Report No. K-TRAN: KU-17-1 ▪ FINAL REPORT ▪ November 2017

Lime Kiln Dust for Treated Subgrades

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Kansas
Department of Transportation

1 Report No. K-TRAN: KU-17-1	**2 Government Accession No.**	**3 Recipient Catalog No.**
4 Title and Subtitle Lime Kiln Dust for Treated Subgrades		**5 Report Date** November 2017 **6 Performing Organization Code**
7 Author(s) Jamal Kakrasul, Robert L. Parsons Ph.D., P.E., Jie Han Ph.D., P.E.		**7 Performing Organization Report No.**
9 Performing Organization Name and Address The University of Kansas Department of Civil, Environmental & Architectural Engineering 1530 West 15th St Lawrence, Kansas 66045-7609		**10 Work Unit No. (TRAIS)** **11 Contract or Grant No.** C2088
12 Sponsoring Agency Name and Address Kansas Department of Transportation Bureau of Research 2300 SW Van Buren Topeka, Kansas 66611-1195		**13 Type of Report and Period Covered** Final Report May 2016–August 2017 **14 Sponsoring Agency Code** RE-0714-01
15 Supplementary Notes For more information write to address in block 9.		

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Based on the results of this research, consideration of the use of LKD as a soil stabilization agent was recommended.

17 Key Words Lime Kiln Dust, Treated Subgrade, Subgrade Soil, Soil Stabilization		**18 Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service www.ntis.gov.	
19 Security Classification (of this report) Unclassified	**20 Security Classification (of this page)** Unclassified	**21 No. of pages** 97 + Appendices	**22 Price**

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A Report on Research Sponsored by

THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

and

THE UNIVERSITY OF KANSAS
LAWRENCE, KANSAS

November 2017

PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

Chemical and cementitious materials are often used to modify and stabilize the subgrade soils that serve as foundations for pavements. Improvement of the subgrade provides a better working platform for construction of the layers above and improves the strength of the pavement structure. Lime, cement, and fly ash have all been successfully used for soil modification/stabilization; however, increasing material costs and availability concerns have motivated Departments of Transportation and the construction industry to investigate alternatives. This report describes the results of a laboratory and field investigation of the performance of lime kiln dust added as an alternative soil stabilization material.

Lime kiln dust (LKD) is a byproduct of lime production. It is sold in the form of a dry powder that contains a significant percentage of lime along with a substantial amount of inert material. It is currently used for subgrade improvement in multiple states. The purpose of this report is to describe the results of field investigations that took place at three construction sites where LKD was used and laboratory testing of five soils treated with LKD, lime, and fly ash.

Field testing methods included Shelby tube sampling and use of the dynamic cone penetrometer and light weight deflectometer. Tests were conducted on the day of mixing and multiple days thereafter, so the benefits of curing could be evaluated. Lab testing included standard characterization tests followed by strength, swell, resilient modulus, and wet-dry testing. The testing results showed that, after a relatively short curing period, LKD provided substantial improvement to soil properties. Approximately 60% of this improvement was achieved after 1 day, and more than 80% was achieved after 3 days.

During laboratory testing, LKD performed comparably with lime in reducing plasticity and swelling potential and increasing strength and durability. Addition of LKD substantially lowered the plasticity, free volume change, and swelling potential of the native soils tested in this report. Soils treated with LKD showed higher strength gain than unsoaked samples that were lime treated. However, lime-treated soil samples gained more strength for soaked conditions. Fly ash had the least strength gain. The effect of adding LKD on the durability of soil was comparable with lime, and much better than the performance of fly ash.

Based on the results of this research, consideration of the use of LKD as a soil stabilization agent was recommended.

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Chapter 1: Introduction

Chemical and cementitious materials are often used to modify and stabilize the subgrade soils that serve as foundations for pavements. Improvement of the subgrade provides a better working platform for construction of the layers above and improves the strength of the pavement structure. Lime and cement are two of the most common materials added to improve subgrade soils and have been used for this purpose for many decades. Fly ash produced by coal-burning power plants has become widely used in recent decades with good results, and there are a number of other products used on a more limited basis. Although lime, cement, and fly ash have all been successfully used for soil modification/stabilization, increasing material costs and availability concerns have motivated the industry to investigate alternatives. This report describes the results of a laboratory and field investigation on the performance of lime kiln dust added as an alternative soil stabilization material.

Lime kiln dust (LKD) is a byproduct of lime production. It is sold in the form of a dry powder that contains a significant percentage of lime along with a substantial amount of inert material. LKD is currently used for subgrade improvement in Michigan, Illinois, Kansas, and other states. The purpose of this report is to describe the results of field investigations that took place at three sites located near Lawrence and McPherson, Kansas, and within Kansas City, Kansas; and laboratory testing on a total of five soils obtained from the McPherson and Kansas City sites, as well as from Atwood, Kansas, and from the University of Kansas main campus in Lawrence.

Field testing methods included Shelby tube sampling, the dynamic cone penetrometer, and light weight deflectometer. Tests were conducted on the day of mixing and multiple days thereafter, so the benefits of curing could be evaluated. Lab testing included standard characterization tests followed by strength, swell, resilient modulus, and wet-dry testing. Lab tests were conducted on the native soil and soil treated with LKD, lime, and fly ash for comparison. The testing results showed that, after a relatively short curing period, LKD provided substantial improvement to soil properties. Approximately 60% of the improvement was achieved after 1 day, and more than 80% was achieved after 3 days.

During laboratory testing, LKD performed comparably with lime in reducing plasticity and swelling potential and increasing strength and durability. Addition of LKD substantially lowered the plasticity, free volume change, and swelling potential of the native soils tested in this report. Soils treated with LKD showed higher strength gain than unsoaked samples that were lime treated. However, lime-treated soil samples gained more strength for soaked conditions. Fly ash had the least strength gain. The effect of adding LKD on the durability of soil was comparable with lime, and much better than the performance of fly ash.

More detail concerning LKD and its observed performance are contained in the following chapters. Chapter 2 consists of a literature review describing the generation of LKD and research on its use for soil stabilization. Chapter 3 contains a summary of the scope of work for this project and the test protocols followed. Chapters 4 and 5 contain the results of the field and laboratory work, respectively. Chapters 6 and 7 contain the conclusions and recommendations, respectively, developed based on the results of this study.

Chapter 2: Literature Review

This chapter presents a summary of published research on lime kiln dust (LKD) and a brief description of the additives considered in this research.

2.1 Introduction

The strength and stiffness properties of subgrade soils significantly affect pavement construction activities and performance. The finished subgrade must provide sufficient support for construction and compaction of pavement layers, and the maximum rut depth must be limited for all construction traffic prior to construction of the overlying layers (Illinois Department of Transportation, 2005). However, unstable or weak subgrade soils can create significant problems for pavement layers, and often cannot be used as construction materials without improvement. Therefore, modification or stabilization may be required to improve the engineering properties of the soil to meet the desired strength and/or stiffness. One of the improvement methods is chemical treatment (Little & Nair, 2009; National Lime Association, 2004).

Chemical treatment includes short-term treatment, which is called modification, and long-term treatment, more commonly referred to as stabilization. Modification is the improvement that occurs within hours after mixing. Modification changes the soil texture, reduces the plasticity of the soil, improves the soil workability, and provides some short-term strength gain (Little & Nair, 2009). Stabilization is a long-term improvement that includes all the effects of modification with an additional long-term strength gain (Little & Nair, 2009; National Lime Association, 2004).

Lime, fly ash, Portland cement, and kiln dusts, which include cement kiln dust (CKD), and lime kiln dust (LKD), are chemical agents that have been used alone or in combination to modify or stabilize subgrade soils (Bandara, Jensen, & Binoy, 2016; Ismaiel, 2006; Jung, Bobet, Siddiki, & Kim, 2011; Milburn & Parsons, 2004; Nikraz, 1998; Parsons, Kneebone, & Milburn, 2004; Petry, 2001).

A brief description of lime and fly ash and an in-depth description of lime kiln dust (LKD) are presented in the next sections.

2.2 Lime and Fly Ash

Lime, which is a calcium-containing inorganic material, is produced by heating limestone at high temperatures. Lime has been used for many decades as a chemical stabilizer for both modification and stabilization of fine grain soils (Little, 1995; Little & Nair, 2009; National Lime Association, 2004; Milburn & Parsons, 2004; Toohey, Mooney, & Bearce, 2013). During the soil stabilization process, lime improves the strength of soils by two basic mechanisms: flocculation and cementation (initial and long-term reactions). The initial reactions alter the texture and plasticity of soil due to cation exchange and flocculation/agglomeration of soil particles. These processes increase the friability and workability of the soil (Little & Nair, 2009). The long-term reactions (cementation process) involve reaction with pozzolans. An alteration of surface mineralogy and a cementing effect among particles occurs when pozzolans react with free lime and water. Depending on the degree of pozzolanic reaction within a specific lime-soil mixture, pozzolans contribute to an increase in strength. Pozzolanic reactions are slow processes compared to flocculation/agglomeration reactions in soil (Little & Nair, 2009; National Lime Association, 2004).

Fly ash is a coal combustion product composed of fine particles that are driven out of the boiler with the exhaust gasses. In modern power plants, electrostatic precipitators capture fly ash before the flue gasses are emitted. As with lime, fly ash also has been used either alone or in combination with the other additives as a chemical treatment for both modification and stabilization of fine grain soils (Milburn & Parsons, 2004; Nalbantoğlu, 2004; White, Harrington, & Thomas, 2005). Fly ash, like the other by-product additives (LKD and CKD), also depends on pozzolanic reactions and cation exchange to modify and/or stabilize soil properties (Little & Nair, 2009). Based on AASHTO M 295, fly ash can be classified as Class C (self-cementing), or Class F (non-self-cementing). Class C fly ash contains a substantial amount of lime (CaO), and some of this lime is free to react. This lime can react with silicates and aluminates available in soil, or with other unreacted pozzolans, silicates, and aluminates that are present within the fly ash to form cementitious reaction products. These products contribute to strength gain in fly ash-treated soils (Little & Nair, 2009). In contrast to Class C fly ash, Class F fly ash contains little free lime (CaO), and it requires the incorporation of additional additives, such as Portland cement or lime, to get a sufficient source of free lime.

2.3 Lime Kiln Dust (LKD)

2.3.1 Background

Lime kiln dust is a by-product formed during the production of lime. The processing of limestone into lime in a lime kiln generates gasses and dusts that are directed through an air pollution control system (e.g., cyclones, electrostatic precipitators), where the dust is collected and the gasses vented to the atmosphere (Federal Highway Administration [FHWA], 2016; Little & Nair, 2009; National Lime Association, 2004). This dust material, which is LKD, contains a substantial amount of lime, alumina, and silica. The amount of those minerals in LKD depends on the raw material, fuel, and kiln operations used during the lime manufacturing process (National Lime Association, 2004).

In general, LKD contains between about 30 and 40% lime, which may either be free lime or lime combined with pozzolans in the kiln (Little & Nair, 2009). Based on free lime and free magnesia content, fresh LKD can be classified into two categories: high- or low-reactive LKD. LKD with a high free-lime content is highly reactive and produces an exothermic reaction upon the addition of water (Chesner, Collins, & MacKay, 1998).

Due to the presence of pozzolans, LKDs may involve cementitious and/or pozzolanic reactions. Highly reactive LKD may have great commercial interest as a substitute for hydrated lime (Recycled Materials Resource Center, n.d.). However, LKDs may be nonreactive due to the presence of dolomitic ($CaMg(CO_3)_2$) lime and/or the absence of pozzolans, or due to the low quality of the pozzolans contained in the LKD (Abdul & Timothy, 2005; Chesner et al., 1998; Little & Nair, 2009).

2.3.2 Material (LKD) Handling

The processing of stockpiled LKD can be difficult to handle because of its fine, dry, powdery nature and caustic characteristics. To mitigate blowing and dusting problems during transport, it is common practice to add water to the material. However, this practice results in premature hydration of the free lime or magnesia and significantly reduces the cementitious potential of the LKD. LKD must be handled in a fashion similar to that used with conventional cement or lime to keep it fresh and to preserve its cementitious potential (FHWA, 2016). In addition, Collins and Emery (1983) stated that fresh LKD must be stored in enclosed bins to keep out moisture and prevent dusting if it is being used.

In addition, LKD may have a tendency to clump or bridge together at the feed opening when stored in silos. Therefore, to mitigate this problem, storage bins should be equipped with suitable vibration devices at the feed opening (FHWA, 2016).

2.3.3 Physical Properties

Particle size and specific gravity are properties of interest when kiln dusts are used for subgrade stabilization. Approximately 75% of kiln dust particles are finer than 0.030 mm (No. 450 sieve). LKD has a maximum size of approximately 2 mm (minus No. 10 sieve), and Blaine fineness ranges between approximately 1,300 and 10,000 cm^2/g (Collins & Emery, 1983). LKD specific gravities vary between 2.6 and 3.0, and the bulk density is commonly about 84 lb/ft^3 (FHWA, 2016; Collins & Emery, 1983). Table 2.1 shows a screen analysis of LKD provided by the U.S. Lime Company-St. Clair.

Table 2.1: LKD Screen Analysis

Sieve Size	Percent Passing
100 Mesh	92.0–93.0%
200 Mesh	64.0–67.0%
325 Mesh	15.0–39.0%

Source: U.S. Lime Company-St. Clair

2.3.4 Chemical Properties

Since LKD is a by-product of lime, the chemical properties of LKD vary depending on the source rock and the lime manufacturing process. In addition to the constituents discussed previously, LKD contains significant alkalis and is considered to be caustic. Due to the caustic nature of LKD, some corrosion of metals (e.g., aluminum) that come in direct contact with LKD may occur. The pH of LKD water mixtures is typically about 12. Tables 2.2 and 2.3 show the chemical composition of LKD from different sources.

Table 2.2: Typical Chemical Composition of Lime Kiln Dust

Parameter	Lime Kiln Dust		
	Fresh		Stockpiled
	High*	Low*	
CaO	54.5	31.2	31.2
Free Lime	26.4	5.1	0.0
SiO_2	9.94	2.46	1.74
Al_2O_3	4.16	0.74	0.71
MgO	0.49	23.5	23.3
Na_2O	0.03	0.00	0.05
K_2O	0.22	0.09	0.03
Fe_2O_3	1.98	0.94	1.3
SO_3	7.97	2.80	3.5
Loss on Ignition, 105°C	14.2	37.4	27.9

* Two types of LKD were classified in the reported data (high reactivity and low reactivity) based on the release of heat and rise in temperature when placed in solution.

Source: Collins and Emery (1983)

Table 2.3: Typical Analysis Lime Kiln Dust

Minerals	Percent (%)
Calcium Oxide (CaO)	80.0 – 90.0
Available Calcium Oxide (CaO)	55.0 –70.0
Magnesium Oxide (MgO)	0.90 – 2.0
Silicon Dioxide (SiO_2)	1.40 – 2.0
Iron Oxide (Fe_2O_3)	1.32 – 2.01
Aluminum Oxide (Al_2O_3)	0.45 – 0.72
Sulfur (S)	0.65 – 1.10
Mechanical Moisture (H_2O)	0.50 – 0.60
Acid Insoluble	1.50 – 2.20

Source: U.S. Lime Company-St. Clair

2.4 LKD in Soil Stabilization

Several research projects that investigated the use of LKD for soil stabilization were reviewed and are summarized as follows:

The Michigan Department of Transportation (Bandara et al., 2016) conducted an in-depth laboratory investigation and some field evaluation tests to better understand the long-term and short-term performance benefits gained from using recycled materials to stabilize subgrade soils. CKD, LKD, fly ash (FA), and concrete fines (CF) were the recycled materials that were selected for subgrade stabilization in this project. In this research project, Bandara et al. (2016) used the three most commonly problematic types of soils in Michigan. The soils used were, as classified by the AASHTO method, (1) an A-6, (2) an A-4, and (3) an A-7-6 soil. Two types of LKD, high-calcium lime kiln dust (LKD) and dolomite lime kiln dust (DLKD) were used and tested. Based on pH test results, treatment levels of 6%, 4%, and 6% LKD by dry weight of the soils were selected for Soil-1, Soil-2, and Soil-3, respectively. Similarly, levels of 12%, 17%, and 16% DLKD by dry weight of the soils were selected for Soil-1, Soil-2, and Soil-3.

Atterberg limit tests presented in Table 2.4 show that adding LKD had very little effect on the liquid and plastic limits of the tested soils. In other words, the soil classification remained the same in most of the cases. Bandara et al. (2016) found that changes in the unconfined compression strength of soaked LKD-treated soils were insignificant. However, the unsoaked unconfined compression strength of the LKD and Soil-1 mix gained 50 psi over the untreated soil after 3 days of curing.

Table 2.4: Atterberg Limit Test Results of LKD-Soil Mixtures

Soil Type	Percentage Stabilizer	Test	Value	Classification of Mixed Soils
LKD and Soil-1 (A-6) Mix	6% LKD	LL	39.3	A-6
		PI	12.2	
	12% DLKD	LL	42.7	A-7-6
		PI	14.8	
LKD and Soil-2 (A-4) Mix	4% LKD	LL	21.9	A-4
		PI	3.4	
	17% DLKD	LL	22.3	A-4
		PI	3.1	
LKD and Soil-3 (A-7-6) Mix	6% LKD	LL	44.8	A-7-6
		PI	20.3	
	16% DLKD	LL	47.3	A-7-6
		PI	19.9	

Source: Bandara et al. (2016)

Therefore, 6% LKD was recommended for modification of Soil-1. Summaries of the unconfined compression strength results of soil samples cured for 7 and 3 days for soaked and unsoaked samples, respectively, are shown in Tables 2.5 and 2.6.

Bandara et al. (2016) made the evaluations in the last column in Tables 2.5 and 2.6 based on ASTM D4609. According to ASTM D4609, if the unconfined compression strength of a treated soaked sample increases more than 50 psi over that of the native soil after 7 days of curing, the additive is considered a long-term treatment (stabilization).

Similarly, if the unconfined compression strength of a treated unsoaked sample increases more than 50 psi over that of the native soil after 3 days of curing, the additive is considered a short-term treatment (modification). Overall, Bandara et al. (2016) reported that CKD and the mixtures of LKD+FA can provide long-term stabilization for all three types of soil when a specific soil-dependent rate is applied. FA and LKD worked as short-term modifiers that improved workability for some, but not all, types of soil. Concrete fines (CF) were ineffective for all three types of soil.

Table 2.5: UCS Test Results & Selection of Stabilizer for Soil-1 (A-6)

Treatment	Soaked UCS (psi)*	Increase (psi)	Unsoaked UCS (psi)+	Increase (psi)	Comments
Untreated	2.61	-	32.26	-	
6% CKD	30.33	28	61.72	29	
8% CKD	71.91	69	70.71	38	Stabilization
12% CKD	77.77	75	153.51	121	
4% CF	4.29	2	55.86	24	
12% CF	18.40	16	48.43	16	
25% CF	19.91	17	57.60	25	
10% FA	10.94	8	63.81	32	
15% FA	4.71	2	92.81	61	Modification
25% FA	4.94	2	79.57	47	
2% LKD/5% FA	8.70	6	88.14	56	
3% LKD/9% FA	85.95	83	162.48	130	Stabilization
5% LKD/15% FA	147.15	145	192.55	160	
6% LKD	26.27	24	84.27	52	Modification
12% DLKD	10.59	8	66.75	34	

*7 days of curing, +3 days of curing

Source: Bandara et al. (2016)

Table 2.6: UCS Test Results & Selection of Stabilizer for Soil-3 (A-7-6)

Treatment	Soaked UCS (psi)*	Increase (psi)	Unsoaked UCS (psi)+	Increase (psi)	Comments
Untreated	1.43	-	62.49	-	
4% CKD	81.42	80	176.23	114	Stabilization
6% CKD	105.05	104	223.26	161	
8% CKD	133.43	132	220.46	158	
4% CF	4.25	3	71.77	9	
15% CF	6.58	5	54.51	-8	
25% CF	13.30	12	58.31	-4	
10% FA	24.26	23	102.48	40	
15% FA	67.99	67	91.12	29	Stabilization
25% FA	63.90	62	105.36	43	
2% LKD/5% FA	45.51	44	105.74	43	
2% LKD/8% FA	47.11	46	82.83	20	
3% LKD/9% FA	130.12	129	121.54	59	Stabilization
6% LKD	35.57	34	44.29	-18	
16% DLKD	27.96	27	53.78	-9	

*7 days of curing, +3 days of curing

Source: Bandara et al. (2016)

Jung et al. (2011) conducted a field investigation on six sites across the state of Indiana to evaluate the in-situ performance of subgrade soils treated with LKD. At each site, 5% of LKD by dry weight of native soil had been mixed with the soil to a depth of 400 mm. All of the sites had been in service for more than 5 years at the time of the study. They performed falling weight deflectometer (FWD), dynamic cone penetration (DCP), and standard penetration tests (SPT) on each site. They observed that the LKD treatment resulted in a reduction of fines content of the original soil by 20% to 40%. The LKD treatment also altered the classification of soil from a silty/clayey soil to a nonplastic silty sand. In addition, it was found that the increase in California Bearing Ratio (CBR) due to LKD treatment was at least 500% above that of the native soil. However, the treatment was not uniform with depth. They concluded that LKD remains in the soil for about 11 years.

Chen, Drnevich, and Daita (2009) conducted a laboratory study to investigate the short-term improvement of penetration resistance and electrical conductivity of LKD-treated soils. They investigated two types of soil, Orchard and Grundite clay. The soils were collected from West Lafayette, Indiana, and the Illinois Clay Products Company, respectively. They examined the change in water content of native soils with the addition of LKD. It was observed that the water content of Orchard clay was reduced 0.49% to 1.73% upon adding LKD. Similarly, adding LKD reduced the water content of Grundite clay by 2.14 to 4.4 percentage points. The higher LKD rates resulted in a greater reduction in water content of the native soils.

Needle penetration tests were performed on the soil-LKD treated specimens just after compaction and after 1, 3, and 7 days curing. Chen et al. (2009) reported that most of the penetration resistance gain was achieved within 1 day of mixing and compaction. They also stated that, since LKD contains a small amount of calcium compounds when compared with lime, a larger percentage of LKD is needed to produce the desired improvement.

Abdul and Timothy (2005) conducted a laboratory investigation to evaluate the use of LKD for stabilization of subgrade soils. They investigated three types of LKD mixed with one type of soil (CL) to determine the engineering properties of the LKD-soil mixture. A series of rates of LKD treatment (2–10% by weight at 2% intervals) were tested. Abdul and Timothy found that liquid limit and plastic limit values for the LKD-soil mixture increased with addition of LKD when compared to the native soil. They also found that liquid limit and plastic limit values tended to decrease with increasing LKD rates beyond 6% to 10% for all the LKD materials.

Abdul and Timothy reported that LKD-soil mixtures gain most of their strength with the addition of 6% LKD, with the unconfined compression strength of the unsoaked samples increasing from 55 psi for the native soil to 90 psi for LKD-treated soil after 3 days of curing. In addition, unconfined compression strength continued to increase to 150 psi after 27–81 days curing. It was observed that the time allowed for LKD-treated soil to cure is an essential aspect of LKD soil stabilization design. Figure 2.1 shows the time-dependent unconfined compression strength values for the 6% LKD-treated soil specimens. It was also observed that unconfined compressive strength values increased gradually with increasing LKD rates. The relation between unconfined compressive strength and LKD rates is shown in the Figure 2.2.

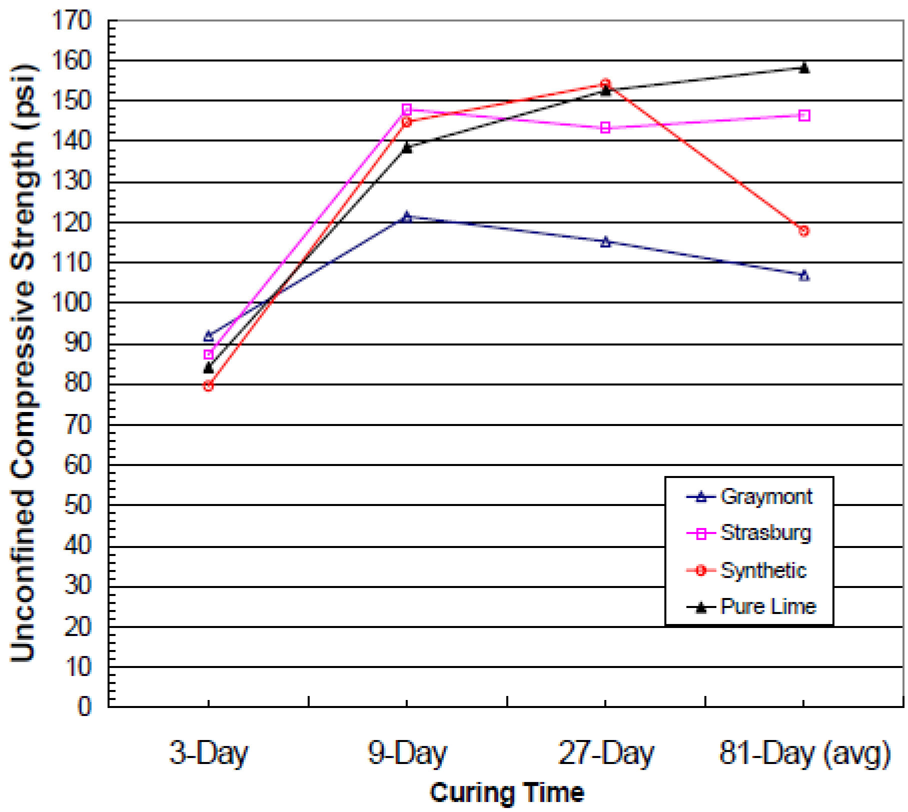


Figure 2.1: Unconfined Compressive Strength for 6% LKD-Treated Soil Cured for Various Times

Source: Abdul and Timothy (2005)

Abdul and Timothy (2005) also found that the CBR values increased from 4% for native soil to about 35–40% for all three types of LKD for LKD rates greater than 4%. It was concluded that 6% of LKD (by dry weight of soil) was the optimum dosage for stabilization purposes, and 4% LKD was sufficient to bring the pH to the required value of 12.45.

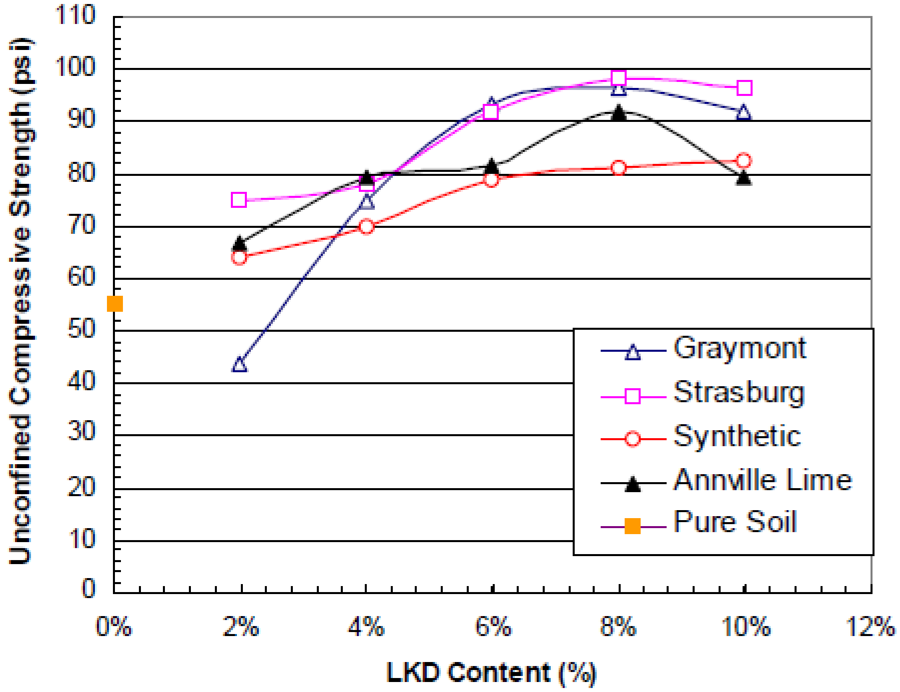


Figure 2.2: Effect of LKD Content on the Unconfined Compressive Strength of LKD-Treated Soil
Source: Abdul and Timothy (2005)

Petry (2001) conducted an extensive laboratory investigation to study the effectiveness of several additives for stabilizing slopes and minimizing erosion along the I-55 corridor south of Sikeston, Missouri. LKD, Portland cement (PC), quicklime (QL), and a mixture of quicklime and fly ash (QL-FA) were selected to treat two different types of soils, a clay soil and a silt. Both soils were actually mixtures of clay and silt. Based on Atterberg limits and pH test results, Petry (2001) recommended 6% and 8% LKD as an optimum treatment level for both the silt and clay soils.

The study reported that both LKD and a 50/50 mixture of quicklime and Class C fly ash from Sikeston were observed to increase the unconfined compression strength substantially when added to the soils at a rate of 12% by dry weight of soil. Adding 12% LKD increased unconfined compression strength by three times, and adding 8% LKD increased unconfined compression strength by two times when compared to that of the native soil. QL-treated soil samples experienced a smaller gain in unconfined compression strength.

Petry (2001) also stated that addition of 6% LKD reduced the horizontal swell from 3.3% to 0.4% and vertical heave from 7.3% to 0%. When adding 8% LKD, the horizontal swell was eliminated and vertical heave decreased to 0.04%. With regard to the durability performance of the LKD-treated soils, LKD-treated silt specimens performed less well than those treated with the other additive combinations in wet-dry testing. Although LKD provided good resistance to the action of freeze-thaw, it did not perform as well as the other additives.

Petry (2001) concluded that LKD reacted well with the clay soil and the addition of 6% LKD provided very good strength gain. LKD also performed well for all the tests at the 12% LKD level of treatment. However, QL had the best performance in wet-dry tests for both the 6% and 12% levels of treatment, and LKD-treated specimens did not perform as well as the lime- and 50/50 mixture-treated specimens.

Chapter 3: Laboratory Investigation

A set of laboratory and field investigation procedures were used to examine the suitability of LKD for stabilizing subgrade soils found in the state of Kansas. Brief descriptions of the soils and additives tested and the laboratory and field procedures followed are presented in this chapter.

3.1 Materials

3.1.1 Soil Selection

Five different subgrade soils taken from three different construction sites in Kansas were selected for this study. The soils were CH, CL, and ML types, and their properties were determined according to the ASTM standards listed in Table 3.1. The CL soils were obtained from the I-35-Mohawk Road interchange near McPherson, Kansas, and from a commercial store foundation pad in Kansas City, Kansas. The soil of CH type was taken from the central district of the University of Kansas in Lawrence, Kansas. Figure 3.1 shows the approximate source locations of the soils.

The soils taken from I-35-Mohawk Road in McPherson are referred to as “McPherson Black” and “McPherson Red” soils in this report. Similarly, the soils taken from the University of Kansas and Kansas City are referred to as “KU” and “KC” soils, respectively. Figure 3.2 shows types of soils used in this research. The fifth soil is from near Atwood, Kansas, and is labeled “Atwood.”

3.1.2 Additives

The primary additive of interest for this study is lime kiln dust (LKD). Lime (quick lime) and Class C fly ash were also used in this study for comparison purposes. The soils were mixed with each of the additives. Additive quantities were determined according to ASTM D6276 (pH criteria) and construction practices from around the region. Figure 3.3 shows the pH determination process.

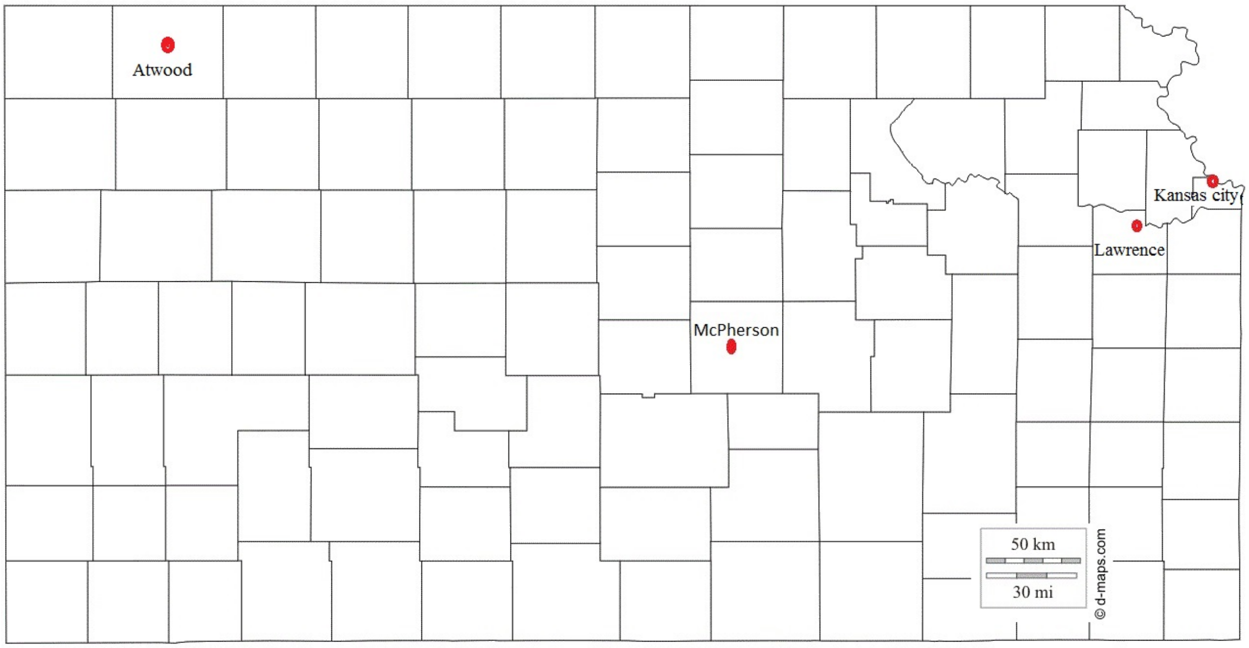


Figure 3.1: Approximate Source Locations of Soils

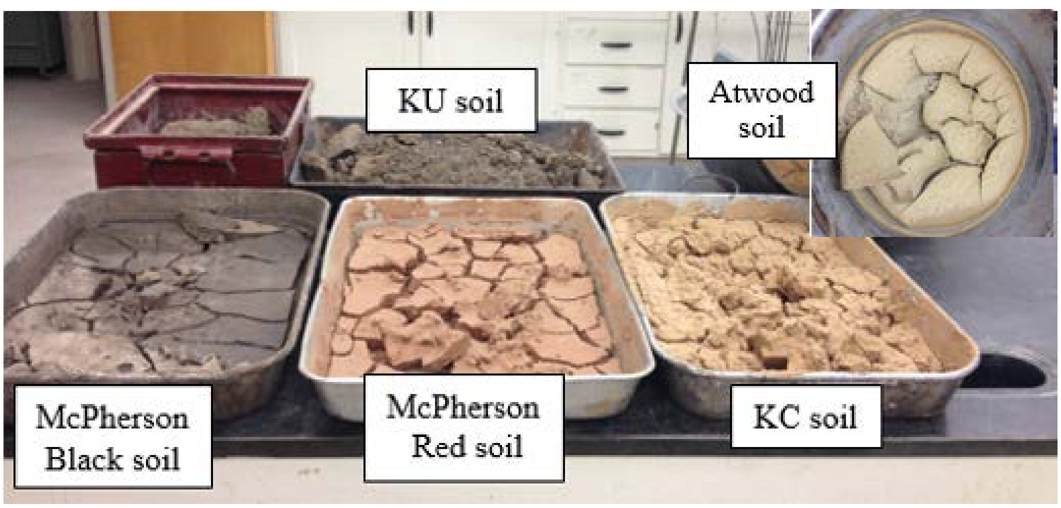


Figure 3.2: Soil Types

Figure 3.3: pH Determination

Table 3.1: Standard-Testing Procedures

Test	ASTM
Grain Size Analysis	D422
Atterberg Limits	D4318
Specific Gravity	D854
pH Lime Stabilization	D6276
Moisture-Density Relationship	D698
Swell	D4546-14, D2435
Freeze-Thaw	D560
Wet-Dry	D559
Harvard Miniature Compaction	D4609
Unconfined Compression	D2166, D5102

3.2 Laboratory Testing

3.2.1 Soil Preparation

Each soil was dried at 60°C in a large oven. For hydrometer analysis and determination of the Atterberg limits, the dry soil was washed through a No. 40 (0.425 mm) sieve in accordance with ASTM D2216. The portion of the soil that passed the No. 40 sieve was dried again at 60°C and then broken down with a mortar and pestle. For determination of moisture-density relationships, unconfined compression strength, and durability, the dry soils were crushed, pulverized, and passed through the No. 4 (4.75 mm) sieve.

3.2.2 Grain Size Distribution

Grain size analyses were performed to classify the particle size of the native (untreated) soils using the wet sieve method in accordance with ASTM D442. Approximately 500 g of oven-dry soil sample was washed through a No. 200 sieve (0.075 mm), and the portion retained on the sieve was dried again. The dry mass of the material retained on the No. 200 (0.075 mm) sieve was recorded, and the percentage of soil passing through the No. 200 (0.075 mm) sieve was used to classify the soil. Figure 3.4 shows the wet sieve method used in this study.

Figure 3.4: Wet Sieve Method

3.2.3 Atterberg Limits

The liquid limit, plastic limit, and plasticity index of the native soils and the LKD-treated, lime-treated and fly ash-treated soil mixtures were determined according to ASTM D4318. Liquid limits were conducted using the multipoint liquid limit method (Method B) described in ASTM D4318, with the following exceptions:

1. For LKD-treated soils, LKD was mixed with the dry soil and water was added to raise the moisture content of the mixture to the desired level. After complete mixing of the soil, the mixture was covered and allowed to mellow for 1 hr. Atterberg limits were then determined in accordance with ASTM D4318. The same procedure was followed for the determination of Atterberg limits of fly ash-treated soils.
2. For lime-treated soils, lime was mixed with the soil and water was added to raise the moisture content of the soil-lime mixture to the desired level. After mixing to a uniform consistency, the soil-lime mixture was then allowed to

mellow at room temperature (22°C) for 24 hr. The mellowing was achieved by placing the soil-lime mixture in an open-end Ziploc bag. The bag was then placed in an airtight container half-filled with water to only allow indirect exposure to moisture, as shown in Figure 3.5.

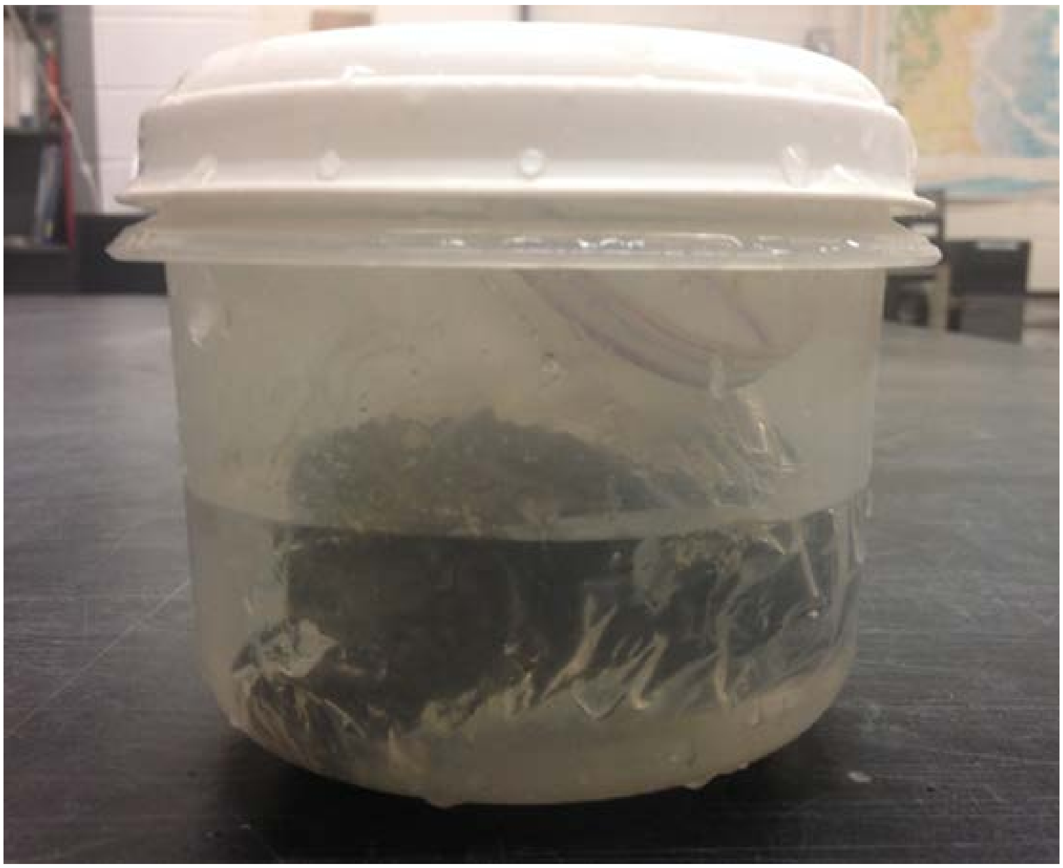


Figure 3.5: Mellowing Process

3.2.4 Moisture-Density Relationships

Moisture-density relationship curves were established for each soil/additive combination using standard Proctor tests in accordance with ASTM D698-Method A. Each soil sample was screened on a No. 4 (4.75 mm) sieve and then mixed with water to the desired moisture content. The soil was compacted in a 4-in.-diameter mold with a $^{1}/_{30}$ ft^3 volume. It was compacted in three layers using 25 blows per layer. The mixture was compacted in accordance with ASTM D698, with the following exceptions:

1. For LKD treated soil, the soil and the additive were mixed together dry to a uniform consistency, and then water was added to bring the moisture content up to the target percentage. The mixture was placed in an airtight container (Ziploc bag) for an hour to simulate a standard construction delay. Then the mixture was compacted according to ASTM D698-Method A. The same procedures were followed for fly ash-treated soil.
2. For lime-treated soil, after dry mixing of the soil and lime, water was added to the lime-soil mixture in the desired amount and then mixed. The mixture was then allowed to mellow overnight before compaction. The mixture was compacted in accordance with ASTM D698-Method A.

3.2.5 Swell

The swell test was conducted according to ASTM D4546-14, Standard Test Methods for One-Dimensional Swell or Collapse of Soils. For this test, approximately 1000 g of soil was placed in a 60°C oven overnight and a moisture content was obtained the following day. Water was added to the soil sample to bring the moisture content to the optimum moisture content. After mixing to a uniform consistency, the desired density (maximum dry density) was obtained by mass and volume control. The measured mass of soil was placed in three layers and each layer was compacted to a predetermined volume. Then, a soil specimen was prepared in a consolidometer ring and assembled in a consolidometer unit in accordance with ASTM D2435. To minimize the change in the moisture content of the specimen, the space around the specimen ring was enclosed with a foil before inundating the specimen. A seating pressure of 1 kPa (0.145 psi) was applied, and the deformation-measuring device was set to zero for the initial reading. A vertical stress of 9.28 kPa (1.347 psi) was then applied to represent the stress in the field. This vertical stress was applied in three increments with 10-minute intervals between each increment. After the amount of deformation for each of the loading stages was recorded, the specimen was inundated with water, and deformation readings were taken at intervals of 0.5, 1, 2, 4, 8, 15, 30, 60, 120, 240, and 480 min, and 24, 48, and 72 hr in accordance with ASTM D2435. At the end of the test, the final mass and the moisture content of the specimen were determined as well. A typical setup of the test is shown in Figure 3.6.

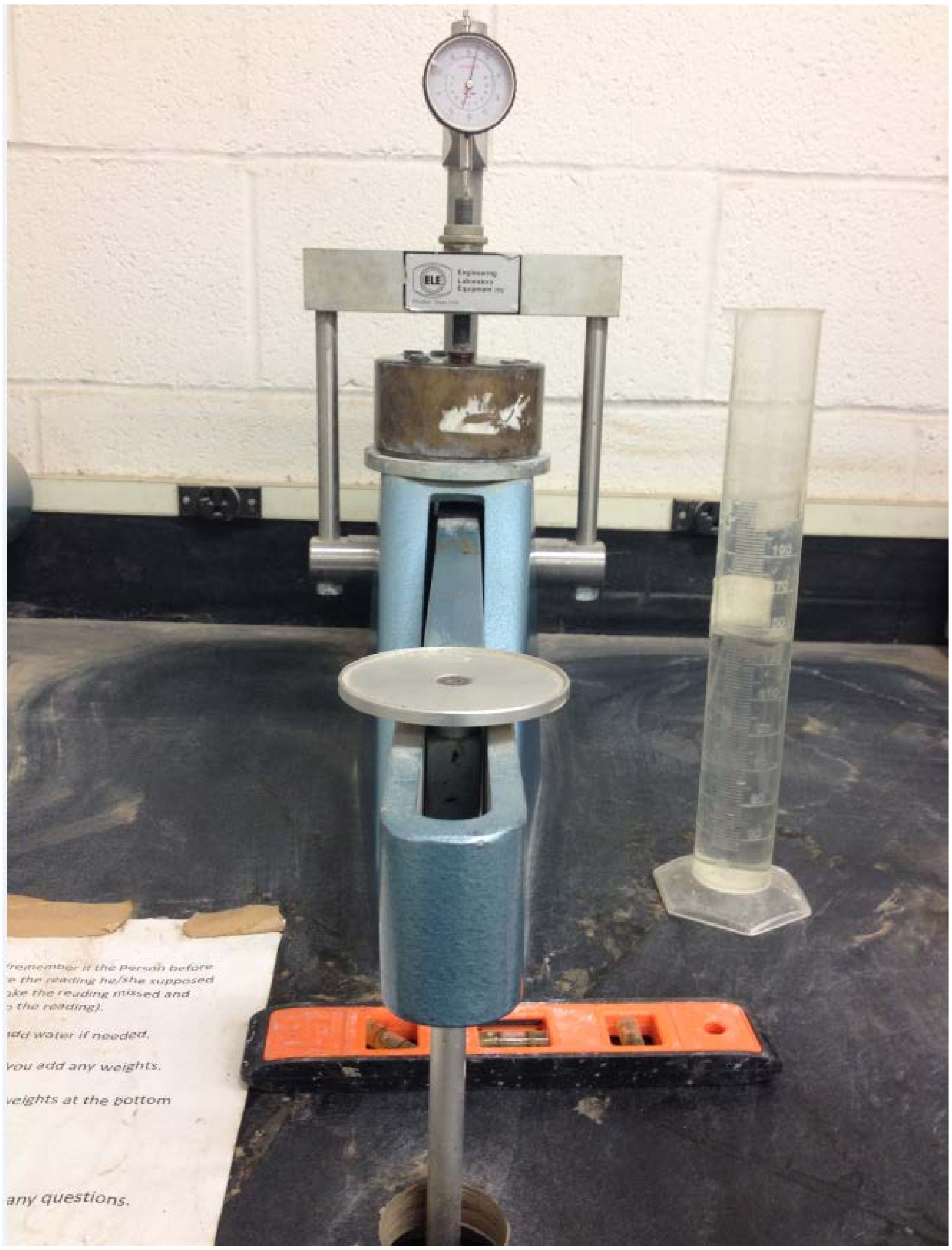


Figure 3.6: Swell Test Setup

The test was performed for all native and LKD- and lime-treated soil samples according to ASTM D4546-14, with the following exceptions:

A. Method A requires preparing four specimens to represent four different depths. However, in this study only one specimen was prepared for each soil/additive combination to represent a specific depth only.
B. For LKD-treated soil samples, the LKD-soil mixtures were set aside to stand for 1 hr before compaction to simulate a standard construction delay.
C. For lime-treated soil samples, the lime-soil mixtures were first allowed to mellow for 24 hr and then compacted to the desired density.

3.2.6 Freeze-Thaw

Freeze-thaw tests were conducted in accordance with ASTM D560. Two identical samples of each soil/additive combination were prepared at the optimum moisture content following ASTM D698 sample preparation procedures. LKD-soil mixtures were allowed to stand for 1 hr prior to compaction, and a similar procedure was followed for fly ash-soil mixtures. The lime-soil mixtures were allowed to mellow for 24 hr before compaction. After compaction, the samples were cured for 7 days in a moisture room and then subjected to freeze-thaw cycles. Each freeze-thaw cycle consisted of placing the two soil samples in a freezer at -23°C for 24 hr, followed by keeping the samples in a moist room for 23 hr. After completing each cycle, the first sample was measured for volume change and weighed to determine any change in moisture content. The second sample was brushed to determine the soil loss. The test was continued until 12 cycles were complete or until the sample failed.

3.2.7 Wet-Dry

Wet-dry tests were performed according to ASTM D559. Two identical samples of each soil/additive combination were prepared at the optimum moisture content following moisture-density sample preparation procedures. LKD-soil mixtures were allowed to stand for 1 hr prior to compaction, and a similar procedure was followed for fly ash-soil mixtures. Lime-soil mixtures were allowed to mellow for 24 hr before compaction. After compaction, the samples were cured 7 days in a moisture room and subjected to wet-dry cycles. Each wet-dry cycle consisted of submerging the two soil samples in water for 5 hr and then placing them in a 71°C oven for 42 hr. After completing each cycle, one sample was brushed and weighed to determine the soil loss. The other sample was measured for volume change and weighed to determine any change in moisture content. The test was continued until 12 wet-dry cycles were completed or until the sample failed.

3.2.8 Calibration of Harvard Miniature Compaction Apparatus

A Harvard Miniature Compaction Apparatus was used to prepare soil samples for unconfined compression strength testing. The Harvard Miniature Compaction Apparatus includes a cylindrical mold with an inside diameter of 1.3125 in., a height of 2.816 in., and a volume of $^{1}/_{454}$ ft^3. It has a spring-loaded plunger that serves as a sample extruder. Figure 3.7 shows the Harvard apparatus. Calibration of the Harvard apparatus was performed in accordance with ASTM D4609 Annex A1. The soils were compacted to determine the required moisture content and compaction effort needed to achieve the maximum dry density obtained from the standard Proctor test. This was achieved by compacting the soil at various moisture contents using a number of layers of compaction and a number of blows per layer. Then the compaction curve obtained from the Harvard apparatus was plotted versus the compaction curve obtained from the standard Proctor tests. The compaction effort having a density within 16 kg/m^3 (approximately 1% or slightly less) of the maximum dry density was selected for preparing samples for the unconfined compression strength tests. This calibration procedure was conducted on all soil/additive combinations.

Figure 3.7: Harvard Miniature Compaction Apparatus

3.2.9 Unconfined Compression Strength

Specimens were prepared for unconfined compression strength testing using the Harvard apparatus. All samples were fabricated at ±1% of optimum moisture content as determined from the calibration process described in Section 3.2.8. Unconfined compressive strength tests were performed on both soaked and unsoaked samples after various curing periods. The soaking and curing procedures followed in this study are described in the following two sections. The unconfined compression tests were conducted in accordance with ASTM D2166. Figure 3.8 shows a typical setup for the unconfined compression strength tests.

Figure 3.8: Standard Setup for Unconfined Compression Strength Test

3.2.10 Curing

After being prepared using the Harvard apparatus, the samples were placed in a small open plastic bag and stored in an airtight container or a larger plastic bag containing about 30 ml of water, as shown in Figure 3.9. This curing technique allowed the samples to retain moisture without coming into direct contact with the water. The curing period varied from zero to 28 days. This curing procedure provided sufficient moisture and time for strength gain by pozzolanic reactions between the free lime and clay minerals.

Figure 3.9: Curing Technique

3.2.11 Capillary Soaking

Prior to unconfined compression strength testing, samples were subjected to a period of 24 hr of capillary soaking that began immediately after compaction, or after compaction and the appropriate curing time. In preparation for the capillary soaking process, the specimens were removed from the plastic bags and wrapped with water-absorbent paper and then placed on porous stones. These porous stones were submerged in water with the water level kept just below the top of the porous stones. Thus, moisture was able to move from the bottom to the top of the soil specimen by capillary soaking without being in direct contact with water, which simulates actual water movement under field conditions. Figure 3.10 shows the capillary soaking technique.

3.2.12 Volume Change Measurements for Soil Specimens

The soil specimens prepared for unconfined compression strength tests were also used for volume change measurements. Vertical and circumferential measurements of the samples before and after capillary soaking were taken to evaluate the volume change between dry and soaked conditions.

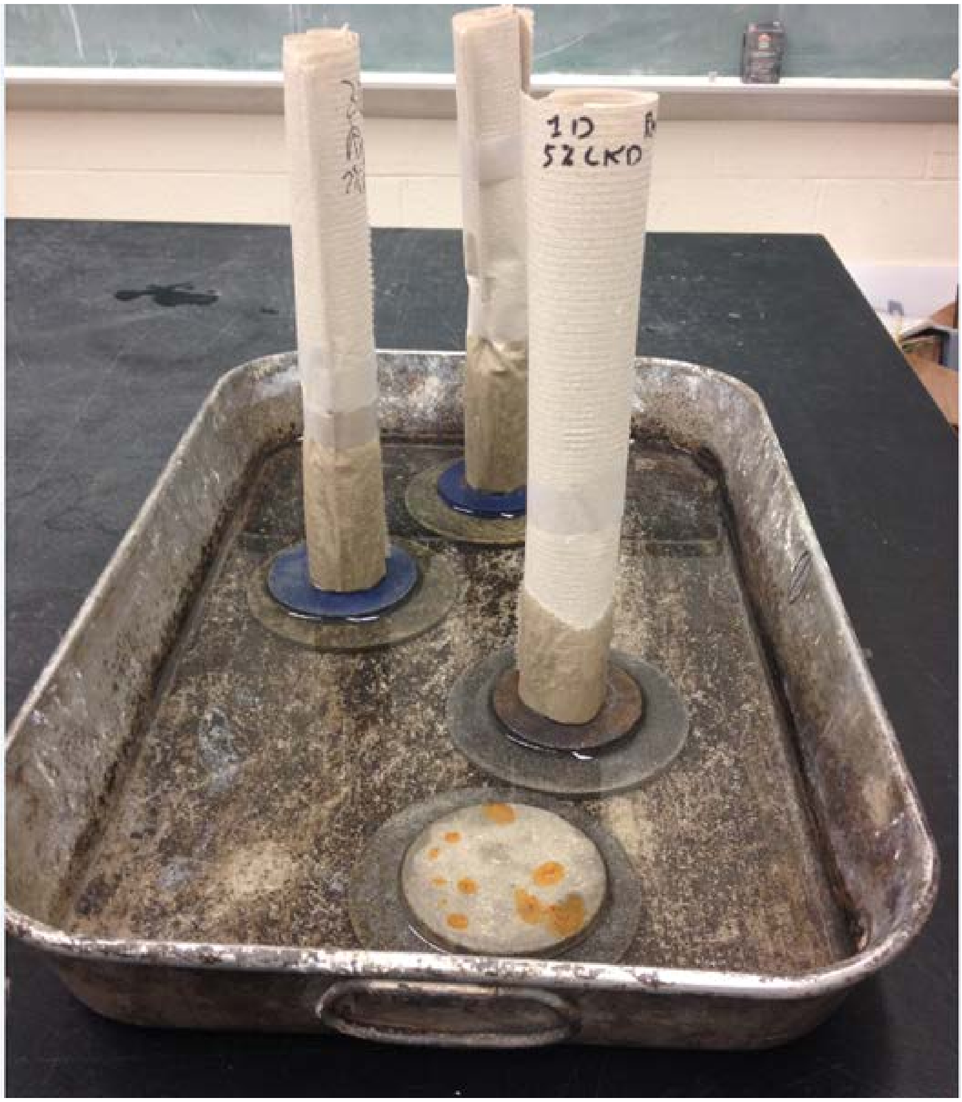


Figure 3.10: Capillary Soaking Technique

3.2.13 Resilient Modulus

Specimens were prepared for resilient modulus testing with the desired levels of additives as measured by dry weight and tested using apparatus designed for this purpose. All samples were fabricated at optimum moisture content and compacted to achieve maximum dry density. The resilient modulus tests were conducted by the Kansas Department of Transportation at their laboratory in Topeka, Kansas.

Chapter 4: Laboratory Results and Discussion

This chapter presents the results and discussion of the laboratory testing program. The testing program included characterization of the native soil properties, properties of the soils treated with various admixture percentages, and performance testing of the soil/additive combinations for several sets of conditions.

4.1 Native Soil Properties and Admixture Properties

The native soil characteristics were determined using grain size analysis, Atterberg limits, specific gravity, standard Proctor, and unconfined compression strength. A summary of these test results is presented in Table 4.1. Volume change, wet-dry, and freeze-thaw tests were also conducted and are discussed in this chapter. Five soils were classified, and these included three CL soils (McPherson Black, McPherson Red, and KC), a CH soil (KU), and a ML soil (Atwood).

Table 4.1 also shows the admixture percentages that were required to modify each soil. The admixture percentages were determined according to either ASTM standards, Atterberg limits, or construction standards. Since no specific standard has been established to determine the amount of LKD required to modify the soil, two different rates of LKD were used, as presented in Table 4.1. The rates shown in the first row of LKD (LKD*) were determined according to the Eades and Grim procedure (ASTM D6276), and the second row shows a rate (5%) commonly used by contractors in the region. The amount of lime required for soil treatment was determined according to ASTM D6276. Twelve percent fly ash was used for treatment for all the soils, which is the lower end of the range (12–16%) used in the region. The graph of pH values versus additives content for each of the additives used in this study is presented in Appendix A. The admixture percentages used to evaluate relative soil performance for the testing procedures are presented in Table 4.2. All reported percentages are based on the dry weight of the soil.

Table 4.1: Native Soil Properties and Admixture Properties

Soil Properties	McPherson		KU	KC	Atwood
	Red	Black			
% Sand	5	3	1	3	12
% Fines	95	97	91	97	88
Liquid Limit	41	38	53	33	30
Plasticity Index	20	16	28	11	7
USCS	CL	CL	CH	CL	ML
AASHTO	A-7-5	A-6	A-7-5	A-6	A-4
Max Unit Weight, lb/ft^3	108.6	107.7	97.5	110.8	98.0
Max Density, kg/m^3	1740	1725	1562	1775	1573
Optimum Moisture, %	17.4	14.8	21.5	15.7	13.5
UC at Optimum, psf	4460	5760	3020	2730	5900
Specific Gravity	2.77	2.78	2.73	2.70	2.75
LKD*	8	10	15	7	6
LKD	5	5	5	5	5
Lime	3	3.5	4	2.5	2.0
Fly Ash	12	12	12	12	12

*Based on ASTM D6276

Table 4.2: Percentages of Admixtures with Different Soil Types

Soil	LKD (%)	Lime (%)	FA (%)
McPherson Black	5, 8, 10	2, 3.5	12
McPherson Red	5, 8, 10	2, 3	12
KU	5, 8	4	12
KC	5, 8	2.5, 4	12

4.2 Atterberg Limits

The results of tests for Atterberg limits with the various soil/additive combinations are presented in Table 4.3. Each soil exhibited a substantial increase in the plastic limit with the addition of 5% LKD. Although changes in the liquid limit were not consistent, increases in the plastic limit were sufficient to lower the plasticity index for all soils by 50% to 75%. Atterberg limit graphs of all soil/additive combinations are included in Appendix B.

Table 4.3: Atterberg Limit Values

Soil		McPherson Black		McPherson Red		KU		KC		Atwood	
		LL	PI	LL	PI	LL	PI	LL	PI	LL	PI
Native		38	16	41	20	53	28	33	11	30	6
LKD	5%	40	8	47	7	55	12	38	7	NP	NP
	8%	37	4	46	8	51	12	34	5	NP	NP
	12%	38	6	41	7	47	8	33	5	NP	NP
Lime	2%	40	9	52	12	56	13	37	4	NP	NP
	3%	35	3	47	6	51	10	36	5	NP	NP
	4%	35	3	49	8	53	8	37	5	NP	NP
Fly Ash	12%	36	11	49	24	55	26	33	9	28	5
	16%	33	9	47	23	58	29	31	7	NP	NP

The native liquid limit (LL) and the plasticity index (PI) for the CH soil (KU soil) were 53 and 28, respectively. The PI value for this soil was reduced to 12 when it was mixed with 5% LKD. Further reduction in the PI value was attained (from 12 to 8) by adding 12% LKD. Addition of 2% lime reduced the PI value of KU soil to 13, and the PI value was reduced to 10 and 8 when the soil was mixed with 3% and 4% lime, respectively. Fly ash had little to no effect on the PI value of KU soil.

The native LL and PI for the CL soils were 41 and 20 for McPherson Red soil, 38 and 16 for McPherson Black soil, and 33 and 11 for KC soil, respectively. The PI values for these soils were reduced to 7, 8, and 7, respectively, when they were mixed with 5% LKD. Introduction of 2% lime to the CL soils resulted in PI values of 12, 9, and 4 for McPherson Red, McPherson Black, and KC soil, respectively. Addition of higher percentages of lime (i.e., 3% and 4%) lowered the PI value further. Fly ash had a significant effect on the reduction of the plasticity of McPherson Black and KC soils. For 12% fly ash, the PI values for both soils were reduced to 11 and 9, and addition of 16% fly ash reduced the PI values to 9 and 7, respectively. The PI value for McPherson Red soil increased slightly.

The ML soil (Atwood) had a native LL value of 30 and PI value of 7. Addition of 5% LKD altered the soil to a nonplastic condition. The soil also became nonplastic when it was mixed with 2% lime and 16% fly ash.

4.3 Moisture-Density Relationships

Each soil/additive combination was tested to determine the optimum moisture and maximum dry density. The optimum moisture content and maximum dry density values for the native soils and each of the soil/additive combinations are presented in Table 4.4. Moisture-maximum density curves are presented in Figures 4.1 and 4.2. Additional maximum density figures are included in Appendix C.

Table 4.4: Optimum Moisture Content and Maximum Dry Density

Soil		McPherson Black		McPherson Red		KU		KC		Atwood	
		w %	Unit Wt. lb/ft³	w %	Unit Wt. lb/ft³	w %	Unit Wt. lb/ft³	w %	Unit Wt. lb/ft³	w %	Unit Wt. lb/ft³
Native		15	107.6	17	108.6	21	97.5	15	110.8	14	98.3
LKD	5%	15	105.3	17	108.0	17	98.2	14	108.9	14	97.5
	8%	18	102.7	16	107.0	15	104.0	15	109.5	-	-
	10%	17	101.2	18	102.5	17	95.7	14	105.9	-	-
Lime	2%	19	98.6	20	98.4	16	98.2	15	100.2	-	-
	OC*	15	93.0	16	95.5	17	95.5	17	101.4	-	-
Fly Ash	12%	16	104.9	15	94.9	20	102.1	16	110.8	-	-

*Optimum lime content
#4% Lime

The effects of soil treatment on the moisture-density relationship for most of the soils are reflected in Figure 4.1 (McPherson Black). As this figure shows, the untreated (native) soil had the highest maximum density and was relatively sensitive to changes in moisture content, as shown by the substantial decrease in dry density as the moisture content varies from optimum in both the wet and dry directions. All of the additives tended to lower the maximum density and reduce sensitivity to moisture (flatten the curve). Increasing the percentage of additive resulted in a larger decrease in density. Lime treatment resulted in the lowest density, while the density for fly ash treatment was consistent with the lesser amounts of LKD treatment. Optimum moistures tended to increase with more treatment; however, this was not universal and was somewhat less significant (with regard to density) given the reduced sensitivity to moisture.

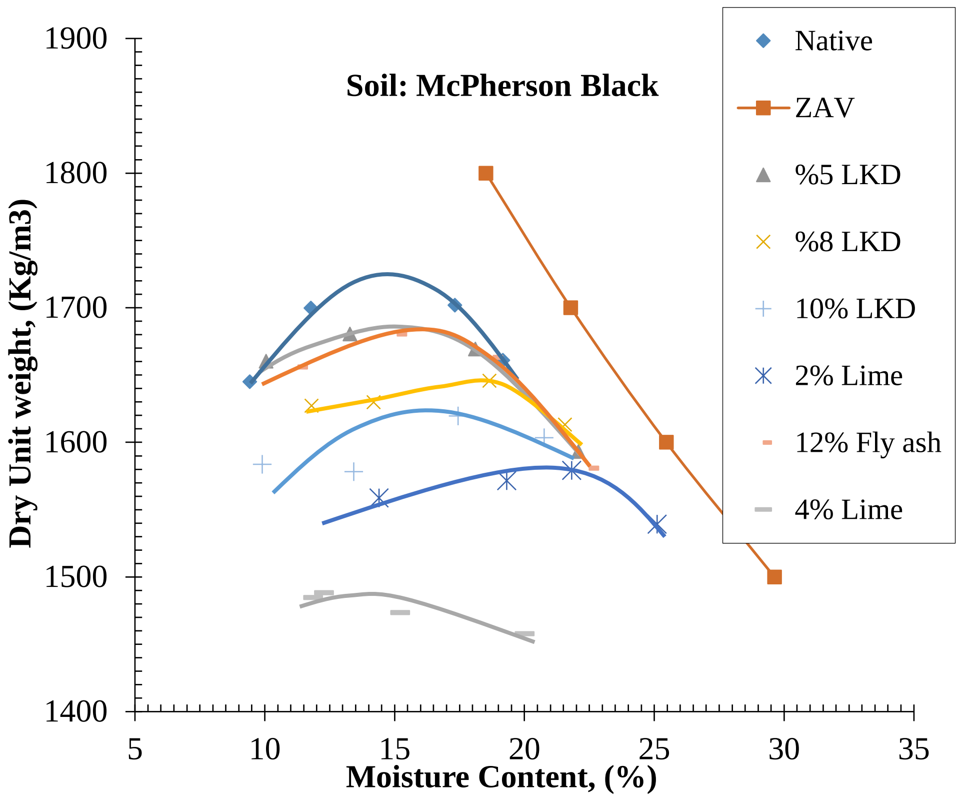


Figure 4.1: Moisture-Dry Density Curve for McPherson Black

The CH soil (KU soil) behaved somewhat differently, as shown in Figure 4.2. For this soil, treatment resulted in similar or increased maximum densities. Optimum moistures for treated soils were similar or lower when compared with the native optimum moisture content. Furthermore, increasing the percentage of LKD from 5% to 8% resulted in an increase in the dry density. An additional increase to 12% resulted in a decrease in density to near or slightly below the native level. As with the other soils, LKD- and fly ash-treated soils had higher density curves than lime-treated soils.

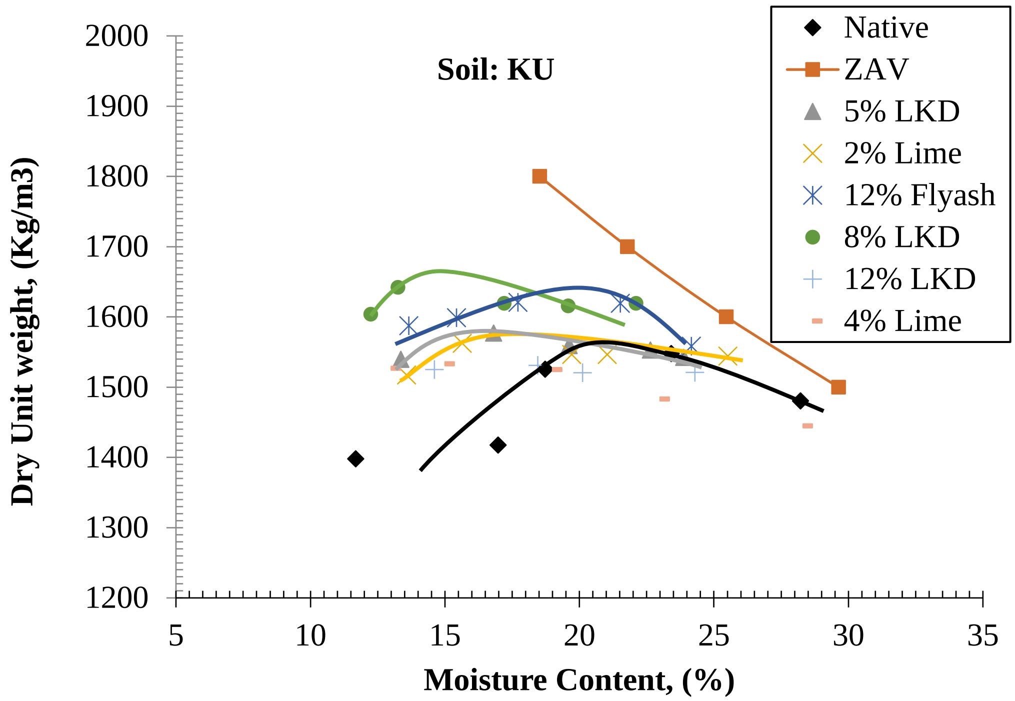


Figure 4.2: Moisture-Dry Density Curve for KU

The ML soil (Atwood) had a native optimum moisture content of 14% and a maximum density of 1575 kg/m^3. The optimum moisture content and the dry density experienced no change with the addition of 5% LKD.

4.4 Calibration of Harvard Miniature Compaction Apparatus

The calibration of the Harvard apparatus was performed to determine the required moisture content and compaction effort needed to achieve the maximum dry density, and the results are presented in Table 4.5. The table shows the number of layers and blows per layer for each soil/additive combination.

Five layers and 20 blows per layer were required to achieve the maximum dry density for McPherson Black/additive combinations. The number of layers and blows per layer required to achieve the maximum density ranged from 4 to 5 layers and 15 to 27 blows per layer for the rest of soils.

Table 4.5: Calibration Results for the Harvard Miniature Compaction Apparatus

Soil		McPherson Black		McPherson Red		KU		KC	
		Layers	Blows/ Layer	Layers	Blows/ Layer	Layers	Blows/ Layer	Layers	Blows/ Layer
Native		5	20	4	25	4	20	4	20
LKD	5%	5	22	4	25	5	15	5	24
	8%	5	20	5	20	5	15	5	15
	10%	5	20	-	-	4	20	-	-
Lime	2%	5	20	5	27	5	20	4	15#
	OC*	5	20	-	-	5	20	4	15
Fly Ash	12%	-	-	4	25	5	25	5	25

*Optimum Content
#4% lime

4.5 Unconfined Compression Strength

The results of the unconfined compression strength tests are presented in Figures 4.3 to 4.12. The samples were compacted at optimum moisture conditions in a Harvard Miniature Compaction Apparatus and the UC strength was determined in accordance with ASTM D5102. Soil samples were cured for curing times of 1–2 hr, 1 day, 3 days, 7 days, and/or 28 days prior to the test. Some soil samples were also soaked for 24 hr after a certain curing time and prior to the test to determine the soaked strength of the samples.

In general, the LKD- and lime-treated samples experienced an increase in strength with time. While fly ash-treated samples had modest strength gains over the strength of the native soil, LKD-treated samples experienced the highest increase in strength, and the strength of LKD-treated soil samples slightly increased with increasing LKD content. However, the rate of strength gain was not consistent with time for higher rates of LKD. The soil samples treated with 8% LKD showed the highest strength gain when compared with other LKD rates and additives. Overall, LKD-treated soil samples performed better than lime-treated samples with regard to strength gain.

Figures 4.3 and 4.4 show the unsoaked and soaked strengths of LKD- and lime-treated samples of McPherson Black soil for various curing times. The strength of all the treated samples increased with time, and the samples treated with 8% LKD had the highest strength gain. Addition of 5% and 8% LKD to the soil caused 120% and 200% increases in strength, respectively, after 7 days of curing when compared with the native soil strength. However, the trend of the strength gain for 10% LKD-treated samples was irregular and the samples had less strength gain when compared with the 8% LKD-treated samples. The soaked samples of LKD-treated soil had increases of 760%, 1800%, and 2000% over the native soil soaked strength after 7 days of curing for 5%, 8%, and 10% LKD content, respectively. The sample treated with 2% lime also had a 2000% increase in soaked strength when compared with the soaked strength of the native samples. McPherson Red soil samples had similar performance to McPherson Black soil samples when they were mixed with LKD, as shown in Figures 4.3 and 4.5 (unsoaked), and Figures 4.4 and 4.6 (soaked). McPherson Red LKD samples had an increase of 200% over the native strength for 5% LKD content. However, the samples treated with 10% LKD and 2% lime had 60% and 100% increases in strength, respectively, over the native strength after 7 days of curing. As shown in Figure 4.6, the soaked strengths of McPherson Red LKD-treated samples were increased by 700% and 2000% after 3 days of curing and 1400% and 1750% after 7 days of curing for 5% LKD and 8% LKD contents, respectively, when compared with the soaked strength of the native samples. The soaked samples treated with 2% lime had 2000% and 2400% increases in strength when compared with the soaked strength of the native samples after 3 and 7 day curing periods, respectively.

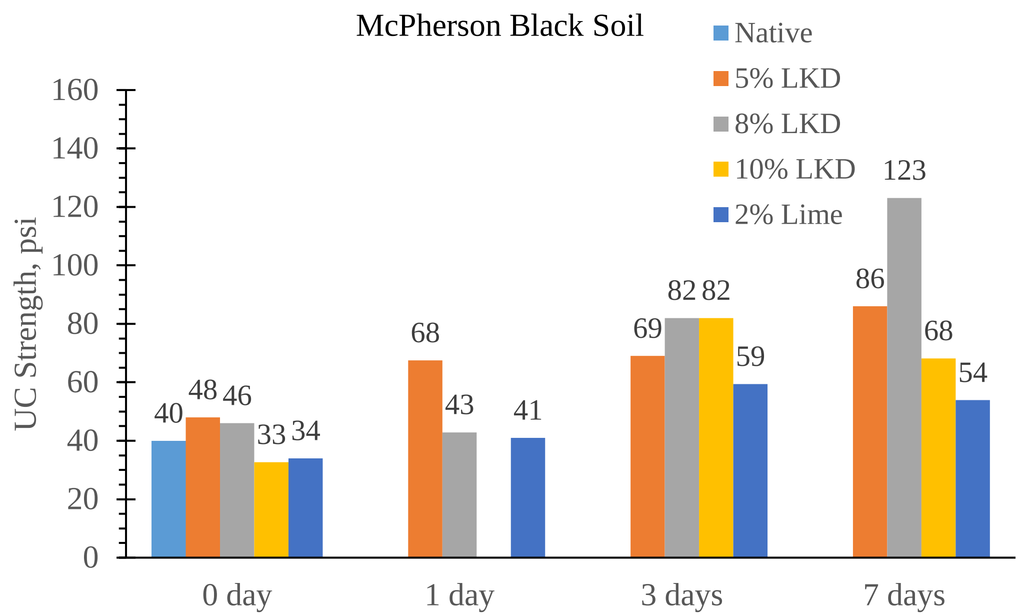


Figure 4.3: Unsoaked UC Strength of McPherson Black Soil/Additive Combinations

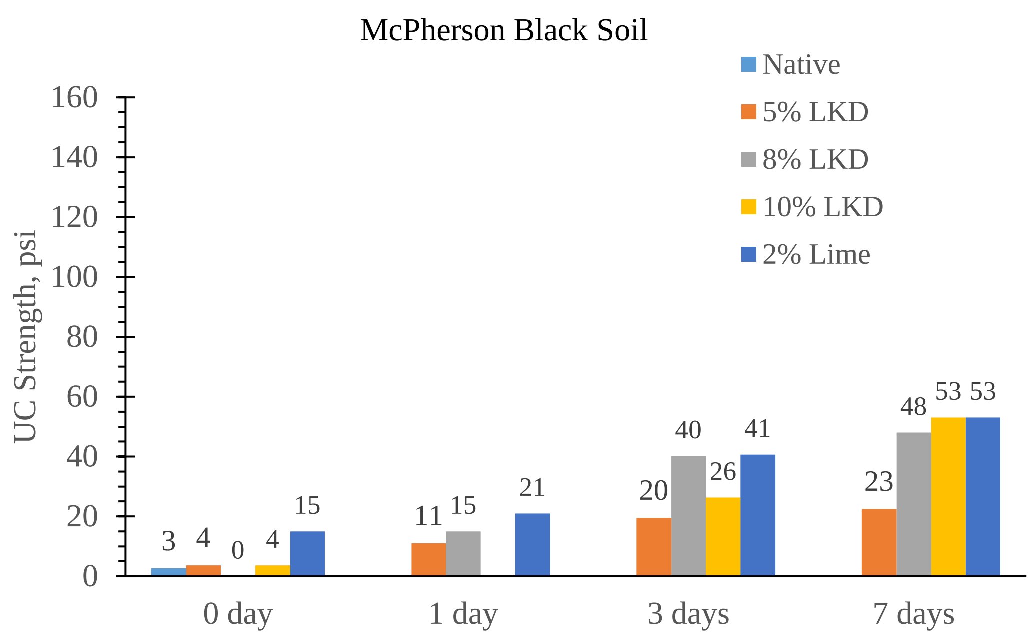


Figure 4.4: Soaked UC Strength of McPherson Black Soil/Additive Combinations

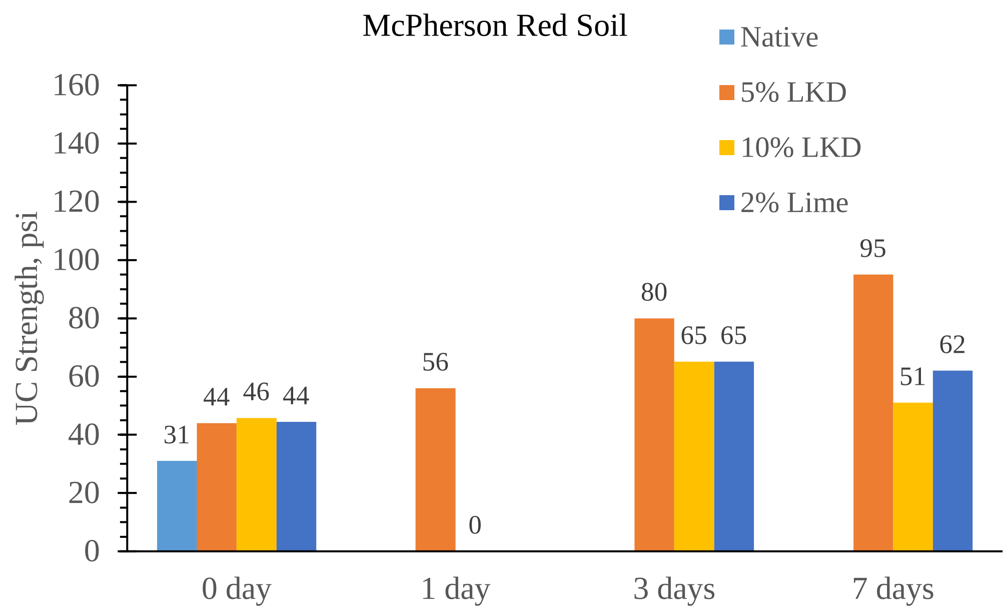


Figure 4.5: Unsoaked UC Strength of McPherson Red Soil/Additive Combinations

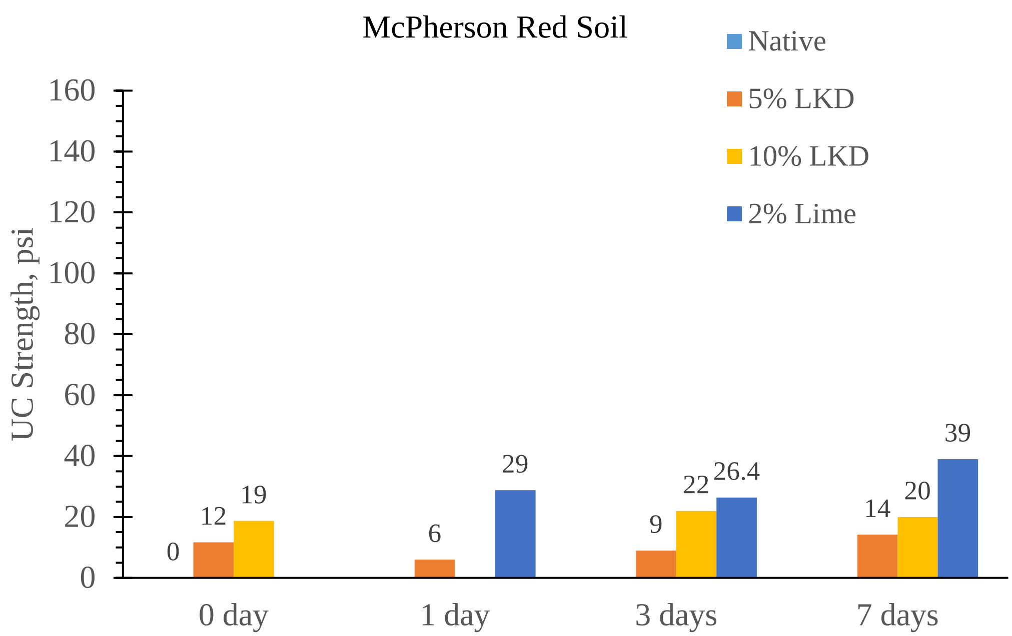


Figure 4.6: Soaked UC Strength of McPherson Red Soil/Additive Combinations

Figures 4.7 and 4.8 show the unsoaked and soaked UC strength of KC soil/additive combinations for various curing times. KC soil samples had substantial strength gains with time when they were mixed with LKD or lime. The UC strength of unsoaked samples was increased by

400% and 500% after 7 days curing time for the samples treated with 5% LKD and 8% LKD, respectively. Addition of 2.5% lime resulted in a 250% increase in UC strength for the unsoaked samples when compared with the native samples after 7 days of curing. The UC strength of the soaked samples was substantially increased with the addition of LKD, and the magnitude of the improvement increased with curing time. The soaked samples of KC soil had increases of 1300% and 2500% over the native strength with the addition of 5% and 8% LKD, respectively. Soaked KC soil samples treated with 2.5% lime experienced a 1400% increase in strength over the strength of the native soil.

Figures 4.9 and 4.10 show that the CH (KU) soil also showed a substantial improvement in UC strength with the addition of LKD and with increased curing time. Addition of 5% LKD to the soil caused increases in strength of 320% and 400% when compared with the strength of the native soil after 3 and 7 days of curing, respectively. KU soil samples treated with 2% lime had an increase of 200% in strength when compared with the strength of native soil. Similarly, the strength of the soaked samples of KU soil increased substantially with the addition of 5% LKD.

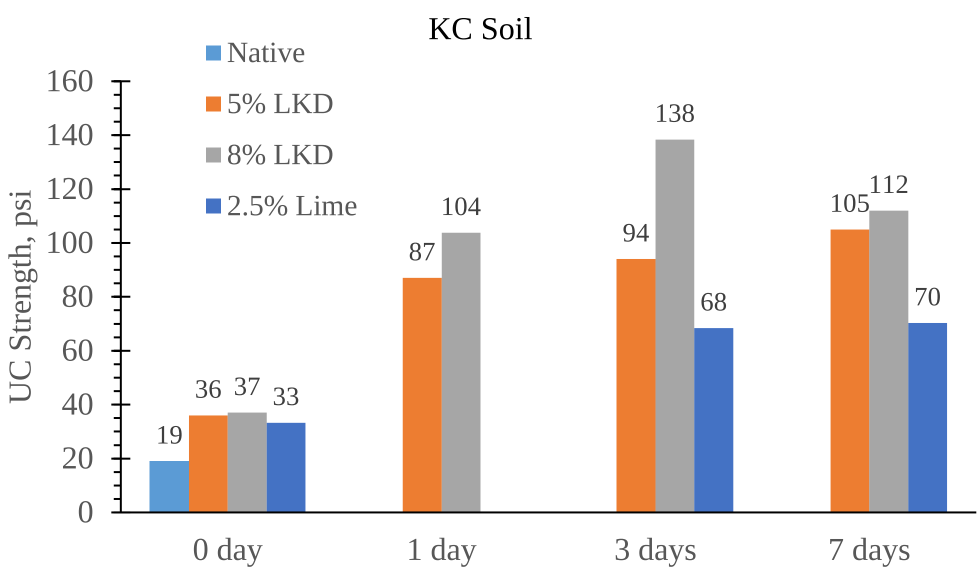


Figure 4.7: Unsoaked UC Strength of KC Soil/Additive Combinations

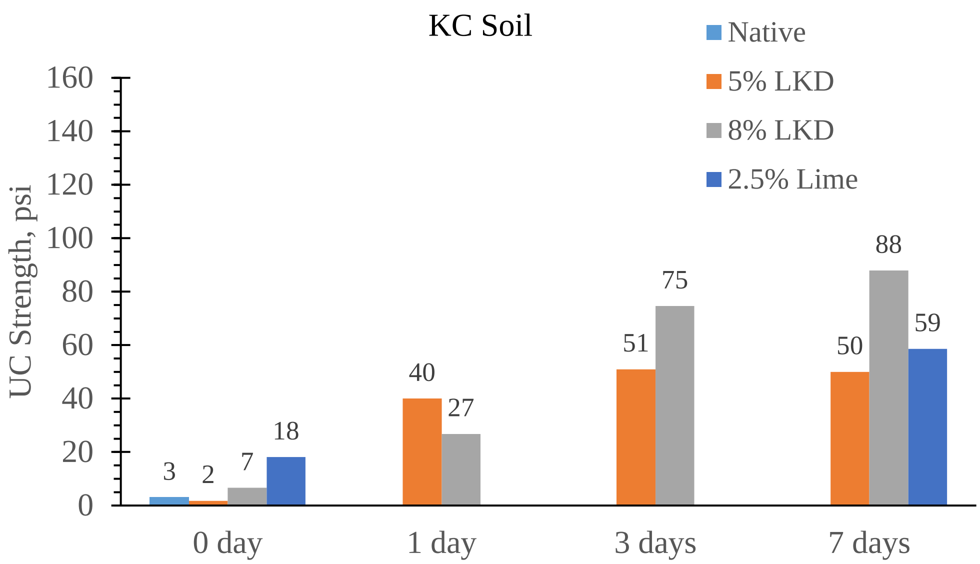


Figure 4.8: Soaked UC Strength of KC Soil/Additive Combinations

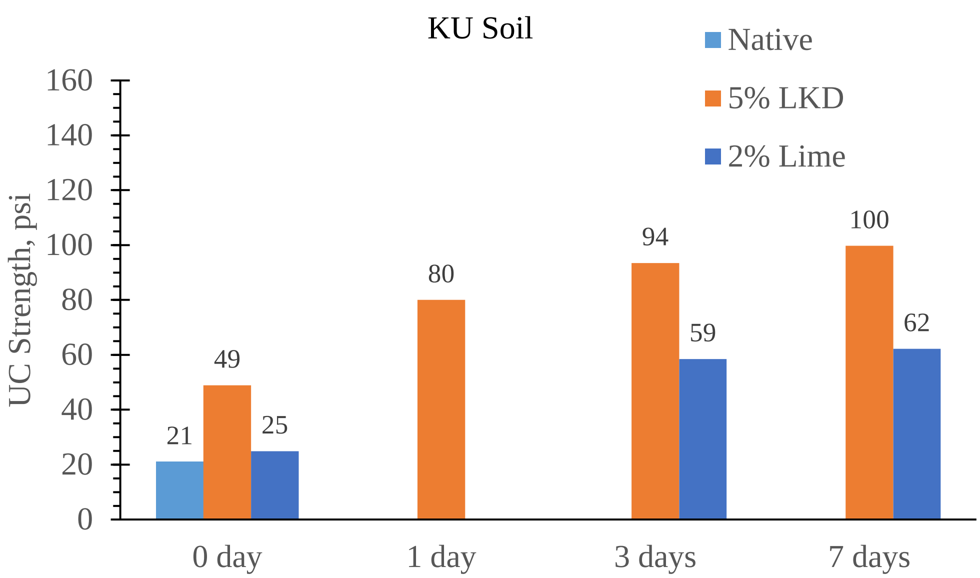


Figure 4.9: Unsoaked UC Strength of KU Soil/Additive Combinations

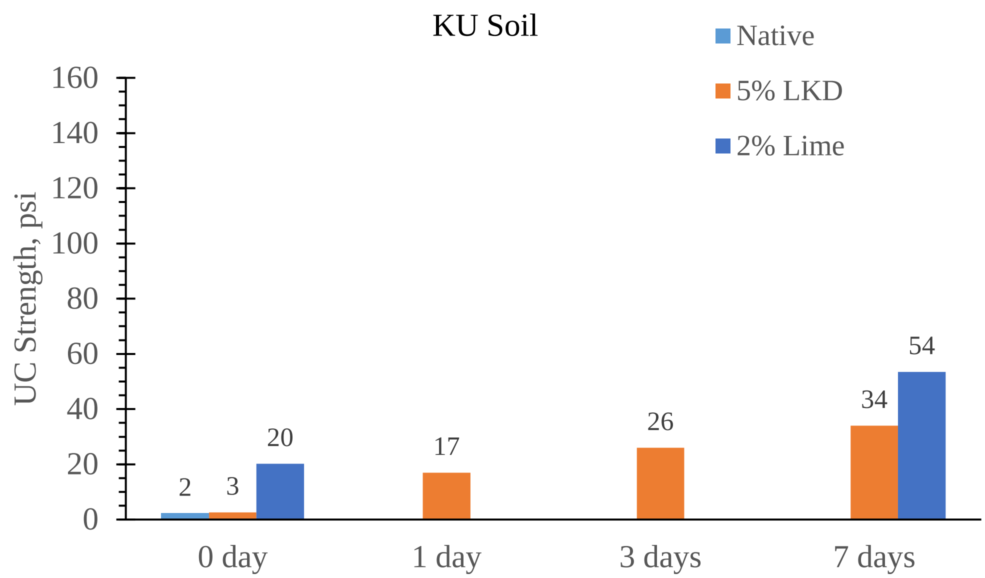


Figure 4.10: Soaked UC Strength of KU Soil/Additive Combinations

Figures 4.11 and 4.12 show the strength of all soil/additive combinations at 28 days curing time for unsoaked and soaked samples. All the soil samples experienced a significant improvement in strength for both unsoaked and soaked conditions when they were prepared with LKD or lime. Fly ash-treated samples behaved somewhat differently, with the unsoaked samples experiencing only a modest strength gain in three of four cases, while the soaked samples had an increase of 600% in strength over the soaked strength of native soils.

In general, compressive strength was substantially increased for all soil samples with the addition of LKD. LKD-treated soil samples had more strength gain than lime-treated samples for the unsoaked condition; however, the soil samples treated with lime had better performance than those treated with LKD for soaked conditions.

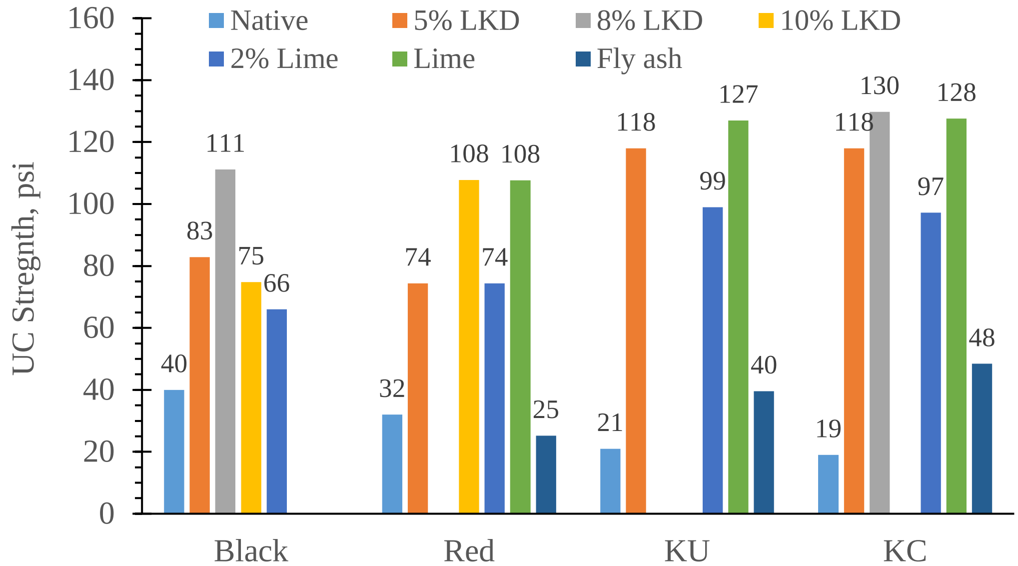


Figure 4.11: Unsoaked UC Strength of All the Soil/Additive Combinations at 28 Days

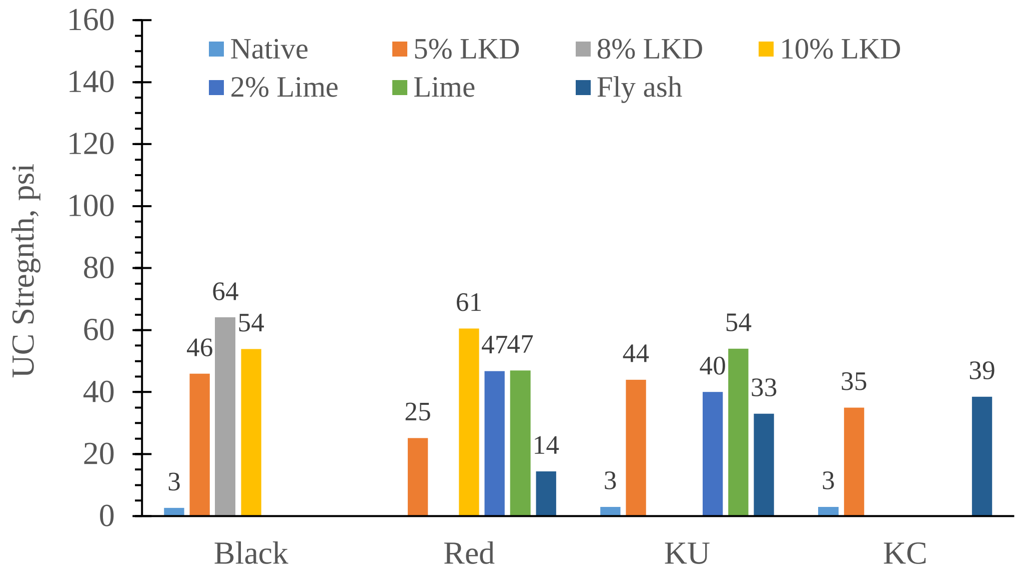


Figure 4.12: Soaked UC Strength of All the Soil/Additive Combinations at 28 Days

4.6 Volume Change Measurements for Soil Specimens

Samples prepared for UC strength tests were also used for volume-change measurements. Vertical and circumferential measurements of samples were taken before and after capillary soaking to evaluate the volume change between dry and soaked conditions. The results of the volume change measurements are presented in Figures 4.13 to 4.15. The figures show that LKD and lime substantially reduced the volume change of soaked samples. Figure 4.13 shows that

McPherson Black soil swelled 8% when it was soaked for 24 hr. The LKD-treated samples had a substantial reduction in volume change when compared with the native samples after 3 days of curing. However, the lime-treated samples showed the best performance in controlling the volume change of soaked samples, with virtually no swelling observed in samples cured for 7 days or more.

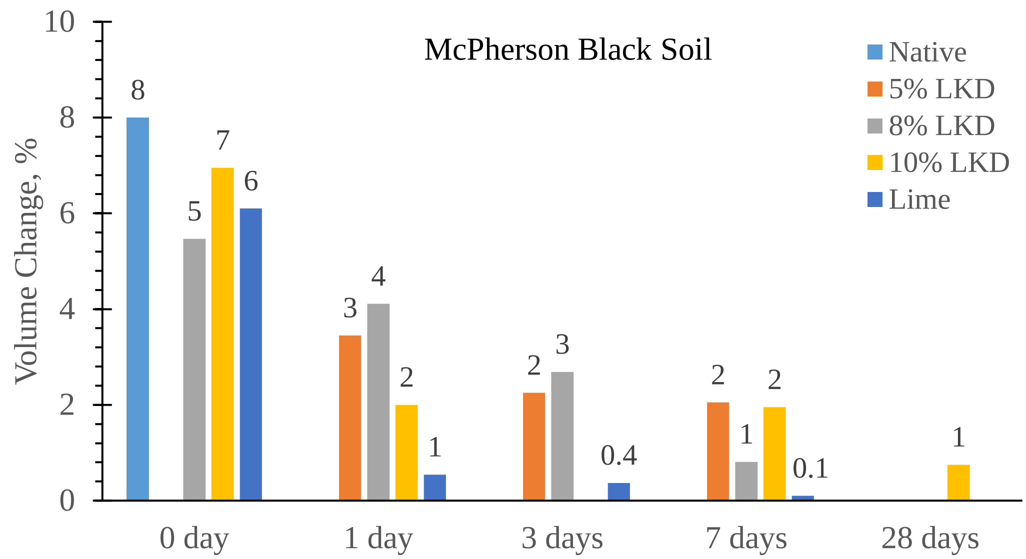


Figure 4.13: Measurements of Volume Change of Black Soil/Additive Combinations

Figure 4.14 shows that McPherson Red soil swelled 17% when soaked for 24 hr. However, as with the McPherson Black soil, the volume change of the Red soil was reduced substantially when mixed with 5% LKD. In addition, further reduction in volume change was achieved when a higher rate of LKD was applied to the soil (i.e., 10% LKD), and the rate of reduction increased with increasing curing time. Lime treatment was most effective at controlling swell with only minimal swell occurring with lime treatment and a curing period of 3 days or more.

As Figure 4.15 shows, the KC soil displayed the highest tendency to swell (19%) when it was soaked for 24 hr; however, the swell potential was greatly reduced with LKD or lime treatment. The samples treated with 5% LKD and cured for 28 days had a volume change near zero (i.e., 0.1%). Lime treatment was also very effective at controlling swell.

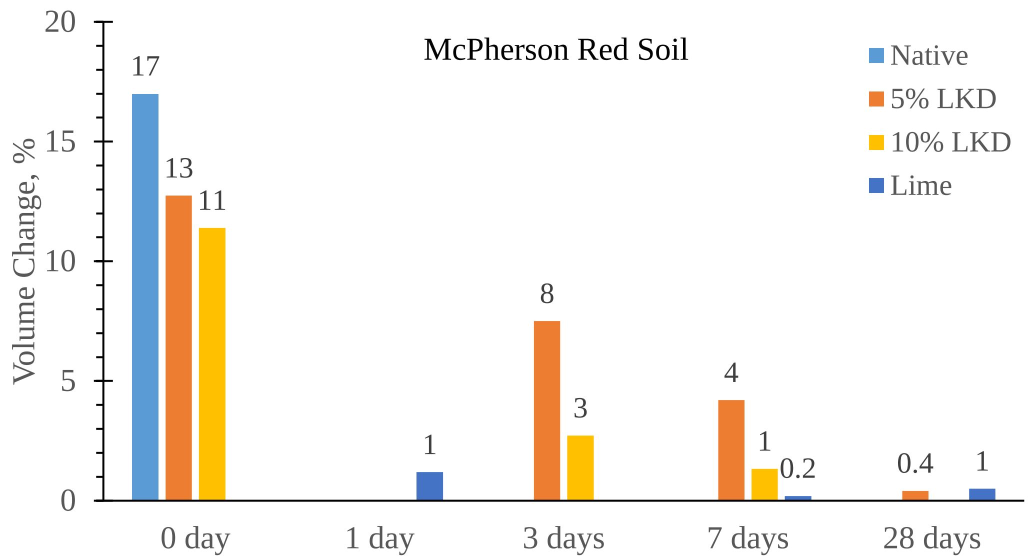


Figure 4.14: Measurements of Volume Change of Red Soil/Additive Combinations

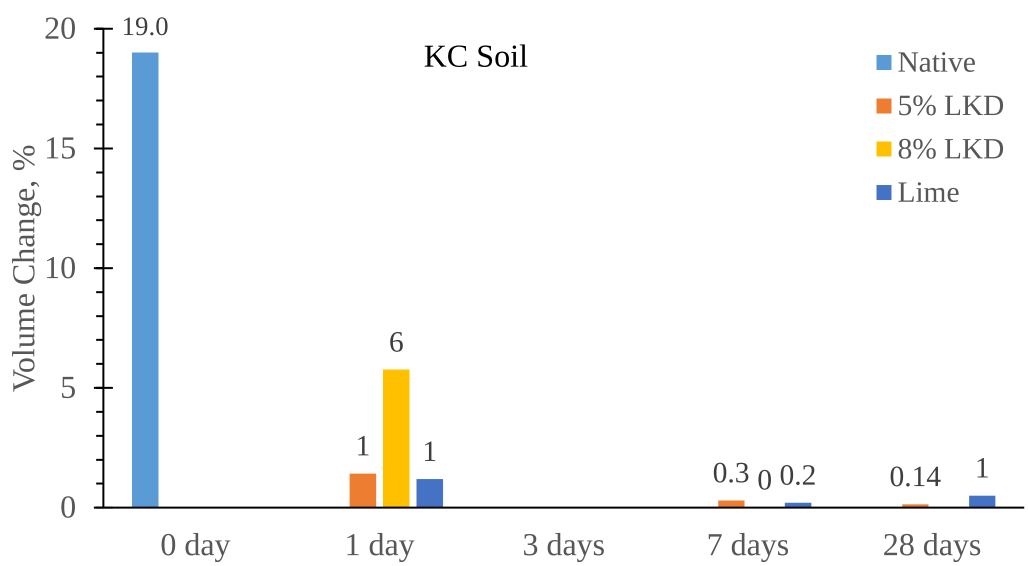


Figure 4.15: Measurements of Volume Change of KC Soil/Additive Combinations

4.7 One-Dimensional Swell Testing

The results of one-dimensional swell testing (ASTM D4546-14) of the soil/additive combinations are shown in Figure 4.16. The figure presents the amount of one-dimensional swell measured under a surcharge of 9.28 kPa (1.35 psi), which represents the estimated stress in the field. Figure 4.16 shows that LKD and lime treatments for all percentages tested greatly reduced the potential for swelling in all soils, except for 8% LKD in the KC soil. Lime was the most effective, with minimal swelling observed for all soils. LKD greatly reduced swelling for all soils when added at a rate of 5% by dry weight. Increasing the LKD percentage to 8% did not provide a benefit with regard to additional swell reduction, as there was more swelling measured in the 8% LKD samples than the 5% LKD samples. Similar behavior was observed previously in some, but not all, of the soaked specimens, as shown in Figures 4.13 and 4.15.

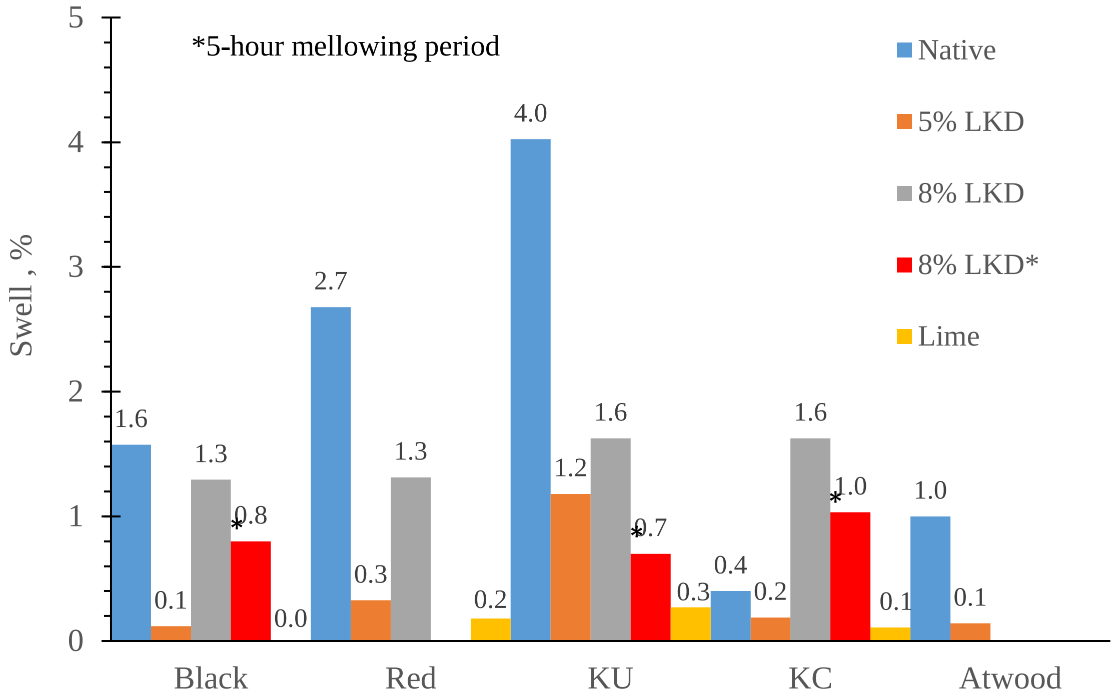


Figure 4.16: Swell Percent of All Soil/Additive Combinations

Increasing the mellowing period for LKD-treated samples to 5 hr prior to compaction for soil samples treated with 8% LKD reduced the swelling potential by approximately 40% when compared to samples with a 1-hr mellowing period.

4.8 Freeze-Thaw

The results of freeze-thaw tests on KU soil/additive combinations are presented in Figure 4.17. Only KU soil/additive combinations were evaluated using the freeze-thaw test. This test was performed to determine the reaction of the untreated and treated soil to this extreme weathering process. Figure 4.17 shows that most of the samples did not survive all 12 cycles. However, the samples treated with 5% LKD and 4% lime performed the best, and the unbrushed samples were able to complete all 12 cycles. The sample with 12% LKD did not perform as well as the sample with 5% LKD. Fly ash also performed well.

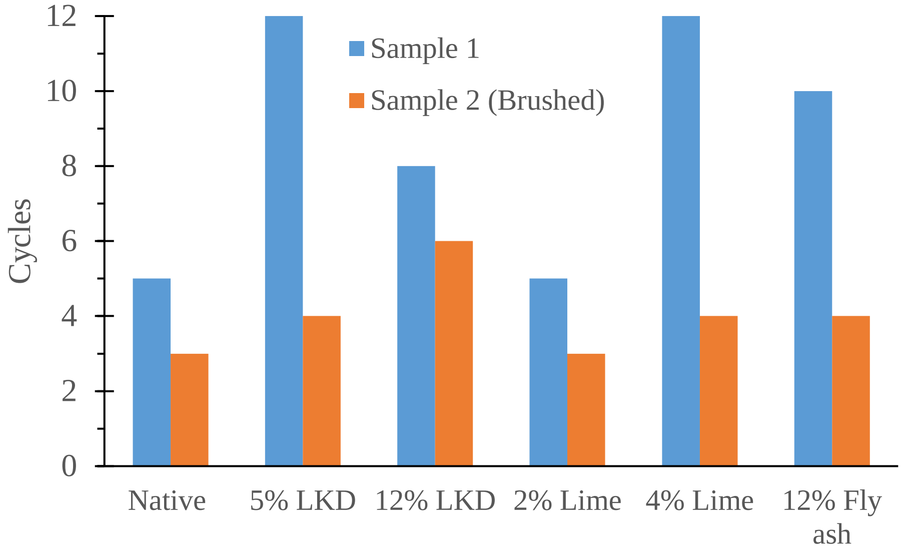


Figure 4.17: Freeze-Thaw Cycles for KU Soil/Additive Combinations

4.9 Wet-Dry

The results of wet-dry tests are shown in Figures 4.18 and 4.19. Wet-dry testing was conducted to determine how well the untreated and treated materials would respond to this extreme condition. The results for Sample 1 (unbrushed sample) for each of the soil/additive combinations are presented in Figure 4.18, and the results for Sample 2 (brushed sample) for all combinations are shown in Figure 4.19. It is important to note that, although none of the samples completed 12 cycles of this aggressive test, most of the treated soil samples survived for more cycles than their untreated counterparts.

Figures 4.18 and 4.19 show that LKD-treated specimens for both conditions (Sample 1 and Sample 2) performed as well as the lime-treated specimens. In addition, most of the samples treated with a higher rate of LKD had better performance than those treated with 5% LKD. Soil/additive combinations that did not complete any cycles are designated with a zero and the soil combinations that were not evaluated are designated with a star.

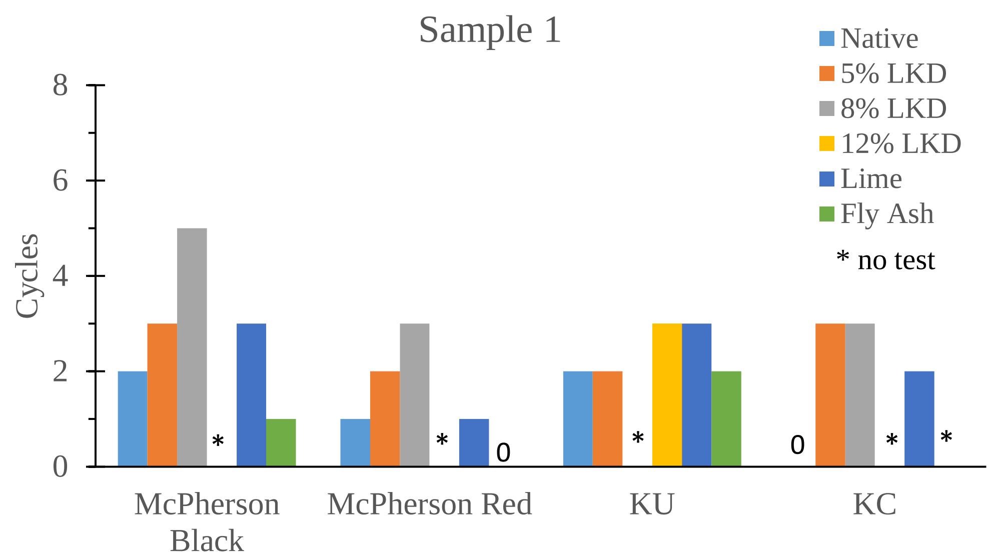


Figure 4.18: Wet-Dry Cycles of Unbrushed Samples for All the Soil/Additive Combinations

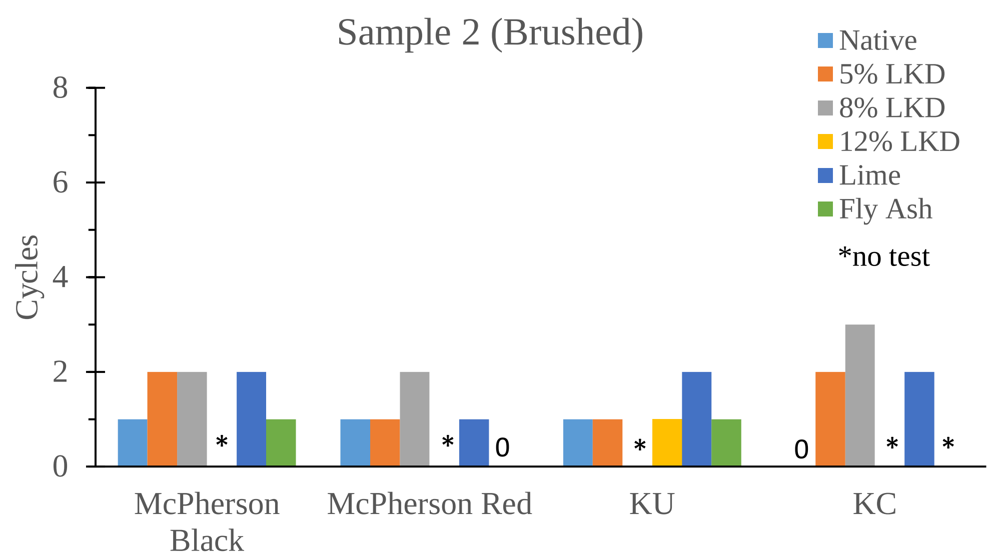


Figure 4.19: Wet-Dry Cycles of Brushed Samples for All the Soil/Additive Combinations

4.10 Resilient Modulus

Resilient modulus tests were conducted on the McPherson, KU, and KC soils; and soil obtained from an additional project near the Baker Wetlands Visitors Center, which is located 1 mile south of Lawrence, Kansas. Native samples were prepared along with LKD- and lime-treated samples. All resilient modulus tests were conducted by KDOT. Figure 4.20 shows the result of resilient modulus tests for the McPherson, KU, and KC soils. This figure shows there was a substantial amount of variability in resilient modulus values. The contribution of LKD is unclear, with values increasing for two of the soils and decreasing for two. The resilient modulus for the lime-treated samples increased for three of four cases.

Figure 4.21 shows the resilient modulus tests of native and LKD-treated soil samples from the Baker Wetlands site. Resilient modulus for this soil increased more than 100% with the addition of 5% LKD. However, samples with higher percentages of LKD had smaller increases in resilient modulus. The resilient modulus test data are included in Appendices D and E.

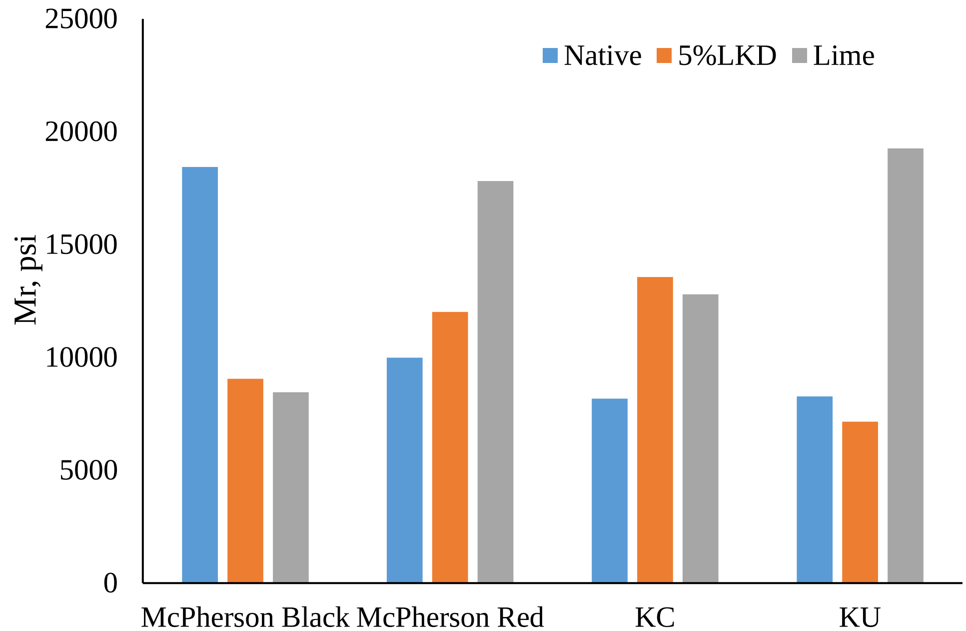


Figure 4.20: Resilient Modulus (Mr) of All the Soil/Additive Combinations

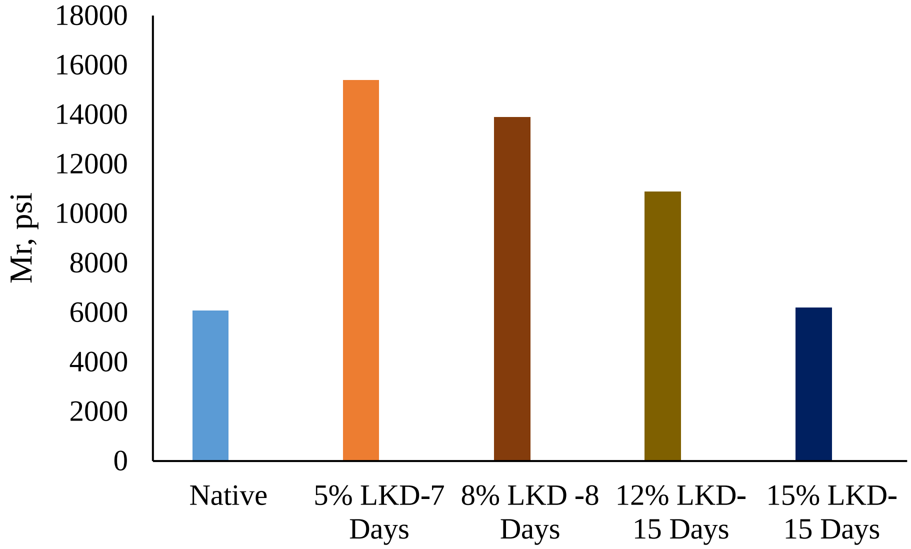


Figure 4.21: Resilient Modulus (Mr) of Native and LKD-treated Samples for the Soil of a Project near Lawrence, Kansas

KDOT also conducted UC compressive tests on the native and LKD-treated soil samples from the Baker Wetlands. The results are shown in Figure 4.22. The UC strength of the soil increased by approximately 500% with addition of 5% LKD and 3 days of curing, and continue to increase with 7 days of curing. However, increasing the LKD rates (i.e., 8%–15%) resulted in reduced UC strength compared to the strength of the samples treated with 5% LKD.

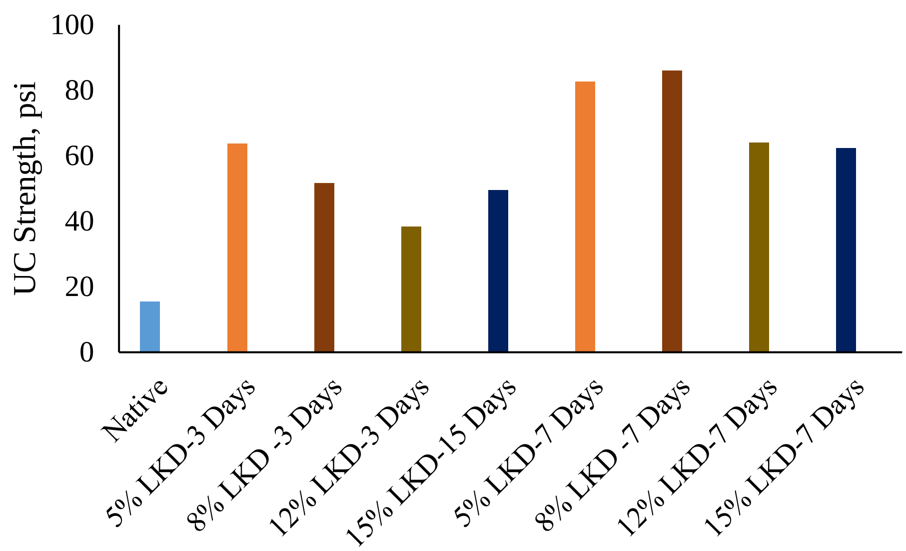


Figure 4.22: UC Strength of Native and LKD-Treated Samples for the Soil of a Project near Lawrence, Kansas

Chapter 5: Field Investigations

This chapter presents the results of field investigations on LKD-treated subgrades. It includes a review of construction procedures for LKD-treated subgrades, an evaluation of the in-situ performance of LKD-treated subgrade soils, and the results of laboratory tests on the field samples.

5.1 Testing Sites

The principal field investigation was performed on the I-135-Mohawk Road project near McPherson, Kansas. This investigation included six test sections: Mohawk Road west and east of the interchange, and four ramps: Ramp A (southeast), Ramp B (northeast), Ramp C (southwest), and Ramp D (northwest). A second field investigation was conducted for a large foundation pad for a commercial store in Kansas City, Kansas, and an earlier, preliminary investigation was conducted on a project site near Lawrence, Kansas. Results for those investigations are included in this report as well. The locations of the project and layout of the testing sites are included in Appendix F.

5.2 LKD-Treated Subgrade Modification Procedures

LKD was applied at a rate of 5% by dry weight of the soil being treated for all locations. The target depth of treatment was 300 mm (12 in.) for all the testing sites except for the foundation pad of the commercial store, where the treatment depth was 400 mm (16 in.). The LKD treatment procedures observed at the testing sites included subgrade preparation, material delivery, material spreading, LKD and soil mixing, compaction, finishing, and curing. A summary of these procedures is presented below.

5.2.1 Preparation of Subgrade

Before the application of the LKD, the subgrade surface at all the sites was trimmed to the specified elevations using a motor grader.

5.2.2 Material Delivery and Spreading

LKD was delivered by bulk pneumatic tankers and transferred into a spreader truck that was built specifically for the lime-treatment process. The LKD then was applied to the subgrade at a rate of 5% by dry weight of the soil being treated. The spreader truck distributed LKD evenly over a 2.4 m (8 ft) wide spreading area through a rotary feeder that was fed by two augers (conveyors), which were attached to the hoppers of the spreader (Figure 5.1).

Figure 5.1: A Spreader Truck Distributing LKD

5.2.3 Mixing and Adding Water

The contractor used a high-powered, self-propelled rotary mixer to mix LKD with the subgrade soil. The materials were mixed to a depth of 300 mm (12 in.) at the I-35-Mohawk Road project in McPherson and 400 mm (16 in.) for the foundation pad of the commercial store in Kansas City, Kansas. Water was added during the mixing process through a water truck that was attached to the rotary mixer (Figure 5.2). The contractor made forward and backward passes with the rotary mixer over the LKD-treated subgrade to ensure the LKD was evenly mixed with the subgrade soil and to ensure that the target depth of treatment was achieved.

Figure 5.2: The Rotary Mixer and the Attached Water Tank

5.2.4 Compaction, Grading, and Finishing

The LKD-treated soils were compacted immediately after mixing using a vibratory pad foot roller (Figure 5.3). Then a motor grader shaped the LKD-treated subgrade to provide a consistent grade to promote drainage. Following grading, the LKD-treated subgrade was sealed with two passes with a smooth-drum steel wheel roller.

Figure 5.3: Compacting LKD-Soil Mix Using a Vibratory Pad Foot Roller

5.2.5 Curing

The LKD-treated subgrade soil was cured for 48–72 hr following compaction and finishing. Selected photographs of construction operations are included in Appendix F.

5.3 Field Evaluation (Testing) Program

For all test sections, dynamic cone penetration (DCP) and light weight deflectometer (LWD) measurements were conducted to measure the in-situ stiffness and strength of the LKD-treated subgrade. The measurements were conducted on the testing site immediately after compaction, 1 or 2 days after compaction, 3 days after compaction, and 14 or 15 days after compaction. Three test sections on Mohawk Road and one test section on each ramp were investigated. Figure 5.4 shows the layout of a typical test section. In addition, laboratory tests that included unconfined compression strength, moisture content, and dry density were conducted on the Shelby tube soil samples taken from the testing sites.

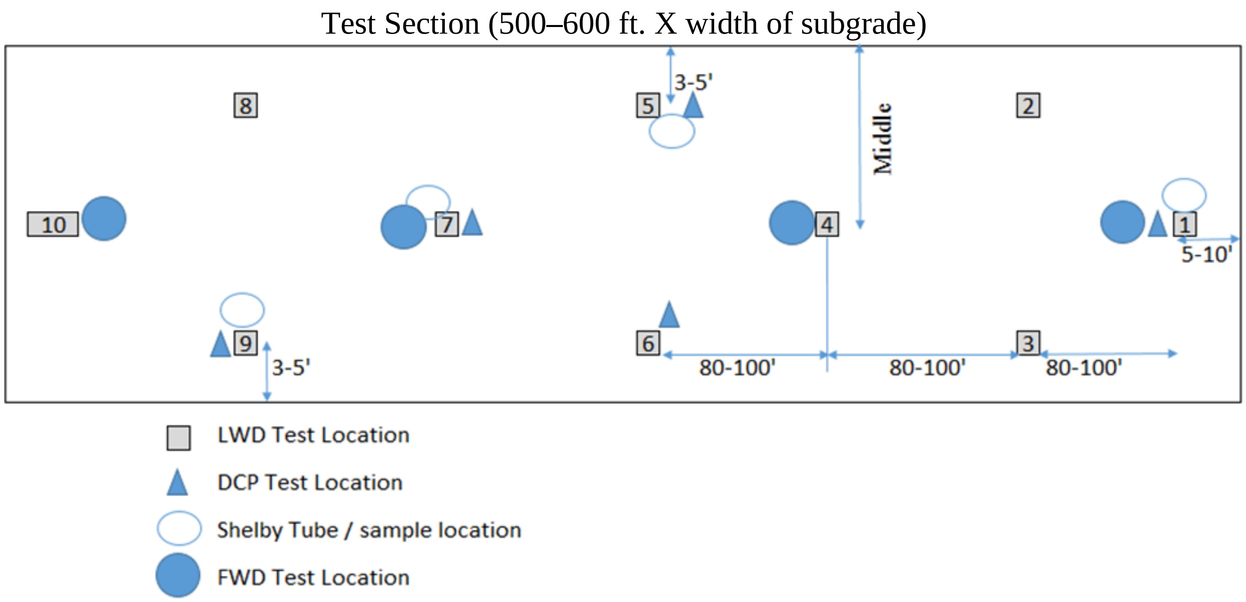


Figure 5.4: Layout of Field Test Measurements

5.4 Field Testing

5.4.1 Dynamic Cone Penetrometer (DCP) Testing (ASTM D6951)

Dynamic cone penetration (DCP) testing is used to measure the strength of undisturbed soil and/or compacted materials (in-situ strength) by driving a rod into the soil with a sliding hammer and measuring the rod penetration rate (i.e., mm/blow). The DCP penetration rate, referred to as the DCP-Index in this report, is also used to measure the thickness and location of subsurface soil layers, and for this project was used to identify the effective depth of the treated soil. For this study, a DCP with an 8-kg (17.6-lb) hammer was used (Figure 5.5).

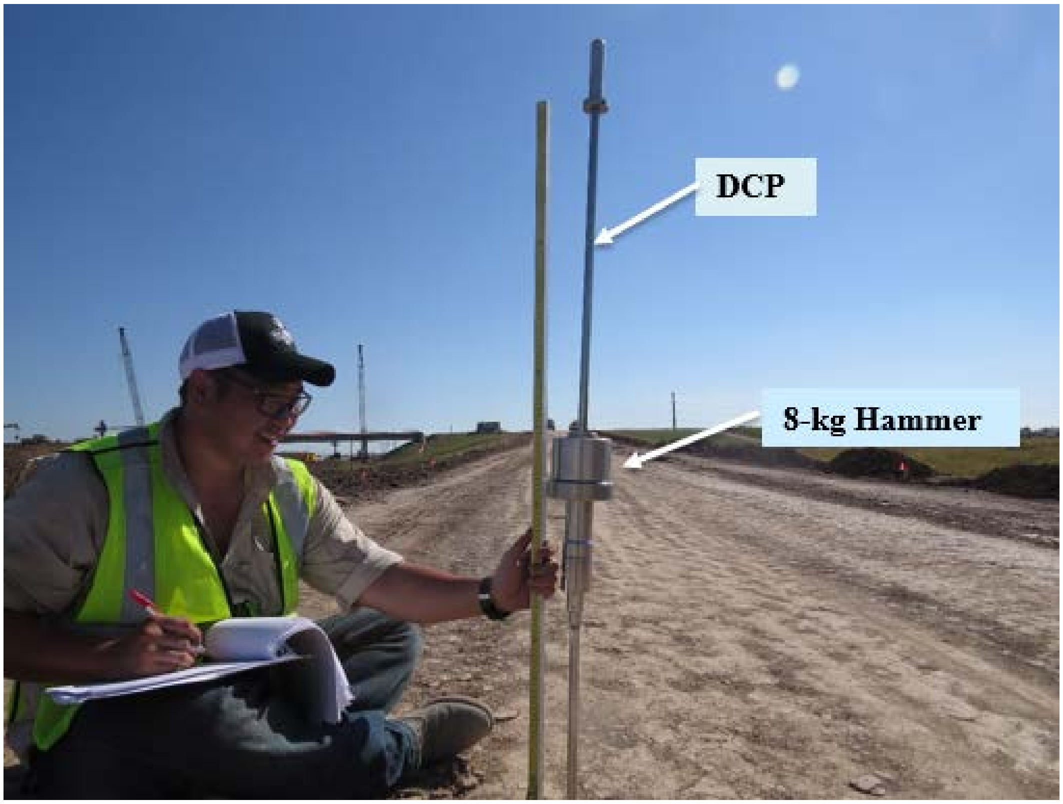


Figure 5.5: Dynamic Cone Penetration (DCP) Testing

5.4.2 Light Weight Deflectometer (LWD) Testing (ASTM E2583)

The Light Weight Deflectometer (LWD) was developed in Germany as an alternative to the plate load test. The LWD measures the center deflection of the loading plate and uses the measured deflection to back-calculate the elastic stiffness modulus based on the elastic half-space concept. For this project, an LWD with a 300-mm (12-in.) diameter loading plate and a 10-kg falling weight (Figure 5.6) was used to estimate the in-situ stiffness of the LKD-treated subgrade.

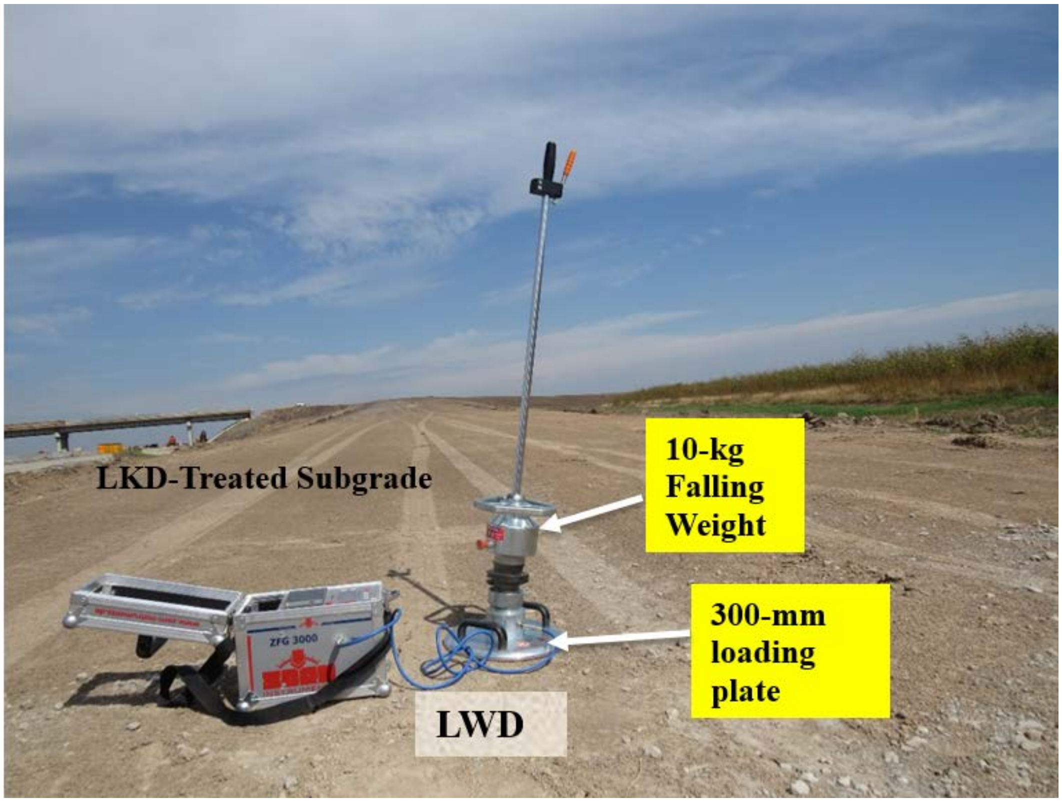


Figure 5.6: Light Weight Deflectometer (LWD) Used in the Field

5.4.3 In-Situ Soil Samples

To provide additional data on the in-situ performance of LKD-treated subgrade, several Shelby tube soil samples were taken at each testing site. The samples were taken to the depth of approximately 600 mm (24 in.) using a drill rig (Figure 5.7) provided by KDOT. The samples were then transported to the laboratory at the University of Kansas and prepared for unconfined compression strength tests.

Figure 5.7: Taking Shelby Tube Soil Samples (KDOT Drill Rig)

5.5 Field Test Results and Analysis

5.5.1 DCP Test Results and Analysis

5.5.1.1 DCP-Index

Based on the collected DCP test data, the penetration rate (penetration per blow of a DCP hammer), referred to as DCP-Index, was calculated with depth for each station for all test sections. A lower penetration rate corresponds to a stronger/stiffer soil. A typical profile of DCP-Index with depth is shown in Figure 5.8. The figure shows the DCP-Index versus the investigated depth at Station 33+00 for the test section on West Mohawk Road. Figure 5.8 shows a significant change in DCP-Index value at a depth of 300 mm (12 in.), which was the depth of LKD treatment. The figure shows that the DCP-Index value is lowest (strongest soil) near the surface and increases gradually from the surface to a depth of 300 mm, where the DCP-Index increases dramatically. The lower DCP-Index in the upper 300 mm is attributed to LKD treatment and interpreted as an increase in stiffness of the LKD-treated layer. In addition, the change of DCP-Index at 300 mm (12 in.) in depth indicates that the target depth for LKD treatment of 300 mm was achieved. The average DCP-Index values of the treated depth and in-situ soil for all the testing stations were calculated and are presented in Appendix G.

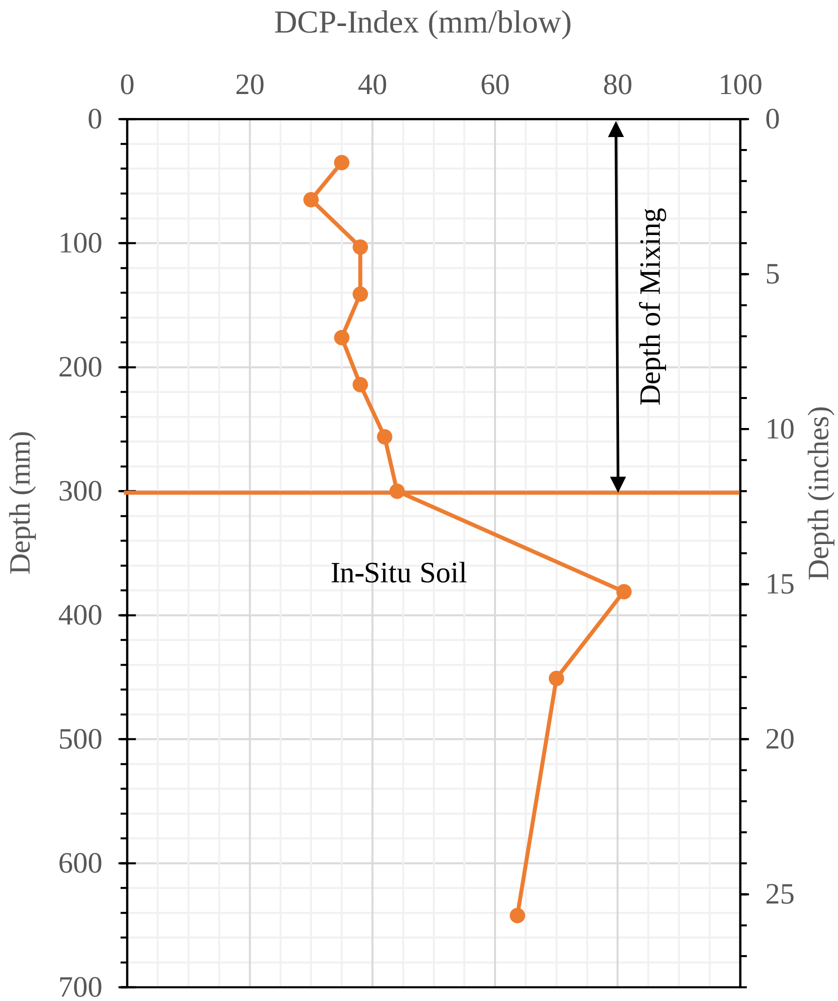


Figure 5.8: DCP-Index Results versus Depth at West Mohawk Road (Station 33+00)

Additionally, the average DCP-Index values for all sites were calculated for the LKD-treated subgrade layer (i.e., upper 300 mm) and the in-situ soil layer (depth greater than 300 mm) for a series of curing times (i.e., 1–2 hr, 1 day, 3 days, and 14 days after compaction). The average DCP-Index results are presented in Table 5.1. The table shows that the LKD-treated subgrade has a lower DCP-Index (stronger soil) than the in-situ soil for all testing sites, and the DCP-Index for all testing sites decreased with time. It was concluded that LKD treatment increased the strength of subgrade and the LKD-treated portion of the subgrade gained strength with time.

Table 5.1: Average Penetration Rate (DCP-Index)

Location		Time	DCP-Index (mm/blows)	
			In-Situ Soil	LKD-Treated Subgrade
I-135-McPherson, KS	SE Ramp	1–2 hr	44	24
		2 days	21	12
		14 days	21	14
	NE Ramp	1–2 hr	22	19
		2 days	23	11
		14 days	20	13
	SW Ramp	1–2 hr	36	27
		1 day	29	12
		3 days	22	11
		15 days	22	7
	NW Ramp	1–2 hr	30	25
		1 day	31	15
		3 days	26	14
		15 days	27	7
	East Mohawk Road	1–2 hr	52	36
		1 day	38	18
	West Mohawk Road	1–2 hr	44	33
		2 days	25	16
		14 days	23	12
A foundation pad, KC, KS		1–2 hr	36	21
		1 day	35	12

5.5.1.2 California Bearing Ratio (CBR)

The DCP-Index values were used to estimate CBR values based on the correlation recommended by the U.S. Army Corps of Engineers and included within ASTM D6951. The correlation is presented in Equation 5.1.

$$\log(CBR) = 2.465 - 1.12\log(PR) \text{ or } CBR = 292/PR^{1.12} \qquad \text{Equation 5.1}$$

Where PR is DCP-Index (mm/blow)

The estimated CBR values with depth for all stations for all test sections are included in Appendix G.

Figures 5.9 to 5.16 show the calculated CBR with depth determined from the DCP test results for West and East Mohawk Road and the SW Ramp, NW Ramp, NE Ramp, and SE Ramp near McPherson; a project site near Lawrence; and a foundation pad in Kansas City, Kansas. The figures also show the CBR values with depth 1–2 hr, 1 day, 2 or 3 days, and 14 or 15 days after compaction.

All figures (Figures 5.9 to 5.16) illustrate that the CBR values generally decrease with increasing depth and that CBR values are substantially greater in the top 300 mm of the subgrade, which is the target depth of LKD treatment. This change indicates that the CBR values for the LKD-treated portion of the subgrade increased with LKD treatment compared with the value of in-situ (untreated) soil. The change in CBR values at a depth of 300 mm also indicates that the target depth of LKD treatment was generally achieved.

All figures (Figures 5.9 to 5.16) illustrate that the CBR values for all the testing sites increased with time within the LKD-treated layer, which indicates that LKD-treated soil layers gained strength with time. While there was little strength gain immediately (1–2 hr) after compaction, the figures show that the LKD-treated subgrade typically gained 60–70% of its 14-day strength (i.e., strength after 14 days curing) in 24 hr and approximately 80% of its strength within 3 days of compaction.

In addition, for all test sections, the LKD-treated soil layer gained more strength in the upper portion of the treated layer than the lower portion of the layer. In other words, the improvement was not uniform throughout the profile of the LKD-treated soil layer. The reason for this difference cannot be stated with certainty; however, this variation may be because the soil nearest the surface dries faster than the lower portion, which directly affects the moisture content and hence the stiffness of the LKD-treated soil. Table 5.2 summarizes the average estimated CBR values calculated for the untreated subgrade and the LKD treated layer, and the percentage improvement for each test section for a series of curing times. It can be concluded from Table 5.2 that the estimated CBR value of LKD-treated subgrade increased by approximately 24% in 1–2 hr, 94% in 1 day, 124% in 3 days, and 140% in 14 days compared to the CBR value of the in-situ soil.

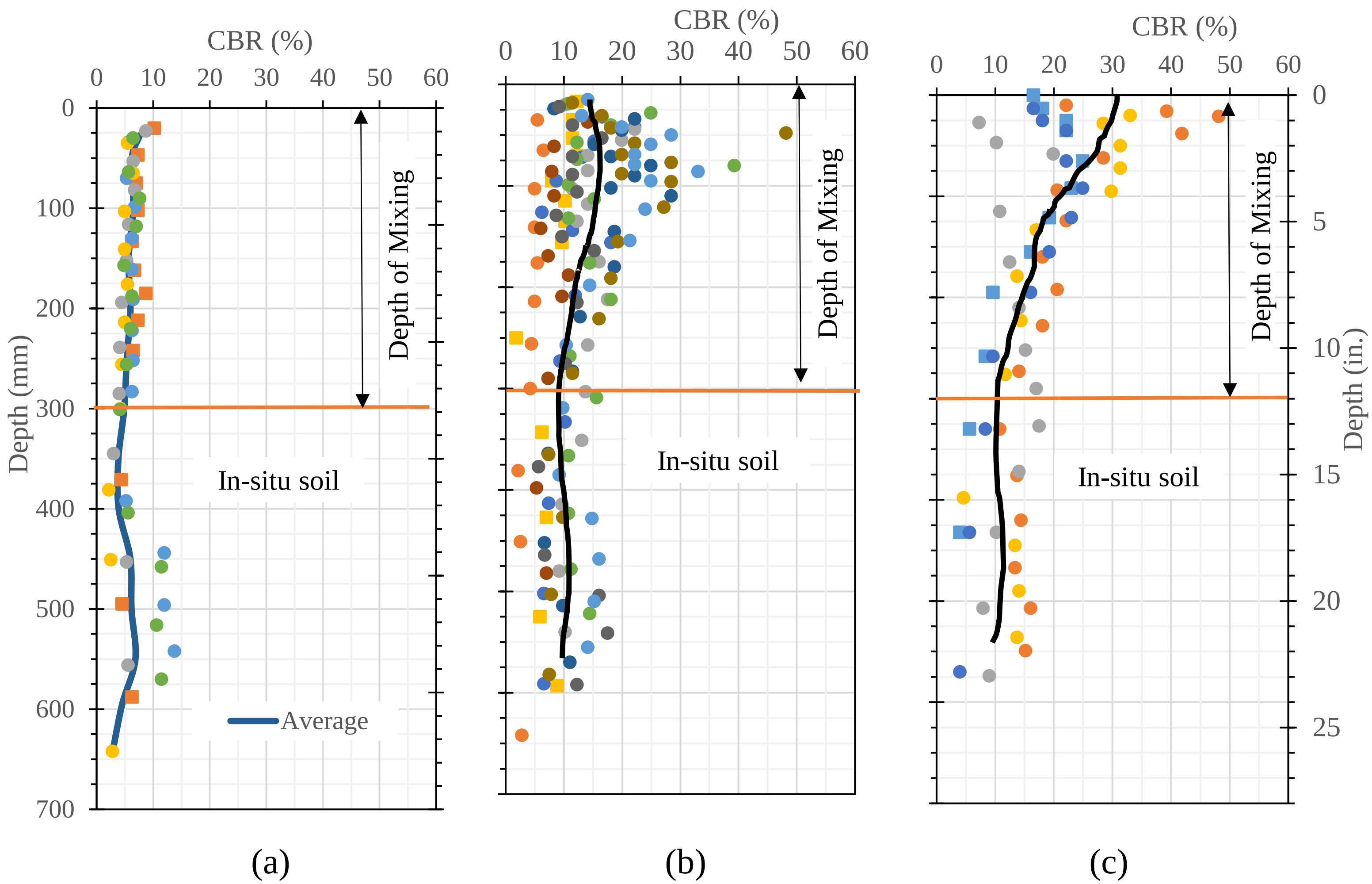


Figure 5.9: CBR versus Depth for West Mohawk Road: (a) 1–2 Hours, (b) 2 Days, and (c) 14 Days after Compaction

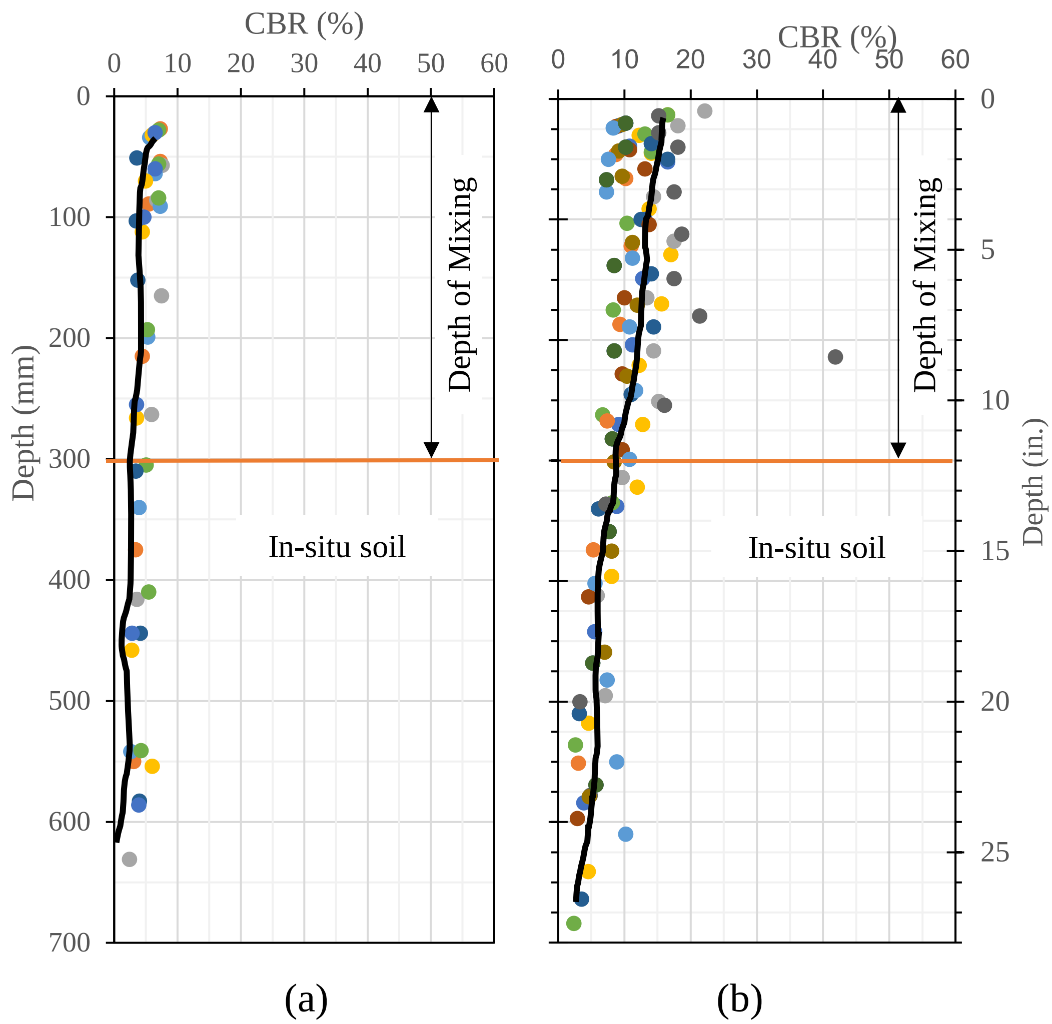


Figure 5.10: CBR versus Depth for East Mohawk Road: (a) 1–2 Hours, and (b) 1 Day after Compaction

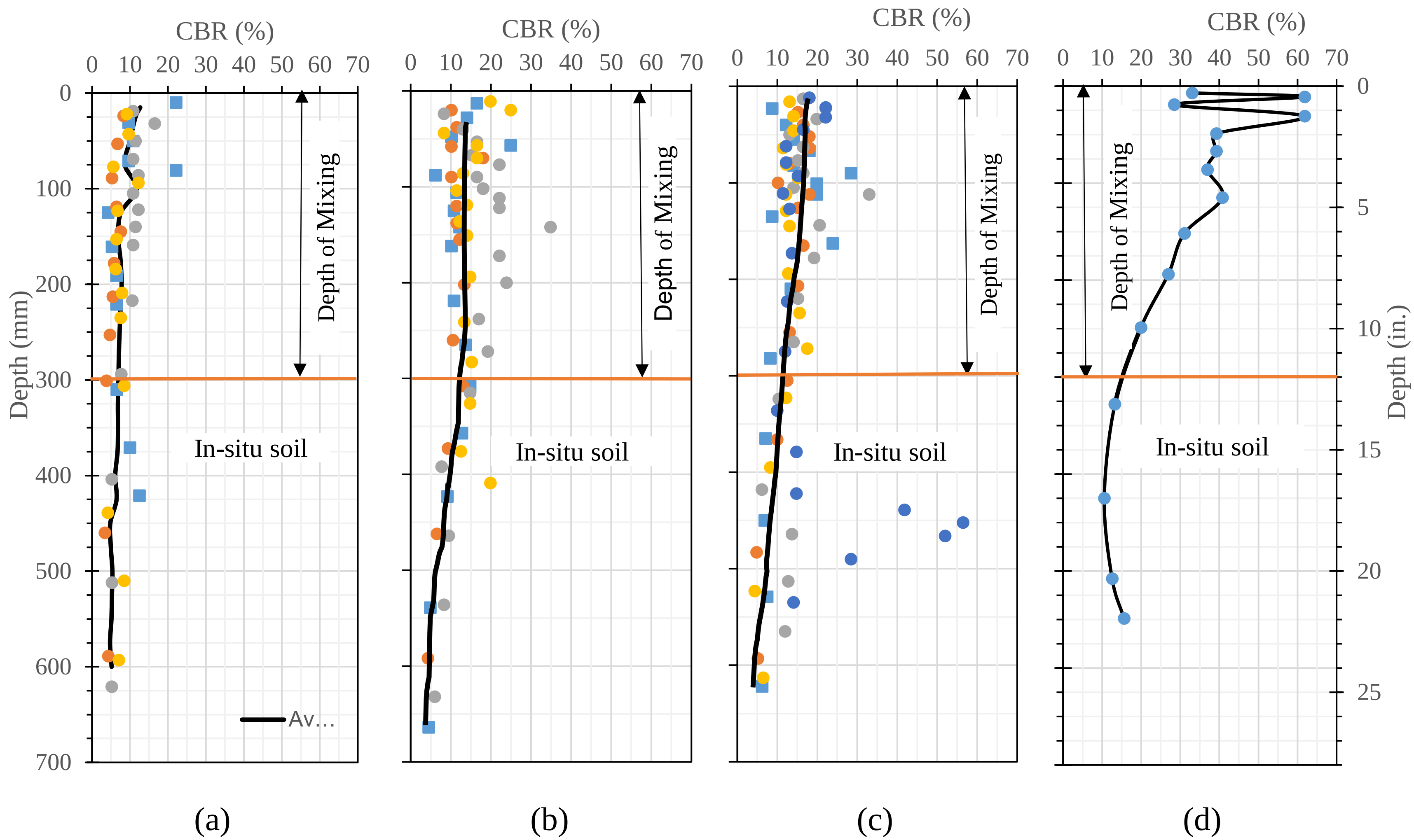


Figure 5.11: CBR versus Depth for SW Ramp: (a) 1–2 Hours, (b) 1 Day, (c) 3 Days, and (d) 15 Days after Compaction

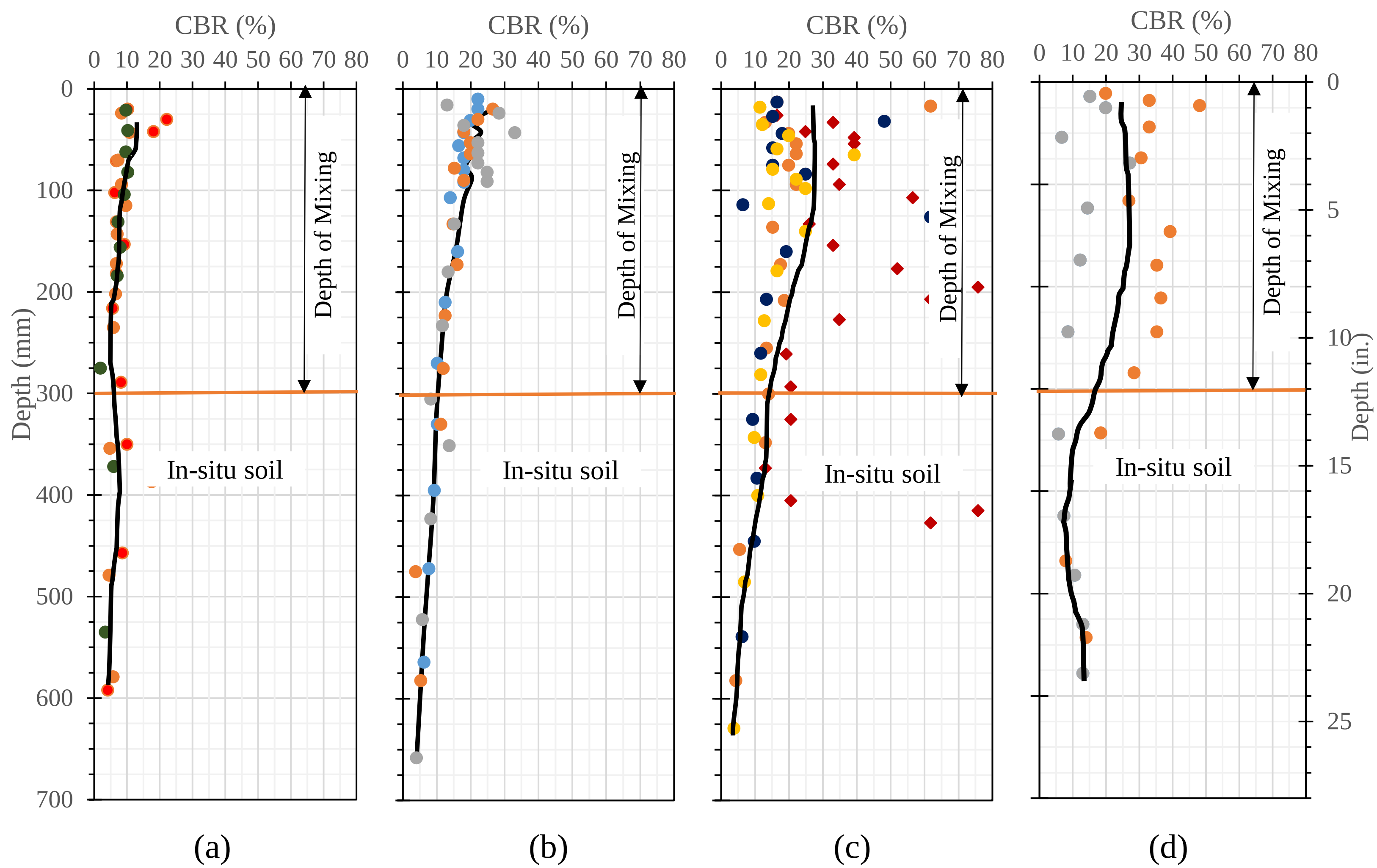


Figure 5.12: CBR versus Depth for NW Ramp: (a) 1–2 Hours, (b) 1 Day, (c) 3 Days, and (d) 15 Days after Compaction

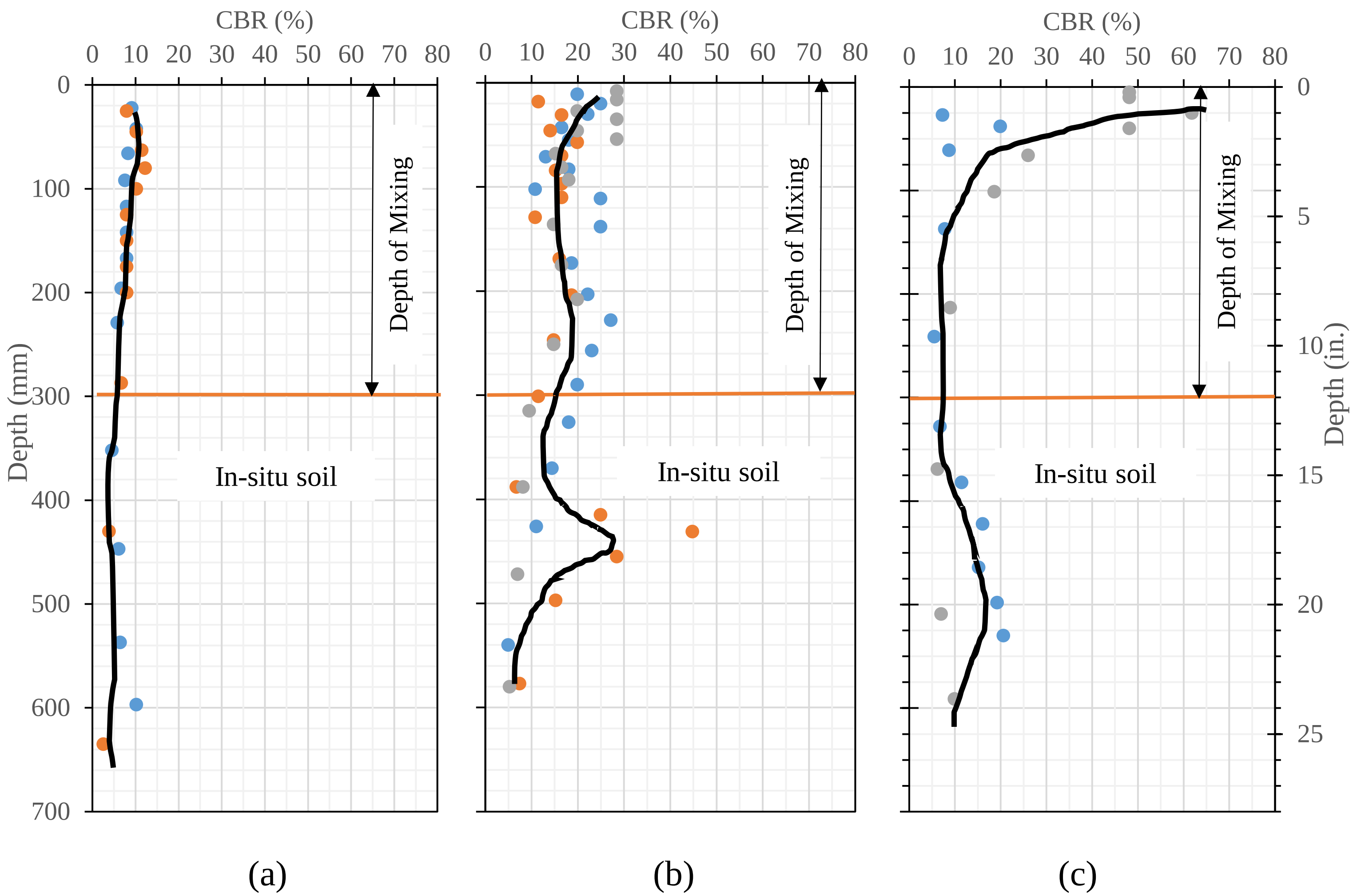
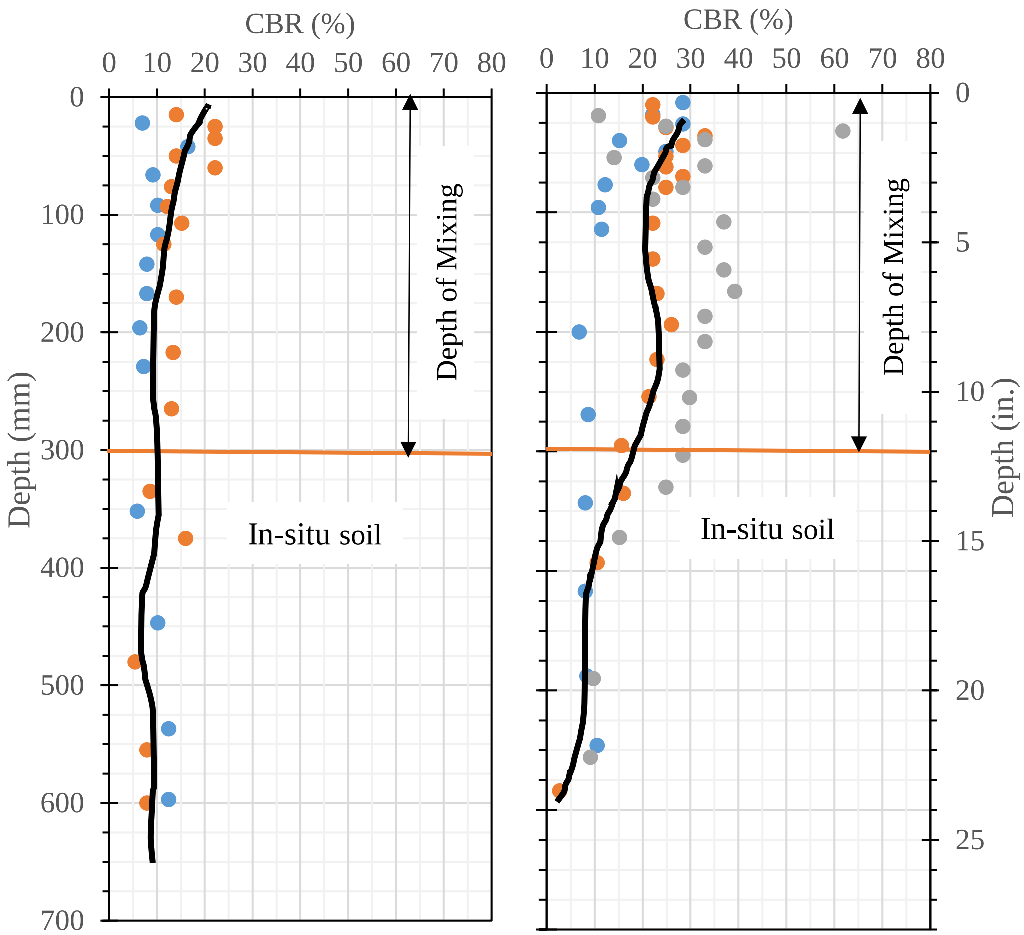


Figure 5.13: CBR versus Depth for SE Ramp: (a) 1–2 Hours, (b) 2 Days, and (c) 14 Days after Compaction



(a) (b)

Figure 5.14: CBR versus Depth for NE Ramp: (a) 1–2 Hours, and (b) 2 Days after Compaction

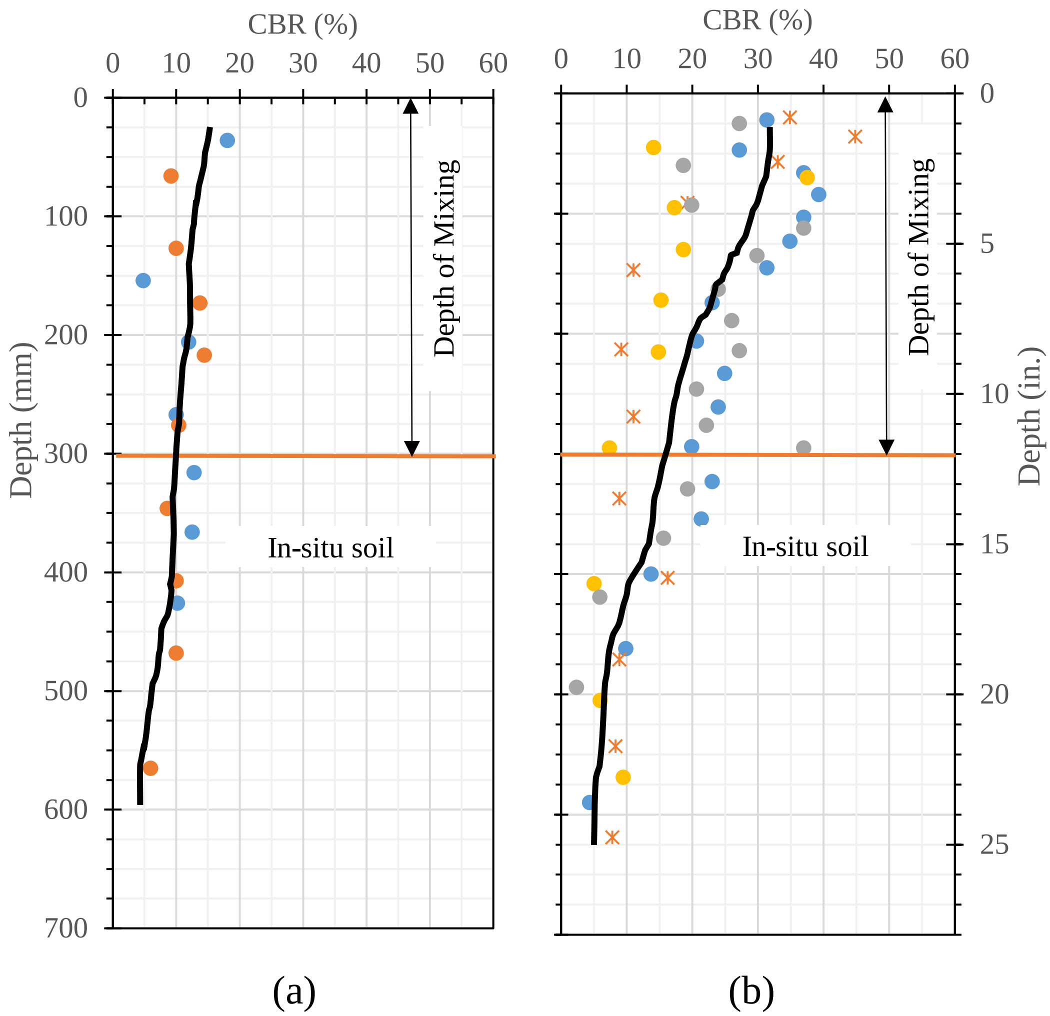


Figure 5.15: CBR versus Depth for a Foundation Pad near Kansas City, KS: (a) 1–2 Hours, and (b) 1 Day after Compaction

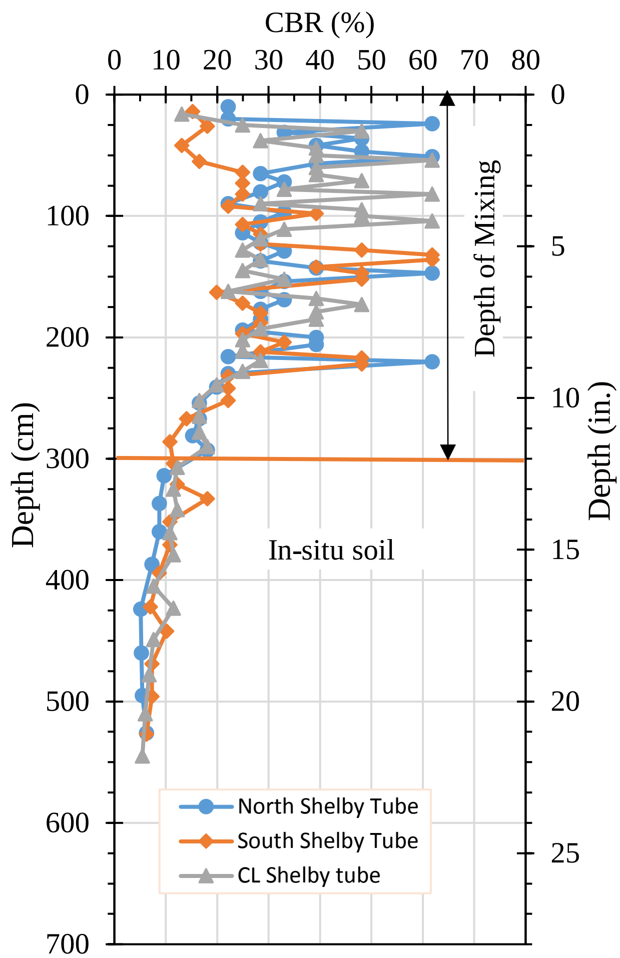


Figure 5.16: CBR versus Depth for a Project Site near Lawrence, KS

Table 5.2: Average Calculated CBR (%) from DCP Test Data

Location		Time	In-Situ Soil CBR (%)	LKD-Treated Subgrade CBR (%)	Strength Gain (%)
I-135-McPherson, KS	SE Ramp	1–2 hr	6.6	8.4	27
		2 day	11.3	18.3	62
		14 days	11.0	23.0	109
	NE Ramp	1–2 hr	10.0	12.1	21
		2 day	10.3	22.0	114
	SW Ramp	1–2 hr	7.2	9.7	35
		1 day	8.1	15.3	89
		3 days	7.1	16.6	134
		15 days	12.9	36.3	181
	NW Ramp	1–2 hr	6.2	8.0	30
		1 day	7.4	19.1	158
		3 days	10.4	22.6	118
		15 days	10.1	25.0	148
	East Mohawk Rd	1–2 hr	4.2	5.6	33
		1 day	6.5	12.5	92
	West Mohawk Rd	1–2 hr	5.7	6.1	7
		2 days	9.3	15.9	71
		14 days	9.9	20.0	102
Foundation pad, KC, KS		1–2 hr	9.5	14.5	53
		1 day	7.0	21.2	203

5.5.1.3 Field Moisture Content

The moisture contents of some field test stations were determined from the soil samples taken from the holes formed by DCP tests. Field moisture contents and the corresponding optimum moisture contents obtained from Proctor tests are presented in Table 5.3.

The field moisture contents were consistent with lab moisture contents for all the tested sections except East Mohawk Road, which averaged more than 6% above the lab optimum moisture.

Table 5.3: Field Moisture Content

Location	Station	Field Moisture Content (%)	Optimum Moisture Content (%)	Days after Compaction	Difference
West Mohawk Road	28+00	16	15	1	1
	31+00	14	15	1	-1
	32+00	14	15	1	-1
	35+00	16	15	1	1
	Average	15	15	1	0
NW Ramp	37+22	19	17	2	2
	41+06	17	17	2	0
	Average	18	17	2	1
East Mohawk Road	55+25	25	17	Same day	8
	57+75	22	17	Same day	5
	Average	23	17	Same day	6
SE Ramp	35+23	18	17	Same day	1

5.5.2 LWD Test Results and Analysis

Table 5.4 presents the light weight deflectometer (LWD) results for West and East Mohawk Road; the SE Ramp, NE Ramp, SW Ramp, and NW Ramp on the I-135 Mohawk Road project in McPherson, Kansas; and a foundation pad in Kansas City, Kansas. The results are the calculated average of all the measurements for each test section. The LWD results for all the measurements for all testing points are included in Appendix H.

Table 5.4 shows the elastic stiffness modulus (E_{LWD}) back-calculated from the measured deflection of the center of the LWD loading plate. The table also presents the standard deviation (SD) and coefficient of variation (CV%) for each testing site.

Table 5.4: LWD Test Results

Location		Time	E_{LWD} (MPa)	SD (MPa)	CV (%)
I-135-McPherson, KS	SE Ramp	1–2 hr	32	5.6	17.6
		2 day	61	6.4	10.5
		14 days	47	3.5	7.6
	NE Ramp	1–2 hr	48	11.6	24.3
		2 day	63	11.9	18.8
		14 days	52	0.2	0.5
	SW Ramp	1–2 hr	46	10.9	23.8
		1 day	64	14.6	22.9
		3 days	68	5.4	7.9
		15 days	72	3.6	5.0
	NW Ramp	Untreated	23	4.2	18.2
		1 hr	49	11.1	22.4
		1 day	62	11.5	18.7
		3 days	64	13.4	21.0
	East Mohawk Road	Untreated	17	5.5	31.7
		1 hr	37	8.3	22.2
		1 day	54	7.7	14.4
	West Mohawk Road	1–2 hr	40	8.8	21.8
		2 days	55	7.4	13.4
		14 days	40	6.0	15.1
A foundation pad, KC, KS		1–2 hr	28	8.6	30.8
		1 day	57	13.1	22.9
		3 days	72	5.2	7.2

Table 5.4 indicates that the measured elastic modulus (E_{LWD}) increased with time by 30–100% within 3 days after compaction. This strength improvement is consistent with the strength gain shown in the DCP test results. However, LWD test results on Mohawk Road, NE Ramp, and SE Ramp showed less stiffness after 14 days than after 3 days. The reason for this decrease in elastic modulus (E_{LWD}) is unclear; however, it may be due to cracking of the surface of the soil with time, which could have adversely affected the stiffness of the soil. Since the LWD is very

sensitive to surficial cracks, the results of the LWD tests performed on the subgrades with surface cracking may not accurately represent the actual stiffness of the treated layer as a whole.

The statistical analysis shows that the coefficient of variation for LWD measurements for the analyzed field tests ranged from 0.5% to 30.8%, and the standard deviation ranged from 0.24 MPa to 14.61 MPa. Table 5.4 shows that, for most cases, the CV value decreased as the measured elastic modulus increased.

5.5.3 Results of Laboratory Tests on In-Situ Soil Samples

As mentioned in Section 5.4.4, a number of in-situ soil samples were taken from the test sections using Shelby tubes (samplers). The samples were transported to the laboratory at the University of Kansas and cured for varying time intervals to match the curing time of the field measurements. Unconfined compression strength, moisture content, and dry density of the soil samples were determined, and the results are presented in Table 5.5.

Table 5.5 shows the curing time, moisture content, and dry density of the soil samples and the results of the unconfined compression strength tests. Most of the soil samples had moisture contents higher than the optimum moisture content obtained from the standard Proctor test for that particular soil. For example, the samples taken from the West Mohawk Road site had moisture contents of 23 and 26% for the untreated (deeper) portion of the soil samples and 26, 27, and 29% for the LKD-treated (upper) portion of the soil samples. Those values are much higher than the optimum moisture content obtained from the standard Proctor test for laboratory soil samples, which is 14.6% for native and 15.1% for 5% LKD-treated soil.

The high moisture contents for most of the soil samples were consistent with observations made during the extraction process; the samples were very wet and there was evidence of water inside the Shelby tubes. The water may have penetrated into the Shelby tube samples during drilling because water was observed in the filled Shelby tube locations a few hours to a day after taking the soil samples.

Table 5.5: Laboratory Results of Field Soil Samples

Location	Station	Curing (days)	w%	Dry Density kg/m^3	Dry Unit Weight lb/ft^3	Test	Stress (psi)	Strain (%)	Comment
McPherson West-Mohawk Road	35+00	15	26.1	1458	91.0	UC	22.8	1.20	
		In situ	26.1	-	-	UC	19.0	4.47	Native soil
	33+00	14	29.3	1718	107.2	UC	24.4	0.95	Top portion
	31+00	14	27.0	-	-	UC	22.5	1.39	Top portion
	29+00	>28	-	-	-	UC	22.1	1.38	Top portion
	27+00	In situ	23.1	1605	100.2	UC	15.1	6.10	Native soil
McPherson East-Mohawk Road	53+33	3	27.4	-	-	UC	18.4	0.90	
	55+50	7	23.0	-	-	UC	44.2	1.58	
	56+25	-	-	-	-		-	-	Disturbed
	57+00	4	24.7	-	-	UC	18.6	1.03	
	63+00	-	-	-	-		-	-	Disturbed
	64+00	3	23.7	-	-	UC	34.9	0.78	
	65+50	-	-	-	-	-	-	-	Disturbed
SE Ramp	18+4039	-	-	-	-	UC	-	-	Disturbed
	15+3372	>28	21.3	1469	91.7	UC	54.9	2.48	
NE Ramp	30+25	4	19.9	-	-	UC	20.3	1.30	Top portion
		7	19.2	-	-	UC	20.4	1.17	Bottom portion
	32+00	15	18.2	-	-	UC	21.1	6.30	
	35+2616	15	25.3	-	-	UC	30.0	1.43	Top portion
		In situ	25.3	-	-	UC	26.1	4.23	Native soil
	39+2376	>28	23.1	1480	92.4	UC	10.8	2.40	
SW Ramp	13+00		20.7	-	-	UC			Disturbed
	14+9574	14.00	22.3	1540	96.1	UC	30.4	1.54	
	16+8777	14	10.1	-	-	UC			Top portion
		>28	26.0	-	-	UC			Bottom portion
	18+9575	-	-	-	-				Disturbed
NW Ramp	35+2610	15	21.8	-	-	UC	39.8	1.08	Top portion
	37+2235	15	24.3	-	-	UC	23.3	1.01	
	39+1435	-	-		-	-	-	-	Disturbed
	41+6635	4	-	-	-	UC	5.4	1.08	Bottom portion
		4	-	-	-	UC	7.3	3.10	Top portion
		In situ	-	-	-	UC	21.5	2.20	Native

With regard to dry density, most of the soil samples had a lower dry density compared to the maximum dry density obtained from standard Proctor test on laboratory soil samples. The percent compaction ranged from 85% to 95%. The low dry density values may be a function of high moisture contents during compaction.

Table 5.4 shows that the unconfined compression strength of the LKD-treated portions of the soil samples had little strength gain compared to untreated (in-situ) portions of the samples. Some of the soil samples were disturbed either through extraction or trimming processes. Some samples were noticeably disturbed inside the Shelby tubes before extracting. High moisture contents and sample conditions might be the cause of the low measured strengths. Selected photographs of Shelby tube soil samples are included in Appendix I.

Based on the test results and observations of the samples, it was concluded that unconfined compression strength tests on Shelby tube samples of the LKD-treated soil may not be reliable. However, Shelby tube samples of LKD-treated soils can be used to determine moisture content, dry density, and index properties of the treated soil. The soil samples also can be used to determine the amount of LKD in the treated soil and the effective depth of treatment.

5.6 Correlations

A statistical analysis was conducted on the collected data to determine the correlations between the measurements obtained from DCP and LWD devices and the data obtained from the laboratory samples.

5.6.1 DCP versus LWD Correlation and Effect of Curing Time

A regression analysis was conducted to find the linear correlation, if any, between the average DCP penetration rate (DCP-Index) for the top 300 mm (12 in.) and LWD elastic stiffness modulus (E_{LWD}) for all the tests conducted in the field. The results of the analysis yielded the following regression model (Equation 5.2 and Figure 5.17). This figure also shows a clear trend of increasing E_{LWD} and reduced DCP-Index as curing time increases (dots move up and to the left with increased curing time).

E_{LDW} = 79.57 – 1.269 (DCP-Index) (R^2 = 0.66) **Equation 5.2**

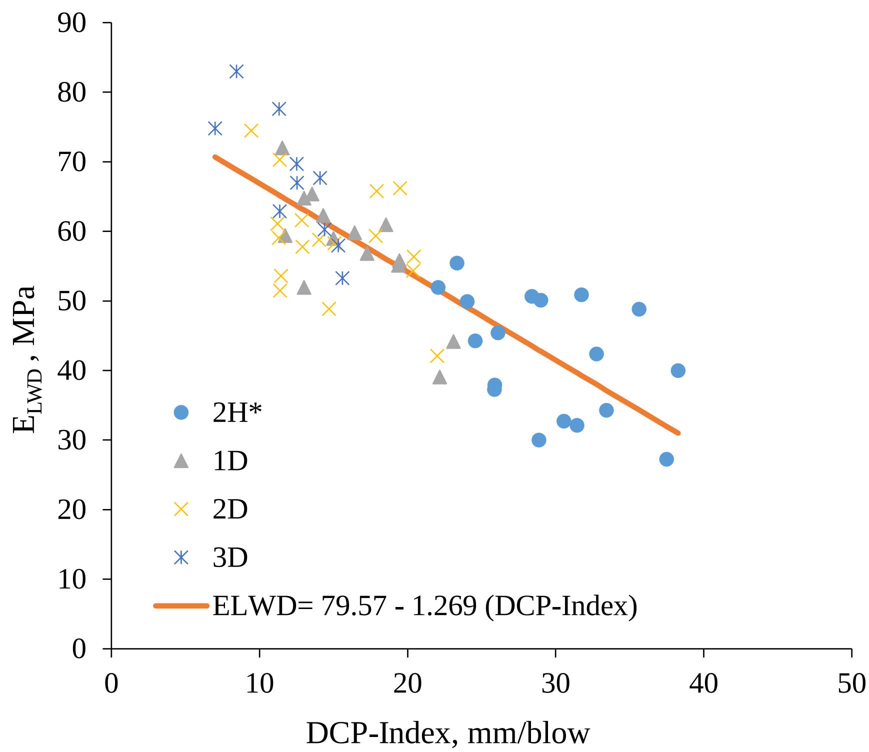
Or

DCP-Index = 48.2 – 0.525 (E_{LWD})

Where:

E_{LWD} = LWD elastic stiffness modulus, MPa

DCP-Index = DCP penetration rate, mm/blows



*2 hr, 1 day, 2 days, and 3 days after compaction

Figure 5.17: Correlation between DCP-Index and LWD Elastic Stiffness Modulus

5.6.2 DCP versus UC Strength of Laboratory Soil Samples

A regression analysis was also conducted on the average DCP-Index data obtained from the field and the UC strength of samples prepared in the laboratory with the same material, and the results are presented in Figure 5.18. The results of the analysis yielded the following nonlinear regression model (Equation 5.3):

UCS = 407.2/(DCP-Index)$^{0.67}$ (R^2 = 0.92) Equation 5.3

Where:

UCS = unconfined compression strength, psi

DCP-Index = DCP penetration rate, mm/blow

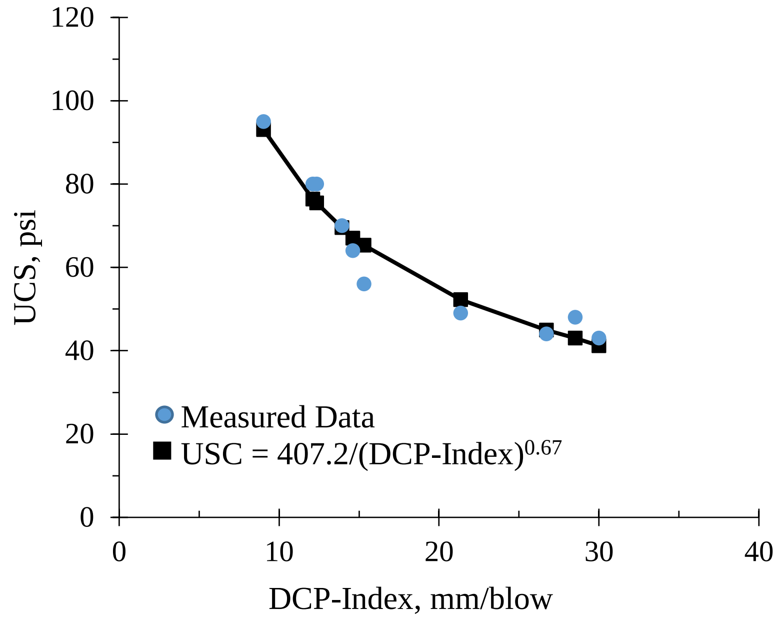


Figure 5.18: Correlation between DCP-Index and UC Strength

Chapter 6: Conclusions

A series of laboratory experiments and field investigations were conducted to evaluate the characteristics of LKD-stabilized subgrade soils. Laboratory tests were conducted on samples of native soil and soil treated with LKD, as well as samples treated with lime and fly ash for comparison. The laboratory tests included characterization of basic soil properties, UC strength, swell, resilient modulus, and durability.

The field investigation included documentation of construction procedures for LKD-treated subgrades and testing of the treated subgrades with the dynamic cone penetrometer, light weight deflectometer, and Shelby tube sampling. Based on the information obtained, the following conclusions were made:

1. The percentage of LKD required to raise the pH level of the soils to 12.4 was approximately two times the required percentage of lime for the ML and CL soils, and three times as much as the percentage of lime for the CH soil.
2. LKD was effective in reducing the plasticity of all soils used in this study. Addition of 5% LKD reduced the plasticity index values of all soils to levels lower than those achieved with fly ash, but not to the extent achieved with lime. The reduction in plasticity with the addition of LKD was consistent with the increasing of pH values of the soils tested.
3. The free volume change of the native soils was lowered substantially with LKD after 1 day of curing, and with more extended curing, the volume change was reduced further. However, lime reduced volume change even more than LKD.
4. LKD and lime dramatically reduced swelling tendencies of all the native soils tested, including the highly plastic soil. Five percent LKD by dry weight of soil reduced the native vertical swell potential values by more than 90% for the three soils tested with a 28-day curing period. These swell

reductions were comparable with lime, although lime did appear to achieve high levels of swell reduction more quickly.

5. Higher rates of LKD (i.e., 8%) did not provide an additional swelling reduction over 5% LKD for short (1-hr) curing times.
6. Providing additional mellowing time prior to compaction (i.e., 5 hr) for samples with higher rates of LKD resulted in greater swelling reduction.
7. LKD improved the durability of the soil over the native state as evaluated by wet-dry and freeze-thaw testing. The addition of 5–8% LKD provided moderate wet-dry protection and moderate-to-good resistance to freeze-thaw testing.
8. The UC strength of all samples increased substantially with the addition of LKD. LKD-treated soils showed the highest strength gain, and strength continued to increase with time. Samples gained most of their strength during the first 3 days after compaction. Lime-treated samples also experienced an increase in strength, and this strength gain was ongoing with time as well. Fly ash samples had the least strength gain.
9. LKD-treated soil samples showed more strength gain than lime-treated samples for unsoaked conditions in unconfined compression; however, the soil samples treated with lime had better performance than those treated with LKD for soaked conditions. The soaked samples treated with fly ash had the least strength gain for both conditions.
10. Dynamic cone penetrometer testing has the potential to provide valuable information on subgrade strength and the depth of treatment.
11. The DCP data showed that the LKD treatment substantially increased the strength of subgrade and that the LKD-treated portion of the subgrade gained additional strength with time. The DCP data also showed that the LKD-treated subgrade gained most of its strength (i.e., strength at 14 days curing) within 3 days of compaction.

12. The average of the estimated CBR values for LKD-treated subgrade increased by approximately 125% within 3 days of compaction, compared to the CBR value of the in-situ soil. The portion of the soil close to the surface of the subgrade had more strength gain than the lower portion of the layer.
13. The LWD can provide useful data on in-situ subgrade soil stiffness without disturbing the soil.
14. The LWD data showed that the measured elastic modulus of the subgrade soil increased with time, and the rate of modulus improvement was approximately 30%–100% within 3 days after compaction. The LWD data results were consistent with the DCP test results. LWD results after 14 days declined in some cases, probably due to surficial cracking of the stabilized layer. LWD readings can be sensitive to surface irregularities and should be used with caution if there are cracks on the surface of the soil.
15. The LKD-treated portion of the Shelby tube samples showed limited strength gain compared to untreated (in-situ) portions; however, multiple samples appeared to have experienced sample disturbance during the sampling and extrusion process, and this data was not considered to be as reliable as the DCP and LWD data.
16. An excellent correlation (i.e., $R^2 = 0.92$) was documented between the DCP data collected from the field testing and the UC strength obtained from the laboratory-prepared samples, suggesting that DCP testing is a valuable proxy for unconfined compression strength testing of LKD-stabilized soils.
17. A good correlation ($R^2 = 0.66$) was also found between the DCP and LWD data collected from the field investigation.

Chapter 7: Recommendations

The following recommendations were developed for the use of lime kiln dust for stabilizing subgrade soils and for testing of LKD-stabilized soils.

7.1 Usage of Lime Kiln Dust (LKD)

Based on the results described in this report, LKD is an effective soil-stabilization additive, and it is recommended that it be considered for use in the stabilization of subgrade soils as an alternative soil stabilizer. Treatment with 5% LKD by dry weight of soil is the typical recommended rate of application, and the soils tested as part of this project were substantially improved when LKD was added at a 5% rate. As with all soil additives, the preferred method for establishing the rate of LKD to be used for a particular project should be selected based on the expected contribution of the stabilized soil to the pavement system and the laboratory performance of LKD-treated soil samples.

If the primary use of LKD is to modify the soil to provide a working platform and control volume change of the soil, 5% LKD by dry weight of the soil is recommended as a typical rate. However, a more precise rate of LKD application may be determined based on the results of Atterberg limits, pH (ASTM D6276) testing, shrink/swell testing (ASTM D4546-14 and/or ASTM D2435), and ASTM D4609 criteria as well.

If the purpose of the use of LKD in stabilizing subgrades is to provide a significant contribution to the pavement layers in addition to controlling the swell potential of the soil, strength and durability testing should be included as a part of determination of the appropriate rate of application. Strength testing using procedures such as ASTM D4609 are recommended.

It was observed that mellowing periods of longer than 1 hour may have additional benefit with regard to swell control; however, the potential for a reduction in strength gain with longer mellowing periods is unclear. Additional research on the impact of mellowing time is recommended, especially when more than 5% LKD by dry weight of the soil is required.

7.2 Correlations

The correlations developed in this study between DCP, LWD, and laboratory testing show substantial promise for relating field and laboratory performance. Additional research relating these and other tests is encouraged. While the relationships published herein are potentially significant, they should be used with caution until the results can be confirmed based on experience with additional soils from additional sites.

7.3 Subgrade In-Situ Evaluation Tools

The DCP can provide a continuous profile of strength with depth and valuable information on the depth of treatment and the degree of soil improvement compared with the subgrade below. Therefore, the DCP is recommended for use to assess the in-situ strength of subgrade and depth of subgrade treatment.

The LWD provides a direct measurement of the in-situ stiffness of the pavement materials, including the subgrade soils. However, the LWD is very sensitive to the cracks developed on the surface of the subgrades, and the measurements on such subgrades may underestimate the true stiffness of the soil being tested. Therefore, while the LWD provides valuable information, data from the LWD should be used with care, and the condition of the subgrade surface should be evaluated before use. Data from a surface that has experienced surface cracking may not be a reliable measure of the stiffness of the layer as a whole.

Shelby tube samples can provide valuable information, such as the moisture content, dry density, index properties of the treated soil, the amount of additive in the treated soil, and the effective depth of treatment. However, Shelby tube soil samples were often disturbed to a substantial degree, which limited the value of the UC strength data. Given the advantages of time and effort, use of the DCP and LWD are preferred for assessment of in-situ strength and stiffness of the treated layers.

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