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FINAL REPORT

USE OF CEMENT KILN DUST FOR SUBGRADE STABILIZATION

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16 Abstract

Poor subgrade soil conditions can result in inadequate pavement support and reduce pavement life. Soils may be improved through the addition of chemical or cementitious additives. These chemical additives range from waste products to manufactured materials and include lime, Class C fly ash, Portland cement, cement kiln dust from pre-calciner and long kiln processes, and proprietary chemical stabilizers. These additives can be used with a variety of soils to help improve their native engineering properties. The effectiveness of these additives depends on the soil treated and the amount of additive used.

This report contains a summary of the performance of a wide range of soils treated with pre-calciner cement kiln dust (CKD), and is intended to be viewed as a companion report to the previously published Kansas Department of Transportation report, *Performance of Soil Stabilization Agents*. CKD has been used as a soil additive to improve the texture, increase strength and reduce swell characteristics. CKD was combined with a total eight different soils with classifications of CH, CL, ML, SM, and SP. Durability testing procedures included freeze-thaw, wet-dry, and leach testing. Atterberg limits and strength tests were also conducted before and after selected durability tests. Changes in pH were monitored during leaching. Relative values of soil stiffness were also tracked over a 28-day curing period using the soil stiffness gauge.

Treatment with cement kiln dust was found to be an effective option for improvement of soil properties, based on the testing conducted as a part of this research. Strength and stiffness were improved and plasticity and swell potential were substantially reduced. Durability of CKD treated samples in wet-dry testing was comparable to that of soil samples treated with the other additives, while performance was not as good in freeze thaw testing. CKD treated samples performed very well in leaching tests and in many cases showed additional reductions in plasticity and some strength gains after leaching.

It is recommended based on the results of this research that cement kiln dust be considered a viable option for the stabilization of subgrade soils. As with all additives, it is recommended that a mix design be conducted prior to selection to confirm the CKD selected and the amount specified will provide satisfactory performance.

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NOTICE

DISCLAIMER

EXECUTIVE SUMMARY

Poor subgrade soil conditions can result in inadequate pavement support and reduce pavement life. Soils may be improved through the addition of chemical or cementitious additives. These chemical additives range from waste products to manufactured materials and include lime, Class C fly ash, Portland cement, cement kiln dust from pre-calciner and long kiln processes, and proprietary chemical stabilizers. These additives can be used with a variety of soils to help improve their native engineering properties. The effectiveness of these additives depends on the soil treated and the amount of additive used.

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additives, while performance was not as good in freeze thaw testing. CKD treated samples performed very well in leaching tests and in many cases showed additional reductions in plasticity and some strength gains after leaching.

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Chapter 1

Introduction

Poor subgrade soil conditions can result in inadequate pavement support and reduce pavement life. Soils may be improved through the addition of chemical or cementitious additives. These chemical additives range from waste products to manufactured materials and include lime, Class C fly ash, Portland cement, proprietary chemical stabilizers, and cement kiln dust. These additives can be used with a variety of soils to help improve their native engineering properties. The effectiveness of these additives depends on the soil treated and the amount of additive used. This report contains a summary of the performance of cement kiln dust (CKD) when used with a wide range of soils. It has been developed as part of a companion study to the Kansas Department of Transportation report, *Performance of Soil Stabilization Agents* by Milburn and Parsons (1), which contained a summary of the results observed when the same soils were treated with lime, fly ash, cement and an enzymatic stabilizer.

The purpose of using CKD, and the other additives, is to improve the texture, increase the strength and reduce the swell characteristics of the various soils. When the additives containing free calcium hydroxide are mixed with the soil, the calcium causes the clay particles to flocculate into a more sand-like structure reducing the plasticity of the soil (2). This reduction in plasticity, which is called modification, reduces the shrink/swell characteristics of the soil. Soil stabilization includes the effects from modification with a significant additional strength gain. The soil must be able to react with the chemical additives to achieve the soil stabilization or modification that is desired.

The different additive types, along with the variety of soil types and conditions, can make choosing the optimum additive and correct percentage to use a difficult decision. To ease the selection process, a soil/additive performance based specification would be of significant help in comparing the relative performance expected from each soil/additive combination based on a variety of soil testing procedures. This report contains a discussion of the relative performance of each CKD/soil combination, and is intended for use in coordination with the previous report by Parsons and Milburn.

Each CKD/soil combination was evaluated to determine its relative performance using strength, swell, stiffness, durability and Atterberg limits. To determine the strength of each combination, samples were compacted and cured for a 28-day period in a moisture room and then tested to determine the unconfined compressive strength. The stiffness values for these samples were tracked over the 28-day curing period using a soil stiffness gauge. The durability testing was used to evaluate the long-term performance of each combination and included leaching, wet-dry, freeze-thaw and free swell testing. The leaching test consisted of compacting a soil sample and placing the sample in a leaching apparatus and leaching distilled water at a constant head through the sample. The leachate that flowed out of the sample was collected and monitored for flow and pH values.

The information presented in this report is organized into five different chapters. Chapter One covers the introduction to the project. A literature review containing descriptions of CKD and results from previous testing of soils mixed with CKD are covered in Chapter Two. Chapter Three describes the testing procedures used during the study. The results of the testing procedures are presented in Chapter Four. Conclusions and recommendations were developed based on those results and are presented in Chapter Five.

Chapter 2

Literature Review

This chapter contains a discussion of the composition of cement kiln dust and its effectiveness in stabilizing subgrade soils as reported in the published literature and by local consultants. Data from local consultants was provided to the University of Kansas by Fly Ash Management.

2.1 Composition of Cement Kiln Dust

As an industrial by-product, the composition of cement kiln dust is a function of many variables. Its constituents include partially calcined and unreacted raw feed, clinker dust, and fuel ash, enriched with alkali sulfates, halides, and other volatiles. For the purpose of soil stabilization, CKD's may be segregated into two categories, pre-calciner kiln dust and long-wet or long-dry kiln dusts. Pre-calciner kiln dust is generally coarser, higher in free lime, and concentrated with alkali volatiles, while dust from the long kilns will contain more calcium carbonate with more limited amounts of free lime (3). Examples of the two types of CKD from two Ash Grove plants are shown in Table 2.1. The Chanute ash is a pre-calciner dust and Midlothian (Texas) is a long-kiln dust. As Table 2.1 shows, the Chanute ash has a much higher free lime content than the Midlothian ash. As the compositions of the two CKDs are quite different, their effects on soil can be expected to differ. Pre-calciner CKD's can be expected to perform more like lime as they contain substantial amounts of free lime as a constituent. The research described in this report was conducted exclusively with pre-calciner CKD from Chanute and all results and conclusions of the report are intended to refer to CKD from the Chanute plant and CKDs of similar composition.

Table 2.1: Chemical Analysis of Pre-Calciner and Long-Kiln Ash

Chemical Analysis - Chanute[1] (4)	Pct.
Silicon Dioxide, SiO_2, %	17.62
Aluminum Oxide, Al_2O_3, %	4.9
Iron Oxide, Fe_2O_3, %	2.58
Calcium Oxide, CaO, %	62.09
Magnesium Oxide, MgO, %	1.93
Sodium Oxide, Na_2O, %	0.56
Potassium Oxide, K_2O, %	3.76
Sulfur Trioxide, SO_3, %	5.79
Moisture Content, %	0.07
Loss on Ignition, %	4.94
Available Lime Index, % CaO	33.7
Water-Soluble Chlorides, % CL	--
Physical Analysis	
Retained on No. 325 sieve (%)	16.9
Specific Gravity	2.95

Chemical Analysis - Midlothian[2] (5)	Pct.
Total CaO, %	45.0-49.0
as Calcite $CaCO_3$, %	22.0-25.0
as CaO (free lime), %	5.5-8.0
as Calcium Silicate, %	12.0-15.0
as $CaSO_4$, %	3.0-5.0
Silicon Dioxide, SiO_2, %	11.0-14.0
Aluminum Oxide, Al_2O_3, %	3.5-4.5
Sulfur Trioxide, SO_3, %	8.0-12.0
Iron Oxide, Fe_2O_3, %	1.5-2.5
Sodium Oxide, Na_2O, %	0.1-1.0
Potassium Oxide, K_2O, %	2.0-10.0
pH	12.4-12.9
Unit weight (lb/ft3)	32.0-44.0
volatiles, %	0.3-1.0
Smaller than 0.075 mm, %	55-75

[1]Chanute Plant (Kansas)
[2]Midlothian Plant (Texas)

Several studies have been conducted by area consultants on local CKDs or published by TRB or other organizations. Findings of relevant studies are summarized in the following sections.

2.2 Portland Cement Association

Bhatty and Todres summarized a number of studies in (3). A portion of their conclusions are summarized as follows:

- CKD with high free lime (≈15%) and low alkalies (< 4% water soluble K_2O=Na_2O or < 3% Na_2O equivalent) resulted in improved compressive strengths for clay soils.
- CKDs with low free lime (< 8%) and high alkali CKD (> 7% water soluble K_2O=Na_2O or > 3% Na_2O equivalent) adversely affected the unconfined compressive strength.
- High loss on ignition (LOI) indicates that the CKD is high in slow-reacting calcium carbonate and low in reactive free lime. A high LOI was not defined numerically, however a CKD with an LOI of 28% was described as high.

- Higher concentrations of alkalies in CKDs can counter stabilization reactions because of ionic interference.
- CKD with low LOI (< 9%) and moderate alkalies (> 3% Na_2O) reduced the PI and improved the unconfined compressive strength.
- CKDs with moderate free lime and low alkalies were shown to improve plastic indices, reduce swelling, and improve strength and durability.

2.3 University of Oklahoma

Miller and Zaman (6) evaluated three CKDs in comparison with lime in field and laboratory tests. CKD was added at a rate of 15% and lime was added at a rate of 4% quicklime. All CKD's had relatively high LOI values, suggesting they were from long kilns of some type. CKD was added to a weathered shale described as a moderately plastic clayey soil with a PI of 24 to 30, a second clay referred to as Miller Clay, and to a poorly graded fine sand with little silt.

Miller and Zaman found that unconfined compressive strength increased with all CKD's at least to a level equivalent with lime, with the CKD with the lowest LOI providing the greatest increases in strength. CKD improved the durability of the soils in wet-dry and freeze-thaw tests over untreated soil. Addition of CKD and lime to the weathered shale resulted in *increased* plasticity. A second soil was selected (Miller Clay) and both CKD and lime reduced the plasticity of this soil and were considered to provide a similar level of improvement in the soil.

2.4 Terracon CKD Study

Waters and Schwieger (7) conducted a limited study on the effects of CKD on a moderately plastic soil (liquid limit = 50) as compared with lime. CKD was added at a rate of 6% by weight with a range of delay times prior to mixing. The soil was mixed with 4 and 6% quicklime (CaO) for comparison. Addition of CKD was observed to increase the strength at optimum to 350% of the original strength with a 2-hour compaction delay and 250% with a 48-hour delay. The

California Bearing Ratio (CBR) increased to a value of 11 at approximately 5% above optimum, which was estimated to be 3-4 times greater than for the native soil. Increases in strength were achieved despite a reduction in dry unit weight. Optimum moisture contents increased slightly. Dry unit weights and optimum moisture contents are reported in Table 2.2.

Table 2.2: Maximum Dry Unit Weights and Moisture Contents (7)

Description	Cure time	Max Dry Unit Wt	Optimum Moisture
Native soil*	N/A	105.5	18.5
Native soil with 6% CKD	2 hours	102.0	18.5
Native soil with 6% CKD	48 hours	100.0	20.0
Native soil with 6% CKD	7 days	99.5	20.5

*dark brown lean to fat clay

Plasticity was reduced by the introduction of CKD, although not as much as with the introduction of lime. Some additional decline in plasticity was observed for longer curing times. Waters and Schwieger concluded that the addition of 6% CKD lowered the plasticity index the same amount as 4% quicklime. Atterberg limits for the soil mixtures tested are reported in Table 2.3.

Table 2.3: Atterberg Limits of Native and Treated Soil (7)

Description	Cure time	LL	PL	PI
Native soil*	N/A	50	19	31
Native soil with 6% CKD	2 hours	45	28	17
Native soil with 6% CKD	48 hours	42	28	14
Native soil with 6% CKD	7 days	42	28	14
Native soil with 6% CKD	48 hours	40	30	10
Native soil with 4% Quicklime	48 hours	41	31	10
Native soil with 6% Quicklime	48 hours	39	33	6

*dark brown lean to fat clay

Waters and Schwieger also tested an SM soil mixed with 6% Chanute CKD and reported increases in unconfined compressive strength from 8 – 22 psi to 194 – 256 psi.

2.5 QIS Study

Fu (8) compared the effectiveness of CKD in reducing plasticity for a soil with high plasticity (LL = 79, PI = 62). CKD and lime were added in various percentages and allowed to mellow for 1, 2, and 4 days. The type of CKD used was not reported but is assumed to be pre-calciner CKD. QIS found that similar reductions in plasticity could be achieved with CKD as with lime, although a higher percentage of CKD was required to achieve the same level of improvement as shown in Figure 2.1. The majority of improvement occurred during the first day of mellowing, however a small additional improvement was observed with a second day of mellowing.

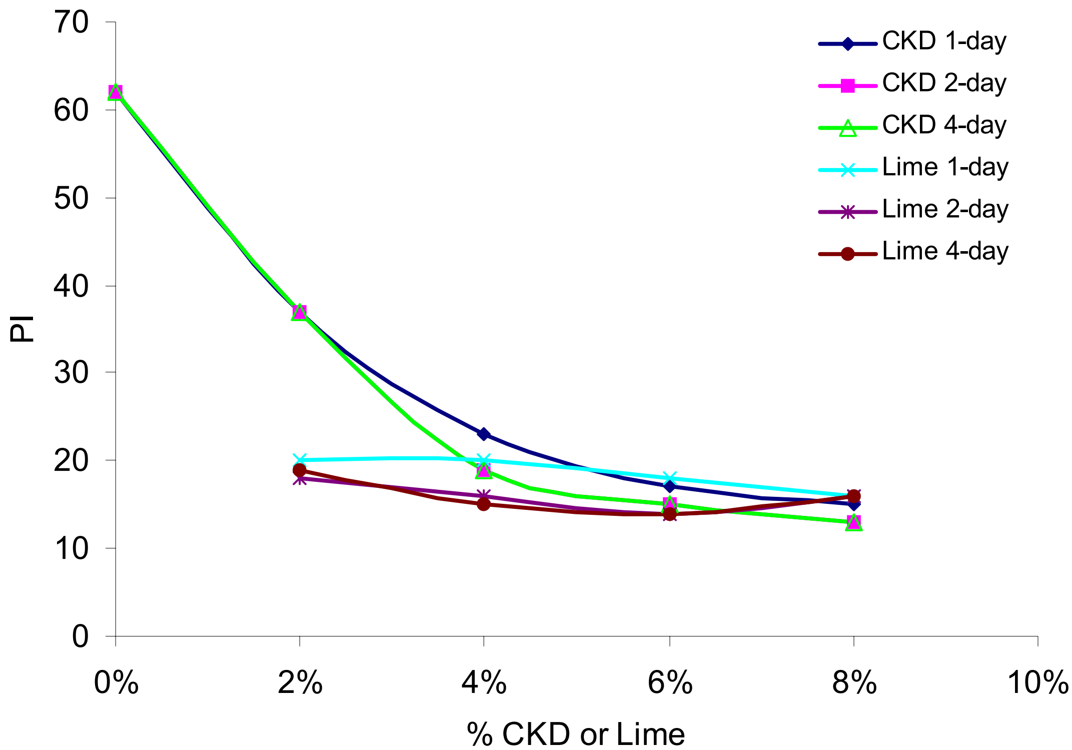

Figure 2.1: Changes in PI with the addition of CKD or Lime (8)

Chapter 3

Procedure

This chapter contains a description of the testing procedures followed as a part of this research. Standard procedures were used where possible. Adjustments to standard procedures are noted and non-standard procedures are described in detail.

3.1 Materials Used

3.1.1 Native Soil

Eight different soils classified as CH, CL, ML, SM and SP were selected for use in the admixture evaluation. The native soil properties were determined according to the ASTM standards listed in Table 3.1, with modifications as described in the following sections. Three CH soils from the Beto Junction area and two CL soils, one from Osage and the other from Hugoton, were tested. The silty soils came from Atwood (ML), Stevens (SM) and Lakin (SP). Lakin has been identified as "Larkin" in some earlier publications. Approximate source locations of the soils are shown in Figure 1.

3.1.2 Additives

Pre-calciner cement kiln dust generated in Chanute, Kansas by Ash Grove Cement was mixed with each of the additives. The amount of additive used was determined based on the increase in pH according to ASTM D 6276 and reductions in plasticity index. The chemical composition of the dust is reported in Table 3.2. CKD was added to the soils at rates of 1.5 to 7 percent, by weight.

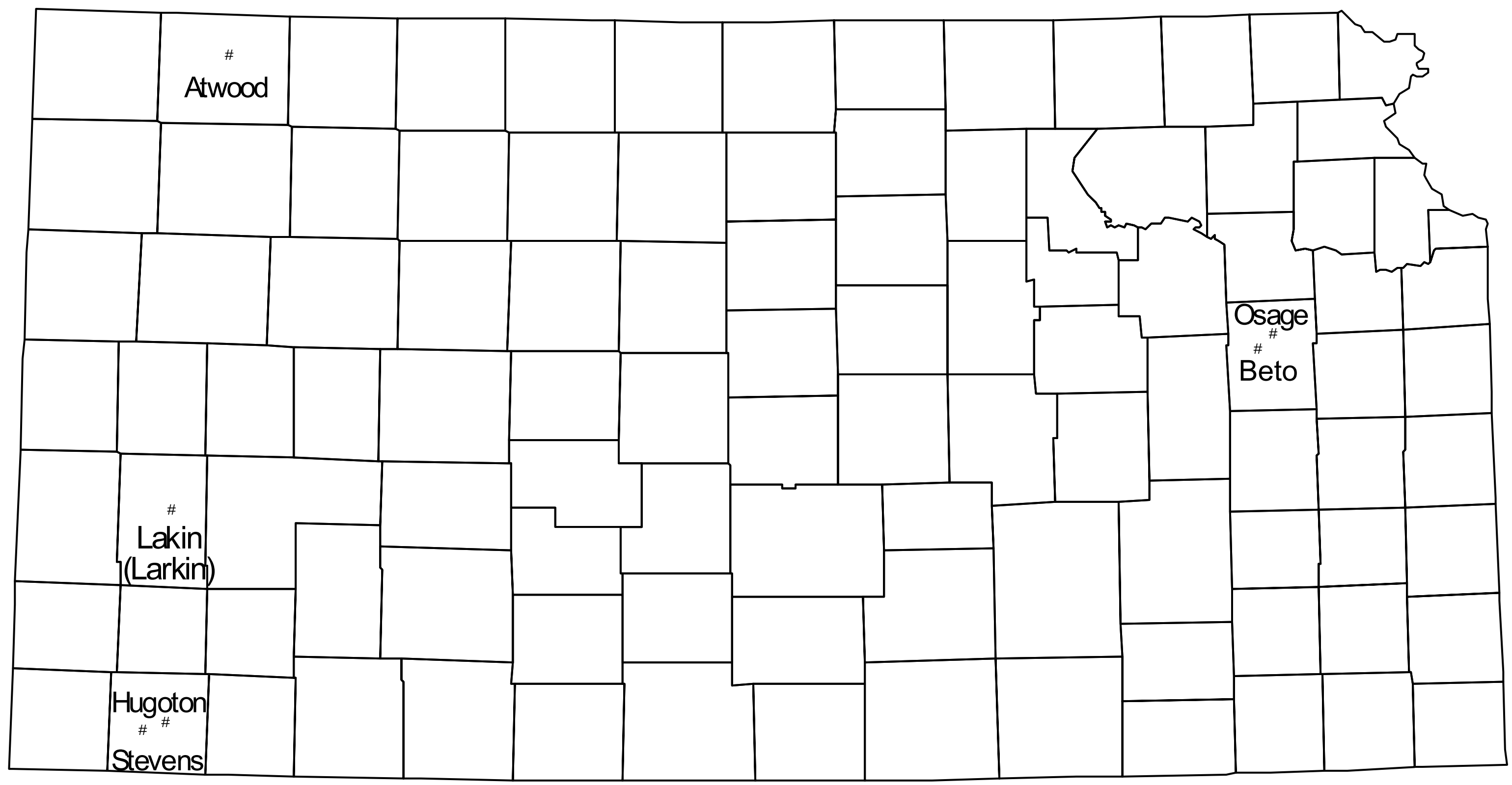

Figure 3.1: Approximate Source Locations of Soils

Table 3.1: Standard Testing Procedures

Test	ASTM
Grain Size Analysis	D 422
Atterberg Limits	D4318
Specific Gravity	D 854
pH Lime Stabilization	D 6276
Moisture-Density Relationship	D 698
Swell	KDOT Spec
Freeze-thaw	D 560
Wet-dry	D 559
Unconfined Compression	D1633, 5102

Table 3.2: CKD Chemical and Physical Analysis

Chemical Analysis	**Percentage**
Silicon Dioxide, SiO_2	17.62
Aluminum Oxide, Al_2O_3	4.90
Iron Oxide, Fe_2O_3	2.58
Calcium Oxide, CaO	62.09
Magnesium Oxide, MgO	1.93
Sodium Oxide, Na_2O	0.56
Potassium Oxide, K_2O	3.76
Sulfur Trioxide, SO_3	5.79
Moisture Content	0.07
Loss on Ignition	4.94
Available Lime Index, CaO	33.70
Water-Soluble Chlorides, CL	--
Physical Analysis	
Retained on No. 325 sieve (%)	16.9
Specific Gravity	2.95

3.2 Lab Testing

3.2.1 Soil-Preparation

Each soil was air-dried overnight in large pans and was then broken up to pass the 3/8" sieve. Samples of the soil were wet sieved according to ASTM D 2216 over a #40 sieve to remove the larger particles. The #40 sieve was used instead of the #10 sieve because the Atterberg limits require material smaller than the #40 sieve. The material that passed the #40 sieve was dried at 60^{o}C and pulverized with a mortar and pestle. After the material was broken up, it was then used for hydrometer analysis, Atterberg Limits, and other durability testing.

3.2.2 Atterberg Limits Procedure

Atterberg Limits for CKD treated material were determined in general accordance with the Portland Cement Association (PCA) procedure for cement modified soils (9), with some modifications for some soils. For the PCA procedure the soil is first wet sieved over a #40 sieve and the material passing the sieve is dried and later broken up with a mortar and pestle. The specified amount of CKD is then added to the dry weight of soil and water and mixed in with the soil-CKD to a uniform consistency just above the native plastic limit. The soil-CKD mixture is then allowed to mellow for 24 hours.

The PCA procedure calls for the mellowed mixture to again be wet sieved over a #40 sieve and then air-dried. The soil is then broken up with a mortar and pestle, mixed with water and the Atterberg limits determined in accordance with ASTM D 4318. This procedure was followed for approximately half of the soils and is referred to as Method 1. However there was great difficulty in breaking down the dried CKD soil after the second wet sieve step so the effect of deleting the second wet sieving process for CKD treated soils was investigated. Atterberg Limits were determined for treated soils that had been sieved both once and twice and there was no significant change in the Atterberg limits. Therefore a modified procedure in which the second sieving step was not used (Method 2) was used for selected soils.

3.2.3 Moisture-Density Relationships (Proctor)

CKD was mixed in with the dry soil and water was added to raise the moisture content to the target moisture. The soil, CKD and water were mixed to a uniform consistency and then placed in an airtight container for one hour prior to compaction to simulate a standard construction delay. The sample was then compacted with standard effort according to ASTM D 698.

3.2.4 Swell

Swell testing for the native soils was conducted in accordance with the KDOT specification, *Determination of Volume Change of Soils*. For this test samples of soil were prepared at three percentage points below and three percentage points above optimum moisture content. The samples were compacted in a 4-inch proctor mold to a height of 2 inches. A surcharge stress of 150 psf (7.18 kPa) was then applied to the sample, water was added and the swell of the sample was measured.

The two 1200 gram samples were placed in a 60^{o}C oven overnight and a moisture content was obtained the following day. Water was added to the soil samples to bring the moisture content of one sample to 3 points below optimum and the other sample was mixed at 3 points above optimum moisture of the native soil. A moisture content was taken of the mixed samples to ensure proper mixing. The samples were then placed in an airtight container and allowed to mellow overnight. After the mellowing period, the moisture content was adjusted if necessary and sufficient soil was used to compact a sample with the required 92% of maximum density as determined by ASTM D 698. The samples were then compacted to a 2-inch height and were allowed to rebound overnight with a surcharge stress of 150 psf (7.18 kPa) in place. After compaction, a moisture content sample was taken to determine the actual moisture content at compaction. After the rebound period, the height for each of the two samples was measured and the molds where then placed in a pan filled with water. The change in height was measured for 96 hours and the swell was determined by dividing the change in height by the original height. The swell of the two samples was plotted vs. moisture contents and the percent swell reported was the swell that corresponded to the optimum moisture content.

The CKD swell procedure was similar to the native swell test. The soil was weighed out for both samples and the lime was mixed in and water was added to raise the moisture to 3 points below and 3 points above the CKD optimum. The samples then mellowed overnight. The swell was then determined in accordance with the procedure for native soils.

3.2.5 Freeze-thaw

Freeze-thaw tests were conducted according to ASTM D 560. Two identical samples of each soil/additive combination were prepared at the optimum moisture content following moisture-density sample preparation procedures. The CKD and soil were mixed and allowed to stand one hour prior to compaction. After compaction, the samples were cured seven days in a moisture room prior to subjecting them to freeze-thaw cycles.

Each freeze-thaw cycle consisted of placing the two soil samples in a freezer at –23 degrees C for 24 hours. The samples were then moved to a moist room for 23 hours. After removal from the moist room, 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.

3.2.6 Wet-dry

Wet-dry tests were conducted according to ASTM D 559. Two identical samples of each soil/additive combination were prepared at the optimum moisture content following ASTM D 698 sample preparation procedures. The CKD and soil were mixed and allowed to stand one hour prior to compaction. After compaction the samples were cured for seven days in a moisture room prior to subjecting them to any wet-dry cycles. Each wet-dry cycle consisted of submerging the two soil samples in water for 5 hours and then placing them in a 71 degree C oven for 42 hours. After removal from the oven, the first sample was measured for volume change and weighed to determine any change in moisture content. The second sample was brushed and weighed to determine the soil loss. The test was continued until 12 wet-dry cycles were completed or until the sample failed.

3.2.7 Unconfined Compression and Soil Stiffness Testing

The soil samples that were compacted for the moisture-density relationships (ASTM D 698) were cured for 28 days and then tested to determine their unconfined compressive strength following ASTM D 1633 and D 5102. The soil stiffness of each soil sample was monitored during the curing period using a soil stiffness gauge device (SSG).

The soil stiffness gauge (Figure 3.2) is a non-nuclear hand carried device manufactured by Humboldt that repeatedly generates a small dynamic vertical force on the compacted surface. The SSG measures the deflection of a known mass resulting from the application of a known vibrating force. The stiffness of the soil for a series of loading frequencies is calculated based on these deflections (10).

Measurements were obtained at 10 minutes, 4 hours, 1 day, 7 days, 14 days and 28 days after compaction. The values reported represent an average of four stiffness gauge readings.

The soil stiffness gauge used a modified foot that was designed for the 4-inch proctor samples that were tested. The readings taken at 10 minutes and 4 hours were determined with the soil sample in the proctor mold. Subsequent readings were determined with the sample extruded from the mold.

Figure 3.2: Soil Stiffness Gauge

3.2.8 Leaching

The leaching test involved leaching distilled water thorough a soil sample under a constant head of 55.5 inches (except where noted) and with a confining pressure of 10 psi for 28 days. The leachate that flowed though the compacted soil sample was collected and used to determine pH and flow-rates over the 28-day leaching period. The leaching tank was modeled after a design from McCallister and Petry (11). The leaching apparatus consisted of a clear tank similar to a triaxial cell with flexible membrane confinement for the samples. The tank design was modified to use a four-inch proctor sample as shown in Figure 3.3. The pH and flow were monitored over regular intervals. The soil samples used were compacted at optimum moisture content and cured for seven days in a moist room prior to leaching.

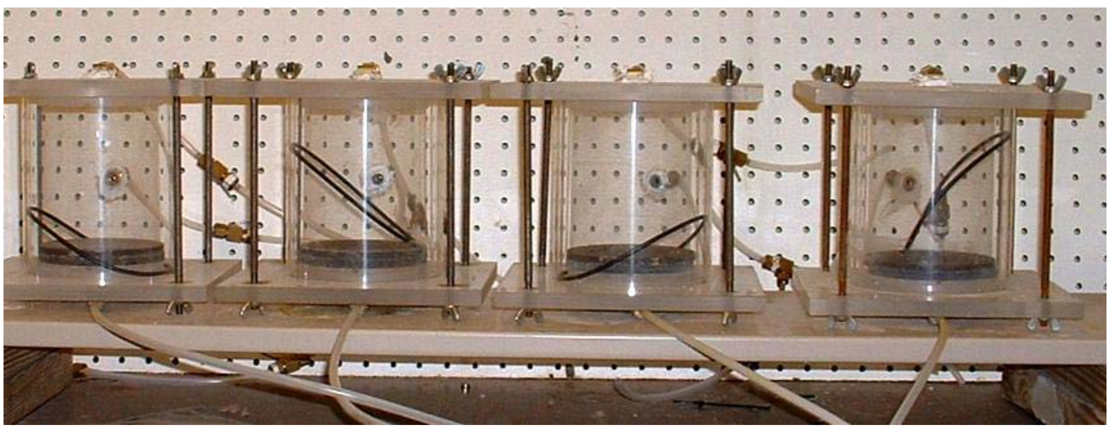

Figure 3.3: Leaching Cells

Chapter 4

Results and Discussion

The results of the testing program are described within this chapter. These results include native soil properties, CKD percentages and test results for the treated soils.

4.1 Native Soil Properties and CKD Percentages

Native soil characteristics were determined using grain size analysis, Atterberg limits, specific gravity, swell, standard proctor and unconfined compression. A summary of the test results is presented in Table 4.1. The eight soils were classified and the results showed a combination of three CH soils, (Beto "Red", "Tan" and "Brown") two CL soils, (Osage and Hugoton) and three silty to sandy soils that classified ML, SM and SP (Atwood, Stevens and Lakin).

The CKD percentages that were used to evaluate relative soil performance for the testing procedures are presented in Table 4.1 along with the percentages of quicklime, cement, Class C fly ash, and Permazyme used previously. Table 4.2 shows the properties of the CKD treated soils. The amount of CKD used was based on pH and Atterberg limits results, while the percentage of quicklime used during the previous study was determined according to ASTM D 6276. The fly ash percentage was fixed at 16 percent, which is a standard percentage in the region. The percentage of cement added for clay soils was determined by the amount of cement needed to lower the PI below 10. For soils that did not have a PI of 10, a cap of 9 percent was used for economic reasons and for soils with a native PI below 10 the Portland Cement Association Handbook criteria (9) were used to determine the cement percentages. Permazyme samples were mixed following the manufacturers recommendations (12).

Table 4.1: Native Soil Properties and Admixture Percentages

Soil Properties	Beto Junction Red	Beto Junction Tan	Beto Junction Brown	Osage	Atwood	Hugoton	Stevens	Lakin
% Sand	5	12	5	8	12	34	70	96
% Fines	95	88	95	92	88	66	30	4
Liquid Limit	70	53	65	36	30	35	20	NP
Plasticity Index	45	31	36	16	7	16	3	NP
USCS	CH	CH	CH	CL	ML	CL	SM	SP
AASHTO	A-7-6	A-7-6	A-7-6	A-6	A-4	A-6	A-2-4	A-3
Max Unit Weight, lb/ft^3	94	105.4	96.6	108	98	104	120	107
Max Density, kg/m^3	1506	1689	1548	1731	1571	1667	1923	1715
Optimum Moisture, %	25.7	20.3	25.3	18.5	13.7	19.9	9.9	2
UC at Optimum, psf	6400	4600	4600	4800	6600	4415	5638	0
Max UC, psf	8600	7500	6400	7500	6600	6200	5638	0
Moisture at Max UC	18.9	18.6	23.5	17	13.7	17.6	9.9	0
Specific Gravity	2.78	2.77	2.73	2.74	2.75	2.69	2.68	2.66
Cement Kiln Dust	7	6	7	6	5	6	3	1.5
Quicklime, %	5.5	3.5	6	4	1.5	2.5	1	-
Fly Ash, %	16	16	16	16	16	16	16	16
Cement, %	9	9	9	5	10	3	7	10
Permazyme	-	-	-	-	Yes	Yes	Yes	-

Table 4.2: Soil Properties with the Addition of CKD

Properties with CKD	Atwood	Beto Junction Brown	Beto Junction Red	Beto Junction Tan	Hugoton	Lakin	Osage	Stevens
% CKD	5	7	7	6	6	1.5	6	3
Liquid Limit	35*	56	54	54	48*	NP	42	NP
Plasticity Index	6*	17	13	17	12*	NP	10	NP
Max Dry Unit Weight (pcf)	84.5	89.5	85	91	86	110	92	110
Opt. Moisture Content (%)	17	20	23	21	24	5.5	23	16
Opt. UC Strength (psf)	12250	12250	17500	18000	15750	780	23000	14000
Maximum UC Strength (psf)	16850	14400	17700	20000	15750	780	23250	14000
Moisture at Max UC (%)	23	23	23.5	23.5	24	5.5	24.5	16

*estimated based on closest CKD percentage

4.2 Atterberg Limits

The addition of CKD changed the Atterberg limits of the soils tested. Changes in the liquid limit were irregular with increases for some soils and decreases for others. However, increases in the plastic limit were consistently large enough to lower the plasticity index for all soils. PI reductions stabilized at values between 6 and 15. Final Atterberg limits are reported in Table 4.2. Plots of Atterberg limits vs. CKD percentages are reported in the Appendix.

4.3 Maximum Unit Weight and Moisture Content

Maximum dry unit weights and optimum moisture contents for CKD treated soils are reported in Table 4.2. Dry unit weights were generally lower after the addition of CKD, often by 5-10 lb/ft^3 or more. The affect of CKD on optimum moisture content was variable, with the most prominent effect being the flattening of the moisture-unit weight curves. This was similar to the effect of lime and other additives on the moisture-unit weight relationships. Moisture-unit weight curves are presented in the Appendix.

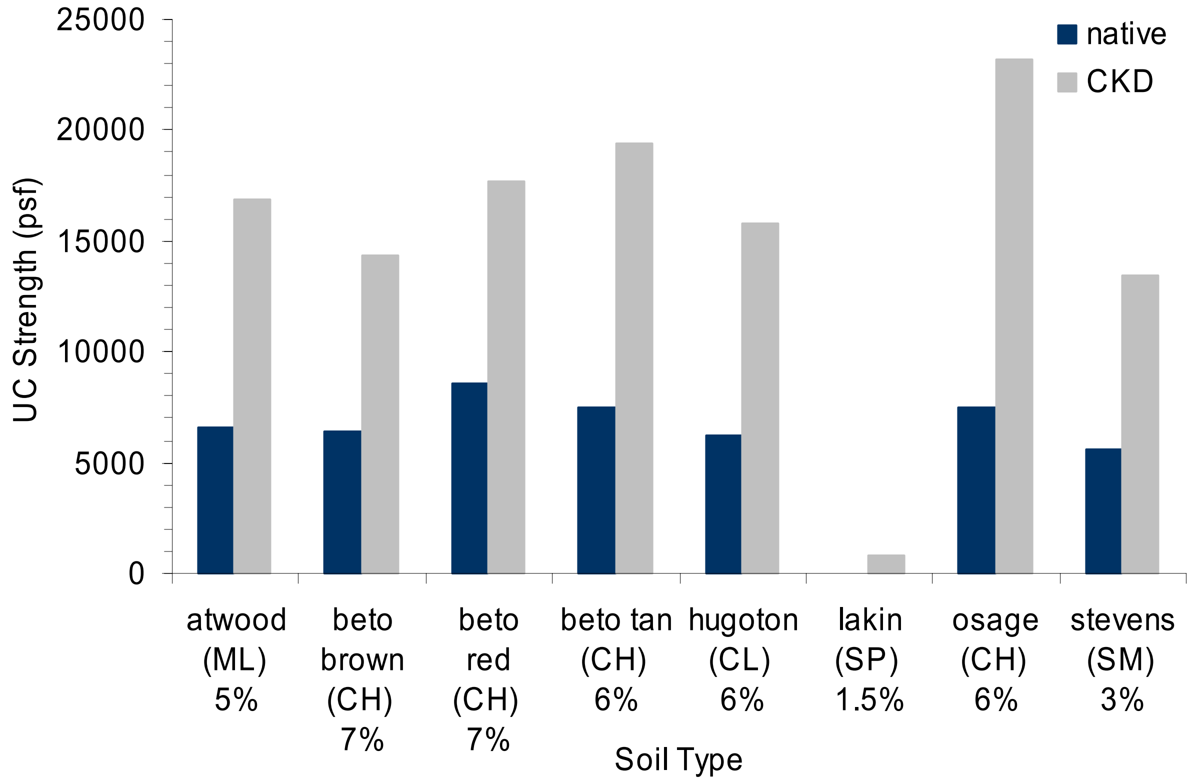

Figure 4.1: UC Strength – Native vs. CKD treated

4.4 Unconfined Compression Strength

Unconfined compressive (UC) strength at optimum moisture increased approximately 100 to 200% for all soils with the exception of Lakin (SP sand), which had no UC strength for the native case. Osage (CL clay) had the greatest improvement with an increase from 7,500 psf to 23,000 psf. Unconfined compressive strengths for native and CKD treated soils are shown in Figure 4.1. Detailed curves showing the relationships between moisture and UC strength for each soil are presented in the Appendix.

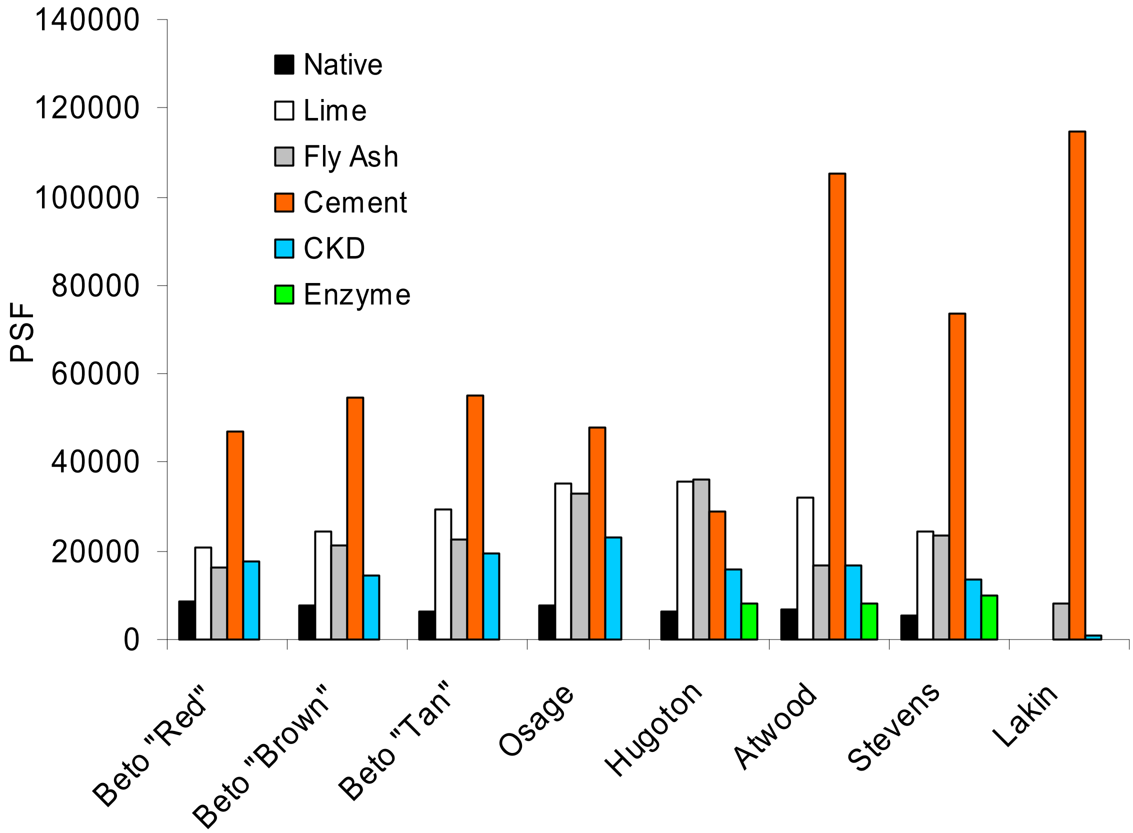

Figure 4.2: Maximum UC strength for All Additives

Figure 4.2 reports the UC strength values for the same soils mixed with a variety of additives by Milburn and Parsons (1) for comparison. This figure shows that cement provided the greatest strength increases, although the cement contents used would likely make it the most costly alternative. CKD produced significant strength improvements that were similar to or slightly lower than those for lime and fly ash, and superior those produced by the enzymatic stabilizer.

4.5 Changes in pH with the Addition of CKD

Cement Kiln Dust has a major affect on the pH of soil similar to that of lime, although the pH of the CKD was actually higher than for lime (pH = 12.45) and was more variable. Changes in pH with the addition of CKD were monitored and are reported in Table 4.3. Plots of the changes in pH with the addition of CKD are presented in the Appendix.

The pH plots served as the primary guide for determination of the amount of CKD to use for other testing, with changes in the Atterberg limits also considered. The amount selected for use in treatment was based on the percentage required to reach a stable pH, which was generally near 12.45.

Table 4.3: pH values for Various Percentages of CKD

Soil	Class	% Cement Kiln Dust										CKD Saturated
		0	1	2	3	4	5	6	7	8	9	
Beto Tan	CH	8.03		11.81	11.98	12.16	12.31	12.44				12.87
Beto Brown	CH	8.03			11.54	11.90	12.11	12.23	12.34	12.20	12.26	12.87
Beto Red	CH	8.15		10.76	11.46	11.85	12.03		12.08	12.15	12.22	12.81
Osage	CL	8.85		11.67	11.99	12.13	12.26	12.38	12.39	12.43		13.07
Hugoton	CL	8.89		11.51	11.91	12.18	12.38	12.47				12.76
Atwood	ML	8.7	11.10	11.62	12.07	12.28	12.45					12.76
Stevens	SM	8.75	11.96	12.24	12.33	12.36	12.36					12.64
Lakin	SP	8.38	12.31	12.46	12.55	12.59	12.64					12.48

4.6 Soil Stiffness with Time

The stiffness of CKD treated samples was monitored during the 28-day curing period. Stiffness values for CKD treated samples were substantially higher than for native samples within a short time after compaction. However there was little additional stiffness gain observed after the first few hours, with the exception of the Hugoton and Stevens soils, for which the stiffness was observed to increase over the 28-day period. The soils tended to retain their stiffness over a wide range of water contents. Changes in stiffness with time and moisture content for each of the soils are reported in the Appendix.

4.7 Swell

Samples prepared with CKD had lower measured swell potential for all soils, with the exception of Beto Tan. Changes in swell are reported in Table 4.4.

Table 4.4: Swell Potential

	Native	CKD
Beto "Red"	4.4	1.4
Beto "Brown"	2.8	1.0
Beto "Tan"	2.5	7.1
Osage	1.4	0.2
Hugoton	1.4	0.1
Atwood	1.0	-
Stevens	0.4	-

CKD treated samples performed well in swell testing when compared with previous results obtained using other additives as shown in Figure 4.3. Swell reductions for CKD treated samples were comparable with or greater than those achieved with lime, fly ash, and cement for all soils tested with the exception of Beto Tan. Beto Tan contains sulfates and none of the additives performed well with this soil.

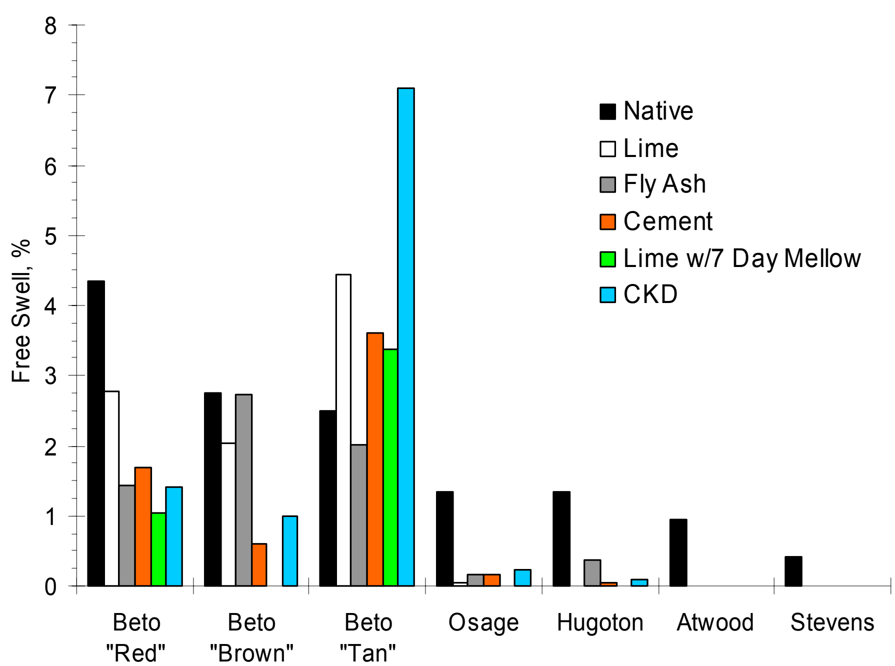

Figure 4.3: Swell potential for native and treated soils

4.8 Effects of Leaching on CKD Treated Samples

CKD treated samples were leached in flexible membrane cells for 28 days as a measure of the durability of the CKD treated soil. The measured permeability values of the treated samples are reported in Table 4.5. The permeability of the samples tended to decrease or remain steady, with the exception of the sulfate-bearing Beto Tan.

Table 4.5: Changes in Permeability with Time

				Permeability (cm/s) / number of days			
Soil	**Type**	**% CKD**	**Sample**	**7**	**14**	**21**	**28**
Atwood	ML	5	1	1.2E-05	1.8E-06	2.3E-06	1.5E-06
			2	1.1E-05	4.6E-06	4.4E-06	3.0E-06
Beto Brown	CH	7	1	1.5E-06	3.1E-08	4.8E-08	2.3E-07
Beto Red	CH	7	1	3.7E-05	2.3E-05	2.1E-05	1.1E-05
			2	8.2E-06	4.7E-06	5.6E-06	3.2E-06
Beto Tan	CH	6	1	3.8E-05	1.8E-05	1.7E-05	7.0E-06
			2	7.4E-05	3.7E-05	2.4E-05	9.8E-06
Hugoton	CL	6	1	1.1E-05	4.5E-06	4.6E-06	1.0E-05
			2	1.1E-05	7.0E-06	5.7E-06	1.4E-05
Lakin [1, 2]	SP	1.5	1	2.6E-03	2.8E-03	2.9E-03	3.5E-03
Osage	CL	6	1	2.2E-06	3.0E-06	5.6E-06	4.0E-06
			2	2.4E-06	2.4E-06	3.4E-06	1.7E-06
Stevens [1]	SM	3	1	4.3E-08	3.9E-08	4.6E-08	4.7E-09

[1]leaching pressure increased to constant head of 111.0 in and confining pressure reduced to 5 psi (138.2 in)

[2]test performed for short periods of time as extreme flow resulted

The CKD treated samples retained a substantial percentage of their original strength after leaching, and in the cases of Atwood and Beto Brown actually had increases in strength after leaching. Figure 4.4 shows the strength of CKD treated samples prepared at optimum moisture content 28 days after compaction, the retained strength of similarly prepared samples after 28 days of leaching, and native strengths at optimum moisture. As this figure shows, strengths of the CKD treated samples after leaching were consistently higher than native samples at optimum moisture. The only exception to this was the sulfate-bearing Beto Tan.

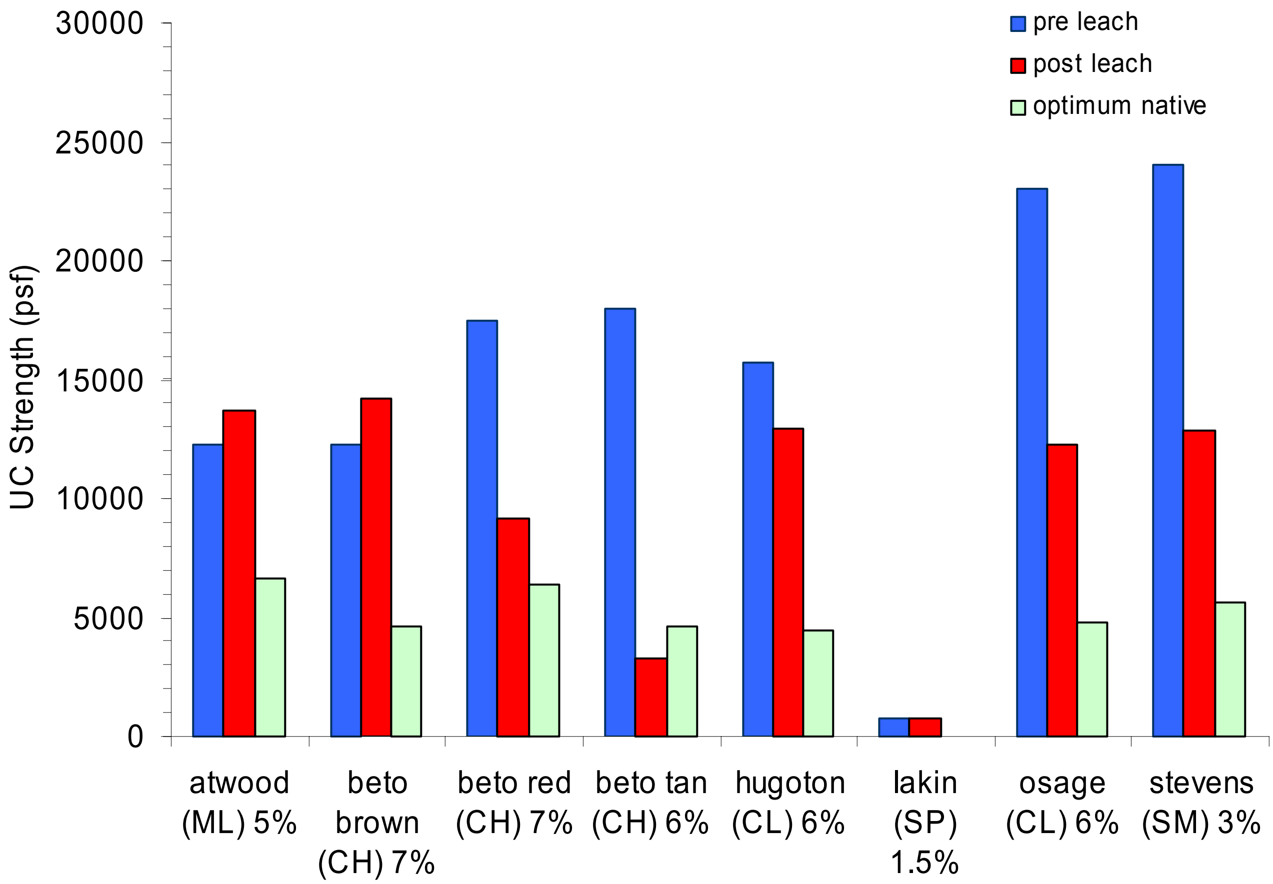

Figure 4.4: Strengths of CKD treated soils after leaching

Atterberg limits were also evaluated after leaching. Atterberg limits before and after leaching are reported in Table 4.6. The liquid limit and plasticity index consistently declined during the leaching process, and in most cases transformed the soil to a non-plastic state.

Table 4.6: Atterberg Limits Before and After Leaching

				Atterberg Limits			
				Pre Leach		Post Leach	
Soil	**Type**	**% CKD**	**Sample**	LL	PI	LL	PI
Atwood	ML	5	1	35*	6*	NP	NP
			2			NP	NP
Beto Brown	CH	7	1	56	17	NP	NP
Beto Red	CH	7	1	54	13	49	11
			2			NP	NP
Beto Tan	CH	6	1	54	17	44	9
			2			44	10
Hugoton	CL	6	1	48*	12*	NP	NP
			2			NP	NP
Lakin	SP	1.5	1	NP	NP	NP	NP
Osage	CL	6	1	42	10.5	NP	NP
			2			NP	NP
Stevens	SM	3	1	NP	NP	NP	NP

*estimated based on closest CKD percentage

A significant portion of the fine material was also permanently bonded together to form conglomerate particles larger than the #40 (0.425 mm) sieve. While over 90 percent of Beto Red and Osage pass the #200 (0.075 mm) sieve in the native state, with the addition of CKD a significant portion of both soils was retained on the #40 sieve after leaching as shown in Figure 4.5. Similar results were observed for the other soils.

Figure 4.5: Conglomerate particles remaining after leaching

4.9 Wet-Dry Testing

Wet-Dry testing was conducted on treated samples prepared at optimum moisture content. The number of cycles survived prior to sample failure is reported in Figure 4.6. As this figure shows, most samples did not survive a full 12 cycles of wet-dry testing. This is consistent with previous behavior observed with lime, fly ash, and cement treated samples.

Figure 4.7 shows the number of cycles the scratched samples survived for all additives. As this figure shows, CKD treated samples performed in a manner similar to the other additives with regard to the number of cycles survived for the range of soils tested.

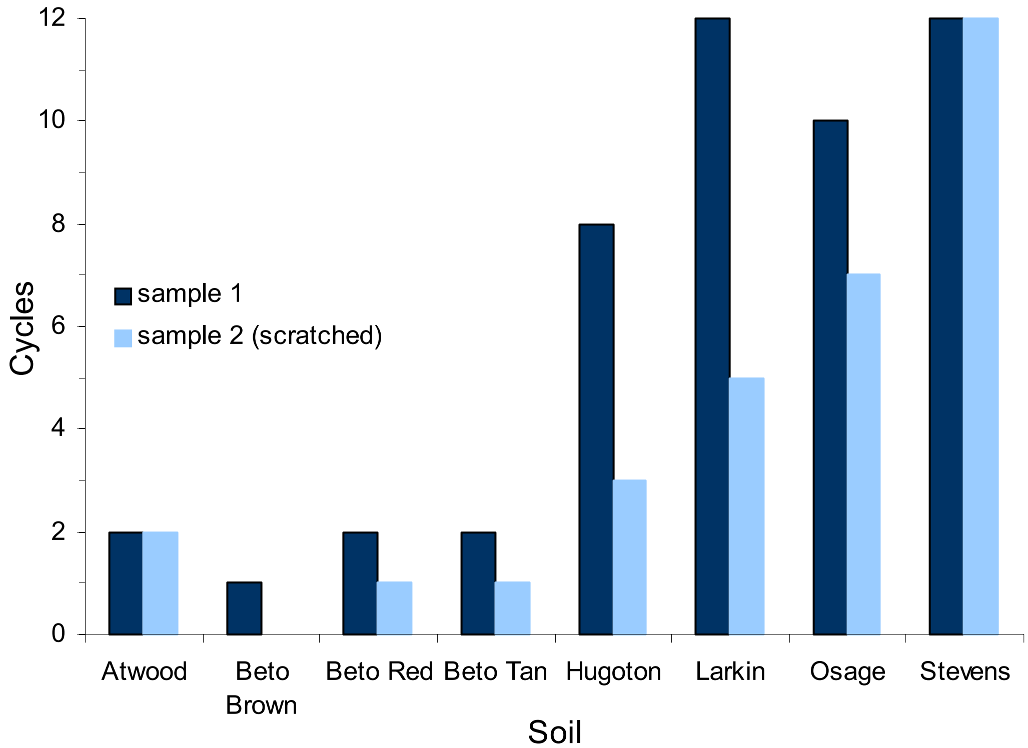

Figure 4.6: Wet-Dry cycles completed prior to failure for CKD treated samples

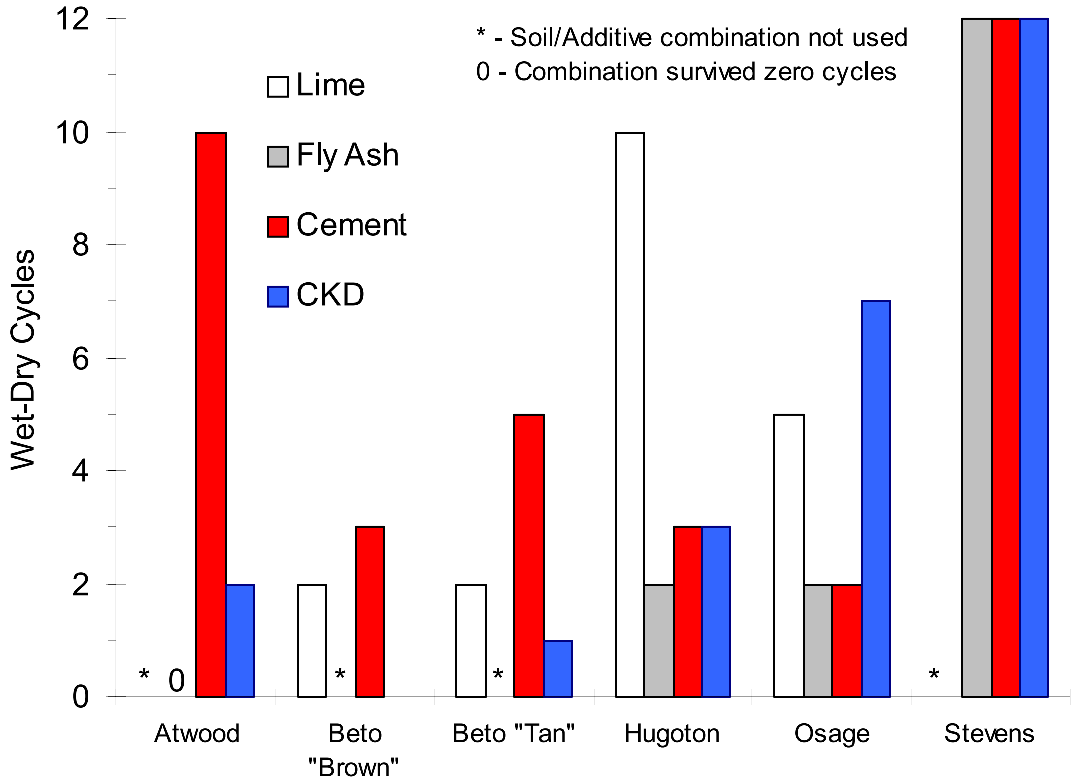

Figure 4.7: Wet-Dry cycles completed after treatment with a range of additives

4.10 Freeze-Thaw Testing

A series of freeze-thaw tests were conducted on samples of each soil prepared at optimum moisture content. The results are reported in Figure 4.8. As this figure shows, only four of the eight unscratched samples and none of the scratched samples survived the 12-cycle test. CKD treated samples did not survive as many cycles as the other additives, for which most of the scratched samples survived the full 12 cycles, although those samples often experienced significant losses of mass.

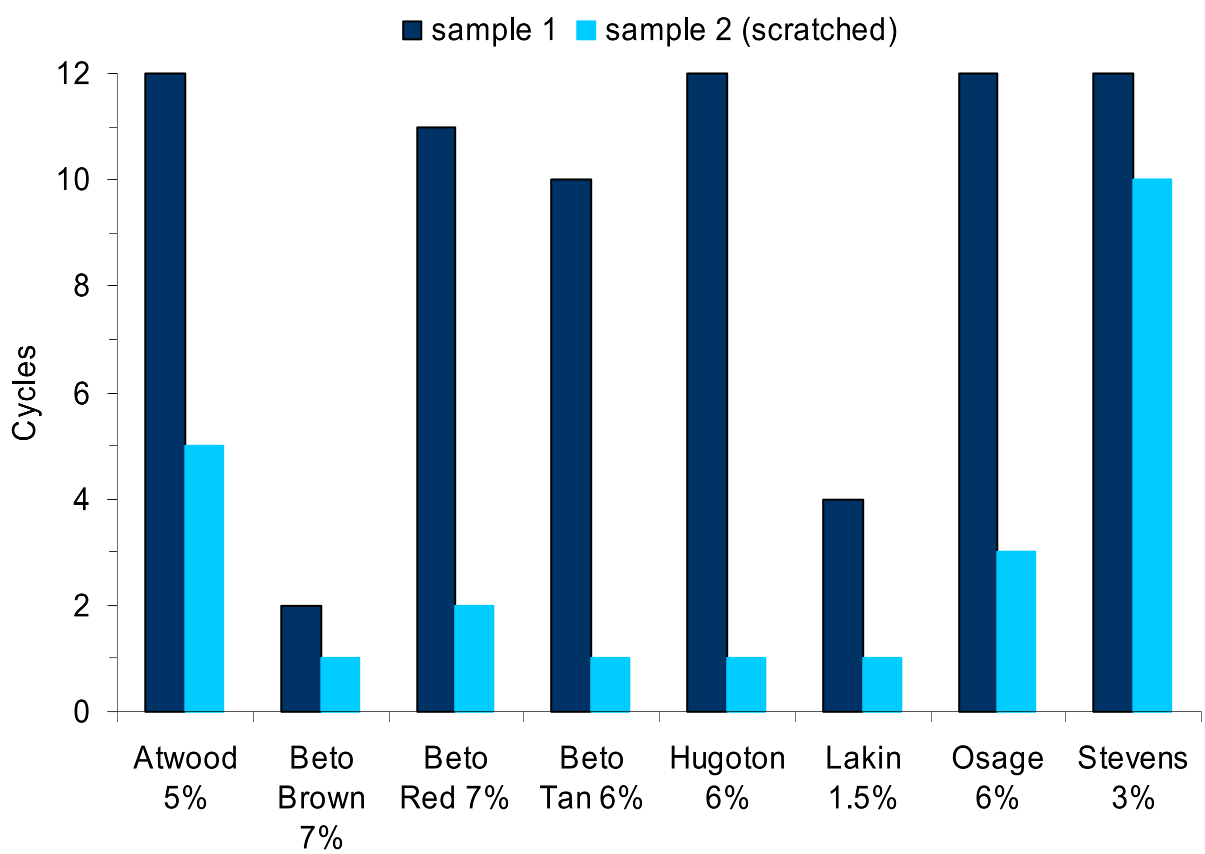

Figure 4.8: Freeze-thaw cycles completed prior to failure for CKD treated samples

Chapter 5

Conclusions and Recommendations for Implementation

This chapter contains a summary of the conclusions developed based on the results of this study and recommendations for the implementation of those conclusions.

5.1 Usage

CKD is an effective soil stabilization agent, based on the results observed and described in this report. It is recommended that it be considered for use in the stabilization of subgrade soils, subject to the conditions described in the following sections.

5.2 Dust Composition

CKD is an industrial by-product and its composition is a function of the source materials and the manner in which the dust is generated. CKD is a generic term that can refer to pre-calciner dust or dust from a long kiln process. All comments contained within this report refer to the pre-calciner form of dust, except where noted. Due to the significant differences in composition between the types of CKD, it is recommended that KDOT consider specifying a minimum free lime content, if CKD is intended for use as a lime replacement, or that dust from plants be prequalified in some way prior to acceptance for use. This is particularly important where volume change of subgrade soils is a concern. Another alternative would be to compensate the contractor based on the tonnage of free lime contained in the CKD.

5.3 Quantity of CKD

With the exception of the sandy soils (Lakin and Stevens), CKD was added in amounts of 5 to 7 percent. These percentages were selected based primarily on pH testing, although Atterberg limits results were also used as an additional guide. The percentages added were somewhat higher than the percentage of quicklime required for the same soil (1). This is consistent with previous work as discussed in Chapter 2.

5.4 Atterberg Limits

Atterberg limits are commonly used to determine the plasticity of a soil and as an indicator of the potential for volume change. CKD was effective in reducing the plasticity of all soils except for Beto Tan, which contained some sulfates. PI values were reduced to levels equivalent to or lower than those achieved with Class C fly ash, but not to the levels achieved with quicklime. PI values continued to decline during leaching.

5.5 Swell

CKD performed very well in swell testing for the entire range of soils except for the sulfate-bearing Beto Tan. This performance is likely a function of the relatively high free lime content within the CKD. Based on the results of this testing, CKD should be effective in controlling volume change in high plasticity soils. However, it is recommended that the effectiveness of CKD or any modification agent be evaluated prior to use to confirm its effectiveness and to establish mixing percentages, particularly with soils of high plasticity.

5.6 Strength and Stiffness

The strength of all samples was improved 100 – 200% with the addition of CKD. Stiffness values also increased as measured by the Geogauge. A significant percentage of the increase in strength was retained after leaching and in some cases the strength increased after leaching. This performance suggests that stabilization reactions were relatively permanent and that some reactions may have been ongoing.

5.7 Effects of Durability Testing and Leaching

CKD improved the durability of the soil over the native state as evaluated by wet-dry and freeze-thaw testing, but this improvement was generally not as great as was achieved with the other soil improvement agents. However, plasticity was observed to continue to decline during leaching, with most soils eventually becoming non-plastic. This was similar to the behavior observed for cement treated samples (1) and considered to be a positive development as it suggests that there are ongoing reactions within the stabilized soil mass and that the soil mass will not revert to the native state after leaching, at least over the short term.

5.8 Testing Recommendations

In many cases stabilization agents are used to modify the subgrade to reduce or eliminate shrink swell behavior. If CKD is to be used for this purpose it is recommended that it be confirmed that substantial free lime is available. The percentage of CKD added should be sufficient to raise the pH above 12.4 or to a level equivalent to the pH of CKD in water without soil. It is also recommended that control of volume change be verified through swell testing of representative soil samples mixed with CKD. A short-term measure of the PI is probably not be a reliable measure of long-term effectiveness by itself, as the PI was observed to continue to decline with time, particularly after leaching. Strength testing of CKD treated soils may provide supporting information for CKD selection. Strength tests will be more important if the subgrades are to be a substantial contributor to the strength of the pavement system.

Sulfates present in either the soil or the CKD could potentially react with free lime and form expansive minerals, resulting in additional swelling where none previously existed. It is therefore recommended that the percentage of sulfates in the CKD be reported as a part of the chemical analysis provided to KDOT. The SO_3 level for the CKD in this study was reported as

5.79 percent and additional sulfates may have been present as a part of the CaO value and not been specifically broken out. However, no negative effects on swelling were observed with this CKD. As the sulfate level increases it becomes increasingly important that swelling tests be conducted to evaluate the potential for the formation of expansive minerals.

The soils to be stabilized should also be monitored for the presence of sulfate bearing minerals (often in the form of gypsum), which may react with any lime-bearing stabilization agent to form expansive minerals.

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Appendix

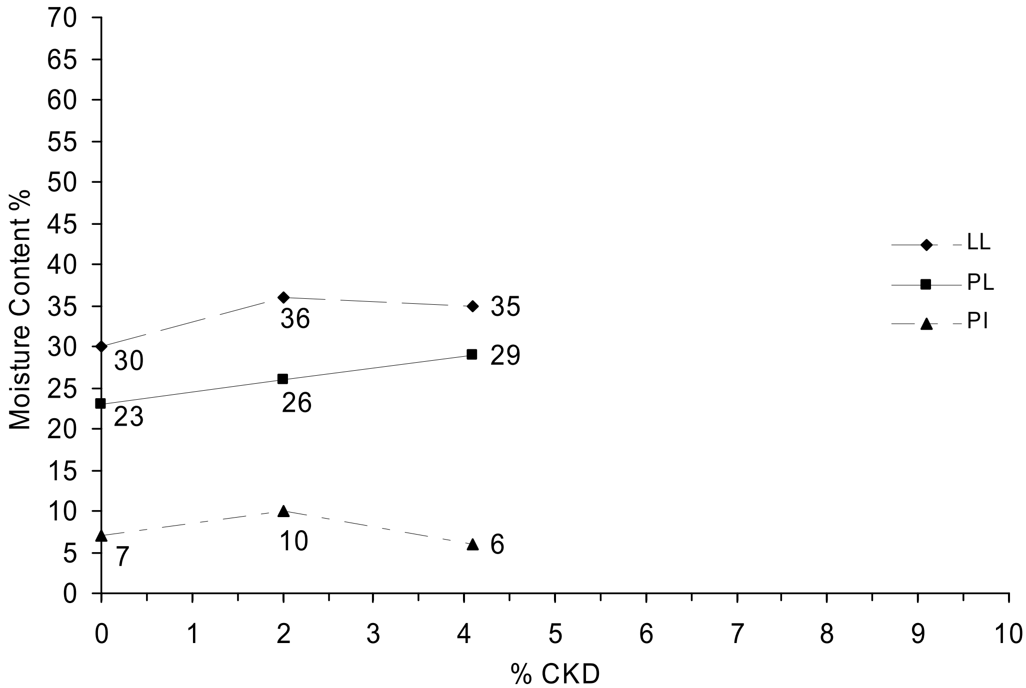

Figure 1a: Atterberg limits at various CKD % - Atwood (ML)

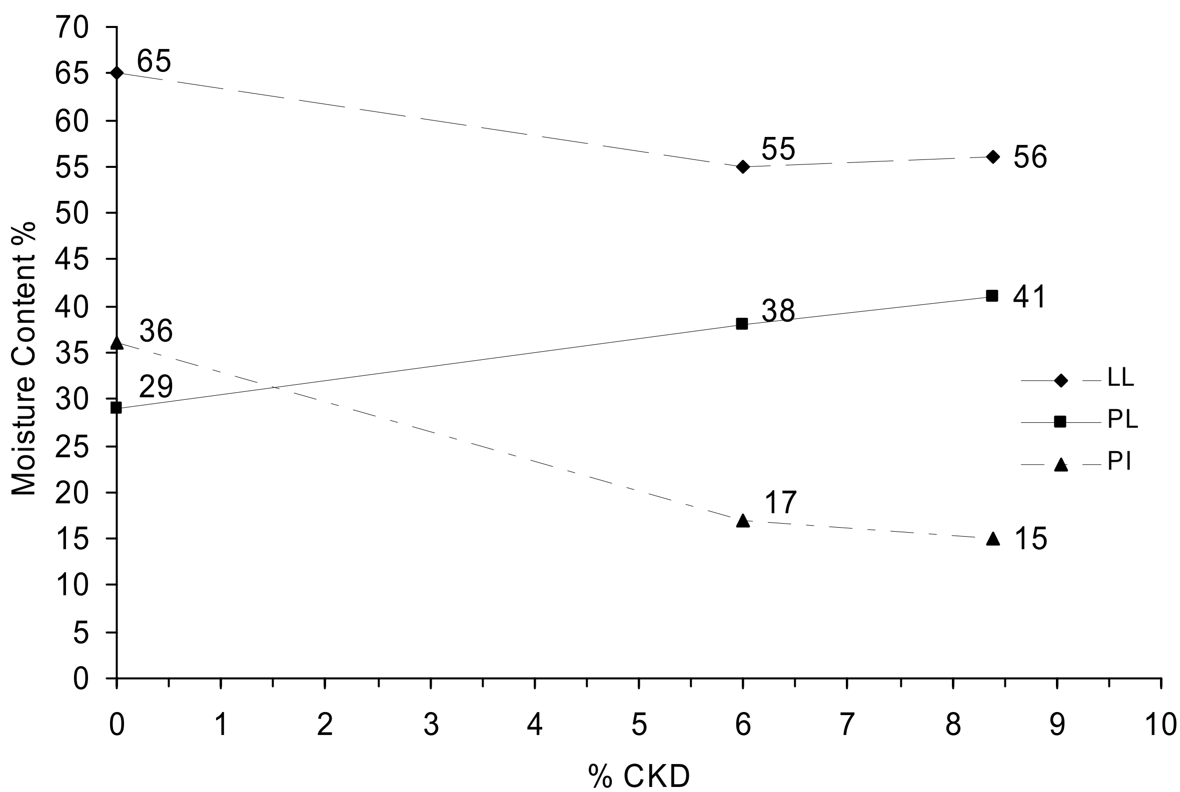

Figure 1b: Atterberg limits at various CKD % - Beto Brown (CH)

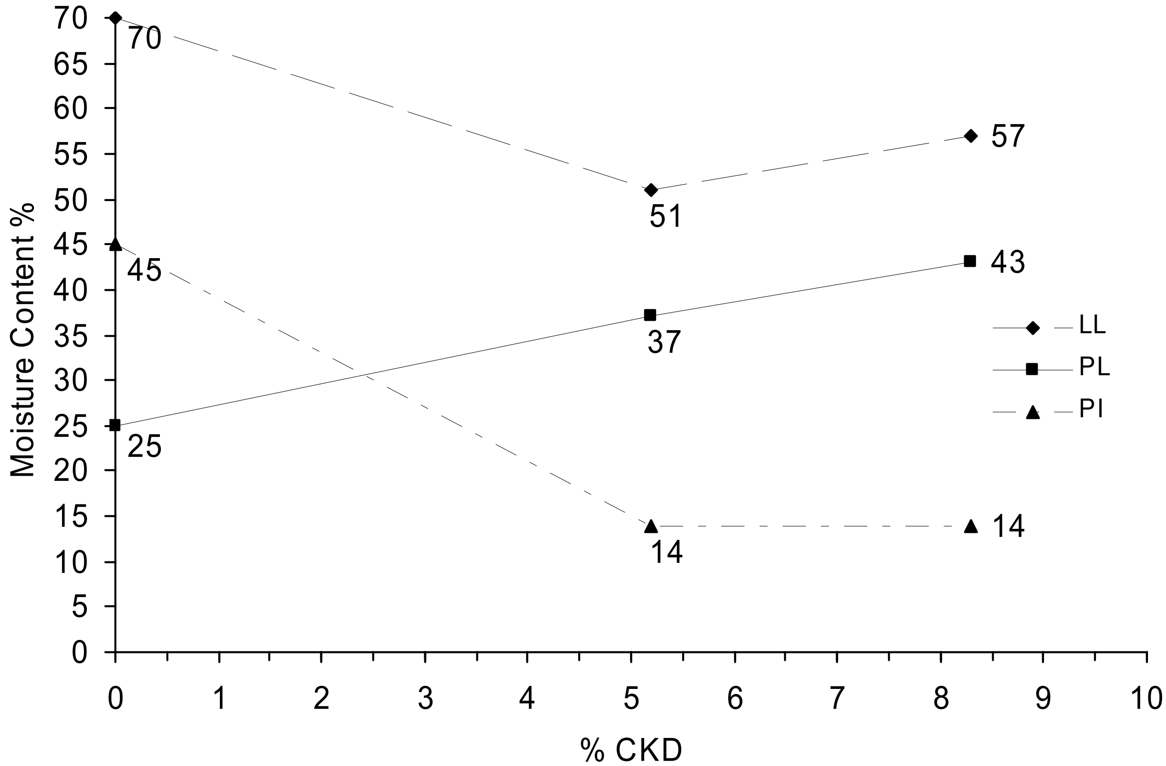

Figure 1c: Atterberg limits at various CKD % - Beto Red (CH)

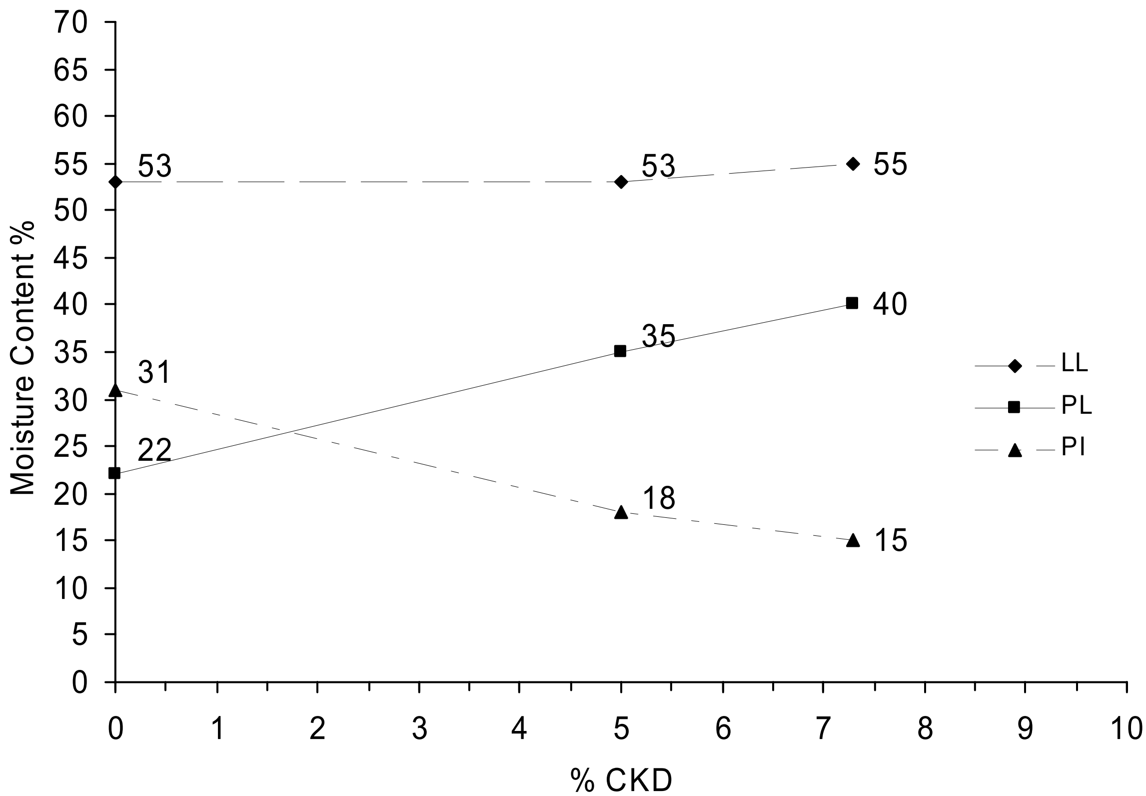

Figure 1d: Atterberg limits at various CKD % - Beto Tan (CH) - contains sulfates

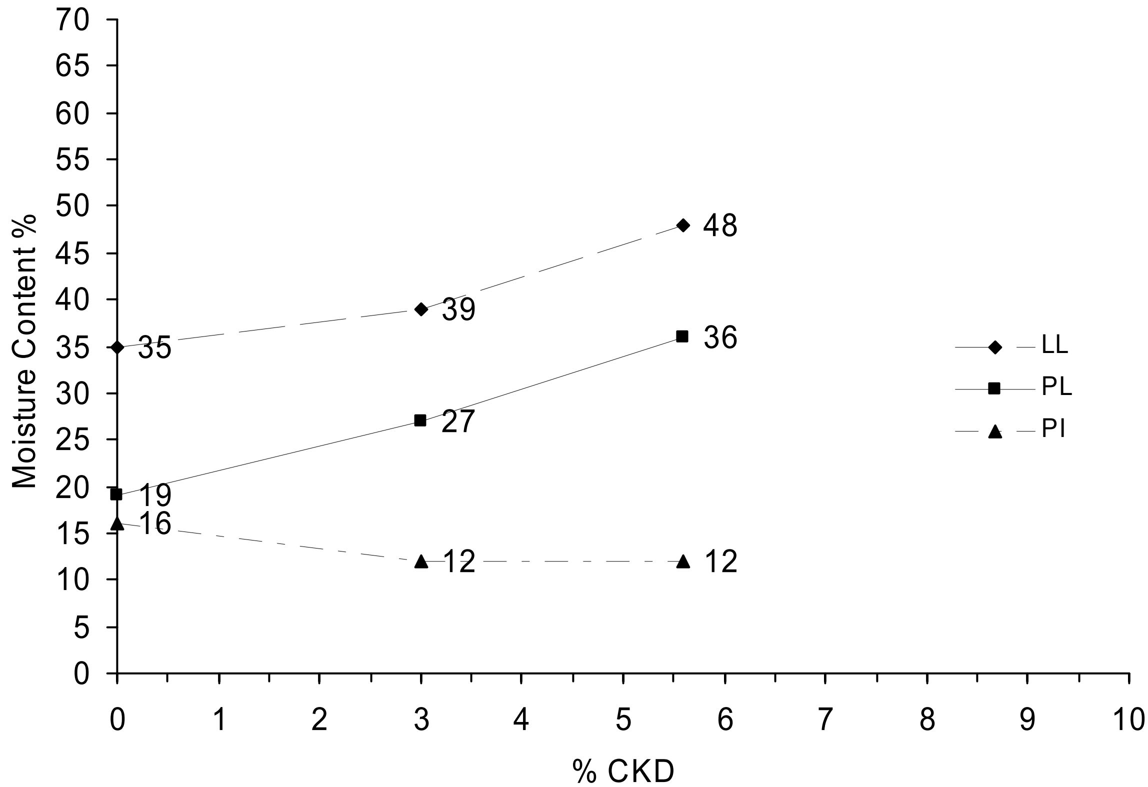

Figure 1e: Atterberg limits at various CKD % - Hugoton (CL)

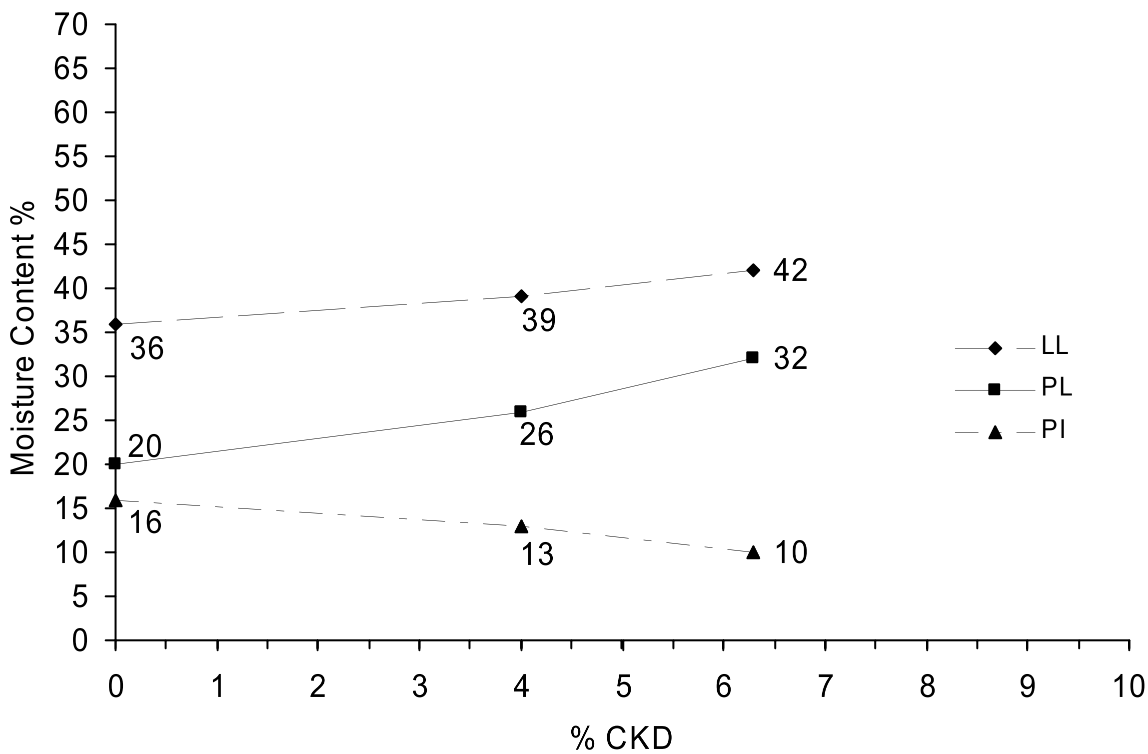

Figure 1f: Atterberg limits at various CKD % - Osage (CL)

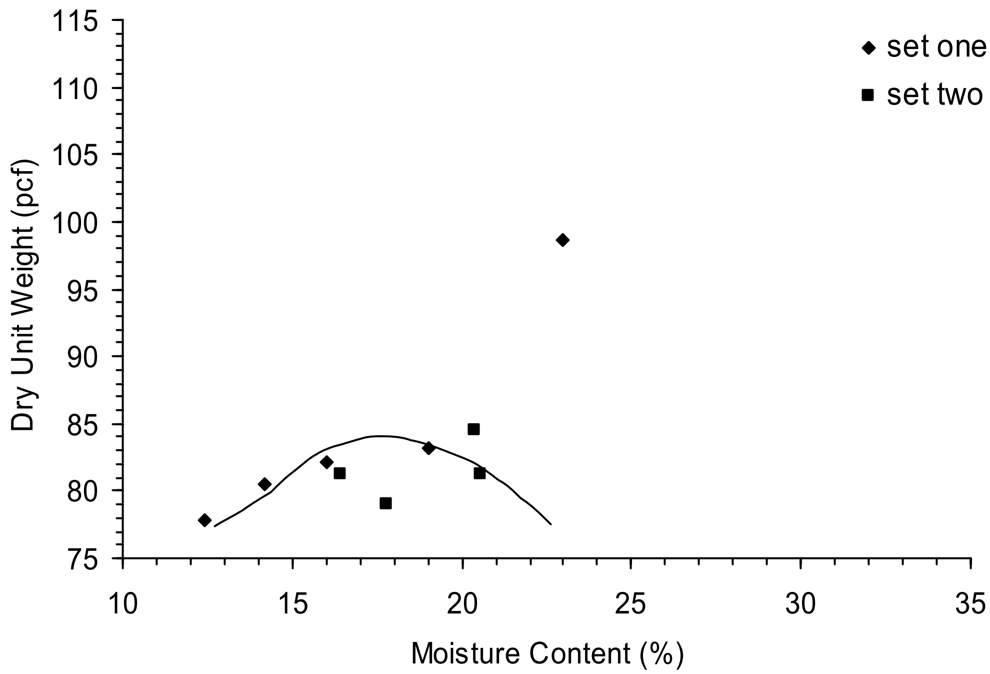

Figure 2a: Proctor Compaction Curve - Atwood (ML) @ 5% CKD

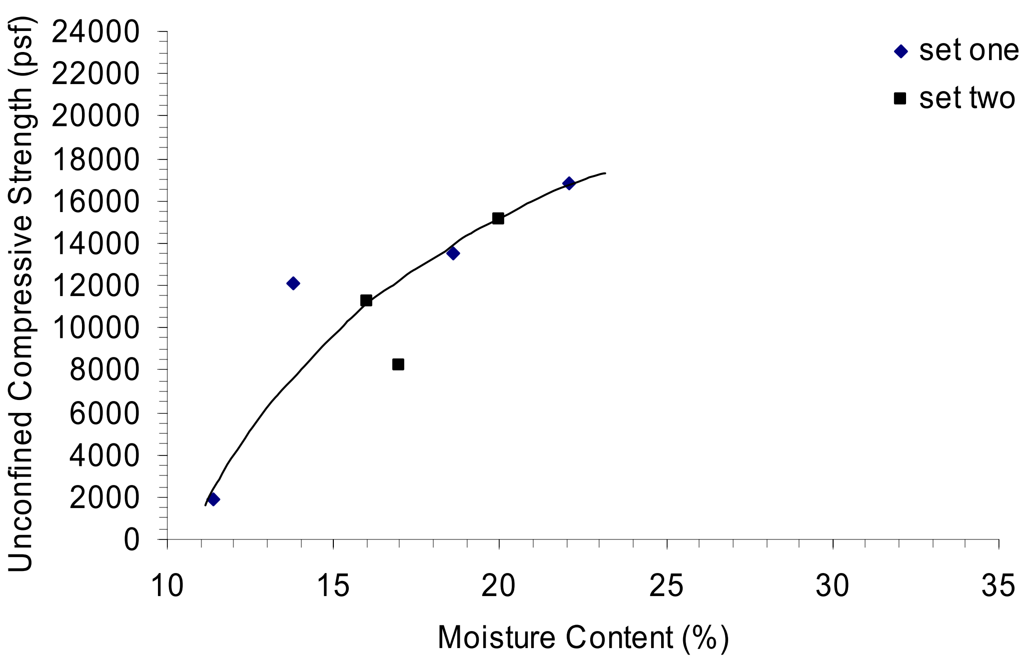

Figure 2b: Unconfined Compressive Strength - Atwood (ML) @ 5% CKD

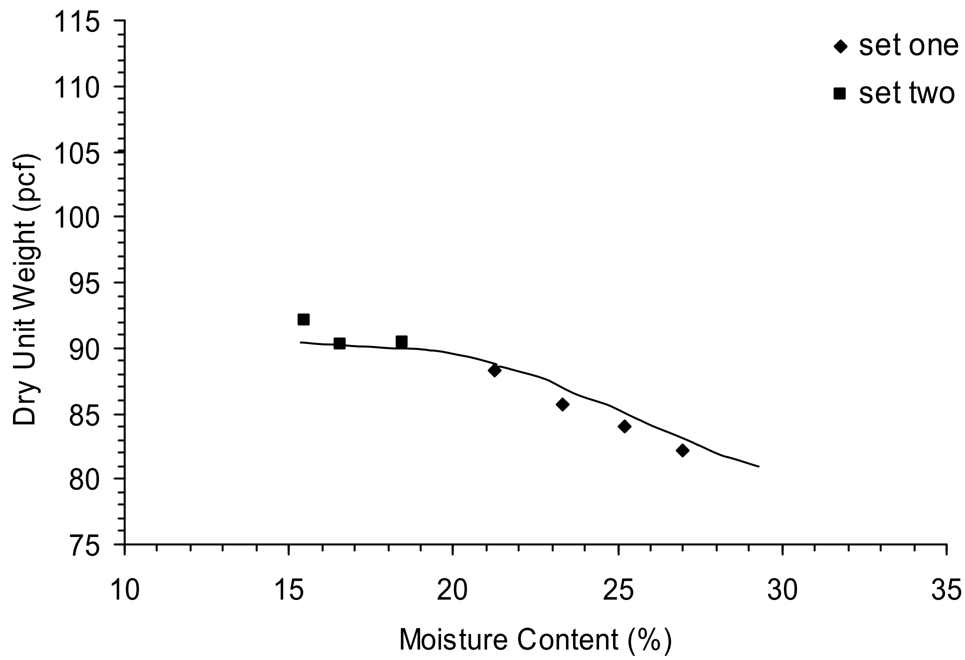

Figure 2c: Proctor Compaction Curve - Beto Brown (CH) @ 7% CKD

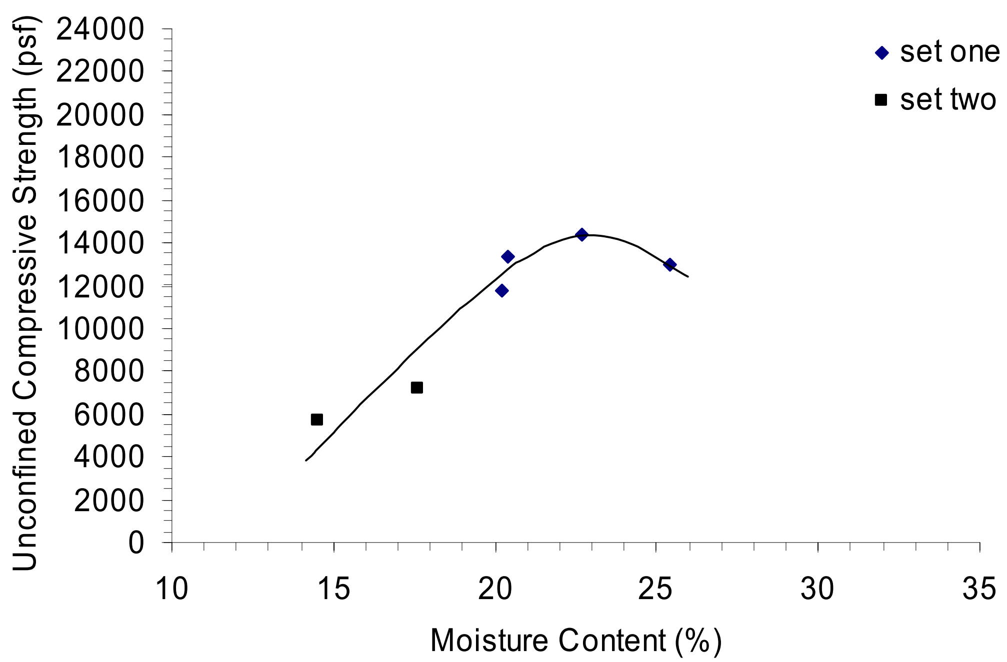

Figure 2d: Unconfined Compressive Strength - Beto Brown (CH) @ 7% CKD

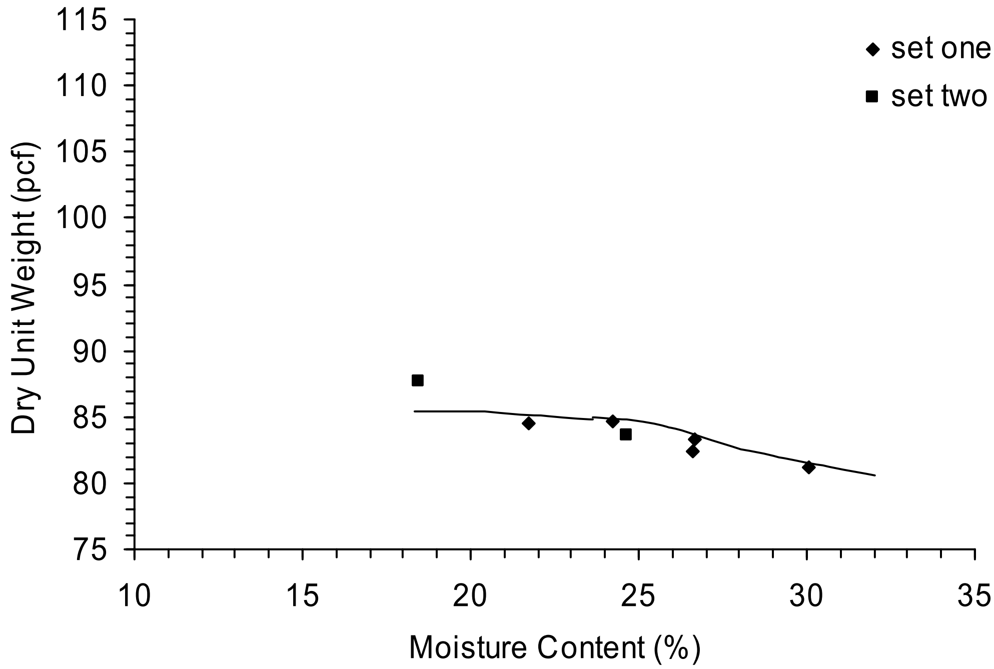

Figure 2e: Proctor Compaction Curve - Beto Red (CH) @ 7% CKD

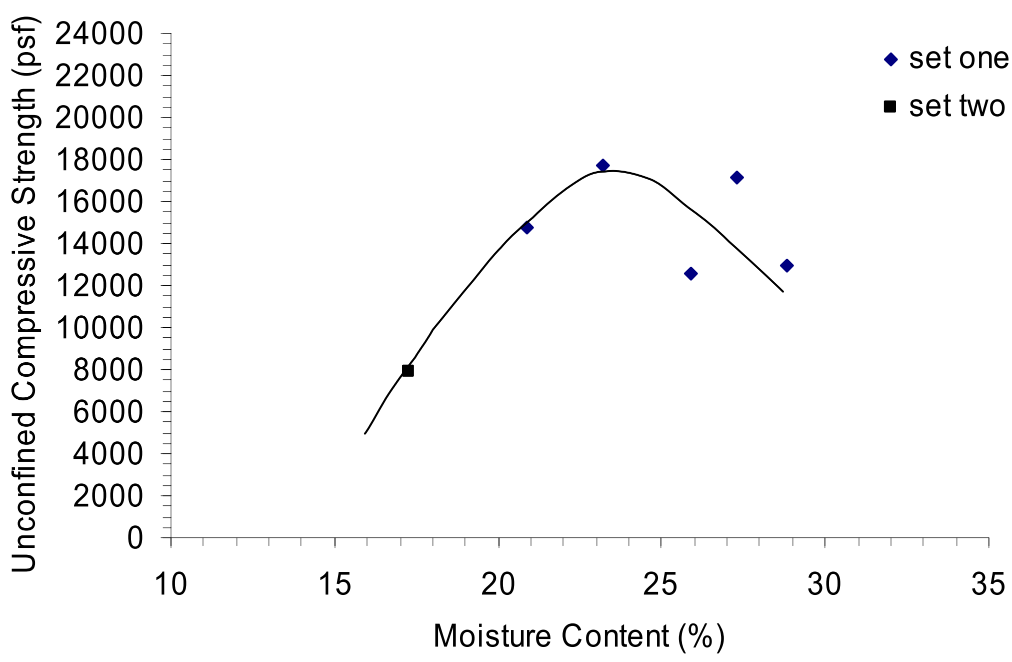

Figure 2f: Unconfined Compressive Strength - Beto Red (CH) @ 7% CKD

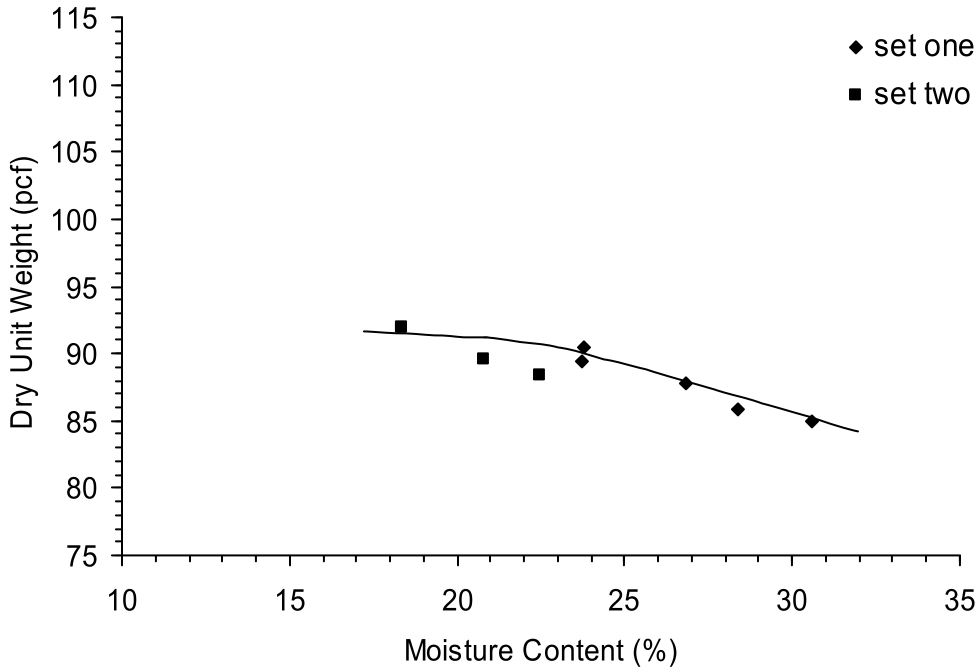

Figure 2g: Proctor Compaction Curve - Beto Tan (CH) @ 6% CKD - contains sulfates

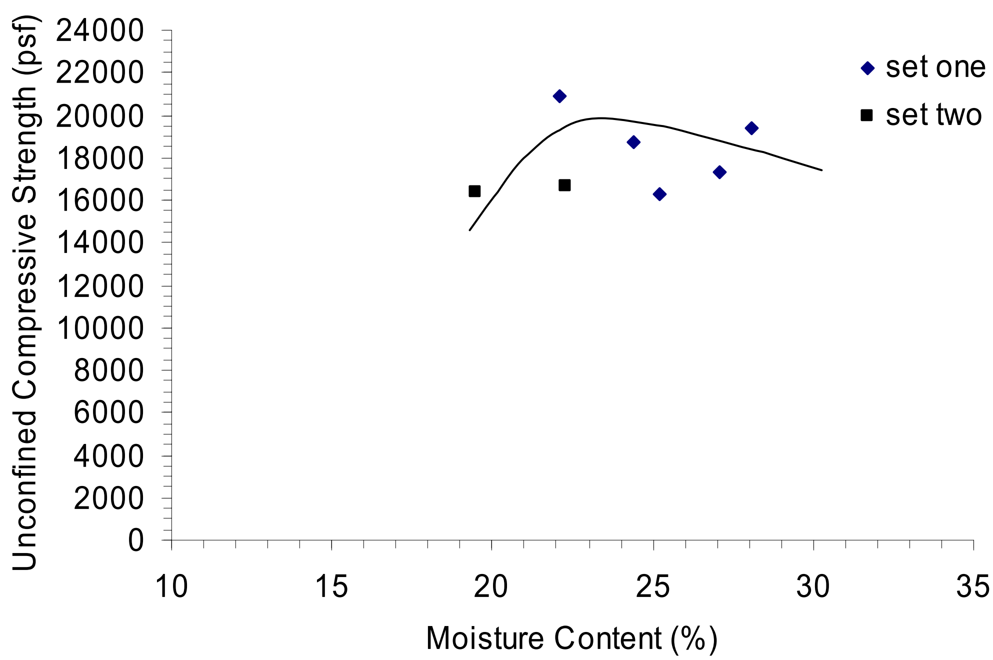

Figure 2h: Unconfined Compressive Strength - Beto Tan (CH) @ 6% CKD

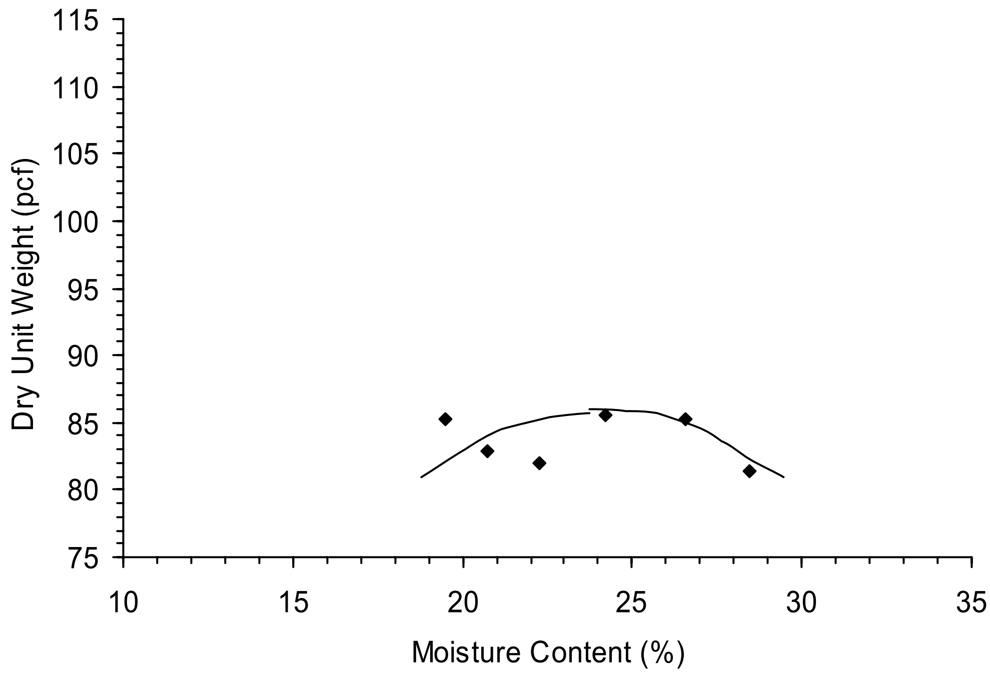

Figure 2i: Proctor Compaction Curve - Hugoton (CL) @ 6% CKD

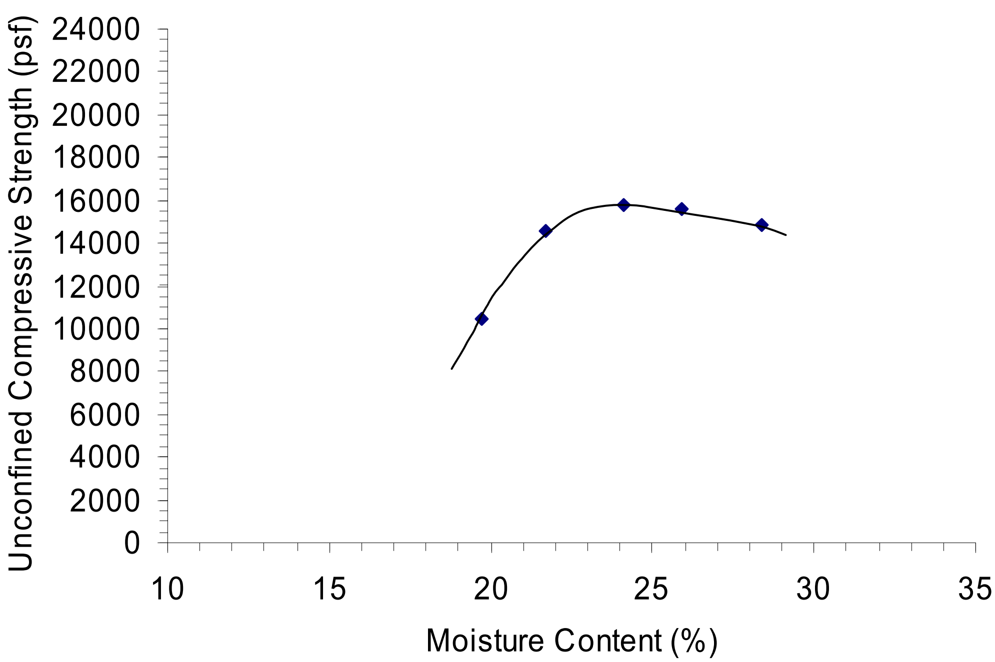

Figure 2j: Unconfined Compressive Strength - Hugoton (CL) @ 6% CKD

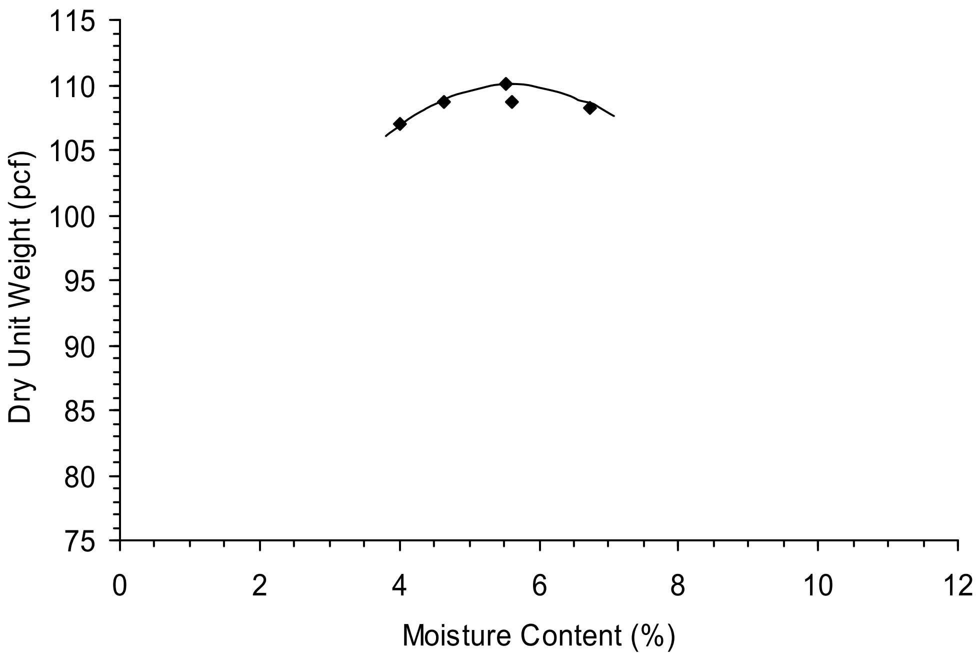

Figure 2k: Proctor Compaction Curve - Lakin (SP) @ 1.5% CKD

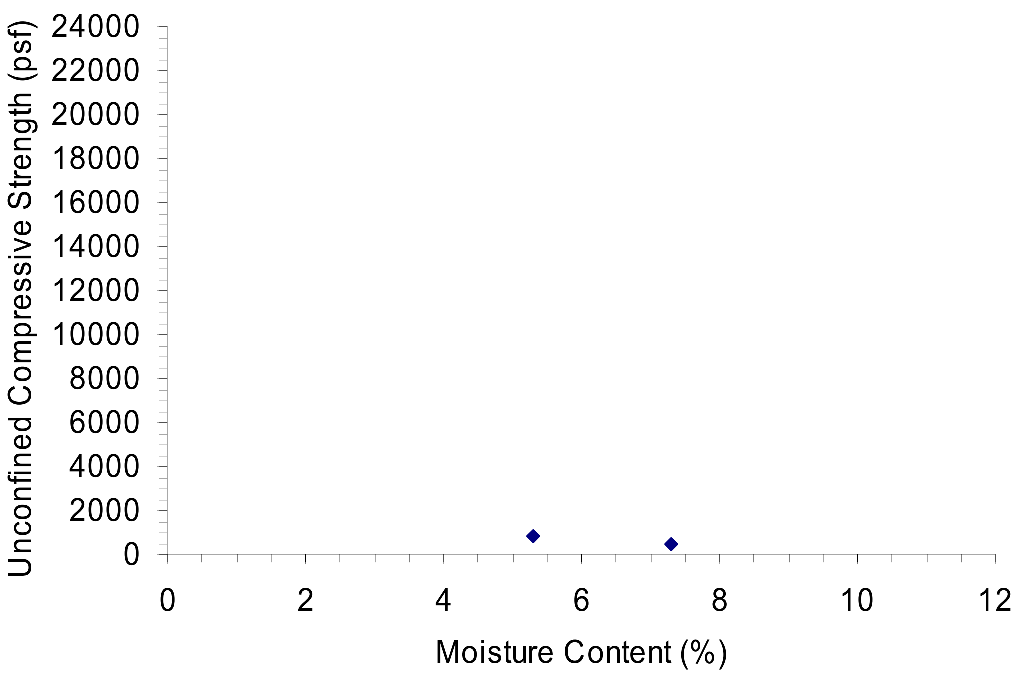

Figure 2l: Unconfined Compressive Strength - Lakin (SP) @ 1.5% CKD

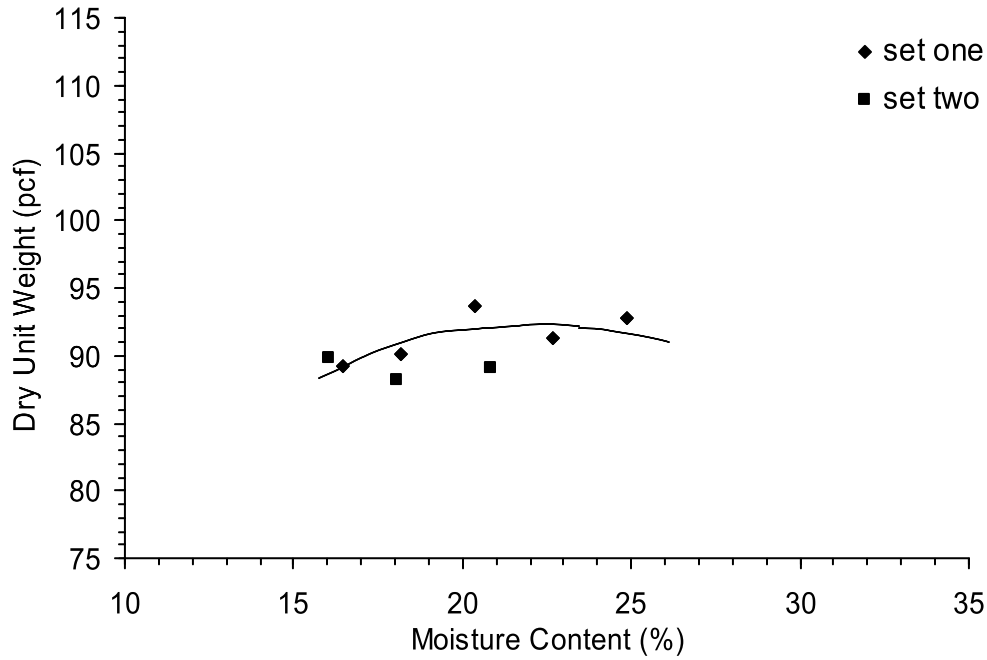

Figure 2m: Proctor Compaction Curve - Osage (CL) @ 6% CKD

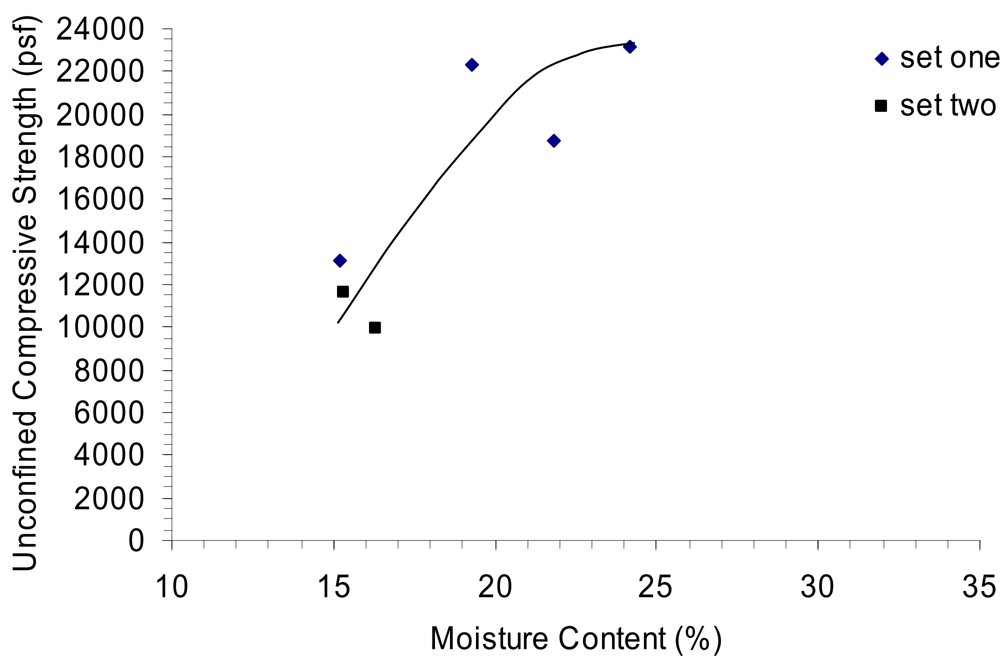

Figure 2n: Unconfined Compressive Strength - Osage (CL) @ 6% CKD

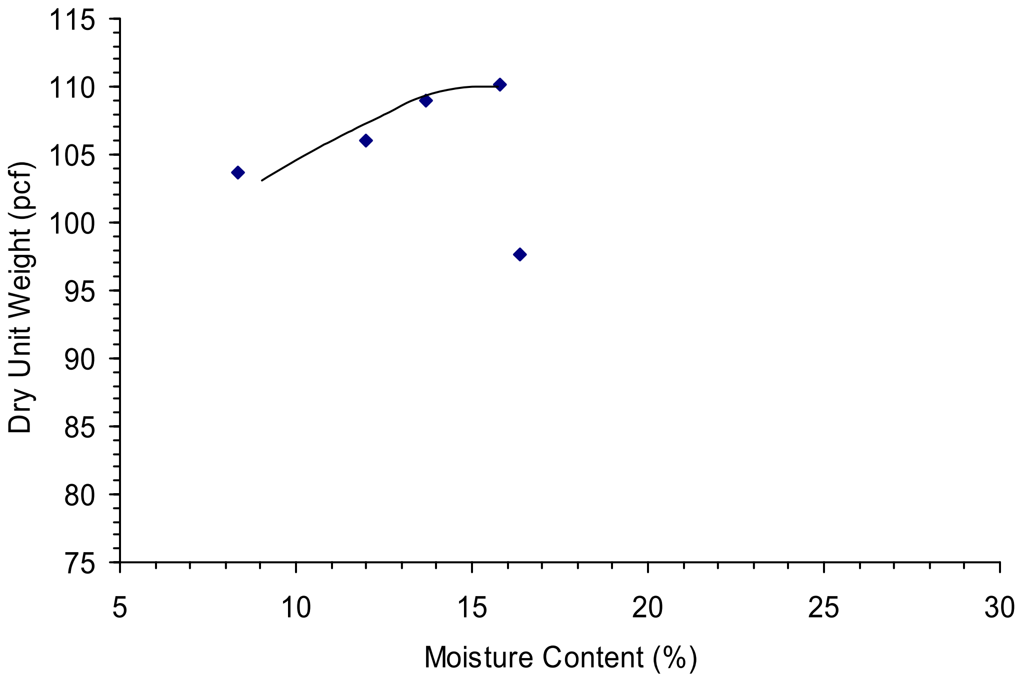

Figure 2o: Proctor Compaction Curve - Stevens (SM) @ 3% CKD

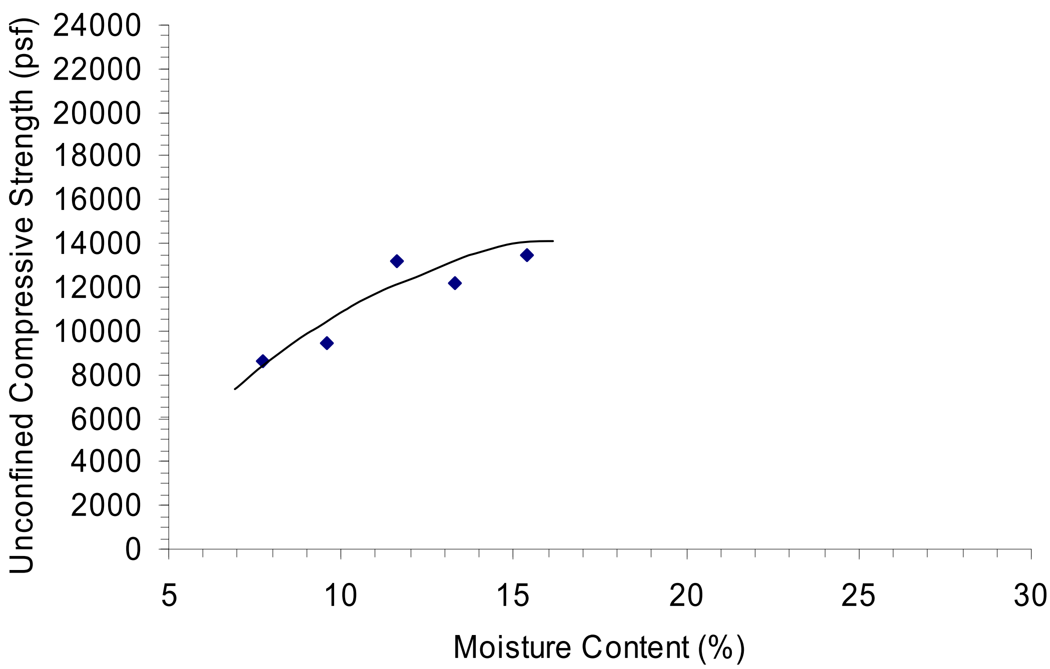

Figure 2p: Unconfined Compressive Strength - Stevens (SM) @ 3% CKD

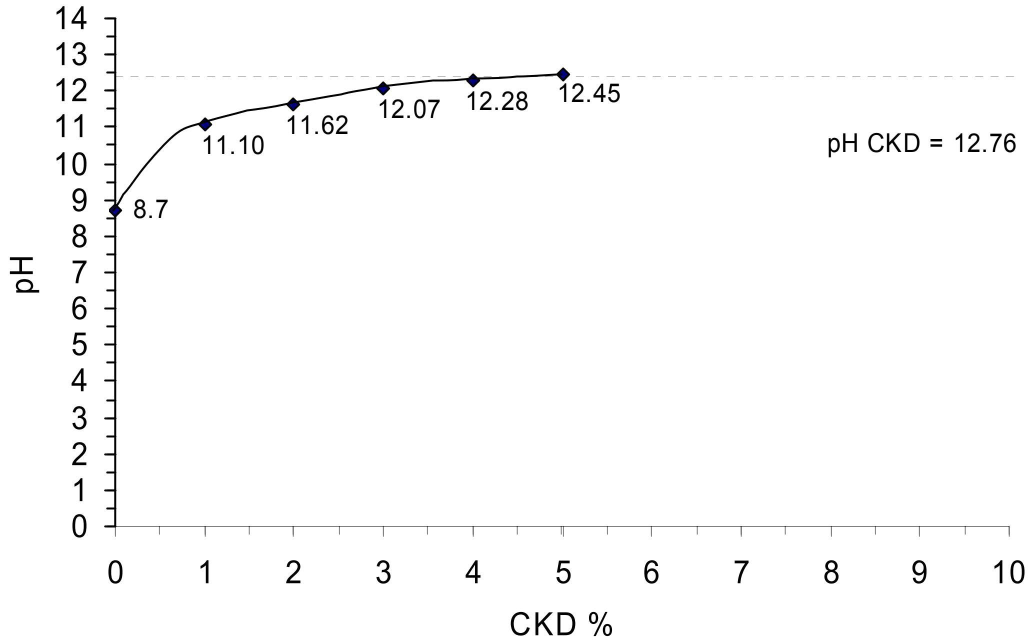

Figure 3a: pH vs CKD content - Atwood (ML)

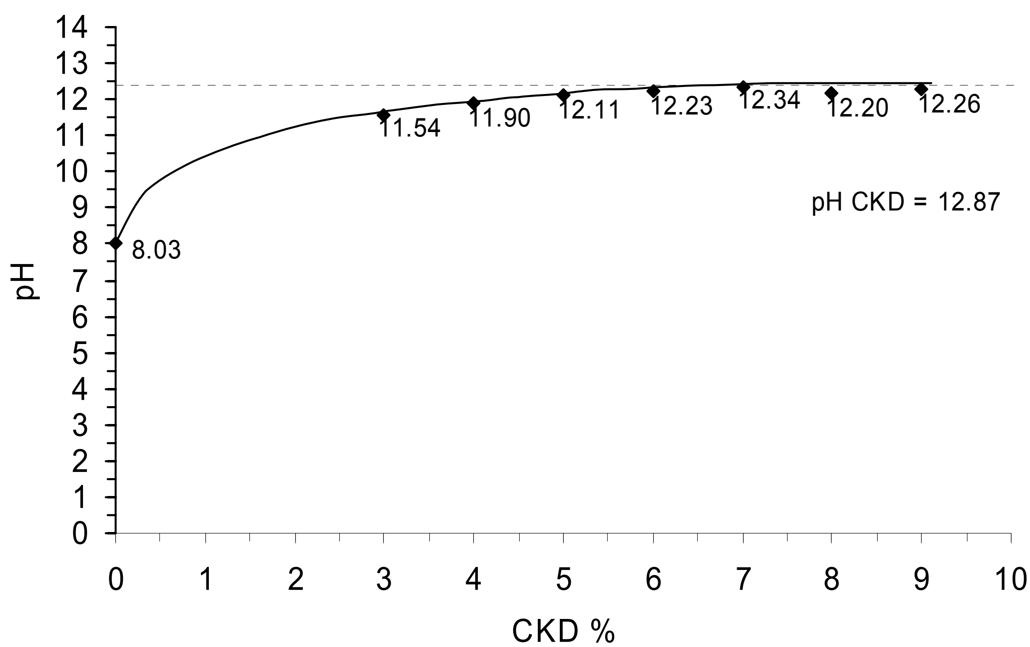

Figure 3b: pH vs CKD content - Beto Brown (CH)

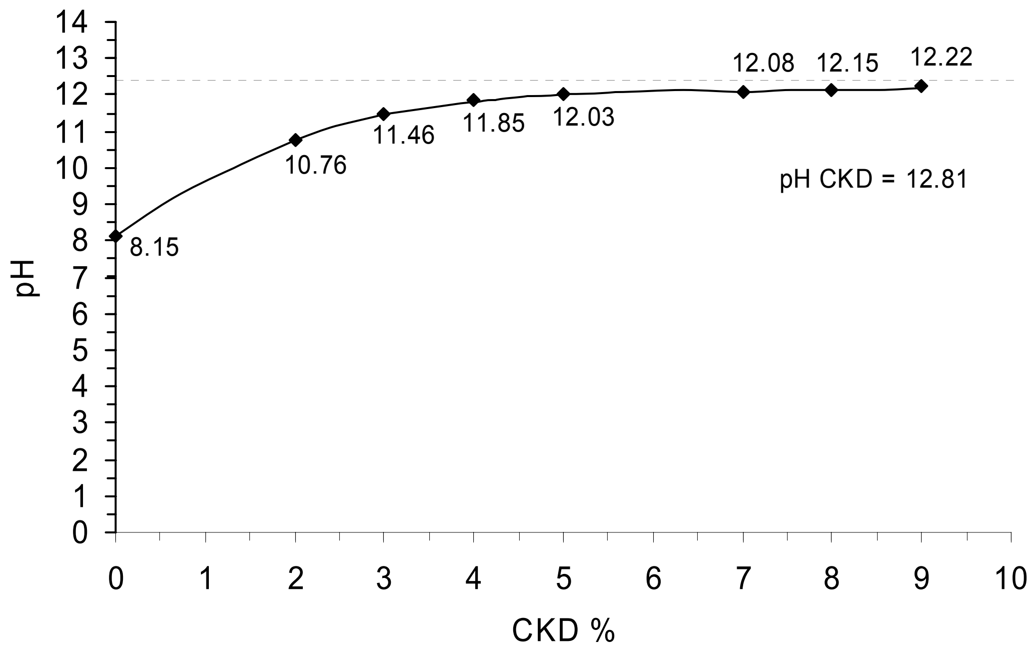

Figure 3c: pH vs CKD content - Beto Red (CH)

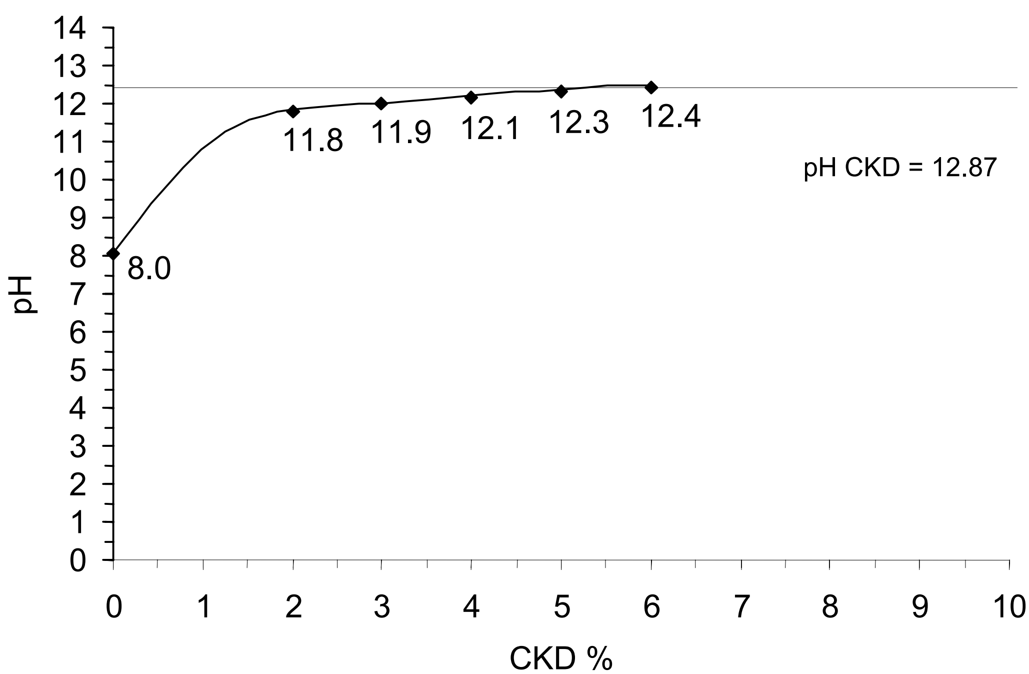

Figure 3d: pH vs CKD content - Beto Tan (CH) - contains sulfates

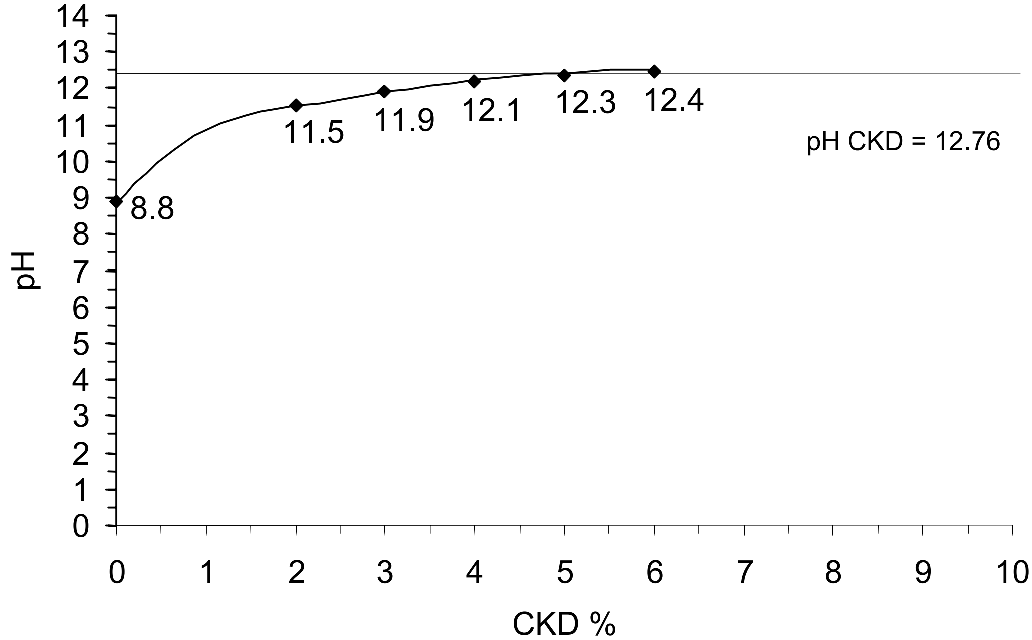

Figure 3e: pH vs CKD content - Hugoton (CL)

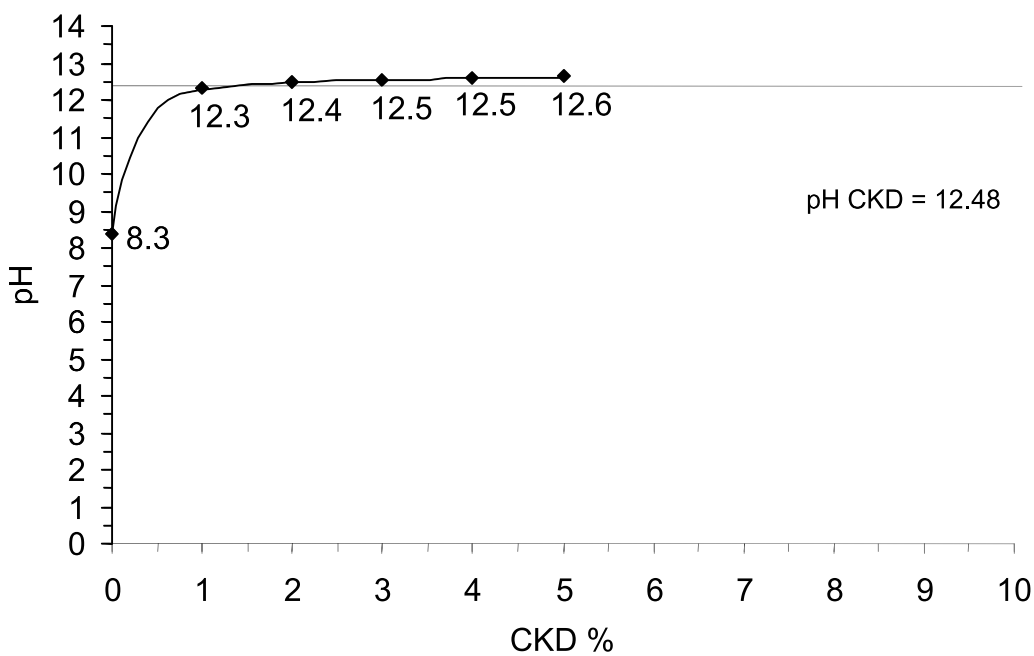

Figure 3f: pH vs CKD content - Lakin (SP)

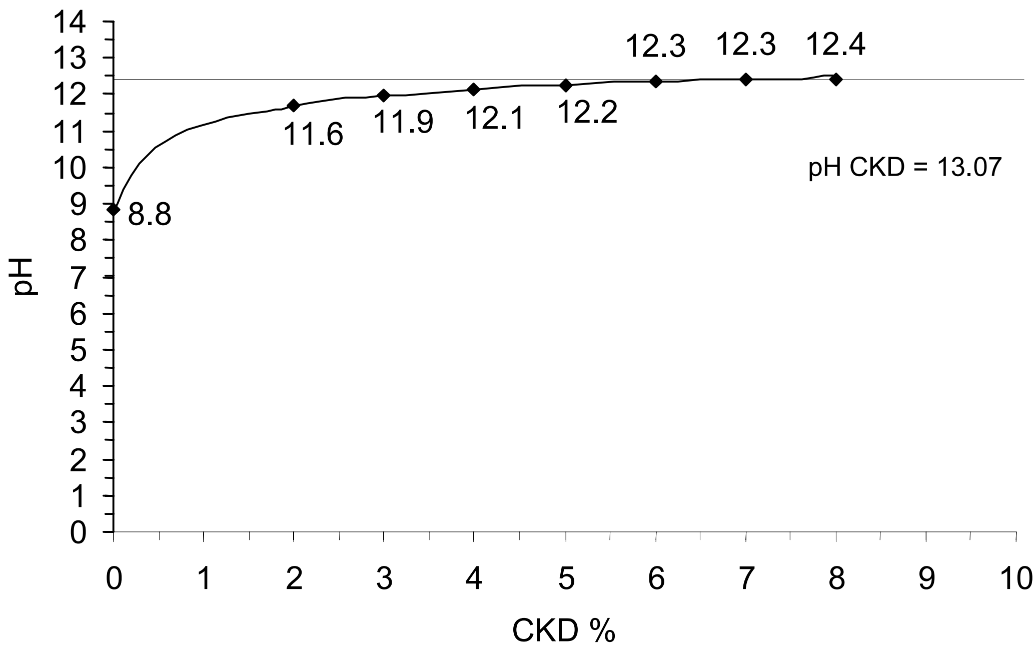

Figure 3g: pH vs CKD content - Osage (CL)

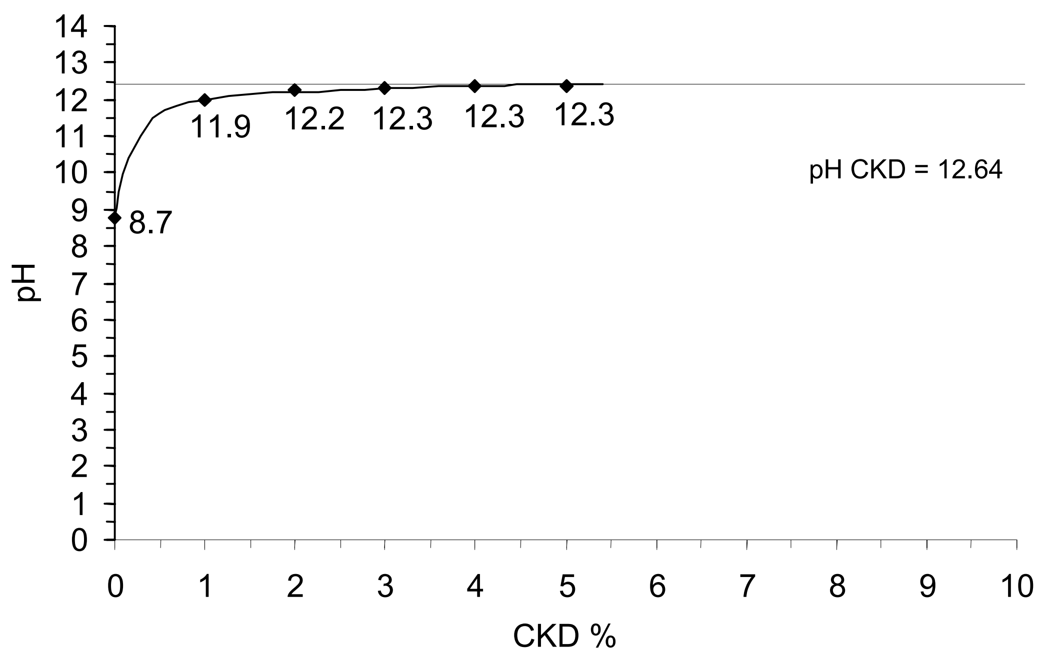

Figure 3h: pH vs CKD content - Stevens (SM)

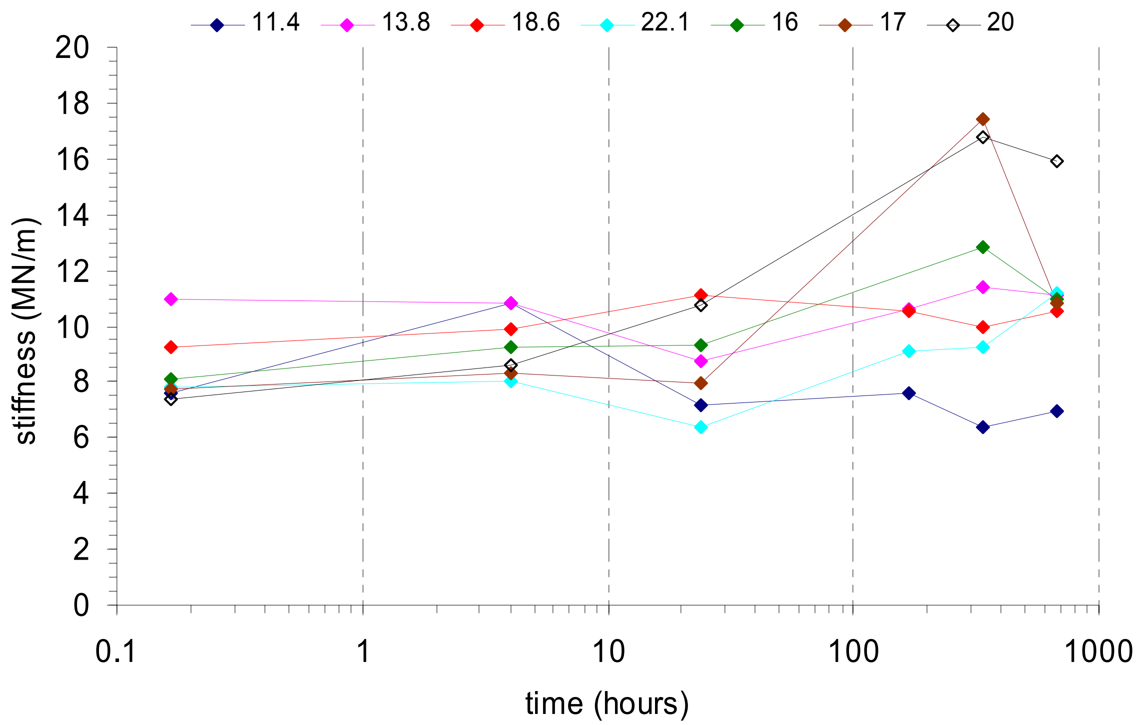

Figure 4a: Stiffness vs Time - Atwood (ML) @ 5% CKD

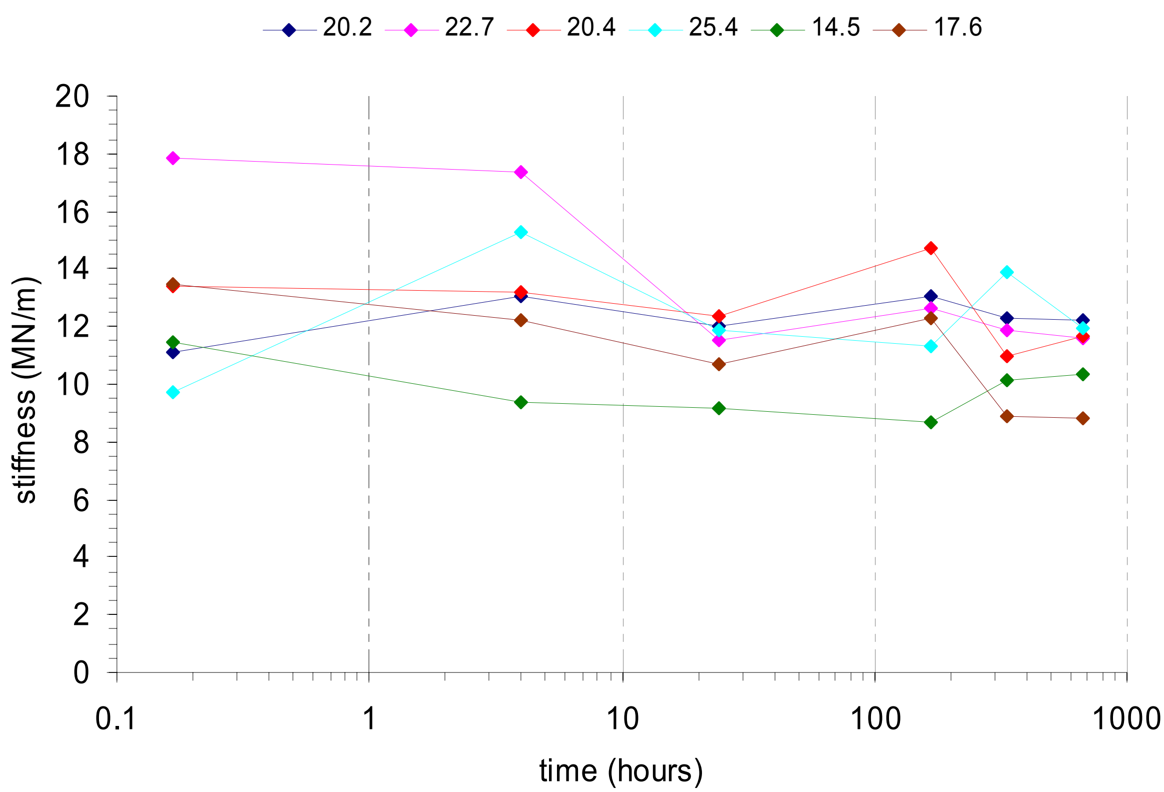

Figure 4b: Stiffness vs Time - Beto Brown (CH) @ 7% CKD

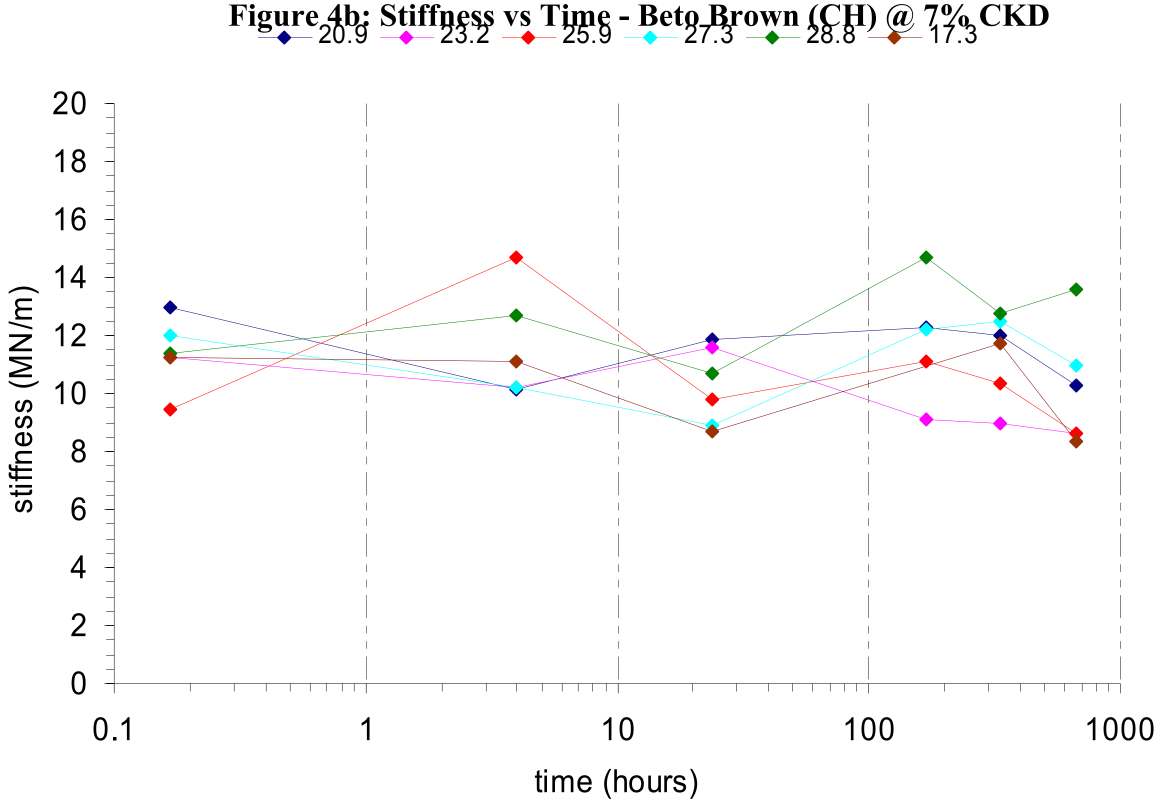

Figure 4c: Stiffness vs Time - Beto Red (CH) @ 7% CKD

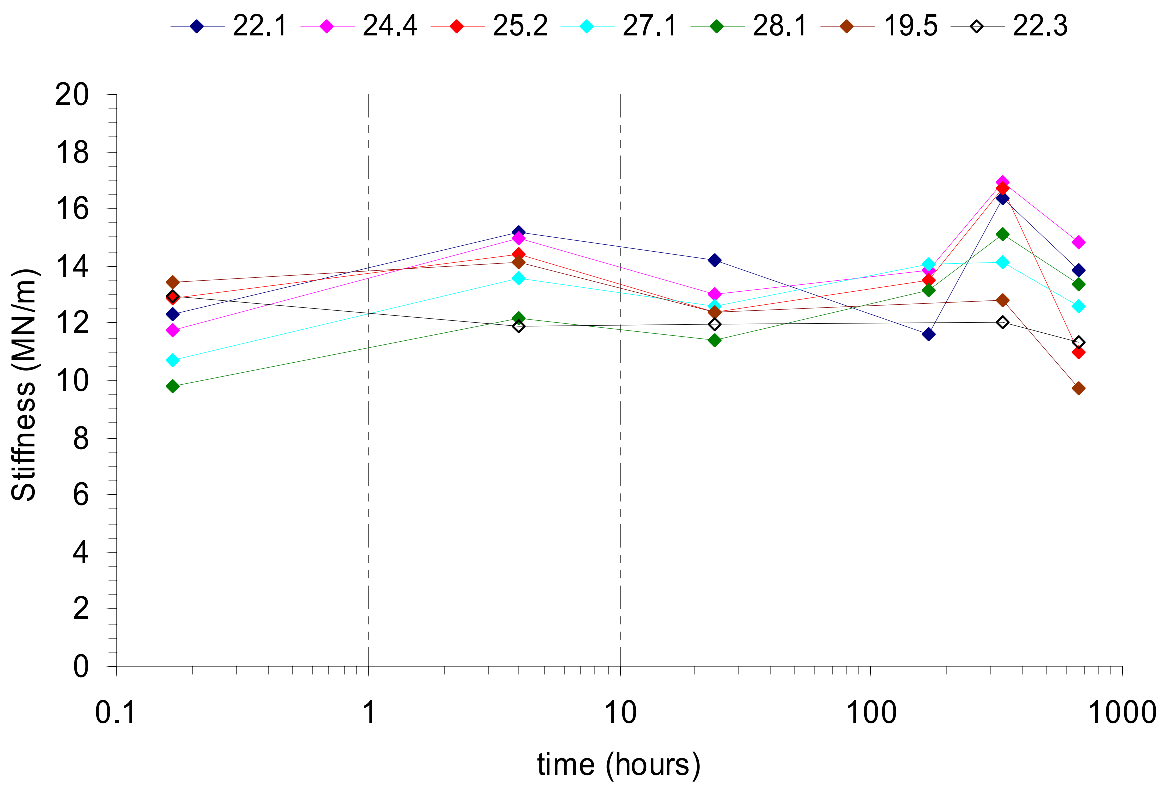

Figure 4d: Stiffness vs Time - Beto Tan (CH) @ 6% CKD

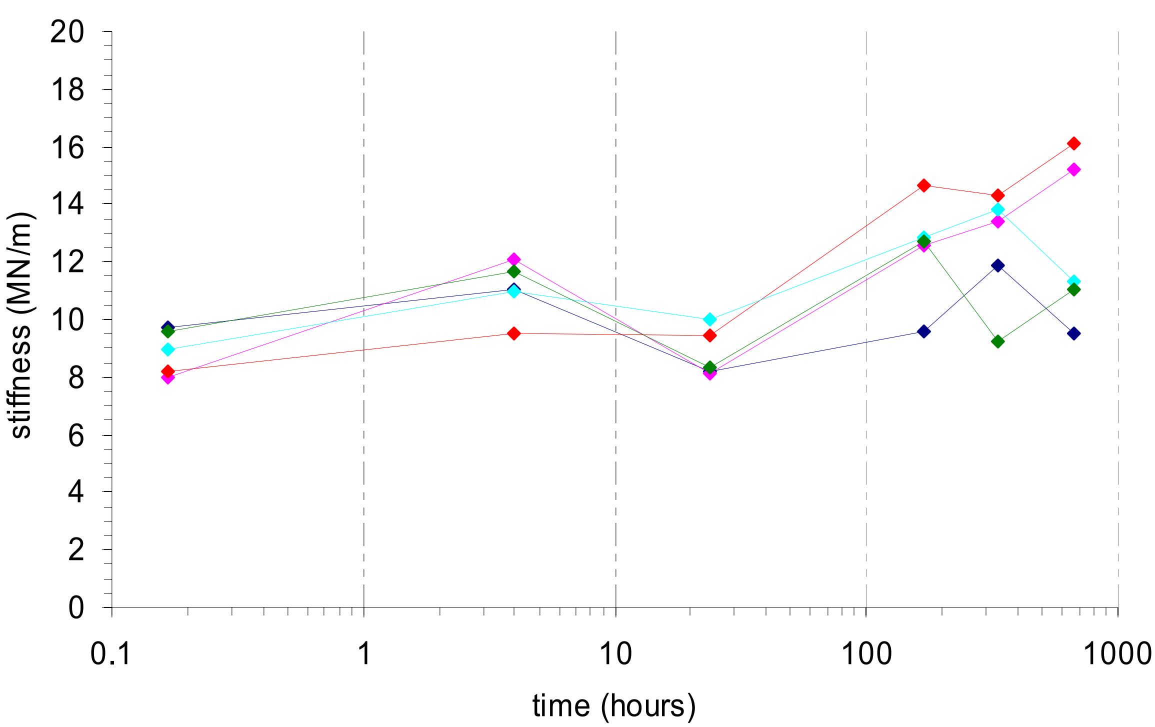

Figure 4e: Stiffness vs Time - Hugoton (CL) @ 6% CKD

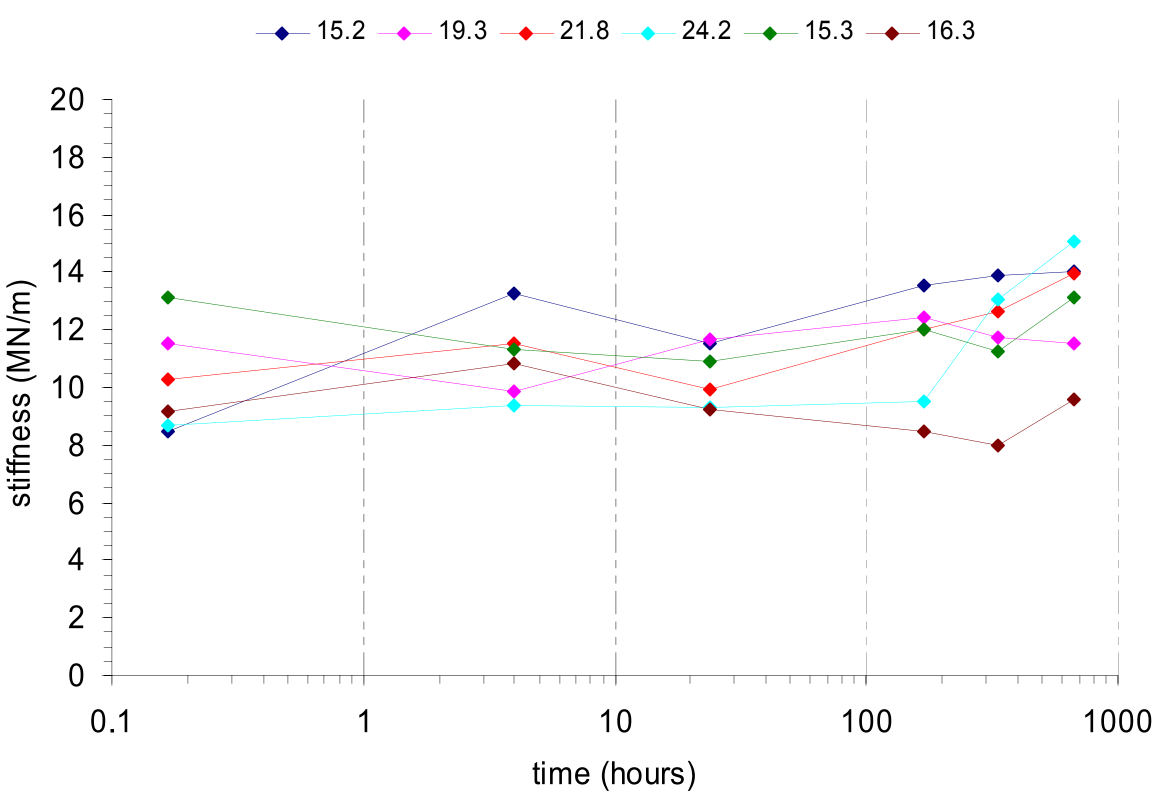

Figure 4f: Stiffness vs Time - Osage (CL) @ 6% CKD

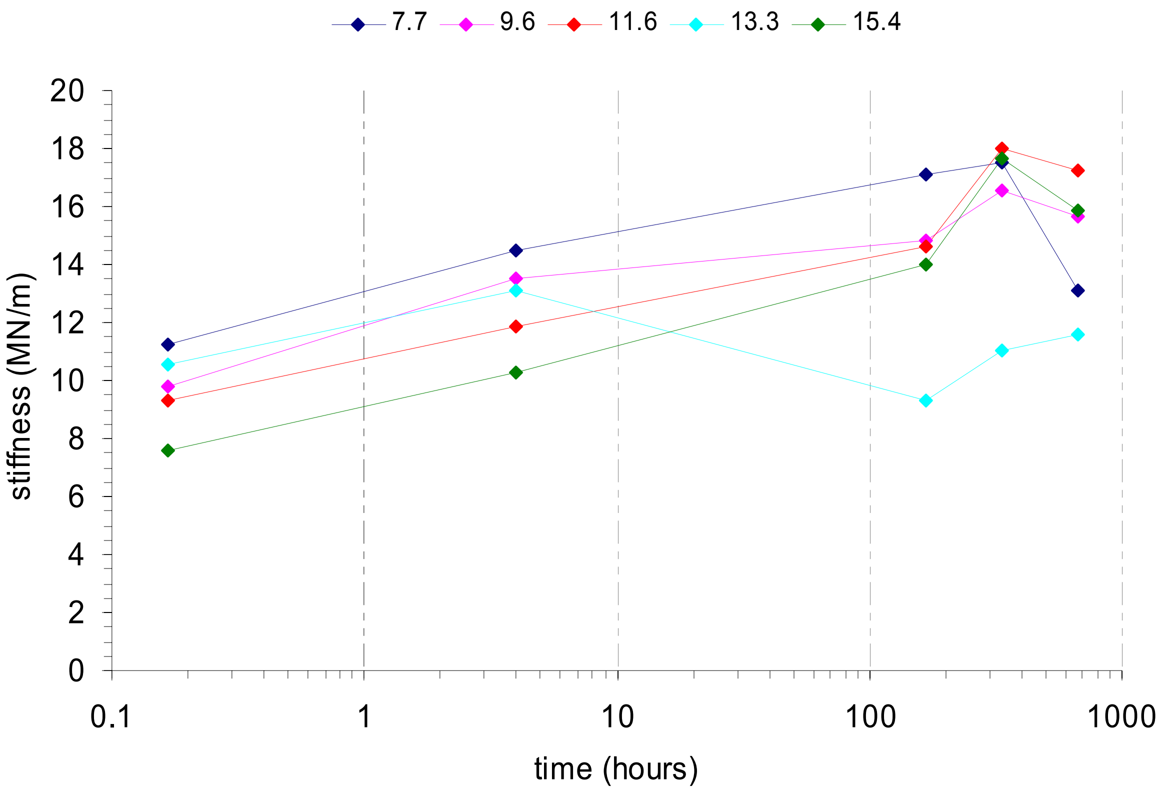

Figure 4g: Stiffness vs Time - Stevens (SM) @ 3% CKD