for FW; and in Figures E.8 to E.10 for BM2 samples.

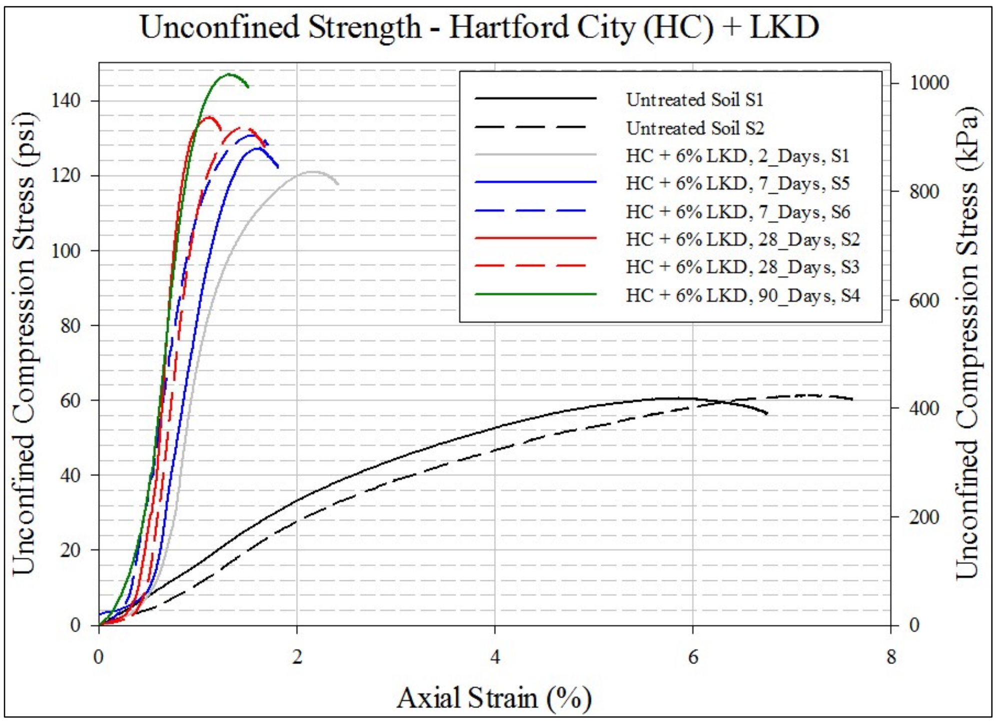


Figure E.1 Unconfined compression strength for untreated soil and soil treated with optimum amount of LKD for different curing periods. Hartford City (HC).

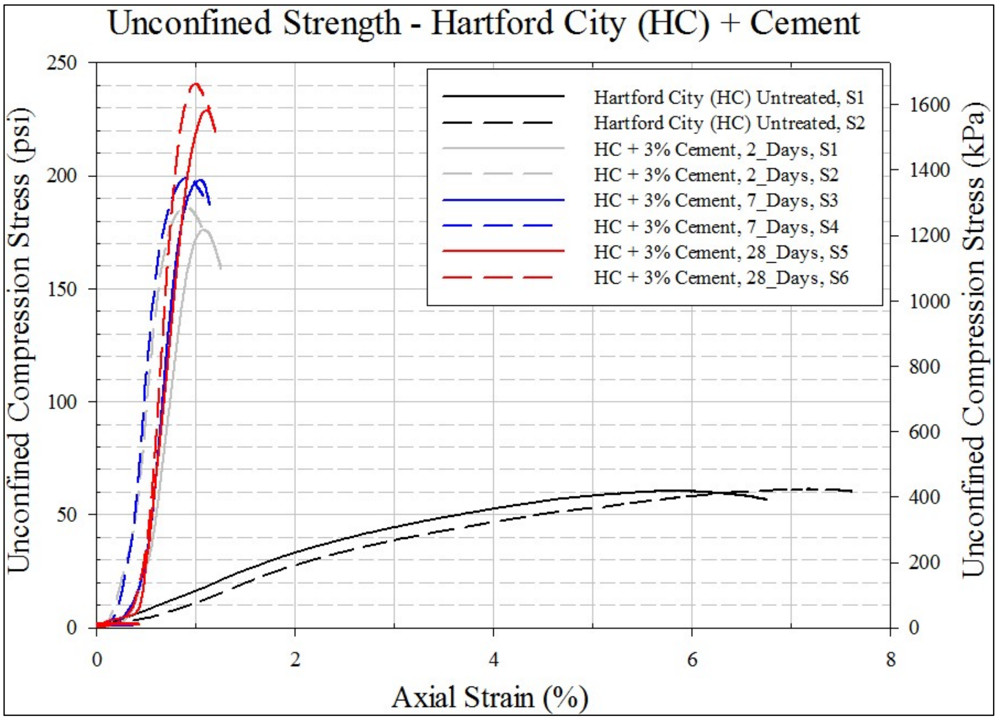


Figure E.2 Unconfined compression strength for untreated soil and soil treated with optimum amount of cement, for different curing periods. Hartford City (HC).

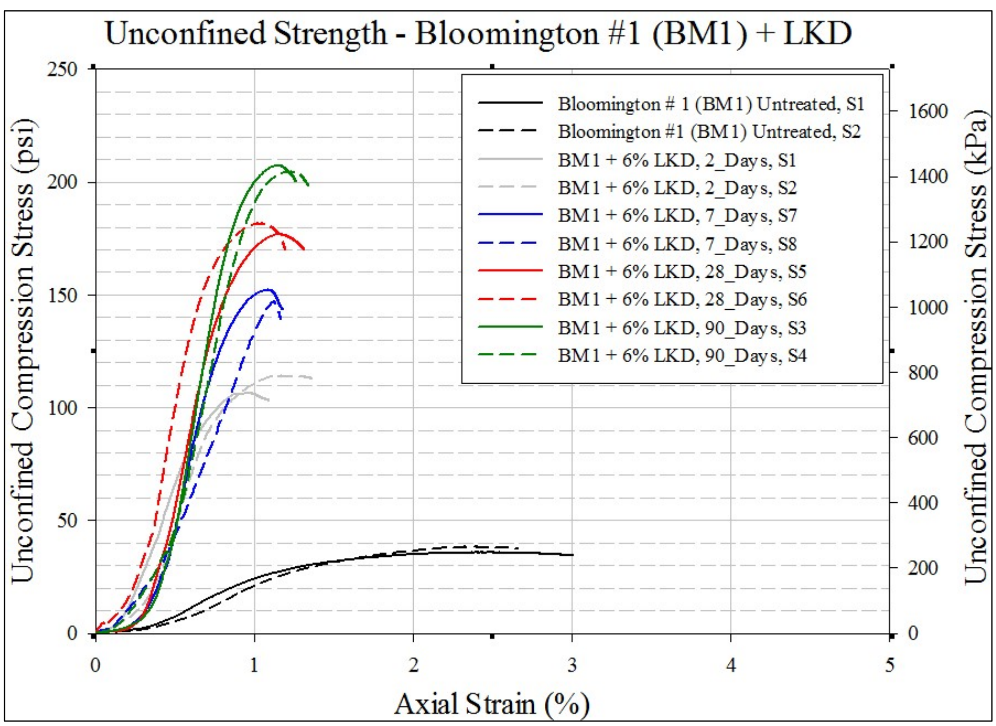


Figure E.3 Unconfined compression strength for untreated soil and soil treated with optimum amount of LKD for different curing periods. Bloomington #1 (BM1).

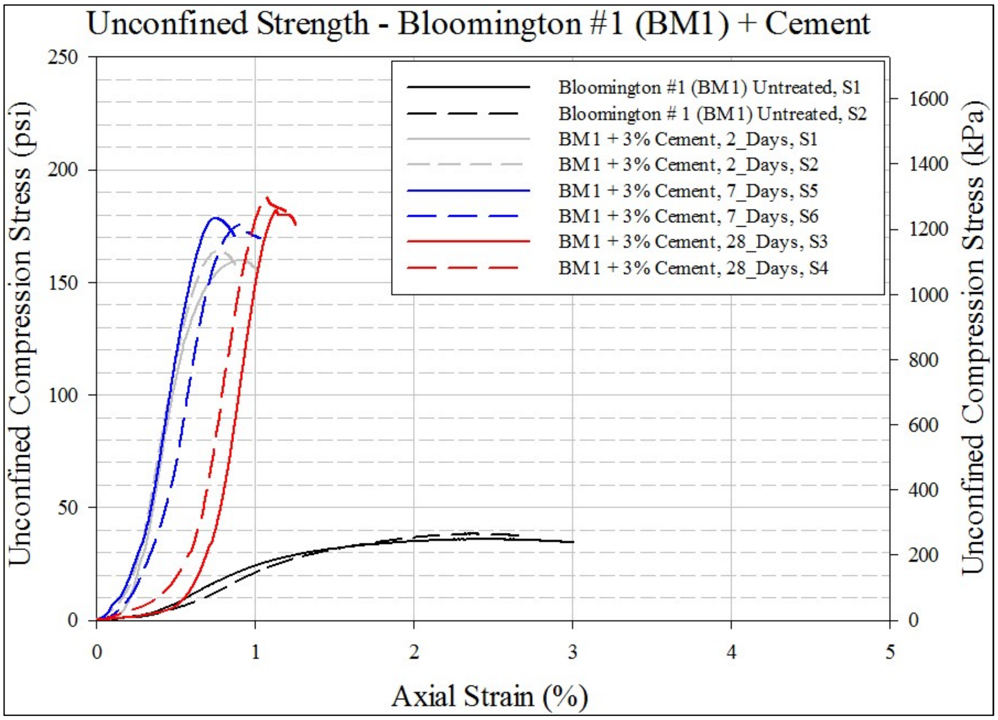


Figure E.4 Unconfined compression strength for untreated soil and soil treated with optimum amount of cement for different curing periods. Bloomington #1 (BM1).

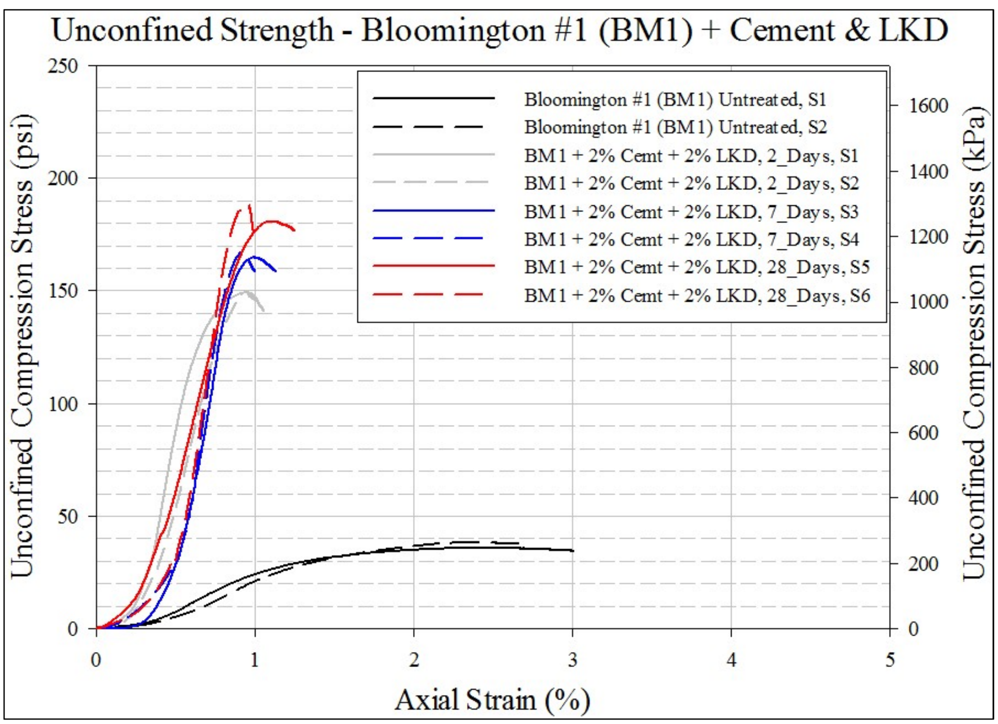


Figure E.5 Unconfined compression strength for untreated soil and soil treated with optimum amount of cement + LKD for different curing periods. Bloomington #1 (BM1).

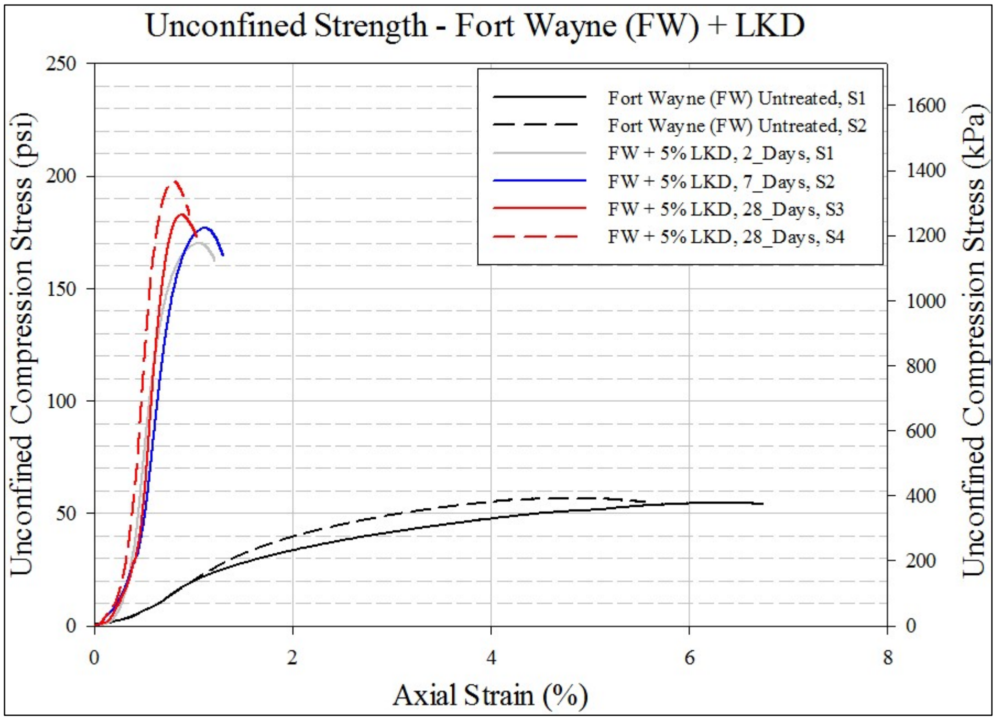


Figure E.6 Unconfined compression strength for untreated soil and soil treated with optimum amount of LKD for different curing periods. Fort Wayne (FW).

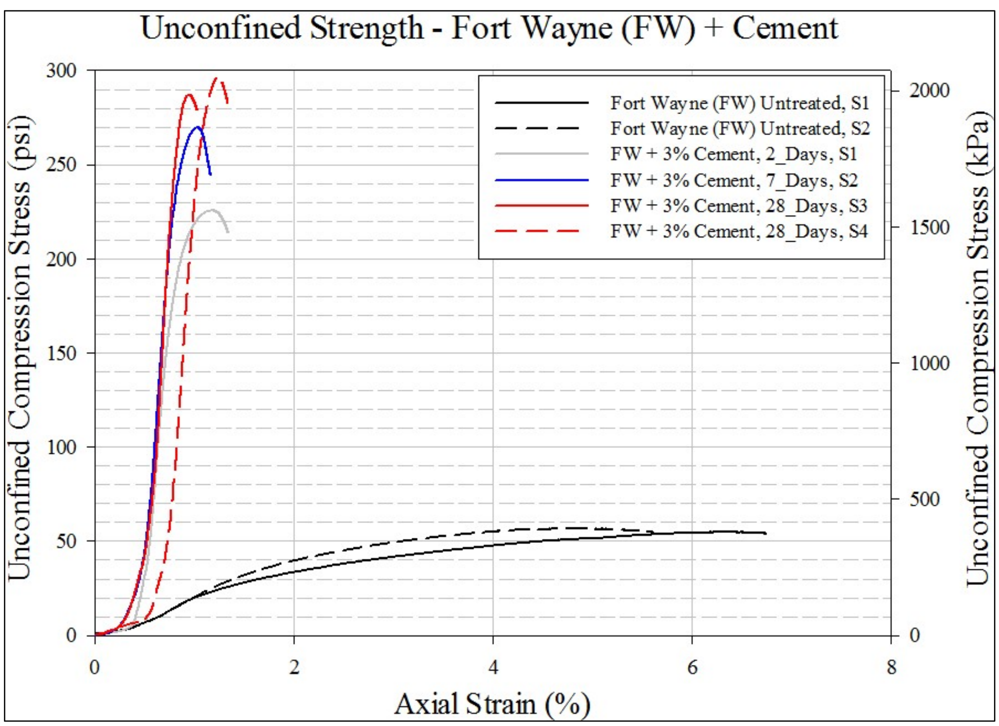


Figure E.7 Unconfined compression strength for untreated soil and soil treated with optimum amount of cement for different curing periods. Fort Wayne (FW).

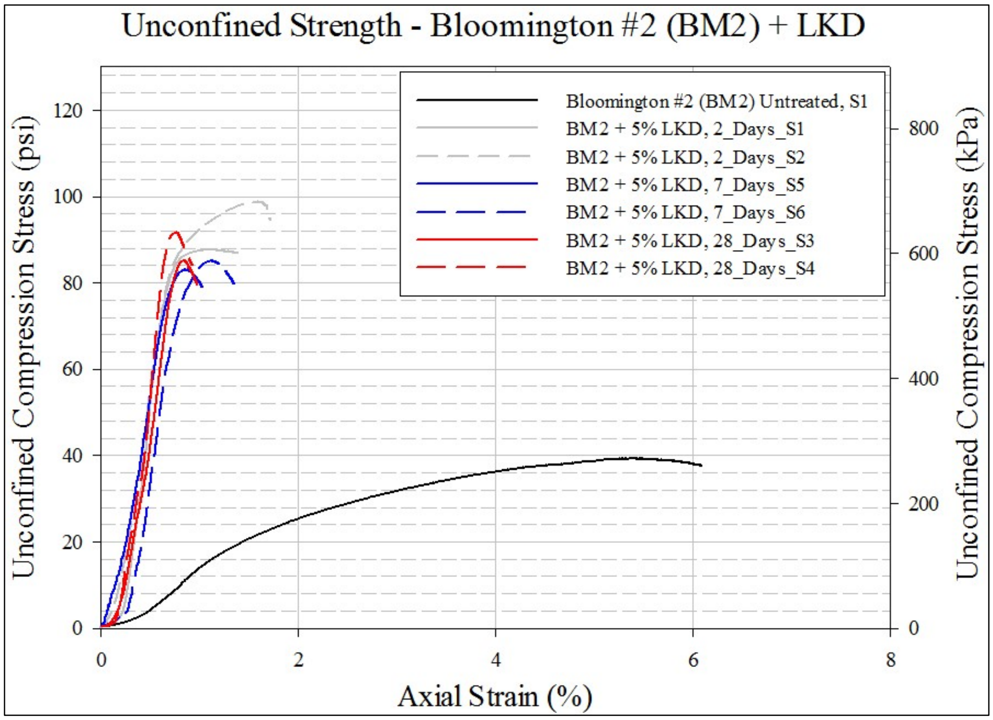


Figure E.8 Unconfined compression strength for untreated soil and soil treated with optimum amount of LKD for different curing periods. Bloomington #2 (BM2).

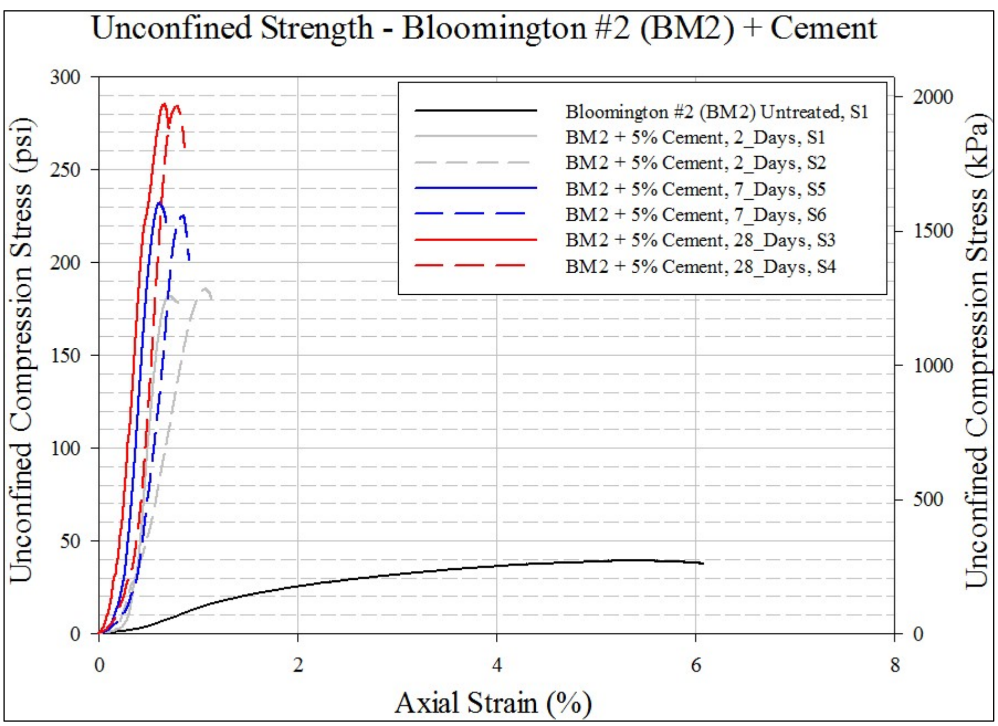


Figure E.9 Unconfined compression strength for untreated soil and soil treated with optimum amount of cement for different curing periods. Bloomington #2 (BM2).

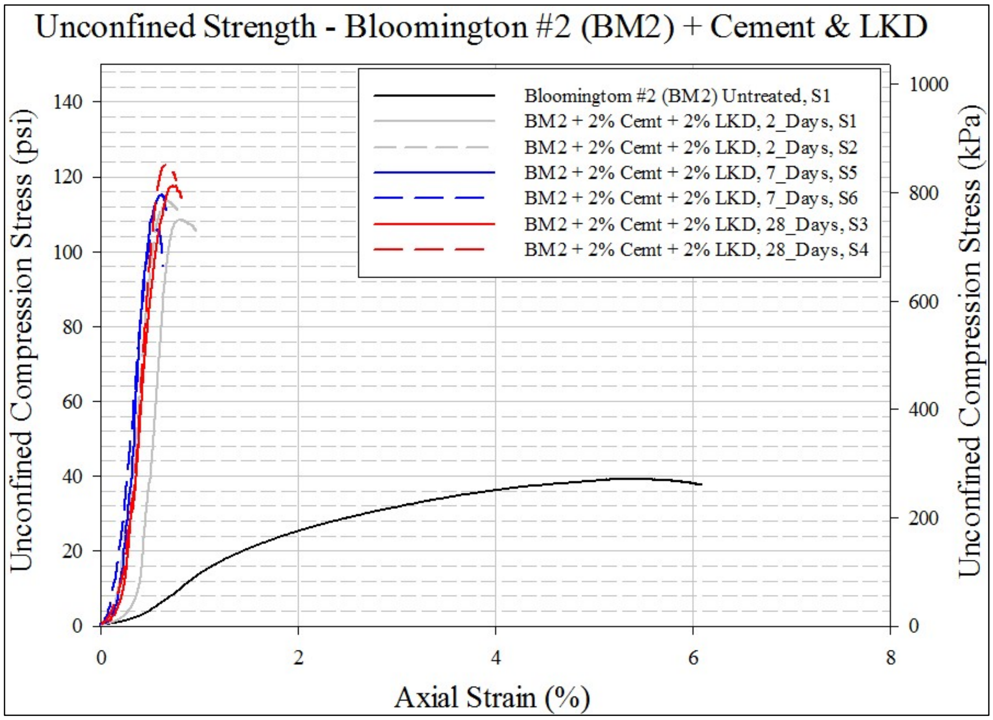


Figure E.10 Unconfined compression strength for untreated soil and soil treated with optimum amount of cement + LKD for different curing periods. Bloomington #2 (BM2).

APPPENDIX F. EFFECT OF OPTIMUM AMOUNT OF TREATMENT ON RESILIENT MODULUS

Remolded samples were prepared to conduct resilient modulus tests (M_R), following AASHTO T307-99 (2007) for Type 2 Material, i.e., fine-grained soils. For mixtures with LKD, samples at 7, 28, and 90 days were prepared. For soils mixed with LKD or LKD + cement, the curing periods were 7 and 28 days. For HC soil + LKD, a sample was tested after 2 days of curing.

The samples were compacted with five layers of equal mass, using the optimum moisture content and density corresponding to the 95% of the maximum density of the Standard Proctor. The samples had 71 mm in diameter and 142 mm in height. The natural soil was mixed with the chemical agent/s and later the water was added. For the compaction, spacers "plugs" of different thickness were used to guarantee all layers had the same volume. Using the spacers, the layers were compacted starting from the middle of the high until the bottom and top (see Annex C in AASHTO T307-99). After compaction, four measurements of height and six of diameter were taken to obtain the average volume of the sample. The mass and density of the sample were also obtained. The samples were placed into a plastic bag inside a cooler in the moisture room at 70°F, where they were stored until tested. Before performing the M_R test, the mass of the sample was measured to check water content (the loss of mass was always < 0.1% for all the samples).

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) and 6 psi (41.4 kPa), 8 psi (55.2 kPa) and 10 psi (69 kPa) were used. An initial sequence known as the "conditioning period" was imposed at the beginning of the test, with a confinement stresses, σ_3 = 6 psi (41.4 kPa) and a deviatoric stresses, σ_d = 4 psi (27.6 kPa). During the conditioning period, 500–1000 load repetitions were used. The loading was applied at a frequency, f = 10 Hz. The resilient modulus, M_R, is given as the ratio between the cyclic axial stress (S_{cyclic}) and its corresponding resilient (recovered) axial strain, ε_r ($M_R = S_{cyclic}/\varepsilon_r$). The average of the last five loading cycles (load repetitions) of 100 cycles performed for each combination of confinement and deviatoric stress, is reported as the resilient modulus.

Results of the resilient modulus tests, for different ages and treatments, are shown in Figures F.1 and F.2 for HC samples; in Figures F.3 to F.5 for BM1; in Figures F.6 and F.7 for FW; and in Figures F.8 to F.10 for BM2 soils. Table F.1 shows M_R values for all the soils, untreated and treated with LKD, cement, or LKD + cement, for different curing ages.

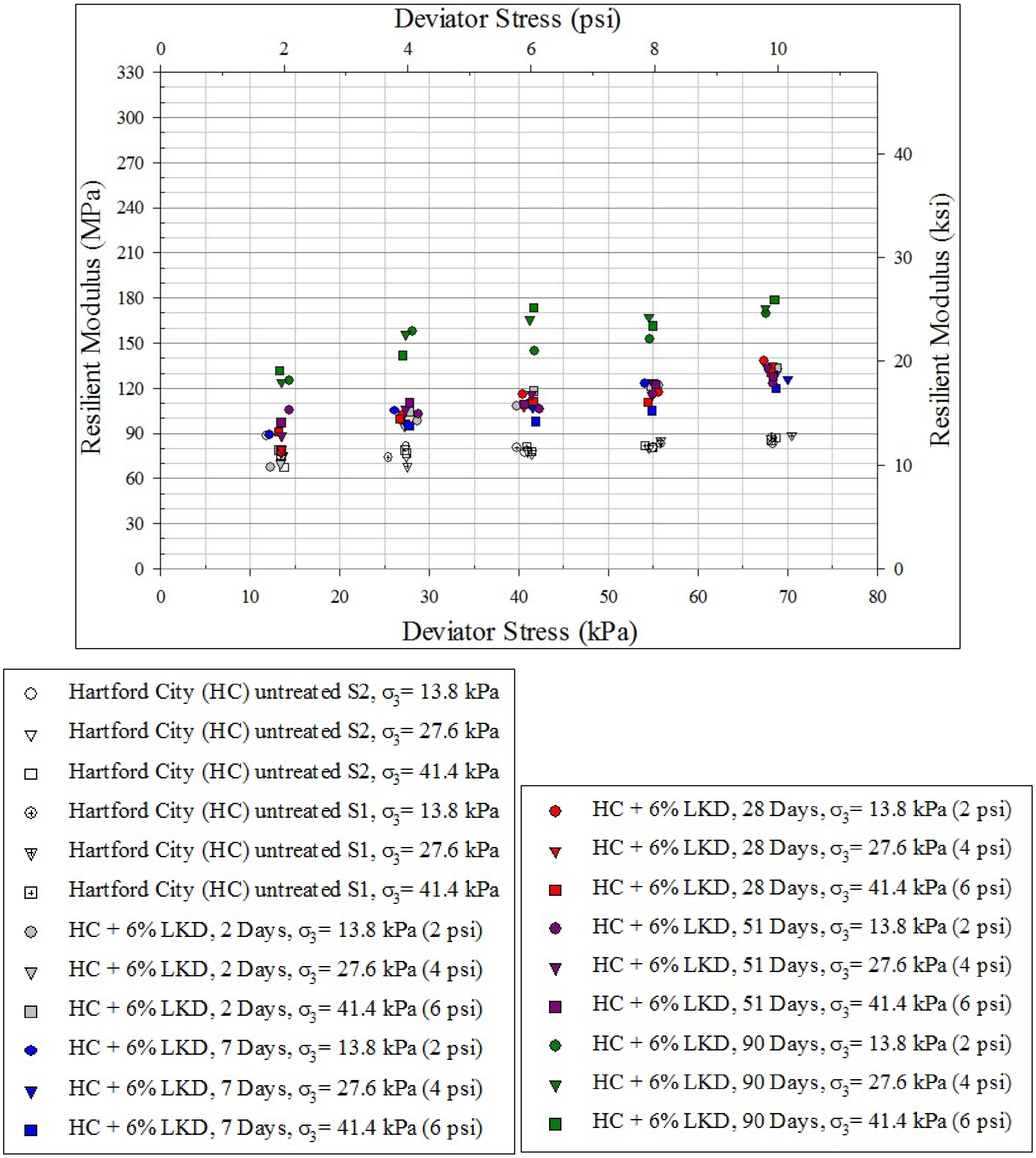


Figure F.1 Resilient modulus for untreated soil and soil treated with optimum amount of LKD for different curing periods. Hartford City (HC).

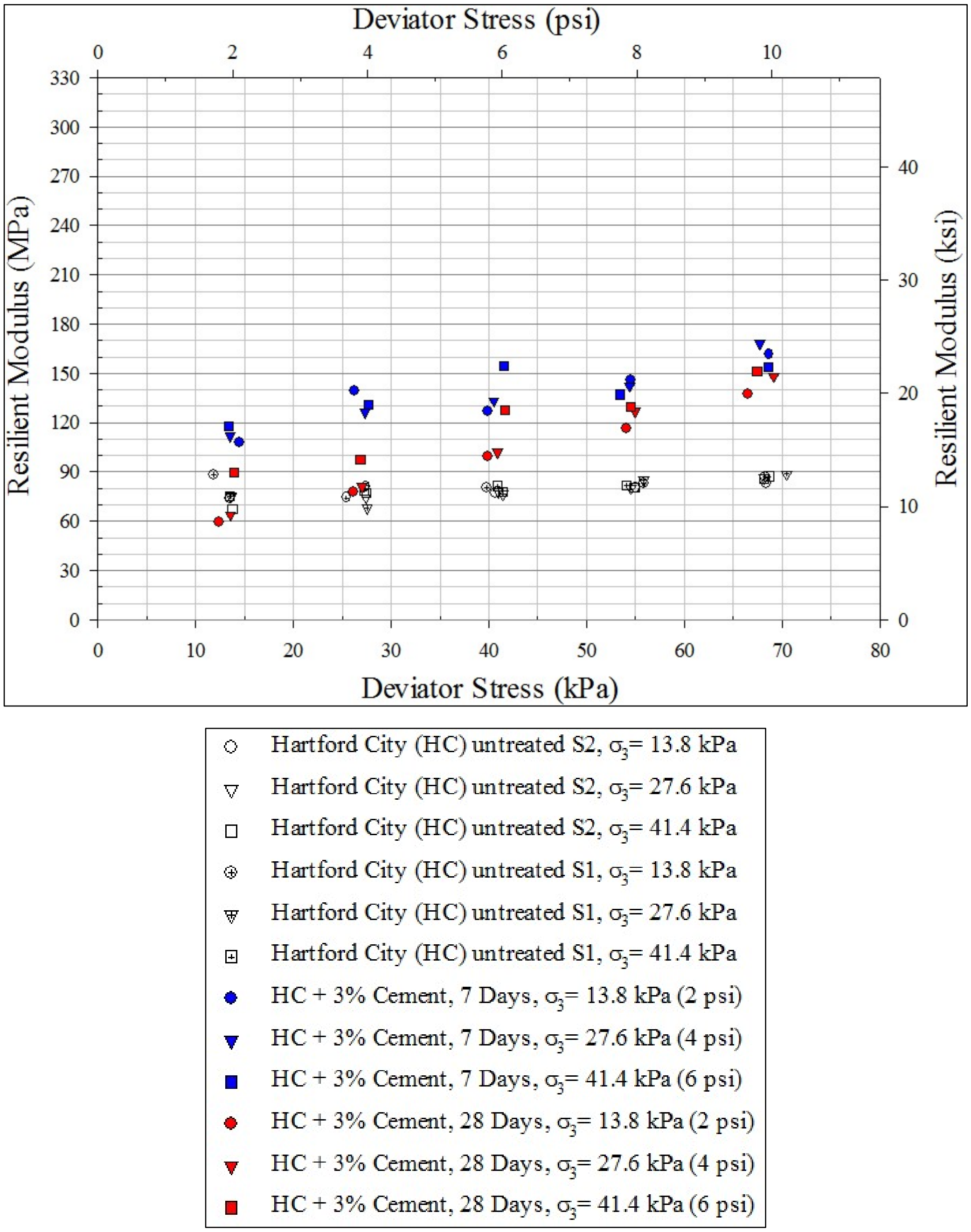


Figure F.2 Resilient modulus for untreated soil and soil treated with optimum amount of cement for different curing periods. Hartford City (HC).

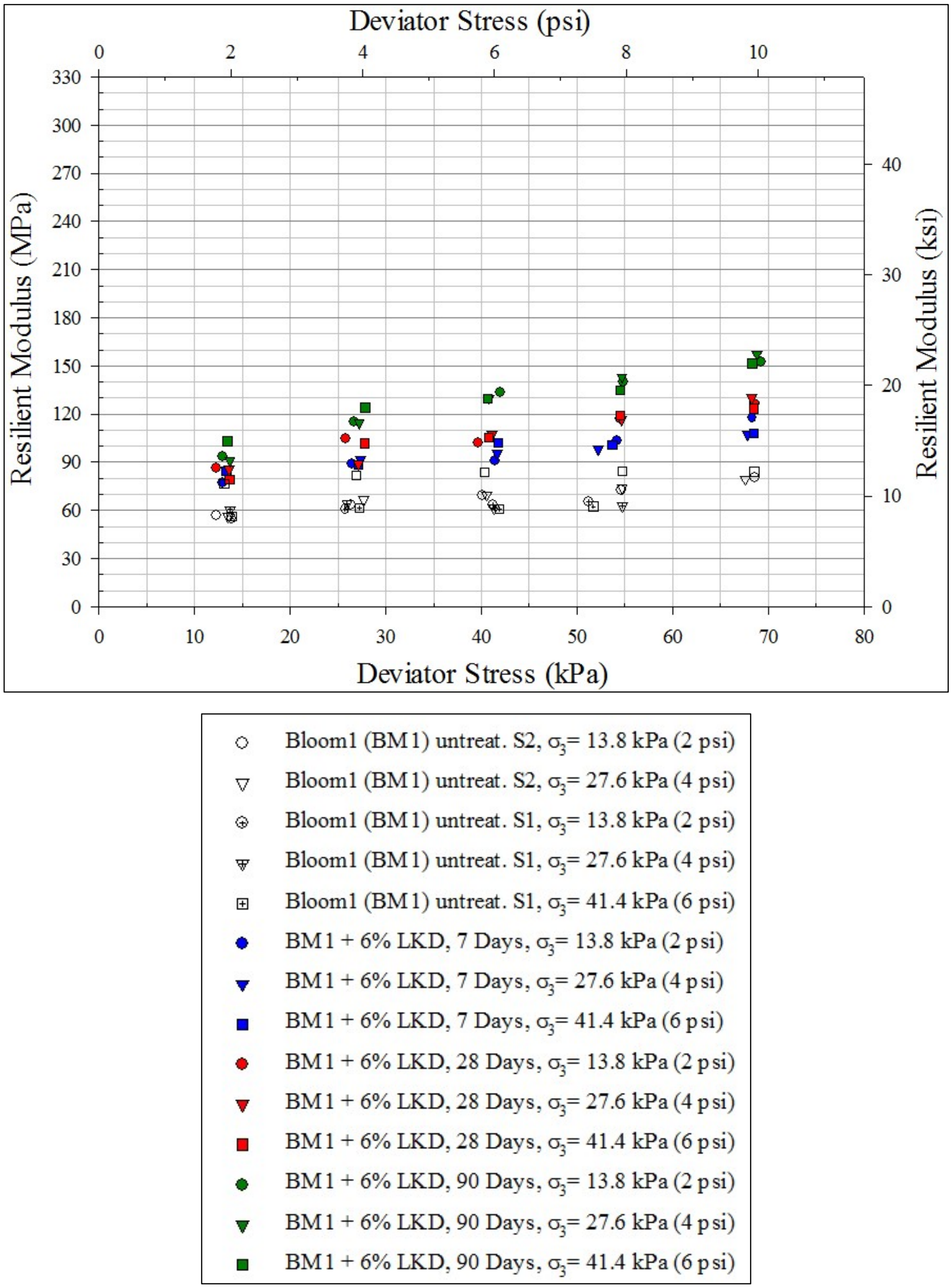


Figure F.3 Resilient modulus for untreated soil and soil treated with optimum amount of LKD for different curing periods. Bloomington #1 (BM1).

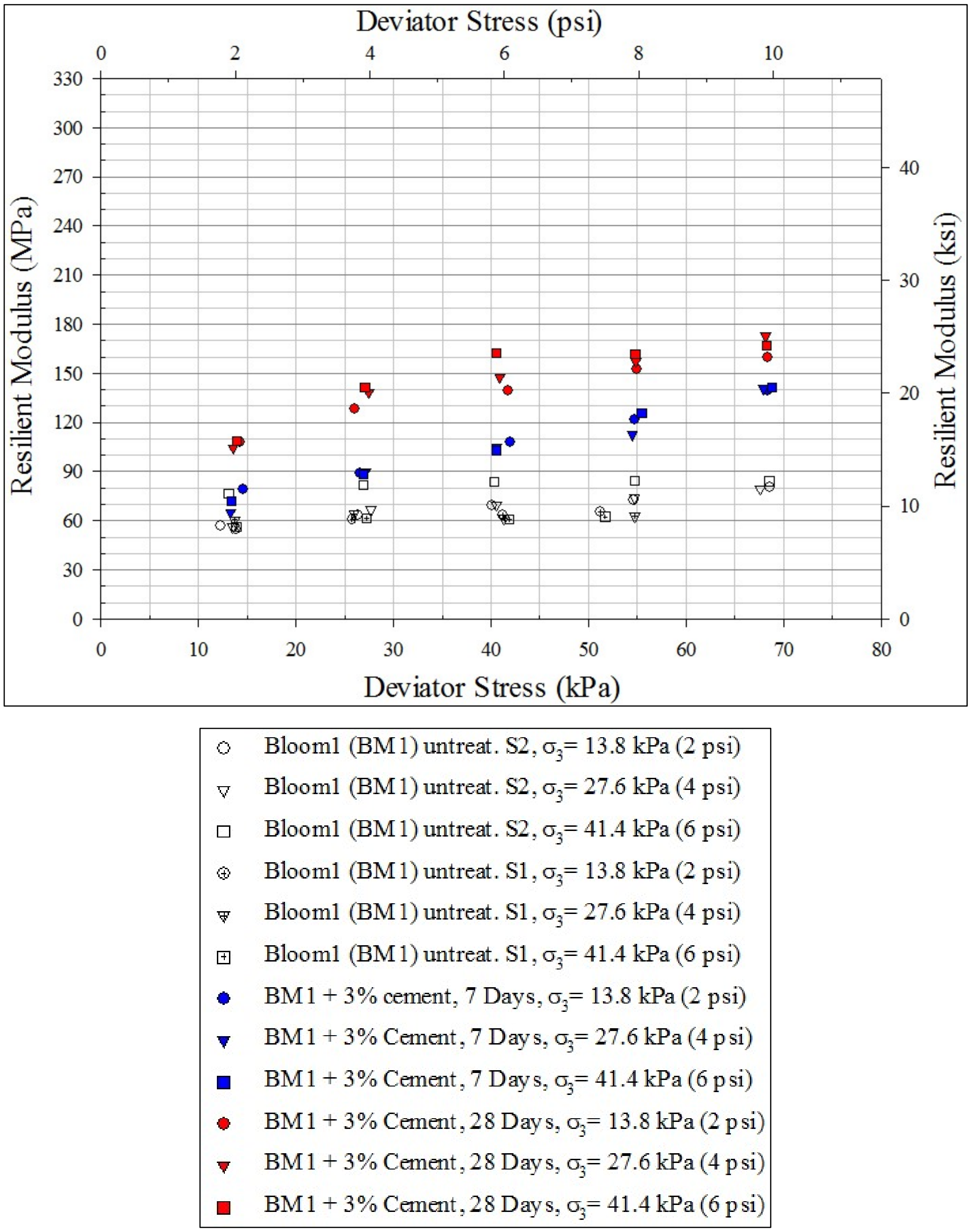


Figure F.4 Resilient modulus for untreated soil and soil treated with optimum amount of cement for different curing periods. Bloomington #1 (BM1).

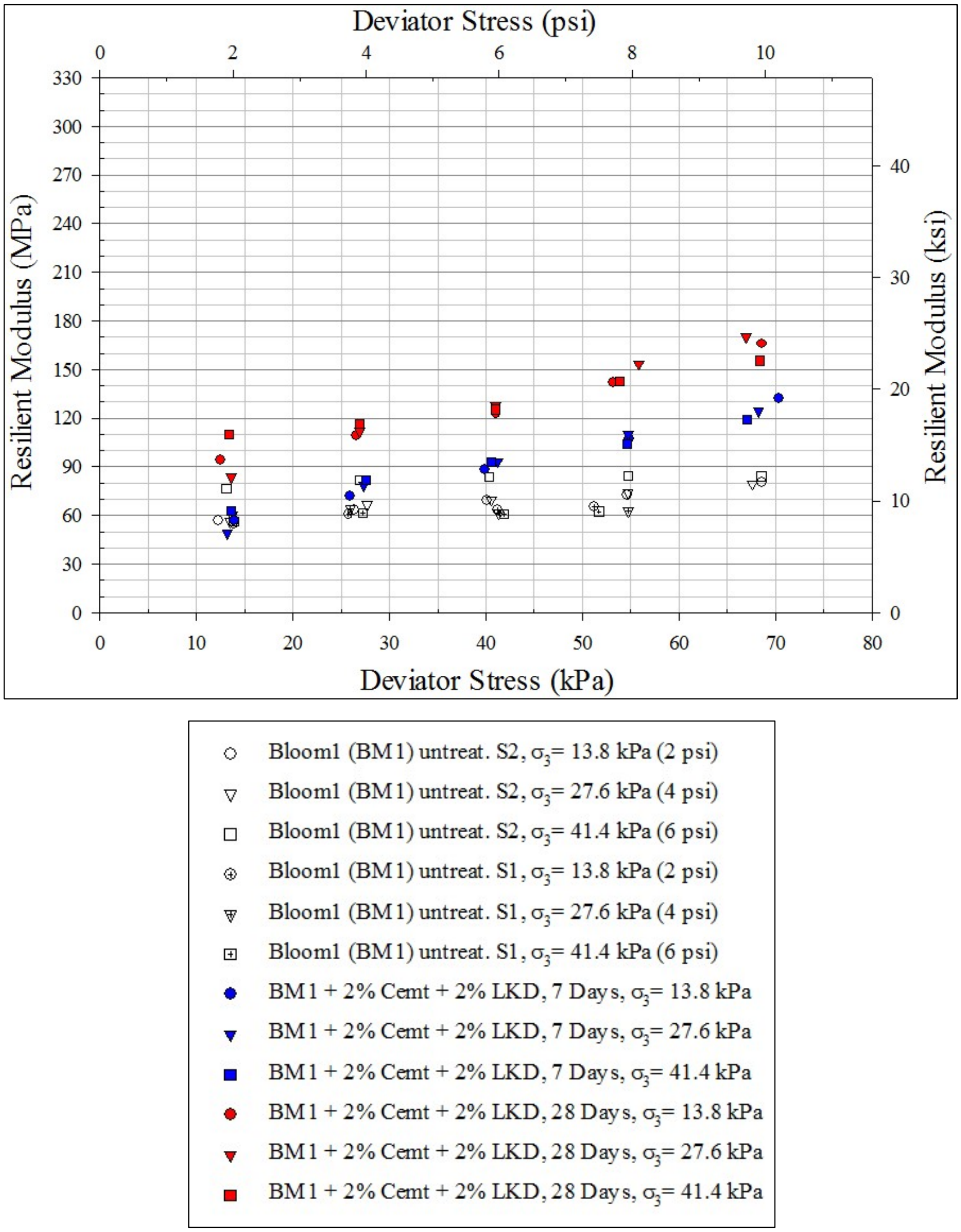


Figure F.5 Resilient modulus for untreated soil and soil treated with optimum amount of cement + LKD for different curing periods. Bloomington #1 (BM1).

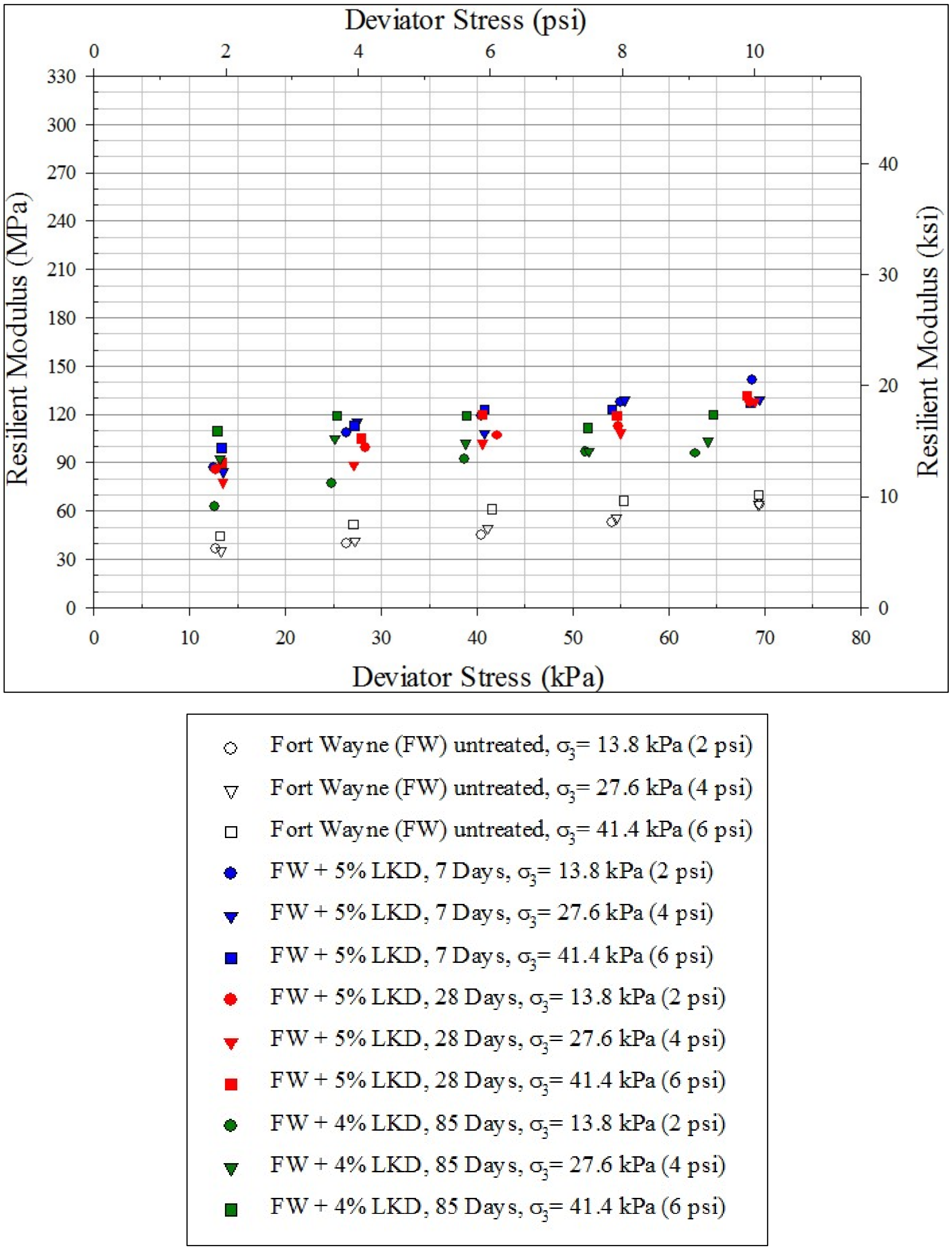


Figure F.6 Resilient modulus for untreated soil and soil treated with optimum amount of LKD for different curing periods. Fort Wayne (FW).

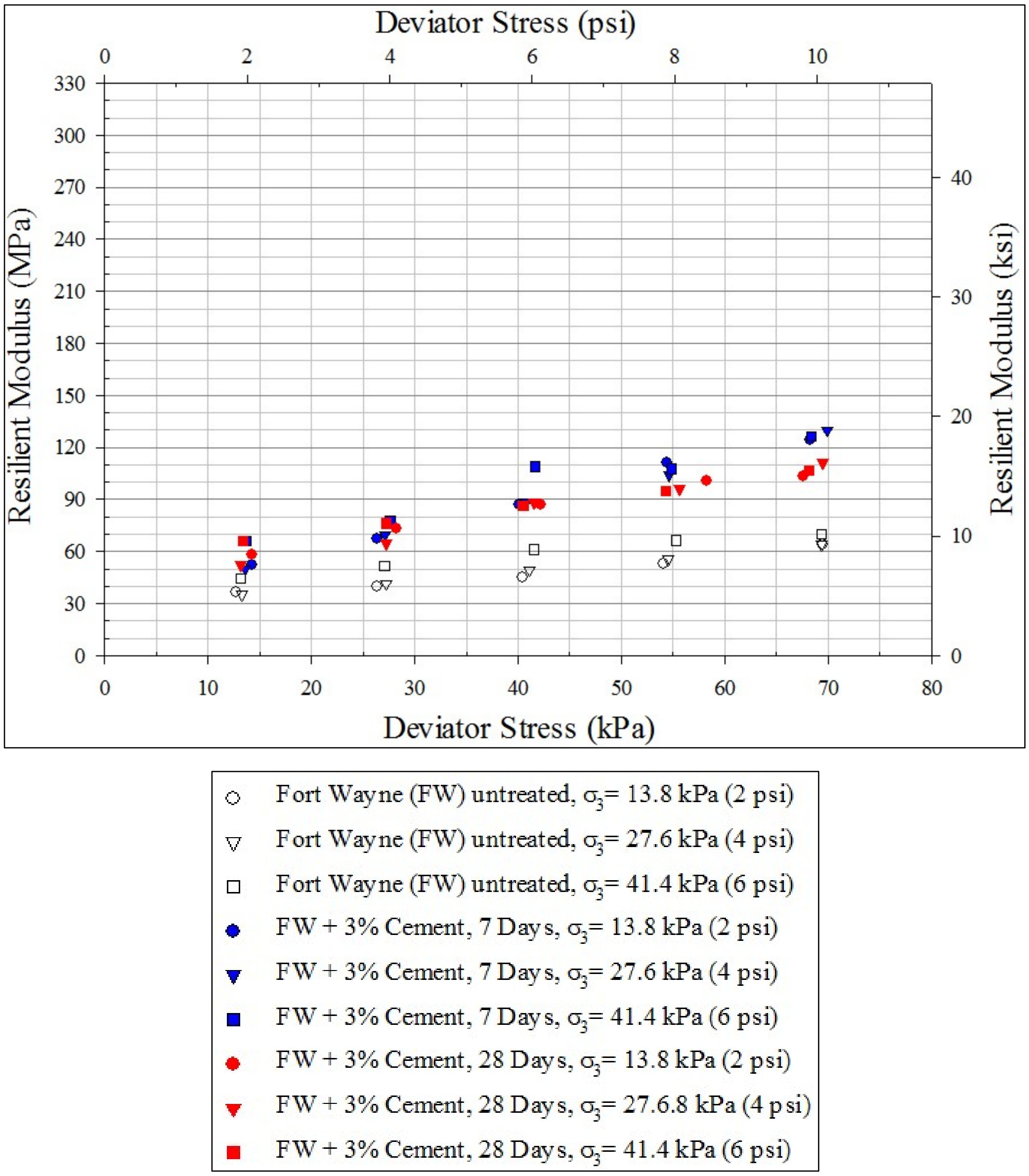


Figure F.7 Resilient modulus for untreated soil and soil treated with optimum amount of cement for different curing periods. Fort Wayne (FW).

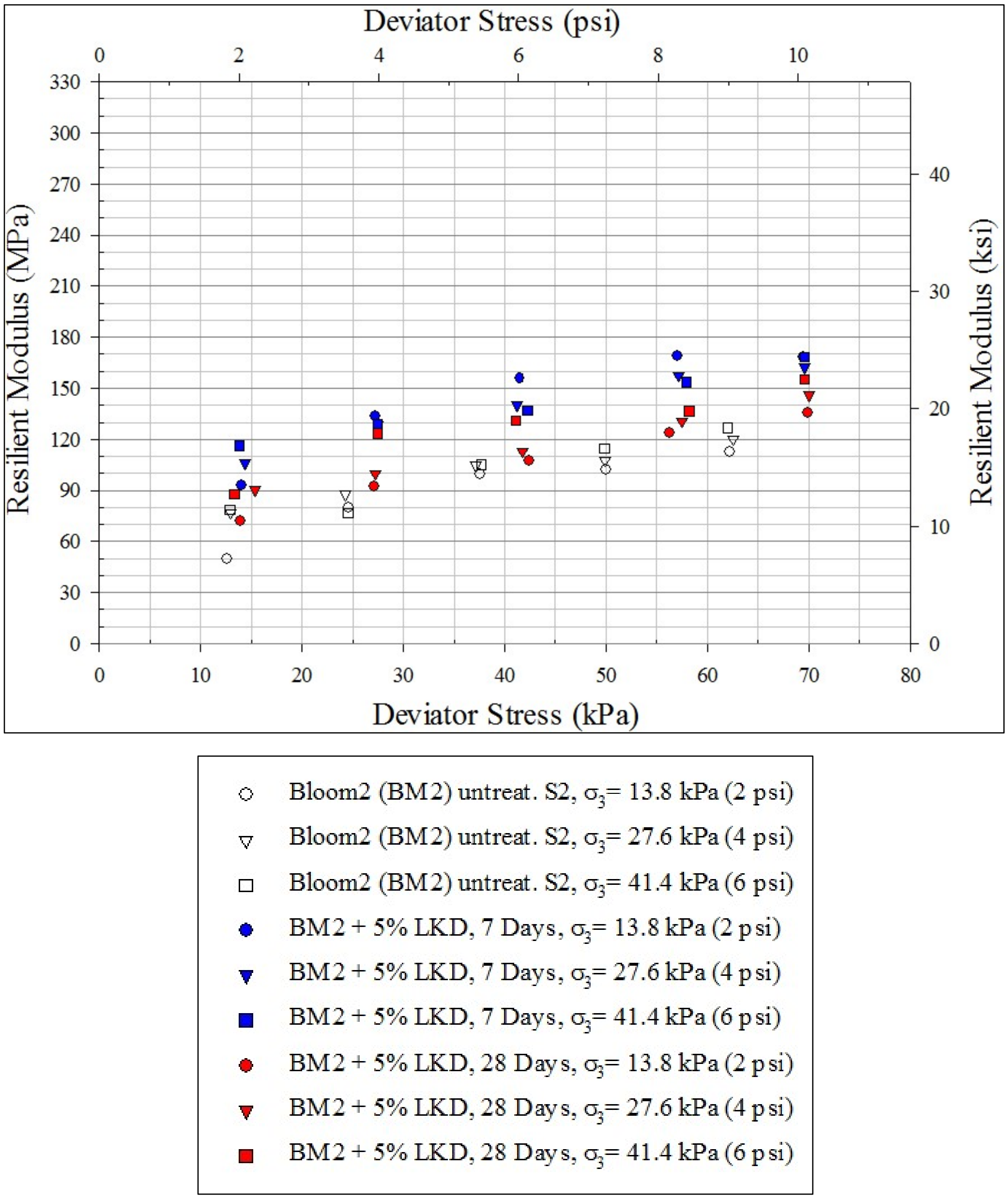


Figure F.8 Resilient modulus for untreated soil and soil treated with optimum amount of LKD for different curing periods. Bloomington #2 (BM2).

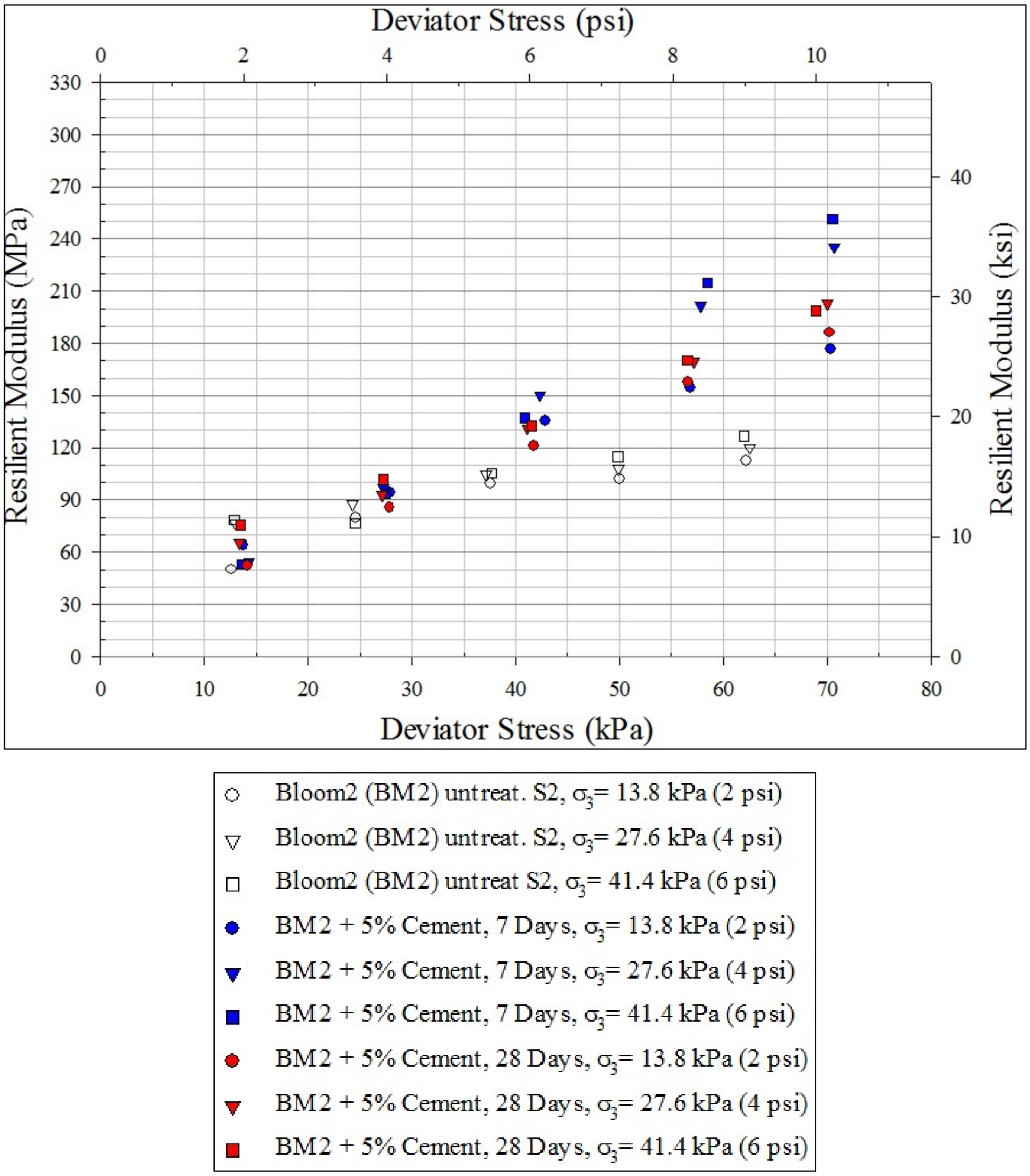


Figure F.9 Resilient modulus for untreated soil and soil treated with optimum amount of cement for different curing periods. Bloomington #2 (BM2).

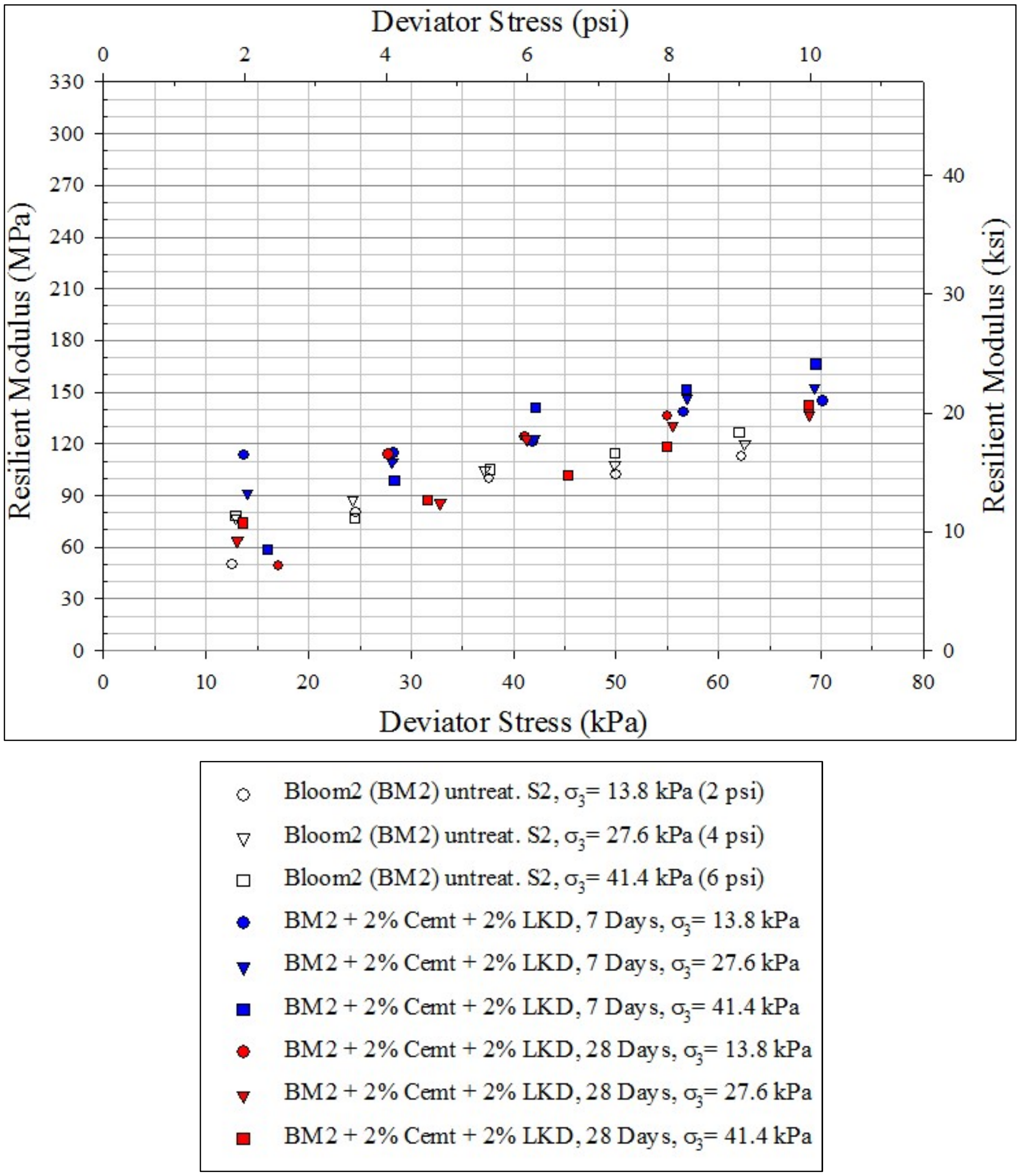


Figure F.10 Resilient modulus for untreated soil and soil treated with optimum amount of cement + LKD for different curing periods. Bloomington #2 (BM2).

Table F.1 Results for M_R tests on untreated soil and soil treated with optimum amount of LKD, cement or cement + LKD for different curing periods. HC, BM1, FW, BM2 soils

Sample	Curing (Days)	**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**
HC Untreated, S1	—	10.7	11.8	11.2	11.7	12	10.9	10.8	11.3	11.6	12.5	9.8	11.2	11.3	11.7	12.4
HC Untreated, S2	—	12.8	10.8	11.6	12.1	12.6	10.9	9.9	11.1	12.3	12.9	10.9	11.4	11.8	11.9	12.7
HC + 6% LKD	2	9.8	14.2	15.7	17.6	19.2	10.1	13.7	16.1	17.1	19	11.5	15.1	17.1	17.6	19.4
HC + 6% LKD	7	12.9	15.2	15.8	17.9	18.7	12.9	14	15.6	16.8	18.3	11.5	13.8	14.2	15.2	17.4
HC + 6% LKD	28	11.2	14.8	16.8	17	20	11.5	14.4	15.6	17.9	19.6	13.2	14.4	16.1	16	19
HC + 6% LKD	51	15.3	14.9	15.4	16.8	17.9	12.8	15.4	16.8	18	19.4	14.1	16	15.9	17.8	18.5
HC + 6% LKD	90	18.1	22.8	20.9	22.1	24.6	18	22.6	24	24.3	25.1	19.1	20.6	25.2	23.4	25.9
HC + 3% Cement	7	15.6	20.2	18.4	21.2	23.5	16.3	18.3	19.3	20.6	24.4	17.1	19	22.4	19.9	22.3
HC + 3% Cement	28	8.6	11.3	14.4	16.9	19.9	9.2	11.8	14.8	18.4	21.5	13	14.2	18.5	18.8	21.9
BM1 Untreated, S1	—	8	8.8	9.2	9.5	—	8.8	9.3	8.9	9.1	—	8.2	8.9	8.9	9.1	—
BM1 Untreated, S2	—	8.2	9.2	10.1	10.5	11.7	8.1	9.7	10.1	10.7	11.5	11.1	11.8	12.2	12.2	12.2
BM1 + 6% LKD	7	11.2	12.9	13.2	15	17.1	11.6	13.3	13.9	14.2	15.6	12.3	12.8	14.8	14.6	15.7
BM1 + 6% LKD	28	12.6	15.2	14.8	17	18.4	12.4	12.9	15.6	16.9	18.9	11.5	14.8	15.3	17.3	17.9
BM1 + 6% LKD	90	13.6	16.7	19.3	20.3	22.1	13.2	16.6	18.8	20.8	22.8	14.9	18	18.8	19.5	22
BM1 + 3% Cement	7	11.5	12.9	15.7	17.7	20.2	9.4	13.1	15.2	16.3	20.4	10.5	12.8	14.9	18.2	20.5
BM1 + 3% Cement	28	15.7	18.6	20.2	22.1	23.2	15.1	20.1	21.4	22.8	25.1	15.7	20.5	23.5	23.5	24.2
BM1 + 2% Cement + 2% LKD	7	8.3	10.5	12.8	15.6	19.2	7.1	11.4	13.5	16	18	9.1	11.9	13.5	15.1	17.3
BM1 + 2% Cement + 2% LKD	28	13.6	15.8	17.8	20.6	24.1	12.2	16.2	18.5	22.3	24.7	16	16.9	18.2	20.7	22.5
FW Untreated	—	5.3	5.8	6.6	7.7	9.3	5.1	6	7.2	8.1	9.3	6.4	7.5	8.9	9.6	10.2
FW + 5% LKD	7	12.6	15.8	17.3	18.5	20.5	12.2	16.7	15.7	18.7	18.7	14.4	16.4	17.8	17.8	18.4
FW + 5% LKD	28	12.5	14.5	15.5	16.3	18.5	11.3	12.8	14.8	15.8	18.5	13.1	15.2	17.4	17.3	19.1
FW + 4% LKD	84	9.1	11.2	13.4	14.1	13.9	13.4	15.2	14.8	14.1	15	15.9	17.3	17.3	16.2	17.4

FW + 3% Cement	7	7.6	9.7	12.7	16.2	18	7.3	10.1	12.8	15.1	18.8	9.6	11.3	15.8	15.6	18.3
FW + 3% Cement	28	8.4	10.6	12.6	14.6	15	7.6	9.4	12.8	13.9	16.1	9.6	11.1	12.5	13.7	15.5
BM2 + Untreated	—	7.2	11.6	14.5	14.8	16.3	11.2	12.7	15.2	15.6	17.4	11.4	11.1	15.3	16.7	18.4
BM2 + 5% LKD	7	13.5	19.3	22.6	24.5	24.4	15.4	18.6	20.3	22.8	23.6	16.9	18.7	19.9	22.3	24.4
BM2 + 5% LKD	28	10.4	13.4	15.5	17.9	19.7	13.1	14.5	16.4	18.9	21.2	12.7	17.9	19	19.8	22.5
BM2 + 5% Cement	7	9.3	13.7	19.6	22.4	25.6	7.9	14.1	21.8	29.3	34.1	7.7	13.5	19.9	31.1	36.5
BM2 + 5% Cement	28	7.5	12.4	17.6	22.9	27	9.5	13.5	19	24.6	29.5	11	14.8	19.2	24.7	28.8
BM2 + 2% Cement + 2% LKD	7	16.4	16.6	17.6	20.1	21	13.2	15.9	17.8	21.3	22.1	8.5	14.4	20.5	22	24.2
BM2 + 2% Cement + 2% LKD	28	7.1	16.5	18	19.7	20.2	9.2	12.4	17.8	19	19.8	10.7	12.7	14.8	17.2	20.7

Note: 1 psi ≈ 6.89 kPa
1 ksi ≈ 6.89 MPa

APPENDIX G. EFFECT OF OVERDOSING THE TREATMENT ON PLASTICITY, GRAIN SIZE, SHEAR STRENGTH AND RESILIENT MODULUS

One A-6 (HC) and one A-7-6 (BM2) soil were mixed with overdosed (doubling the optimum amount) treatment of LKD and cement. The procedures and standards followed were the same than those discussed in Chapters 3 to 6 in this report, for the optimum amount of treatment. Compaction curves for the overdosed treatment were prepared, and the results are shown in Figures G.1 and G.2, for HC and BM2, respectively. Atterberg limits for the overdosed treatment were conducted at ages of 28 and 90 (or 120) days. The results are shown in Figures G.3 and G.4 for HC, and in Figure G.5 and G.6 for BM2. The grain size distribution curves, which were prepared after 150-days curing, are included in Figures G.7 and G.8, for HC and BM2, respectively. Results for the unconfined compression tests, for samples cured at 28 and 90 days, are presented in Figures G.9 and G.10 for HC, and in Figures G.11 and G.12 for BM2. Finally, results of resilient modulus tests, performed after 28-days curing, are shown in Figures G.13 and G.14 for HC soil, and in Figures G.15 and G.16 for BM2 soil. Results for M_R tests on soil treated with double amount of LKD or cement for HC and BM2 soils are shown in Table G.1. For comparison purposes, some of the figures also include results of samples mixed with the optimum amount of treatment.

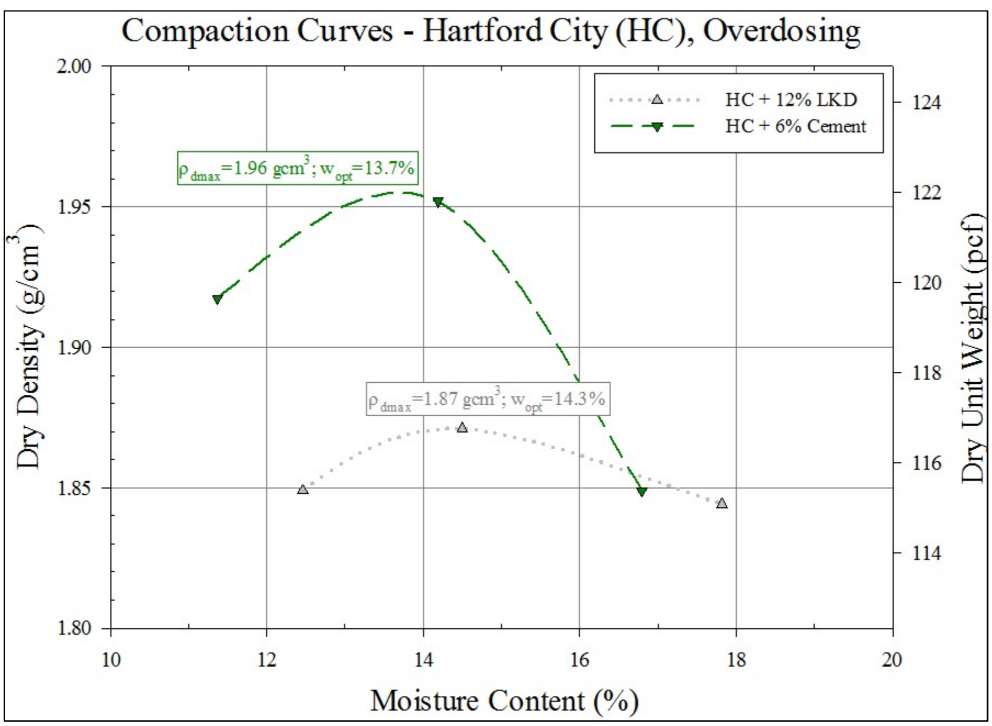


Figure G.1 Compaction curves for soil overdosed with the double of the optimum amount of treatment. Hartford City (HC), A-6 soil.

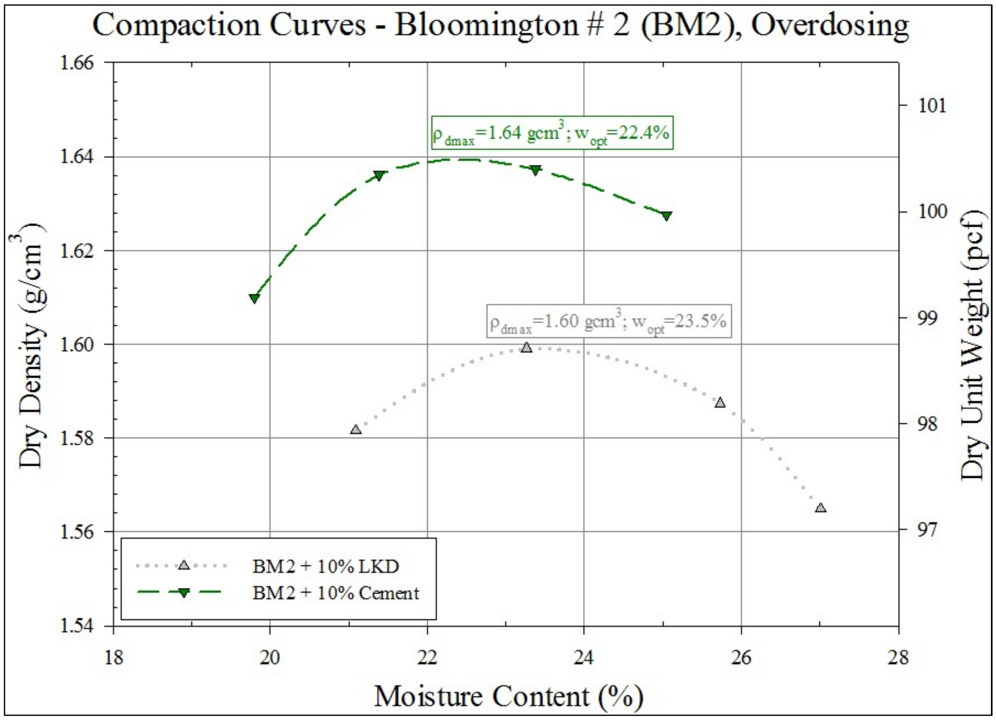


Figure G.2 Compaction curves for soil overdosed with the double of the optimum amount of treatment. Bloomington #2, A-7-6 soil.

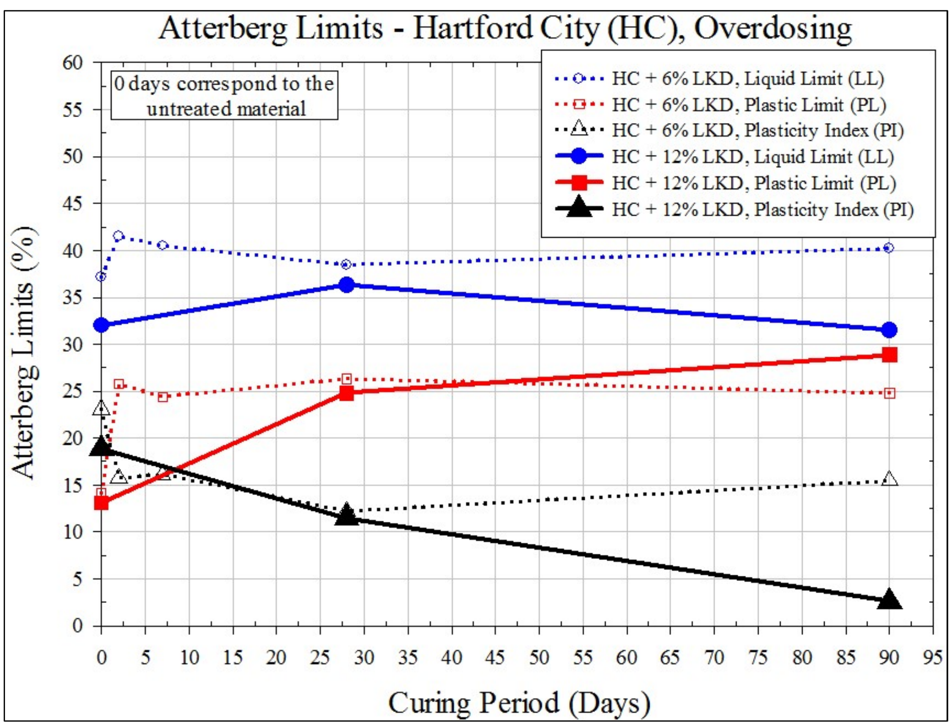


Figure G.3 Atterberg limits for soil with optimum and overdosed treatment with LKD for different curing periods. Hartford City (HC).

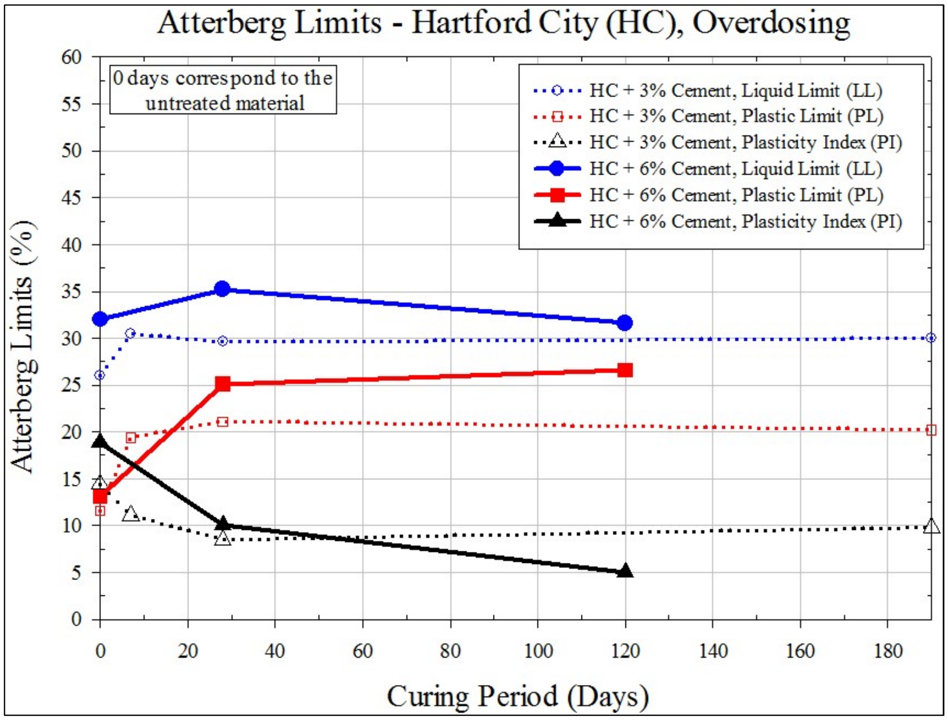


Figure G.4 Atterberg limits for soil with optimum and overdosed treatment with cement for different curing periods. Hartford City (HC).

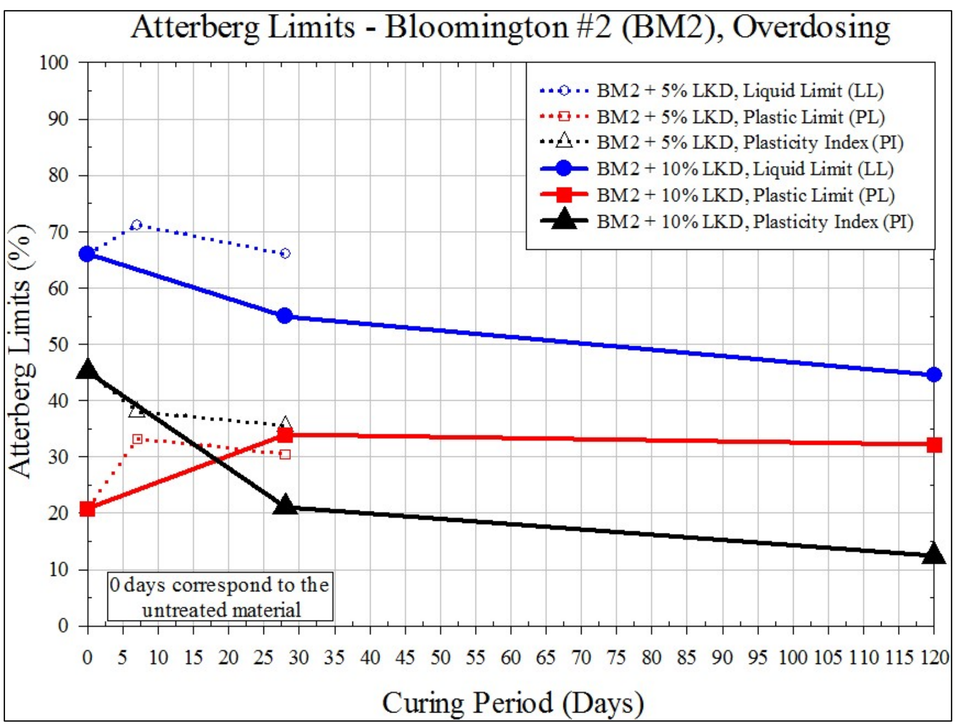


Figure G.5 Atterberg limits for soil with optimum and overdosed treatment with LKD for different curing periods. Bloomington #2 (BM2).

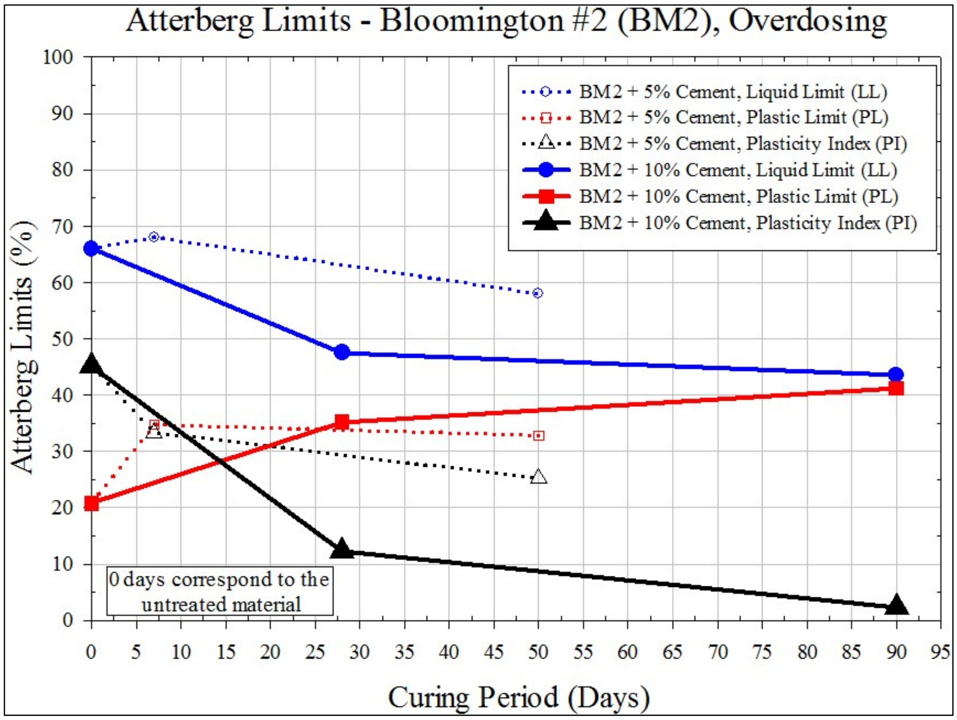


Figure G.6 Atterberg limits for soil with optimum and overdosed treatment with cement for different curing periods. Bloomington #2 (BM2).

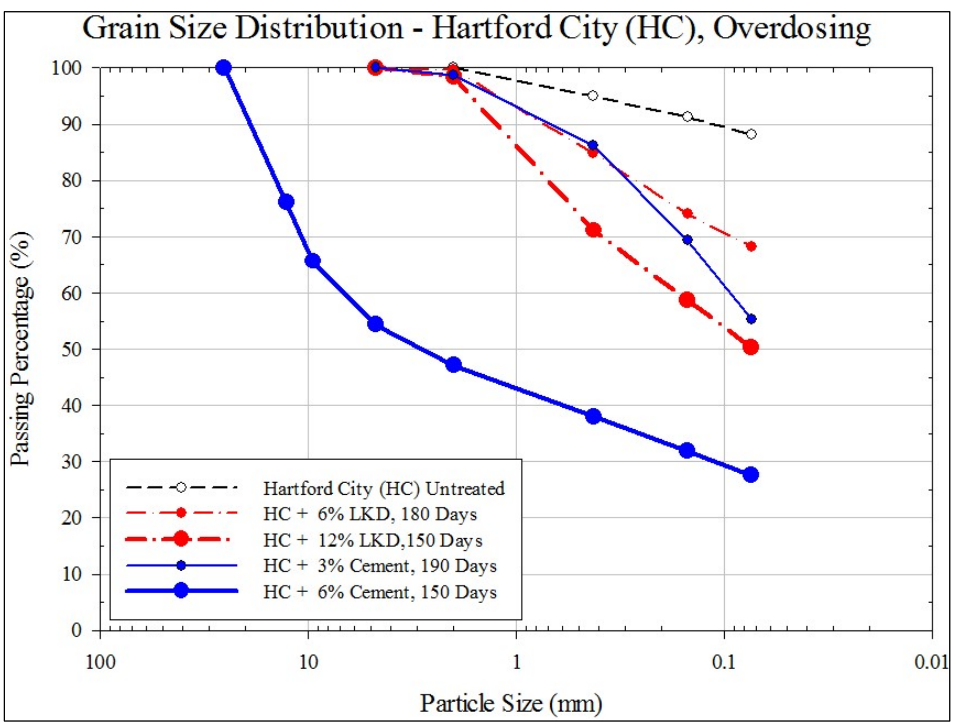


Figure G.7 Grain size distribution for untreated soil and soil treated with optimum and overdosed treatment with LKD and cement. Hartford City (HC).

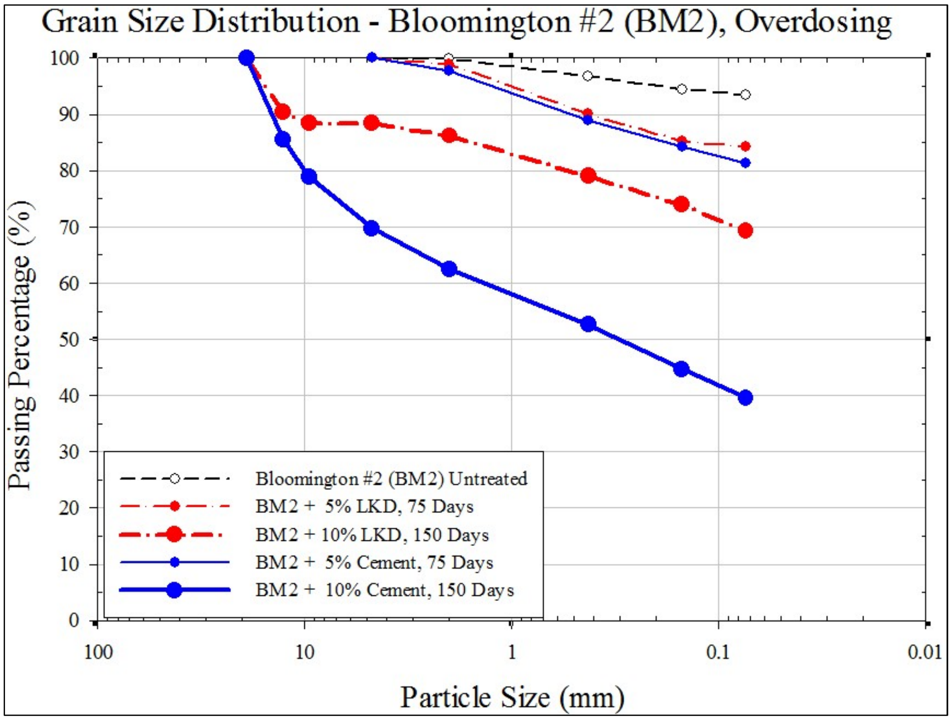


Figure G.8 Grain size distribution for untreated soil and soil treated with optimum and overdosed treatment with LKD and cement. Bloomington #2 (BM2).

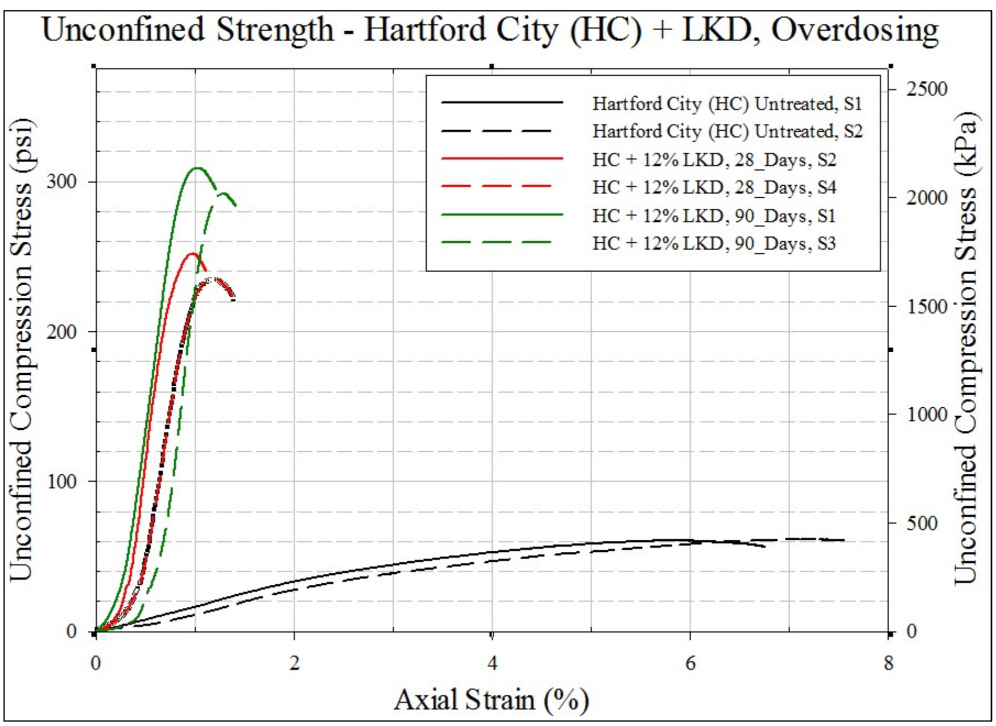


Figure G.9 Unconfined compression strength for untreated soil and overdosed treatment with LKD for different curing periods. Hartford City (HC).

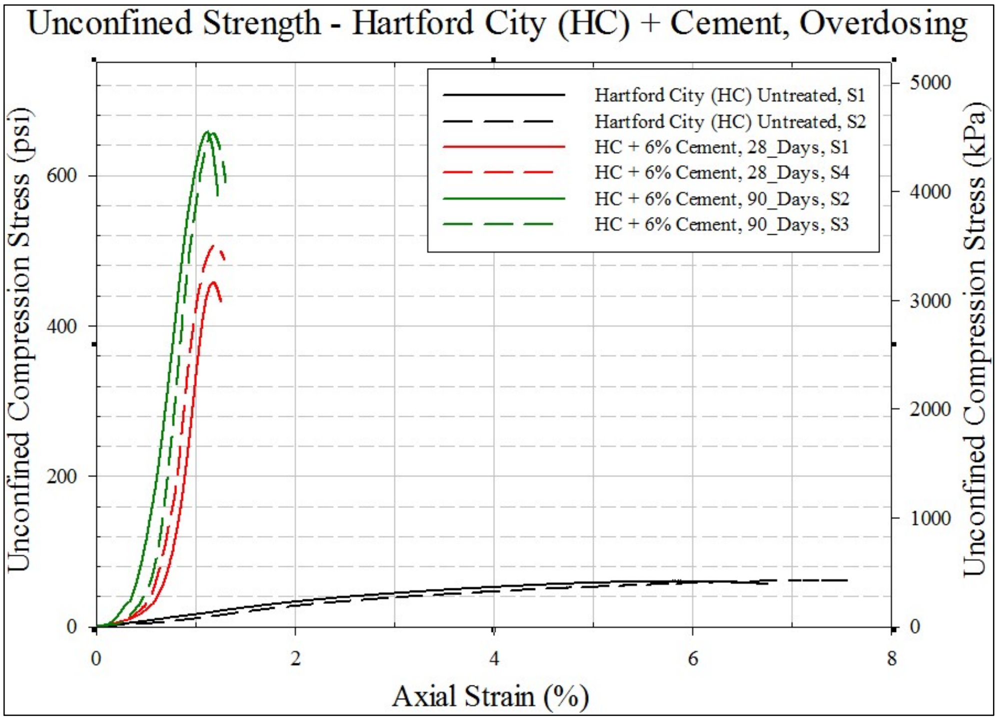


Figure G.10 Unconfined compression strength for untreated soil and overdosed treatment with cement for different curing periods. Hartford City (HC).

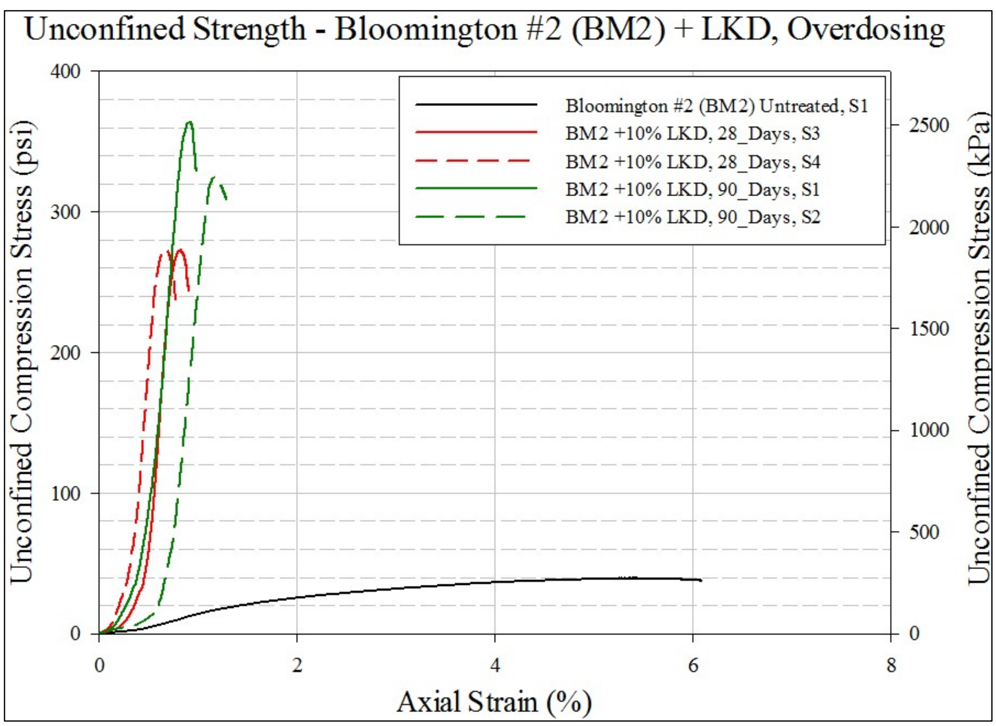


Figure G.11 Unconfined compression strength for untreated soil and overdosed treatment with LKD for different curing periods. Bloomington #2 (BM2).

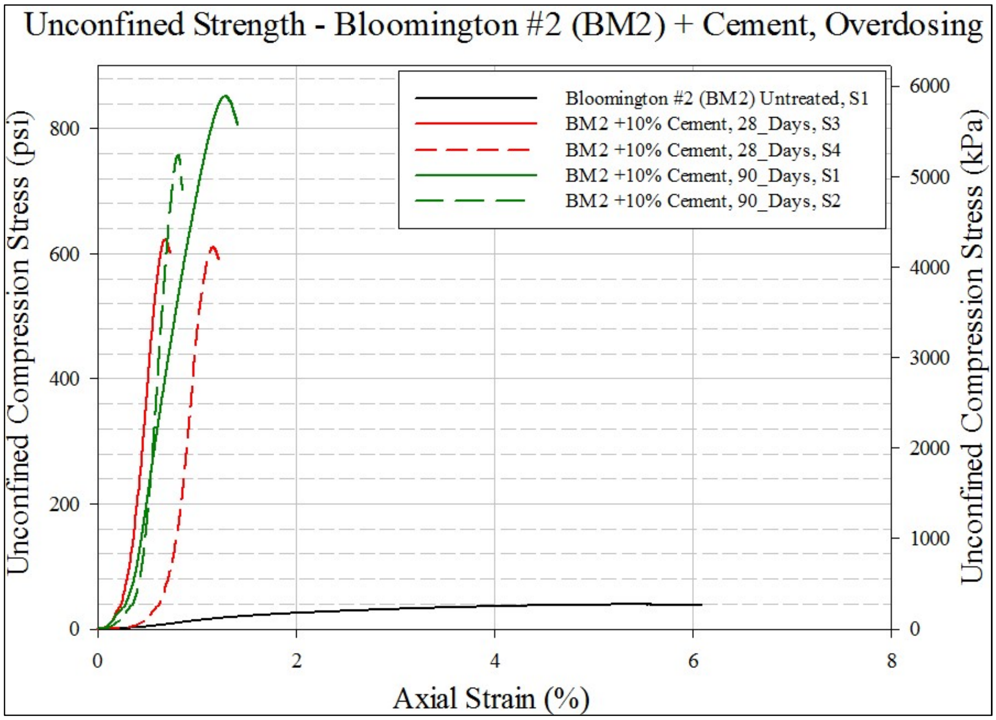


Figure G.12 Unconfined compression strength for untreated soil and overdosed treatment with cement for different curing periods. Bloomington #2 (BM2).

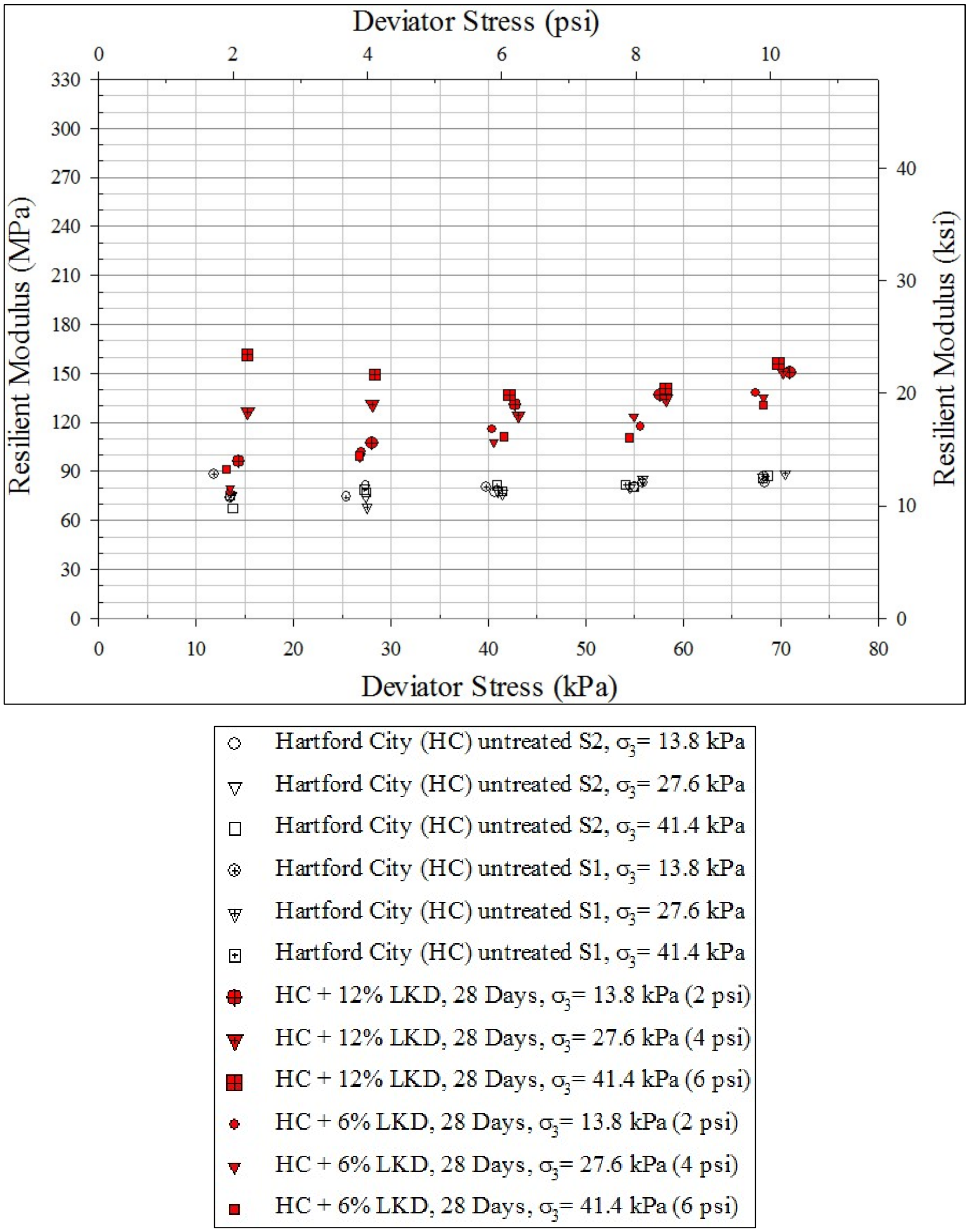


Figure G.13 Resilient modulus for untreated soil and soil treated with optimum and overdosed treatment with LKD. Hartford City (HC).

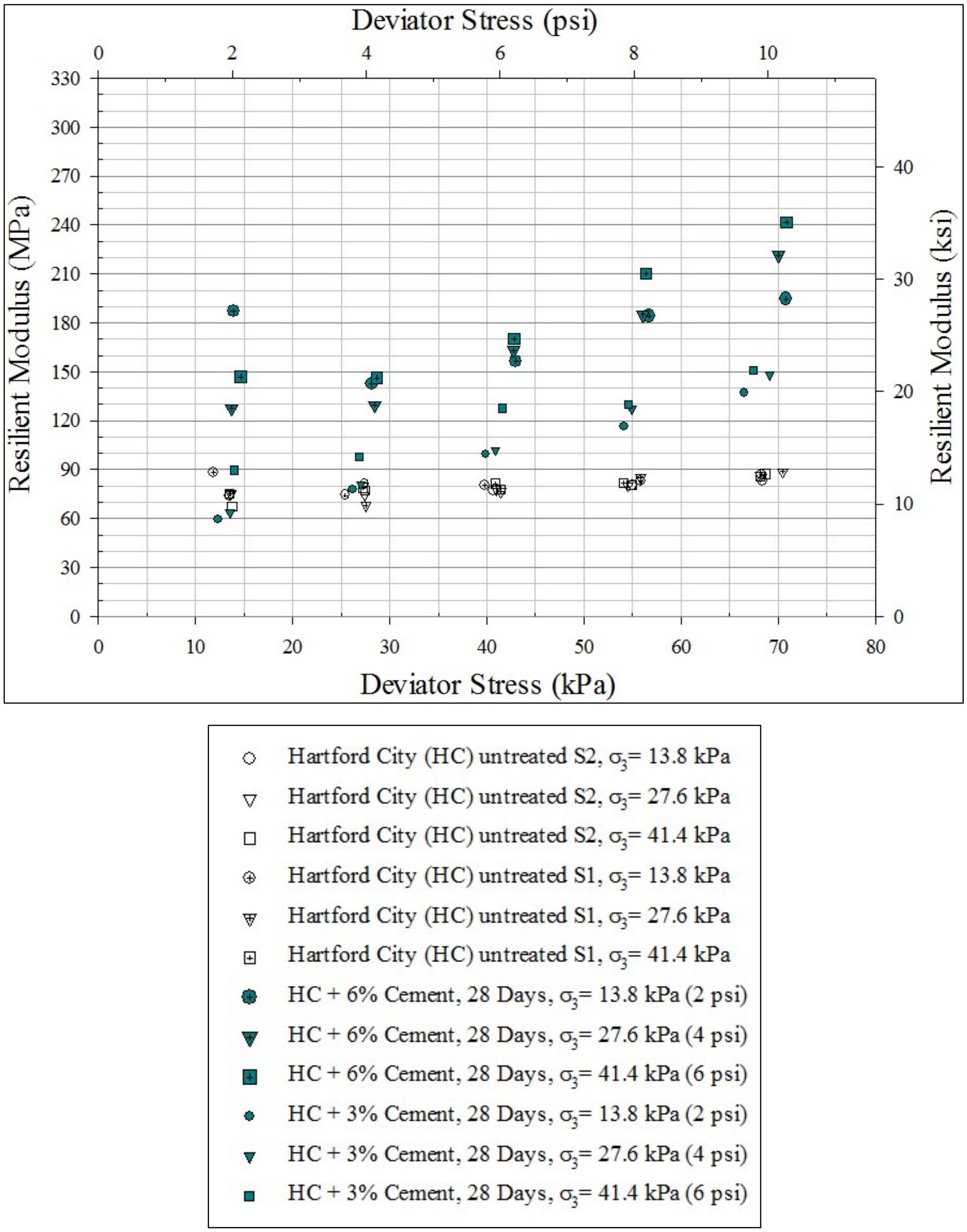


Figure G.14 Resilient modulus for untreated soil and soil treated with optimum and overdosed treatment with cement. Hartford City (HC).

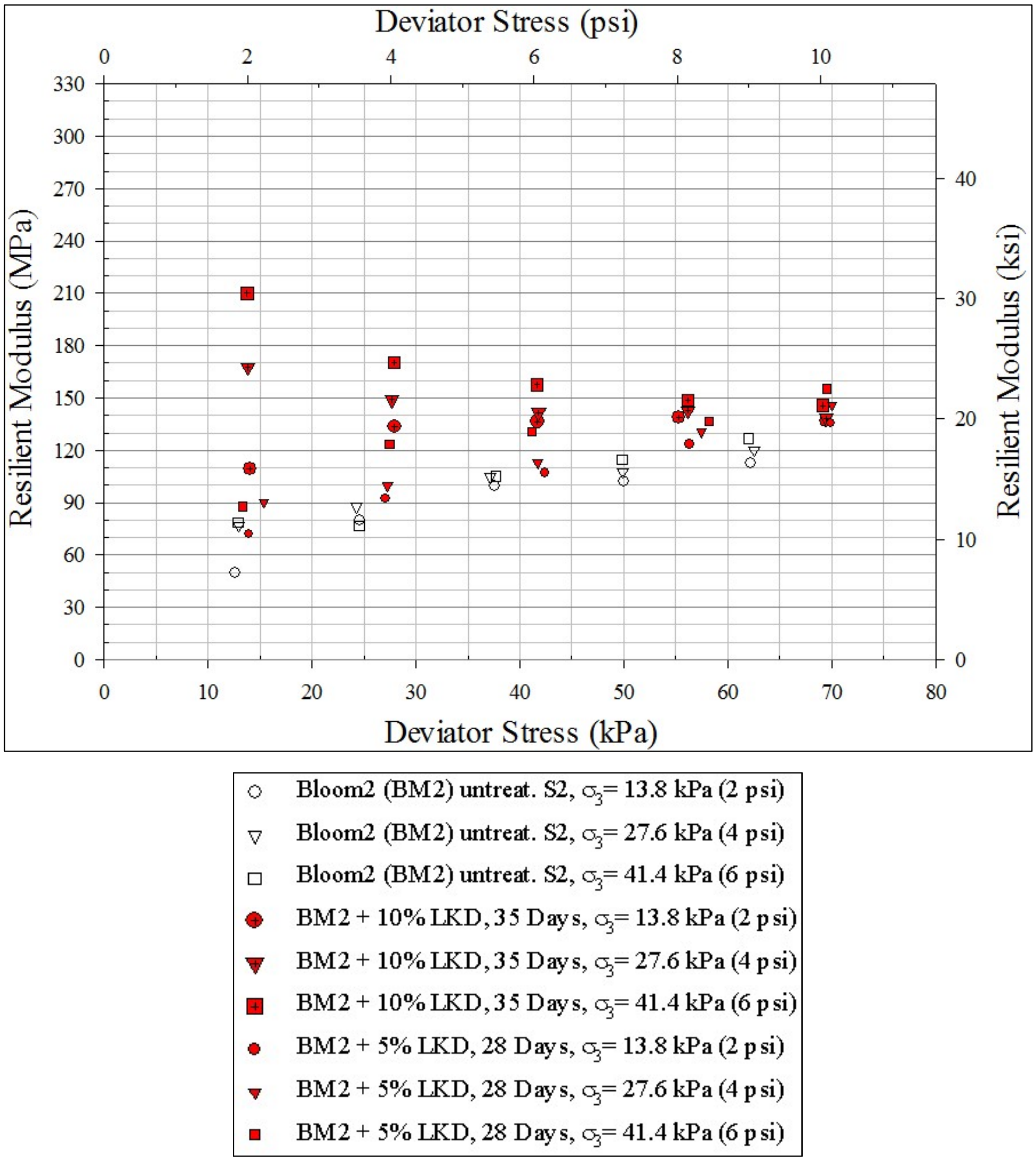


Figure G.15 Resilient modulus for untreated soil and soil treated with optimum and overdosed treatment with LKD. Bloomington #2 (BM2).

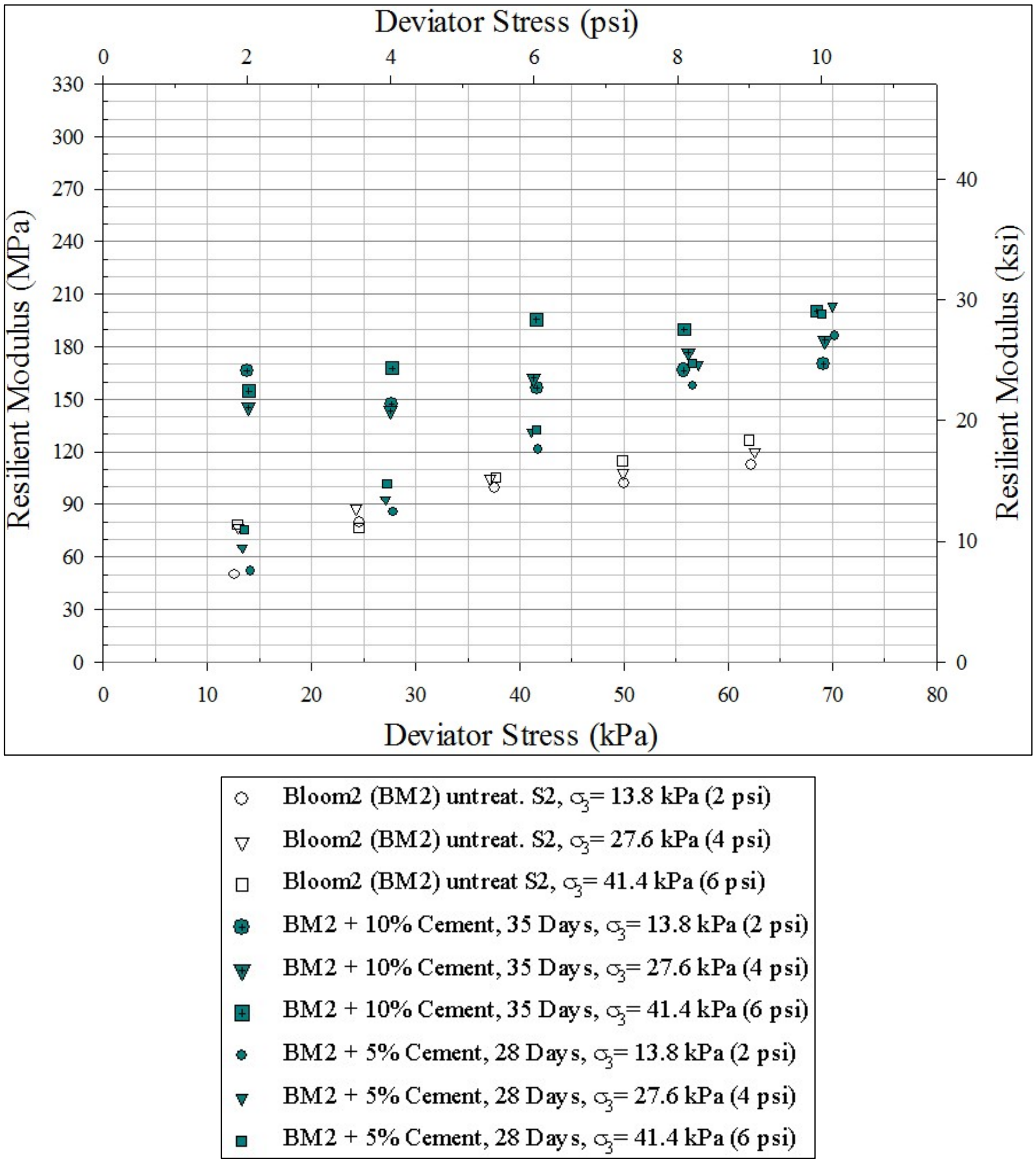


Figure G.16 Resilient modulus for untreated soil and soil treated with optimum and overdosed treatment with cement. Bloomington #2 (BM2).

Table G.1 Results for M_R tests on soil treated with double amount of LKD or cement, for HC and BM2 soils.

Sample	Curing (Days)	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**
BM2 + 10% LKD	35	15.9	19.4	19.8	20.1	19.8	24.3	21.6	20.5	20.7	20.1	30.5	24.7	22.9	21.6	21.1
BM2 + 10% Cement	35	24.1	21.3	22.7	24.2	24.7	21.1	20.8	23.5	25.6	26.7	22.4	24.3	28.4	27.5	29
HC + 12% LKD	35	13.9	15.6	19	19.8	21.8	18.3	19	18	19.5	21.9	23.4	21.7	19.8	20.4	22.6
HC + 6% Cement	35	27.1	20.7	22.7	26.7	28.2	18.5	18.8	23.6	26.9	32.1	21.3	21.2	24.7	30.5	35

Note: 1 psi ≈ 6.89 kPa
1 ksi ≈ 6.89 MPa

APPENDIX H. DIFFERENCE IN PLASTICITY, UNCONFINED COMPRESSION STRENGTH AND RESILIENT MODULUS BETWEEN LKD AND QUICK LIME

The differences in plasticity, unconfined compression strength and resilient modulus, when using LKD or quick lime (QL) were investigated. A highly plastic soil (A-7-6) called Bloomington #3 (BM3) was used for the comparison. The procedures and standards were the same than those described in Chapters 3 to 6 in this report. Figures H.1 to H.3 show the results for Atterberg limits, unconfined compression strength, and resilient modulus tests, respectively. The curing periods were 7 and 75 days for Atterberg limits, 60 days for unconfined compression, and 28 days for resilient modulus.

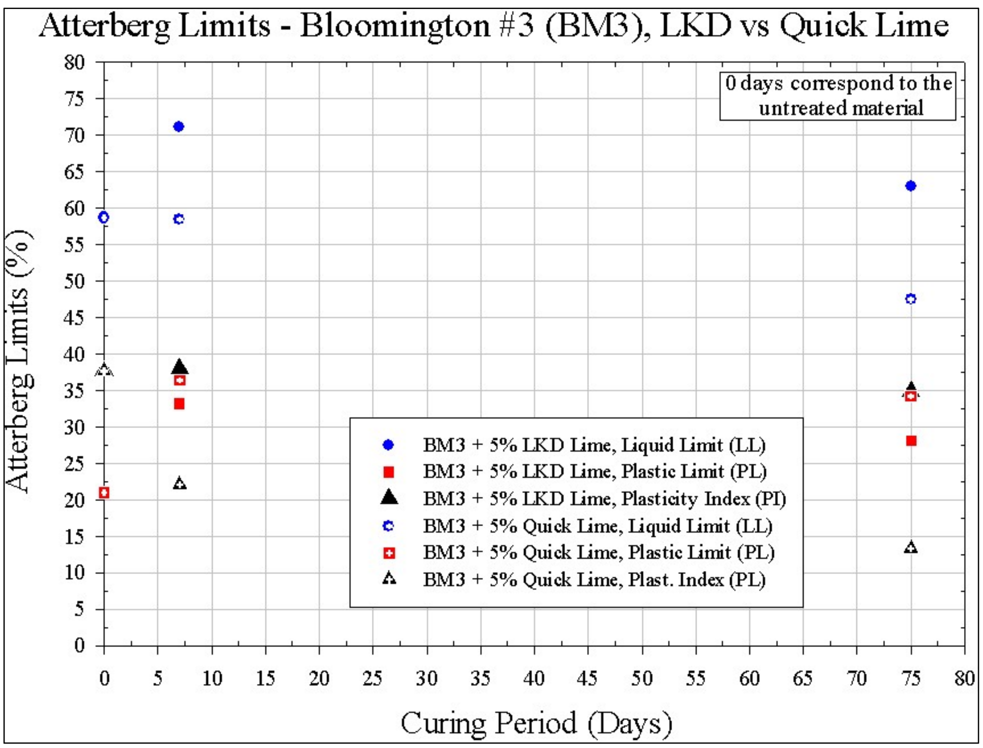


Figure H.1 Atterberg limits for untreated and treated soil with optimum amount of LKD and QL, after 7- and 75-days curing. Bloomington #3 (BM3).

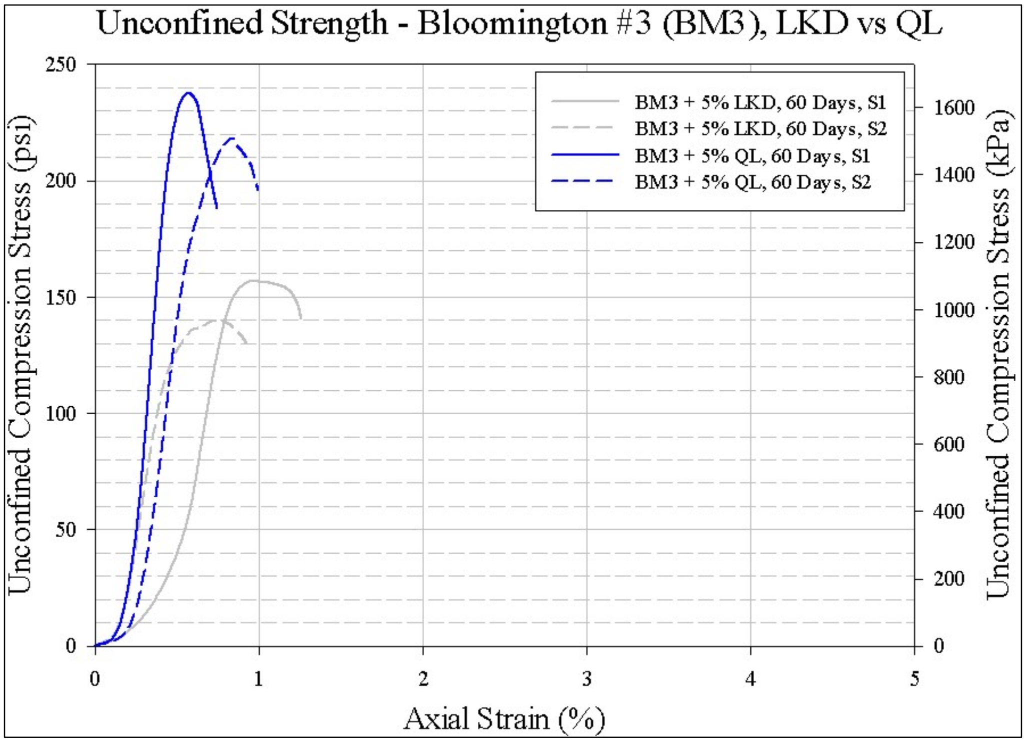


Figure H.2 Unconfined compression strength for soil treated with optimum amount of LKD and QL, after 60-days curing. Bloomington #3 (BM3).

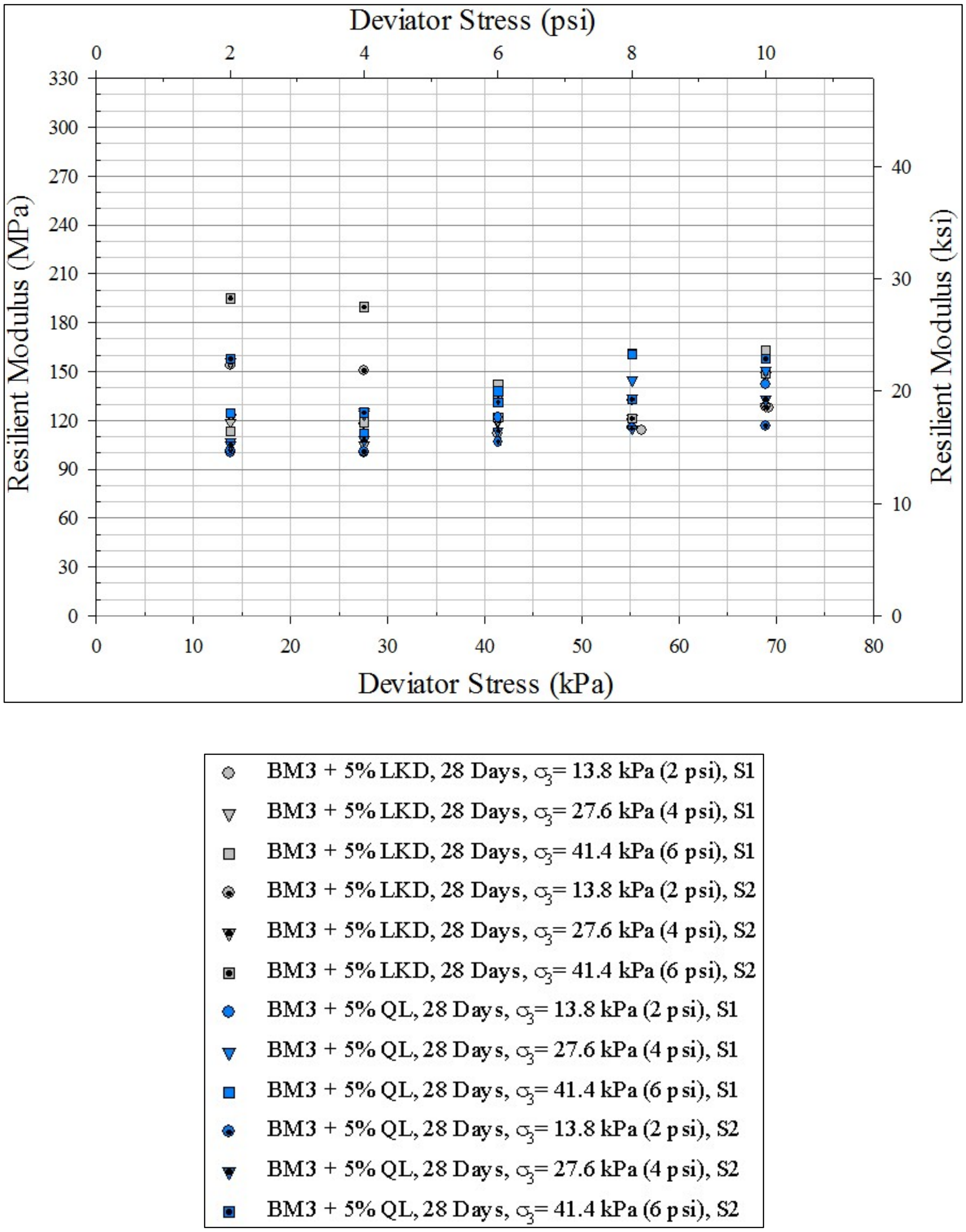


Figure H.3 Resilient modulus for soil treated with optimum amount of LKD and QL after 28-days curing. Bloomington #3 (BM3).

APPENDIX I. EFFECT OF MOISTURE ON RESILIENT MODULUS

As described in 0, remolded samples were prepared to conduct resilient modulus tests (M_R), following AASHTO T307-99 (2007) for Type 2 Material, i.e., fine-grained soils. The density corresponded to the 100% of the maximum density of the Standard Proctor. The specimens were mixed with Lime Kiln Dust (LKD), cement, or Quick Lime (QL). The types and amount of optimum treatment for the M_R tests on each soil were presented in the 0, with the corresponding compaction curves for untreated and treated soils.

I.1 Procedure following the ASTM Standard D559/D559M

After compaction, the specimens were cured inside a plastic bag in a cooler in the moisture room for 7 days. Later, the procedure to determine the M_R was followed. The procedure is described in the American Society for Testing and Materials (ASTM) Standard D559/D559M (2015). Hence, each sample was submerged in tap water at room temperature for 5 hours, and later the samples were oven-dried at 160˚F (71˚C) for 42 hours. The process represents a cycle of wetting and drying (WD), and the entire test was completed by doing 12 cycles for each specimen. However, when following the standard, the treated samples failed during the first three cycles. To better represent the conditions in the field, the specimens were confined and submitted to twelve WD cycles following again the ASTM standard. Nonetheless, the confined treated samples still collapsed. Figure I.1 shows the collapsed samples for Bloomington #1 (BM1) when the unconfined and confined specimens followed the standard procedure.

I.2 Modified protocol test

The temperature variations in the subgrade in the state of Indiana are not as extreme as required by the standard D559/D559M. For this reason, the actual temperatures in Indiana were obtained from the Indiana State Climate Office (iClimate) at Purdue University, which uses information contained in the National Centers for Environmental Information (NOAA). Figure 9.5 in the report shows the eight climatic stations in Indiana that have 10 years (from January 2008 to December 2017) daily temperature at a 4-inch depth. Figures I.2 to I.9 present the daily extreme temperature readings for each station, during a 10-year period. Based on the maximum soil temperature from Figures 9.6 to 9.8 in the report, the following test protocol was proposed by the Study Advisory Committee (SAC) at their meeting on September 2018. This was thought to be a closer representation of the conditions in the field: for the wetting stage, place the specimens in the moisture room for 2 days with water coming from the bottom (without immersion); for the drying stage, 2 days at room temperature (without placing the samples into the oven). Each sample was subjected to twelve wetting/drying cycles, which lasted about two months. After that, thirteen (13) M_R tests, following the standard AASHTO T307-99 (2007) for Type 2 Material, i.e., fine-grained soils, were conducted.

For soils with low plasticity, Hartford City (HC) and Bloomington #1 (BM1), the new protocol, with mixtures with LKD, produced results. For cement, the protocol worked for BM1, but did not for HC samples. For high plasticity clayey soils, Bloomington #2 (BM2), the samples underwent significant cracking at the beginning of the WD cycles, that produced the collapse of the treated specimens with LKD, cement or QL. Figure I.10 shows a sample of Hartford City treated with cement, which collapsed throughout the WD cycling process. Figure I.11 presents failures of BM2 specimens treated with LKD, cement, and QL. Regarding the successful tests, Figure I.12 shows pictures of the samples through the 12 WD cycles for BM1 treated with LKD, and Figure I.13 of BM1 with cement.

It was decided to investigate the effects of overdosing the samples. The soil, Bloomington #3 (BM3), was mixed with double the optimum amount of QL or cement (as discussed in Chapter 7, overdosing consisted in doubling the optimum amount of treatment obtained following the INDOT requirements given in *Design Procedures for Soil Modification or Stabilization* (2015). Pictures of BM3 samples with overdosing, with QL and cement, are shown in Figures I.15 and I.16, respectively.

I.3 Resilient modulus results

Results of the resilient modulus tests for specimens of HC LKD treated samples and BM1 specimens treated with LKD and cement are shown in Figures I.17 to I.25. Results of the resilient modulus tests for BM3 soil treated with overdosed QL are shown in Figures I.26 to I.28, and BM3 soil treated with overdosed cement are shown in Figures I.29 to I.31.

Table I.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.

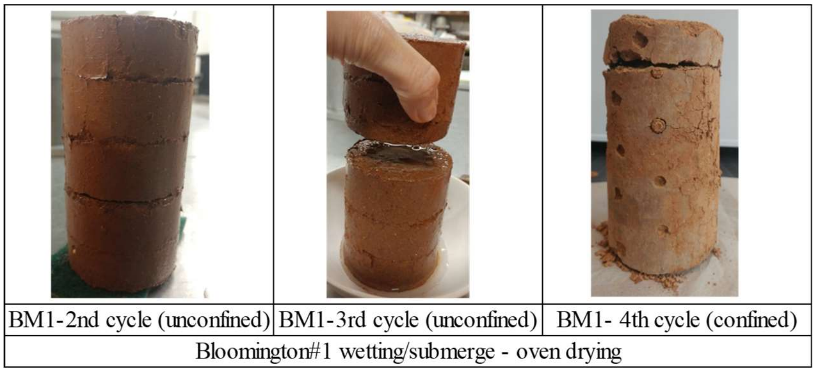


Figure I.1 Collapsed samples during WD cycles following the Standard D559/D559M optimum amount of treatment.

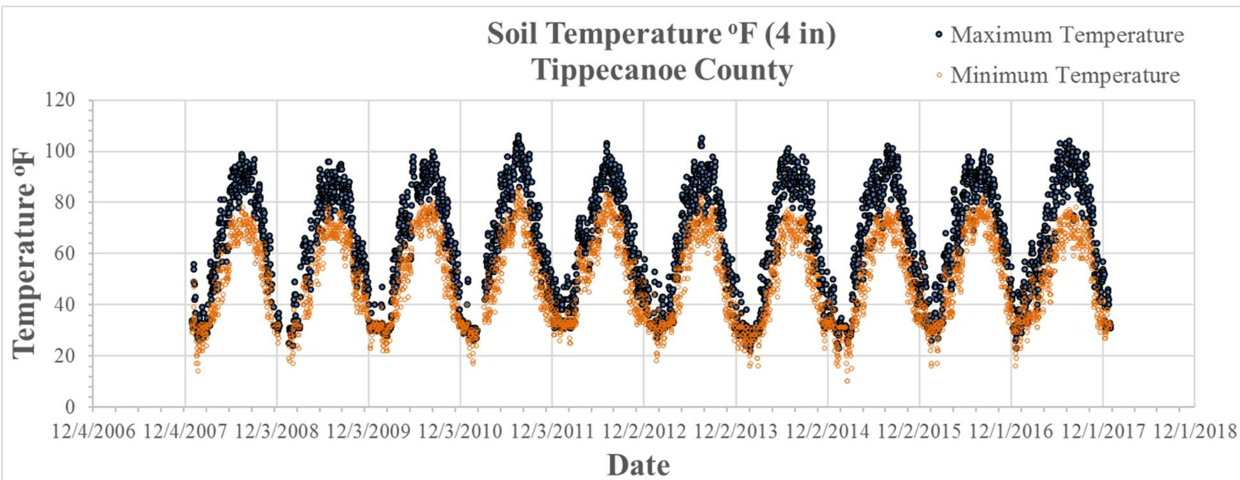


Figure I.2 Daily temperature readings at a 4-inch depth ACRE (iClimate).

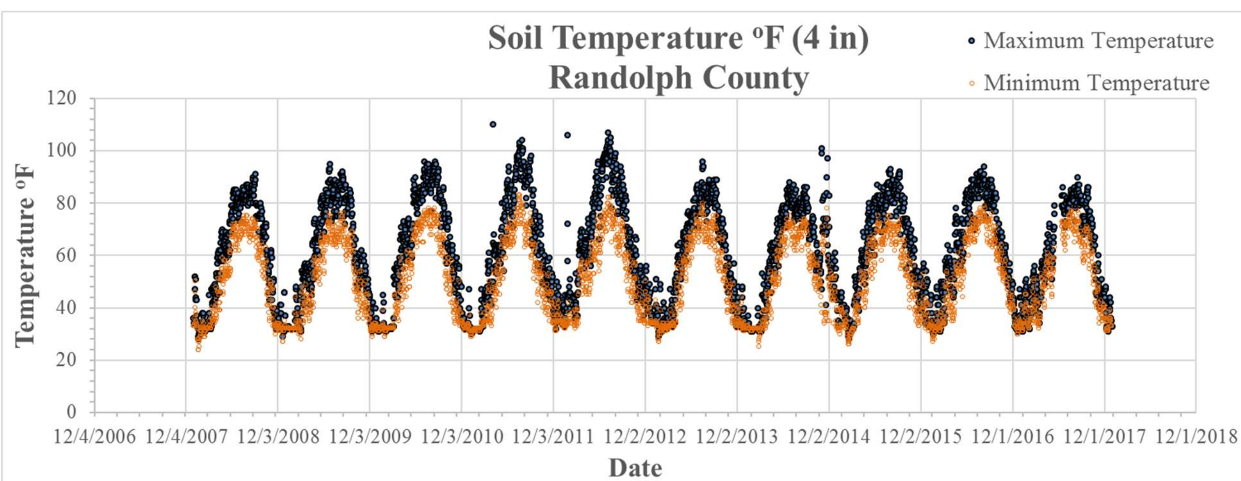


Figure I.3 Daily temperature readings at a 4-inch depth DPAC (iClimate).

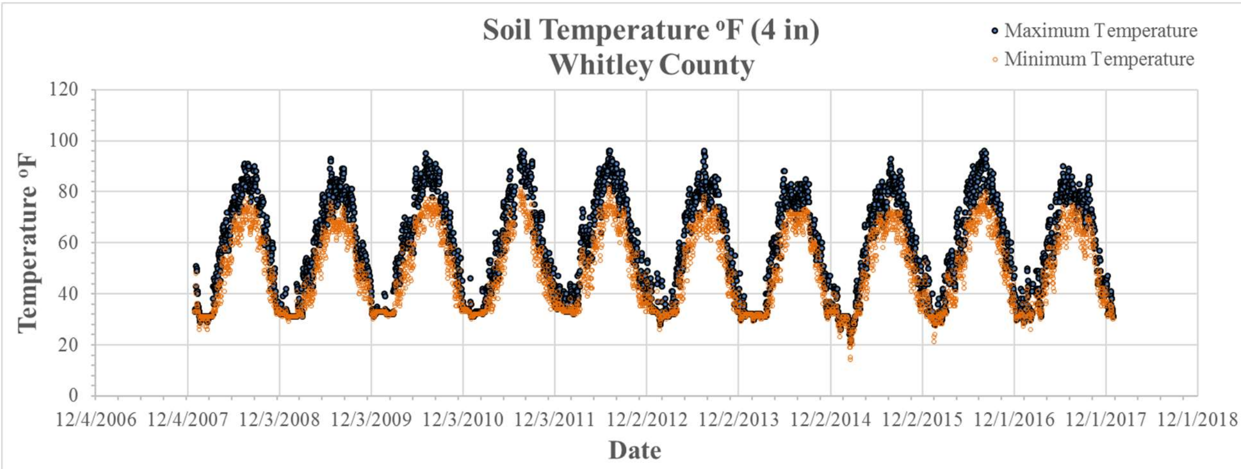


Figure I.4 Daily temperature readings at a 4-inch depth NPAC (iClimate).

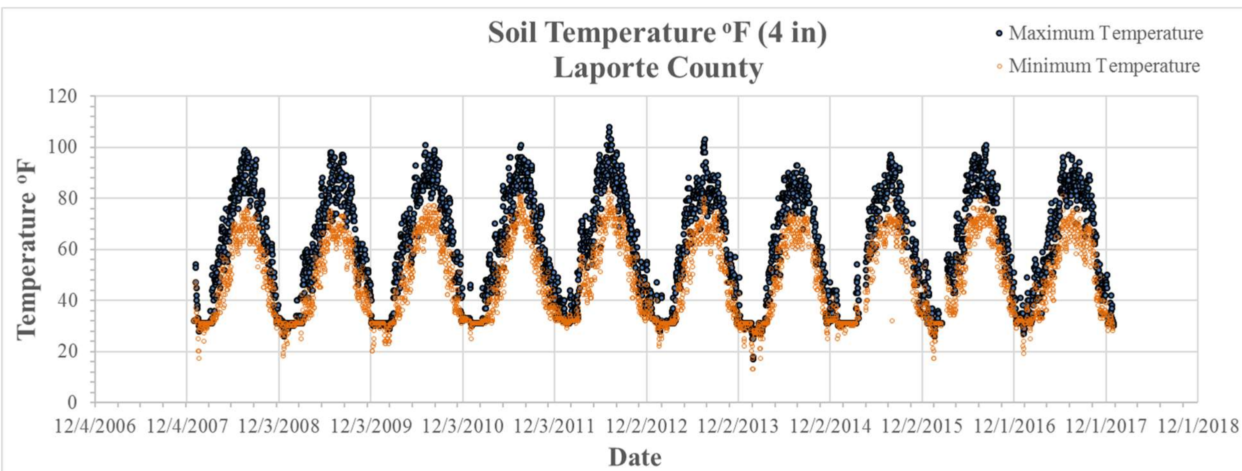


Figure I.5 Daily temperature readings at a 4-inch depth PPAC (iClimate).

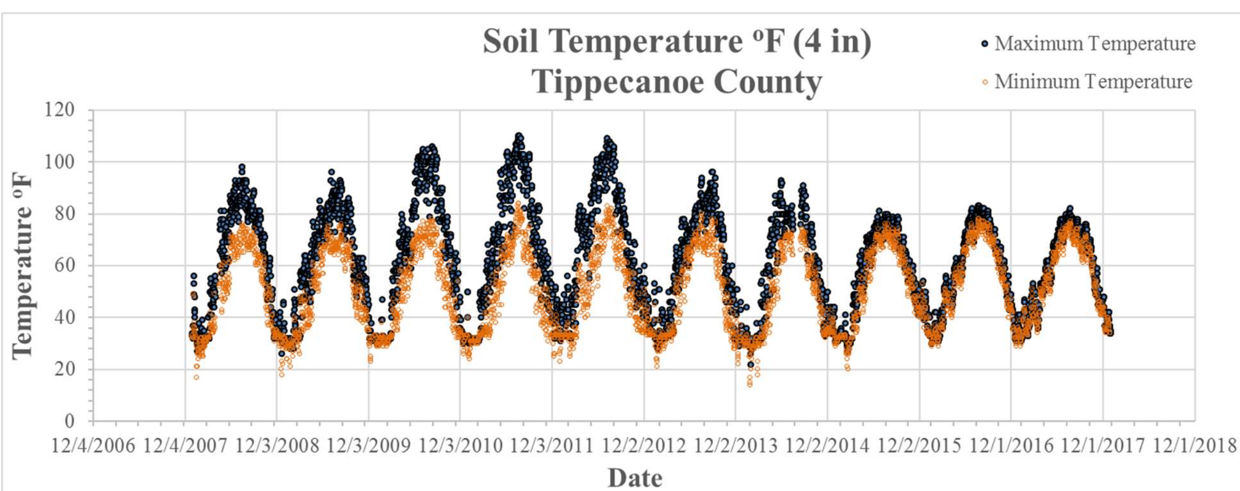


Figure I.6 Daily temperature readings at a 4-inch depth TPAC (iClimate).

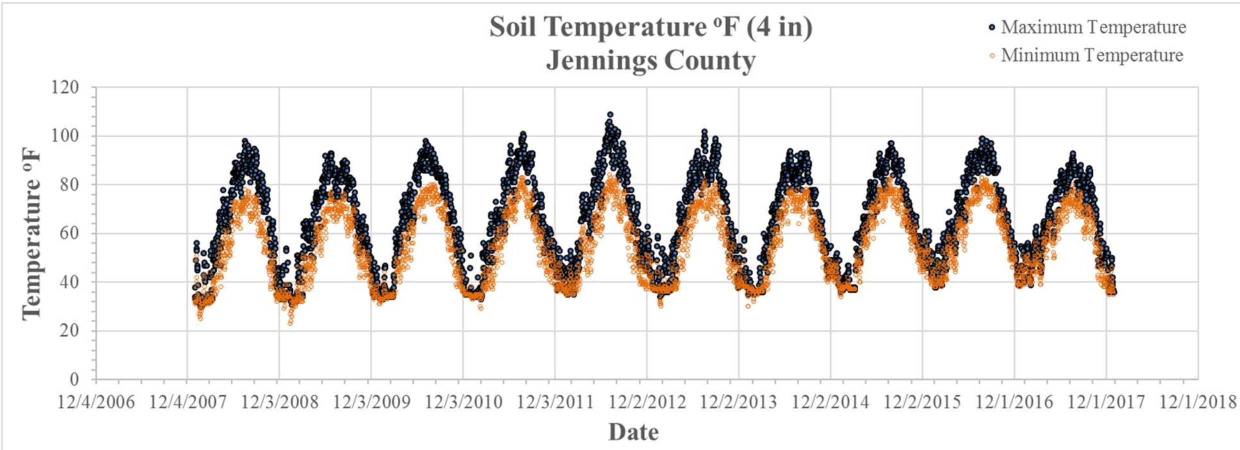


Figure I.7 Daily temperature readings at a 4-inch depth SEPAC (iClimate).

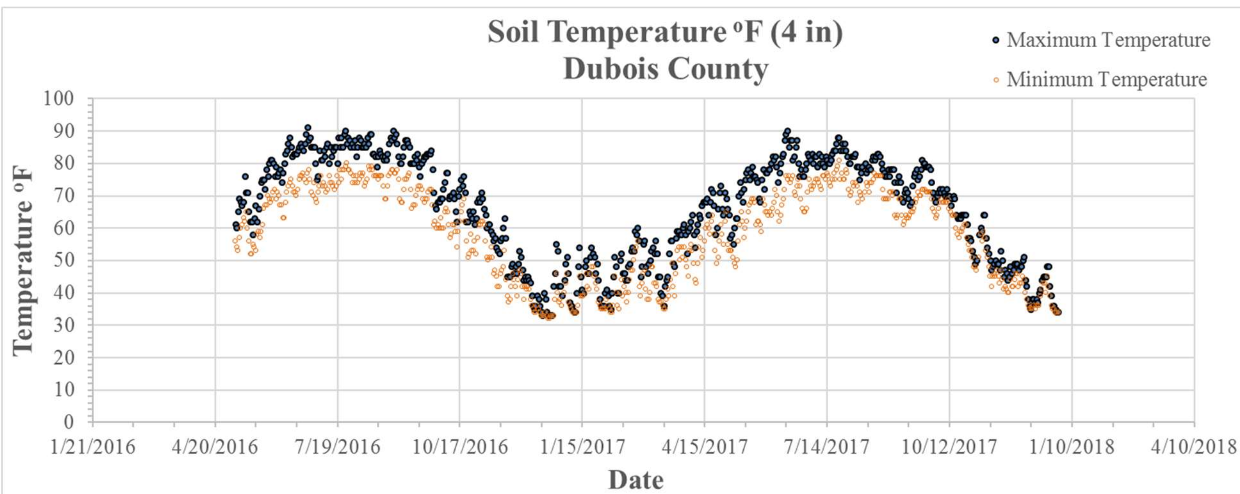


Figure I.8 Daily temperature readings at a 4-inch depth SIPAC (iClimate).

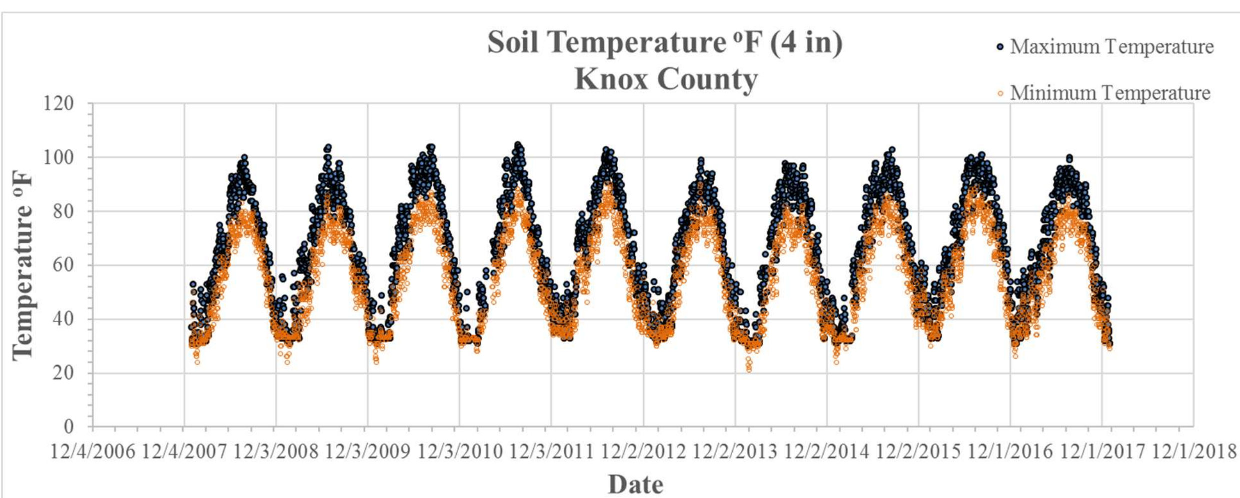


Figure I.9 Daily temperature readings at a 4-inch depth SWPAC (iClimate).

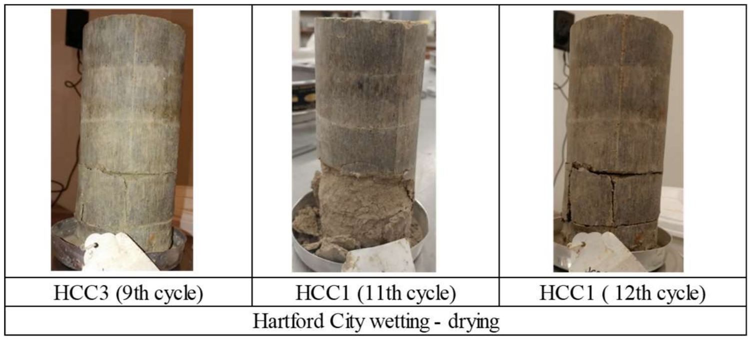


Figure I.10 Collapsed samples during WD cycles Hartford City with cement—adjusted protocol.

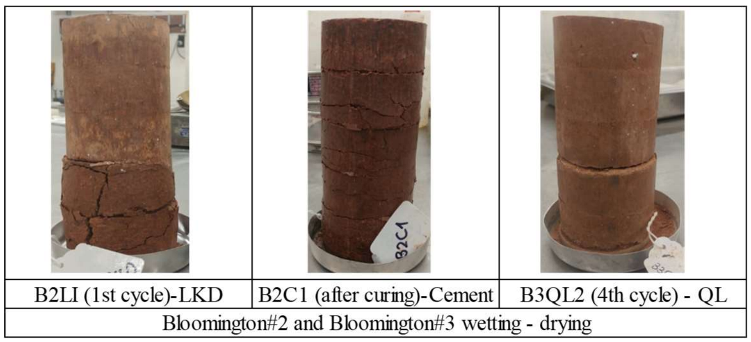


Figure I.11 Collapsed samples during WD cycles Bloomington #2 with LKD, cement, and QL—adjusted protocol.

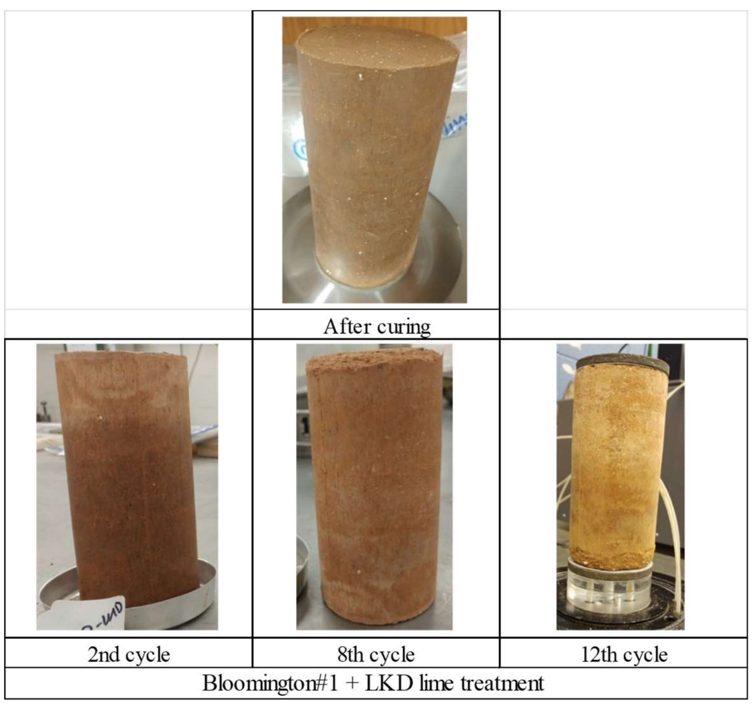


Figure I.12 Bloomington #1 samples treated with LKD during WD cycles—adjusted protocol.

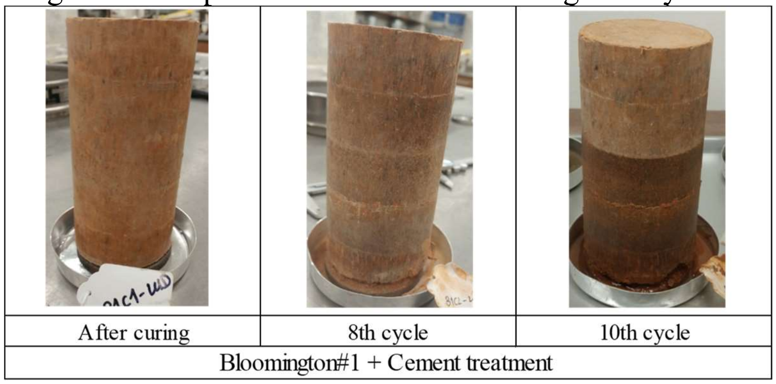


Figure I.13 Bloomington #1 samples treated with cement during WD cycles—adjusted protocol.

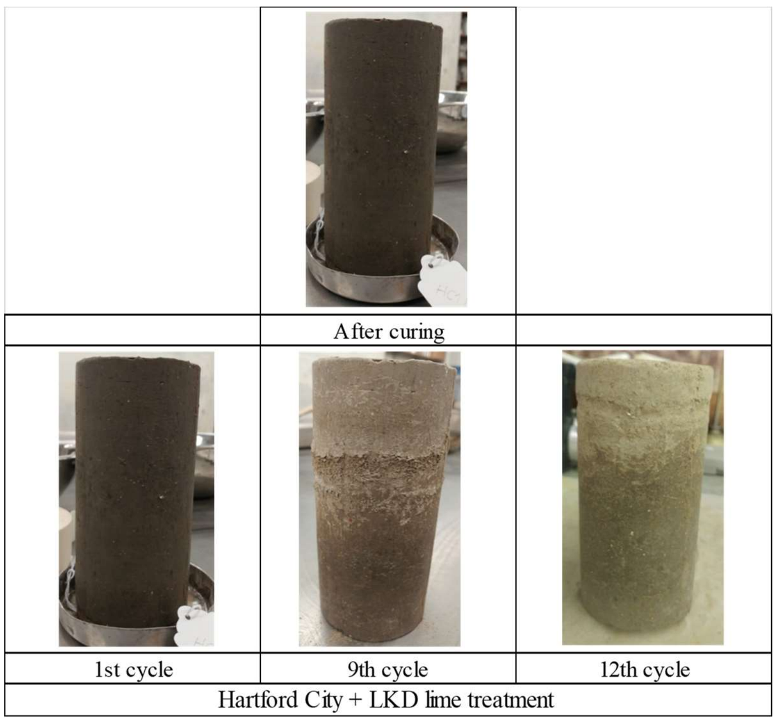


Figure I.14 Hartford City samples treated with LKD during WD cycles—adjusted protocol.

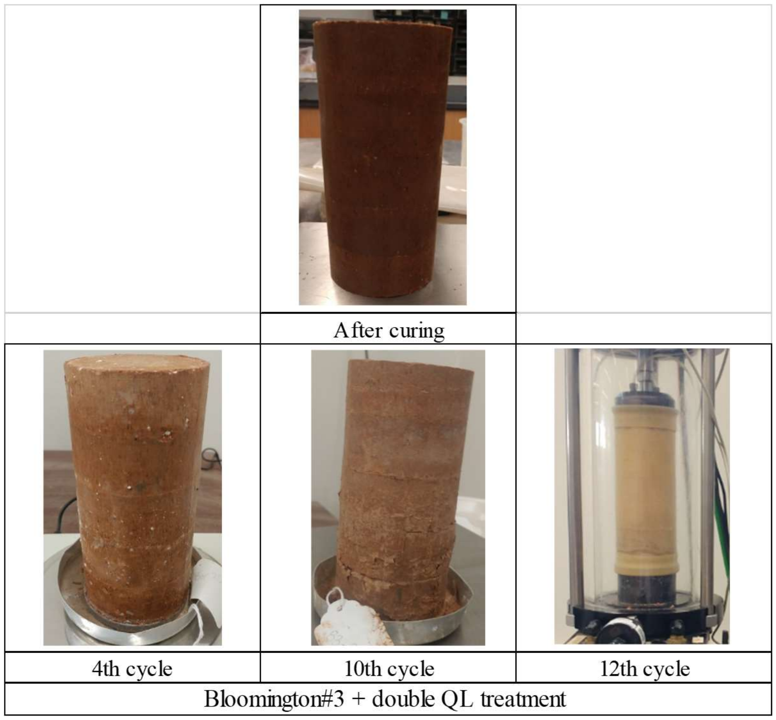


Figure I.15 Bloomington #3 samples treated with double amount of QL during WD cycles—adjusted protocol.

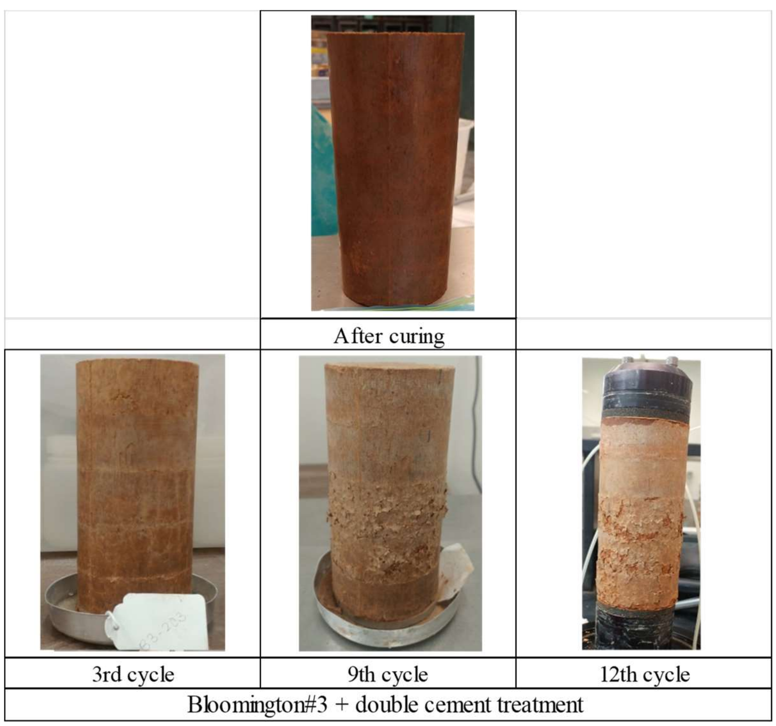


Figure I.16 Bloomington #3 samples treated with double amount of cement during WD cycles—adjusted protocol.

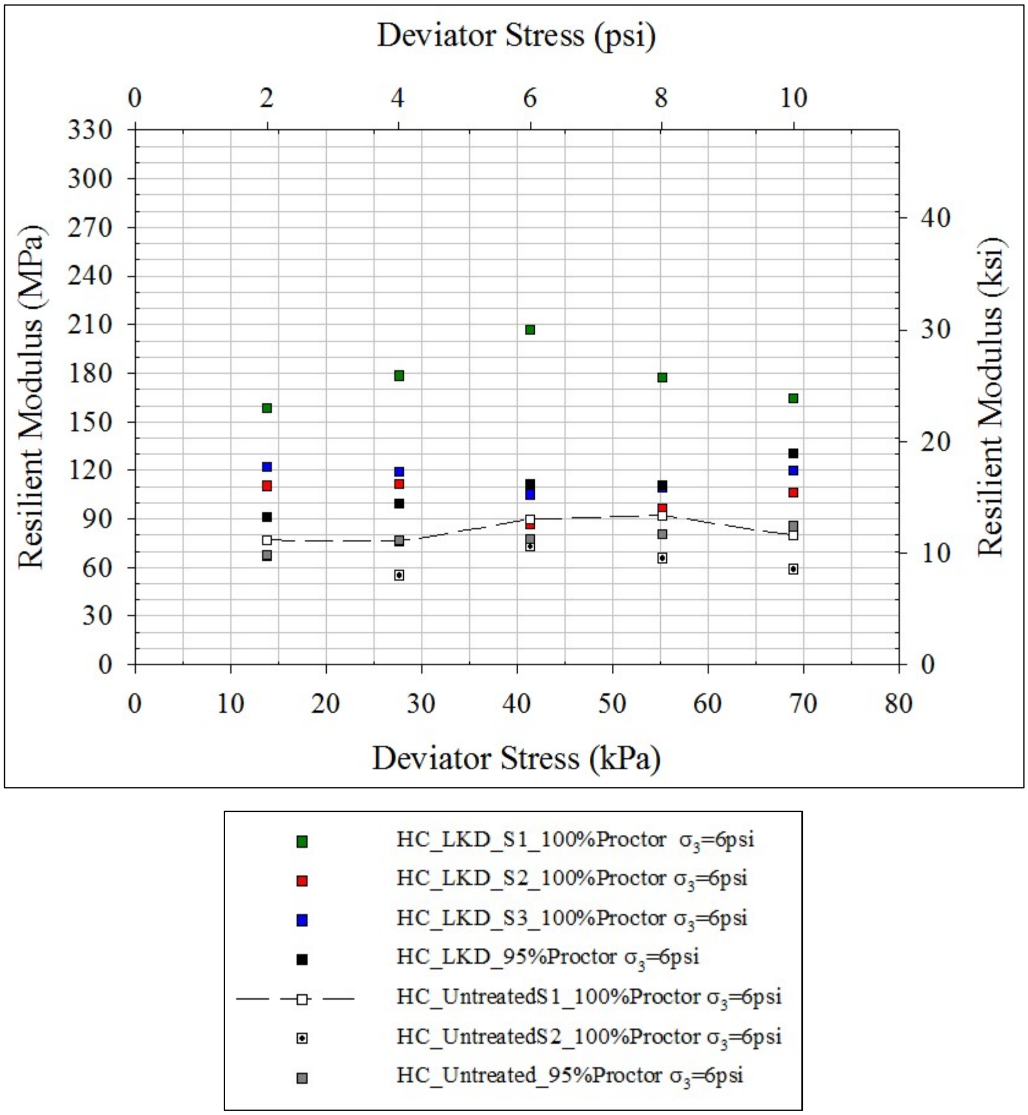


Figure I.17 Resilient modulus for untreated soil and soil treated with optimum amount of LKD after twelve wetting/drying cycles. Confinement stress 6 psi. Hartford City (HC).

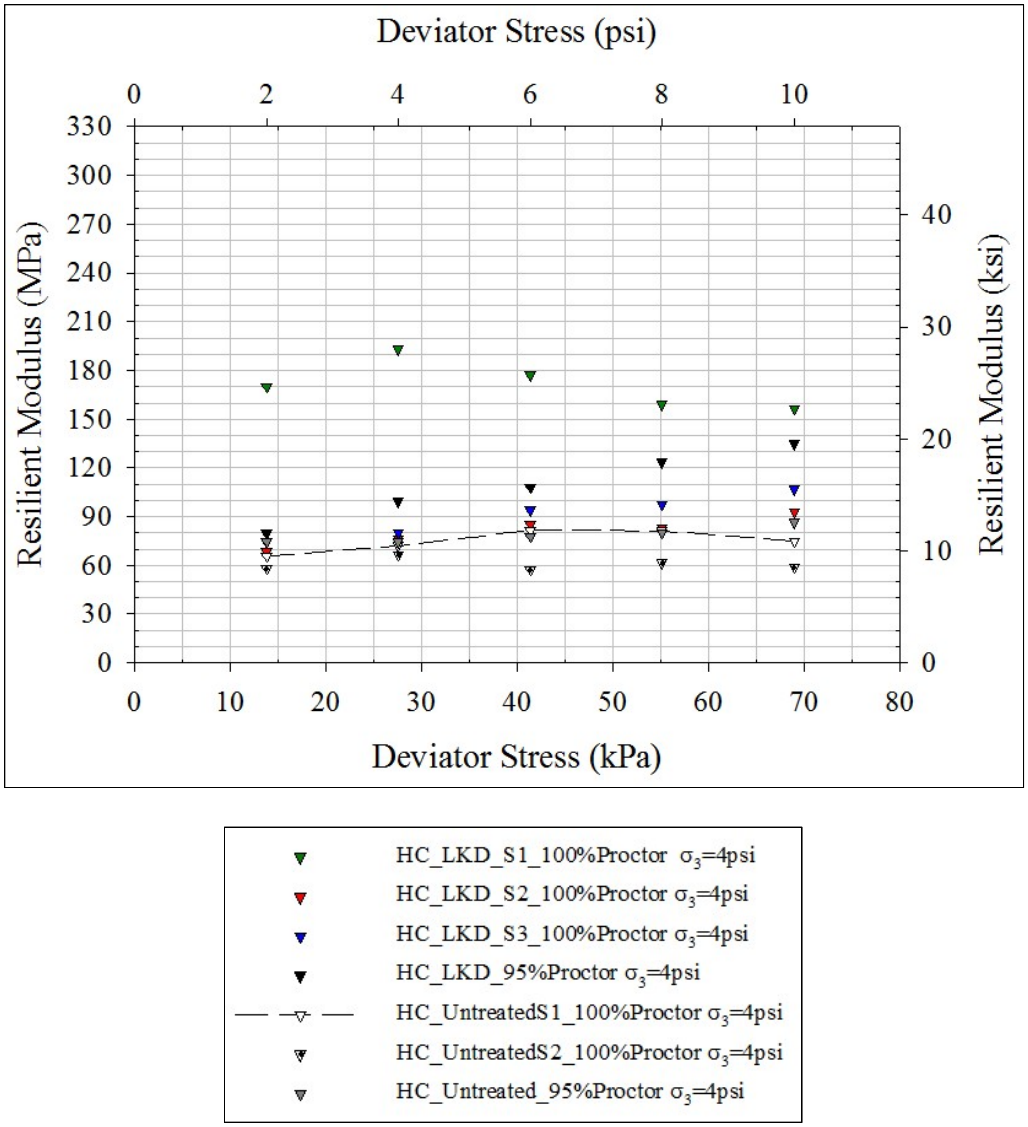


Figure I.18 Resilient modulus for untreated soil and soil treated with optimum amount of LKD after twelve wetting/drying cycles. Confinement stress 4 psi. Hartford City (HC).

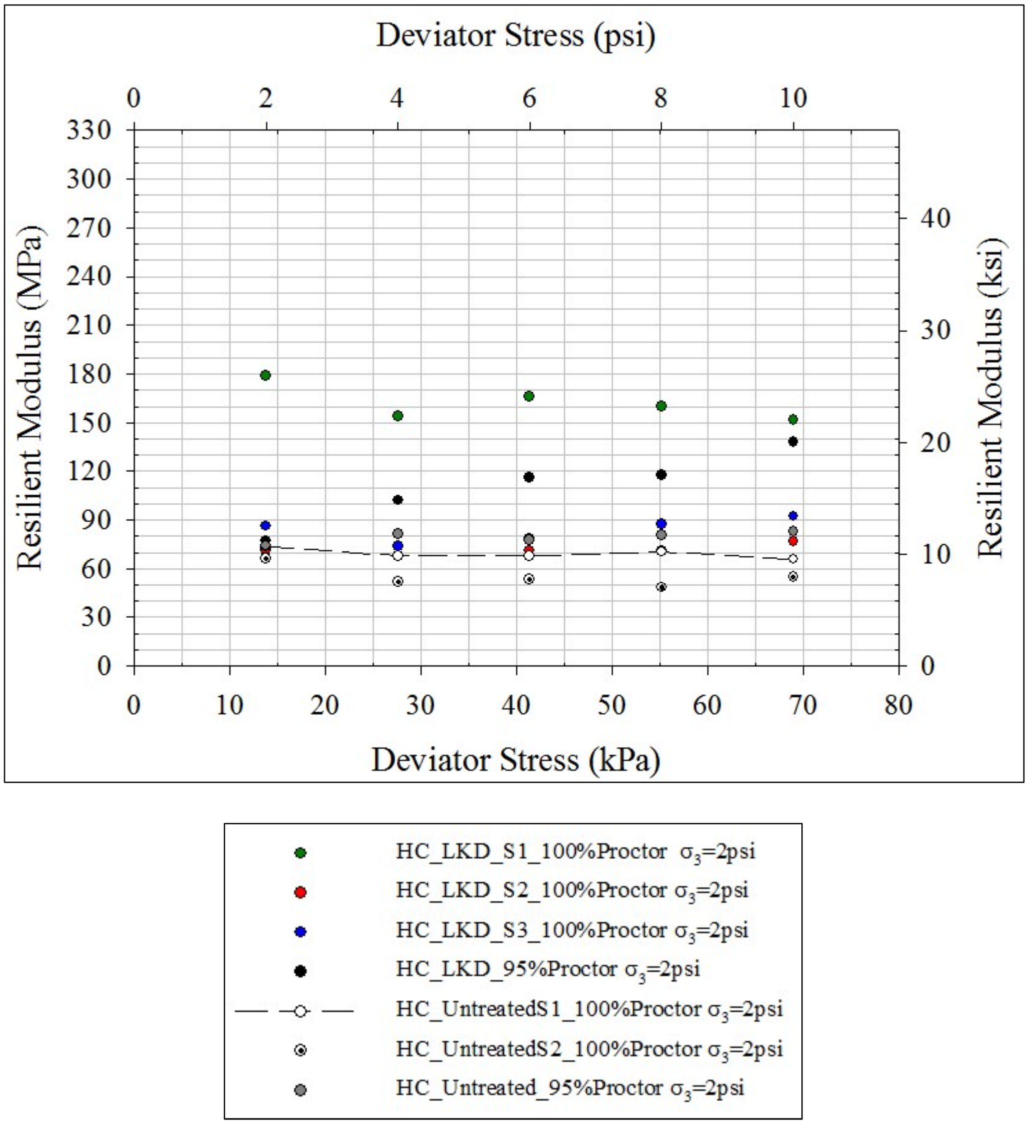


Figure I.19 Resilient modulus for untreated soil and soil treated with optimum amount of LKD after twelve wetting/drying cycles. Confinement stress 2 psi. Hartford City (HC).

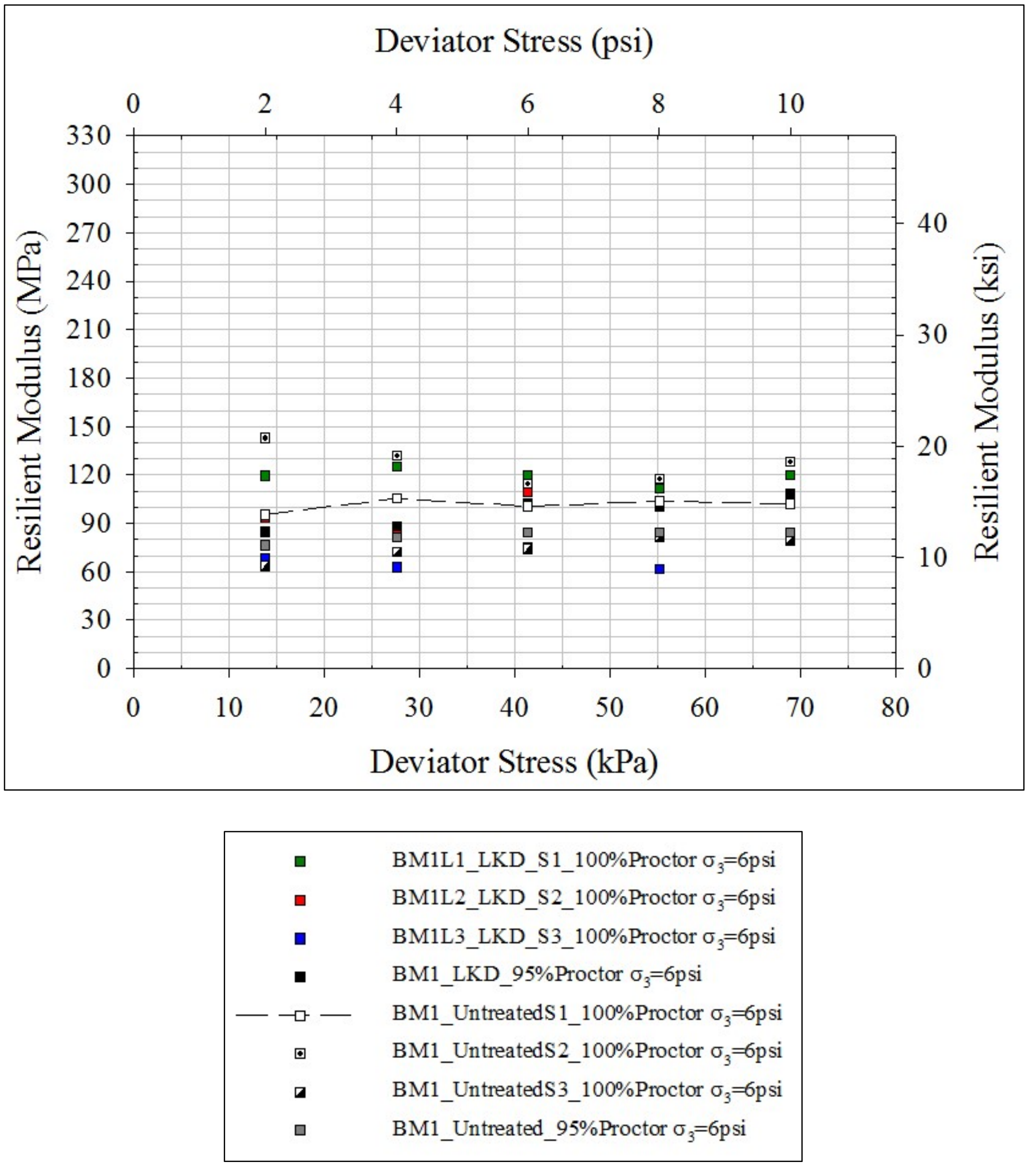


Figure I.20 Resilient modulus for untreated soil and soil treated with optimum amount of LKD after twelve wetting/drying cycles. Confinement stress 6 psi. Bloomington #1 (BM1).

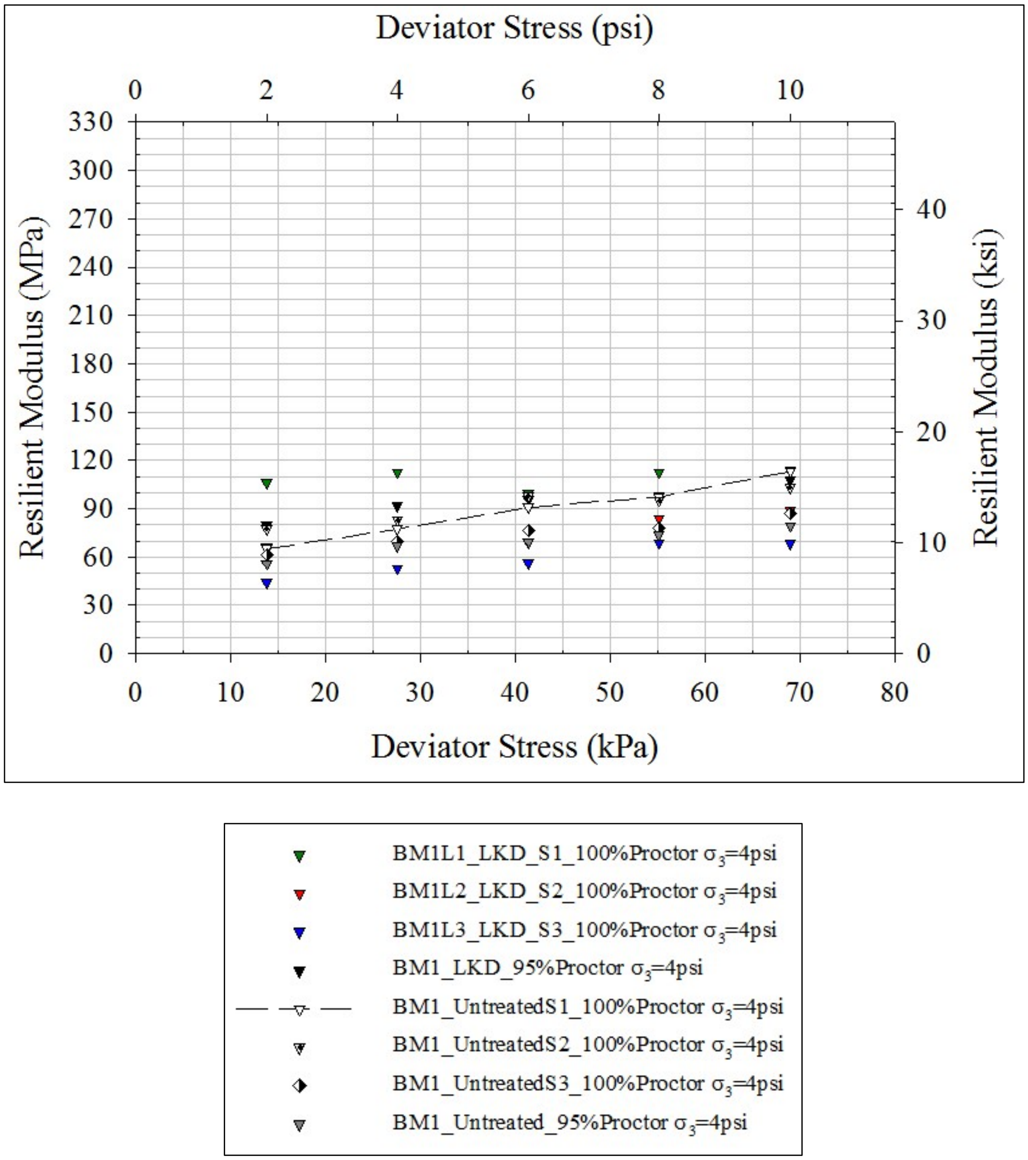


Figure I.21 Resilient modulus for untreated soil and soil treated with optimum amount of LKD after twelve wetting/drying cycles. Confinement stress 4 psi. Bloomington #1 (BM1).

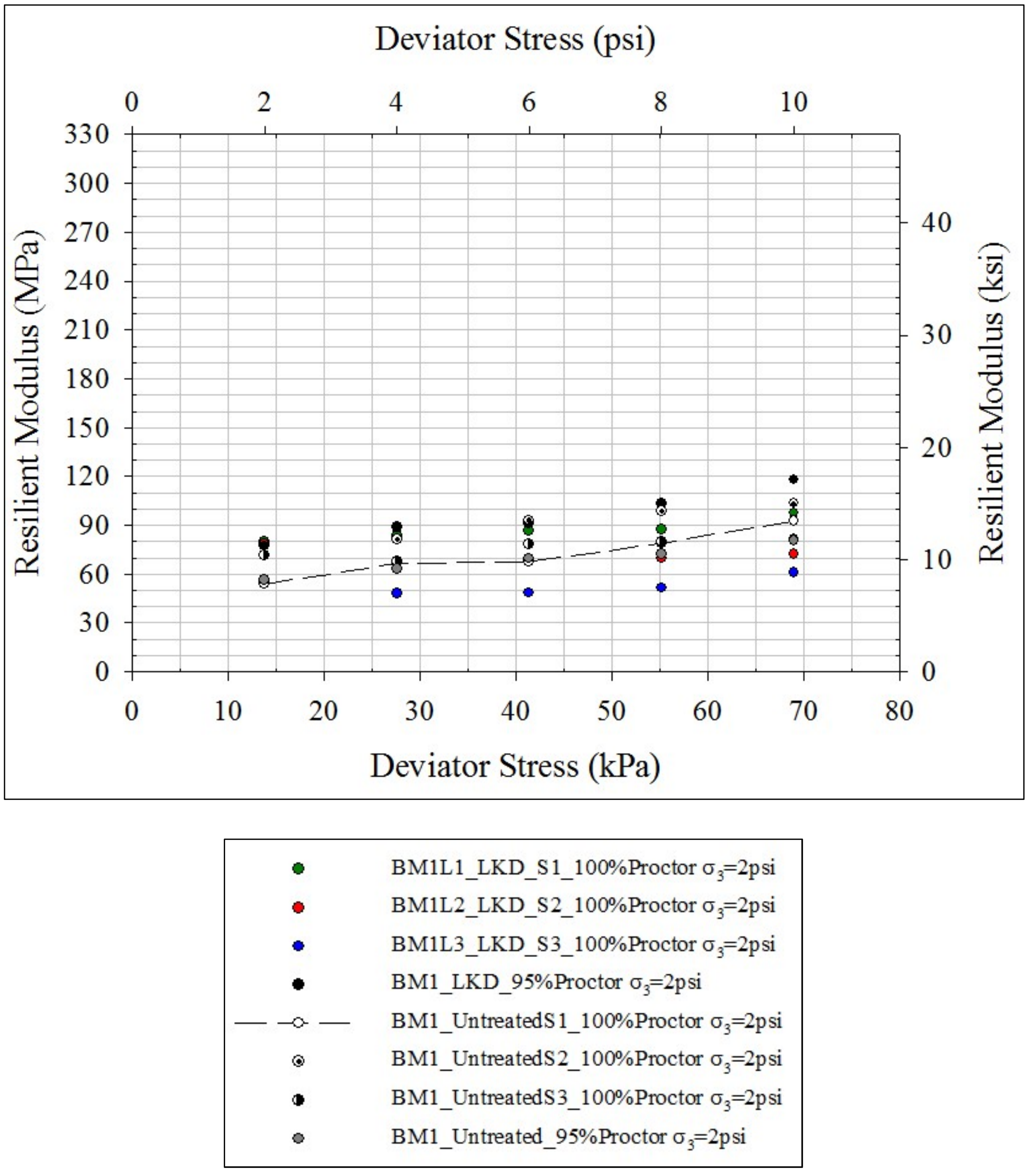


Figure I.22 Resilient modulus for untreated soil and soil treated with optimum amount of LKD after twelve wetting/drying cycles. Confinement stress 2 psi. Bloomington #1 (BM1).

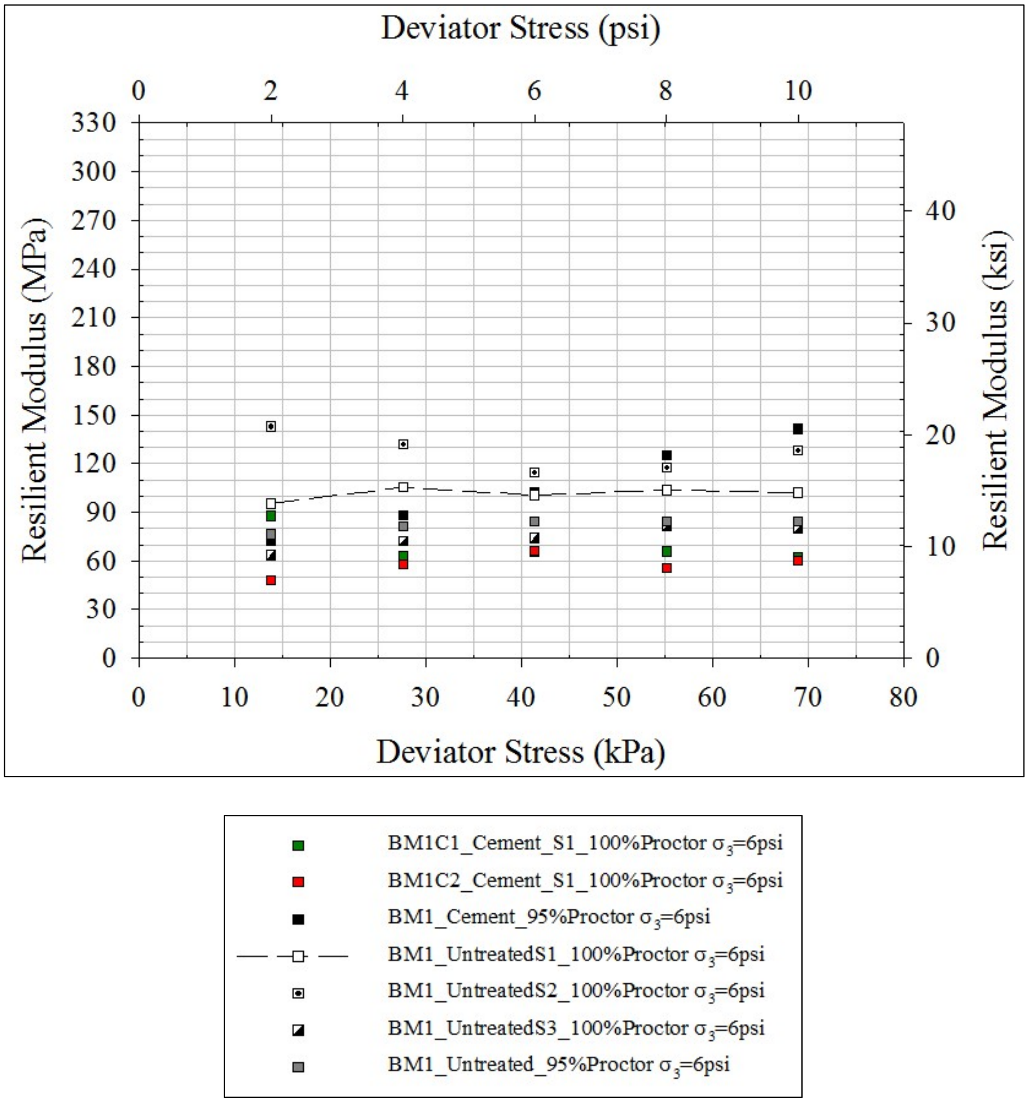


Figure I.23 Resilient modulus for untreated soil and soil treated with optimum amount of cement after twelve wetting/drying cycles. Confinement stress 6 psi. Bloomington #1 (BM1).

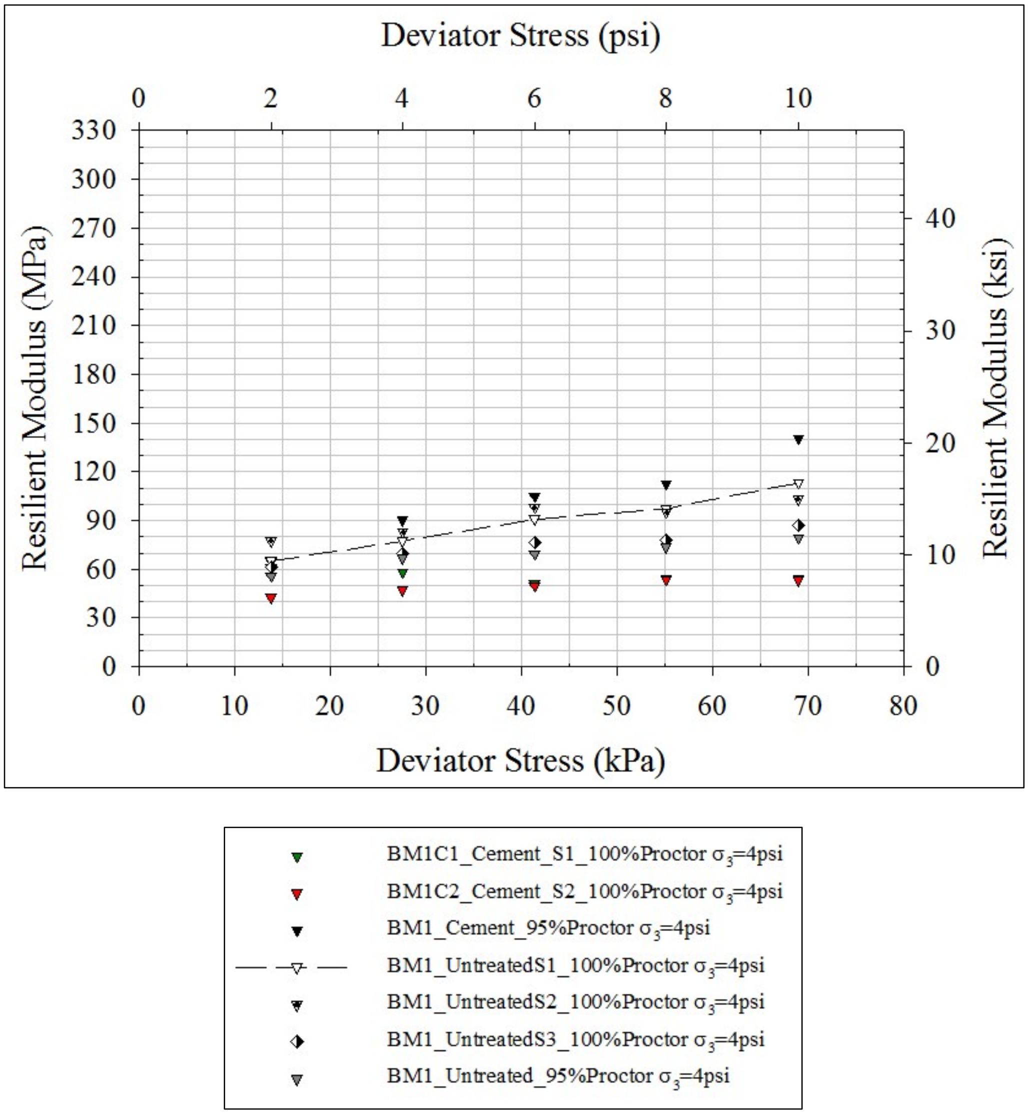


Figure I.24 Resilient modulus for untreated soil and soil treated with optimum amount of cement after twelve wetting/drying cycles. Confinement stress 4 psi. Bloomington #1 (BM1).

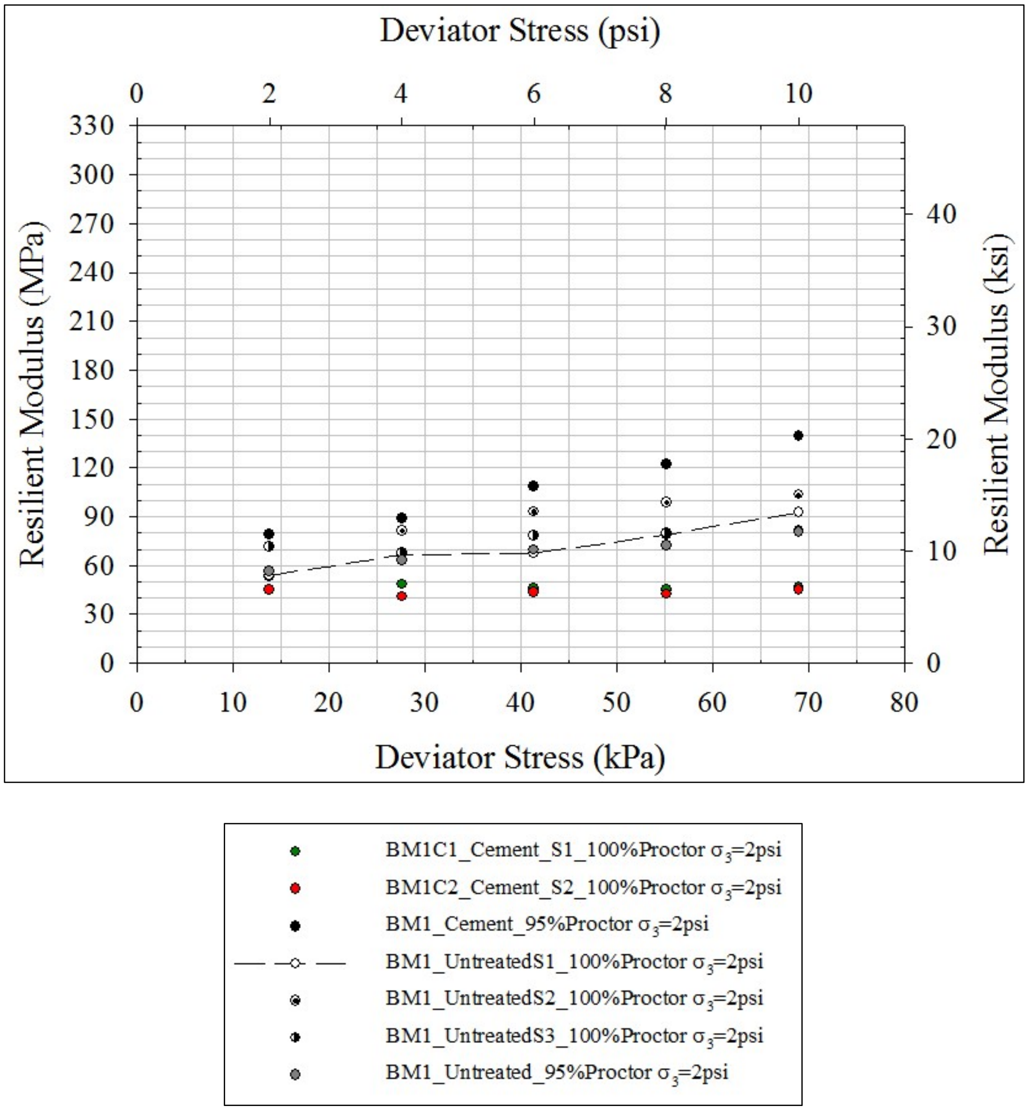


Figure I.25 Resilient modulus for untreated soil and soil treated with optimum amount of cement after twelve wetting/drying cycles. Confinement stress 2 psi. Bloomington #1 (BM1).

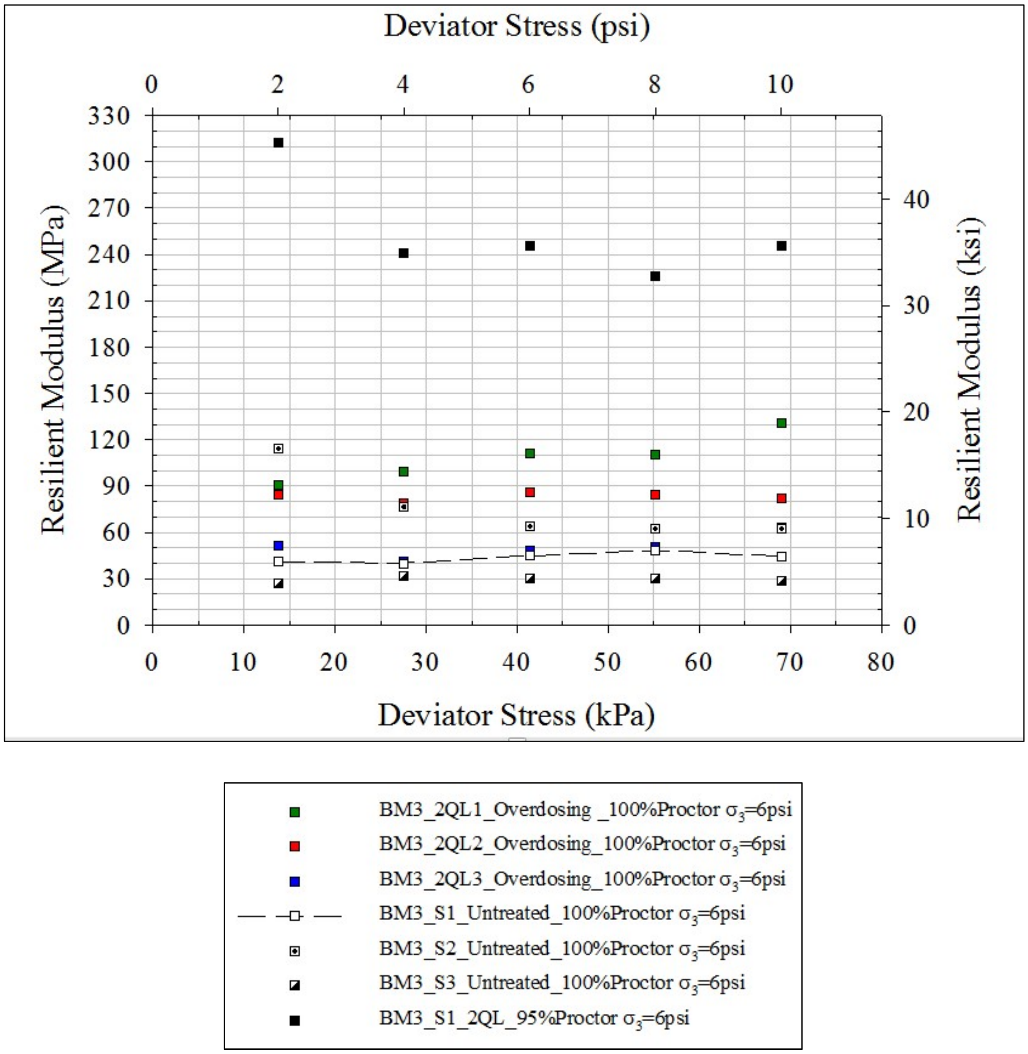


Figure I.26 Resilient modulus for untreated soil and soil treated with double amount of QL after twelve wetting/drying cycles. Confinement stress 6 psi. Bloomington #3 (BM3).

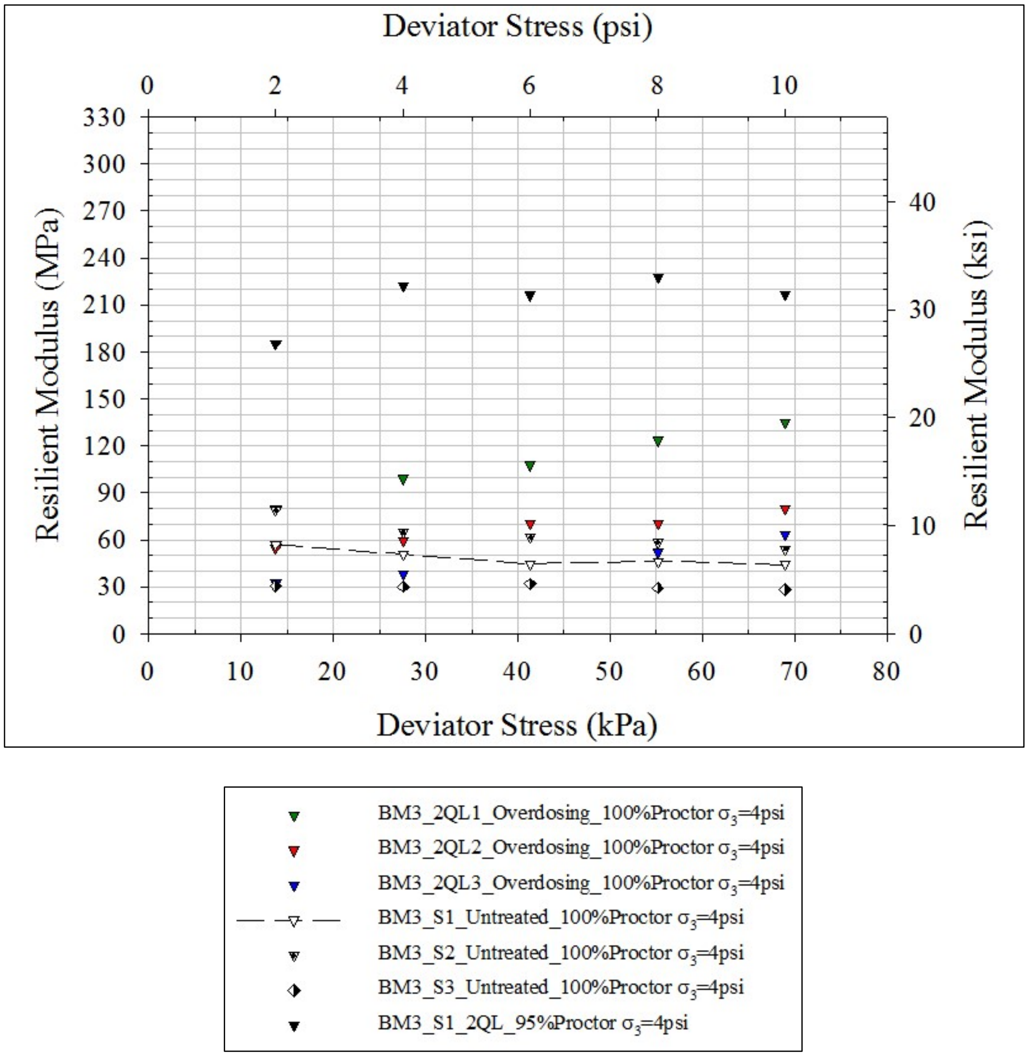


Figure I.27 Resilient modulus for untreated soil and soil treated with double amount of QL after twelve wetting/drying cycles. Confinement stress 4 psi. Bloomington #3 (BM3).

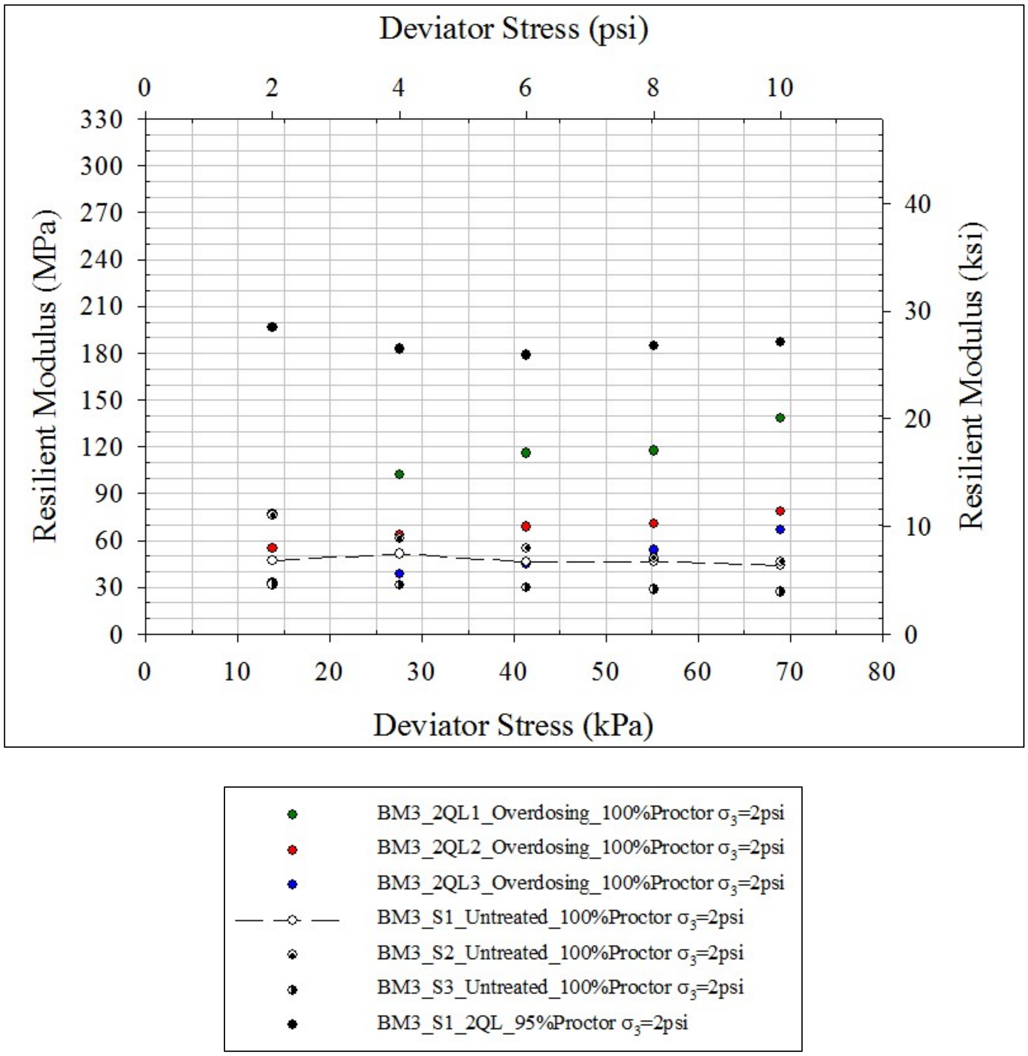


Figure I.28 Resilient modulus for untreated soil and soil treated with double amount of QL after twelve wetting/drying cycles. Confinement stress 2 psi. Bloomington #3 (BM3).

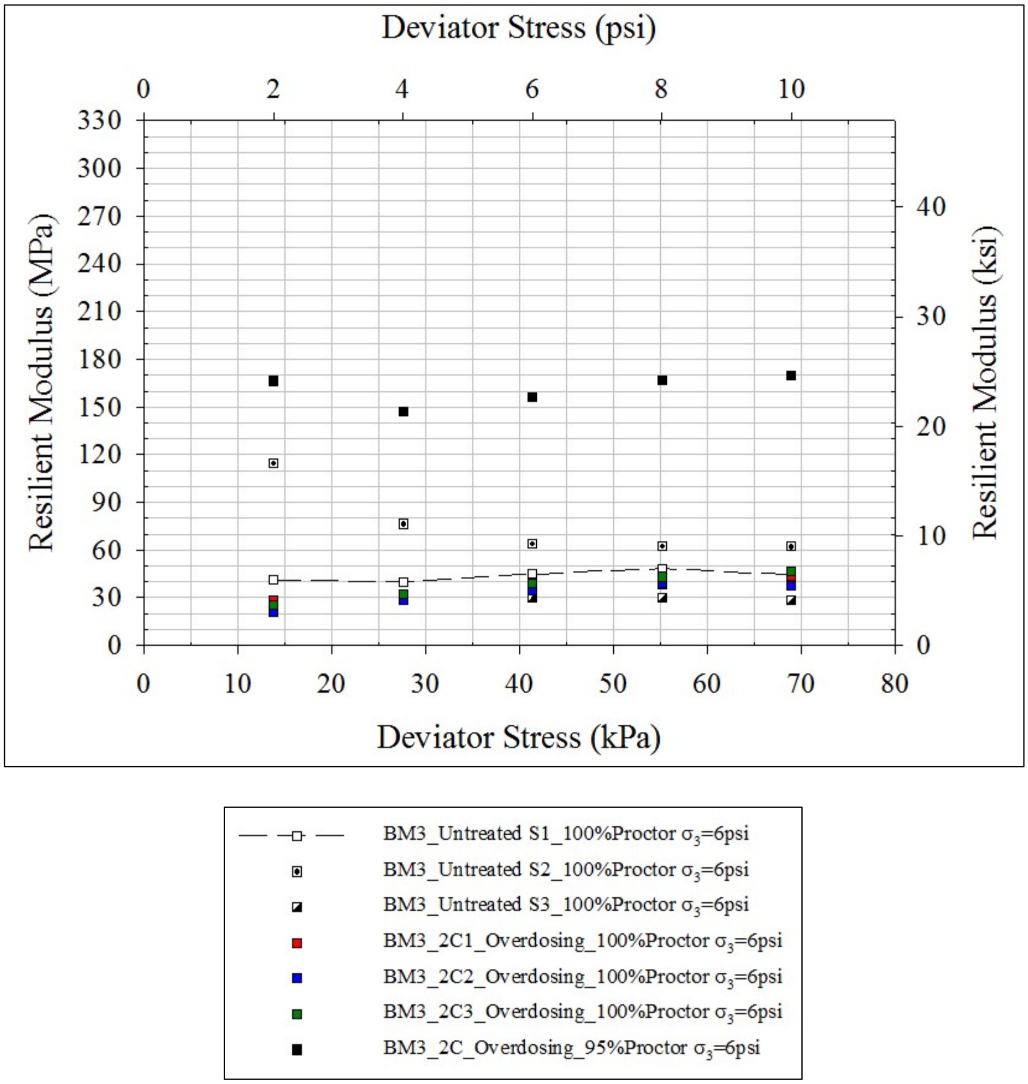


Figure I.29 Resilient modulus for untreated soil and soil treated with double amount of cement after twelve wetting/drying cycles. Confinement stress 6 psi. Bloomington #3 (BM3).

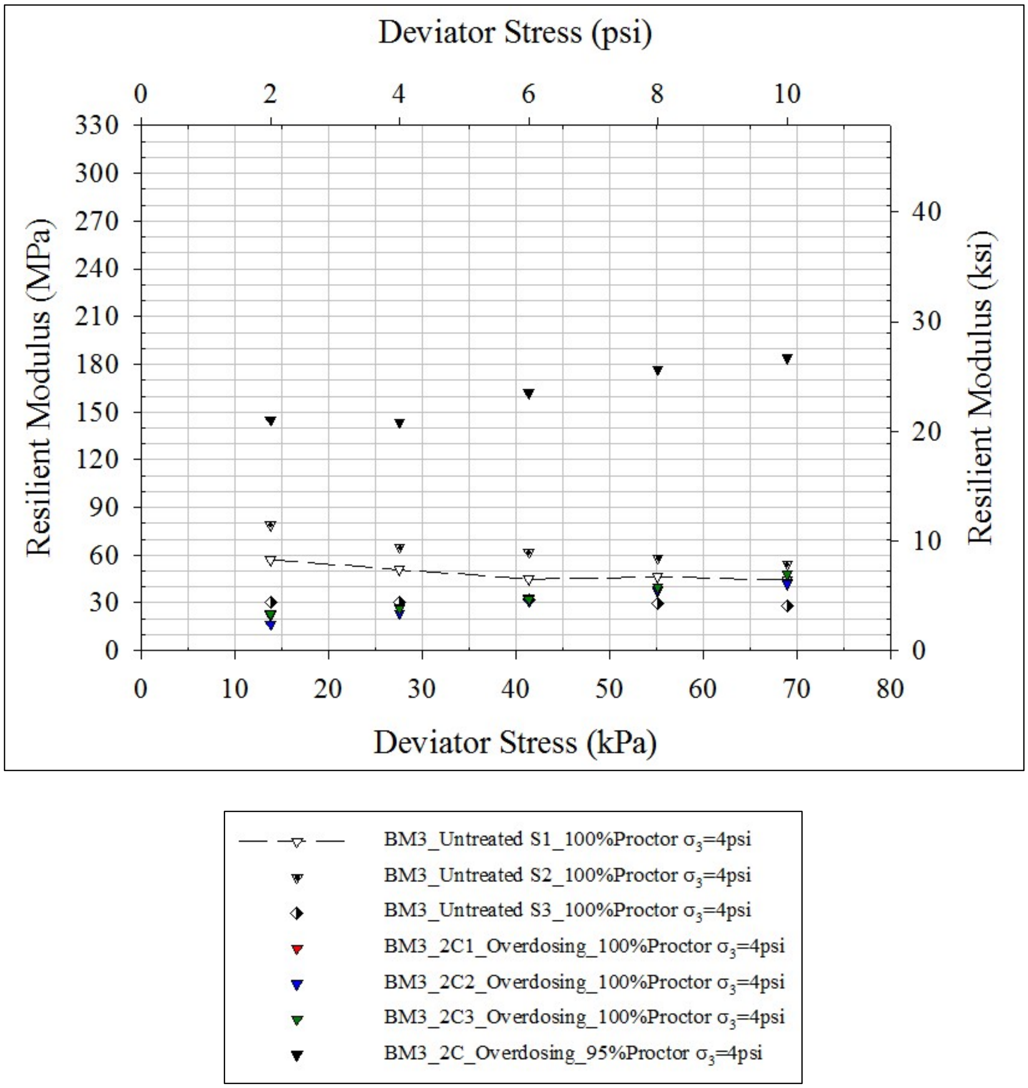


Figure I.30 Resilient modulus for untreated soil and soil treated with double amount of cement after twelve wetting/drying cycles. Confinement stress 4 psi. Bloomington #3 (BM3).

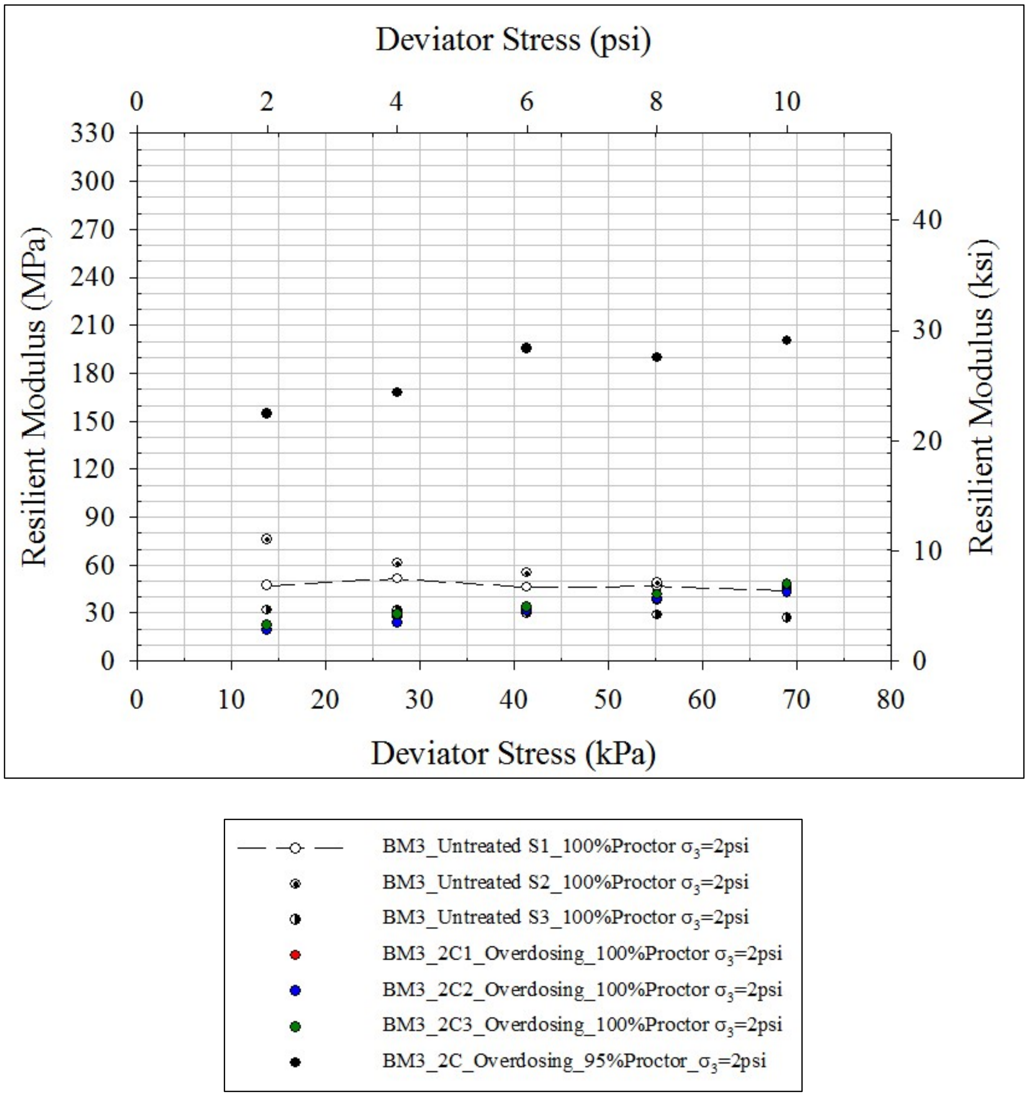


Figure I.31 Resilient modulus for untreated soil and soil treated with double amount of cement after twelve wetting/drying cycles. Confinement stress 2 psi. Bloomington #3 (BM3).

Table I.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

Note: 1 psi ≈ 6.89 kPa
1 ksi ≈ 6.89 MPa

APPENDIX J. EFFECT OF CHANGES OF TEMPERATURE ON RESILIENT MODULUS

Remolded samples were prepared to conduct resilient modulus tests (M_R), based on the standard AASHTO T307-99 (2007) for Type 2 Material, i.e., fine-grained soils, following the procedure described in Appendix G, Bloomington #1 (BM1) specimens were mixed with Lime Kiln Dust (LKD) or cement. The samples were compacted at a density equivalent to the 100% of the maximum density of the Standard Proctor energy. The types and amount of optimum treatment for the M_R tests were presented in the Appendix C, with the corresponding compaction curves for untreated and treated soils.

J.1 Procedure following the ASTM Standard D560/D560M

After compaction, the treated specimens were cured in the moisture room for 7 days. Later, the samples were subjected to Freezing and Thawing (FT) cycles following the ASTM Standard D560/D560M. A confined treated specimen with a perforated PVC pipe, to better represent the field conditions, is shown in Figure J.1. Each sample was placed on a saturated pad into the freezer at -9.5˚F (-23˚C) for 24 hours, and then placed inside the moisture room at 73.5˚F (23˚C) for 23 hours. The process represents a cycle of freezing/thawing (FT), and the entire test was completed by doing 12 cycles for each specimen, which lasted around one month. By following the Standard D560/D560M, the treated sample presented premature failure due to excessive deformations during the twelve FT cycles, as shown in Figure J.2.

J.1.1 Finite element analysis

To evaluate the deformations and tensile stresses generated in the samples during the freezing and thawing cycles, finite elements analyses, using the temperatures required by the ASTM Standard D560/D560M, were performed. The model was implemented in the finite element software ABAQUS, with coupled temperature/displacement elements.

The change in temperature required by the ASTM Standard D560/D560M is from -9.5˚F (-23˚C) to 73.5˚F (23˚C). Thus, in the model, the sample was subjected to a temperature variation of 40˚C, which was applied in one increment. Specimens with different boundary conditions at the interface between the soil and the PVC, namely pinned and rollers were considered. The model geometry and mesh are shown in **Error! Reference source not found.**. The strains in the sample, after twelve FT cycles, are shown in Figure J.4 and J.5, for pin and roller boundaries, respectively. The numbers in the mesh represent the nodes.

Based on the ABAQUS analysis, the estimated tensile stresses in the sample range between 60 kPa (roller boundary) and 250 kPa (pinned boundary). The tensile stresses for clays found in the literature vary according to the different authors. Towner (1987) provided a conservative value for the tensile strength of clays, of 30 to 300 kPa. Zhang et al. (2013), for specimens with dry density of 1.65 g/cm^3 and moisture content 20%, suggested a tensile stress between 35 kPa and 40 kPa. Stirling et al. (2015), for clayey soils subjected to climatic loading, i.e., for a specimen with water content around 20%, recommended a tensile stress of around 30 kPa. A conservative value for the tensile strength of clays could range between 40 and 100 kPa. Consequently, the tensile stresses produced in the sample due to the FT cycles seem large enough to overcome the soil strength.

J.2 Modified test protocol

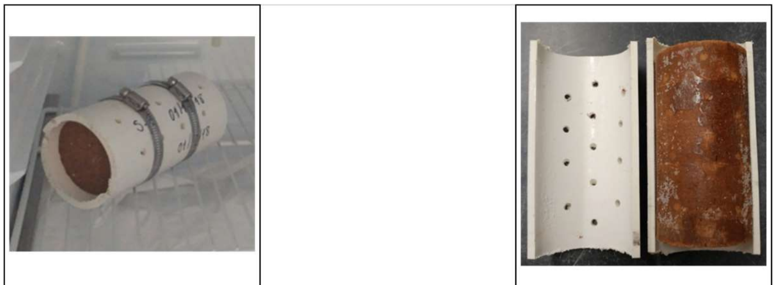
The temperature in the subgrade in Indiana changes with the seasons; nevertheless, these changes are not as extreme as those required by the standard ASTM D560/D560M. The minimum temperatures in Indiana can be found from data recorded by the Indiana State Climate Office (iClimate) at Purdue University, which uses information contained in the National Centers for Environmental Information (NOAA). Figures J.2 to J.9 are plots of the daily extreme temperatures (maximum and minimum) at each station. From Figure 10.6, the lowest temperature was 10˚F (-12˚C) which is the minimum in the North of the state.

These findings were discussed with the Study Advisory Committee (SAC) on September 2018 and a new test protocol was decided, which was thought to better represent the conditions in the field; that is: for the freezing stage, the specimens are placed with no confinement in the freezer for twenty-four hours at 10˚F (-12˚C); afterwards, for the thawing stage, the specimens are placed in the moisture room at 73˚F (23˚C) for twenty-four hours. The specimens are subjected to twelve FT cycles, which last around one month.

After the FT cycles, two M_R tests, BM1 mixed with LKD or cement, were conducted. Figures J.6 and J.7 show the treated samples, throughout the FT cycles, mixed with LKD and cement, respectively.

J.3 Resilient modulus results

Results of the resilient modulus tests, after twelve FT cycles, for BM1 specimens treated with LKD are shown in Figures J.8 to J.10. For BM1 treated with cement, the results are shown in Figures J.11 to J.13. Tables I.1 and J.1 lists the M_R values for the specimens, i.e., untreated and treated.



BM1+LKD FT cycles (ASTM D560/D560M)

Figure J.1 Bloomington #1 confined samples treated with LKD during freezing and thawing cycles following the Standard D560/D560M—optimum amount of treatment.

BM1+LKD 12th FT cycle (ASTM D560/D560M)

Figure J.2 Sample deformation after twelve freezing and thawing cycles following the Standard D560/D560M—optimum amount of treatment.

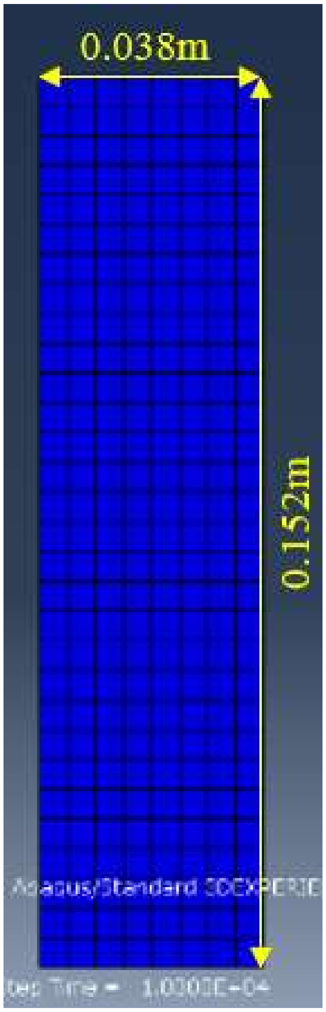


Figure J.3 Model geometry and mesh.

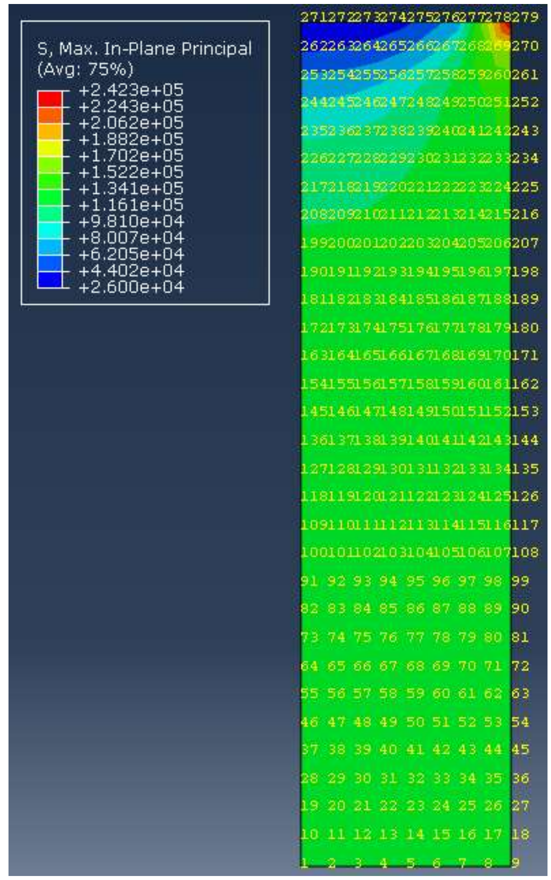


Figure J.4 Strains in a BM1 sample treated with LKD—fixed (pinned) boundary.

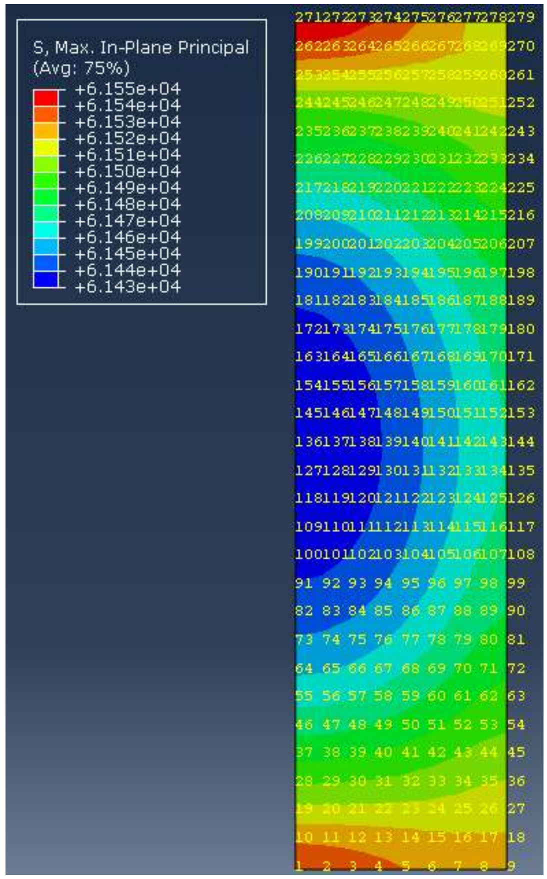


Figure J.5 Strains in a BM1 sample treated with LKD—roller boundary.

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

Figure J.6 Bloomington #1 sample treated with LKD during FT cycles following the modified protocol—optimum amount of treatment.

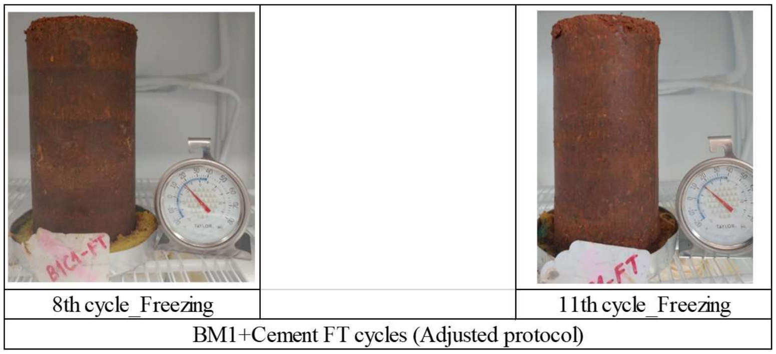


Figure J.7 Bloomington #1 sample treated with cement during FT cycles following the modified protocol—optimum amount of treatment.

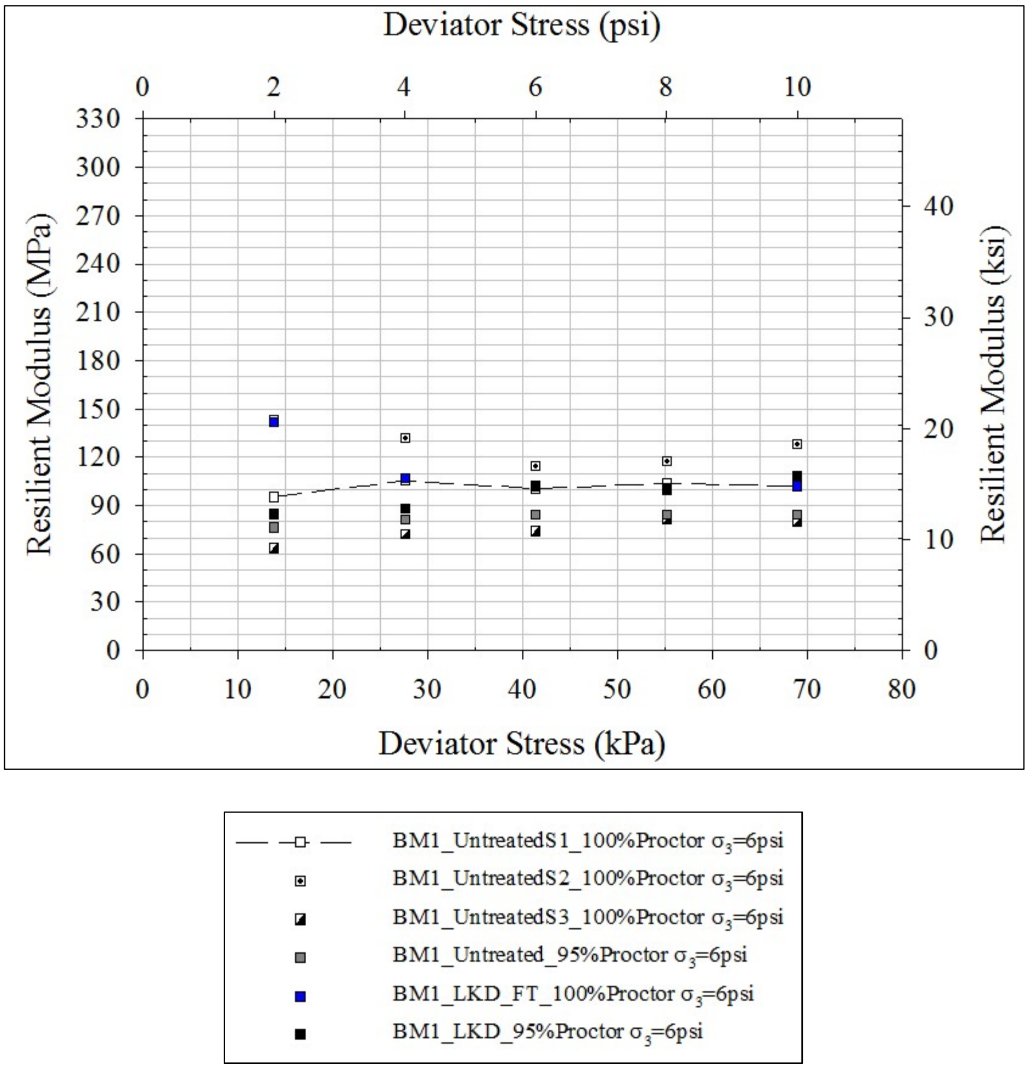


Figure J.8 Resilient modulus for untreated BM1 soil and BM1 soil treated with optimum amount of LKD after twelve FT cycles. Confinement stress 6 psi.

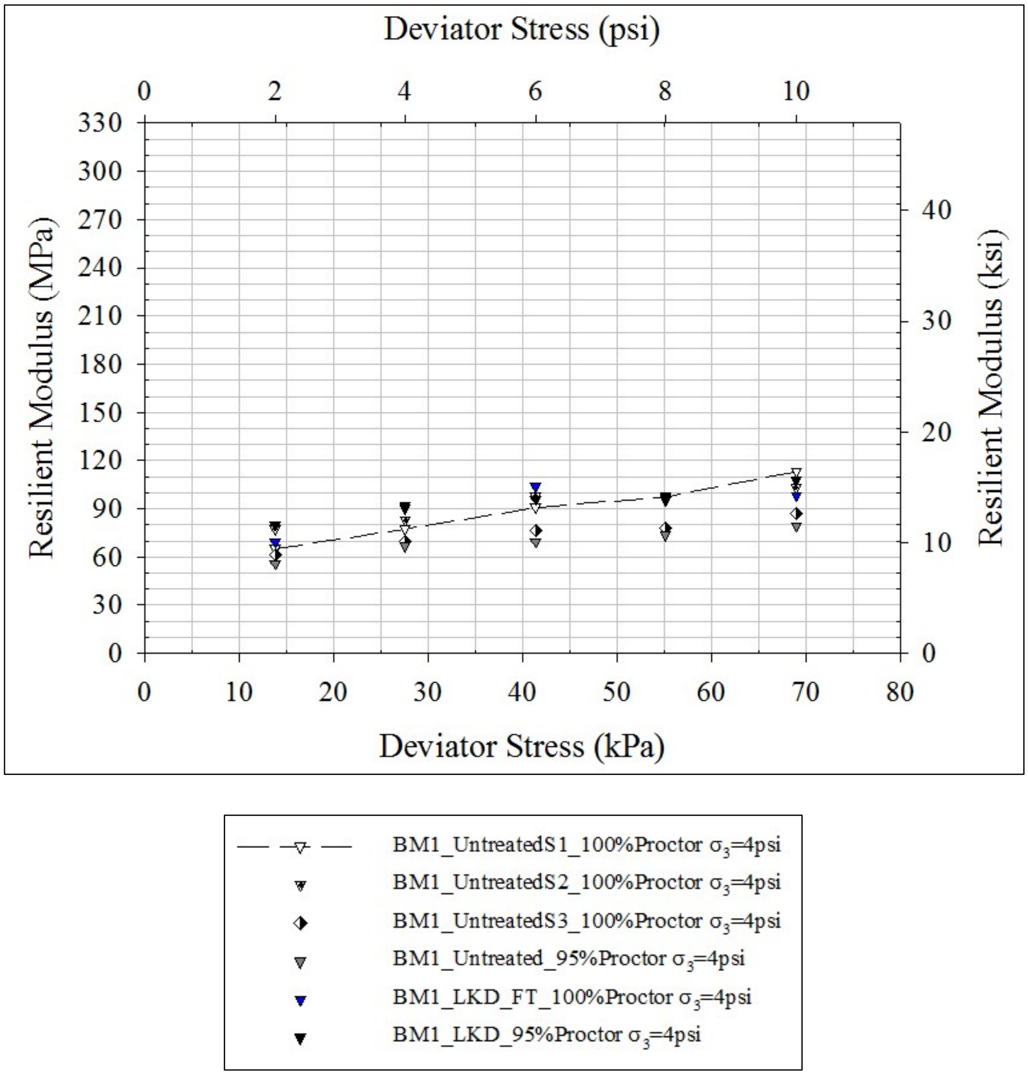


Figure J.9 Resilient modulus for untreated BM1 soil and BM1 soil treated with optimum amount of LKD after twelve FT cycles. Confinement stress 4 psi.

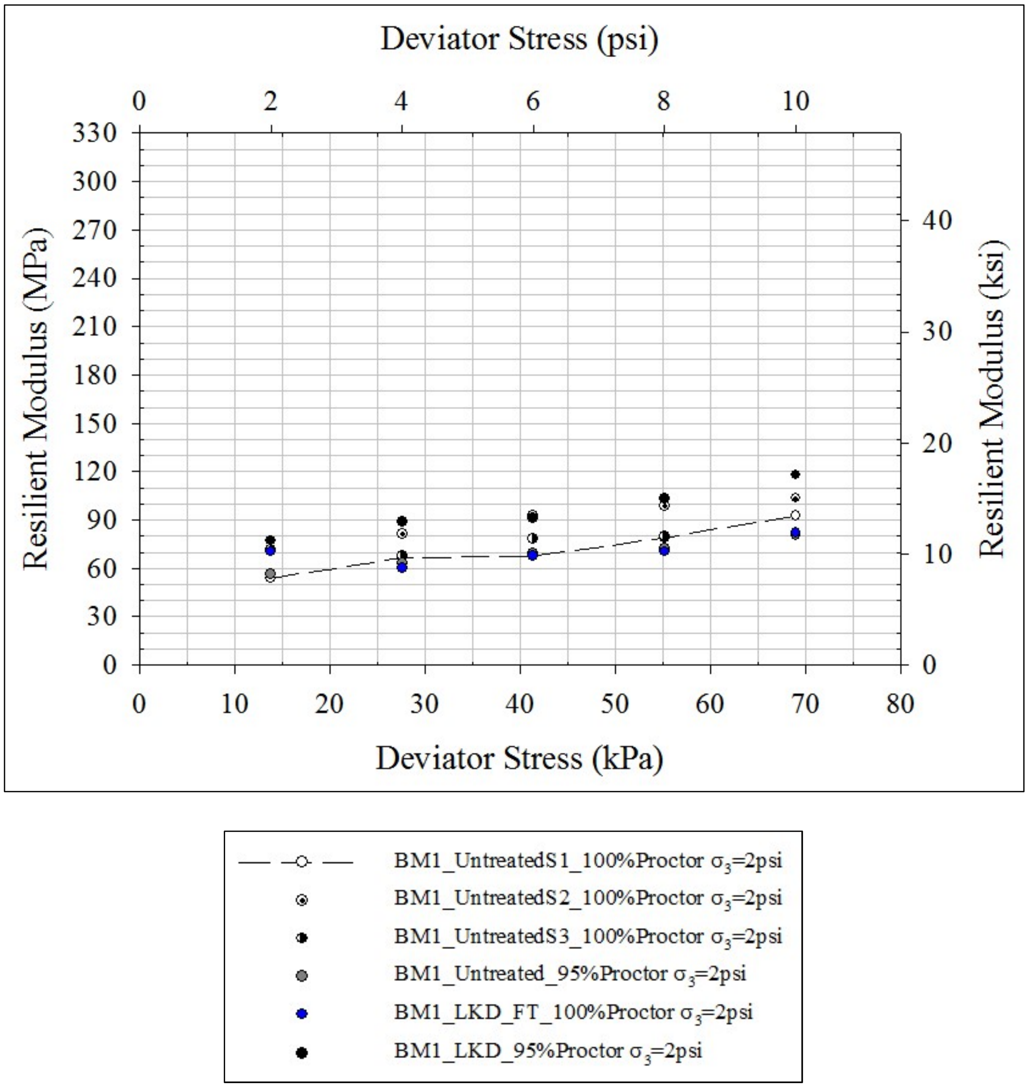


Figure J.10 Resilient modulus for untreated BM1 soil and BM1 soil treated with optimum amount of LKD after twelve FT cycles. Confinement stress 2 psi.

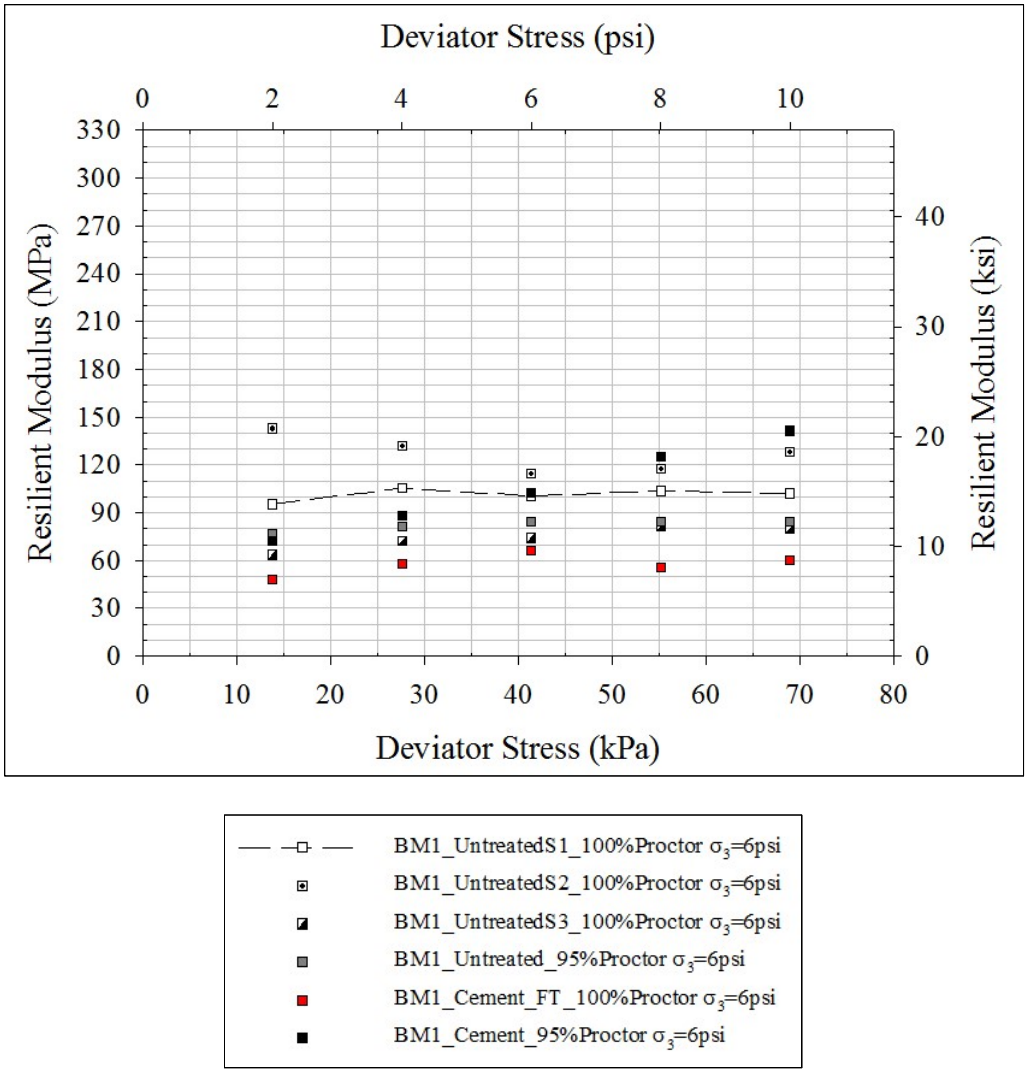


Figure J.11 Resilient modulus for untreated BM1 soil and BM1 soil treated with optimum amount of cement after twelve FT cycles. Confinement stress 6 psi.

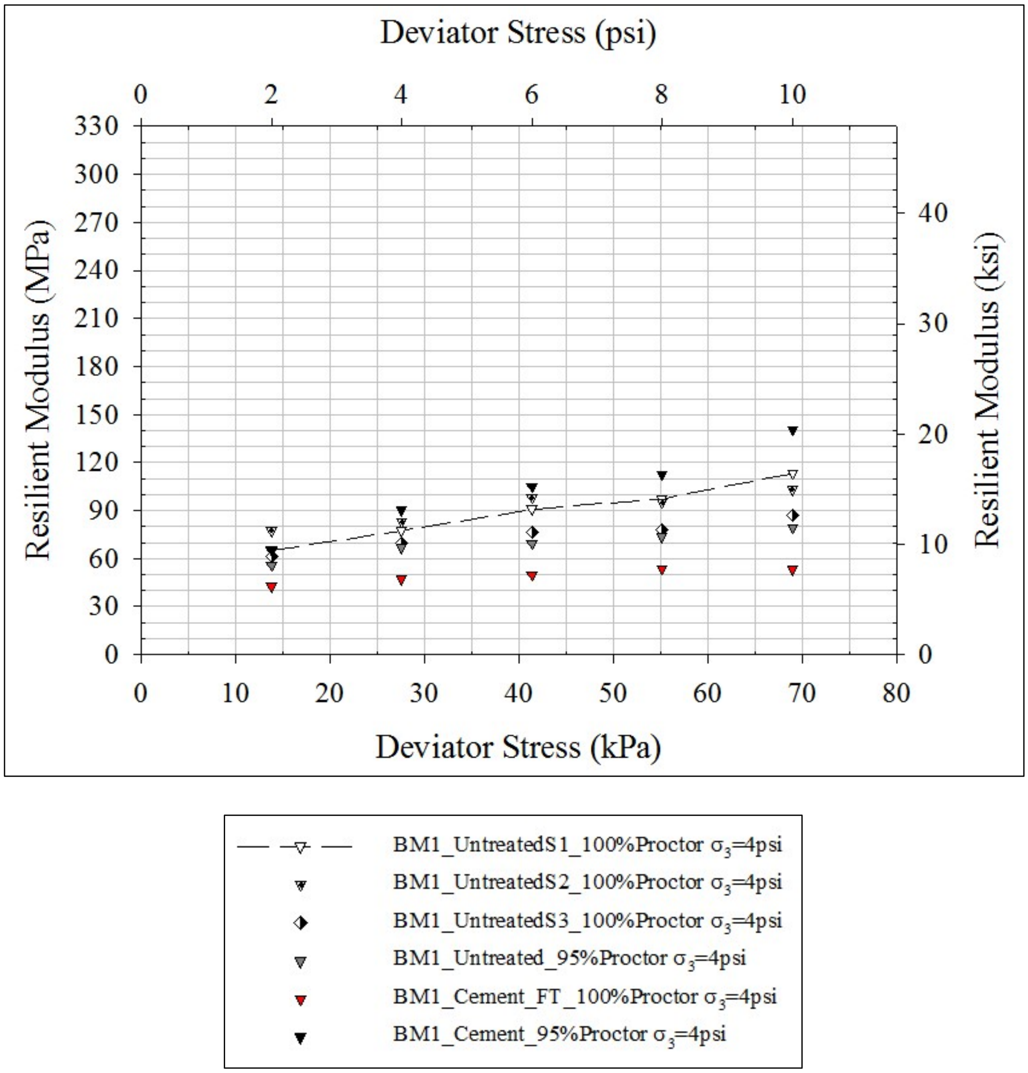


Figure J.12 Resilient modulus for untreated BM1 soil and BM1 soil treated with optimum amount of cement after twelve FT cycles. Confinement stress 4 psi.

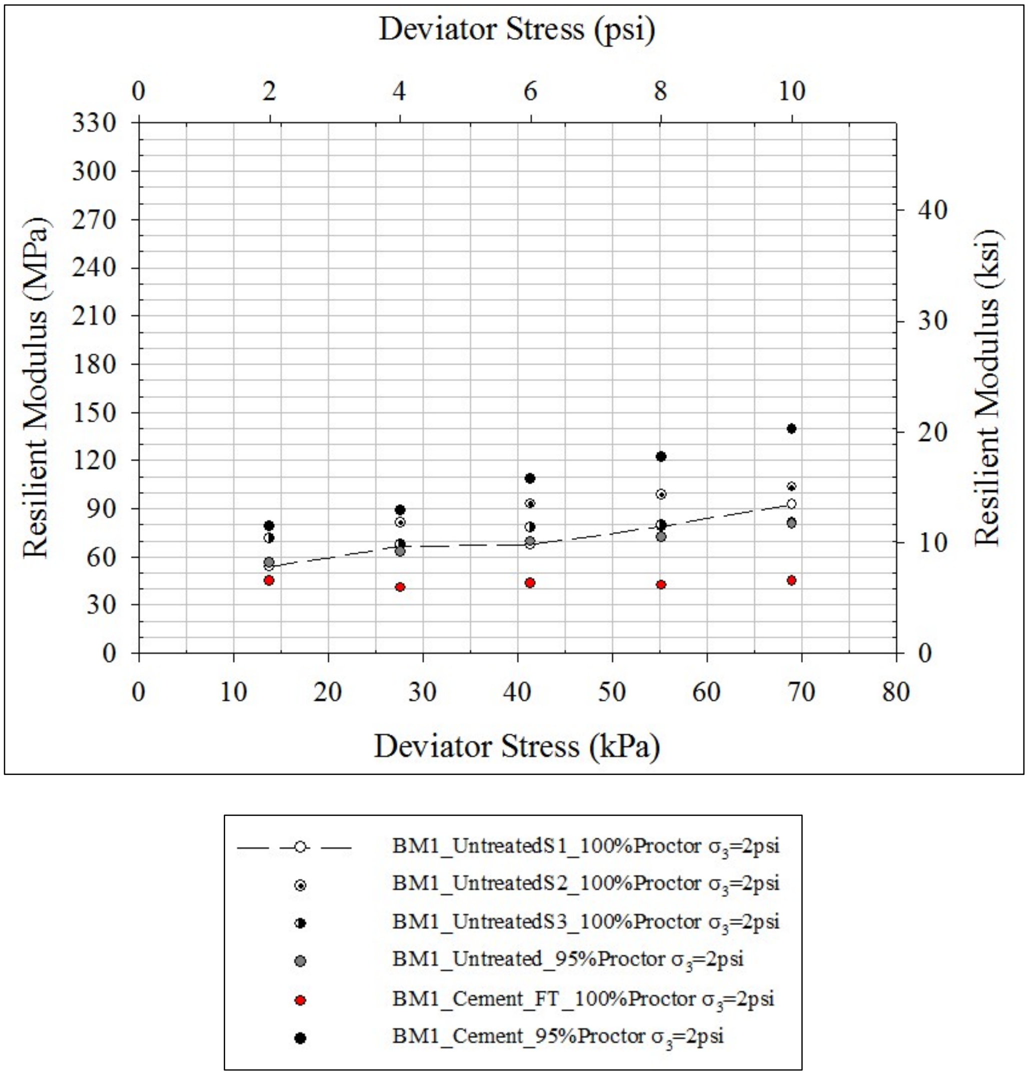


Figure J.13 Resilient modulus for untreated BM1 soil and BM1 soil treated with optimum amount of cement after twelve FT cycles. Confinement stress 2 psi.

Table J.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

Note: 1 psi ≈ 6.89 kPa
1 ksi ≈ 6.89 MPa

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

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