JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
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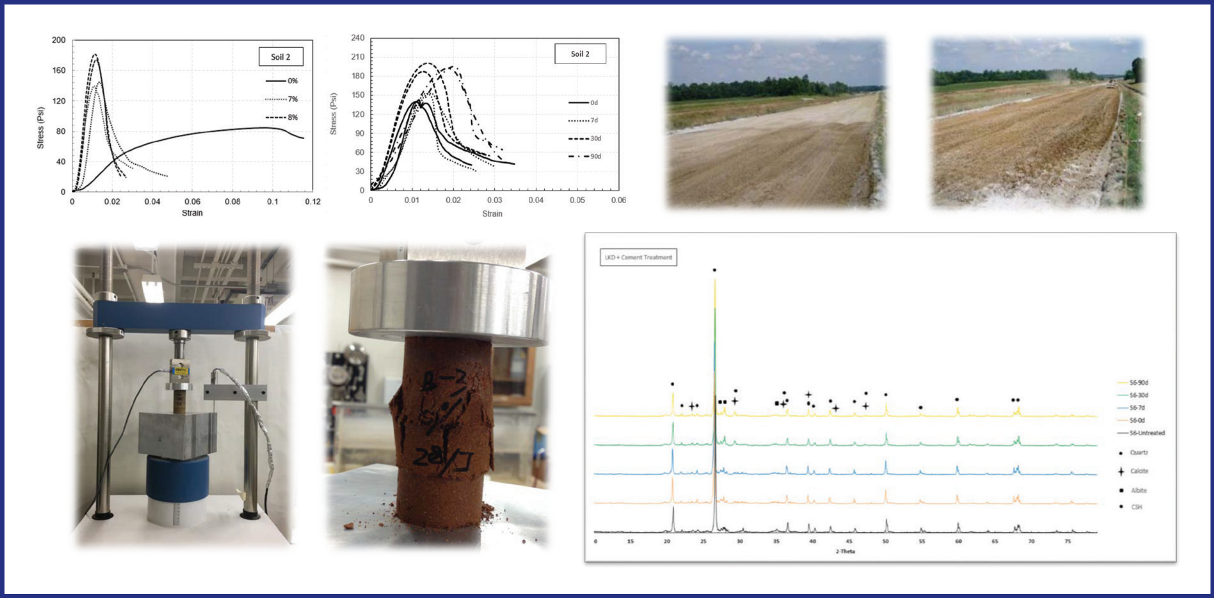
Chemical Modification of Uniform Soils and Soils with High/Low Plasticity Index



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SPR-3940 • Report Number: FHWA/IN/JTRP-2016/32 • DOI: 10.5703/1288284316359

RECOMMENDED CITATION

Tao, F., Li, X., Bobet, A., & Siddiki, N. Z. (2016). *Chemical modification of uniform soils and soils with high/low plasticity index* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2016/32). West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284316359

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Published reports of the Joint Transportation Research Program are available at http://docs.lib.purdue.edu/jtrp/.

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Print ISBN: 978-1-62260-451-7
ePUB ISBN: 978-1-62260-452-4

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JTRP-2016/32		

4. Title and Subtitle	5. Report Date
Chemical Modification of Uniform Soils and Soils with High/Low Plasticity Index	August 2016
	6. Performing Organization Code
7. Author(s)	**8. Performing Organization Report No.**
Fei Tao, Xuanchi Li, Antonio Bobet, Nayyar Zia Siddiki	FHWA/IN/JTRP-2016/32
9. Performing Organization Name and Address	**10. Work Unit No.**
Joint Transportation Research Program Purdue University 550 Stadium Mall Drive West Lafayette, IN 47907-2051	**11. Contract or Grant No.** SPR-3940
12. Sponsoring Agency Name and Address	**13. Type of Report and Period Covered**
Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204	Final Report **14. Sponsoring Agency Code**

15. Supplementary Notes

Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.

16. Abstract

The addition of chemicals into the subgrade has been widely used during construction to improve the soil properties. The chemicals, often Lime Kiln Dust (LKD) and Portland cement, are added to the soil to improve its workability, compactability and engineering properties. Many DOTs have been using chemical modification for more than 20 years. In fact, 90% of the current subgrade is treated. Despite the wide experience-based in treating subgrade soils, several problems still exist. The INDOT (Indiana Department of Transportation) design manual states that subgrade clays with low plasticity (PI< 10) must be treated with cement and that high plasticity clays (Density < 95 pcf, or PI ≥ 25) in the subgrade must be replaced with suitable soils. Uniform granular soils do not stabilize with lime products or with low dosage of cement. Current knowledge does not provide information about stabilization of these soils. This research explores LKD, combinations of LKD and Portland cement to treat high and low plasticity clayey soils (problem soils, e.g. expansive and organic soils are not considered in the research) and treatment with Portland cement of uniform granular soils. A comprehensive laboratory testing program has been undertaken to investigate the potential for the treatment and to report the changes in mineralogy and engineering properties of the treated soils with time. Unconfined compression tests performed over time, as well as XRD tests, show that treatment is possible and that it remains over time since the strength of the treated soil improves with time and its mineralogy does not change.

17. Key Words	18. Distribution Statement
high/low plasticity soil, LKD, cement, modification	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	28	

Form DOT F 1700.7 (8-69)

EXECUTIVE SUMMARY

CHEMICAL MODIFICATION OF UNIFORM SOILS AND SOILS WITH HIGH/LOW PLASTICITY INDEX

Introduction

The addition of chemicals, often lime kiln dust (LKD) and portland cement, into the subgrade during construction to improve soil workability, compactability, and engineering properties is a common practice. Many departments of transportation have been using chemical modification for more than 20 years and, in fact, 90% of current subgrade is treated. Nevertheless, problems persist.

The Indiana Department of Transportation (INDOT) Design Manual states that subgrade clays with low plasticity (PI $<$ 10) must be treated with cement and that high plasticity clays (density $<$ 95 pcf, or PI $\geq$ 25) in the subgrade must be replaced with suitable soils. However, uniform granular soils do not stabilize with lime products or with a low dosage of cement, and current knowledge does not provide information about stabilization of these soils.

This research explores LKD, including combinations of LKD and portland cement to treat high and low plasticity clayey soils, and treatment with portland cement of uniform granular soils. (Problem soils, e.g., expansive and organic soils, are not considered in the research.) A comprehensive laboratory testing program was undertaken to investigate the potential for treatment and to report changes in mineralogy and engineering properties of the treated soils over time.

Findings

The objective of this study was to evaluate the treatment of uniform granular soils, and clay soils that have high or low plasticity, with lime, cement, or a combination of lime and cement. Two uniform granular soils, three fat clays, and three lean clays were selected for the study. For each soil, a comprehensive set of laboratory tests was completed. The results from the tests led to the following conclusions:

- The high plasticity clays required an LKD percentage between 7% and 8%, while for the low plasticity clays the requirement ranged between 6% and 7%.
- With treatment of equal amounts of LKD and cement, the high plasticity clays required 4% to 6% of the combination of LKD and cement, while the low plasticity clays required only 4%.
- Results of the cement treatment of the uniform soils showed that 5% cement with 10% water provided acceptable results.
- Unconfined compressive strength tests revealed that the uniform sand with higher calcium/magnesium content and more angular particles achieved the highest strength with the cement treatment.
- Results from unconfined compression tests and x-ray diffraction (XRD) tests conducted at different times after treatment of the soil showed that the strength of the soil increased with time and that the improvement obtained did not degrade with time.

Implementation

- Granular uniform soils and clayey soils with low and high plasticity index can be successfully treated with adequate amounts of LKD, cement, or LKD and cement.
- The actual percentages and type(s) of chemical(s) (or their combination) needed, strength improvement achieved, and construction procedures to reach the target performance in the field are site specific and will depend on the actual soil conditions and properties.
- It is recommended that proper laboratory testing be performed in each case on representative soil samples to evaluate potential soil treatment, improved properties of the treated soil, and the most cost-effective treatment for the site.

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1. INTRODUCTION

1.1 Background

The subgrade, the foundation of the pavement, plays an important role in the long-term performance of the pavement. In some instances, it may pose challenging design, construction and performance problems, depending on the type of soil. For example, the subgrade may consist of soft soil that does not have enough capacity to support the traffic loads (Abu-Farsakh & Hoyos, 2014) or that shrinks and swells due to moisture content changes. The end result is that the subgrade may not be able to satisfy the long-term performance requirements for the pavement (Gallage, Cochrane, & Ramanujam, 2012). There are two methods currently accepted to enhance the performance of the subgrade. The first method consists of the replacement of the undesirable soil, which may be expensive. The second method involves improving the engineering properties of the soil (Jung, 2011) through compaction or chemical treatment (Makusa, 2013). Chemical treatment consists of the addition of chemicals into the soil to modify the structure and/or properties of the soil. The most widely used chemicals for treatment are lime and cement.

Lime has been used as a chemical additive for soil stabilization ever since its appearance in ancient history. The most important reason for its wide use is that it is less expensive than other methods or treatments, e.g. with cement. During the past years, geotechnical engineers have been using lime to stabilize successfully various types of problem soils to yield better engineering properties (INDOT, 2015), as the treatment reduces the plasticity of the original soil, increases its strength, and lowers its shrink and swell potential (Gallage et al., 2012). The reaction between soil and lime can be categorized into short-term and long-term. The short-term reaction happens within several hours after mixing the soil with the lime and involves cations exchange, flocculation and agglomeration. This results in an improvement of the workability of the soil and a decrease in the swelling potential (Khattab, Al-Mukhtar, & Fleureau, 2007). It also increases, at least temporarily, the pH of the mixture, which needs to be higher than 12.4 for the long-term reactions to occur (Little, 1995), which consist of pozzolanic reactions between soil and lime. Those produce compounds that bind the soil particles together thus improving the strength of the treated soil (Jung, Jung, Siddiki, & Bobet, 2013). Typical percentages of lime used range from 2 to 6 percent by dry weight of soil (Halsted, Adaska, & McConnell, 2008).

Cement has been used as a stabilizer for over 70 years. The reaction of cement with soil is similar to that of the lime-soil mixture. It consists of cation exchange, flocculation, agglomeration, cementitious hydration and pozzolanic reaction (Abu-Farsakh & Hoyos, 2014). Cement hydration is relatively fast and occurs in about one day after mixing. It is the most important reaction that contributes to the improvement of the engineering properties of the soil (Pendola, Kennedy, & Hudson, 1969). The percentage of cement needed to improve the properties of the soil is typically smaller than lime, but on the other hand, cement is much more expensive.

1.2 Problem Statement

Many DOTs have been using chemical modification for the last 20 years. Despite using it for such a long period, several problems still exist.

1. The INDOT (Indiana Department of Transportation) Design Manual states that clay with low plasticity (PI $<$ 10) must be treated with cement, which has resulted in numerous change orders in recent years because small variations in the field of the threshold PI require changes in treatment.
2. High plasticity clays (density $<$ 95 pcf or PI $\geq$ 25) may not break down (mellow) with lime in the short term.
3. Dune sand, sugar sand and other uniform soils are found in southwestern and northwestern Indiana. These soils do not stabilize with lime products or with low dosage of cement.

1.3 Objectives

The objectives of this study are:

1. Explore the possibility of treating clay soils that have high or low plasticity with lime or with a combination of cement and lime.
2. Investigate the possibility of stabilization of uniform soils such as dune sand and sugar sand.
3. Evaluate the long-term performance of the lime, cement, and lime and cement treatment on clays with high/low plasticity and uniform soils.

Problem soils that exhibit large swell/shrink potential or have organic content have not been considered in the investigation.

2. LABORATORY TESTS

2.1 Tests on Low and High Plasticity Clays

Three fat and three lean clays were selected for the investigation. Soil classification tests, Atterberg limits, granulometry and proctor tests were performed to characterize the soils. Eads–Grim Tests were then done to determine the starting percentage of Lime Kiln Dust (LKD) that would produce a 12.4 pH of the lime-soil mixture. Unconfined compression (UC) tests were conducted to determine the strength of the treated soils and x-ray diffraction (XRD) tests to determine the mineralogy of the soil before and after treatment.

Atterberg limits were done following ASTM D4318-10 (2014). Wet sieve analysis and hydrometer tests were performed to obtain the particle size distribution in accordance with ASTM D422-63 (2007) and ASTM D4221-99 (2005), respectively. The particle size distribution curves are included in Appendix A, Figure A.1. Standard proctor tests were carried out to obtain the maximum dry density (MDD) and optimum moisture content (OMC) of the soils. They were done in accordance with ASTM D698-12 (2007). The results of the Proctor tests can be found in Appendix A, Figure A.2. A summary of the results of the tests is presented in Table 2.1.

According to the Unified Soil Classification System (ASTM D2487-11, 2010), soils 1 to 3 can be classified as fat clays (CH), and soils 4 to 6 can be categorized as lean clays (CL). According to AASHTO, soils 1 and 2 are classified as A-7-5, while soil 3 is classified as A-7-6. Soils 4 to 6 are classified as A-4. With INDOT classification, soil 1 is silty clay, soils 2 and 3 are clays. Soil 4 is loam and soils 5 and 6 are categorized as silty loam. Table 2.1 also shows that the fat clays have PI>25, while the lean clays have PI<10. All soils have a fines content larger than 55%, with the fat clays having fines percentages greater than 86%. The optimum moisture content for the lean clays ranges from 7.4% to 9.6% but varies between 13.9% and 26.9% for the fat clays.

Two sets of tests were performed on these clays to investigate the increase of strength with treatment. The first set was geared towards determining the strength gain with LKD, while the second set was done to investigate the strength increase with equal proportions of lime and cement.

The Eads–Grim Test (ASTM D6276-99, 2006) was done to determine the minimum amount of lime or lime and cement to be added to the soil such that a minimum pH of 12.4 was reached. The Eads–Grim Test results are listed in Appendix A, Figure A.3. The minimum percentage of LKD or LKD and cement required is listed in Table 3.1.

Unconfined compression tests were done on specimens of treated soil at different times after preparation, to investigate the strength gain with the percentage of the chemical and with time. All specimens were prepared in a similar manner. The soil was first mixed with the target dosage of the chemical(s) using a spatula. Then, water was added using a spray to obtain 95% of the optimum moisture content of the soil-chemical mixture. After that, the specimen was placed in a mold 71.12 mm (2.8 inches) tall and 33.03 mm (1.3 inches) in diameter. To achieve the target density, all the specimens were compacted in five layers with 10 blows per layer. The specimens were cured in a humid room with a constant temperature of 21°C (70°F) and 100% humidity. Two specimens prepared, one of soil with high plasticity and the other with low plasticity, are shown in Figure 2.1 after curing. The unconfined compression tests followed AASHTO T-208.

2.2 Tests of Uniform Granular Soils

This project also explored the treatment of uniform granular soils. Two sands were selected for the study. Figure B.1 plots the particle size distribution of the two sands and indicates that the two soils are poorly graded. Indeed, the Coefficient of Curvature, C_c of the two sands ranged between 1 to 2, and the Coefficient of Uniformity, C_u, was 1.1 for the two sands. The fines percentage of the two sands were smaller than 3% and non-plastic. The organic and calcium/magnesium tests were done for these two sands. The organic matter determination tests followed AASHTO T267, while the calcium/magnesium tests were in accordance with INDOT Loss on Ignition method. Table 2.2 lists the organic and calcium/magnesium content of the uniform soils. The result shows that the organic content of the sands was small, less than 0.5%, but a significant difference between the two sands was found in their calcium/magnesium carbonate content, where for sand 1 it was 17.6%, and for sand 2, 0.3%. The Proctor tests were done in accordance with ASTM D698-12 for both of the sands. The results can be found in Figure B.2. As expected, given the uniformity of the soils, the proctor results were insensitive to water content.Figure B.3 includes photographs of the grains of the two sands using an optical microscope. From visual observations, the sands are described as sub-angular; however, the particles of sand 2 are more rounded than of sand 1.

TABLE 2.1
Summary of Soil Indices

Soil No.	LL (%)	PL (%)	PI (%)	OMC (%)	MDD (pcf)	Fines (%)	AASHTO Classification	USCS Classification	INDOT Classification
1	80.5	48	32.5	26.9	87.6	91.39	A-7-5	CH	Silty clay
2	61.0	30	31.0	19.4	102.3	86.09	A-7-5	CH	Clay
3	59.0	29	30.0	20.0	96.1	89.27	A-7-6	CH	Clay
4	23.4	15	8.4	12.0	118.7	56.87	A-4	CL	Loam
5	26.6	17	9.6	13.0	114.0	69.17	A-4	CL	Silty loam
6	23.4	16	7.4	12.2	119.6	55.31	A-4	CL	Silty loam

LL: liquid limit; PL: plastic limit, PI: plastic index; OMC: optimum moisture content; MDD: maximum dry density.

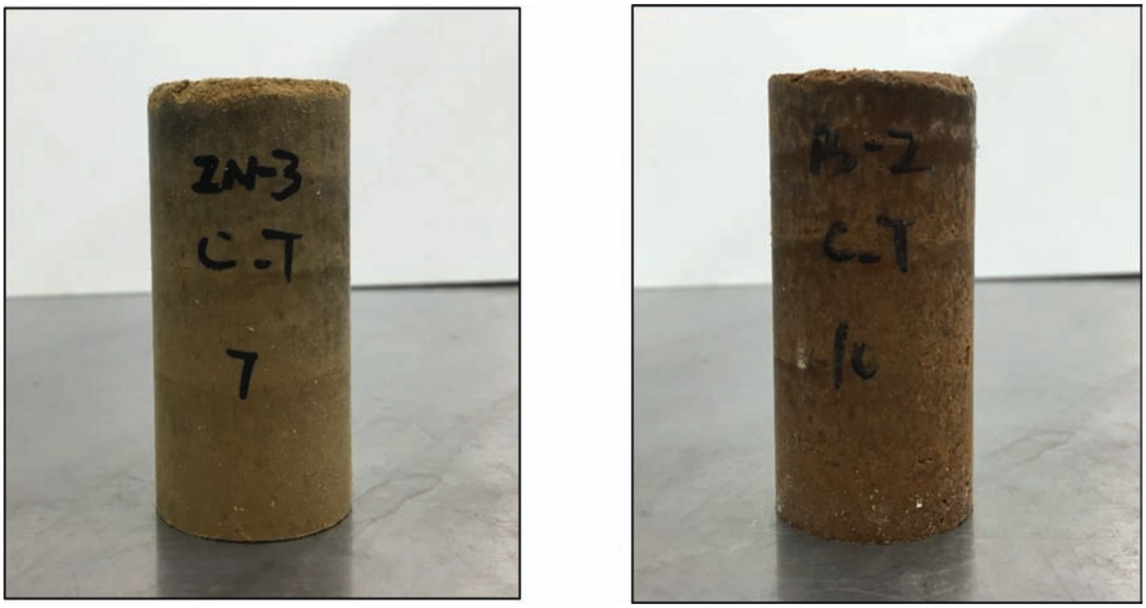

Figure 2.1 Cylindrical soil specimens (left: low plasticity; right: high plasticity).

TABLE 2.2
Organic and Calcium/Magnesium Content of Sands 1 and 2

Sand No.	Organic Content (%)	Calcium/Magnesium Carbonate (%)
1	0.3	17.6
2	0.4	0.3

3. RESULTS AND DISCUSSION

3.1 Clay Treatment Results and Discussion

Figure 3.1 (a) shows the stress-strain response of soil 2 (fat clay) when subjected to unconfined compression. It includes results of the untreated soil and the soil treated with LKD. As one can see, the treatment increases the unconfined compressive strength of the soil and, the larger the amount of LKD used, the larger the strength. The figure also shows that the addition of the chemical increases the stiffness of the soil and decreases the strain at which peak strength is reached. In other words, the soil changes response from ductile to brittle. The reduction of strain corresponding to peak strength could be the result of the break of the bonds between the soil particles and the stabilizing agent. A similar result has been reported by Alshawabkeh, Reddy, and Khire (2008) and Han and Alzamora (2011). The results from the tests indicate that the addition of 7% LKD satisfies the requirement of minimum strength improvement of 50 psi. Figure 3.1 (b) is a similar plot, but for soil 6 (lean clay). Similar to what has been shown for the fat clay, the LKD treatment increases the unconfined compressive strength, the stiffness, and all this at the expense of a brittle behavior with a reduction of strain at failure. The LKD percentage required for this soil to fulfill the strength requirement is 6%. The stress-strain

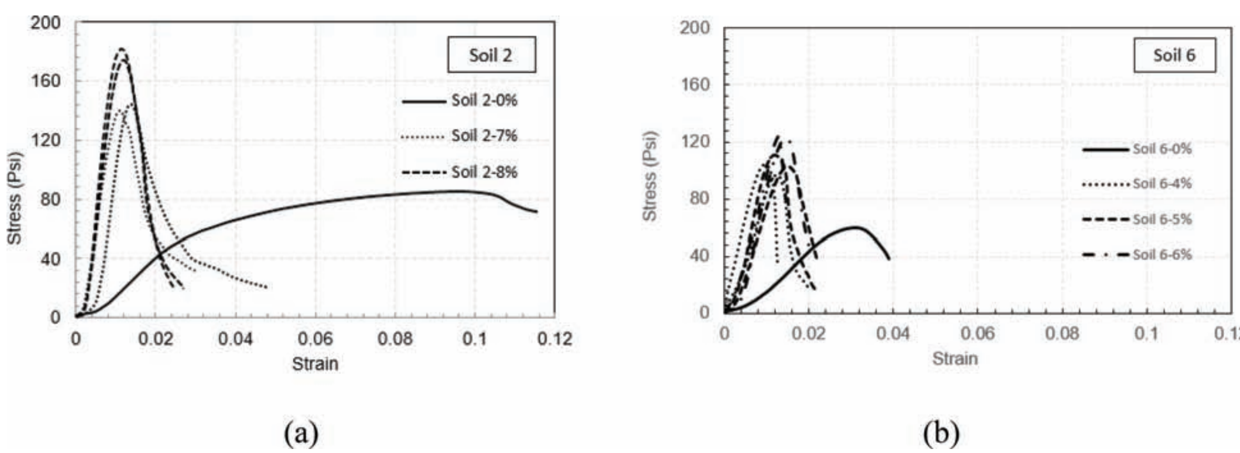

Figure 3.1 Unconfined compressive strength for (a) soil 2 (CH); and (b) soil 6 (CL) treated with LKD (percentages shown in legend).

plots of all the other soils show similar results and can be found in Appendix A, Figure A.4.

Table 3.1 summarizes the results of LKD treatment. It shows that fat clays need a higher percentage of LKD than low plasticity soils to reach the minimum pH, and also a higher percentage of the chemical to reach the desired improvement of strength. The laboratory results indicate that fat clays needed LKD in the range of 7% to 8% and 6% to 7% for lean clays. What is interesting is that, with treatment, the fat clay experiences a larger increase of strength from its original, untreated state, than the lean clay.

Additional tests were done to observe the effects of curing temperature and moisture content on the strength of the treated soil (Figure 3.2). A specimen of soil 3 (high plasticity soil) treated with 8% LKD cured at 120° F was tested in unconfined compression. The results indicated that higher curing temperature increased the soil strength. When a specimen of soil 3, also treated with LKD, was prepared at moisture content 2% above optimum, a substantial decrease of unconfined strength, compared to that of a specimen treated at optimum water content, was observed.

Similar to what was done to investigate the results of the LKD treatment, a series of pH and UC tests was conducted to determine the optimum dosage of the chemical consisting of equal parts of LKD and portland cement. The starting percentage was 4% (2% LKD and 2% cement), which was the minimum content required by the INDOT design manual.

Figure 3.3 (a) plots the UC test response of soil 2 (fat clay) before and after treatment with 4% LKD and cement. It shows that the treatment increases the unconfined compressive strength of the soil. As one can see, 4% of the chemical is sufficient to attain an increase of UCS of 75 psi with respect to the UCS of the untreated soil. The treated soil, however, displays a brittle behavior, with larger stiffness than the untreated soil and smaller strain at failure. These results are analogous to those observed with the treatment with LKD (see Figure 3.1). Similar results were obtained for soil 6 (lean soil), as one can see in Figure 3.3 (b). However, when comparing different treatment methods, the fat clays attain lower stiffness, lower strength, but higher strain at failure when treated with equal parts of cement and LKD, than with LKD only. This can be observed by comparing Figure 3.1 (a) and Figure 3.3 (a). For lean clays, a comparison between Figure 3.1 (b) and Figure 3.3 (b) shows that equal parts of cement and LKD produce higher stiffness and strength, and a lower strain at failure than with LKD alone. The results of UC test for all soils are included in Appendix A, Figure A.5, which shows similar results. Overall, the tests point to better performance when adding cement.

TABLE 3.1
Results of Treatment with Equal Parts of LKD and Cement

Soil No.	pH Required LKD (%)	pH Required LKD + cement (%)	LKD required for strength (%)	LKD+Cement required for strength (%)	Untreated Soil UCS (psi)	LKD Treated Soil UCS (psi)	LKD+Cement Treated Soil UCS (psi)
1	8	4	8	4	52	223	155
2	7	4	7	4	84	148	165
3	8	6	8	6	72	187	200
4	4	4	7	4	51	118	174
5	4	4	6	4	51	105	139
6	4	4	6	4	59	111	174

LKD: Lime kiln dust.
UCS: Unconfined compressive strength.

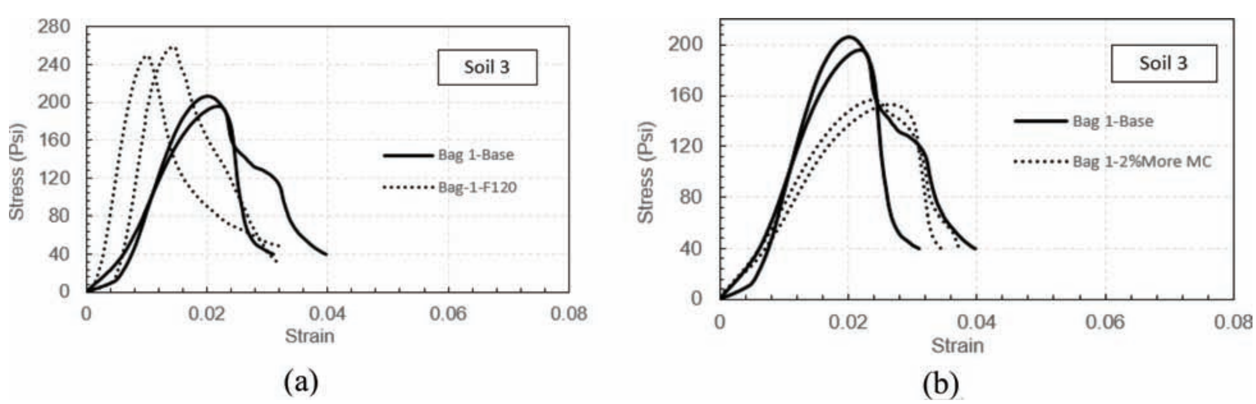

Figure 3.2 Unconfined compressive strength for (a) LKD treatment with higher curing temperature; and (b) higher moisture content.

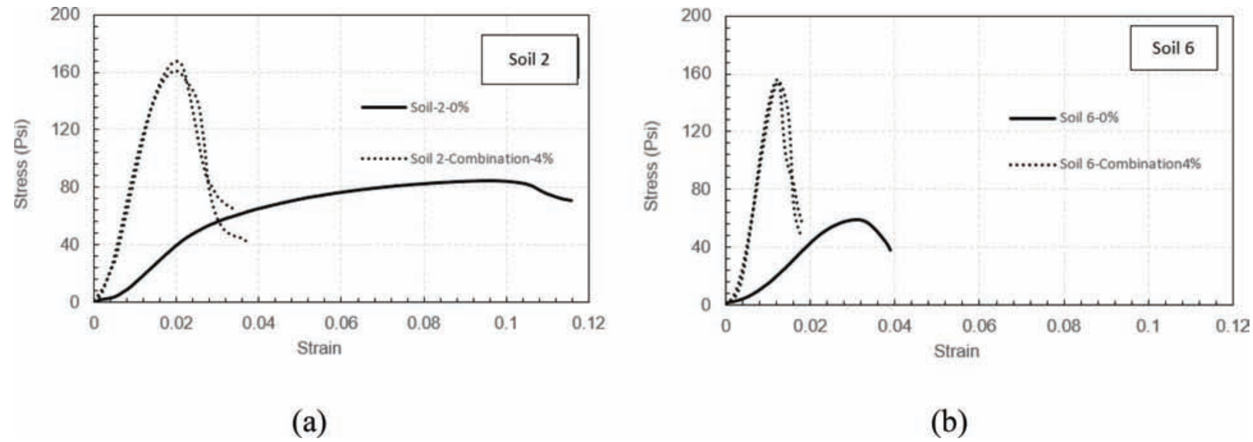

Figure 3.3 Soil 2 (CH) and soil 6 (CL) treated with equal amounts of cement and LKD treatment.

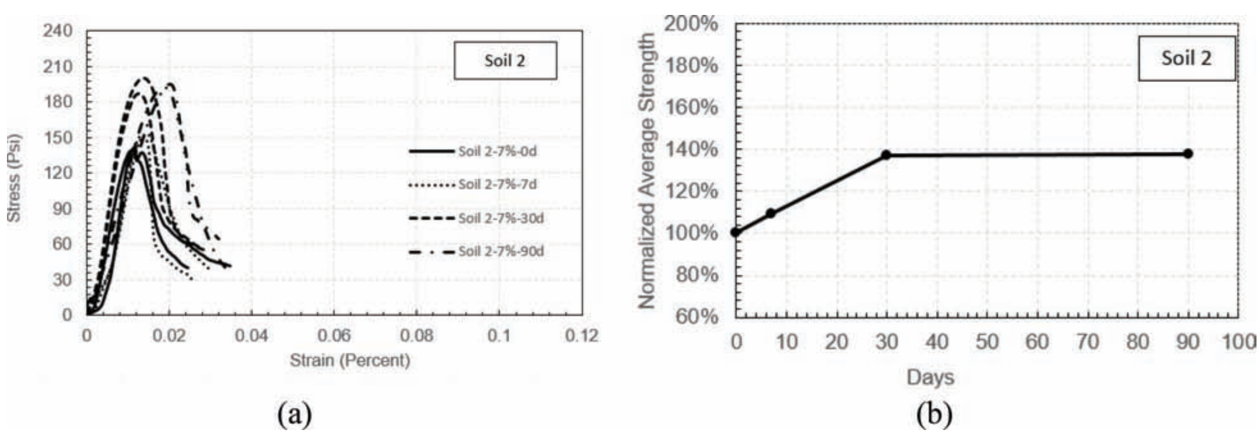

Figure 3.4 Soil 2 (CH) strength with time with LKD treatment.

A summary of the results observed in all the soils is presented in Table 3.1. It can be seen that the amounts of portland cement and LKD required to reach the minimum pH and the minimum strength are the same. The optimum content of the chemicals needed for all soils is 4%, except for soil 3 that requires 6%. The result is a smaller amount of treatment, compared to what is required when using LKD alone, which ranged from 6% to 8%. Comparatively, a higher increase of strength was attained with the treatment of lean clays than fat clays. Also, the addition of LKD and cement yielded higher strength to the treated soil than LKD alone, even when using percentages smaller than those with LKD.

As mentioned, it is expected that, with time, the treated soil will experience an increase of unconfined compressive strength. Figure 3.4 and Figure 3.5 depict the effects of time on the strength of the treated soils with LKD. Soils 2 and 6 are tested as representative of the two types of soil investigated: fat clays, CH, and lean clays, CL. Soil 2 was mixed with 7% LKD, while soil 6 was mixed with 6% LKD. These percentages of LKD are the minimum percentages to satisfy the INDOT requirements. Specimens were prepared and tested at time 0, i.e. immediately after curing, at 7 days, 30 days, and 90 days after curing. The results indicate an increase of strength, as expected. It is interesting to point that, with time, the strain at failure increases, while the stiffness of the treated soil does not change substantially. The figures show that there was a significant strength increase during the first 30 days, with a much smaller improvement with time afterwards. The strength gain is more important for the fat clay (soil 2) than for the lean clay (soil 6), which seems to be associated with also an increase of the strain at peak strength.

Figure 3.6 and Figure 3.7 are plots analogous to those of Figure 3.4 and Figure 3.5, but for treatment with equal amounts of portland cement and LKD. The same soils chosen for the time effects of LKD are used, to provide comparisons between the two treatments. Both soils 2 and 6 were treated with 4% chemical, i.e. 2% portland cement, and 2% LKD. The results show that the unconfined compressive strength and the strain at failure increase with time. The stiffness slightly changes over time. Again, this is an expected result. The addition of cement shows a significant strength increase over time, which does not seem to stop at the end of the time period investigated. This could be the result of the pozzolanic reaction since cement provides more calcium oxide (CaO) than LKD. Soil 2 (CH) shows an initial larger strength and strain at failure than soil 6 (CL), as

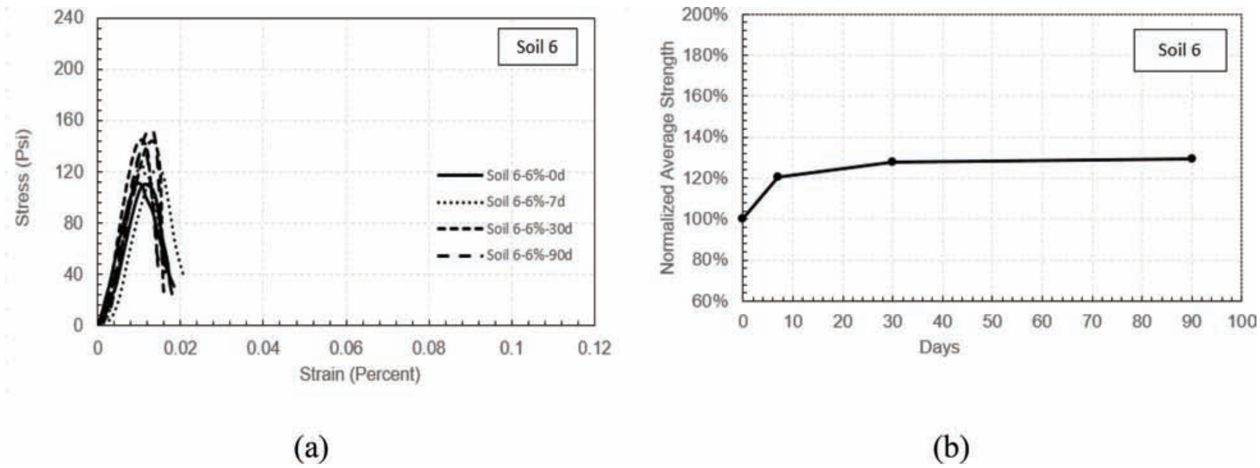

Figure 3.5 Soil 6 (CL) strength with time with LKD treatment.

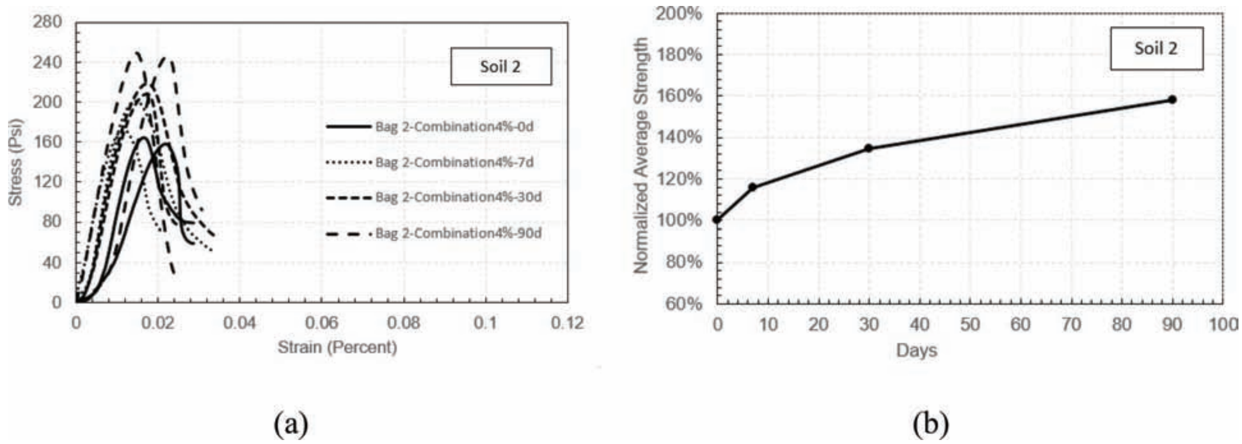

Figure 3.6 Soil 2 (CH) strength with time with treatment of equal amounts of portland cement and LKD.

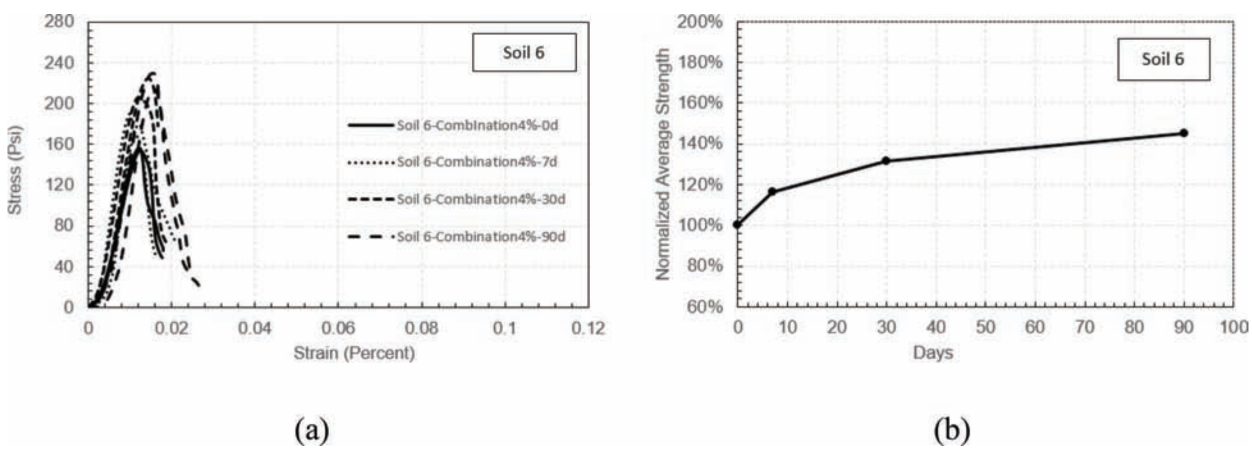

Figure 3.7 Soil 6 (CL) strength with time with treatment of equal amounts of portland cement and LKD.

well as a more rapid increase of strength with time. The addition of cement, in terms of increased strength, can be assessed by comparing the results in Figure 3.5, obtained using only LKD, and Figure 3.7, using equal parts of LKD and cement. As one can see, cement results in a noticeable strength gain.

The time-evolution of the microstructure of the treated soil was evaluated through XRD tests. The objective was to determine whether the products of the reaction between the chemical additions and the soil remained after the treatment. XRD tests were done first on the original, untreated soil, and then at periods of time after the treatment was completed; more specifically at times 0 days, i.e. immediately after treatment, 7 days, 30 days and 90 days. A Siemens D500 XRD was used for the tests. All the samples for the XRD tests were prepared following the procedures described by Schulze (1984). The following discussion focuses on the results of soil 2, since the major observations are also applicable to other soils (XRD results for soil 6 are plotted in Figures A.6 and A.7 in Appendix A).

Figure 3.8 includes the XRD results of LKD treated soil 2, as well as the untreated soil. The plots are staggered to show results better. Each peak in the figures is labeled. Dots represent Quartz, crosses stand for Calcite, and squares represent Albite. All soil samples yielded similar results. It shows that the original soil was mainly composed of Quartz and Albite. The original soil also had Calcite. The peaks of the calcite in the original soil are at 35.98°, 39.48°, while the new peaks of the Calcite in the treated soil are at 29.50°, 43.41°, 47.54°, and 48.68°. Additionally, the XRD tests at 7 to 90 days show that these peaks remain with time, which indicates that Calcite does not disappear with time. By combining this observation with the results over time of the unconfined compression tests, we conclude that the LKD treatment does not degrade with time.

The XRD results of equal parts of cement and LKD treated soil 2 are summarized in Figure 3.9. In this figure, the plots are also staggered to better present the results. The markers in the figure are similar to those in Figure 3.8, except the six-point star that represents calcium-silicate-hydrate (CSH). In Figure 3.9, similar to Figure 3.8, there are new peaks of calcite after treatment. These new peaks do not disappear with time.

One of the differences between Figure 3.9 and Figure 3.8 is that Figure 3.9 shows the existence of pozzolanic compounds (CSH) in the treated soils. The peaks are at 29.20°, 32.00°, 49.80° and do not disappear over time. This explains the continued increased strength of the cement and LKD treatment after 30 days. Again, the results show that the treatment with equal parts of cement and LKD will not degrade with time.

As already mentioned, Figures A.6 and A.7 are plots of the XRD results for soil 6 (CL). Similar to soil 2, new peaks of Calcite appear after treatment and do not disappear with time.

3.2 Uniform Soils Treatment Results and Discussion

The treatment of the uniform soils with LKD was not successful, even for very large percentages of lime, in excess of 10%. However, as discussed below, the treatment was effective with cement.

Unconfined compression (UC) tests were performed on both sands after cement treatment. The results are shown in Figure 3.10.

Figure 3.10 (a) and (b) display the effect of moisture content under constant cement of 5%. The results indicate that, for the same cement content, the unconfined compressive strength of the treated sand decreases with water content. Figure 3.10 (c) and (d) plot the influence of cement under the same water/cement ratio (2.0 w/c ratio). The plots show that the unconfined compressive strength decreases with the decrease of cement under the same water/cement ratio. All these are expected outcomes that confirm that treatment improves with the increase of cement and with the reduction of the water/cement ratio. The results also show that the UCS (unconfined compressive strength) of sand 1 is significantly higher than of sand 2. This may be caused by the higher calcium/magnesium carbonate content of the sand, together with the presence of more angular particles (discussed later). We chose, as a reference, a target UC of 75 psi with the treatment, which aligns with INDOT's requirements for clay soils. The requirement is satisfied with 5% cement and 10% water for the sands treatment.

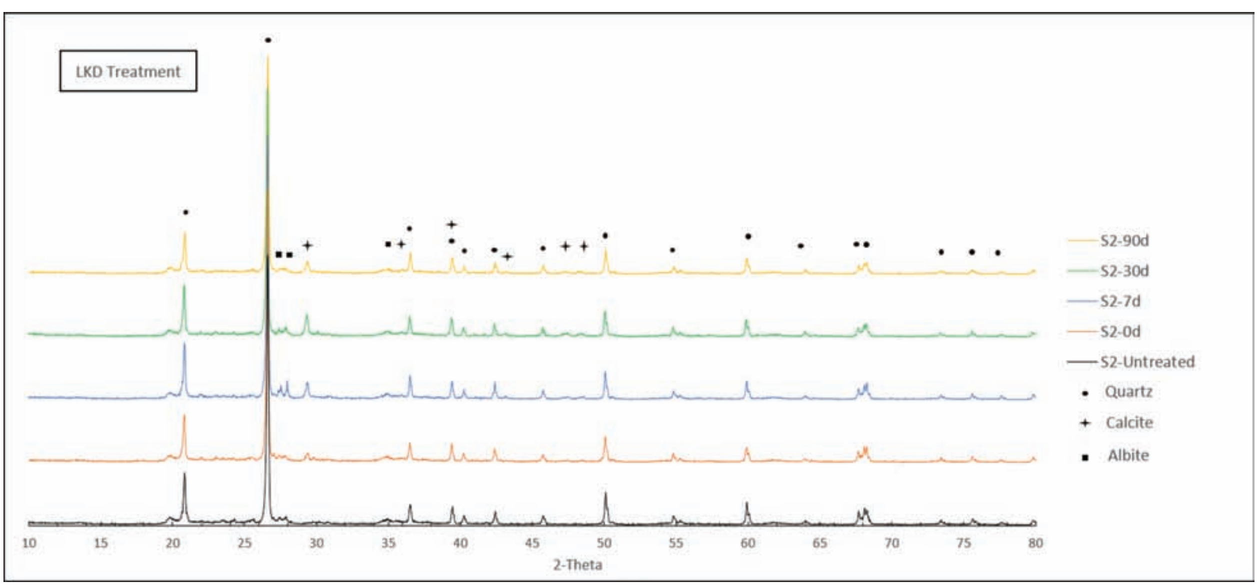

Figure 3.8 LKD treated soil. XRD tests for soil 2.

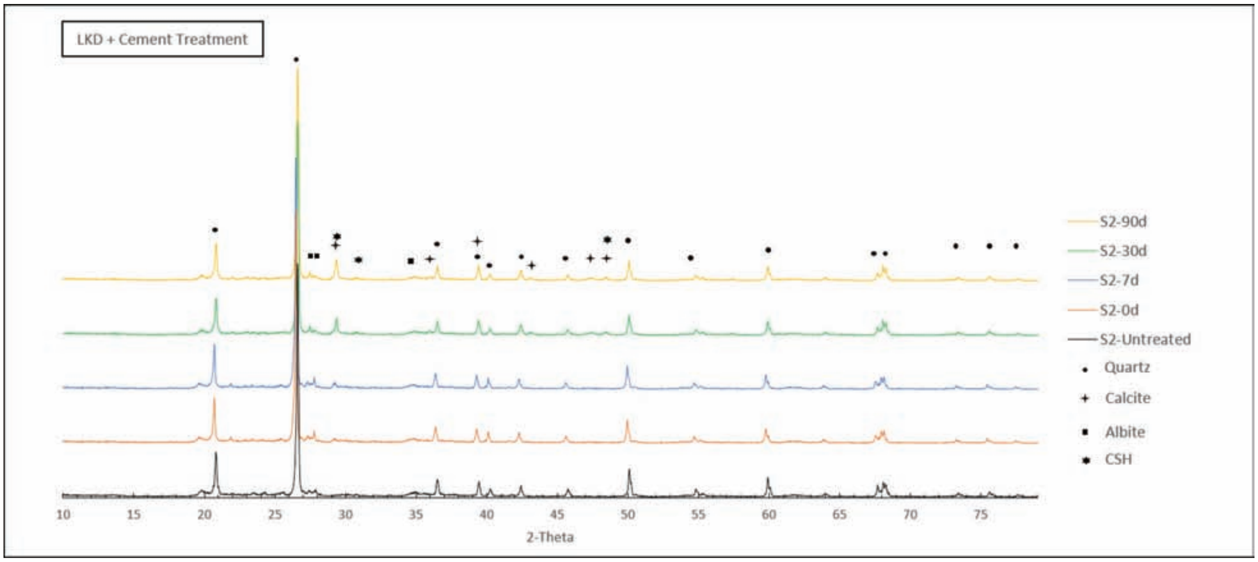

Figure 3.9 Cement and LKD treated soil. XRD tests for soil 2.

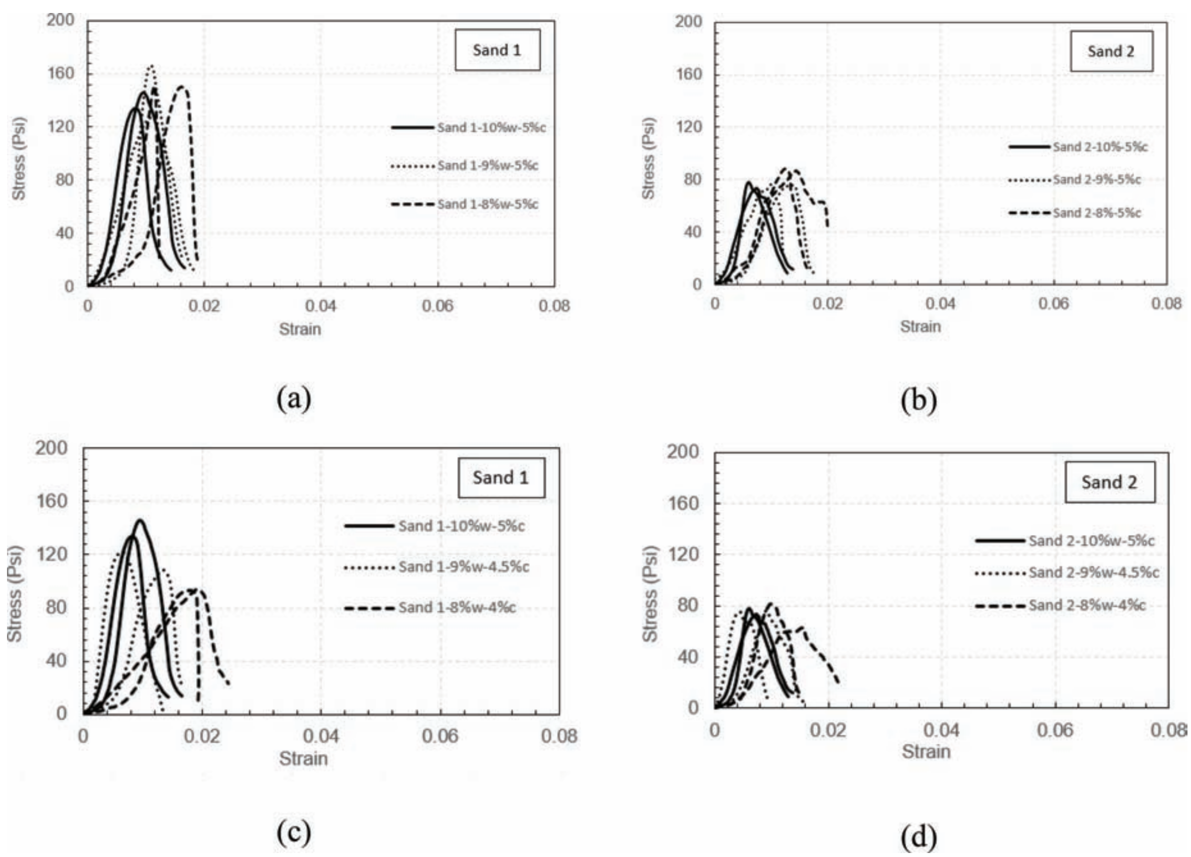

Figure 3.10 UCS results with cement treatment (UCS: unconfined compressive strength).

Time effects were investigated by testing specimens of sand 1 and 2 treated with 5% cement and 10% water content (the target values that satisfy a 75 psi UC strength) at 0, 7, 30, and 90 days after treatment. Note that the times are the same times used for the tests in the clays. Figure 3.11 and Figure 3.12 plot the effects of time on the strength of the treated sands with cement. The results indicate that the strength of the treated sands increased with time, and the increase did not seem to stop at the end of the time period investigated. This is thought to be the result of pozzolanic reaction.

Figure 3.13 includes the XRD results of cement treated sand 1 as well as the untreated sand. Similar to previous XRD plots, the graphs are staggered to show results better. In the figure, the markers are similar to those in Figure 3.8, except the triangle and diamond that represents portlandite ($Ca(OH)_2$) and Dolomite ($CaMg(CO_3)_2$), respectively. The plots show that there is calcite in the original sand, which supports the results listed in Table 2.2 Additionally, the XRD tests at 0 to 90 days show new peaks of portlandite that do not disappear with time, which are indicators of pozzolanic reactions over time. This is consistent with the finding that the strength of the treated soil did not stop increasing after 90 days. The XRD results for sand 2 are analogous and are included in Appendix B, Figure B.4. Similar to Figure 3.13, it also shows that the new peaks of portlandite do not disappear over time.

Additional tests were done to compare the effects of the normal type I cement (10% water content and 5% type I cement) with the ESSROC type I cement (water/cement ratio of 2), which is about half the price of the normal cement, at the time of this report. The results indicate that sand 1 needs 9% ESSROC cement to reach the same strength as with the normal cement, while for sand 2, the requirement is 7% (all the results can be found in Appendix B, Figure B.5). Given the current price difference between the two cements, it does not seem that the use of ESSROC is advantageous over normal type I cement.

A study was also done to explore the influence of particle shape on the unconfined compressive strength of the treated sands, and in particular further investigate the difference in UC between sand 1 and 2, with sand 1 having larger UC and more angular particles than sand 2. The task involved first sieving Ottawa sand, a silica sand with round particles, to have the same particle size distribution as sands 1 and 2, and then comparing the unconfined compressive strength between the treated sieved Ottawa sand and the treated uniform granular soils. For the treatment, a 7% cement with w/c=2 was used for all the sands, which is the minimum content needed for Ottawa sand stabilization (note that the cement content was larger than what was needed for the original sands 1 and 2). Table 3.2 summarized the unconfined compressive strength of the different sands (all the results are given in Appendix B, Figure B.6). As one can see, the treated Ottawa sand and the sieved Ottawa sands have a smaller unconfined compressive strength than sands 1 and 2. The first observation is that, for the same gradation, the increase of roundness of the shape of the particles decreases strength with cement treatment, and that the particle size distribution of sand 1 provides better results, with cement treatment, than sand 2. The effects of gradation, however, are small compared to the effects of grain shape and chemical

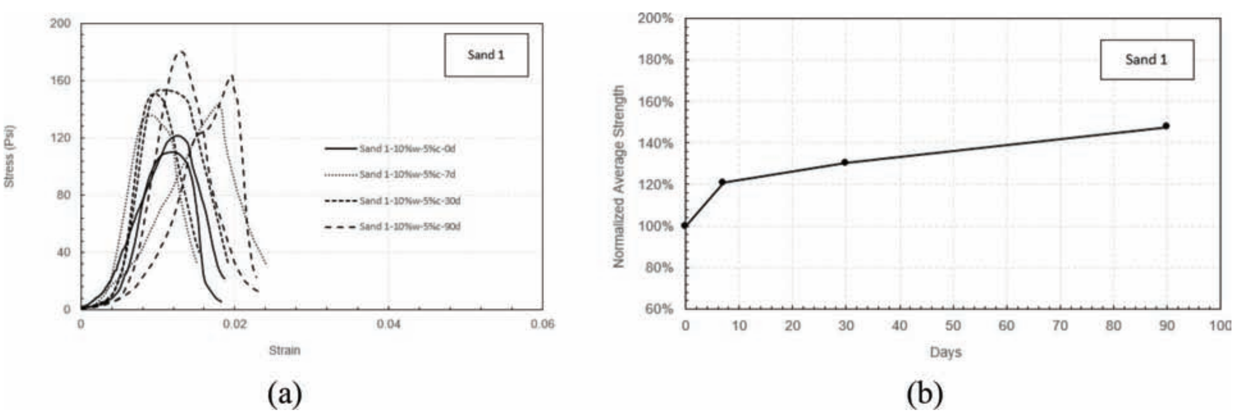

Figure 3.11 Sand 1 strength with time, with treatment of cement.

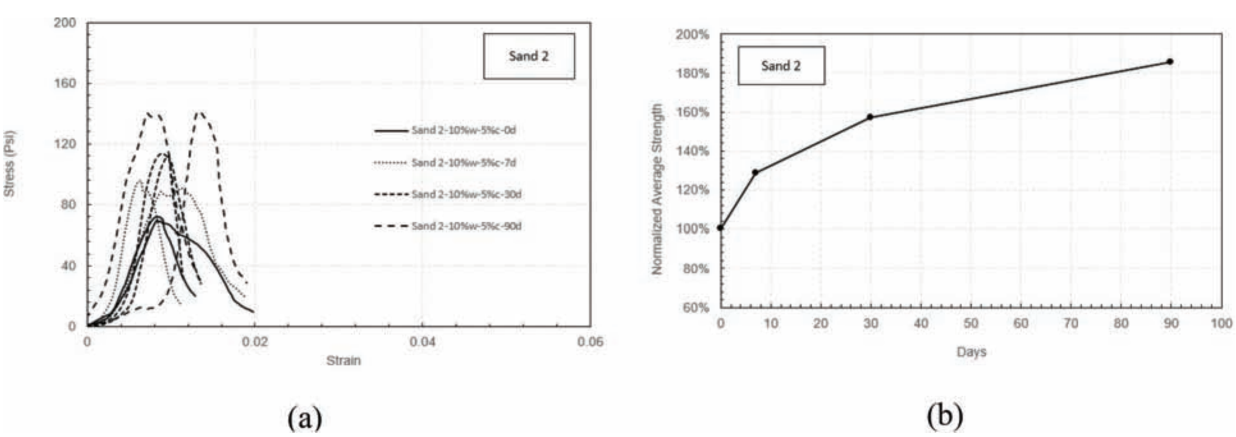

Figure 3.12 Sand 2 strength with time, with treatment of cement.

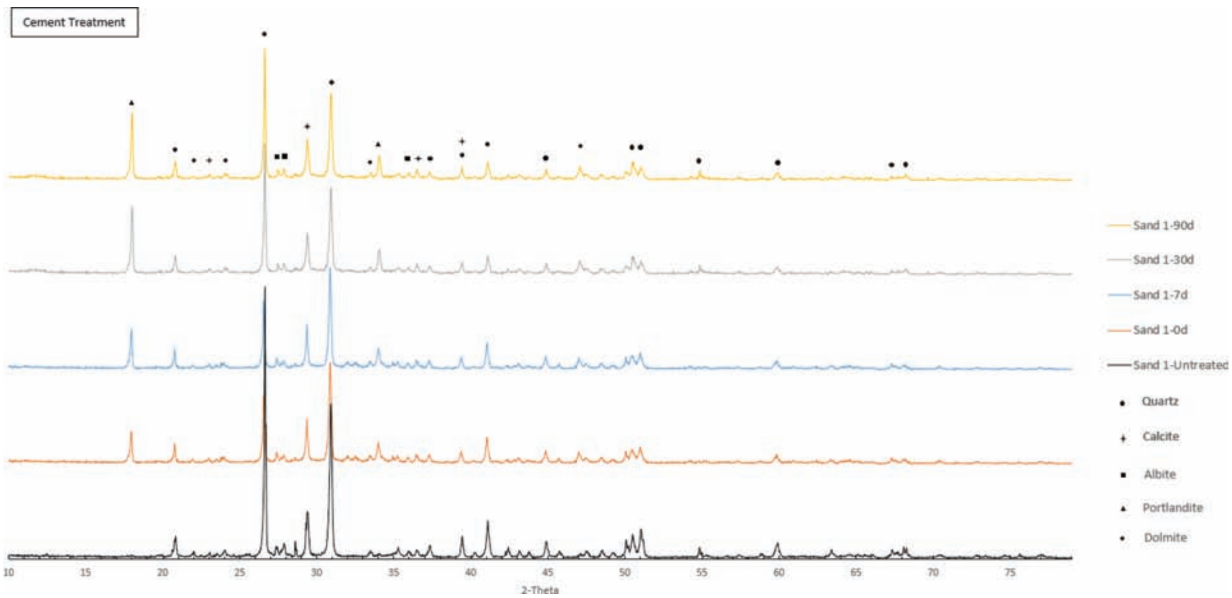

Figure 3.13 Cement treated sand. XRD tests for sand 1.

TABLE 3.2
Unconfined Compressive Strength of Different Treated Sands

	Sand 1	Sand 2	OS	Sieved OS to Sand 1 Size Distribution	Sieved OS to Sand 2 Size Distribution
Strength (psi)	176	146	113	117	105

OS: Ottawa sand.

composition (sand 1 is rich in carbonates). Thus, it seems that the differences in UCS between sands 1 and 2 can be attributed to particle shape and carbonate content, both factors having, for the two soils analyzed, similar importance.

4. SUMMARY AND CONCLUSIONS

Extensive laboratory experiments were performed to determine the properties of uniform soils, lean and fat clays treated with cement or lime or with equal quantities of lime and portland cement. Problem soils such as expansive and organic soils were not considered in the research.

Two uniform granular soils, three fat clays and three lean clays were selected for the tests. For each soil, Atterberg limits, Granulometry and Proctor tests were done. Unconfined compression tests were performed to investigate the changes of strength and strain at failure that occur over time in all soils with the treatment. In addition, XRD tests were done to observe any changes, with time, of the mineral composition of the treated soil.

The following conclusions, specific to the soils investigated, can be drawn from this study:

1. The LKD treatment showed that high plasticity soils required an LKD percentage between 7% and 8%, while for the low plasticity soils, the requirement ranged between 6% and 7%.
2. The treatment of equal amounts of LKD and cement indicated that the high plasticity soils required 4% to 6% of the combination of LKD and cement, while the low plasticity soils, the need was only 4%.
3. The cement treatment of the uniform soils showed that 5% of cement with 10% of water provided acceptable results.
4. The tests revealed that the uniform sand with higher calcium/magnesium content and more angular shape had the highest strength with the cement treatment.
5. The tests showed that the strength of the treated soils increased with time and that the improvement obtained did not degrade with time.

While the specific results obtained are applicable to the soils tested, a much broader conclusion can be reached in that treatment with lime, with cement or with a combination of the two may be successful for a variety of soils with the right proportions of the chemicals. As a result, the specifications in the INDOT design manual that determine the type of chemical to be used given the soil plasticity, can be relaxed.

5. IMPLEMENTATION

Below are the recommendations for changes to the design manual. Text with strikethrough font corresponds to suggested deletions, while text in red denotes suggested additions.

3.1 Suggested Criteria for Chemical Selection

When the chemical stabilization or modification of subgrade soil is considered the most economical or feasible alternate, the following criteria shall be considered for chemical selection: ~~based on the index properties of the soils~~.

1. Chemical Selection for Stabilization.

   a. Lime: Clay content $>$ 20% and PI $>$ 10.
   b. Lime, Cement or Lime and Cement: Clay content $<$ 20% and PI $\leq$ 10.
   c. Cement: Uniform clean sands, with fines content $<$ 5%

2. Chemical Selection for Modification

   a. Lime: Clay content $>$ 20% and PI $>$ 10.
   b. Lime - Fly ash blends: clay content $<$ 20% and 20 $>$ PI $>$ 10.
   c. Lime or Cement - Fly ash blends: Clay content $<$ 20% and 5 $<$ PI $<$ 15.
   d. Lime, Cement or Lime and Cement: Clay content $\leq$ 20% and PI $\leq$ 10.
   e. Lime or Cement or Fly ash: Clay content $<$ 20% and PI $\leq$ 10
   f. Cement: Uniform clean sands, with fines content $<$ 5%

Note 1. Lime shall be quick or hydrated lime only and lime shall have a soluble sulfate content $<$ 5%.
Note 2. Fly ash shall be class C only and shall have a soluble sulfate content $<$ 5%.
Note 3. Appropriate tests showing the improvements such as the strength gain and swell percentage are essential ~~for the exceptions listed above~~.
Note 4. Lime treated A-4 and A-6 soils may not provide immediate stability due to presence of a shallow water table. Geotechnical consultants may recommend cement as modifier for faster strength gain in these conditions.
Note 5. When chemical modification is planned for silty or sandy soils and there are weather limitations on chemical modification, the consultant, may use cement/ with fly ash or lime to improve rate of strength gain.
Note 6. Use of fly ash is not permitted between October 15 and April 15.
Note 7. For uniform clean sands, a high water to cement ratio may be needed to obtain uniform and workable soil-cement mixtures. Water/cement ratios may be within the range 2–3, or higher.

3.2 Suggested Chemical Quantities for Modification or Stabilization

1. Lime or Lime By-Products: 4% to ~~6%~~ 8%
2. Cement: 4% to 6%
3. Fly ash: 10% to 15%
4. The percentage for each combination of lime-fly ash or cement-fly ash shall be established based on laboratory testing. A minimum of 2% quick lime or cement shall be used in all combinations.

3.3 Suitable Soils for Modification/Stabilization

The reaction of a soil with lime, cement, fly ash or blends of these materials is important for stabilization and modification. Design methodology shall be based on an increase in the unconfined compressive strength of the mixture. A pair of specimens of 2 in. diameter by 4 in. height or larger diameter with a ratio of 2:1, height/diameter, is prepared at 95% of the standard Proctor and the optimum moisture content: ~~A 4% cement, 5% lime or 10% fly ash can be used in soils mixture~~. To obtain high-quality soil samples and reliable laboratory test data, it is recommended to use the following procedures to prepare soil specimens: (1) Mix the soil with the target dosage of the chemical(s) using a spatula; (2) Add water using a spray; (3) Place the specimen in a mold and compact the soils in layers to achieve the target density. These specimens are cured for 48 hours at 21°C (70°F) and 100% humidity in the laboratory and tested in accordance with AASHTO T-208. A complimentary set of two specimens are also prepared of the soil at 95% of standard Proctor and optimum moisture content. All specimens are then subjected to unconfined compressive testing. The minimum strength gain of both samples of the lime-soil mixture shall be 50 psi over that of the natural soil.

The minimum strength gain of the cement-soil mixture shall be 100 psi over that of the natural soil mixture and minimum strength gain for the fly ash-soil mixture shall be 50 psi over that of the natural soils.

4.5 Combination of Cement Fly Ash and Lime Mixtures

To enhance the effectiveness of lime, cement, or fly ash combinations for modification, the subsequent guidelines shall be used. The minimum gain of 75 psi over the natural soils is required.

- Lime and fly ash: The ratio between lime and fly ash mixture shall be chosen from strength test. Lime shall be quick lime and shall not be less than 2% in blend.
- Cement and fly ash: The ratio of cement and fly ash shall be chosen based on strength test. Cement content shall not be less than 2% in blend.
- Lime, cement, and fly ash combinations may be used if strength criteria are met and a minimum of 2% cement shall be used in combination.
- Lime and cement combinations: The ratio between lime and cement mixture shall be chosen from strength test. Lime shall be quick lime and the cement content shall not be less than 2%.

6. ACKNOWLEDGMENTS

This work was supported by the Joint Transportation Research Program administered by the Indiana Department of Transportation and Purdue University. The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein, and do not necessarily reflect the official views or policies of the sponsoring organizations. These contents do not constitute a standard, specification, or regulation. The authors are grateful to the Indiana Department of Transportation/Joint Transportation Research Project for supporting this research.

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APPENDIX A. LABORATORY TESTS: CLAYS

This appendix includes the laboratory tests done on clays with high plasticity index (soils 1 to 3) and on clays with low plasticity index (soils 4 to 6). Figures A.1 to A.8 show the granulometry tests results; Figure A.2, the proctor tests; Figure A.3, the pH tests; Figure A.4 the unconfined compression tests results with LKD treatment and Figure A.5 with equal amounts of cement and LKD; Figures A.6 and A.7, the XRD tests of soil 6 with different treatments.

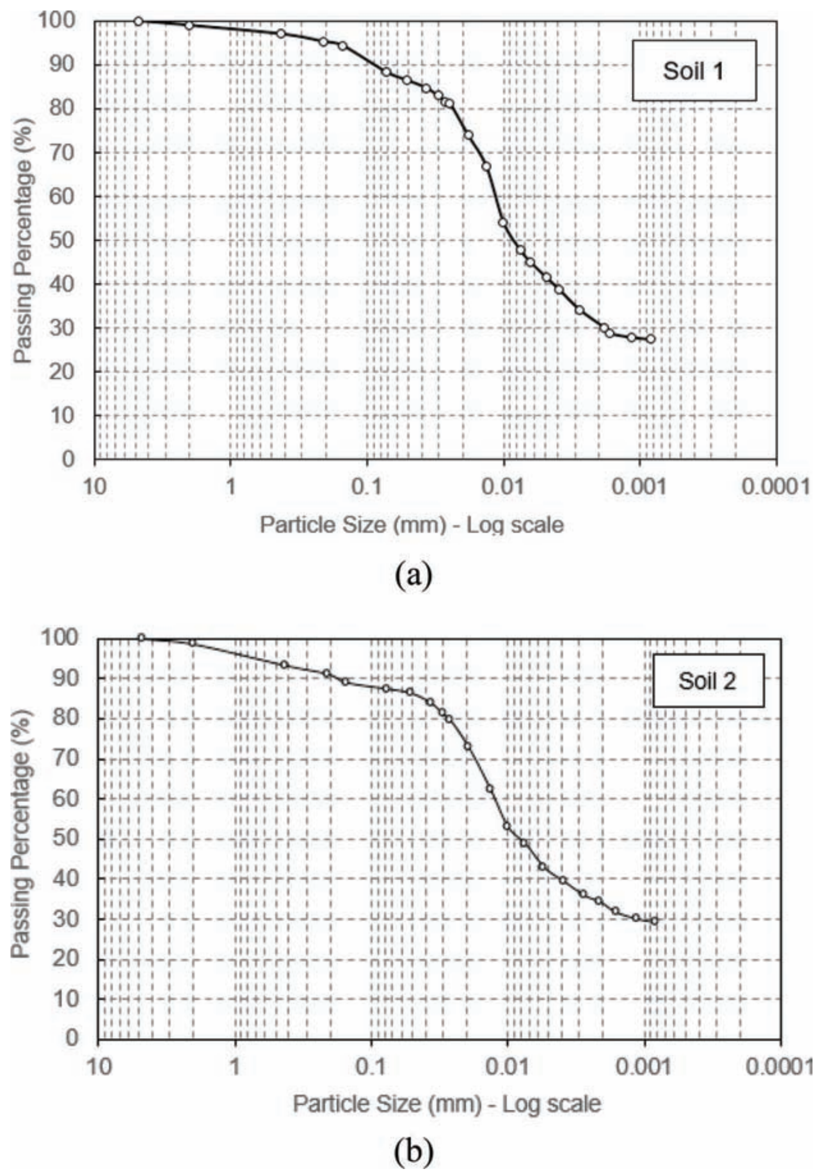
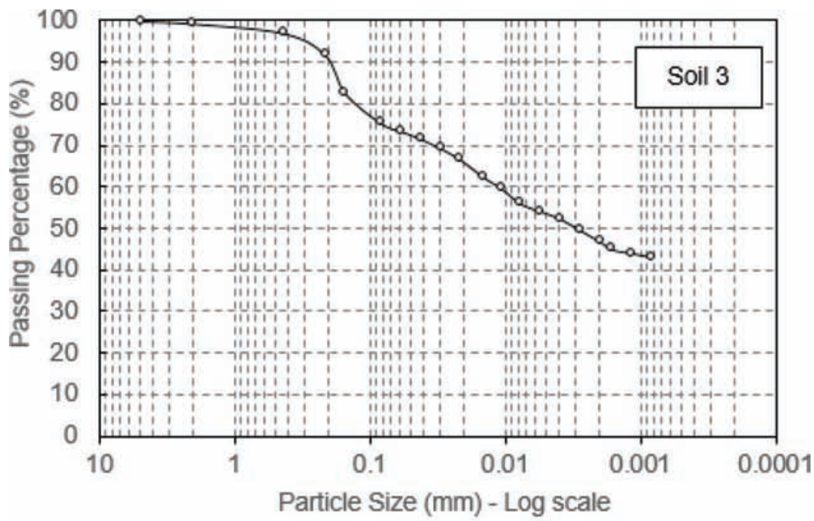
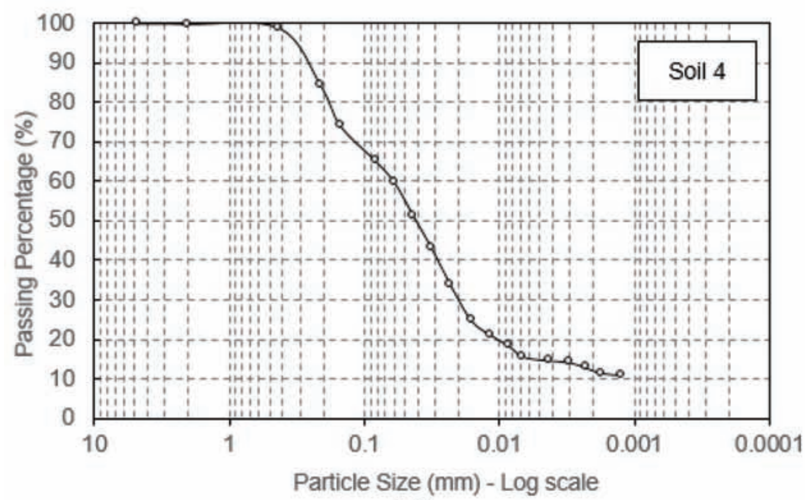


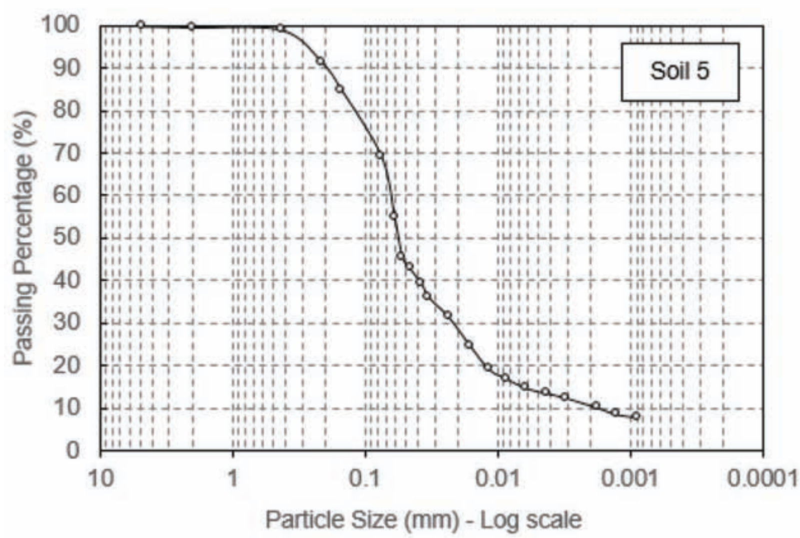
Figure A.1 Granulometry tests of high and low plasticity clays.



(c)



(d)



(e)

Figure A.1 Continued

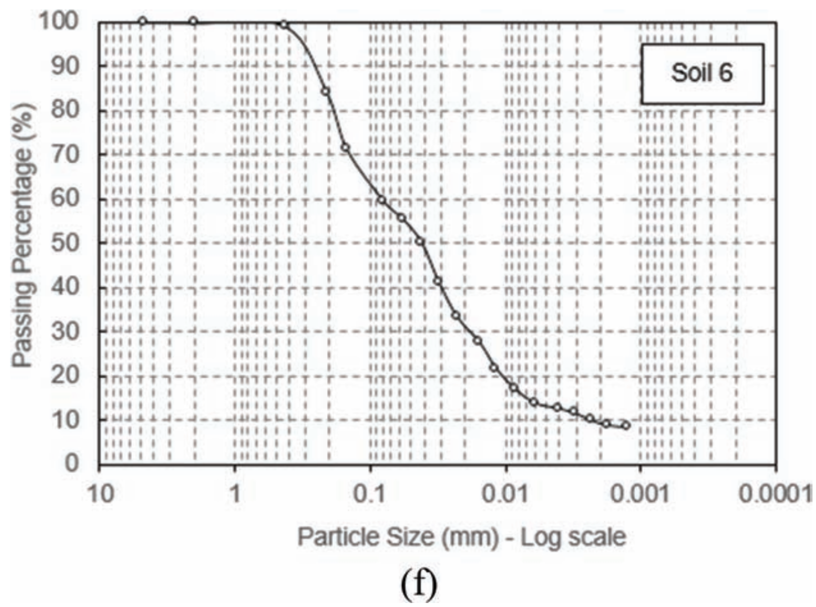


Figure A.1 Continued

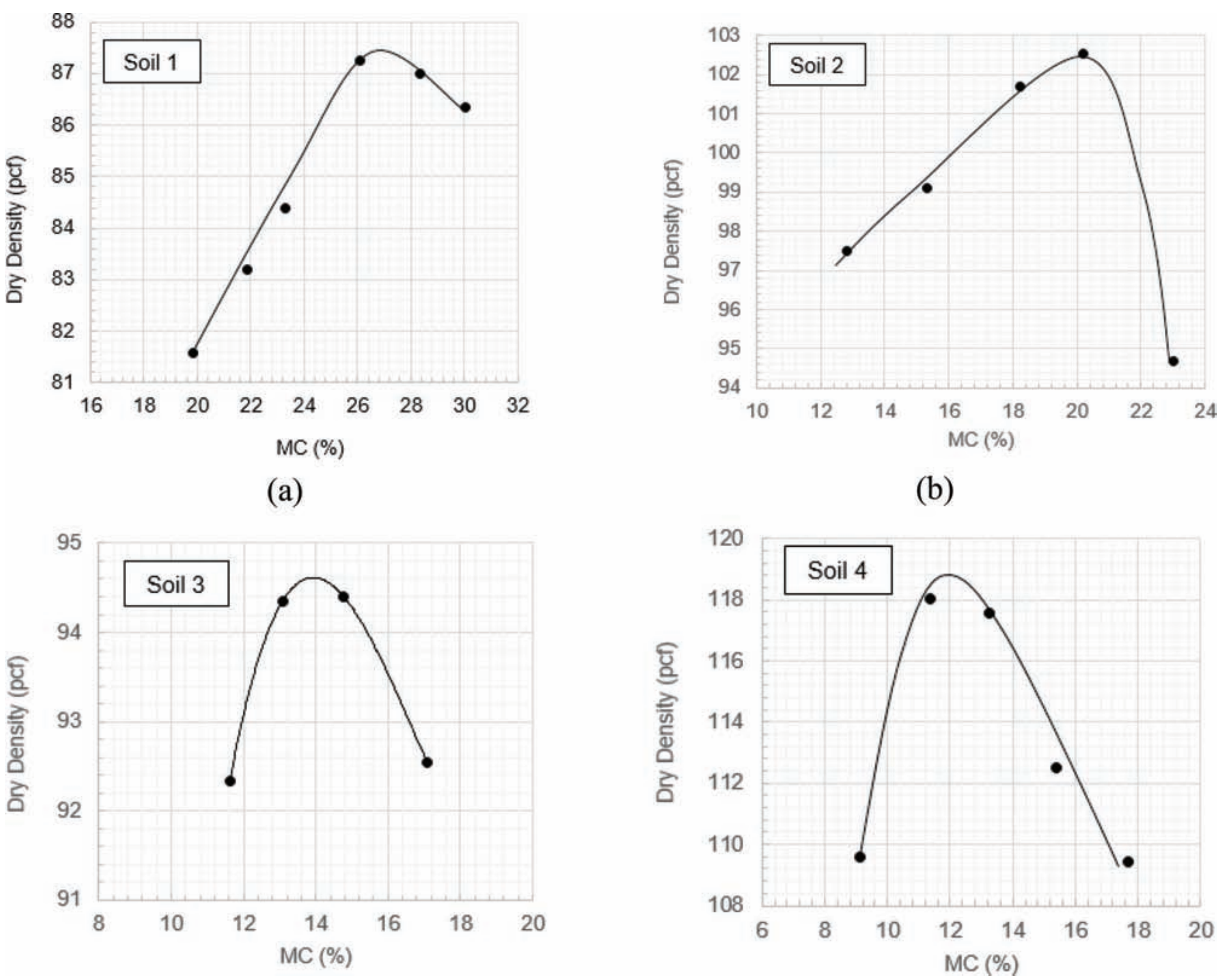


Figure A.2 Proctor tests of high and low plasticity clays.

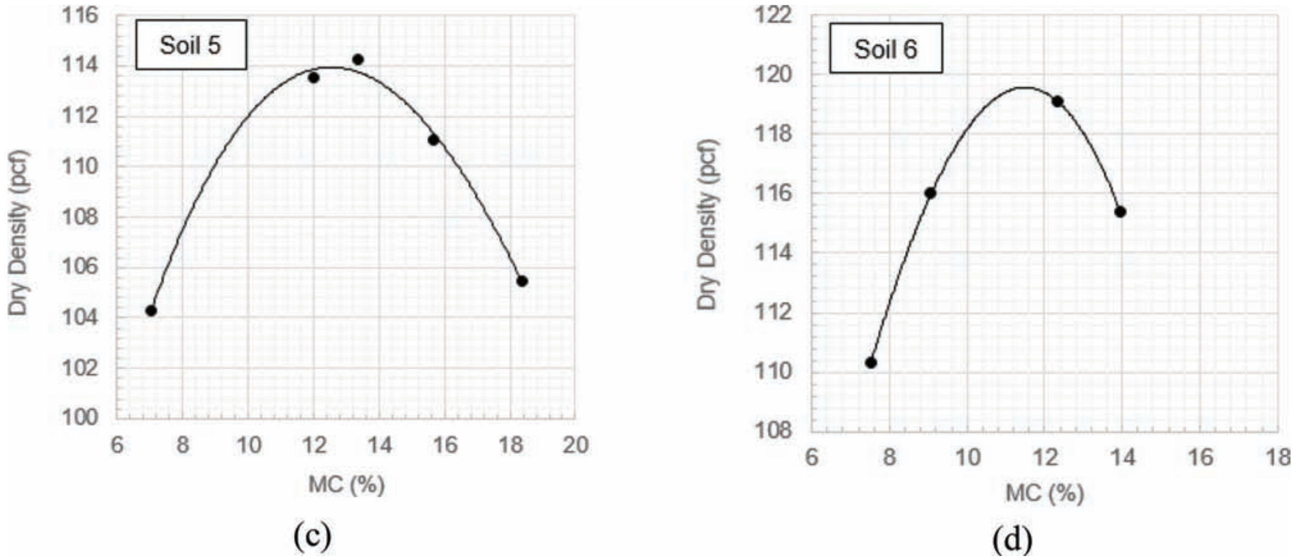


Figure A.2 Continued

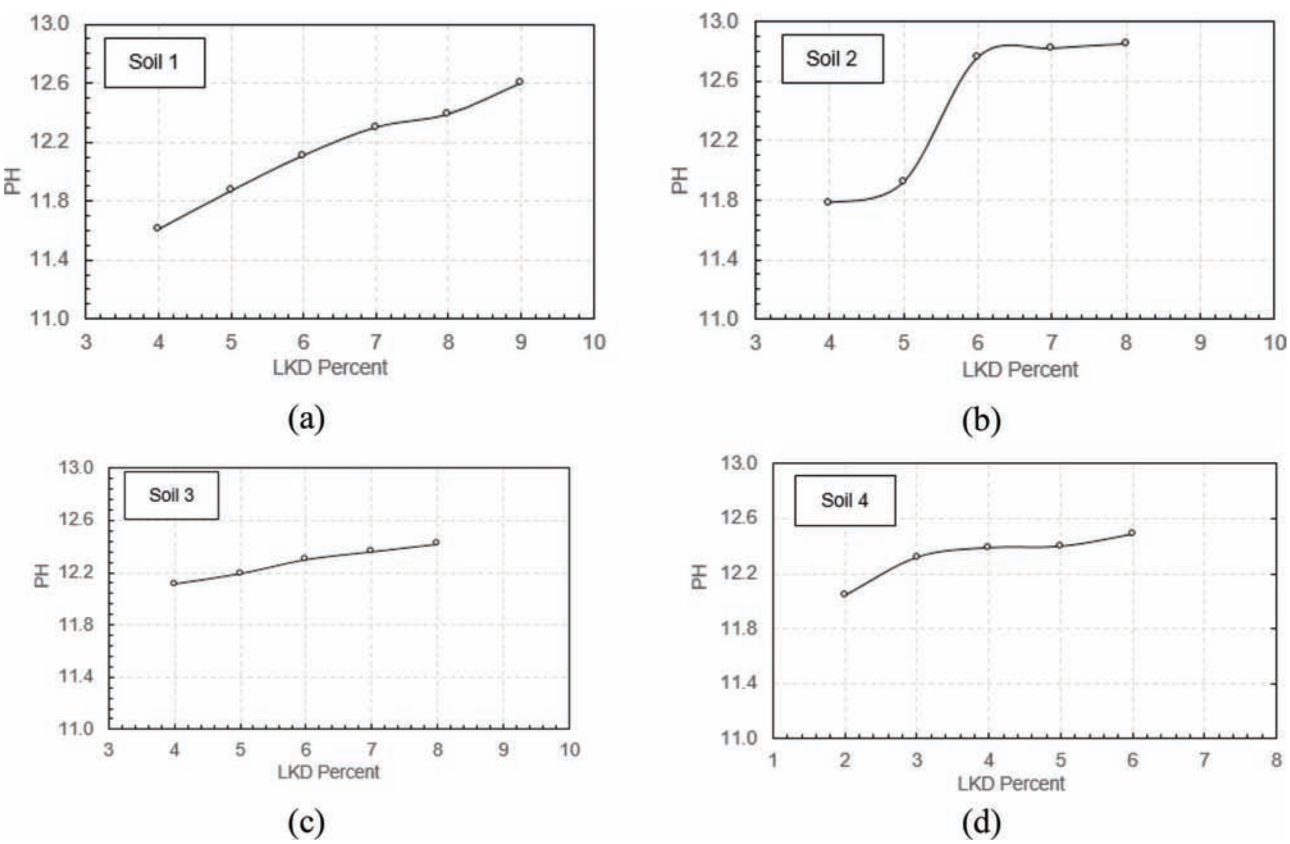


Figure A.3 Background pH with LKD for high and low plasticity clays.

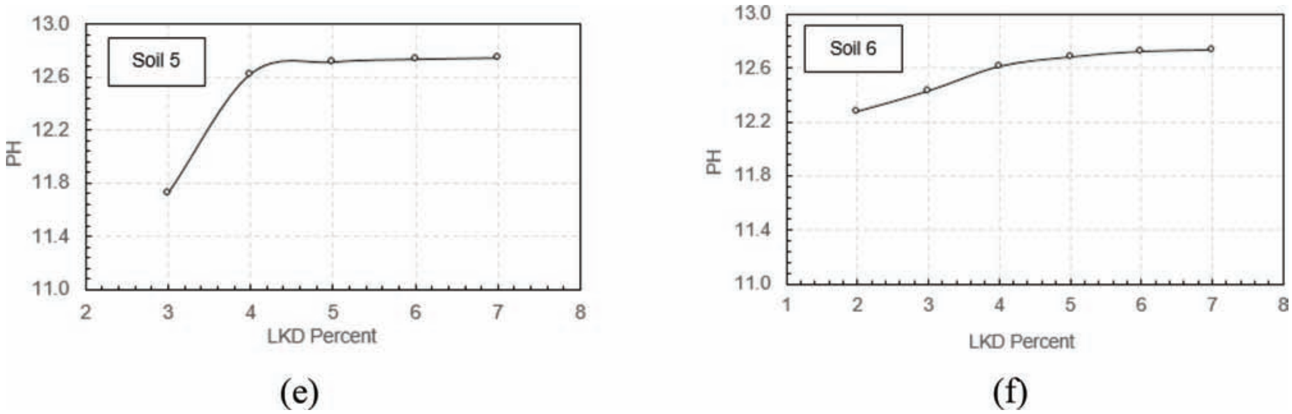


Figure A.3 Continued

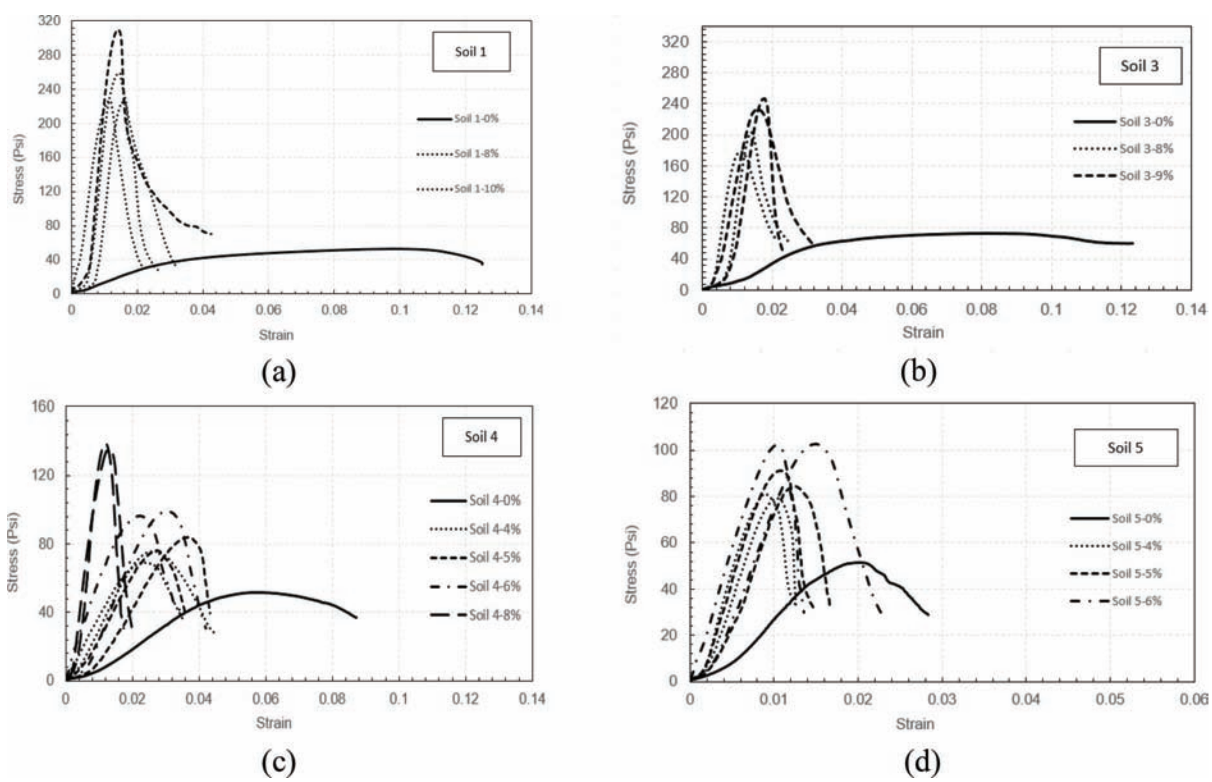


Figure A.4 Fat clays (CH) and lean clays (CL) treated with LKD. Unconfined compression test results.

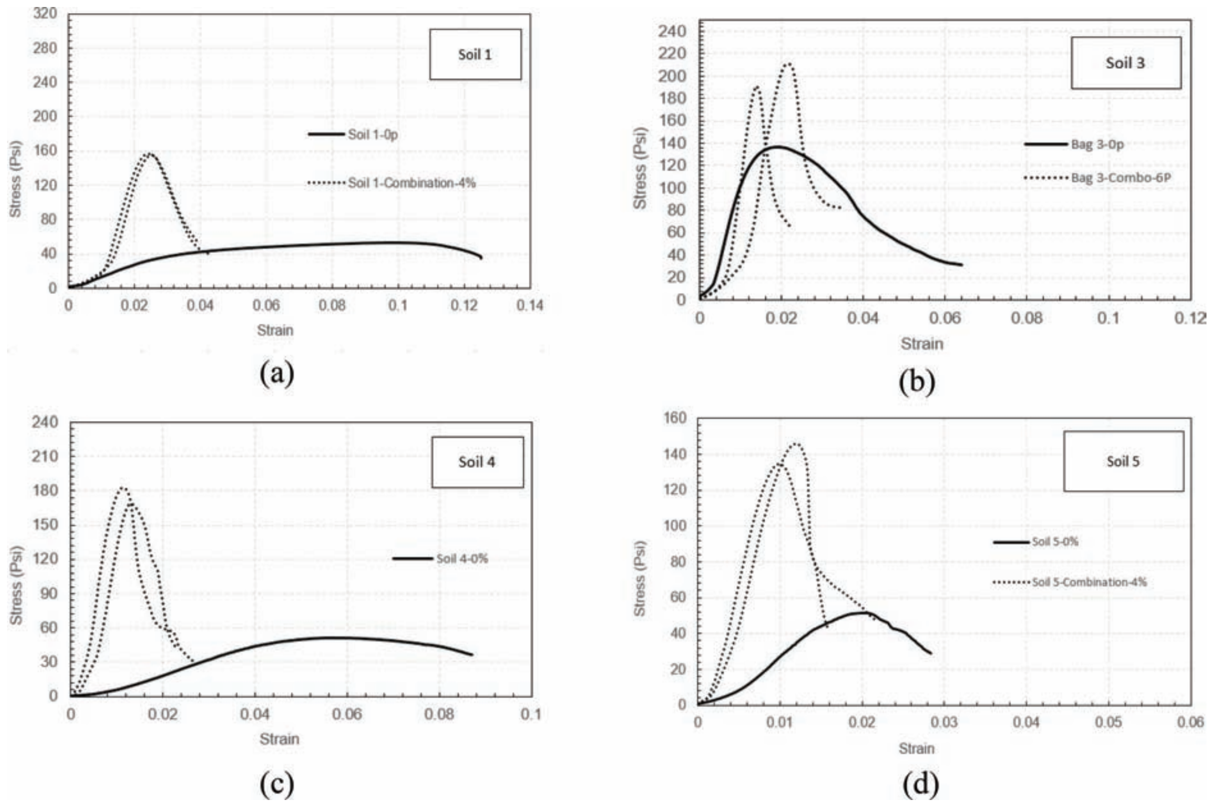


Figure A.5 Fat clays (CH) and lean clays (CL) treated with equal amounts of portland cement and LKD. Unconfined compression test results.

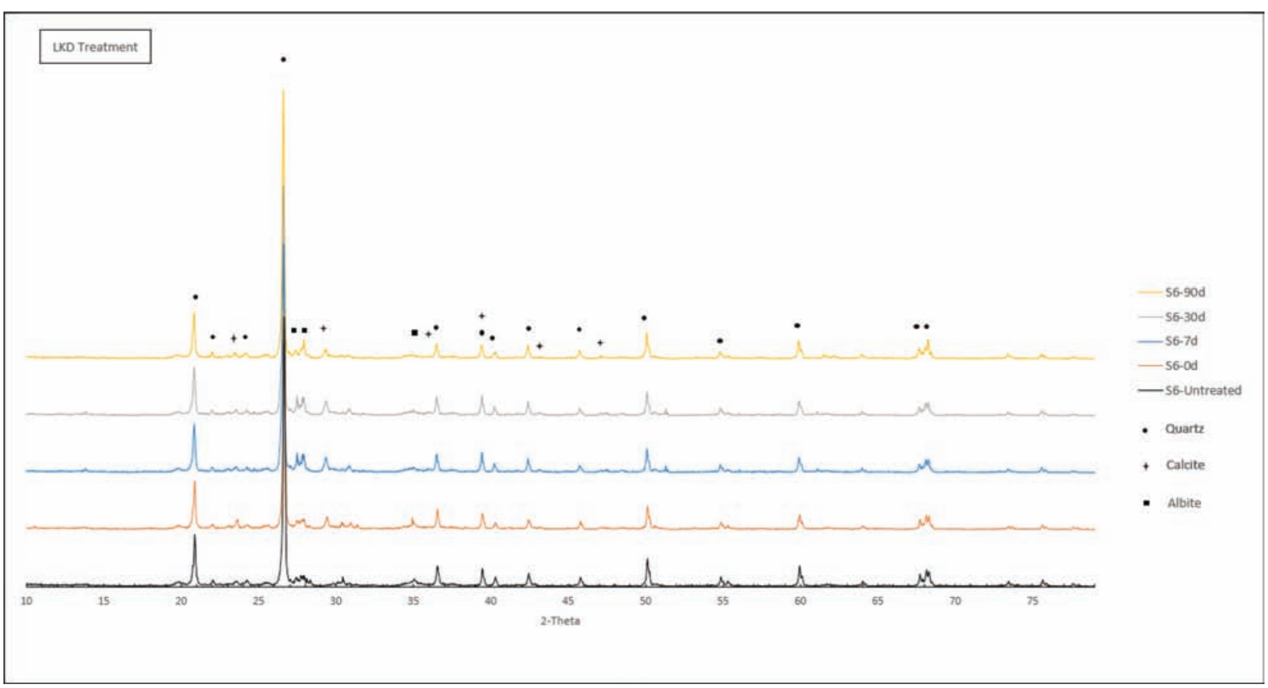


Figure A.6 XRD tests for soil 6: untreated and treated with LKD.

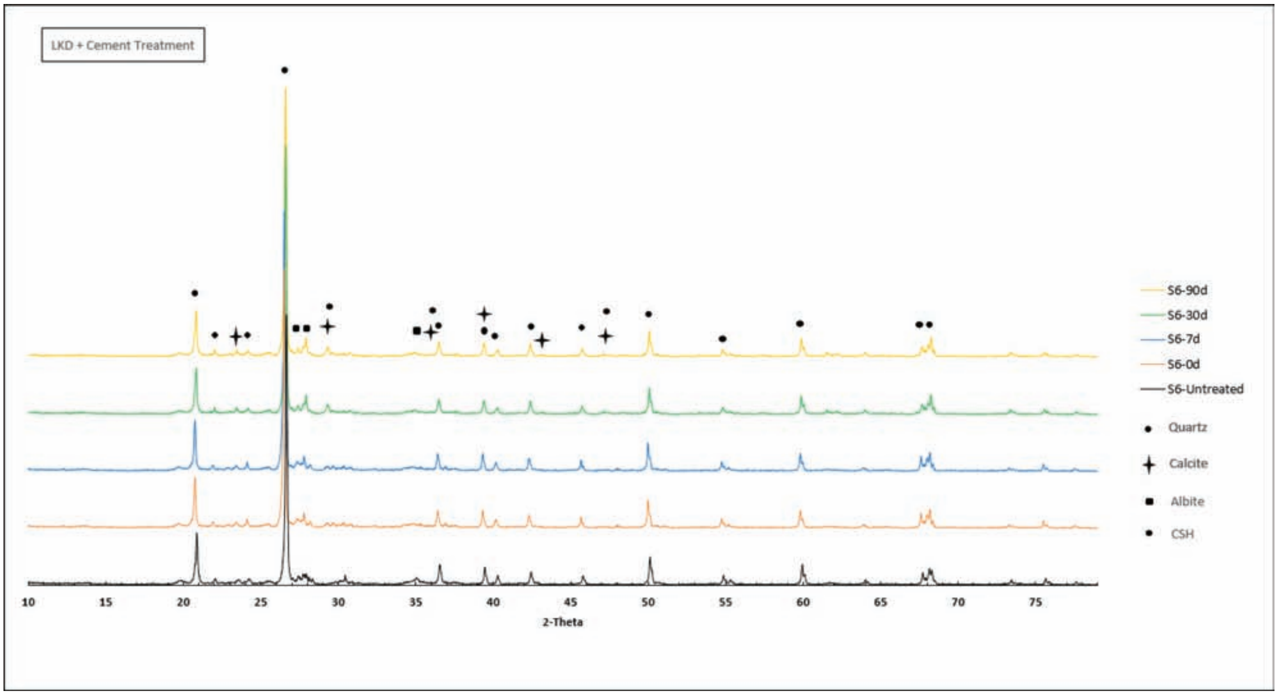


Figure A.7 XRD tests for soil 6: untreated and treated with cement and LKD.

APPENDIX B. LABORATORY TESTS: UNIFORM SANDS

This appendix includes the laboratory tests done on the uniform sands (sands 1 and 2). Figure B.1 shows the granulometry tests results; Figure B.2, the proctor tests; Figure B.3, images of the grains of the sands obtained with an optical microscope; Figure B.4 the XRD tests of sand 2 with cement treatment; Figure B.5 the unconfined compression tests results with ESSROC cement; and Figure B.6 the unconfined compression tests results of Ottawa sand and sieved Ottawa sand treated with cement.

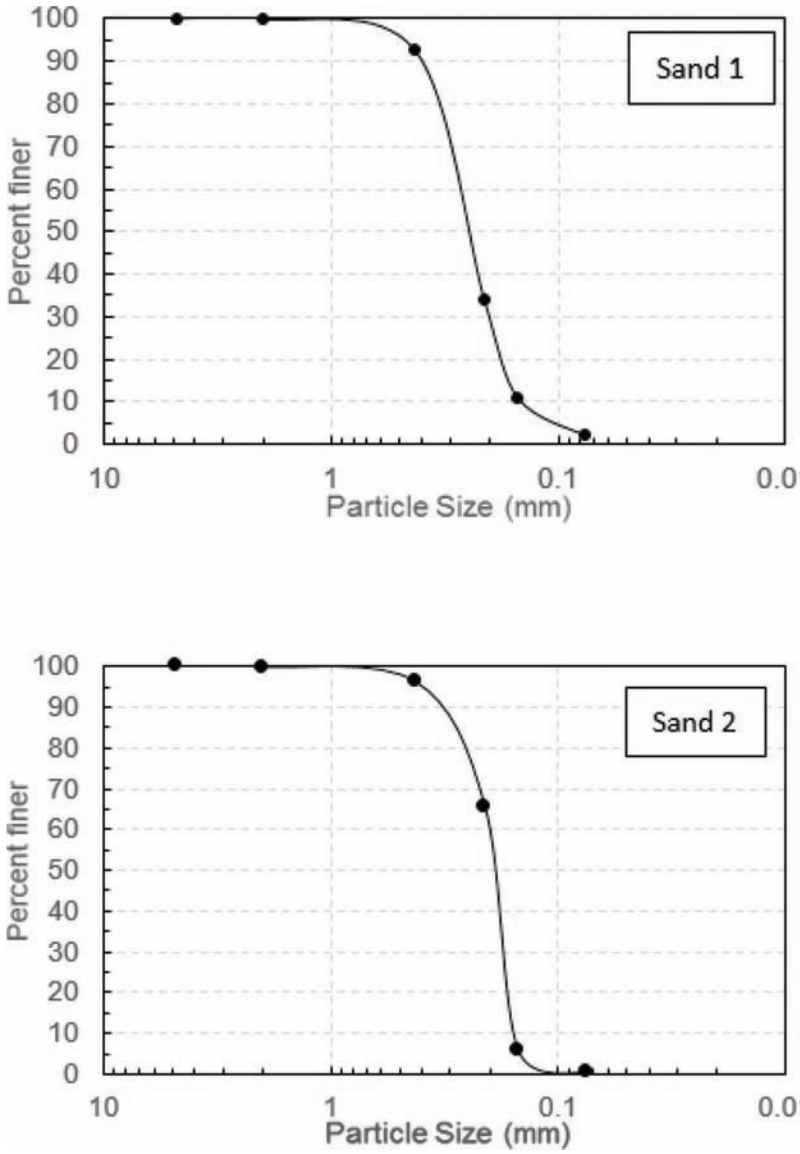


Figure B.1 Particle size distribution of uniform granular soils.

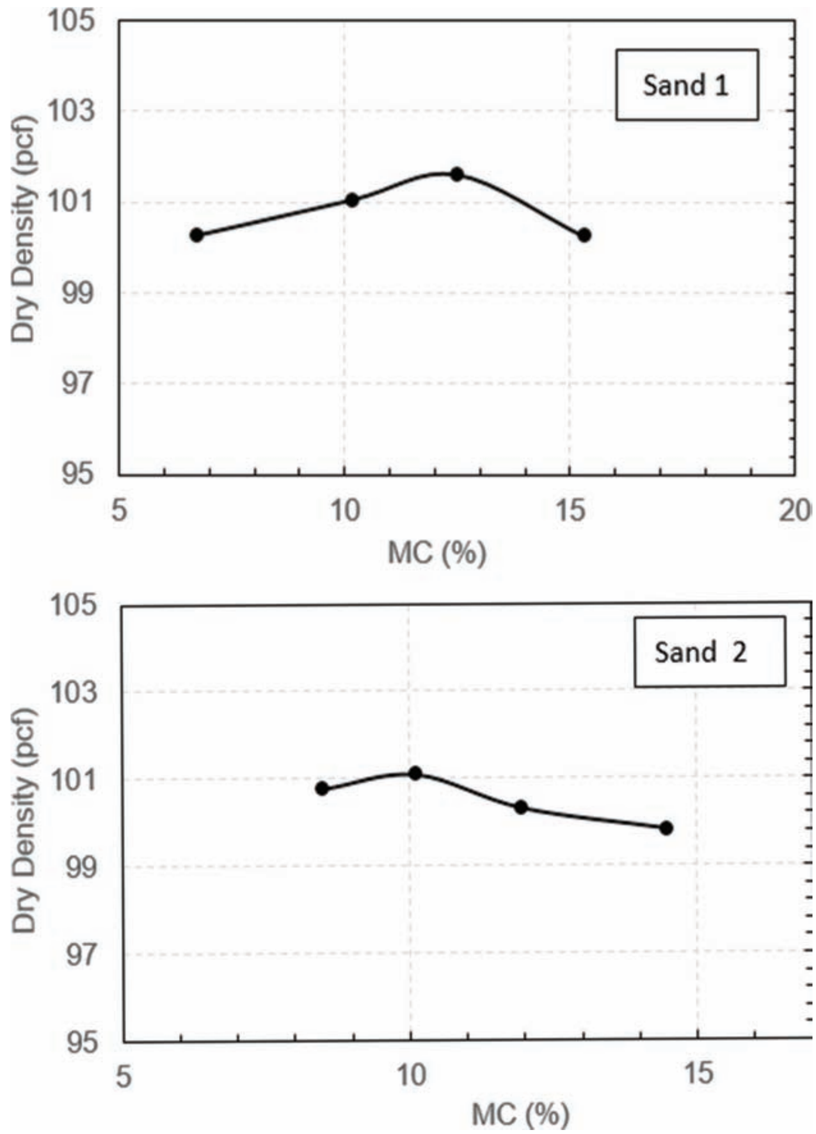


Figure B.2 Proctor tests of uniform granular soils.

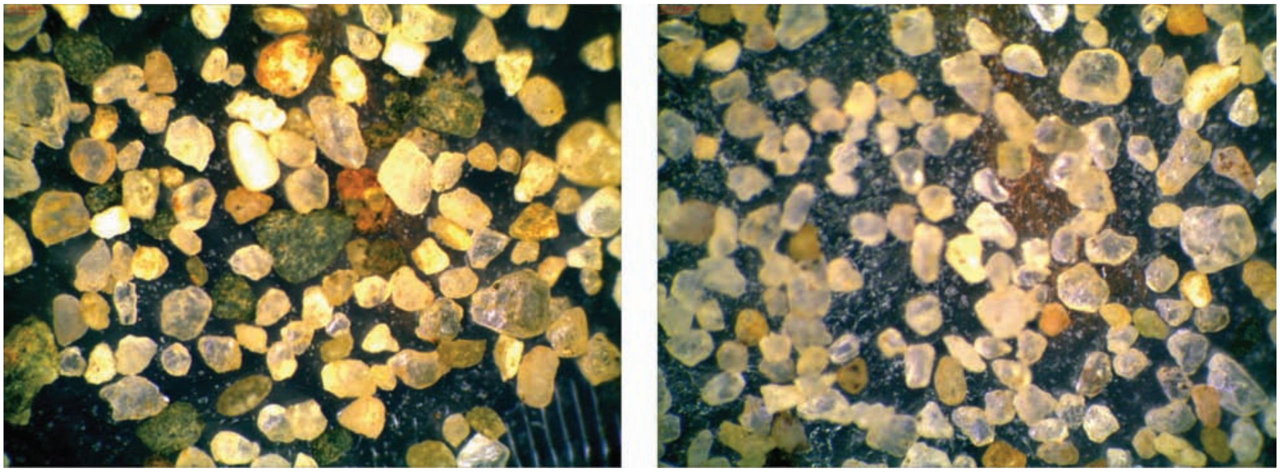


Figure B.3 Photographs of sand grains using an optical microscope (left: sand 1; right: sand 2).

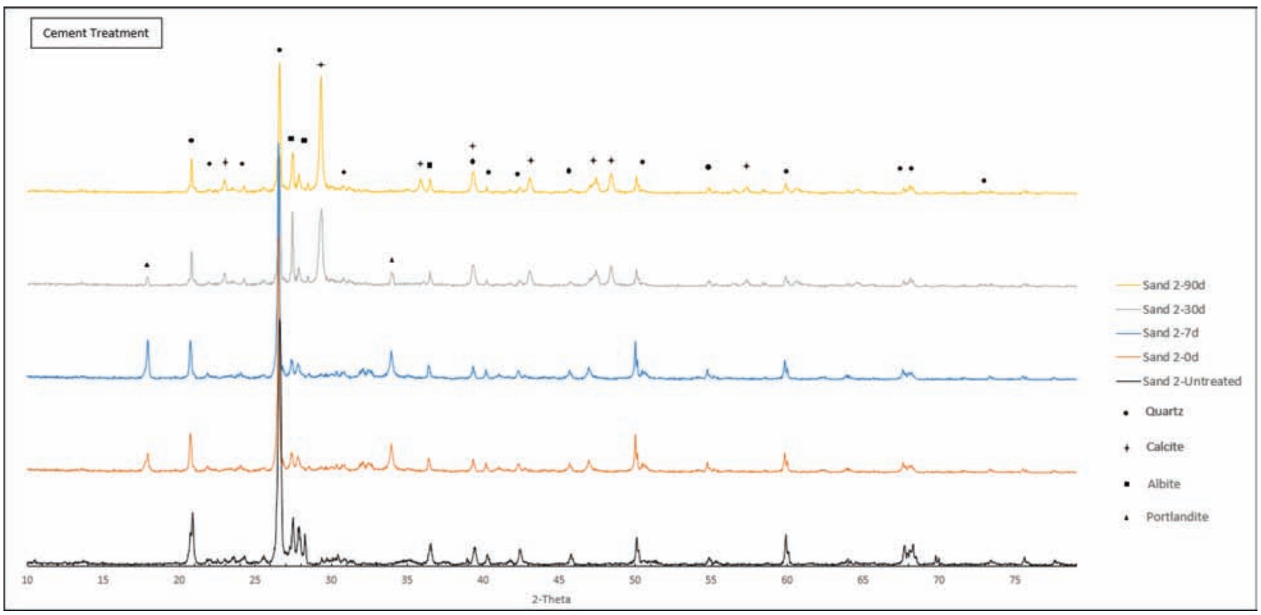


Figure B.4 Cement treated sand. XRD tests for sand 2.

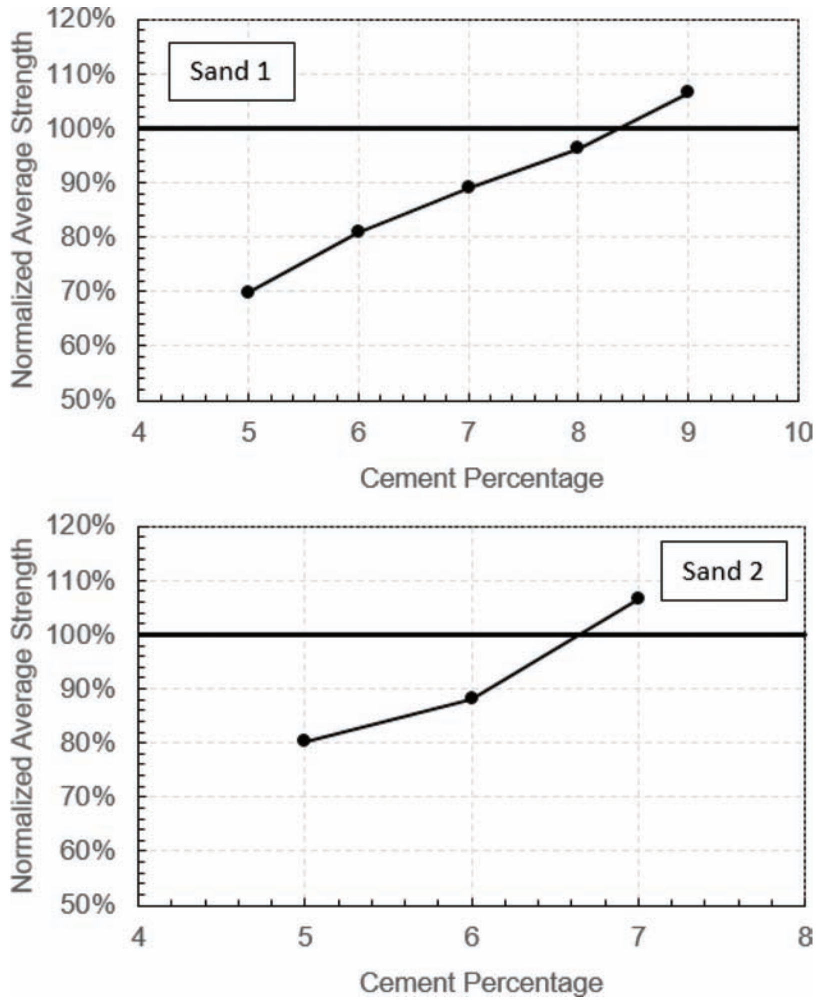


Figure B.5 Comparison between normal type I cement and ESSROC type I cement (normalized average strength: S_{ESSROC}/S_{Base}, where S_{ESSROC} is the strength of ESSROC type I cement treated soil, S_{Base} is the strength of normal type I cement with 10% moisture content and 5% cement).

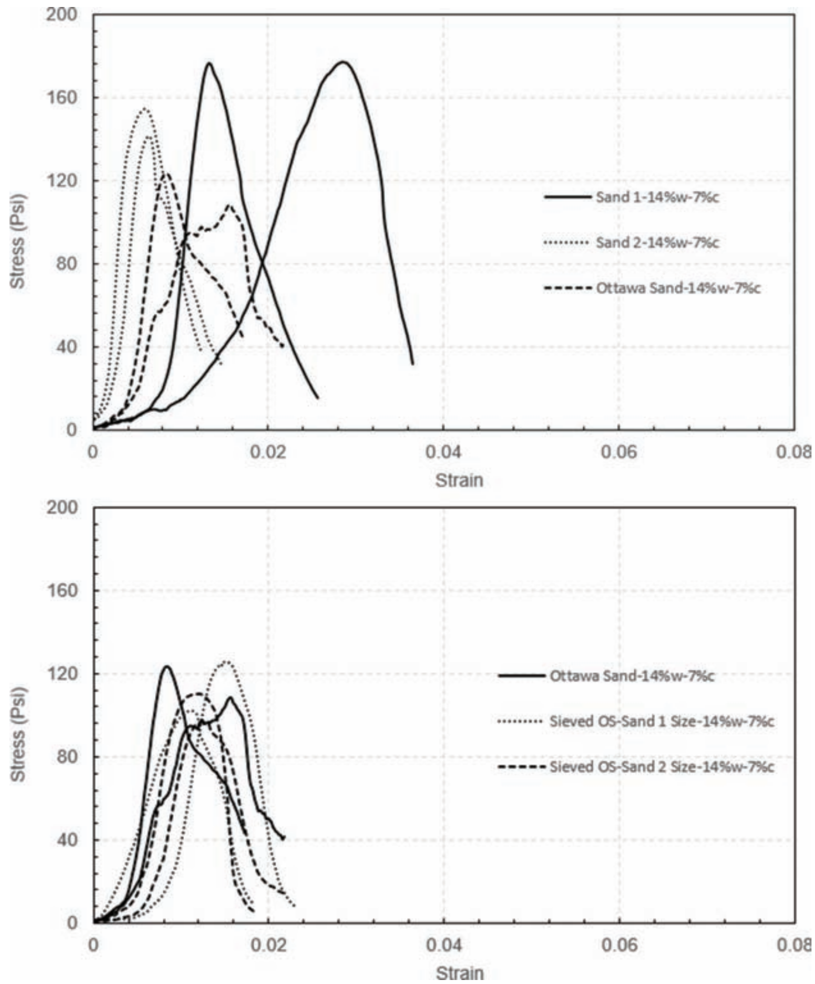


Figure B.6 Unconfined compression tests of treated sands (top: sand 1, 2 and Ottawa sand; bottom: Ottawa sand and sieved Ottawa sand).

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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 1,500 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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The recommended citation for this publication is:

Tao, F., Li, X., Bobet, A., & Siddiki, N. Z. (2016). *Chemical modification of uniform soils and soils with high/low plasticity index* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2016/32). West Lafayette, IN: Purdue University. http://dx.doi.org/10.5703/1288284316359