LABORATORY AND FIELD EVALUATION OF SOIL STABILIZATION USING CEMENT KILN DUST

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16 . ABSTRACT

A field and laboratory study was undertaken to evaluate Cement Kiln Dust (CKD) as a soil stabilizer. The performance of CKD from three different sources, Holnam of Ada, Blue Circle Cement of Tulsa, and Lone Star Industries, Inc. of Pryor was compared to the performance of Quick Lime. The field component involved the construction of four test sections along a rural highway near Lula, Oklahoma. During construction, observations were made so that the construction requirements for different additives could be compared. In addition, soil samples were collected before stabilization for the purpose of soil classification. Treated soil samples were collected prior to compaction to prepare laboratory specimens for unconfined compression testing. Field testing included Dynamic Cone Penetration (DCP) testing in the stabilized subbase, and Falling Weight Deflectometer (FWD) testing after completion of the pavement.

An in-depth laboratory study was conducted on a clay and sand soil obtained from a cut section next to the test site. These two soils represented a broad range of possible subgrade soil types along the test sections. Unconfined compression tests were conducted on samples prepared with each of the four additives (3 CKDs, lime) after moist-curing for 3, 7, 14, 28, and 90 days. Tests on raw shale were made for comparison. In addition, Atterberg limit tests were conducted on both moist- and dry-cured mixtures of shale, as well as two additional soil types taken from different sites. One of the CKDs and lime were used to investigate the durability of treated soils under freeze-thaw and wet-dry cycles. This was accomplished by evaluating the unconfined compression strength of samples after different number of durability cycles. Other laboratory testing included: swell testing, California Bearing Ratio testing, pH testing, and Scanning Electron Microscopy.

Results from the field study showed that the CKD obtained from the Holnam plant in Ada gave the best performance overall. Quick Lime, Lone Star CKD and Blue Circle CKD performed similarly. Results of the laboratory study were more conclusive because many of the variables that can not be controlled in the field, such as degree of mixing, weather, and subgrade variation, are not a significant factor under laboratory conditions. The laboratory test data showed that overall, CKD was at least as effective if not more effective than Quick Lime for stabilizing the shale. For sand, CKD is clearly a more effective stabilizer than Quick Lime, as expected. The influence of CKD and lime on the PI of the three soils that were tested was similar. Durability tests showed that CKD-treated shale was more durable that lime-treated shale, and CKD-treated sand was much more durable than CKD treated shale. In addition, durability of the treated soils was better than the untreated soils. Overall, the results of the study suggest that CKD can be an effective soil stabilizer; however, because of the variation in effectiveness between the three CKD sources, the use of CKD should be evaluated on a job specific basis.

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A field and laboratory study was undertaken to evaluate Cement Kiln Dust (CKD) as a soil stabilizer. The performance of CKD from three different sources, Holnam of Ada, Blue Circle Cement of Tulsa, and Lone Star Industries, Inc. of Pryor was compared to the performance of Quick Lime. The field component involved the construction of four test sections along a rural highway near Lula, Oklahoma. During construction, observations were made so that the construction requirements for different additives could be compared. In addition, soil samples were collected before stabilization for the purpose of soil classification. Treated soil samples were collected prior to compaction to prepare laboratory specimens for unconfined compression testing. Field testing included Dynamic Cone Penetration (DCP) testing in the stabilized subbase, and Falling Weight Deflectometer (FWD) testing after completion of the pavement.

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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

In recent years the importance of recycling voluminous industrial waste streams has been recognized with regard to natural resource conservation and efficient landfill utilization. This has led to extensive research on alternative uses of waste materials in different geotechnical applications including soil improvement and use as fill materials. In Oklahoma, problematic soils and shales are prevalent and stabilization with recycled materials, such as fly ash from coal combustion, is common practice. There are some major Portland Cement manufacturing facilities in Oklahoma, and recently interest has turned to the potential of using Cement Kiln Dust (CKD) in soil stabilization on state highway projects.

Portland Cement Kiln Dust (CKD) is emerging as an effective stabilizer for certain soil types. A considerable amount of effort has been expended on laboratory evaluations of CKD for soil stabilization and some limited scientific studies involving field implementation of CKD have been performed. However, there is much that must still be addressed through scientific research in order to evaluate the long-term benefits to be gained from using CKD. For example, little is known about the durability of CKD-stabilized soils under the influence of freezing and thawing and/or wetting and drying cycles. Also, CKD chemistry is known to vary from plant to plant, and therefore, it is important to know how this variability influences the effectiveness of CKD as a soil stabilizer.

The laboratory and field study described herein provides additional scientific evidence regarding the effectiveness of CKD in stabilizing soils with low to moderate plasticity along a rural highway in Oklahoma. In addition, the relative performance of CKD from three sources in Oklahoma and Quick Lime is compared. Scientific evidence and experience gained from this research will help to guide the Oklahoma Department of Transportation (ODOT) in their development of a policy and specifications regarding the use of CKD on state highways.

1.2 OBJECTIVES

A study was conducted by the University of Oklahoma with the support of the Oklahoma Department of Transportation to evaluate the effectiveness of Portland Cement Kiln Dust (CKD) as a soil stabilizer. The study involved both laboratory testing and a field study involving pavement test sections along a rural highway near Lula Oklahoma.

The primary objectives of the study were to:

1. evaluate the effectiveness of CKD, relative to Quick Lime, for reducing the plasticity of clayey soils;
2. evaluate the effectiveness of CKD for improving bearing strength and stiffness of soils with low to moderate plasticity;
3. evaluate the durability of CKD-treated soils;
4. compare the cost and construction procedures used for CKD and lime;
5. evaluate the difference in effectiveness of CKD from three different Portland cement producers; and
6. provide recommendations for implementing CKD soil stabilization in road building practice;
7. provide a draft specification for subgrade stabilization with CKD.

1.3 REPORT CONTENTS

A review of pertinent literature is presented in Chapter 2. Chapter 3 of this report presents the results of the field study including: a description of the subgrade properties along the test sections, construction observations, cost comparisons for different additives, results of laboratory tests on soil samples collected during construction, and results of field tests. Chapter 4 presents the results of in-depth laboratory testing on soil-additive mixtures prepared in the laboratory. The emphasis is on the influence of the three CKDs and Quick Lime on the mechanical and index properties of two different soils. Also discussed in Chapter 4 are durability tests that were conducted to evaluate the results of wet-dry and freeze-thaw cycles on stabilized soil and chemical aspects of the additives and test soils. Chapter 5 presents conclusions and recommendations based on the results of the field and laboratory study.

CHAPTER 2

LITERATURE REVIEW

2.1 CEMENT KILN DUST (CKD)

During manufacturing of Portland cement, materials containing lime, silica, alumina, and iron are blended and fed into the upper end of a kiln. The mix passes through the kiln at a rate controlled by the slope of the kiln and the speed at which the kiln rotates. Burning fuel is forced into the lower end of the kiln where it produces temperatures of 1,400° C to 1,650° C, changing the raw mix to a cement clinker. During this operation a small percentage of the material in the form of dust (CKD) is collected and removed as an industrial waste. The accumulated amount of this waste is a source of concern for authorities since it represents a major disposal problem. More than 3,500,000 metric tons of CKD, unsuitable for recycling in the cement manufacturing process, is disposed of annually in the United States (Todres et al. 1992).

The physical and chemical properties of CKD can vary from plant to plant depending on the raw materials and type of collection process used. However, the dust collected from the same kiln and producing the same cement type can be quite consistent (Baghdadi et al. 1995). It is a good practice to frequently test the material to evaluate its characteristics and quality. The chemical composition of a typical CKD from a plant in Oklahoma is given in Table 2.1. Shown for comparison in Table 2.1 are the chemical composition of cement compounds, Alite and Belite, that were used to guide the manufacturing of a cement stabilizer developed by Kamon and Nontananandh (1991). For material control it is suggested that a cement stabilizer should have a hydration modulus between that of Alite and Belite. As shown in Table 2.1, CKD satisfies this requirement and thus, having self-cementing characteristics it is expected to react with soil in a manner similar to Portland cement. In comparison, CKD has about one-half the amount of cement oxides present in Portland cement.

2.2 CEMENT KILN DUST STABILIZATION

Cement Kiln Dust has been used in a variety of applications. Morgan and Halff (1984) investigated the effectiveness of oil sludge solidification using CKD; based on field data obtained from a landfill site, CKD was found to be a cost effective and efficient solidifying agent when compared to sulfur, cement, fly ash and lime. Eoery (1972) developed a stabilization process for sludges and sediments that meets both environmental (solubility of constituents) and engineering (shear strength) requirements. The stabilization process involved combinations of stabilizing agents - CKD, fly ash, slag cement and Portland cement, resulting in a material that would produce strength gain in various sludges and sediments. Baghdadi (1990) found that the compressive strength of kaolinite clay was substantially improved by the addition of CKD. For example, after 28 days of curing the Unconfined Compressive Strength (UCS) was found to increase from 30.5 psi to 161 psi with the addition of 16% (by weight) CKD. Also, for a highly plastic bentonite clay, Baghdadi (1990) found that the addition of 8% CKD resulted in a reduction of the Plasticity Index (PI) from 513% to 326%. This reduction in PI was found to increase with increasing CKD content. Fatani and Khan (1990) utilized CKD in stabilizing dune sand and asphalt mixes used for pavement bases and reported a ten fold improvement in mix stability with the addition of 11% CKD. Baghdadi et al. (1995) found that CKD significantly increased the compressive strength of dune sand and that the compressive strength increased with increasing amount of CKD and curing duration. Zaman et al. (1992) found that CKD improved the UCS and decreased the Plasticity Index (PI) of a highly expansive clay. For example, it was found that with the addition of 15% CKD, the PI was reduced from 64% to 46% two hours after mixing, and the UCS was increased from 15 psi to 38 psi after 28 days of curing. Furthermore, results of scanning electron microscopy revealed that crystalline hydration products were present in CKD treated soils and these hydration products were presumed to be the major factor contributing to strength improvements.

Recently completed research (Azad 1998) at the University of Oklahoma suggests that CKD in modest amounts can effectively modify soils with low to moderate plasticity. However, tests on a high plasticity soil indicated that the CKD requirements may be excessive as shown in Fig. 2.1, which shows a comparison of unconfined compression strengths for three different soils after 28 days of curing. In addition, durability tests involving freeze-thaw and wet-dry cycles indicated that low PI soils treated with modest amounts of CKD were much more durable than high PI soils treated with higher percentages of CKD, as shown in Fig. 2.2. In Fig. 2.2 it is observed that for the high-PI Doolin soil, unconfined compression strength (UCS) after wet-dry and freeze-thaw cycles is lower than that obtained from similarly cured samples not subjected to durability cycles. On the other hand, the low PI Shawnee soil experienced much less strength loss from durability cycles. In a separate study at OU, CKD treatment was found to be effective at reducing the collapse potential and compressibility of compacted shales (Miller et al. 1997).

Recently, a field implementation study was conducted by the FHWA at the Oklahoma PRA-CHIC 12(1) Guy Sandy Area of the Chickasaw National Recreation Area (Marquez 1997). Laboratory optimization of the CKD content for the soil on this project (PI ≈28) resulted in the use of 10% CKD which resulted in an estimated cost savings of $25,000 (Shawn 1997) for 21,500 yd^2 of treated area. Using 10% CKD by weight of soil, the PI was reduced from 28 to 15 and the CBR value was increased from slightly less than 10 with no CKD to about 50 for 10% CKD. Compared to lime, the increase in CBR due to CKD was much greater; however, lime proved to be more effective in reducing the PI, giving a PI reduction from 28 to 0% at 5% lime content.

Generally, the available literature indicates that given the proper soil conditions, CKD can be a cost-effective soil stabilizer. There is a lack of scientific field studies to evaluate CKD soil stabilization under different soil and traffic conditions. The study described herein partly fills this void of information.

Table 2.1 Chemical Composition of CKD and Cement Compounds

Chemical compound	CKD	Alite	Belite
Silica (SiO_2), %	15.14	24.83	32.50
Aluminum oxide (Al_2O_3), %	3.91	1.24	2.13
Iron oxide (Fe_2O_3), %	1.97	0.94	1.03
Calcium oxide, (CaO), %	48.40	72.23	62.83
Magnesium oxide (MgO), %	1.38	0.98	0.52
Sulfur oxide (SO_3), %	4.53	...	...
Sodium oxide (Na_2O), %	0.19	0.09	0.20
Potassium oxide (K_2O), %	2.40	0.14	0.30
Loss on ignition, %	22.09	...	...
Specific gravity, Gs	2.78	...	...
Hydration modulus	2.30	2.67	1.76

Note : Hydration modulus = $CaO/(Al_2O_3+SiO_2+Fe_2O_3)$

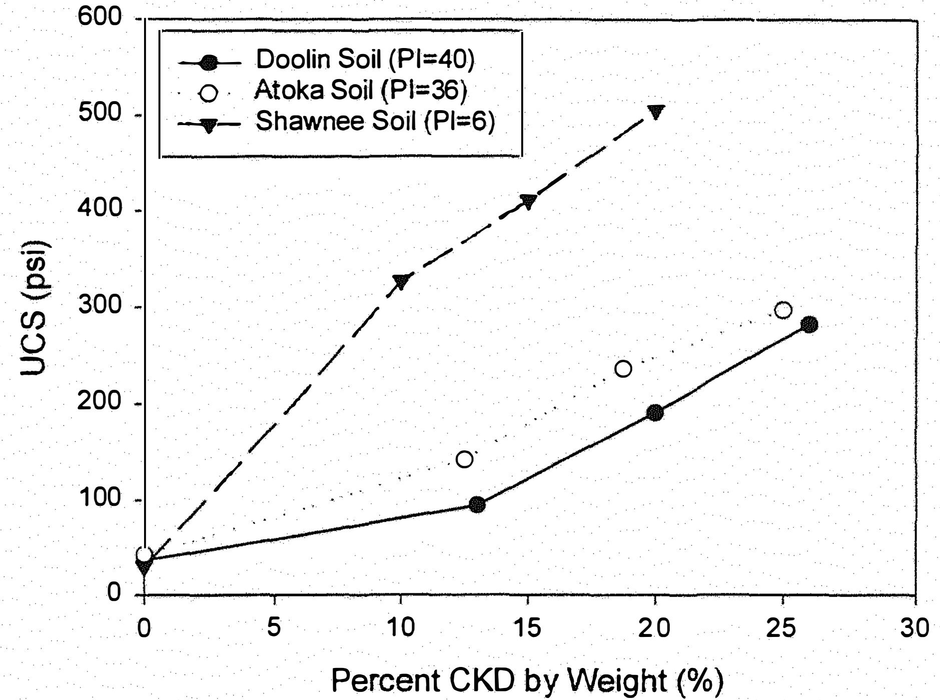


Fig 2.1 Unconfined Compression Test Data for Three Different Soils Mixed with CKD and Cured for 28 Days

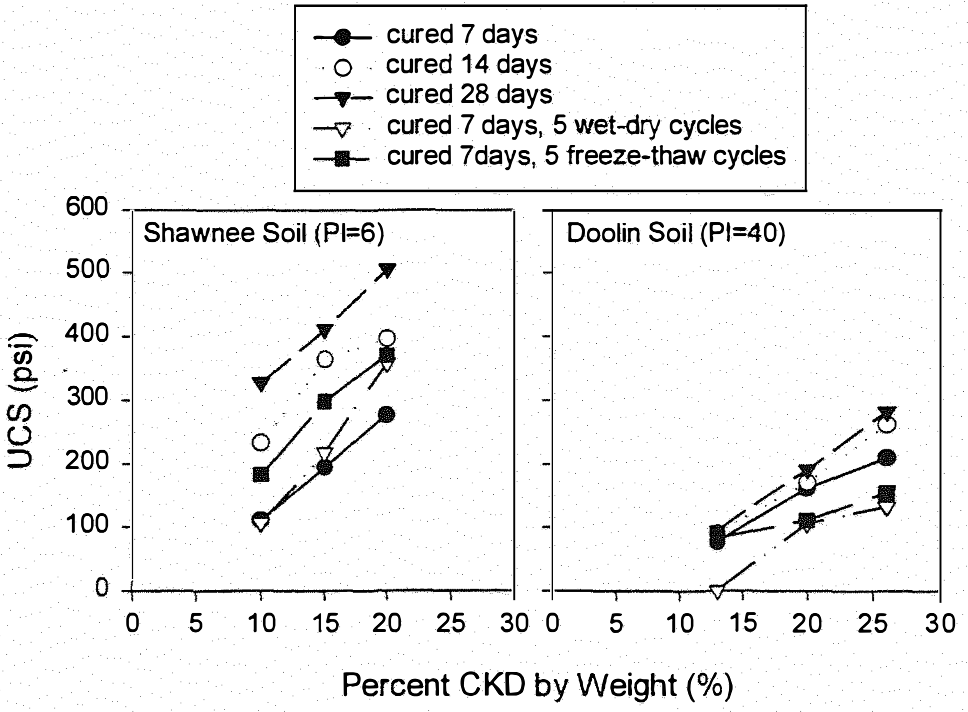


Fig 2.2 Unconfined Compression Test Data for Two Different Soils Mixed with CKD for Different Curing Conditions

CHAPTER 3

FIELD TEST SECTIONS

3.1 INTRODUCTION

To evaluate the effectiveness of CKD relative to lime, four test sections were selected along Lula Road. The location of the test area is shown in Fig. 3.1. One of the test sections was stabilized with 4% (by weight) granular Quick Lime and the three remaining test sections were stabilized with 15% CKD. Granular Quick Lime, as opposed to hydrated lime, was used throughout this study and is referred to as Quick Lime or lime in this report. Each of the three CKD test sections was designated for a different CKD supplier, namely Holnam of Ada, Blue Circle Cement of Tulsa, and Lone Star Industries, Inc. of Pryor. The contractor constructed these test sections as described in Table 3.1. Also listed in Table 3.1 are locations where sampling and field testing were conducted. Due to scheduling difficulties and actual material quantities delivered, the test sections vary slightly in length, and the Holnam CKD was used in two sections. The contractor decided to use Holnam CKD to complete the west-end of the Lone Star test section since Holnam is located a short distance from the site and Lone Star is located in Pryor, OK. Also, note that the lime test section is separated from the beginning of the CKD test sections between stations 151 to 155+80, and thus, on some of the figures presented subsequently there are no data for this gap.

Field sampling and testing activities before, during and after construction activities on each test section included the following tasks completed by ODOT and OU research personnel:

- Subgrade samples were collected prior to stabilization for index property tests.
- Observations of construction were made during subgrade stabilization activities.
- Subgrade samples were collected immediately following application of soil modifiers, just prior to compaction activities. These samples were used to prepare Harvard miniature samples for unconfined compression tests.

- Dynamic cone penetration (DCP) tests were conducted at selected stations.
- Falling weight deflectometer tests were conducted at selected stations.

Results of each of the field testing activities and associated laboratory test results are presented in the remainder of this chapter.

3.2 INDEX PROPERTIES AND CLASSIFICATION OF SUBGRADE SOILS

Subgrade samples were collected by the ODOT Materials Division at regular intervals along the test sections prior to subgrade stabilization, and subjected to index property testing including Atterberg Limit tests and sieve analysis. Soil samples were obtained from the surface to a depth of 24 inches below the top of subgrade. Results of these tests are summarized in Fig. 3.2 and in tabular form in Tables A-1 through A-5 of Appendix A. Table 3.2 contains a summary of the average soil characteristics determined from the values in Tables A-1 through A-5.

As shown in Table 3.2 and Figure 3.2, the subgrade soils were generally similar in the three test sections toward the east end of the test sections alignment. The lime test section tends to have less fines than other test sections as indicated by the average PI and percent passing the number 200 sieve. Also, the short Holnam test section to the west has a higher prevalence of clayey soils. The three major test sections for the three CKD sources, toward the east end of the alignment are generally similar and provide for a good comparison between the three CKD sources. The subgrade soils are derived partly from weathered sandstone and shale fill from the cut sections and partly from natural in-place soils.

3.3 CONSTRUCTION OBSERVATIONS

The goal of field observations during subgrade stabilization on the test sections was to provide information for quantitatively comparing the construction activities and rates of production for lime and CKD stabilized subgrades. To achieve this goal a record of construction activities and time required to prepare the subgrade for compaction was produced. A summary of construction daily activities prepared by the OU field representative is attached to this report in Appendix B. Photographs of various construction activities are also included in Appendix B. In Table 3.3, a summary of the test section extents, construction dates, stabilizer doses, rates of production, and sampling locations are tabulated.

Several observations can be made based on the data presented in Table 3.3. Generally, the rate of production for completing the mixing operations was similar for lime and CKD, which seems reasonable as equipment and manpower requirements indicated on the daily logs (Appendix B) were similar for both lime- and CKD-treated sections. However, in the case of the lime-treated section there was considerably more use of the motor grader to facilitate uniform mixing. This would suggest that uniform spreading and mixing of the CKD were more easily accomplished than for the smaller doses of granular Quick Lime. On some test sections where the slope of the roadbed was steeper, a steel tooth harrow was also used during water applications to help prevent the water from flowing down-slope and provide uniform mixing.

While the rate of mixing was about the same for lime and CKD, it is important to clarify some distinctions that should be considered in comparing the cost-effectiveness of the two stabilizers. First, mixing and compacting of the CKD-treated subgrade is performed one time; on the other hand, it is necessary to remix and compact the lime-treated section a second time after approximately 48 hours. Remixing requires less time compared to first time mixing; however, remixing does add a substantial construction time as well as the delay incurred by the 48-hour waiting period. A second consideration is that the CKD reaction appears to occur more quickly than lime, and therefore the CKD-treated subgrade can better withstand traffic-induced stresses after a shorter curing time. A downside observed for CKD was that on windy days some of the CKD was blown offsite. Airborne CKD represents a potential dust hazard and may cause problems on property adjacent to the roadway. The dust problem associated with CKD application on windy days can be seen on Photograph-B in Fig. B-1 of Appendix B. Wind is also a factor for the use of fly ash and powdered lime as well.

3.4 COST COMPARISON

Another important consideration for selecting a soil stabilizer is the cost of materials and hauling. In the case of CKD versus lime, the cost of hauling more CKD may be offset by cheaper material costs. Table 3.4 provides a comparison of costs associated with the delivery of CKD and Quick Lime to the Lula Road Site. Cost figures shown in Table 3.4 were provided by the contractor, actual costs were different because the manufacturers donated the CKD. Costs were calculated assuming a 30-foot wide stabilized base to a depth of 8 inches. Cost comparisons indicate that the use of Holnam CKD was least expensive due to low material costs ($8/ton) and close proximity to the site. Quick Lime, having a much higher material cost ($61/ton), is comparable in cost to Lone Star CKD ($5/ton) and Blue Circle CKD ($8/ton). In Fig. 3.3 a comparison of lime and CKD costs is shown for a similar roadway of varying constructed length and for different hauling distances. Figure 3.3 was generated assuming lime is about $75/ton delivered in Oklahoma (typical for Texas to Oklahoma), CKD costs $8/ton at the plant, and freight charges are variable for the CKD as shown in Table 3.4. The results indicate that beyond a hauling distance of about 130 miles the use of CKD becomes more expensive than lime, and the disparity between the cost of lime and CKD is noticeably larger for longer constructed roadway lengths. This crossover point (130 miles) will vary depending on the percentage of CKD used and would be greater for CKD prices less than $8/ton. In addition, freight charges for lime may vary slightly depending on location in Oklahoma, but generally, lime prices are relatively insensitive to location within the State (personal communication with contractor).

Based on material and hauling costs, CKD can be cheaper than Quick Lime. In addition, other factors should be considered in comparing the cost of CKD versus Quick Lime. In particular, the Quick Lime requires a second mixing and compaction 48 hours after initial mixing. The additional, time, manpower, equipment and fuel costs associated with re-mixing should also be considered. Furthermore, CKD-treated soil appears to gain strength more rapidly than lime-treated soil, which could save money by allowing for traffic earlier than might be possible with lime treatment.

3.5 UNCONFINED COMPRESSION TEST RESULTS ON FIELD SAMPLES

Immediately prior to compacting the soil in the test sections, samples were collected and unconfined compression test (UCT) specimens were prepared in the field using a Harvard miniature apparatus. The Harvard miniature compaction procedure was calibrated with soil collected from the test alignment in accordance with the procedure in ASTM Standard D 4609, "Standard Guide for Evaluating Effectiveness of Chemicals for Soil Stabilization." Calibration was performed so that Harvard miniature samples compacted at the standard Proctor optimum moisture content (OMC) would achieve the standard Proctor maximum dry unit weight. The same compaction effort was used on all specimens prepared with the Harvard miniature device.

For each sampling location a minimum of three compacted samples were prepared and in some cases up to 12 samples were prepared depending on the time available and the number of locations sampled on a given day. Samples were subjected to UCTs after curing periods of seven and 28 days. Curing involved wrapping samples in cellophane and placing them in a humidity chamber. In some cases the unconfined compression strength (UCS) was determined after submerging the samples in water for two days following the curing period. Submerged samples were tested to assess the resistance of treated samples to water intrusion. Unconfined compression tests were performed in triplicate to quantify statistical variation in the UCS results.

Results of UCTs on field samples are summarized for each test in Figs. 3.4 to 3.6 and in Table C-1 of Appendix C. Average values of UCS are tabulated in Table 3.5. Also shown in the Figures is the range of UCS for representative samples of the raw soil.

Referring to figures and tables mentioned, several important observations are made as follows:

1) Unconfined compression strength values for samples treated with Holnam CKD are considerably higher than for other CKD sources and lime, for both 7-day and 28-day curing periods. This distinct difference between CKD sources appears to be related to the differences in chemical makeup. As discussed in a Section 4.3, the CKD from Holnam has a higher Calcium Oxide (CaO) content than other CKD sources and at an additive concentration of 15% by dry weight, the pH of treated soil is higher for the Holnam CKD. This appears to cause greater pozzolanic activity in the case of soil treated with Holnam CKD.
2) The performance of granular Quick Lime and Lone Star CKD appears to be similar with regard to UCS although the increase in strength from 7 to 28 days is generally more distinct

for the lime-treated soil. On average the UCS in the Lone Star section increased slightly between 7 and 28 days, except for Station 167 where a slight decrease is seen. It is important to note that the soil in the lime section is generally more granular than the CKD-treated sections as discussed in Section 3.2. The results of laboratory testing using the same soil (discussed in Section 4.4) provide a better comparison of lime and CKD performance.

3) Blue Circle CKD showed the worst performance relative to other additives, which appears to be the result of differences in the chemical makeup of the CKD sources. Laboratory test results obtained under controlled conditions, discussed in Section 4.4, were similar in this regard with the exception that Blue Circle CKD generally gave UCS values higher than that of lime and of the untreated soil. Differences in field and laboratory results are expected given the variation in soil type along the test roadway alignment and the much better control over mixing and compaction that is achieved in the laboratory.
4) Generally, the percent increase in UCS between 7- and 28-day curing periods is greater for the lime than the CKD-treated soils. Results of laboratory tests indicate that the most of the strength gain for CKD-treated soils occurs in the first seven days of curing while lime-treated soil gains strength steadily from 3 to 90 days.
5) In all but one case, samples submerged in water for two days prior to testing showed a decrease in strength compared to similarly cured samples that were not submerged. However, that some strength was retained is noteworthy because untreated soil specimens disintegrated upon immersion in water. Results of UCTs on specimens subjected to freeze-thaw and wet-dry cycles discussed in Section 4.6 provide more insight into the durability of treated soils.

To summarize, results of UCTs on field samples indicate that the performance of Holnam CKD (15% by weight) was superior to Blue Circle CKD (15% by weight), Lone Star CKD (15%

by weight), and granular Quick Lime (4% by weight). Lone Star CKD performed slightly better than lime, while Blue Circle CKD performed the worst. While an effort was made to locate test sections that were similar in character, some obvious differences were apparent especially with regard to the lime section. Furthermore, mixing in the field is far more variable than a laboratory environment with regard to temperature, humidity and wind conditions, all of which were variable during the construction activities. Therefore, further in-depth comparison of the performance of the various additives was accomplished through laboratory testing where soil type, mixing conditions, and environmental factors were carefully controlled. Furthermore, dynamic cone penetration (DCP) tests and falling weight deflectometer (FWD) tests were conducted by ODOT personnel to provide additional field data for the comparison of test section performance. These field test results are described in subsequent sections.

3.6 DYNAMIC CONE PENETRATION TESTING ON STABILIZED BASE COURSE

Dynamic Cone Penetration (DCP) tests were conducted in the test sections after 28 days and 56 days following compaction of the treated subbase. Results of 28-day and 56-day DCP tests are shown in Figs. 3.7 and 3.8, respectively, and tabulated in Tables C-2 and C-3 of Appendix C. Each sounding was conducted to a depth of approximately 24 inches below the ground surface. The data reported in Figs. 3.7 and 3.8 covers the top eight inches since this represents the design thickness for the stabilized base. Data is presented as the Cone Index (CI), which represents the depth of penetration per blow of the DCP hammer. Lower CI values indicate stronger material. Reported CI values for each test were calculated by averaging individual CI values (per each blow) for depths of 0-4 inches, 4-8 inches and 0-8 inches. This way the variation of the CI from top to bottom of the stabilized base is captured. Also, shown in

Figs. 3.7 and 3.8 are the CI values obtained by averaging values from each profile at a given location.

After 28 days, three DCP profiles were conducted at selected stations in the CKD test sections and a single profile was conducted at selected stations in the lime test section. After the first tests were conducted in the lime section, it was decided that at least three profiles within one foot of each other should be conducted at each station to capture random variation in the results. The 56-day data represents a complete set of data with three test profiles per location.

In Fig. 3.9 a comparison of the 28-day and 56-day CI values and the 28-day UCS values is shown. The inverse of CI (1/CI) values is shown in Fig. 3.9 since this allows for easier visual comparison with UCS data. That is, higher values of inverse CI indicate higher strength, as do higher UCS values. Based on the results shown in Figs. 3.7 to 3.9, the following observations are made:

1) With a few exceptions, 28-day and 56-day CI values are lower (higher strength) for the top four inches compared to the bottom four inches of the stabilized base. This may reflect better compaction and/or possibly higher additive content in the upper four inches.
2) At 28-days, average CI values for the full depth of stabilized base (0-8 in.) indicate that the subbase strength in the lime and first Holnam (Sta. 159+00) test sections are similar, except for values from Station 144+00 in the lime section where a weak spot was encountered. Generally, the three CKD sections from about Station 160+00 to 187+00 performed similarly based on 28-day CI values for 0-8 inches.
3) By 56 days, average CI values for the stabilized subbase (0-8 in.) are considerably lower in the Holnam test sections. Lime and Blue Circle CKD appeared to give similar performance and changed little compared to 28 days. In the Lone Star CKD test section, CI values

increased significantly from 28 to 56 days for unknown reasons. The significant difference between 28-day and 56-day DCP test results may have in part occurred because cool weather conditions slowed the curing process in the field relative to the laboratory environment.

4) The comparison of UCS and 1/CI values in Fig. 3.9 indicates that the general trend of 56-day 1/CI values is similar to 28-day UCS values except that Lone Star and Blue Circle performance is reversed. That is, 28-day UCS values show that Lone Star outperformed Blue Circle, whereas the DCP data indicate the opposite. Differences between the field compaction and curing environment, which is largely uncontrolled, and compaction in a Harvard device and laboratory curing, which is very controlled, are likely responsible for the discrepancy between DCP and UCT test results.

To summarize, the results of DCP tests generally corroborate the conclusions drawn from UCS testing on field samples. Performance of the Holnam test sections is superior while the lime section tends to be on par with Blue Circle and Lone Star CKD test sections. One difference in the outcome of UCS and DCP testing is that the DCP results suggest that Blue Circle generally out performed Lone Star.

Complete DCP profiles are shown in Figs. 3.10 to 3.13 for 56-day tests. Several interesting observations are made from these plots, as follows:

1) In many of the profiles a distinct change is seen at a depth of approximately eight inches. See for example Sta. 144+00, 159+00 171+00, 179+00 and others in each of the test sections. This is an indicator that the actual stabilized depth was close to the target value of eight inches.

2) Where the subgrade below the stabilized subbase is competent, as indicated by low CI values, the results of stabilization generally appear better. For example, at Sta. 140+00 in the

lime section, CI values below eight inches indicate a competent subgrade whereas at Sta. 144+00 a weaker subgrade is indicated by higher CI values. Corresponding CI values in the top eight inches indicate a stronger and weaker subgrade, respectively. Similar observations were made in other test sections, for example, compare Sta. 179+00 with 181+00 in the Holnam section.

3) The superiority of the performance in the Holnam CKD section is further reflected by the DCP profiles shown in Fig. 3.13. While the subgrade appears to be relatively softer at some locations in this section, CI values in the stabilized base are among the lowest.

3.7 FALLING WEIGHT DEFLECTOMETER TESTS

Falling weight deflectometer (FWD) tests were conducted to provide additional information about the structural integrity of the stabilized subbase. Tests were conducted by ODOT personnel on September 9, 1998, shortly after completion of pavement construction. The completed pavement was designed for six inches of asphalt concrete over four inches of aggregate base over eight inches of stabilized soil (subbase).

Falling weight deflectometer tests were conducted on 100-foot intervals in the eastbound and westbound lanes throughout the test sections using Dynatest equipment. During FWD testing, after a seating load of approximately 6,500 lb. was applied, a nominal impulse load of 7,000 lb. was applied four times to an 11.81-inch plate atop the pavement. For each impulse load, pavement deflections were measured with sensors located 0, 8, 12, 24, 36, 48, and 60 inches away from the center of the loading plate. These sensors are designated D1 through D7, respectively.

For the purpose of evaluating the composite character of the subbase and subgrade, the sensors located at 24, 36, and 48 inches were selected for determining a composite subbase/subgrade resilient modulus. Resilient modulus was calculated using (AASHTO 1993),

$$M_R = \frac{0.24P}{d_r r} \qquad [1]$$

where: M_R = backcalculated subgrade resilient modulus, psi

P = applied load, pounds

d_r = deflection at a distance r from the center of the load, inches

r = distance form the center of the load, inches.

This equation is only valid for distance (r) far enough away from the loading so that the corresponding deflection is primarily a function of subgrade deformation. However, it must be close enough to the loading so that the deflections are measured accurately. The AASHTO 1993 design manual provides recommendations for estimating the minimum r-value to satisfy these requirements. Using these recommendations and comparing values of M_R calculated for the different sensors, it was found that the D4, D5, and D6 sensors gave similar results, which are assumed to be representative of the composite response of the stabilized subbase and subgrade.

Results of the FWD analysis are shown in Fig. 3.14 and tabulated in Tables C-4 and C-5 of Appendix C for Sensors D4, D5 and D6. In Fig. 3.14, sensor deflections and corresponding backcalculated modulus values are shown for eastbound and westbound lanes. Each point represents an average of values obtained from the four impulse loads at a given location. A comparison of FWD, DCP and UCS test results is presented in Fig. 3.15. Following are some observations based on Figs. 3.14 and 3.15:

1) Eastbound and westbound FWD results are very similar at a given station, which indicates that the pavement is quite uniform across lanes.
2) Composite subbase/subgrade modulus values along the alignment were quite high in a range of 15 to105 ksi with a majority falling between 20 and 50 ksi. These values are indicative of a fairly competent subbase/subgrade.
3) Modulus values are quite high in the Holnam CKD test section between Stations 155+80 and 159+60. This is consistent with the results of DCP and UCS tests and reflects both the integrity of stabilized soil and superior strength of the underlying subgrade at these locations.
4) Following the Holnam CKD test section mentioned in 3), the next highest modulus values were found in the lime section. The remaining CKD test sections beginning at about Station 163 gave similar FWD results.
5) While the subbase has a significant impact on FWD results, the subgrade below the subbase also influences the measured deflections. Thus, FWD data gives a partial indication of stabilizer effectiveness, and reflects the general character of the subgrade below the stabilized subbase as well. This is demonstrated by comparing FWD and DCP data shown in Fig. 3.15, where FWD moduli correlate well with CI values averaged from 8-24 inches of depth.

Table 3.1 Description of Field Test Sections

Test Section	Target Amount (% by weight)	Test Section Extent (Sta. Nos.)	Dates Construction was observed	Sampling Locations (Sta. Nos.)
Granular Quick Lime	4%	141 to 151	2/4-2/5/98	142, 144, 146, 148, 150
Holnam CKD	15%	155+80 to 159+30	3/3/98	157,159
		177 to 186	2/23/98	179, 181, 183, 185
Lone Star CKD	15%	159+30 to 167+50	2/27&3/2/98	161, 163, 165, 167
Blue Circle CKD	15%	167+50 to 177	2/24&2/26/98	169, 171, 173, 175, 177

Table 3.2 Average Soil Characteristics for Test Sections

Test Section	Test Section Extent (Sta. Nos.)	PI (%)	%<#4 Sieve	%<#200 Sieve	OSI	Dominant Soil Types
Granular Quick Lime	141 to 151	11	98	60	8	A-6, A-4 Sandy Lean Clay and Clayey Sand
Holnam CKD	155+80 to 159+30	26	100	97	21	A-7-6 Lean and Fat Clay
	177 to 186	19	99	73	14	A-7-6, A-6 Lean Clay with Sand and Sandy Lean Clay
Lone Star CKD	159+30 to 167+50	24	98	81	18	A-7-6, A-6 Sandy Lean Clay, Lean Clay, and Lean Clay with Sand
Blue Circle CKD	167+50 to 177	22	96	73	15	A-7-6, A-6 Lean Clay with Sand and Sandy Lean Clay

Table 3.3 Summary of Field Observations and Sampling Locations

Chemical Additive	Test Section Extent (Sta. Nos.)	Date	Extent of Treatment (ft.)	Stabilizer Dose (tons)	Mixing[1] Rate (ft./hr)	Sampling Location (Sta. Nos.)
Granular Quick Lime	141 to 151	2/4/98	1,000	---	---	---
		2/5/98	500	25	107	142, 144, 146, 148, 150
Holnam CKD	155+80 to 159+30	3/3/98	350	50	108	157, 159
	177 to 186	2/23/98	900	150	100	179, 181, 183, 185
Lone Star CKD	159+30 to 167+50	2/27/98	480	80	80	165, 167
		3/2/98	340	54	105	161, 163
Blue Circle CKD	167+50 to 177	2/24/98	800	127	100	171, 173, 175, 177
		2/26/98	150	25	50	169

Notes: 1- Average length completed along roadway alignment per hour.

Table 3.4 Cost Comparison Between CKD and Lime for Lula Road Site

Roadway Width = 30 ft.
Stabilized Depth = 0.67 ft.
Soil Dry Unit Weight = 106 pcf
Lime by Dry Weight = 4 %
CKD by Dry Weight = = 15 %

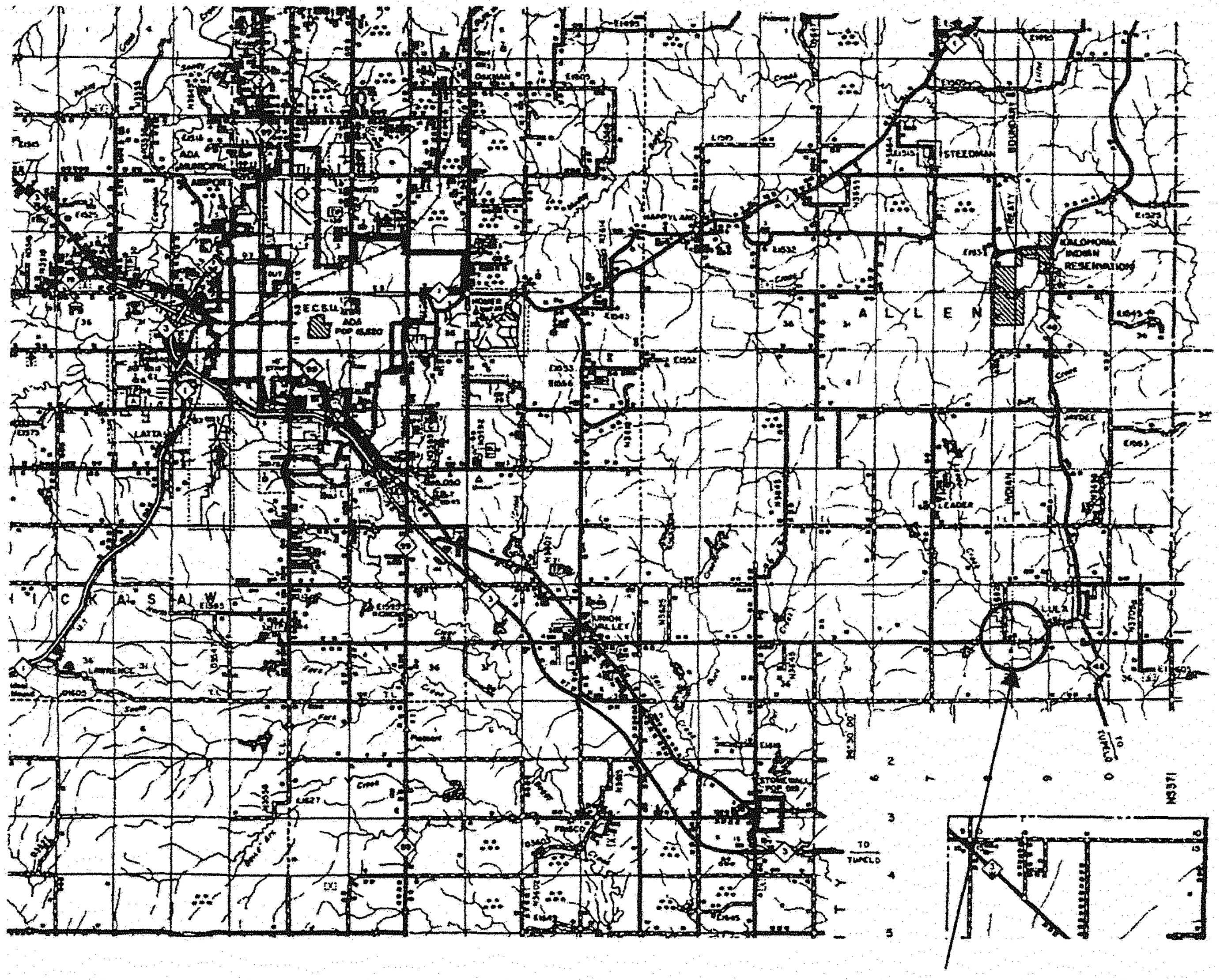
Source	Material Cost	Freight Charges	
Holnam:	$ 8.00 per ton	Ada-Lula (0-25 miles):	$ 4.92 per ton
Lone Star:	$ 5.00 per ton	Pryor-Lula (160-170 miles):	$ 15.08 per ton
Blue Circle:	$ 8.00 per ton	Tulsa-Lula (110-120 miles):	$ 11.03 per ton
Lime:	$ 61.00 per ton	Texas-OK:	$ 14.00 per ton

Road Length (ft.)	Soil Weight (tons)	CKD Required (tons)	Lime Required (tons)	Cost Holnam CKD ($)	Cost Lone Star CKD ($)	Cost Blue Circle CKD ($)	Cost Lime ($)
50	53	8.0	2.1	$ 103	$ 160	$ 151	$ 159
100	106	16	4.2	$ 205	$ 319	$ 303	$ 318
500	530	80	21	$ 1,027	$ 1,596	$ 1,513	$ 1,590
1000	1060	159	42	$ 2,054	$ 3,193	$ 3,026	$ 3,180
2000	2120	318	85	$ 4,109	$ 6,385	$ 6,052	$ 6,360
5280	5597	840	224	$ 10,847	$ 16,858	$ 15,976	$ 16,790

Table 3.5 Average Unconfined Compression Test Data from Field Samples for 7- and 28-Day Curing

Chemical Additive	Station (ft.x100)	Average 7-Day UCS (psi)	Average[1] 7-Day Sub. UCS (psi)	Average 28-Day UCS (psi)	Average 28-Day Sub. UCS (psi)
Granular Quick Lime	142	34.6	38.0	49.8	46.4
	144	49.4	---	69.6	---
	146	64.8	---	90.3	---
	148	56.4	---	90.3	---
	150	52.6	38.6	95.4	54.2
Holnam CKD	157	172.2	---	248.6	---
	159	155.3	---	232.6	---
Lone Star CKD	161	59.9	---	78.9	---
	163	77.5	---	81.9	---
	165	56.8	34.2	---	---
	167	93.7	---	86.1	---
lue Circl CKD	169	24.9	---	34.2	---
	171	41.4	---	69.2	---
	173	---	24.5	---	---
	175	21.1	---	33.1	---
Holnam CKD	177	71.8	---	97.5	---
	179	187.4	111.9	---	---
	181	181.5	---	248.6	---
	183	168.8	113.6	---	---
	185	157.9	---	207.7	149.0

__Notes:__ 1-Sub. indicates samples submerged in water for 2 days before UCS Test.



TEST SITE LOCATION

Fig. 3.1 Test Site Location Map (Adapted from General Highway Map of Pontotoc County, prepared by ODOT Planning Division in Cooperation with FHWA)

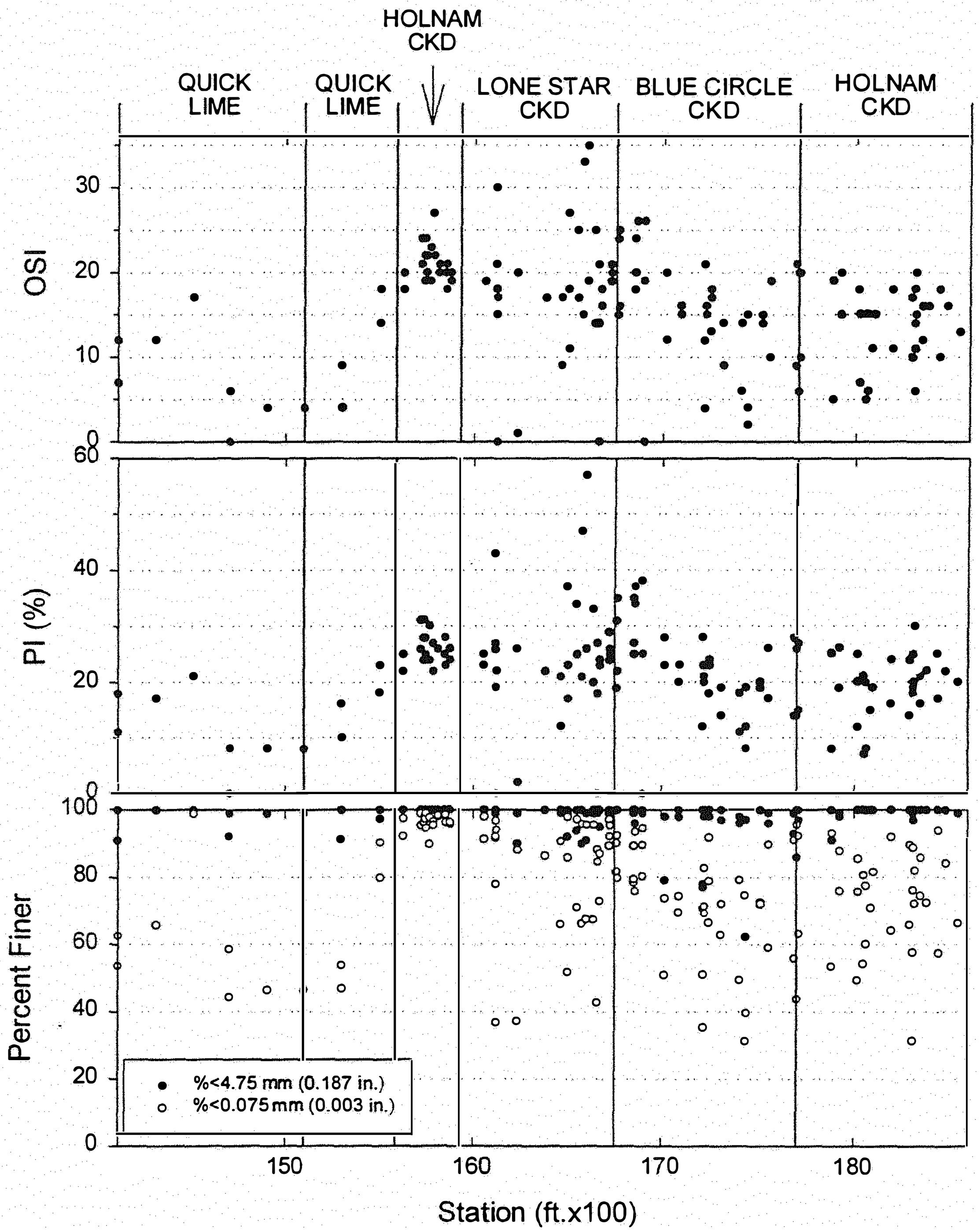


Fig. 3.2 Index Property Test Results

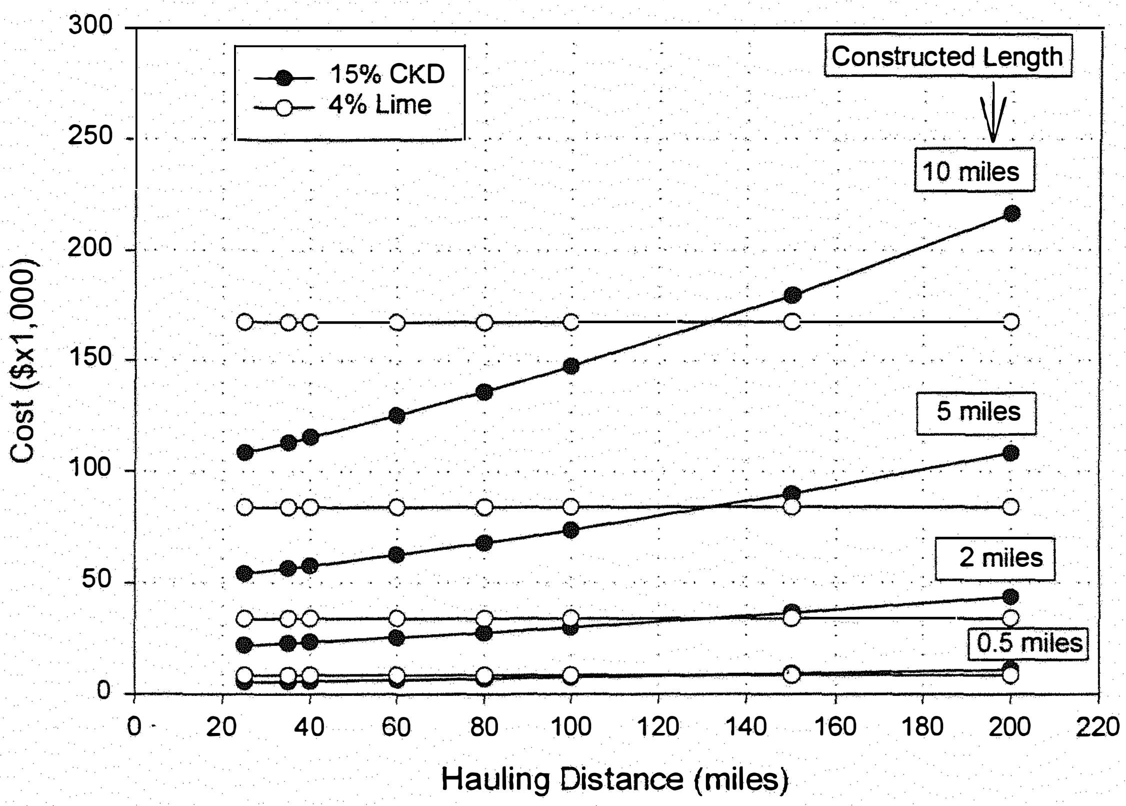


Fig. 3.3 Comparison of Costs for Stabilizing a 30-foot Wide Roadway to a Depth of 8 inches (CKD=$8/ton + Freight Charges, Lime=$75/ton Delivered)

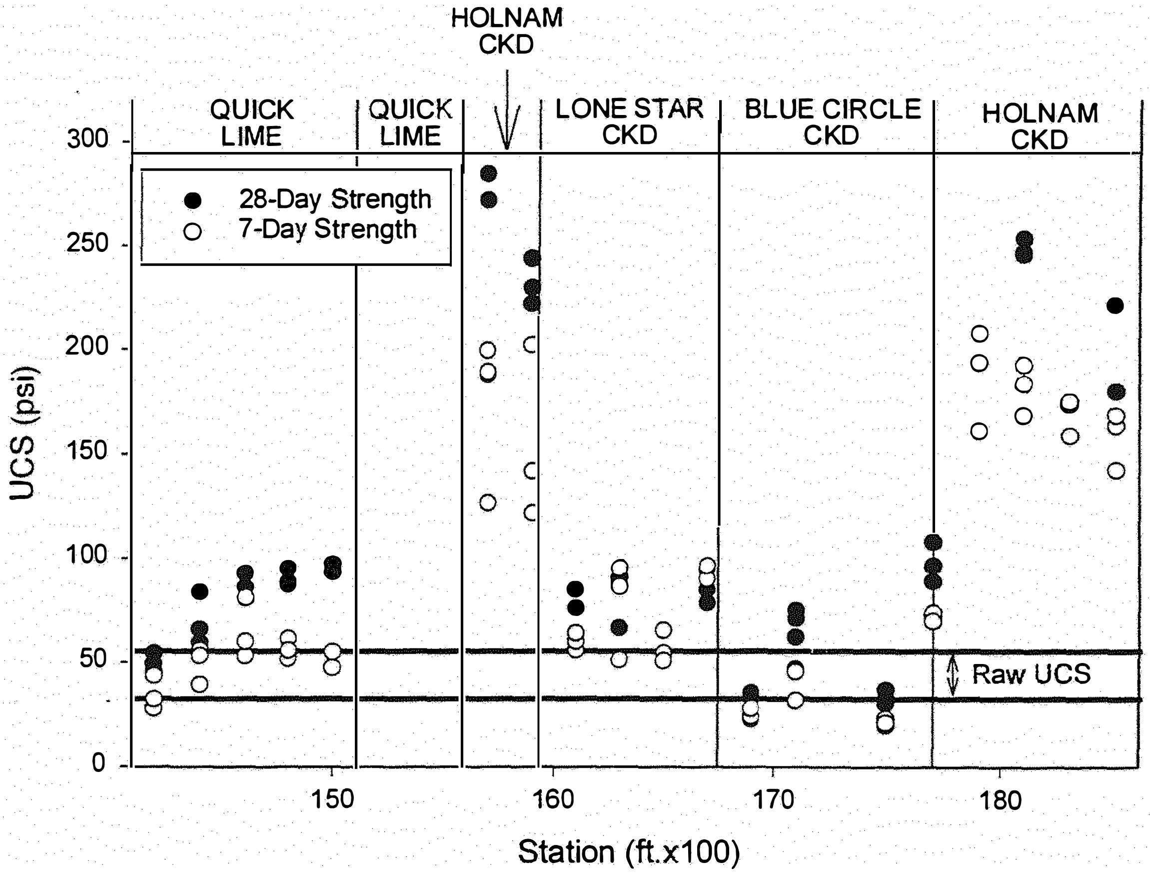


Fig. 3.4 7-Day and 28-Day Unconfined Compressive Strength from Harvard Minature Samples Prepared from Soil Sampled During Construction

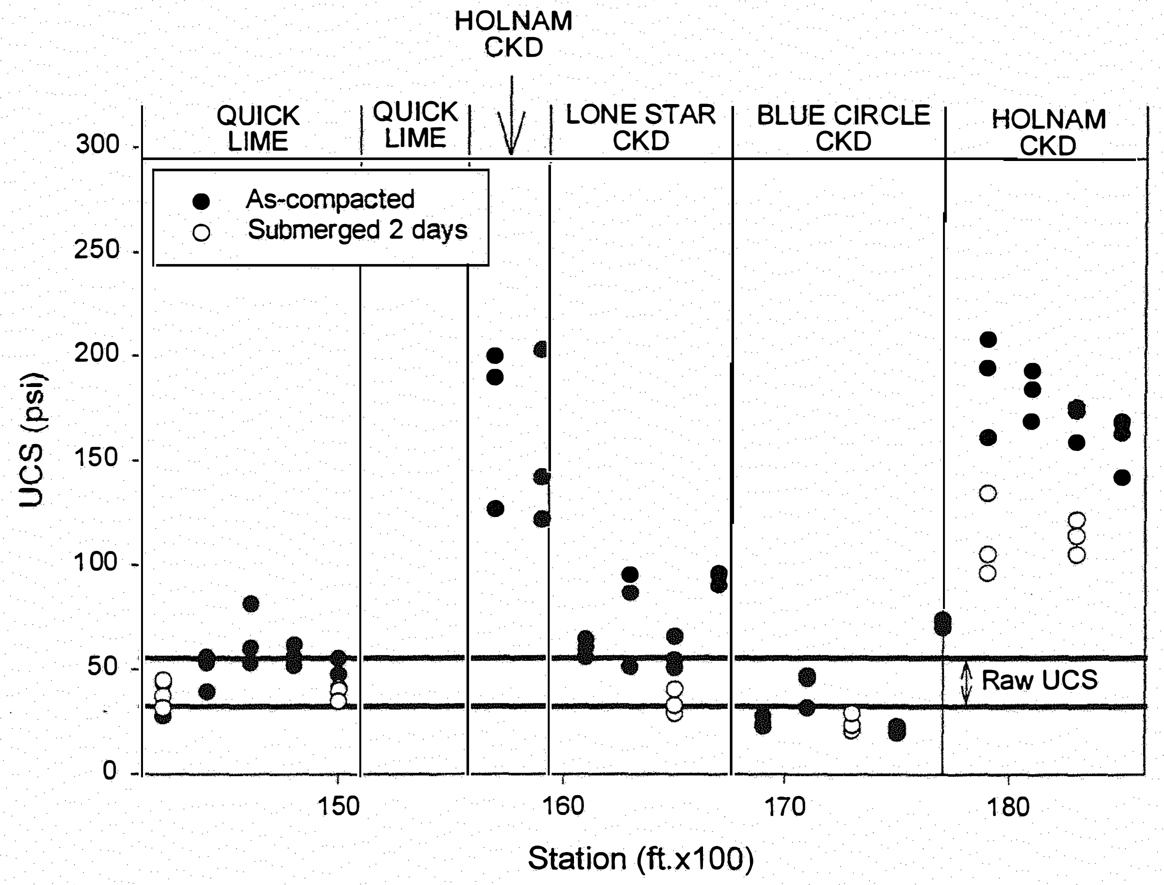


Fig. 3.5 7-Day Unconfined Compressive Strength from Harvard Minature Samples Prepared from Soil Sampled During Construction

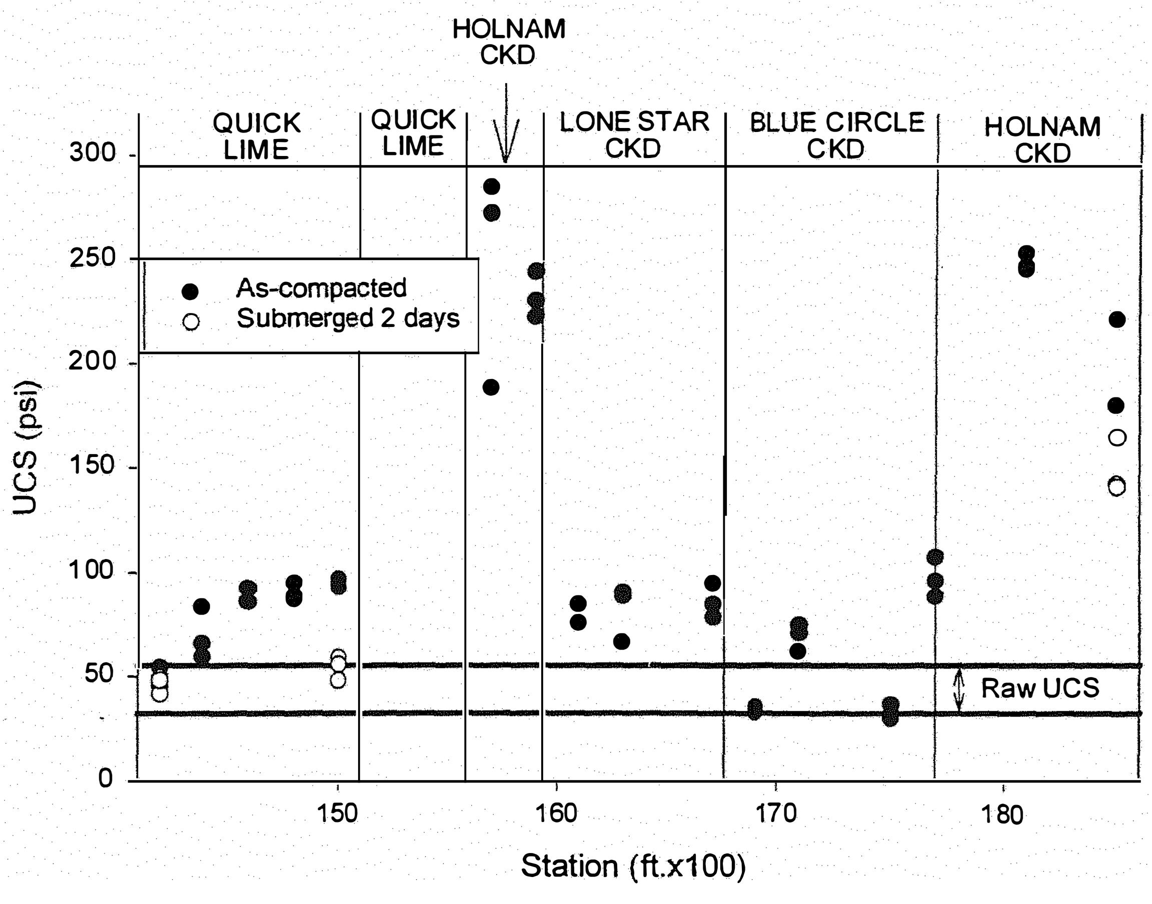


Fig. 3.6 28-Day Unconfined Compressive Strength from Harvard Minature Samples Prepared from Soil Sampled During Construction

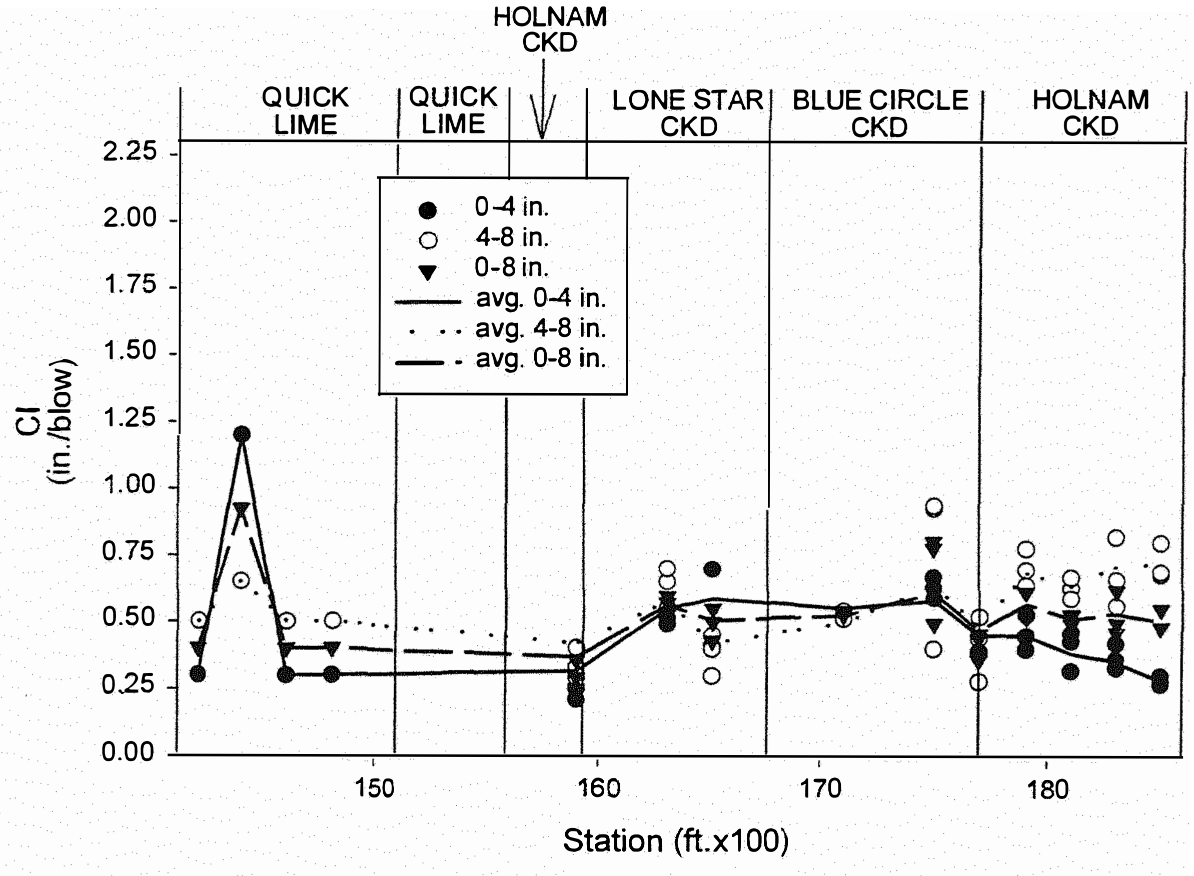


Fig. 3.7 Dynamic Cone Penetration (DCP) Test Results Obtained 28 Days After Compaction of the Treated Subbase

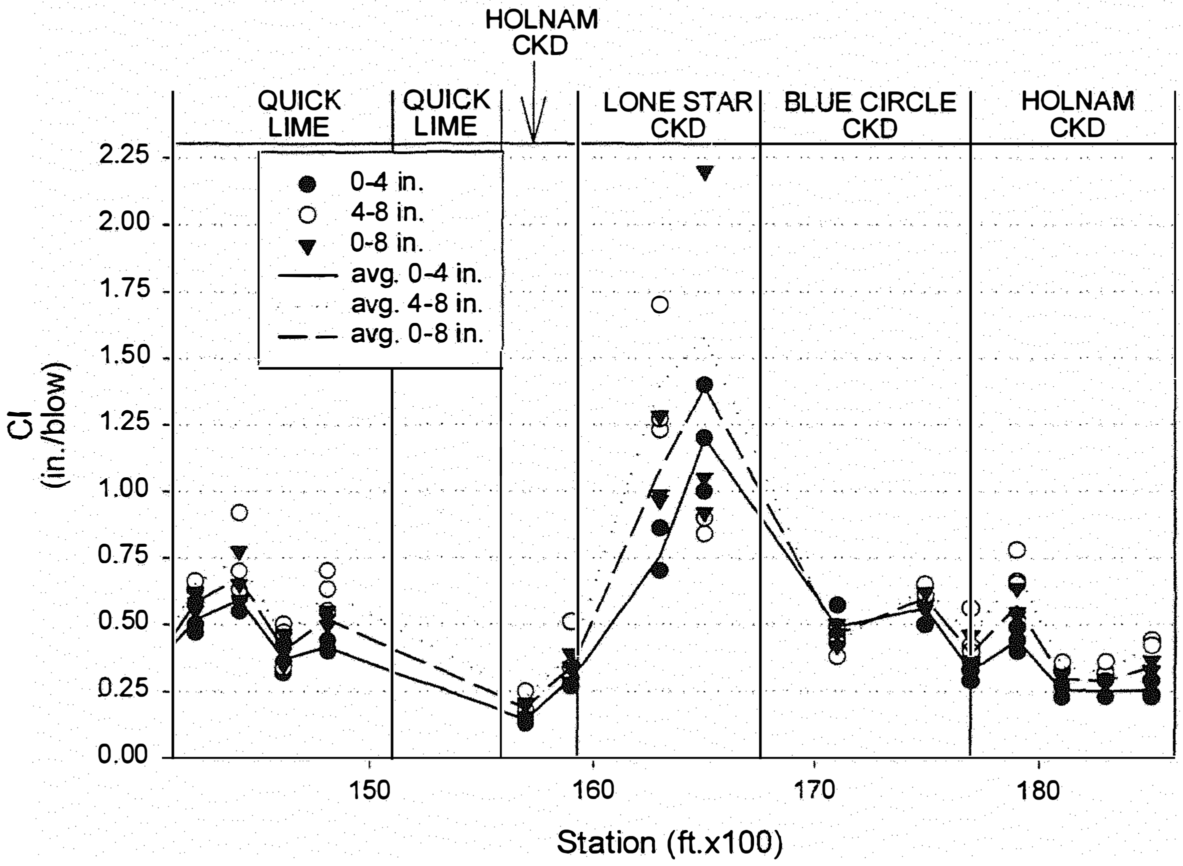


Fig. 3.8 Dynamic Cone Penetration (DCP) Test Results Obtained 56 Days After Compaction of the Treated Subbase

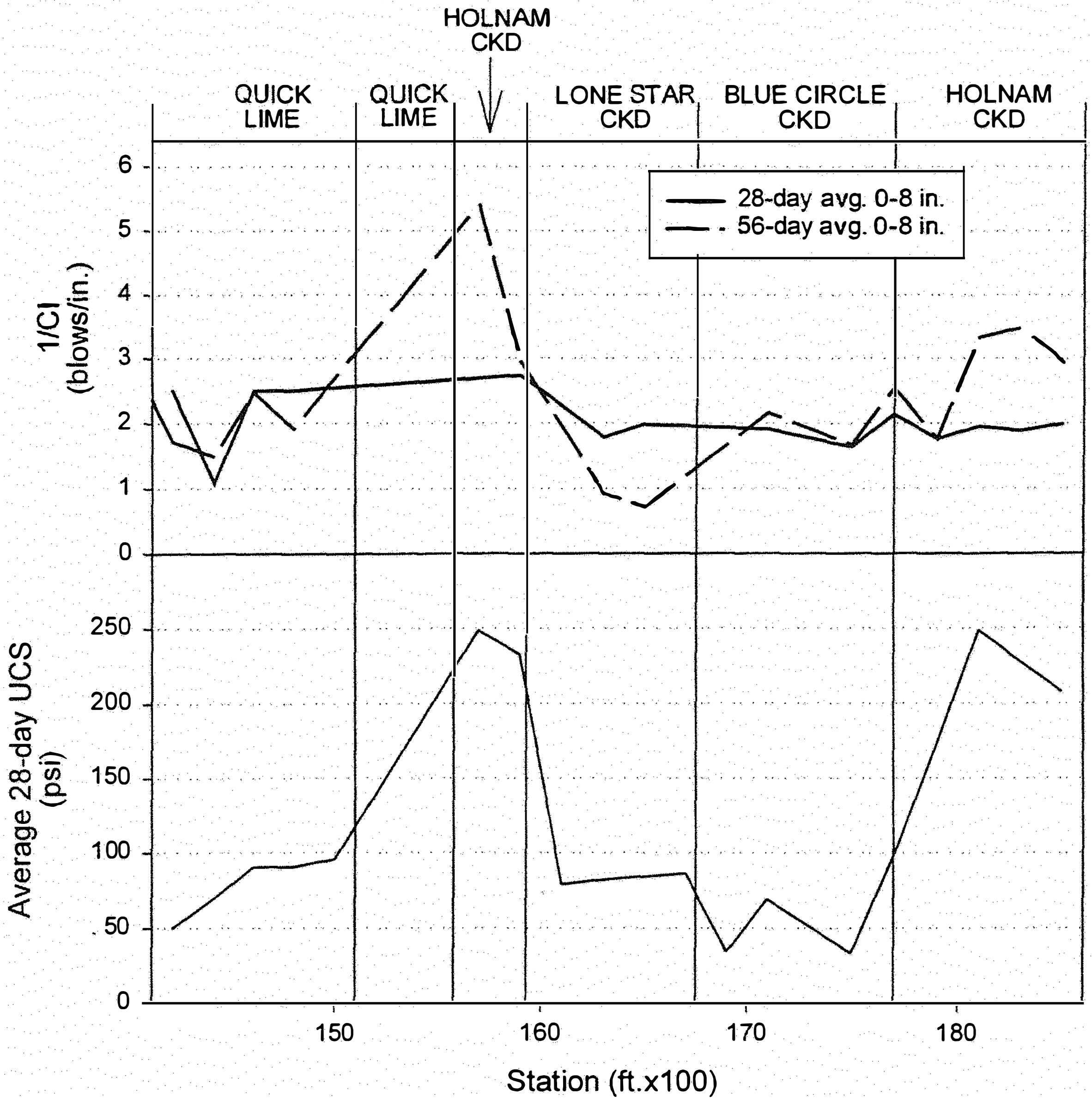


Fig. 3.9 **Comparison of Dynamic Cone Penetration (DCP) Test Results and 28-Day Unconfined Compression Strengths from Harvard Miniature Samples**

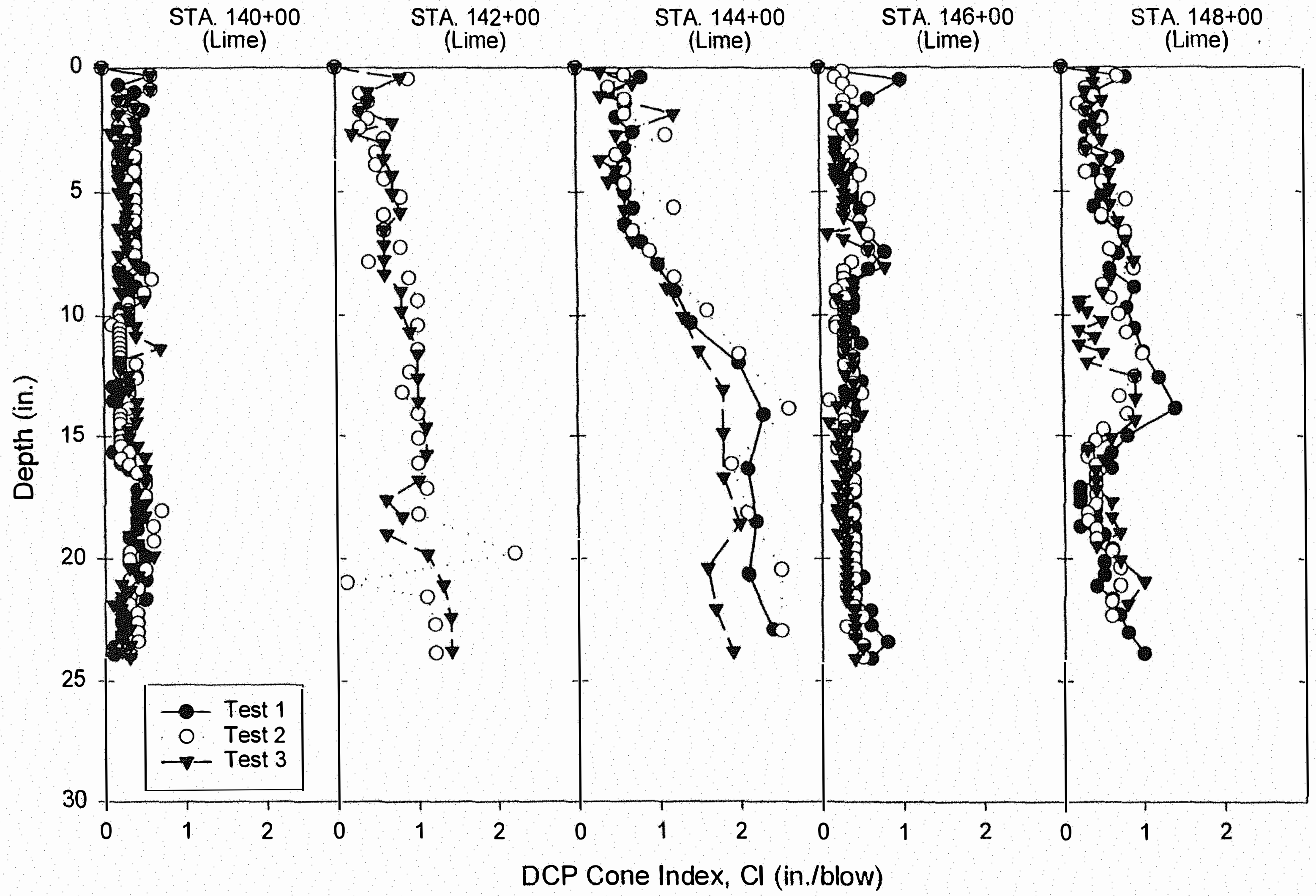


Fig. 3.10 56-Day Dynamic Cone Penetration Test Profiles for the Lime Test Section, Stations 140+00 to 148+00

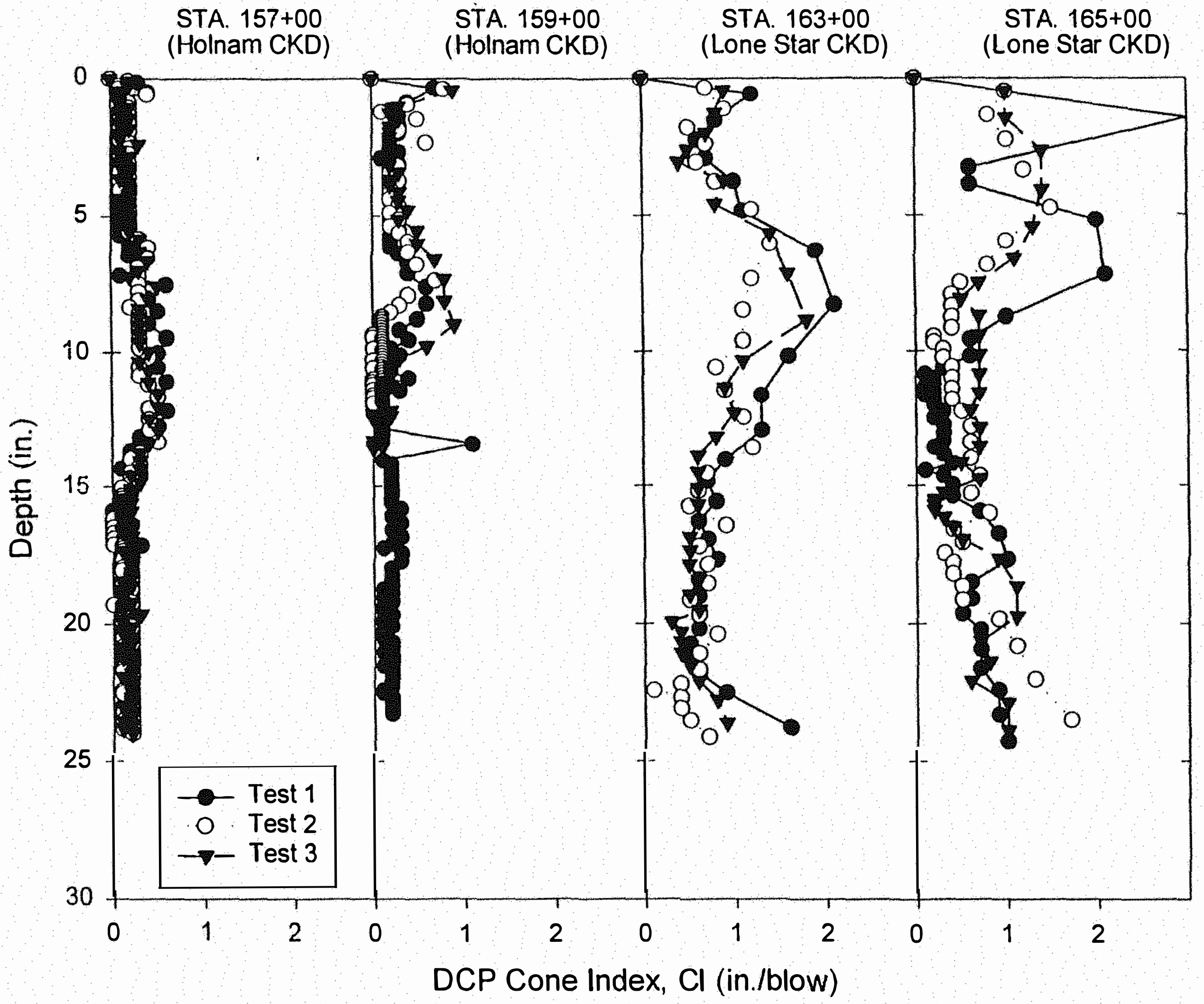


Fig. 3.11 56-Day Dynamic Cone Penetration Test Profiles for the Holnam and Lone Star Test Sections, Stations 157+00 to 165+00

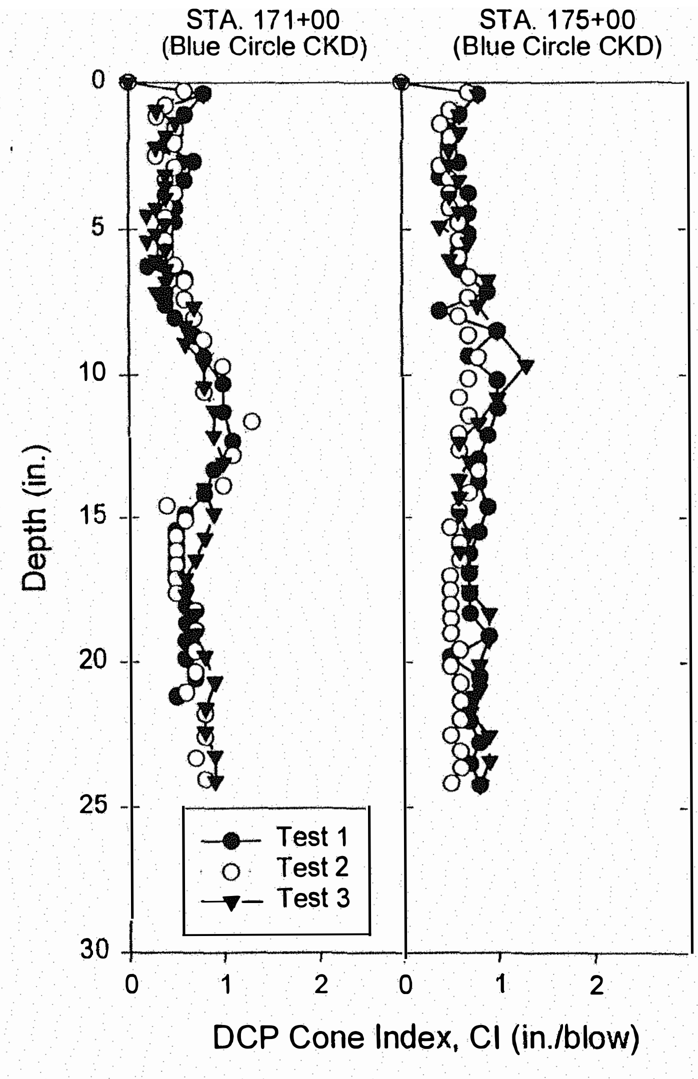


Fig. 3.12 56-Day Dynamic Cone Penetration Test Profiles for the Blue Circle Test Section, Stations 171+00 and 175+00

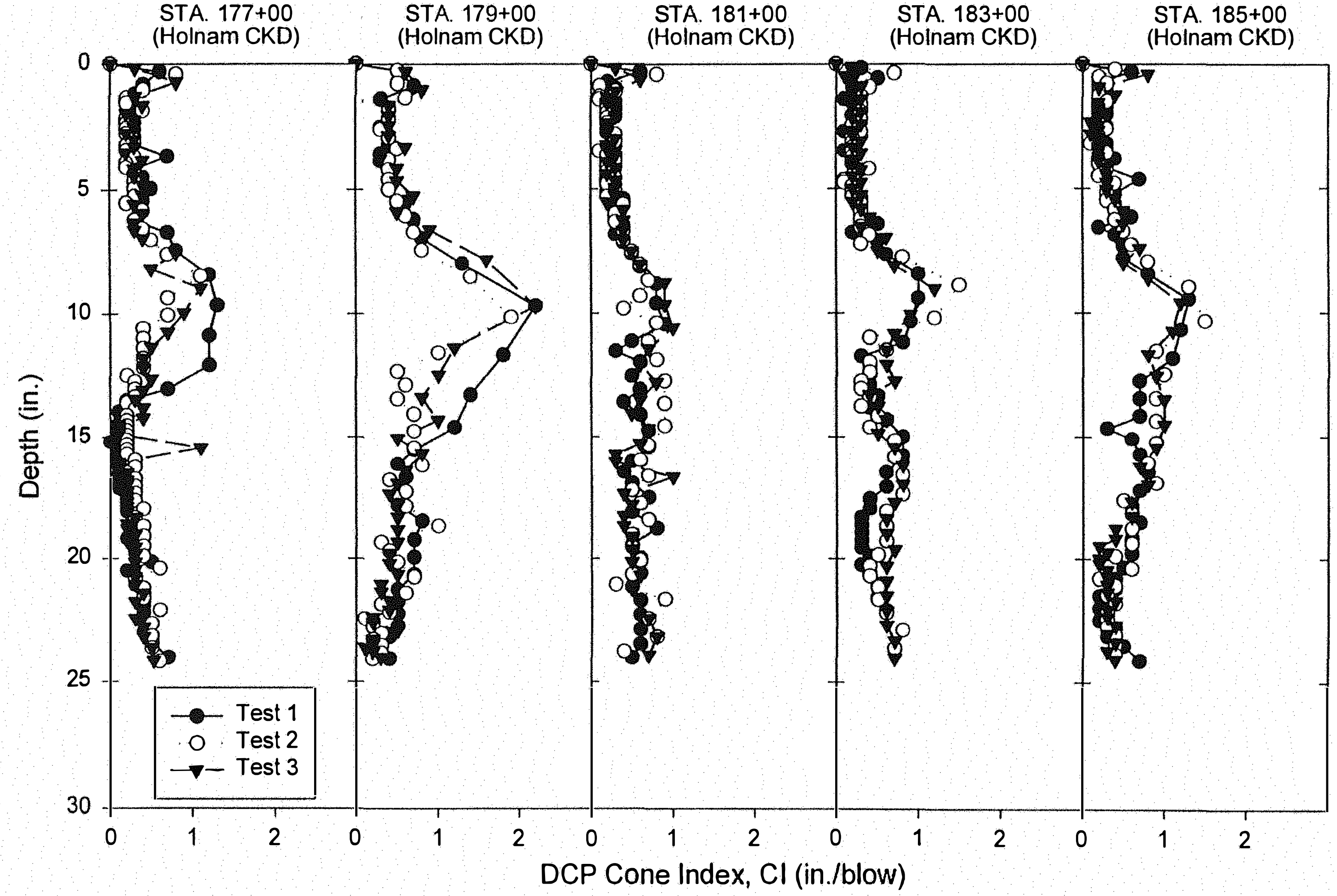


Fig. 3.13 56-Day Dynamic Cone Penetration Test Profiles for the Holnam Test Section, Stations 177+00 to 185+00

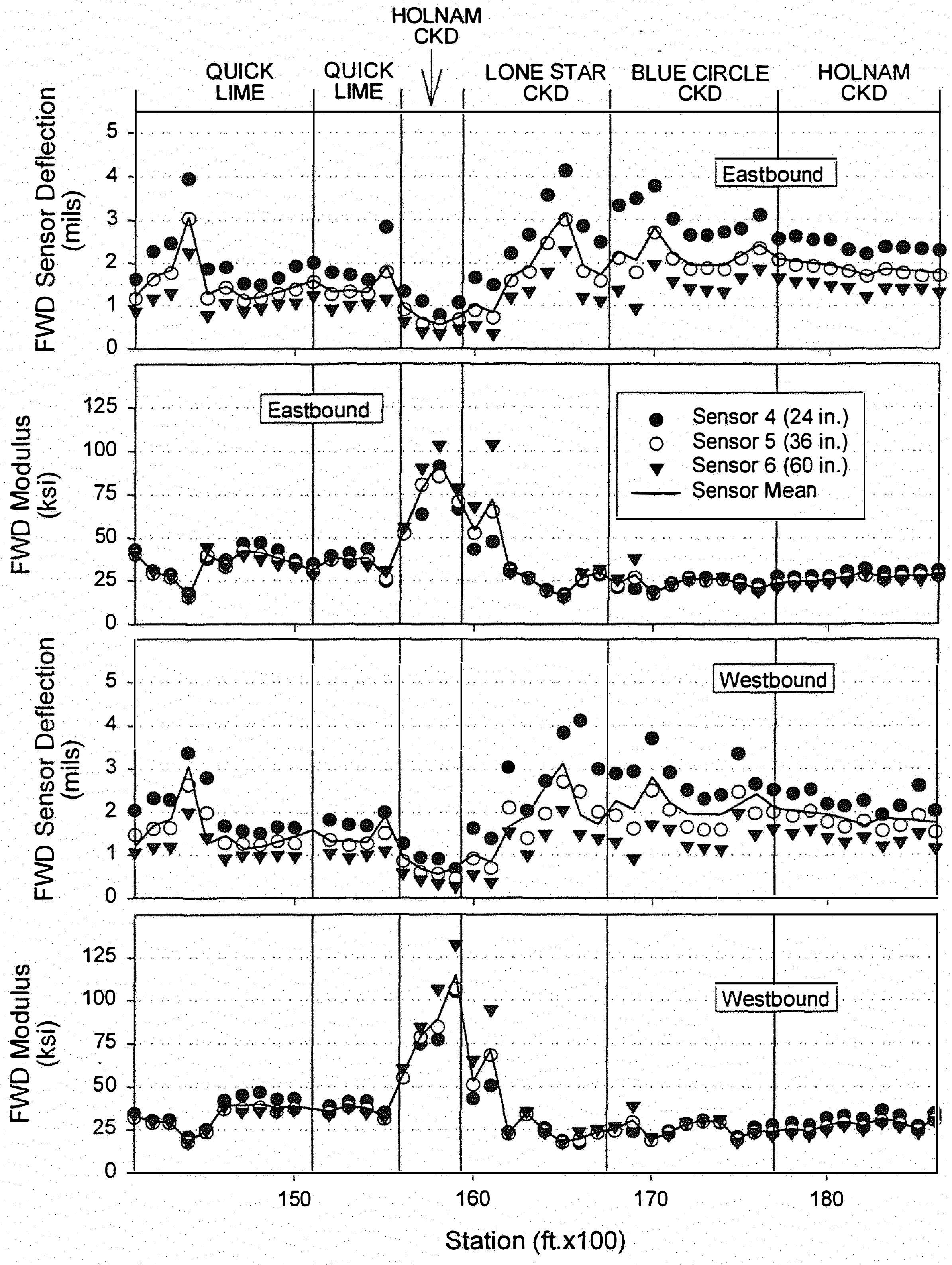


Fig. 3.14 Falling Weight Deflectometer Deflection Measurements and Calculated Composite Subbase/Subgrade Modulus Values

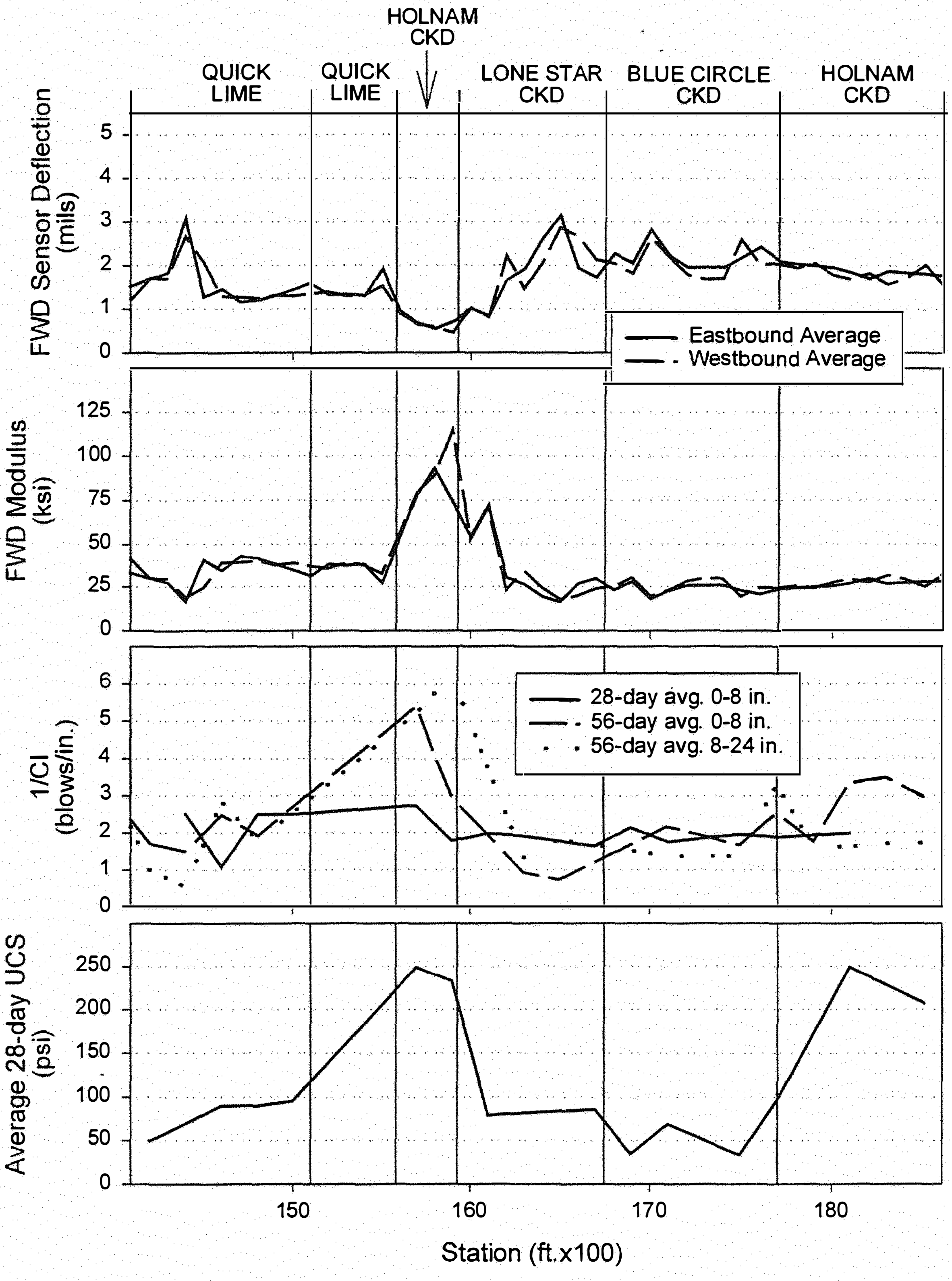


Fig. 3.15 Comparison of Falling Weight Deflectometer, Dynamic Cone Penetration and 28-Day Unconfined Compression Test Data

CHAPTER 4

LABORATORY TESTING

4.1 INTRODUCTION

Laboratory testing was conducted to compare the performance of CKD and lime under carefully controlled conditions. Tests were conducted on two different soils, taken from the test site and representative of the end-points of a broad range of possible soil compositions along the test sections. Several different laboratory tests were conducted on soil-additive mixtures to compare the performance of different additives including pH testing, Atterberg limit testing, unconfined compression tests, durability tests, and one-dimensional swell tests.

4.2 TEST SOILS

A large portion of the fill used along test sections consisted of various proportions of reworked shale and sandstone from cut sections. This weathered rock easily broke down to a soil-like consistency. Samples of weathered shale and sandstone were processed in the laboratory to pass a Number 10 sieve (2-mm). The resulting soils represent two possible extremes in soil composition at the test site. Test soil properties as determined by OU and ODOT Materials Division personnel are summarized in Table 4.1, and supporting test data are presented in Appendix D. Soil derived from processing the shale and sandstone are simply referred to as shale and sand in this report. As indicated, results obtained by OU and ODOT personnel vary slightly with regard to PI and moisture-density characteristics. These variations are likely natural and may be the result of obtaining samples from slightly different positions in the cut sections. As indicated in Table 4.1, the shale classifies as a moderately plastic clayey soil having a PI in a range of 24 to 30. The sandstone after processing classifies as poorly graded fine sand with little silt.

4.3 CKD PROPERTIES

Cement Kiln Dust (CKD) used in the laboratory study was collected in the field during construction of the test sections. Multiple samples of dusts from the same source were combined to form a composite sample. Typical compositions of CKDs from each source are shown in Table 4.2. For Blue Circle and Holnam CKDs, compositions determined at different times are provided to show variability. Generally, the variability from a given plant appears small; however, between the three sources there are considerable differences. In particular, the total calcium oxide content and Loss on Ignition (LOI) are notably different among CKD sources. Total calcium oxide includes both bound and free lime, and loss on ignition gives an indirect indication of lime available for reaction. That is, if LOI is high, generally there is more water bound in the structure of the CKD, which is driven off upon heating. If more water is present then less of the total CaO is available for reaction. This appears to explain in part the superior performance of Holnam CKD relative to the others.

The pH values presented in Table 4.2 for the CKD-shale mixtures are another indication of the greater reactivity of the Holnam CKD. On the other hand, the sand particle surfaces are much less reactive compared to clay particles in the shale; thus, sand particles consume very little lime resulting in small pH changes relative to the raw CKD values. Testing for pH was conducted using the method recommended by Eades and Grim (1966). The pH curves for each soil and the various additives are shown in Fig. 4.1, and pH data is tabulated in Tables E-1 and E-2 of Appendix E. Another parameter of significance may be the Hydration Modulus (shown in Table 4.2), which according to Kamon and Nontananandh (1991) is an indication of the intrinsic self-cementing characteristics of a stabilizer.

4.4 UNCONFINED COMPRESSION TEST RESULTS FOR DIFFERENT ADDITIVES

Unconfined compressive strength was used as one measure to evaluate differences in the stabilizing effectiveness of additives. All samples were prepared in similar fashion, which involved mixing dry ingredients (minus #10 sieve soil and additive) followed by mixing with the water. For CKD, samples were compacted immediately after mixing; however, samples prepared with lime were covered, allowed to sit for 48 hours and re-mixed prior to compaction. This was meant to simulate the process used in the field. In addition, it was discovered that if lime-treated samples were compacted immediately after mixing, the samples would swell and crack as the lime hydrated. Lime-treated samples were mixed with 4% by weight of pulverized granular (pebble) quick lime. The lime was pulverized to pass a #10 sieve to facilitate uniform mixing with the soil. CKD-treated samples were mixed with 15% CKD by dry weight of soil. Selected additive percentages were the same as those used by the contractor during field construction. Samples were compacted in five layers using a Harvard Miniature device that was calibrated on raw shale to replicate the standard Proctor dry unit weight at the OMC. Moisture-density curves for shale and sandstone are provided in Appendix D. Test samples were nominally 2.8 inches high by 1.4 inches in diameter. The target molding moisture content was 20%, which represents the OMC + 4%. This moisture content was selected because this was the target during construction of the test sections discussed in Chapter 3. The additional moisture provides water of hydration for the stabilizing additives. For each evaluation of Unconfined Compressive Strength (UCS), at least three specimens were tested to account for statistical variation.

Samples were moist cured for 3, 7, 14, 28, and 90 days following compaction. After curing, samples were subjected to unconfined compression loading to failure under strain controlled loading with a strain rate of 1% per minute in general accordance with ASTM

Standard D 2166 "Standard Method for Unconfined Compressive Strength of Cohesive Soil" (ASTM 1998). Results for the four different additives are presented in Figs. 4.2 for the two soil types. Tabulated values of average UCS are presented in Table 4.3, and detailed test data are presented in Appendix E. Fig. 4.3 contains typical stress-strain data obtained from UCT samples. Noteworthy aspects of the data presented in Figs. 4.2 and 4.3 include:

1) Holnam CKD is clearly superior to the other CKDs and Quick Lime with regard to the strength imparted to the test soils.
2) In shale, Lone Star CKD outperforms Blue Circle CKD and Quick Lime, and Blue Circle CKD outperforms Quick Lime except at 90 days.
3) In sand, the Lone Star and Blue Circle CKD perform similarly.
4) In sand, Quick Lime has a very small affect as expected since the framework silicates that compose sand are relatively chemically inactive and lime has no intrinsic cementitious properties. The small increase in strength that did occur probably resulted from lime reactions with the small amount of fines present.
5) In sand, the intrinsic cementitious properties of CKD are clearly demonstrated.
6) The strength gain over time exhibited by CKD-treated soil is similar to that exhibited by aggregates and soil mixed with Portland Cement. Most of the strength gain occurs by 7 to 14 days followed by little change or a gradual increase over time. For Lone Star and Blue Circle CKD in shale, there appears to be a slight decrease in UCS after about 14 days. The reason for this slight decrease is unknown; however, the magnitude of the decrease is small and appears to be within the scatter of the data.
7) The strength gain over time exhibited by lime-treated soil is gradual, consistent with the slowly occurring pozzolanic reactions that occur.

8) In all cases, the treated soils were stronger than untreated soils except for very early during curing of lime-treated soils.

9) Stress-strain data indicate that the treated soils are much more brittle than the untreated soil. Generally, CKD-treated soils are more brittle than lime-treated soils.

In summary, based on the UCS data, the performance of CKD in shale was comparable to lime in the case of Lone Star and Blue Circle CKD, while Holnam CKD was far superior. In the non-plastic sand, CKD was far superior to lime as expected. To judge the degree of effectiveness based on UCS, ASTM Standard D 4609 ("Standard Guide for Evaluating the Effectiveness of Chemicals for Soil Stabilization") indicates that if the UCS of soil increases by 50 psi due to an additive, then the additive can be judged effective. Using the ASTM criteria, all of the CKDs are clearly effective for sand, while lime falls short for sand as expected. For the shale, Holnam and Lone Star CKD are clearly effective, and Blue Circle CKD at 7 and 14 days of curing just meets the criteria but falls slightly below after 90 days. Lime falls short of the 50-psi criteria in shale until 90 days where it meets the criteria. Generally, the Quick Lime shows a gradually increasing trend in UCS, while the UCS of CKD-treated soil increases rapidly over the first 7 to 14 days and then more slowly or levels off depending on the dust. The data for the Blue Circle and Lone Star CKD-treated shale exhibit a slight decreasing trend but this appears to be within the scatter of the data.

4.5 ATTERBERG LIMIT TEST RESULTS

To assess the effectiveness of additives for reducing plasticity, liquid and plastic limit tests were conducted in general accordance with Method A of ASTM Standard D 4318 "Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils." Limits were determined by the multi-point method starting with a moist specimen and drying to reduce moisture content during the test. The liquid limit (LL) and plastic limit (PL) tests were performed for the shale in two ways, using a dry curing and a moist curing process.

For dry curing, shale (passing a No. 40 sieve) and additive were mixed in appropriate proportions with water to produce a viscous liquid, and then the mix was allowed to air-dry. Following drying to the appropriate curing time, the soil was pulverized to pass a No. 40 sieve, mixed with water, and allowed to sit for about 1 day before conducting the LL and PL test. Dry-cured specimens were tested after 7, 14, 28 and 90 days of curing. As with other tests, Quick Lime and CKD were added to achieve additive contents of 4% and 15% by dry weight of soil, respectively.

Moist cured specimens were prepared similarly except that the soil-additive-water mixture was kept in an airtight container to prevent moisture loss during the entire curing period. Testing was conducted immediately after mixing and after curing times of 3, 7, 14, 28 and 90 days. Results of Atterberg limit tests on the shale are shown in Figs. 4.4 and 4.5 and Tables E-7 and E-8 of Appendix E. The following observations are made:

1) PI reduction does not occur to any significant degree in the case of dry curing and in fact the PI for shale treated with Holnam CKD and lime is noticeably higher than the natural PI of the soil after seven days of curing.
2) The PI increases to some asymptotic value during moist curing of the shale-additive mixtures. The corresponding moisture contents are larger by roughly 12% to 20% compared to the PI of the natural soil.
3) For moist curing, the behavior of Holnam CKD and lime is very similar, whereas Lone Star CKD and Blue Circle CKD exhibit similar behavior.

These results suggest that for the shale, all of the additives are relatively ineffective for PI reduction. Apparently, the chemistry of the shale-additive mixtures is such that the reaction products are hydrophilic and thus, absorb more water into the soil structure.

To further investigate this phenomena, similar Atterberg limit testing was conducted for two other soils, a clayey soil (CL) obtained near Atoka in southeastern Oklahoma, and a highly plastic clay (CH) obtained near Stroud, OK and referred to as Miller Clay. Results are shown in Figs. 4.6 to 4.9. For these tests, only the Quick Lime and Holnam CKD were used in amounts equal to 4% and 15% of the dry soil weight, respectively. As shown in Fig. 4.6, substantial reductions in PI occurred for dry-cured lime- and CKD-treated soil. The moist-cured results shown in Fig. 4.7 are less consistent and generally seem to indicate an initial PI reduction followed by an overall increase with time. At 90 days, the PI of moist-cured soils treated with both additives are similar and near to the PI of the natural soil. In the case of Miller Clay, represented by data in Figs. 4.8 and 4.9, similar and substantial PI reduction occurs during both wet and dry curing of lime- and CKD-treated soil.

In summary, it appears that the shale chemistry is such that substantial PI reduction does not occur with either lime or CKD as the additive. In soils conducive to PI modification, such as the Atoka and Miller clay, the PI modification was similar and substantial for both the Holnam CKD (15% by weight) and Quick Lime (4% by weight).

4.6 DURABILITY TESTS

Durability of treated soil was investigated by performing unconfined compression tests on samples subjected to cycles of freezing and thawing, and wetting and drying. Samples were prepared in the manner described previously. Tests were conducted using Holnam CKD with sand and shale, and Quick Lime with shale. After molding, the samples were cured for a period of seven days in the moisture chamber.

Following the seven-day curing period, durability cycles were initiated. One wet-dry cycle consisted of immersing samples in water for five hours, followed by oven-drying for a period of twenty-four hours at a temperature of 71° C. Samples that survived the durability cycles were subjected to unconfined compression testing after 0, 1, 3, 7 and 12 wet-dry cycles. The compression tests were conducted following the drying cycle so that moisture conditions would be uniform for each sample tested. While this necessarily leads to higher UCS values than testing wet, it reduces UCS variability resulting from variations in water content from sample to sample, and thus shows clearly the influence of wet-dry cycles on UCS values. The samples for zero cycles were also subjected to oven drying so that moisture conditions would be comparable to other cycles. UCT tests were conducted in triplicate to quantify statistical variability.

The same procedure was used to prepare and cure samples during the freeze–thaw testing. To achieve one freeze-thaw cycle, samples were placed in a freezer with a temperature setting of –23° C for a period of 24 hours, followed by placement in a moisture chamber with a humidity of approximately 95% for another 24 hours. As in the wet-dry durability tests, UCTs were conducted after 0, 1, 3, 7 and 12 cycles. Samples were tested at the end of the thawing period. Measurements of the weights of the samples were made after every change in the environment. This was done to calculate the change in the moisture content of the soil with the changes in temperature and moisture conditions.

Results of durability tests are presented in Fig. 4.10 and Tables E-11 to E-13 of Appendix E. Noteworthy observations include the following:

1) Shale treated with Holnam CKD exhibits increasing UCS for three cycles, beyond which samples did not survive immersion in water. Thus, cementation and pozzolanic reactions were occurring until the immersion failure. Cracks were observed in the sample after the first cycle, and these cracks worsened until samples broke up upon immersion in water.
2) Shale treated with lime survived only one wet-dry cycle and exhibited a decrease in UCS from zero to one cycle. Apparently, negligible pozzolanic activity was occurring during this one cycle to cause an increase in UCS. This is consistent with the gradual increase in strength observed during UCT testing described in Section 4.4.
3) Sand treated with Holnam CKD showed an increase in UCS over the full 12 cycles wetting and drying. This indicates that cementation and pozzolanic reactions were continuing and adverse effects of wet-dry cycles were negligible.
4) All of the samples survived 12 freeze-thaw cycles. Lime-treated shale gradually gained strength during the freeze-thaw cycles while CKD-treated shale showed a slight increase in average strength after 7 cycles. The trend of UCS values for sand treated with the CKD increased then decreased, then increased again so that after 12 cycles the UCS was slightly higher than the initial UCS. The moisture content of samples decreased significantly during freezing cycles, which may partly explain the slight increase in UCS observed near the end of the 12 cycles for some tests.

In summary, on a comparative basis the durability of shale treated with 15% Holnam CKD is at least as good or better than shale treated with 4% Quick Lime, under wetting/drying and freezing/thawing conditions. On the basis of the tests conducted, it appears that neither of the two additives produces a very durable material with regard to wetting and drying. However, it must be remembered that the testing conditions in the laboratory are extreme and not particularly representative of in situ conditions. In the field, soil is not rapidly dried to a near zero water content at the extreme temperature of 71° C. Generally, moisture content changes beneath pavements are gradual because of the encapsulating effect of the overlying pavement layers. This encapsulating effect will be enhanced if the underlying subgrade is a low permeability cohesive soil similar to the test site. Furthermore, soils under pavements are confined by adjacent soil, which will positively influence the durability of the treated subbase. Thus, while the durability tests conducted provide a good relative comparison of different additives, the results are not necessarily a good indicator of expected field performance. Furthermore, it must be remembered that the untreated soils did not survive even one cycle of wetting and drying. Thus, any resistance exhibited by the treated soil represents an improvement.

While durability tests for wetting and drying effects may be too severe, in some regards the freeze-thaw tests may not be severe enough relative to field conditions. For example, freezing and thawing conditions in the field will be more severe in cases where the subbase becomes saturated. Also, a slowly freezing subbase may be susceptible to formation of ice lenses leading to frost heave. The development of realistic durability testing techniques is needed to better predict the long-term performance of stabilized soil.

4.7 SWELL TESTS

One-dimensional swell tests were conducted to evaluate the swelling potential of treated and untreated shale. Tests were conducted in general accordance with Method-B of ASTM Standard D 4546 “Standard Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive Soils.” Samples were compacted by tamping soil into three layers within the oedometer ring. Raw shale, shale treated with 4% Quick Lime, and shale treated with 15% Holnam CKD were mixed at a moisture content of 20% and were compacted to a unit weight of approximately 106.5 pcf.

Six tests were conducted in front-loading oedometers manufactured by Soil Test. Three tests were performed on samples immediately after compaction in the oedometer ring, and three tests were conducted on samples that had been cured for 14 days in the oedometer ring within a humidity chamber. Before curing, samples were wrapped in plastic wrap to maintain moisture conditions.

Tests were conducted by placing the sample in the oedometer ring, applying a vertical stress of 0.87 psi, which is the smallest practical load for the oedometers, followed by inundation with water. This stress level was selected because it is similar to the vertical overburden stress expected at the mid-level of the treated subbase beneath the test pavement sections. Following inundation with water, vertical deformation of the specimens was monitored for five to nine days depending on the rate of deformation.

Swell test results are presented in Fig. 4.11 and Tables E-14 and E-15 of Appendix E. The results show the following:

1) For the samples that were tested immediately after compaction, the maximum amount of vertical swell for shale treated with Holnam CKD and Quick Lime was similar.
2) The amount of swell exhibited by treated shale was about a third of the swell measured for the untreated shale for samples tested immediately after compaction. This can be attributed to the cation exchange and compression of the diffuse-double layer surrounding the clay particles. Compression of the diffuse-double layer results when for example, divalent Ca^{+2} ions replace monovalent Na^{+} ions.

3) After curing for 14 days, the Holnam CKD-treated shale showed negligible swelling tendency, probably because of the extensive cementation that had occurred.
4) Lime-treated shale after 14 days of curing shows less tendency to swell as compared to tests with no curing. This can be attributed to the pozzolanic activity that occurs with time.
5) The raw shale showed less tendency to swell after 14 days of curing, which suggests that thixotropic hardening of the soil occurred with time.

To summarize, swelling tendency of the shale was greatly reduced by the cementing action of the Holnam CKD. Lime performed similarly to Holnam CKD where samples were not allowed to cure prior to testing; however, after 14 days of curing the Quick Lime proved much less effective than CKD. It is likely that swelling tendency of lime-treated soil would improve even more with time. In this regard, test results indicate that Holnam CKD is clearly better than lime. Not only does the CKD have an immediate positive effect on swelling behavior due to cation replacement, but also, the intrinsic cementitious properties of the CKD continue to rapidly reduce the swelling potential.

4.8 CALIFORNIA BEARING RATIO TESTS

California Bearing Ratio (CBR) tests were conducted on treated and untreated shale by the Materials Division at ODOT in accordance with AASHTO Procedure T-193. Soil specimens were sealed and cured for 7 days and then immersed in water for 96 hours before punching. The test results are presented in Table 4.4 and Fig. 4.12. The results indicate that all of the additives caused a substantial improvement in CBR. Quick Lime performed best followed closely by the Holnam CKD, then Lone Star and Blue Circle.

4.9 SCANNING ELECTRON MICROSCOPY

Selected scanning electron micrographs are shown in Figs. F-1 to F-7 of Appendix F for raw shale and sand (sand stone), raw CKD and Quick Lime, raw CKD and Quick Lime after mixing with water and curing, and additive-soil mixes after various curing times. While qualitative in nature, these pictures clearly show reaction products that result from additive-water and additive-soil-water reactions. Of particular interest are Figs. F-4, F-5, F-6, and F-7 where the reaction products are clearly seen as compared to the raw soils in Fig. F-1.

Table 4.1 Test Soil Characteristics

Soil Property	Shale (ODOT)	Shale (OU)	Sand (OU)
Specific Gravity, G_s	2.84	2.83	2.66
% passing 4.75 mm	100	100	100
% passing 0.075 mm	96	94	9
% passing 0.002 mm	49	45	7
D_{10} (mm), D_{60} (mm)	---	---	0.078, 0.19
Coeff. of Curvature, C_c	---	---	1.3
Coeff. of Uniformity, C_u	---	---	2.4
Liquid Limit, LL (%)	48	45	NP
Plasticity Index, PI (%)	30	24	NP
Activity, A	0.61	0.53	---
USCS Classification	CL	CL	SP-SM
AASHTO Classification	A-7-6	A-7-6	A-3
Standard Optimum Moisture Content (%)	18.9	16.0	16.5
Standard Maximum Dry Unit Weight, γ_{dmax} (pcf)	106.4	106.5	107.6
Unconfined Compressive Strength, UCS (psi)^1	---	47	2
California Bearing Ratio, CBR (%)^2	3.0	---	---
pH	---	7.54	5.40
Organic Content (%)	---	1.07	0.00
Sulfate Content (%)	---	0.10	---

__Notes:__ 1-UCS at OMC, 2-Average of CBR for top and bottom of sample

Table 4.2 CKD Chemical Data

Provided by CKD Suppliers[1]					
Additive Type	Lone Star CKD	Blue Circle CKD	Blue Circle CKD	Holnam CKD	Holnam CKD
Approximate Date Tested	8/8/97	8/12/97	2/26/98		2/20/98
Silicon Dioxide, SiO_2 (%)	11.9	13.8	15.3	15.1	16.0
Aluminum Oxide, Al_2O_3 (%)	4.7	4.1	4.7	3.9	3.6
Iron Oxide, Fe_2O_3 (%)	1.8	1.5	1.7	2.0	2.3
Total Calcium Oxide, CaO (%)	42.5	44.1	46.3	48.4	52.8
Magnesium Oxide, MgO (%)	1.4	1.4	1.4	1.4	2.2
Sulfur Trioxide, SO_3 (%)	7.3	3.0	2.0	4.5	6.0
Sodium Oxide, Na_2O (%)	---	0.4	0.2	0.2	0.3
Potassium Oxide, K_2O (%)	---	1.6	1.7	2.5	3.5
Loss on Ignition (%)	25.8	29.1	27.9	22.1	---
Hydration Modulus, $CaO/(Al_2O_3+SiO_2+Fe_2O_3)$	2.3	2.3	2.1	2.3	2.4
Determined by OU[2] and Independent Laboratory[3]					
Loss on ignition (%)	24.0	---	27.8	---	17.5
pH (Pure CKD + H_20)	12.65	---	12.48	---	12.52
pH (15% CKD + 85% Shale + H_20)	11.76	---	11.72	---	12.23
pH (15% CKD + 85% Sand + H_20)	12.33	---	12.27	---	12.48

Notes: 1-Oxides determined by x-ray fluorescence, 2-pH by OU personnel, 3-Loss on Ignition by QuanTEM Laboratories, LLC.

Table 4.3 Average UCS Values from Unconfined Compression Tests on Raw and Treated Soil

	Unconfined Compression Strength, UCS (psi) for Different Curing Periods				
	3 days	7 days	14 days	28 days	90 days
	Shale				
Raw Soil	---	49	---	---	45
Granular Quick Lime	53	57	62	77	101
Holnam CKD	147	247	226	255	295
Lone Star CKD	97	126	157	144	135
Blue Circle CKD	85	109	104	104	85
	Sand				
Raw Soil	---	1.5	---	2.0	2.5
Granular Quick Lime	8	12	15	18	24
Holnam CKD	38	123	236	233	340
Lone Star CKD	44	70	103	106	136
Blue Circle CKD	42	71	94	115	167

Table 4.4 CBR Data

	Top of Sample				Bottom of Sample				Avg. Top + Bottom
	Trial 1	Trial 2	Trial 3	Avg.	Trial 1	Trial 2	Trial 3	Avg.	
Raw Shale									
Moisture Content (%)	25.7	---	---	**25.7**	21.5	---	---	**21.5**	**23.6**
Dry Density (pcf)	101.3	---	---	**101.3**	104.1	---	---	**104.1**	**102.7**
CBR (%)	1.9	---	---	**1.9**	4.0	---	---	**4.0**	**3.0**
Shale + 4% Quick Lime									
Moisture Content (%)	28.1	---	---	**28.1**	23.3	---	---	**23.3**	**25.7**
Dry Density (pcf)	94.2	---	---	**94.2**	97.3	---	---	**97.3**	**95.8**
CBR (%)	41.6	---	---	**41.6**	27.7	---	---	**27.7**	**34.7**
Shale + 15% Lone Star CKD									
Moisture Content (%)	25.6	26.3	21.5	**24.5**	24.1	26.6	25.7	**25.5**	**25.0**
Dry Density (pcf)	93.3	89.5	97.3	**93.4**	94.1	89.6	93.4	**92.4**	**92.9**
CBR (%)	24.5	24.3	24.5	**24.4**	19.8	16.0	19.9	**18.6**	**21.5**
Shale + 15% Blue Circle CKD									
Moisture Content (%)	33.7	19.8	30.0	**27.8**	26.6	26.6	26.6	**26.6**	**27.2**
Dry Density (pcf)	83.0	94.2	88.3	**88.5**	87.1	88.5	90.1	**88.5**	**88.5**
CBR (%)	10.4	11.3	17.5	**13.1**	10.8	12.6	15.8	**13.1**	**13.1**
Shale + 15% Holnam CKD									
Moisture Content (%)	25.6	33.2	27.5	**28.7**	26.6	26.6	26.6	**26.6**	**27.7**
Dry Density (pcf)	90.5	82.2	86.1	**86.3**	89.1	85.9	86.9	**87.3**	**86.8**
CBR (%)	44.1	19.7	31.9	**31.9**	42.0	19.1	31.8	**31.0**	**31.4**

Notes: Moisture content and dry density correspond to condition immediately before punching.

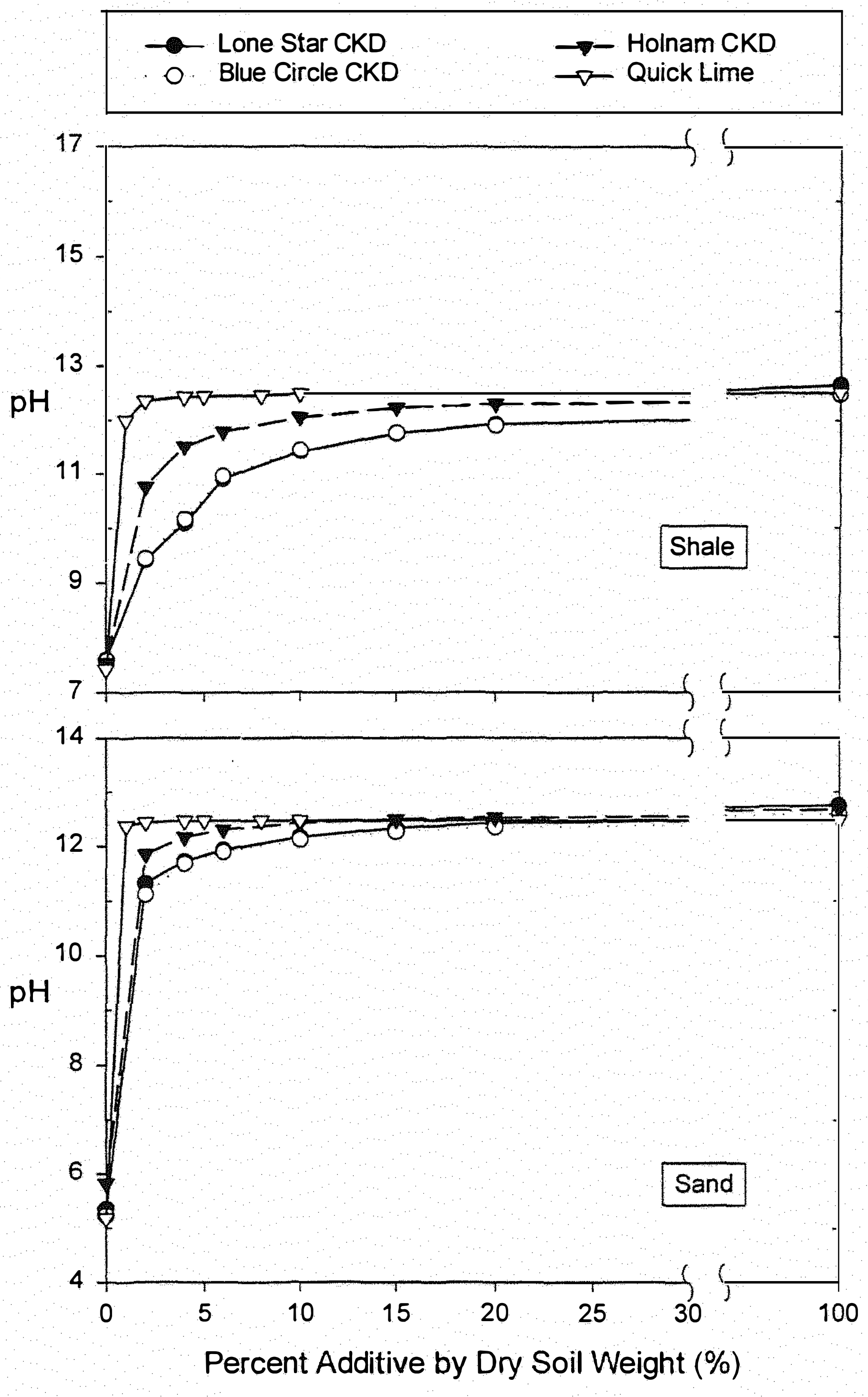


Fig. 4.1 pH versus Additive Content for Shale and Sand

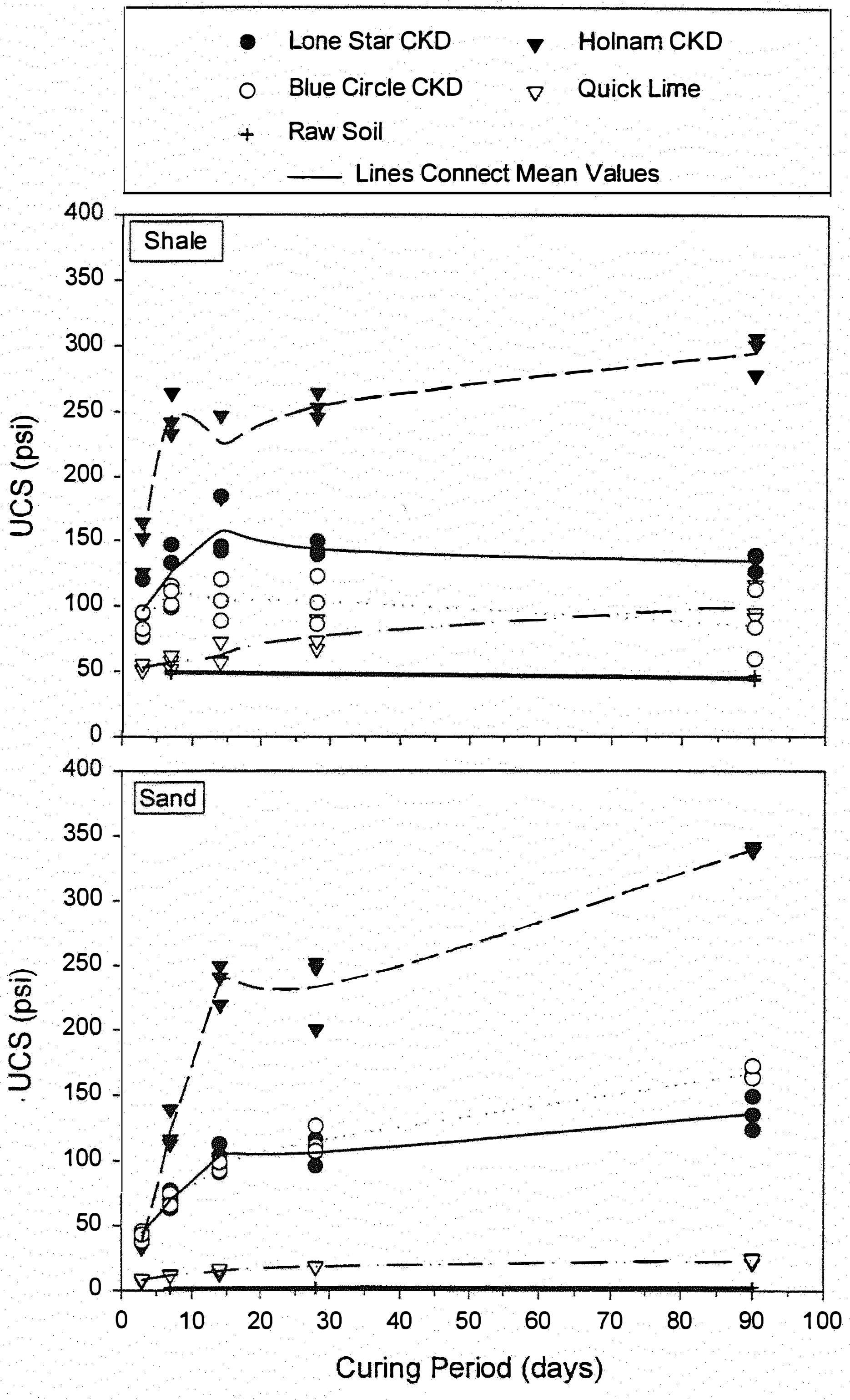


Fig. 4.2 Unconfined Compression Strength versus Curing Period for Different Additives

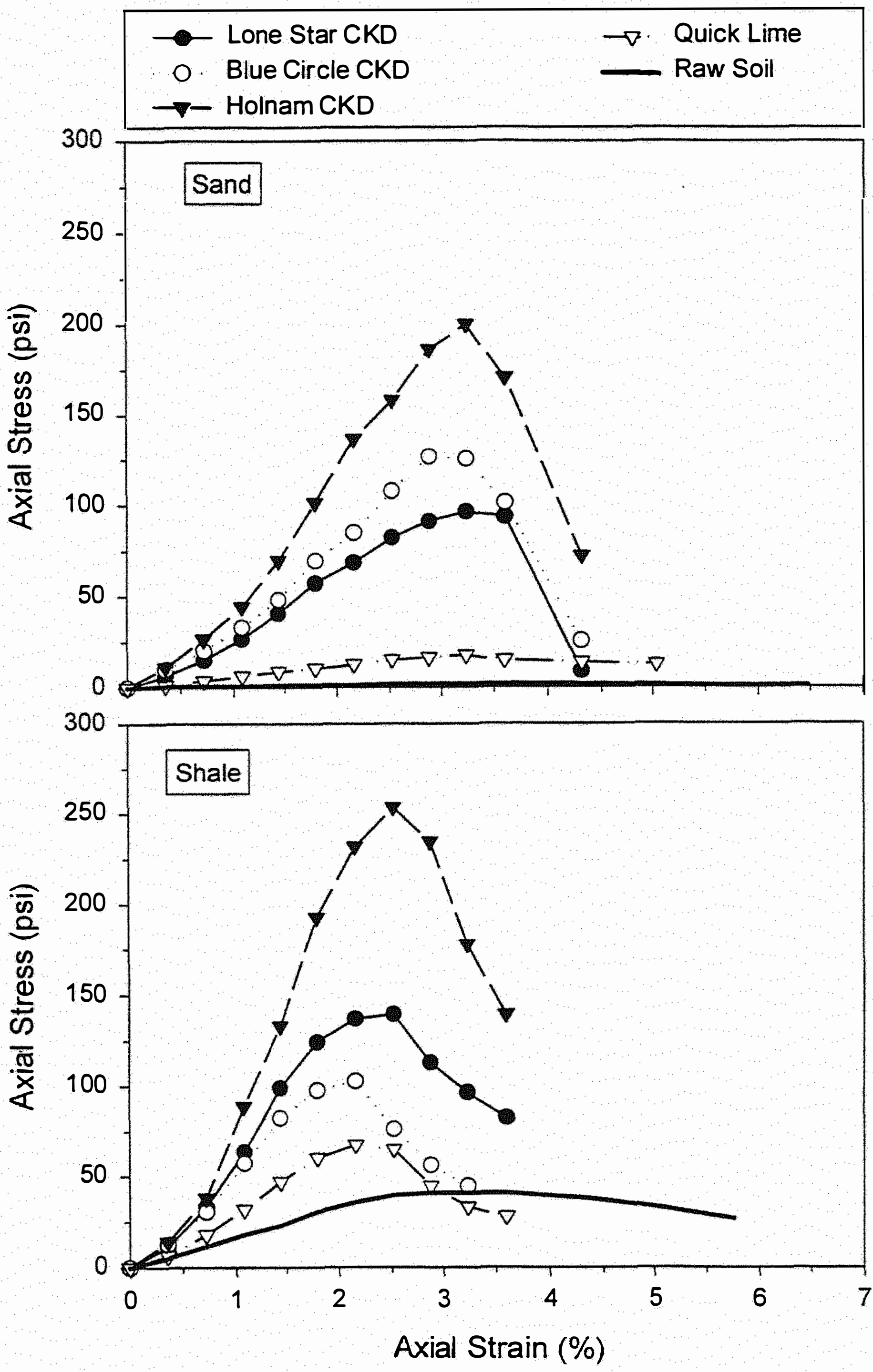


Fig. 4.3 Typical Stress-Strain Data from Unconfined Compression Tests (28-Day)

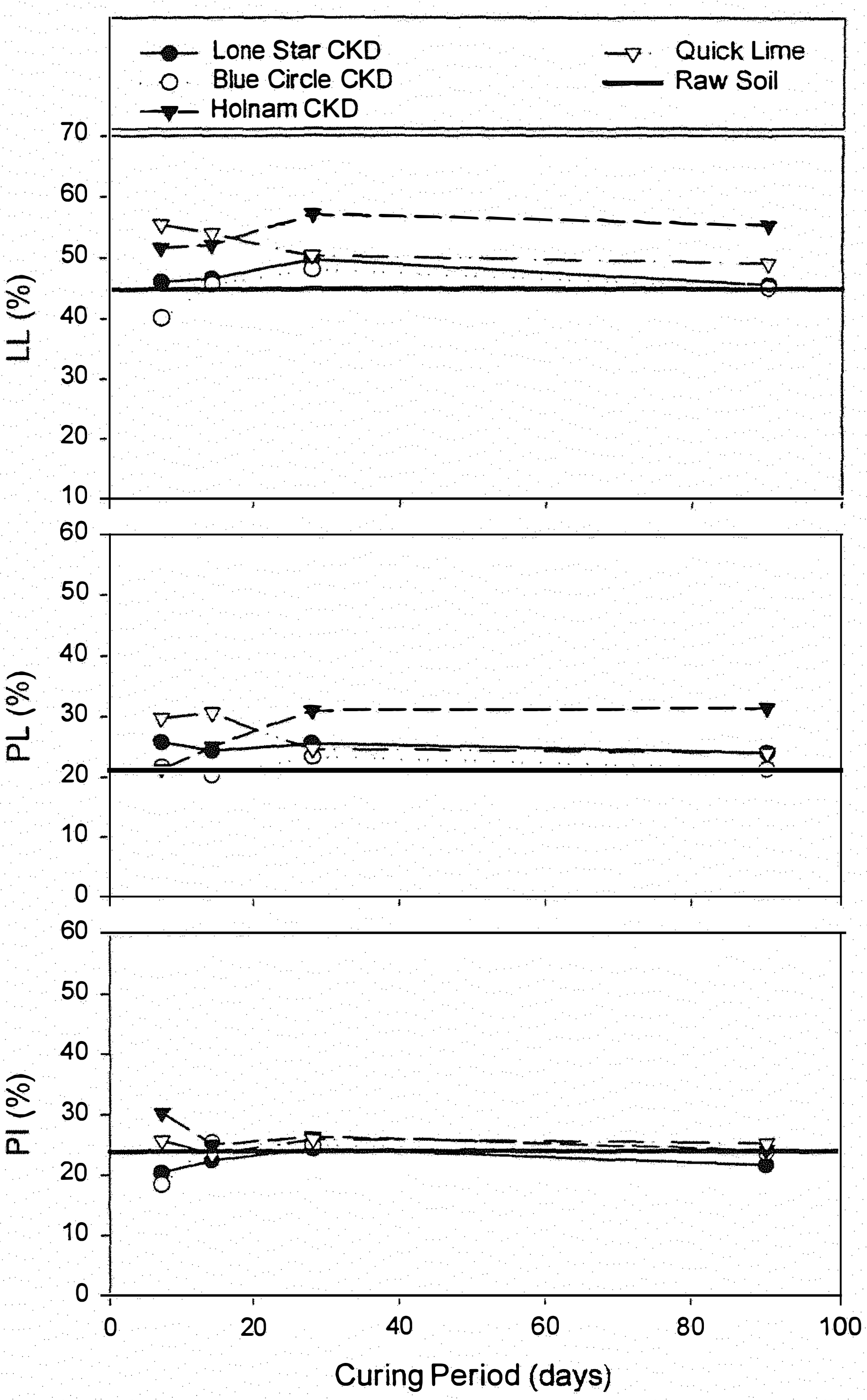


Fig. 4.4 Atterberg Limit Test Results on Dry-Cured Shale and Shale-Additive Mixtures

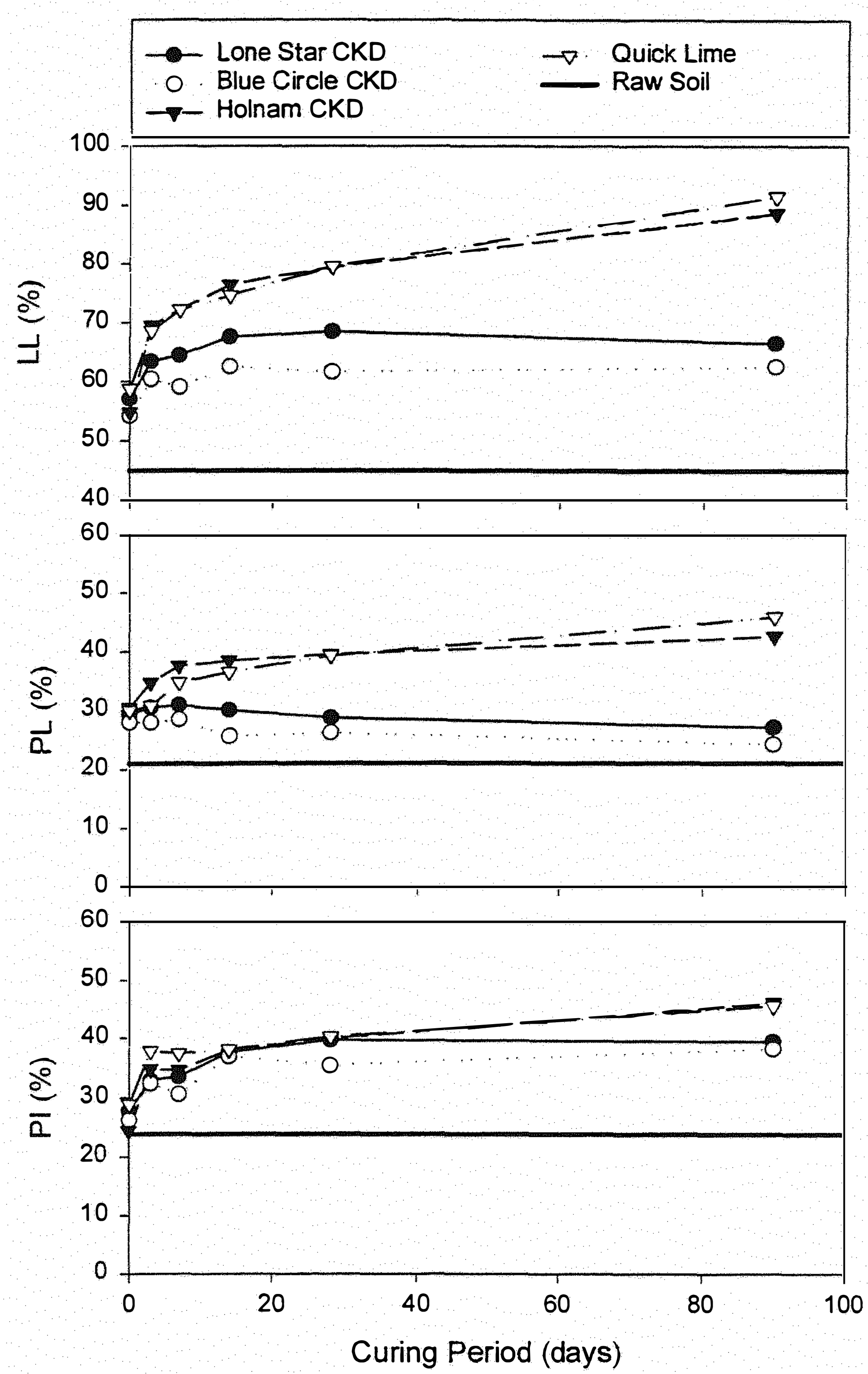


Fig. 4.5 Atterberg Limit Test Results on Moist-Cured Shale and Shale-Additive Mixtures

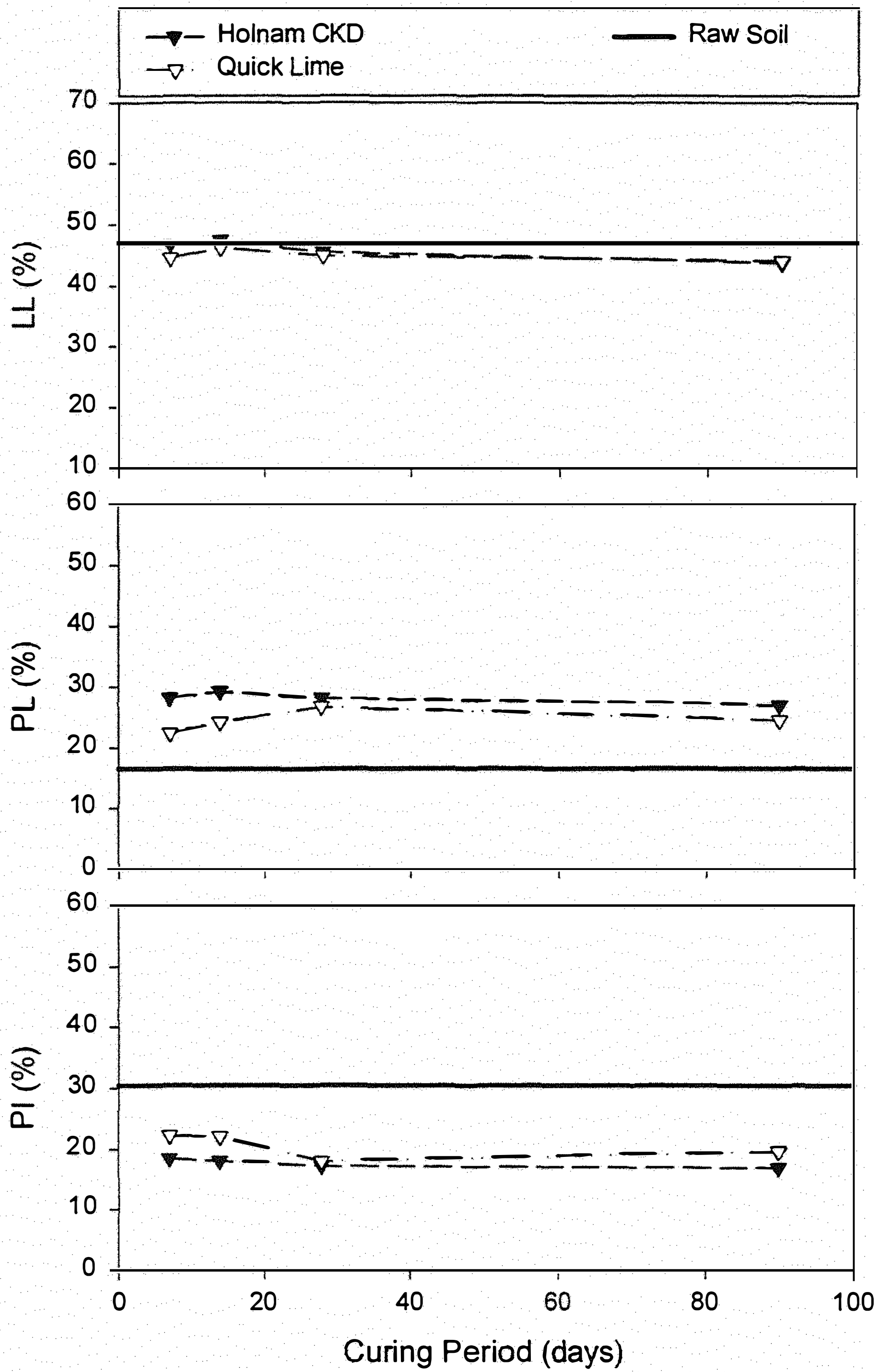


Fig. 4.6 Atterberg Limit Test Results on Dry-Cured Atoka Clay and Clay-Additive Mixtures

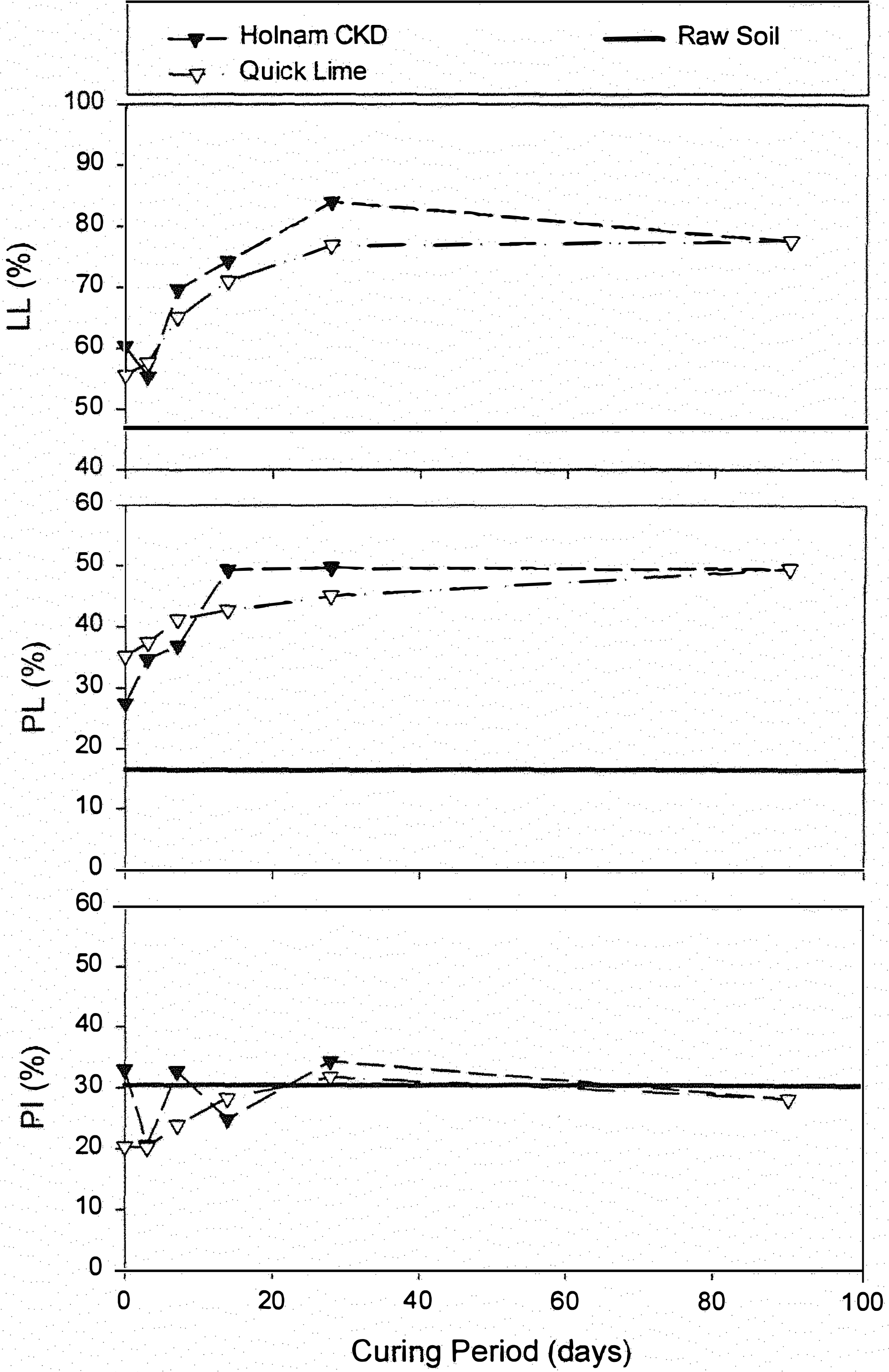


Fig. 4.7 Atterberg Limit Test Results on Moist-Cured Atoka Clay and Clay-Additive Mixtures

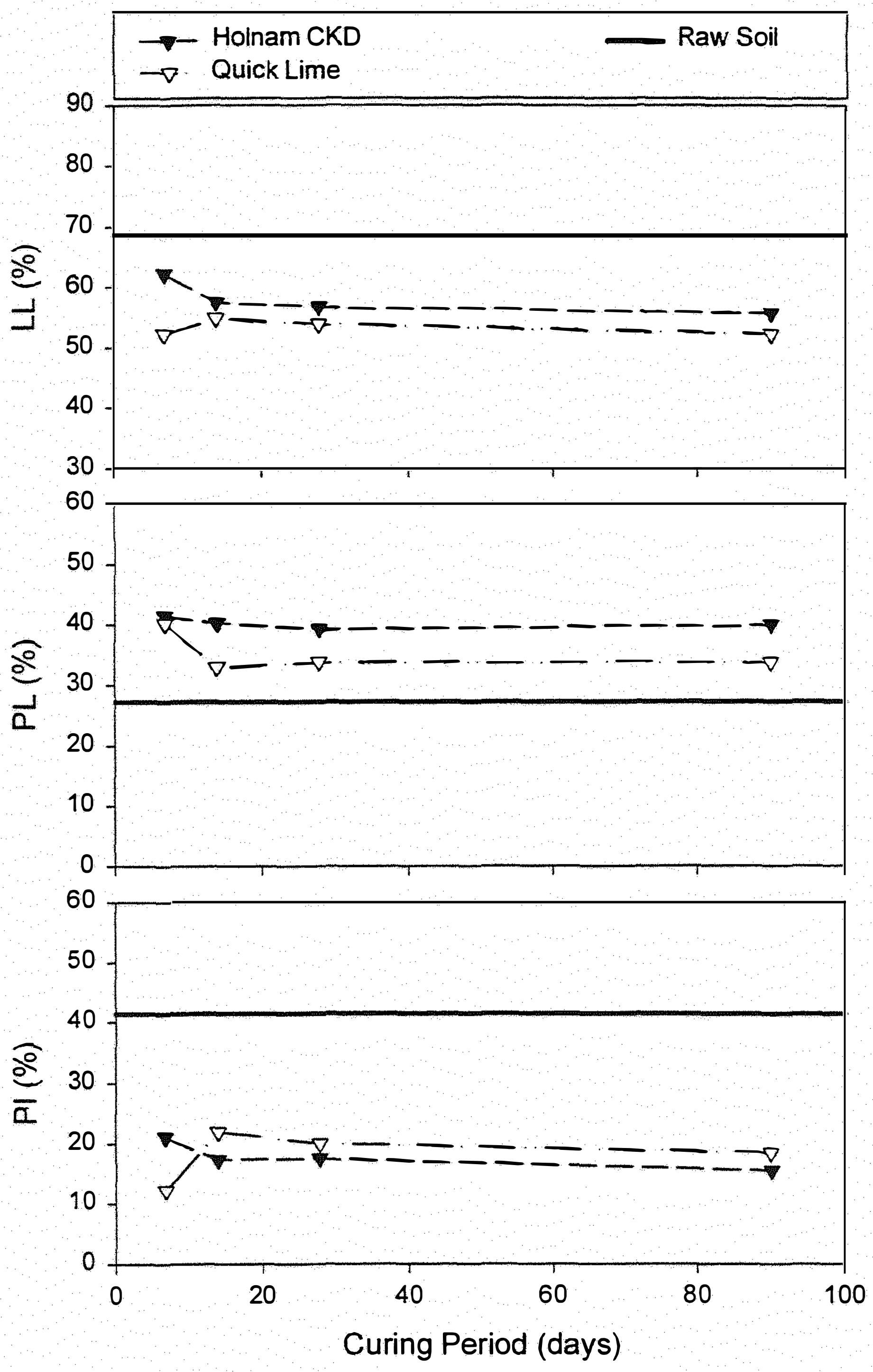


Fig. 4.8 Atterberg Limit Test Results on Dry-Cured Miller Clay and Clay-Additive Mixtures

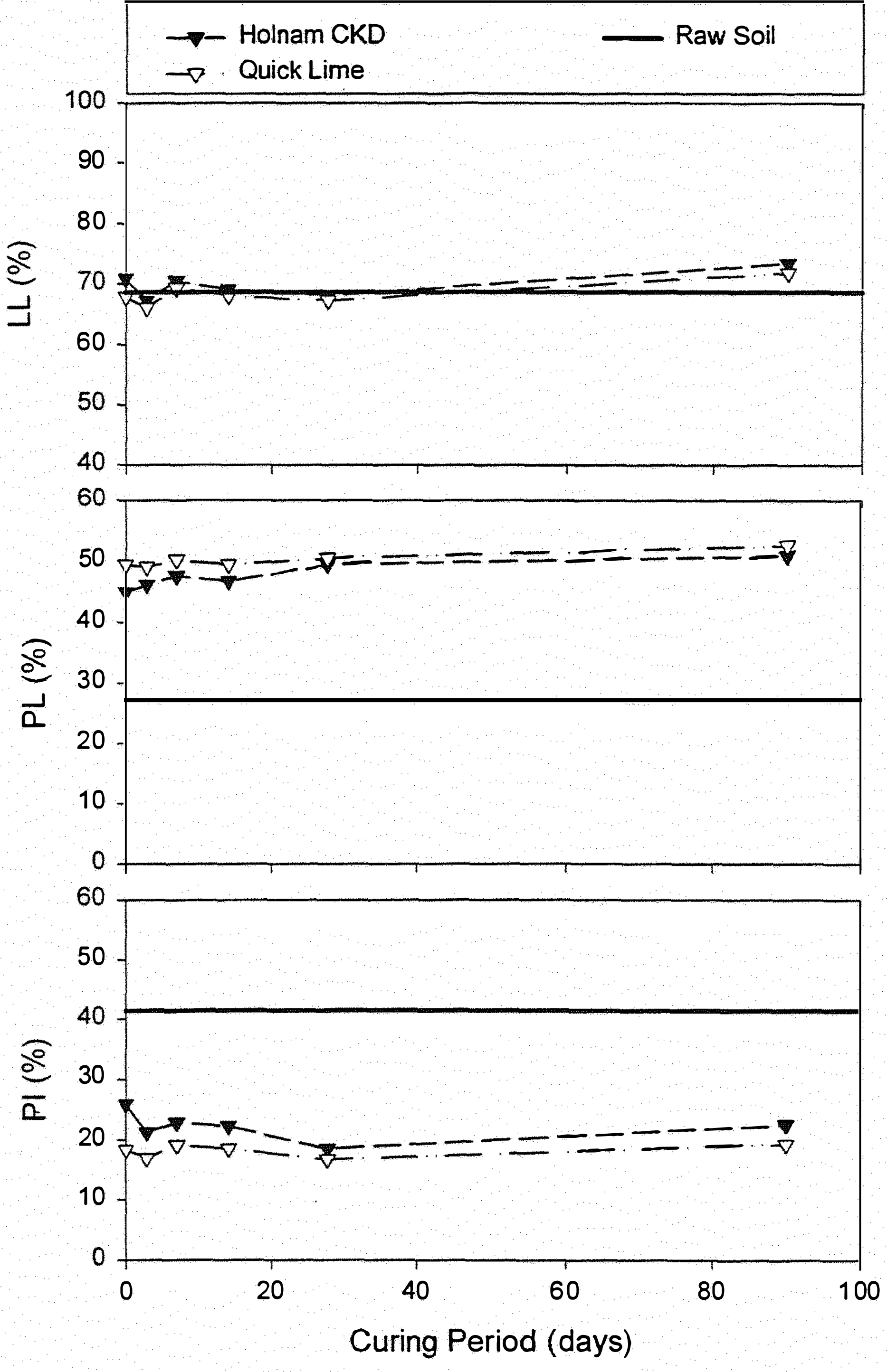


Fig. 4.9 Atterberg Limit Test Results on Moist-Cured Miller Clay and Clay-Additive Mixtures

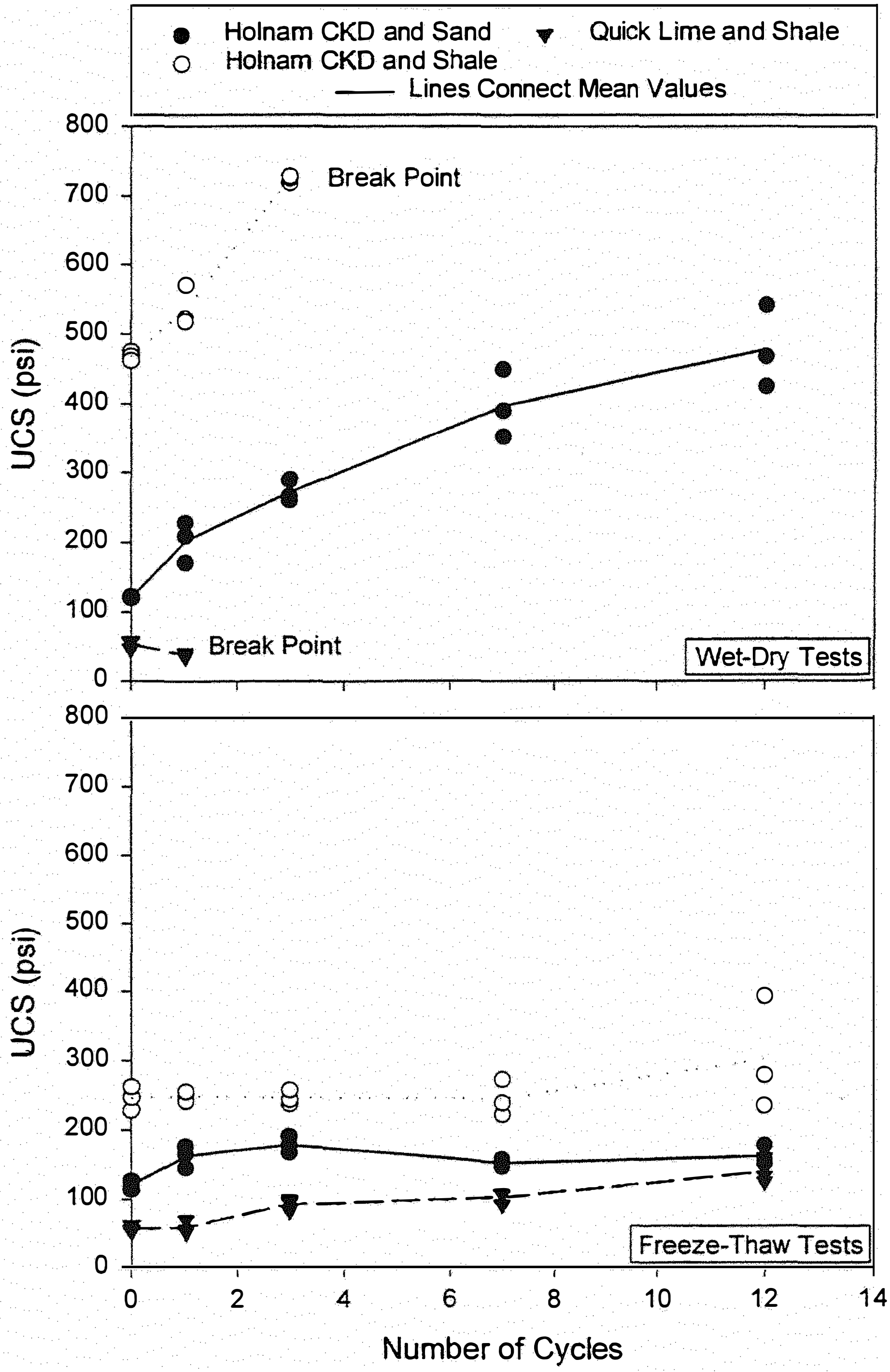


Figure 4.10 Results of Durability Tests

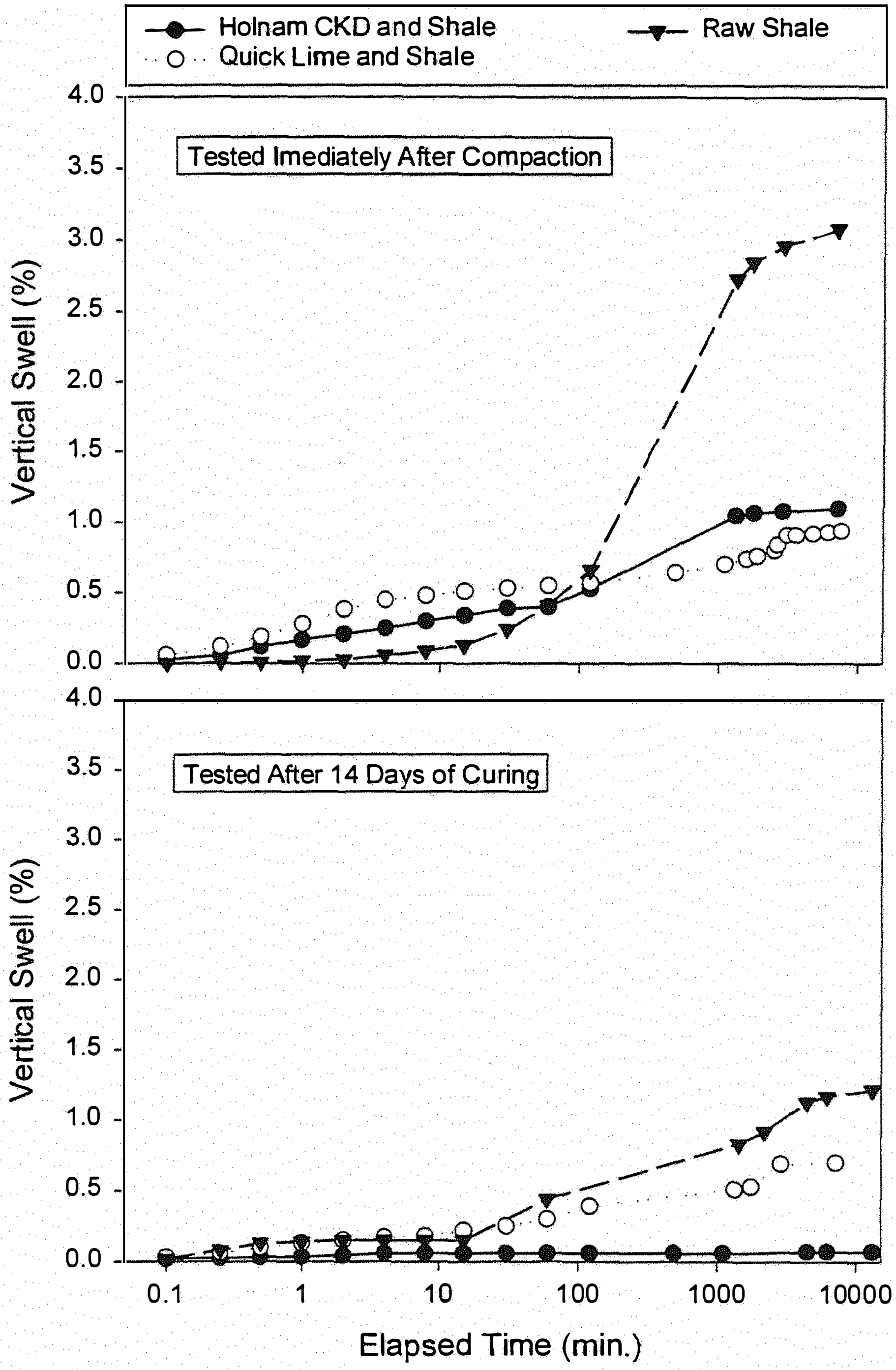


Figure 4.11 Results of One-Dimensional Swell Tests

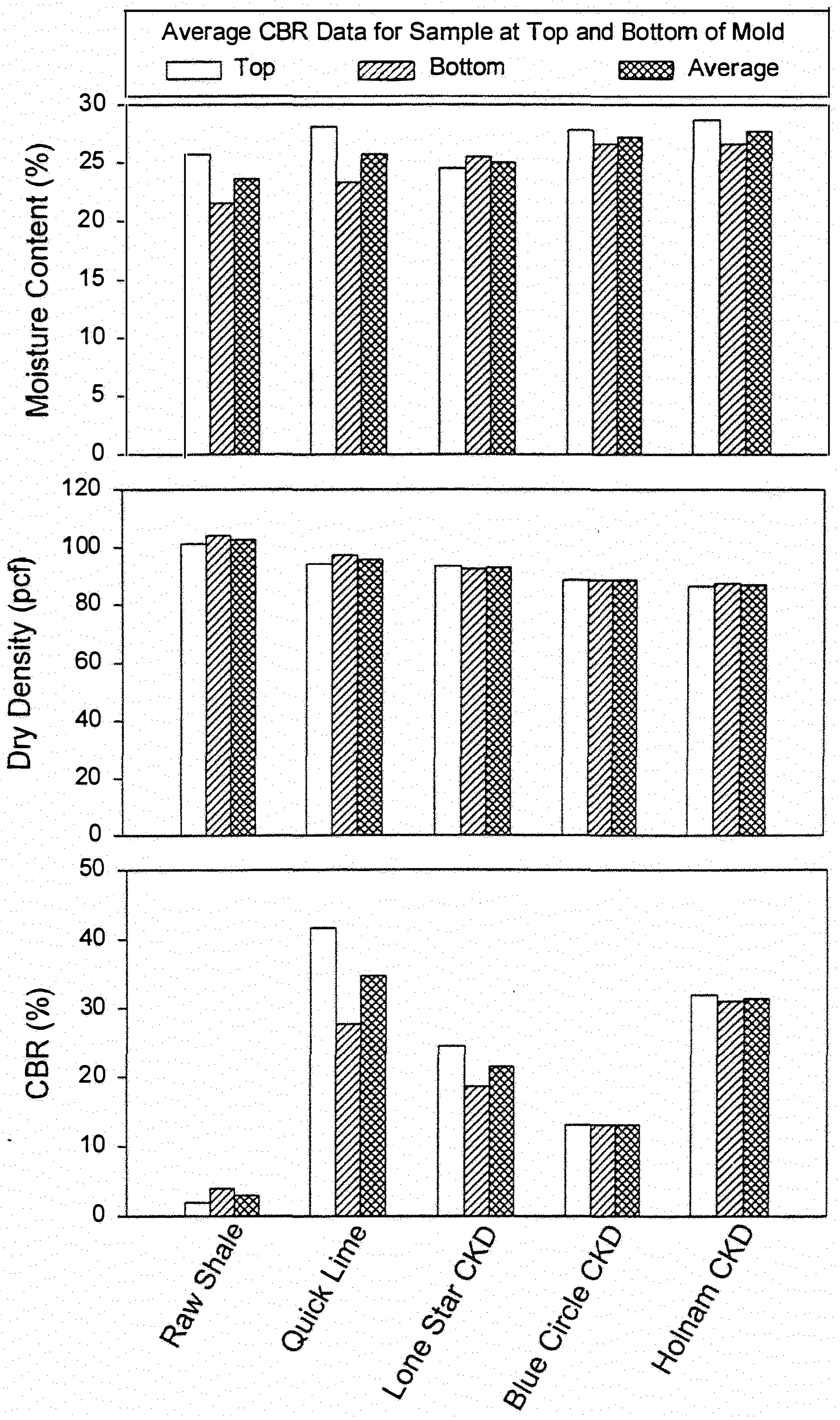


Fig. 4.12 Results of CBR Tests

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Primary goals of the research discussed in this report were to evaluate the effectiveness of CKD relative to Quick Lime, and evaluate the relative effectiveness of CKD from three different sources in Oklahoma. The approaches used to achieve these goals involved construction observations and field testing during construction of test sections, and an in-depth laboratory study of Quick Lime and CKD. In this regard, several conclusions were drawn as follows:

1) The rate of construction for the stabilized base was similar when either 4% granular Quick Lime or 15% CKD by weight was added to the soil. An added advantage of CKD is that compaction can be completed after the first mixing, whereas the Quick Lime had to be remixed after 48 hours and then compacted. On the other hand, CKD is prone to dusting problems due to high winds, not unlike fly ash or lime in powdered form.

2) In some instances CKD maybe cheaper than Quick Lime depending on hauling distances and required stabilizer quantities.

3) In general, in situ tests and laboratory tests on field samples collected during construction indicated that Holnam CKD was the most effective stabilizer, whereas Blue Circle CKD, Lone Star CKD, and Quick Lime performed similarly. Some tests revealed that there were differences in performance between Blue Circle CKD, Lone Star CKD and Quick Lime. However, overall the differences were not large enough to rule out the influence of other factors such as variable subgrade stiffness, soil conditions, weather, and other factors that can not be well controlled in the field.

4) Unconfined compression tests on samples collected during construction showed that the Holnam CKD produced considerably higher unconfined compressive strengths relative to Lone

Star CKD, Blue Circle CKD and Quick Lime. On average, samples from the Quick Lime and Lone Star CKD sections gave similar strengths. The samples from the Blue Circle CKD test section had the lowest strengths.

5) Samples treated with Quick Lime and each of the CKDs, after being immersed in water for two days, gave unconfined strengths that were generally lower than the strengths of samples that were not immersed. Untreated samples of shale and sand disintegrated when submerged in water. Thus, the lime and CKD provided some resistance to the adverse effects of saturation.
6) Results of dynamic cone penetration tests (DCPs) conducted at each of the test sections 56 days after construction, indicate that the Holnam CKD was the most effective stabilizer, followed by the Quick Lime and Blue Circle CKD. In terms of 56-day DCP results, Lone Star CKD was the least effective stabilizer. The 28-day DCP results show less discrepancy between the Holnam and other test sections whereas after 56-days, DCP results indicate a significant strength increase in the Holnam test section. The DCP cone index values for the stabilized subbase appear to depend partly on the strength of subgrade below the 8 inches of stabilized subbase.
7) Results of falling weight deflectometer (FWD) measurements suggest that the first of two Holnam CKD test sections had the stiffest subgrade, followed by the Quick Lime section, and with similar performance in the remaining CKD test sections.
8) The in-depth laboratory study revealed that there were significant differences between the performances of the three CKDs and Quick Lime. Based on unconfined compression data from laboratory prepared samples, Holnam CKD performed better than other CKDs and lime. In treated shale after 7 days of curing, Holnam CKD increased the UCS by approximately 200 psi, Lone Star CKD increased strength by approximately 75 psi, Blue Circle CKD increased the strength by about 60 psi, and the Quick Lime produced an increase of approximately 8 psi. After

90 days, the corresponding increases in UCS were 250 psi, 90 psi, 40 psi, and 56 psi, respectively.

9) In general, the rate of increase in UCS was much faster for CKD- than for lime-treated soil. For CKD-treated soil, UCS rapidly increased for 7 to 14 days of curing and then showed a gradual increase or became roughly constant thereafter (testing halted after 90 days). Lime improved the strength at a nearly steady rate for the full 90 days curing. Average values of UCS obtained for soil treated with Blue Circle CKD and Lone Star CKD showed a slight decrease in UCS after 7 and 14 days respectively; however, this decrease is within the scatter exhibited by the data.

10) The unconfined compression tests on treated sand revealed that CKD is particularly effective in low plastic or non-plastic soils whereas lime has little effect. Again, Holnam CKD was superior, but both Blue Circle and Lone Star CKD performed well. After 14 days of curing, unconfined strengths of the treated sand were increased by approximately 100 psi for Blue Circle and Lone Star CKD, and nearly 200 psi for Holnam CKD.

11) Treated soils exhibited brittle stress-strain behavior during UCTs, whereas untreated soil behaved more plastically. CKD-treated soils generally were more brittle than lime-treated soils.

12) Atterberg limit testing revealed that little or no PI reduction occurred as a result of adding lime or CKD to the shale. For treated shale samples that were moist-cured, the PI increased above the PI of the raw shale. This unusual behavior resulted in testing on two other soils, where significant and similar PI reductions were observed for both Holnam CKD and Quick Lime. It appears that the unusual mineralogy and chemistry of the shale was such that reaction products had a significant affinity for water. Overall, the CKD and Lime performed similarly with regard to PI reduction.

13) Shale samples treated with Quick Lime and Holnam CKD did not survive more than three cycles of wetting and drying. Sand treated with Holnam CKD survived 12 cycles and showed a gradual increase in UCS. Untreated shale did not survive one cycle, it simply disintegrated upon immersion in water. Thus, while treated shale durability was much less than treated sand, it was an improvement over the raw shale.

14) Shale samples treated with Quick Lime and Holnam CKD, and Sand treated with Holnam CKD survived 12 cycles of freezing and thawing with little change in UCS. Moisture content of samples decreased significantly during freezing cycles, which partly the slight increase in UCS observed near the end of the 12 cycles for some tests.

15) Swell tests revealed that the percent of vertical swell was similar for shale treated with Holnam CKD and Quick Lime, for samples that were tested immediately after compaction. Vertical swell after several days was approximately 0.9 to 1.1% for the treated shale. Similarly compacted untreated shale produced a vertical swell of 3.1%. After 14 days of curing the shale treated with Holnam CKD exhibited negligible swelling (0.07%), whereas shale treated with Quick Lime had vertical swell of about 0.7%. Untreated shale exhibited 1.2% vertical swell after 14 days of curing.

16) California Bearing Ratio tests showed that shale treated with Quick Lime or CKD gave a much higher CBR values than untreated shale (CBR=3). Quick Lime (CBR=35) and Holnam CKD (CBR=31) performed similarly with lime giving a slightly higher average CBR, followed by Lone Star (CBR=22) and then Blue Circle (CBR=13).

5.2 RECOMMENDATIONS

Based on the study presented in this report several recommendations can be made with regard to implementing CKD in road building and for continued research.

1) Cement kiln dust has been proven to be a cost-effective stabilizer relative to lime. It appears to perform similarly to Portland Cement (at lower percentages) in terms of the curing behavior and strength increases observed. It should be used with appropriate measures taken to evaluate effectiveness on a case by case basis. This is particularly true because of the variability observed between the performance of CKD from three different sources. The unconfined compression strength can be used as one measure of effectiveness following the criteria given in ASTM Standard D 4609, which deems a stabilizer effective if the UCS increases 50 psi due to addition of the stabilizer. Furthermore, the 50-psi UCS criteria can be used to determine the optimum additive amount. It is recommended that a comparison of alternative stabilizers be made during these evaluations to determine which is most effective in terms of improving soil behavior and in terms of cost. Reduction in plasticity is another measure of effectiveness that can be employed, and again would be most useful on a comparative basis. For low plasticity soils the CKD appears clearly superior to lime but for high plasticity clays the CKD effectiveness is diminished and the required CKD percentages may not be cost-effective. Another useful and simple indicator of CKD effectiveness appears to be the pH of treated soil. It can be used to get a preliminary idea of the percentage of CKD where pH levels become asymptotic, and to assess the magnitude of pH increase. This increase appears to be related to effectiveness.

Draft specifications, modeled after those for fly ash and lime, for implementing CKD in highway construction are presented in Appendix G.

2) In state highway construction, CKD does not have the history that other soil stabilizers have. While it appears to be promising for soil stabilization, additional research should be performed to build the database of information available. Such research should include: field and laboratory evaluations of CKD treated roadways that have been in use for many years, additional laboratory evaluations on other soils types, experiments with CKD in combination with other additives, development of better and more realistic durability tests, and more advanced methods of testing mechanical properties of treated soils.

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TABLE A-1 Soil Characteristics for the Lime Test Section

Sta. 141 to 151 (Data provided by ODOT Materials Division)

Station (ft.x100)	Top Depth (in.)	Bottom Depth (in.)	PI (%)	% Finer than #4 Sieve	% Finer than #200 Sieve	AASHTO Class	OSI	Description
141.00	0	6	11	91	53.6	A-6(3)	7	SANDY LEAN CLAY
141.00	6	24	18	100	62.6	A-6(9)	12	SANDY LEAN CLAY
143.00	0	24	17	100	65.7	A-6(9)	12	SANDY LEAN CLAY
145.00	0	24	21	100	99	A-7-6(24)	17	LEAN CLAY
147.00	0	6	0	99	44.2	A-4(0)	0	SILTY SAND
147.00	6	24	8	92	58.5	A-4(3)	6	SANDY LEAN CLAY
149.00	0	24	8	99	46.3	A-4(1)	4	CLAYEY SAND
151.00	0	24	8	99	46.3	A-4(1)	4	CLAYEY SAND
		AVG.=	11	98	60		8	

TABLE A-2 Soil Characteristics for the Holnam CKD Test Section (First)

Sta. 155+80 to 159+30 (Data provided by ODOT Materials Division)

Station (ft.x100)	Top Depth (in.)	Bottom Depth (in.)	PI (%)	% Finer than #4 Sieve	% Finer than #200 Sieve	AASHTO Class	OSI	Description
156.23	0	16	22	100	97.4	A-7-6(24)	18	LEAN CLAY
156.23	16	24	25	100	92.2	A-7-6(26)	20	FAT CLAY
157.18	0	6	31	100	98.9	A-7-6(37)	24	FAT CLAY
157.18	6	24	26	100	95.4	A-7-6(29)	21	FAT CLAY
157.34	0	8	28	100	96.2	A-7-6(31)	22	FAT CLAY
157.34	8	24	24	100	96.5	A-7-6(27)	19	LEAN CLAY
157.39	0	8	24	100	98.3	A-7-6(26)	19	LEAN CLAY
157.39	8	24	31	100	97.3	A-7-6(35)	24	FAT CLAY
157.45	0	10	28	100	99.1	A-7-6(32)	22	FAT CLAY
157.45	10	24	25	100	94.6	A-7-6(26)	20	FAT CLAY
157.65	0	9	30	100	97.7	A-7-6(34)	23	FAT CLAY
157.65	9	24	24	100	89.9	A-7-6(23)	19	LEAN CLAY
157.85	0	7	27	100	96.5	A-7-6(29)	27	FAT CLAY
157.85	7	24	22	100	95.5	A-7-6(24)	22	LEAN CLAY
158.11	0	5	26	100	97.9	A-7-6(30)	21	FAT CLAY
158.11	5	24	26	100	98.3	A-7-6(28)	20	LEAN CLAY
158.48	0	4	25	100	98.1	A-7-6(28)	20	LEAN CLAY
158.48	4	24	25	100	98.1	A-7-6(28)	20	LEAN CLAY
158.52	0	2	28	100	96.2	A-7-6(30)	21	FAT CLAY
158.52	2	24	23	100	98.5	A-7-6(25)	18	LEAN CLAY
158.77	0	3	26	100	95.8	A-7-6(27)	20	LEAN CLAY
158.77	3	24	24	100	96.3	A-7-6(25)	19	LEAN CLAY
		AVG.=	26	100	97		21	

TABLE A-3 Soil Characteristics for the Lone Star CKD Test Section

Sta. 159+30 to 167+50 (Data provided by ODOT Materials Division)

Station (ft.x100)	Top Depth (in.)	Bottom Depth (in.)	PI (%)	% Finer than #4 Sieve	% Finer than #200 Sieve	AASHTO Class	OSI	Description
160.61	0	4	25	100	91.3	A-7-6(25)	19	LEAN CLAY
160.61	4	24	23	100	98	A-7-6(26)	19	LEAN CLAY
161.2	0	5	27	99	91.7	A-7-6(27)	21	FAT CLAY
161.2	5	17	43	100	92.2	A-7-6(44)	30	FAT CLAY
161.2	17	22	26	100	96.8	A-7-6(25)	18	LEAN CLAY
161.2								ROCK
161.23	0	6	19	100	77.9	A-6(13)	15	LEAN CLAY WITH SAND
161.23	6	18	0	100	36.7	A-4(0)	0	SILTY SAND
161.23	18	24	22	100	94.1	A-7-6(22)	17	LEAN CLAY
162.34	0	9	26	99	88.1	A-7-6(25)	20	LEAN CLAY
162.34	9	24	2	90	37.1	A-4(0)	1	SILTY SAND
163.8	0	24	22	100	86.5	A-7-6(19)	17	LEAN CLAY
164.65	0	6	12	99	65.6	A-6(5)	9	SANDY LEAN CLAY
164.65	6	24	21	100	90.6	A-7-6(20)	17	LEAN CLAY
165.02	0	10	17	92	51.6	A-6(7)	11	SANDY LEAN CLAY
165.02	10	16	23	99	85.8	A-7-6(20)	18	LEAN CLAY
165.02	16	24	37	100	97.9	A-7-6(41)	27	FAT CLAY
165.51	0	3	25	94	71.1	A-6(15)	17	LEAN CLAY WITH SAND
165.51	3	24	34	100	97.3	A-7-6(38)	25	FAT CLAY
165.77	0	5	21	90	65.9	A-6(12)	15	SANDY LEAN CLAY
165.77	5	24	47	100	95.8	A-7-6(52)	33	FAT CLAY
166.02	0	6	26	91	67.2	A-7-6(16)	19	SANDY LEAN CLAY
166.02	6	24	57	99	95.6	A-7-6(61)	35	FAT CLAY
166.39	0	7	20	99	67.1	A-7-6()	14	SANDY LEAN CLAY
166.39	7	24	33	100	95.6	A-7-6()	25	FAT CLAY
166.61	0	5	18	100	84.6	A-6(14)	14	LEAN CLAY WITH SAND
166.61	5	9	0	99	42.6	A-4(0)	0	SILTY SAND
166.61	9	24	27	100	88.2	A-7-6(26)	21	FAT CLAY
166.73	0	7	24	100	86.9	A-7-6(21)	18	LEAN CLAY
166.73	7	24	23	95	72.7	A-6(15)	16	LEAN CLAY WITH SAND
167.23	0	7	24	99	89.5	A-7-6(23)	19	LEAN CLAY
167.23	7	24	29	100	97.2	A-7-6(30)	21	LEAN CLAY
167.26	0	7	26	100	92.2	A-7-6(26)	20	LEAN CLAY
167.26	7	24	25	100	95.4	A-7-6(26)	19	LEAN CLAY
		AVG.=	24	98	81		18	

TABLE A-4 Soil Characteristics for the Blue Circle CKD Test Section

Sta. 167+50 to 177 (Data provided by ODOT Materials Division)

Station (ft.x100)	Top Depth (in.)	Bottom Depth (in.)	PI (%)	% Finer than #4 Sieve	% Finer than #200 Sieve	AASHTO Class	OSI	Description
167.61	0	10	19	100	81.7	A-6(15)	15	LEAN CLAY WITH SAND
167.61	10	24	31	100	90.2	A-7-6(32)	24	FAT CLAY
167.66	0	12	22	100	79.8	A-6(16)	16	LEAN CLAY WITH SAND
167.66	12	24	35	100	92.5	A-7-6(36)	25	FAT CLAY
168.55	0	8	25	99	78.5	A-7-6(18)	18	LEAN CLAY WITH SAND
168.55	8	12	27	100	89.3	A-7-6(26)	20	LEAN CLAY
168.55	12	24	35	99	79.5	A-7-6(28)	24	FAT CLAY WITH SAND
168.61	0	12	34	100	93.5	A-7-6(34)	24	FAT CLAY
168.61	12	24	37	96	75.8	A-7-6(28)	26	FAT CLAY WITH SAND
169.01	0	8	25	99	80.4	A-7-6(20)	19	LEAN CLAY WITH SAND
169.01	8	19	38	100	94.4	A-7-6(39)	26	FAT CLAY
169.01	19	24	0	100	89.5	A-4(0)	0	SILT
170.2	0	14	23	79	50.7	A-6(8)	12	SANDY LEAN CLAY WITH GRAVEL
170.2	14	24	28	98	73.7	A-7-6(20)	20	LEAN CLAY WITH SAND
170.94	0	11	20	98	74.3	A-6(13)	15	LEAN CLAY WITH SAND
170.94	11	24	23	100	69.3	A-6(14)	16	SANDY LEAN CLAY
172.2	0	6	23	77	50.9	A-6(8)	12	SANDY LEAN CLAY WITH GRAVEL
172.2	6	12	12	78	35.3	A-2-6(0)	4	CLAY SAND WITH GRAVEL
172.2	12	24	28	100	70.7	A-7-6(19)	21	LEAN CLAY WITH SAND
172.25	0	10	21	98	82.5	A-6(16)	16	LEAN CLAY WITH SAND
172.25	10	18	20	100	69.1	A-6(12)	15	SANDY LEAN CLAY
172.25	18	24	23	100	71.2	A-6(14)	16	LEAN CLAY WITH SAND
172.51	0	7	23	98	78.8	A-6(17)	17	LEAN CLAY WITH SAND
172.51	7	19	24	100	91.7	A-7-6(23)	18	LEAN CLAY
172.51	19	24	18	100	66.2	A-6(9)	13	SANDY LEAN CLAY
173.15	0	7	19	97	72	A-6(1)	14	LEAN CLAY WITH SAND
173.15	7	24	14	100	62.6	A-6(6)	9	SANDY LEAN CLAY
174.1	0	3	18	98	79.1	A-6(13)	14	LEAN CLAY WITH SAND
174.1	3	24	11	96	49.3	A-6(2)	6	CLAYEY SAND
174.41	0	4	19	97	74.5	A-6(13)	15	LEAN CLAY WITH SAND
174.41	4	8	12	62	31.3	A-2-6(0)	4	CLAYEY GRAVEL WITH SAND
174.41	8	24	8	97	39.6	A-4(1)	2	CLAYEY SAND
175.17	0	18	19	100	72.4	A-6(12)	14	LEAN CLAY WITH SAND
175.17	18	24	20	100	71.9	A-6(13)	15	LEAN CLAY WITH SAND
175.58	0	15	26	99	89.7	A-7-6(23)	19	LEAN CLAY
175.58	15	24	17	96	59	A-6(7)	10	SANDY LEAN CLAY
176.89	0	12	28	99	91.1	A-7-6(28)	21	LEAN CLAY
176.89	12	24	14	93	55.9	A-6(5)	9	SANDY LEAN CLAY
		AVG.=	22	96	73		15	

TABLE A-5 Soil Characteristics for the Holnam CKD Test Section (Second)

Sta. 177 to 186 (Data provided by ODOT Materials Division)

Station (ft.x100)	Top Depth (in.)	Bottom Depth (in.)	PI (%)	% Finer than #4 Sieve	% Finer than #200 Sieve	AASHTO Class	OSI	Description
177.02	0	12	26	100	95.6	A-7-6(27)	20	LEAN CLAY
177.02	12	24	14	86	43.8	A-6(2)	6	CLAYEY SAND
177.11	0	12	27	100	92.3	A-7-6(27)	20	LEAN CLAY
177.11	12	24	15	97	63.1	A-6(6)	10	SANDY LEAN CLAY
178.85	0	17	25	100	93.1	A-7-6(24)	19	LEAN CLAY
~~178.85~~	~~17~~	~~24~~	~~8~~	~~91~~	~~53.4~~	~~A-4(2)~~	~~5~~	~~SANDY LEAN CLAY~~
179.26	0	8	26	98	87.8	A-7-6(24)	20	LEAN CLAY
179.26	8	24	19	99	75.9	A-6(13)	15	LEAN CLAY WITH SAND
180.21	0	2	25	100	85.4	A-7-6(21)	18	LEAN CLAY WITH SAND
180.21	2	12	12	100	49.1	A-6(3)	7	CLAYEY SAND
180.21	12	24	20	100	75.6	A-6(14)	15	LEAN CLAY WITH SAND
180.51	0	10	21	100	80.6	A-6(15)	15	LEAN CLAY WITH SAND
180.51	10	24	7	100	54.1	A-4(2)	5	SANDY, SILTY CLAY
180.61	0	19	20	100	77.4	A-6(14)	15	LEAN CLAY WITH SAND
180.61	19	24	8	100	59.9	A-4(3)	6	SANDY LEAN CLAY
180.87	0	24	15	100	70.8	A-6(8)	11	LEAN CLAY WITH SAND
180.97	0	24	19	100	81.6	A-6(14)	15	LEAN CLAY WITH SAND
181.94	0	10	24	100	91.9	A-7-6(23)	18	LEAN CLAY
181.94	10	24	16	100	63.9	A-6(7)	11	SANDY LEAN CLAY
182.91	0	9	24	100	89.6	A-6(21)	17	LEAN CLAY
182.91	9	24	14	100	65.6	A-6(6)	10	SANDY LEAN CLAY
183.08	0	8	25	100	88.8	A-6(21)	18	LEAN CLAY
183.08	8	24	18	99	57.7	A-6(7)	11	SANDY LEAN CLAY
183.09	0	6	20	97	31.4	A-2-6(2)	6	CLAYEY SAND
183.09	6	24	19	100	76.1	A-6(12)	14	LEAN CLAY WITH SAND
183.14	0	16	20	100	72.1	A-6(12)	15	LEAN CLAY WITH SAND
183.14	16	24	30	100	81.9	A-7-6(23)	20	LEAN CLAY WITH SAND
183.48	0	12	16	100	74.5	A-6(9)	12	LEAN CLAY WITH SAND
183.48	12	24	21	100	85.8	A-6(18)	16	LEAN CLAY
183.81	0	24	22	100	72.3	A-6(14)	16	LEAN CLAY WITH SAND
184.43	0	8	25	100	93.8	A-7-6(24)	18	LEAN CLAY
184.43	8	24	17	100	57.3	A-6(6)	10	SANDY LEAN CLAY
184.84	0	24	22	100	84.2	A-6(17)	16	LEAN CLAY WITH SAND
185.51	0	24	20	99	66.1	A-6(10)	13	SANDY LEAN CLAY
		AVG.=	19	99	73		14	

Daily Field Log – ODOT CKD Project

DATE : 2/5/1998.

CHEMICAL ADDITIVE: LIME

SOIL SAMPLING STATIONS: 142,144,146,148,150

DISTANCE: 500 ft.

TIME TAKEN FROM DUMPING TILL COMMENCEMENT OF COMPACTION: 4.67 HRS

MATERIAL: 1 TRUCK LIME:
= 25.13 TONS.

MACHINERY:

BOMAG:	2 NOS.:	19 PASSES (TOTAL).
MOTOR GRADER:	1 NOS.:	37 PASSES.
WATER TRUCK:	1 NOS.:	7 PASSES (100 TONS).

MIXING RATE: **107 FT/HR.**

DATE : 2/23/1998.

CHEMICAL ADDITIVE: CKD - HOLNAM (ADA).

SOIL SAMPLING STATIONS: 185,183,181,179.

DISTANCE: 900ft.

TIME TAKEN FROM DUMPING TILL COMMENCEMENT OF COMPACTION: 9.00 HRS

MATERIAL: 6 TRUCKS CKD: = 150 TONS.

MACHINERY:

BOMAG:	2 NOS.:	20 PASSES (TOTAL).
MOTOR GRADER:	1 NOS.:	7 PASSES.
WATER TRUCK:	1 NOS.:	4 PASSES (100 TONS).

WORKERS: 4 NOS. + SUPERVISOR.

MIXING RATE: **100 FT/HR.**

DATE: 2/24/98.

CHEMICAL ADDITIVE: CKD - BLUE CIRCLE (TULSA).

SOIL SAMPLING STATIONS: 177,175,173,171.

DISTANCE: 800ft.

TIME TAKEN FROM DUMPING TILL COMMENCEMENT OF COMPACTION: 8.00 HRS

MATERIAL: 5 TRUCKS CKD: = 127 TONS.

MACHINERY:

BOMAG:	2 NOS.:	20 PASSES (TOTAL).
MOTOR GRADER:	1 NOS.:	7 PASSES.
WATER TRUCK:	1 NOS.	8 PASSES (200 TONS).
STEEL TOOTH HARROW	1 NOS.:	13 PASSES

WORKERS: 4 NOS. + SUPERVISOR.

MIXING RATE: **97.5FT/HR.**

DATE: 2/26/98.

CHEMICAL ADDITIVE: CKD - BLUE CIRCLE (TULSA).

SOIL SAMPLING STATIONS: 169.

DISTANCE: 150ft.

TIME TAKEN FROM DUMPING TILL COMMENCEMENT OF COMPACTION: 3.00 HRS

MATERIAL: 1 TRUCKS CKD: = 25 TONS.

MACHINERY:

BOMAG:	2 NOS.:	14 PASSES (TOTAL).
MOTOR GRADER:	1 NOS.:	6 PASSES.
WATER TRUCK:	1 NOS.:	3 PASSES (75 TONS).

WORKERS: 4 NOS. + SUPERVISOR.

MIXING RATE: **50 FT/HR.**

DATE: 2/27/98.

CHEMICAL ADDITIVE: CKD - LONE STAR (PRYOR).

SOIL SAMPLING STATIONS: 167,165.

DISTANCE: 480ft.

TIME TAKEN FROM DUMPING TILL COMMENCEMENT OF COMPACTION: 6.00 HRS

MATERIAL: 4 TRUCKS CKD: = 80 TONS.

MACHINERY:

BOMAG:	2 NOS.:	19 PASSES (TOTAL).
MOTOR GRADER:	1 NOS.:	4 PASSES.
WATER TRUCK:	1 NOS.:	6 PASSES (150 TONS).
STEEL TOOTH HARROW	1 NOS.:	9 PASSES.

WORKERS: 4 NOS. + SUPERVISOR.

MIXING RATE: **80 FT/HR.**

DATE: 3/2/98.

CHEMICAL ADDITIVE: CKD - LONE STAR (PRYOR)

SOIL SAMPLING STATIONS: 163,161.

DISTANCE: 340ft.

TIME TAKEN FROM DUMPING TILL COMMENCEMENT OF COMPACTION: 3.25 HRS

MATERIAL: 3 TRUCKS CKD = 54 TONS.

MACHINERY:

BOMAG:	2 NOS.:	15 PASSES (TOTAL).
MOTOR GRADER:	1 NOS.:	4 PASSES.
WATER TRUCK:	1 NOS.:	6 PASSES (75 TONS).
STEEL TOOTH HARROW	1 NOS.:	4 PASSES

WORKERS: 4 NOS. + SUPERVISOR.

MIXING RATE: **104 FT/HR.**

Daily Field Log – ODOT CKD Project

DATE: 3/3/98.

CHEMICAL ADDITIVE:	CKD - HOLNAM (ADA)
SOIL SAMPLING STATIONS:	159,157.
DISTANCE:	350ft.
TIME TAKEN FROM DUMPING TILL COMMENCEMENT OF COMPACTION:	3.25 HRS
MATERIAL:	2 TRUCKS CKD: = 50 TONS.
WORKERS:	4 NOS. + SUPERVISOR.
MIXING RATE:	**107 FT/HR.**

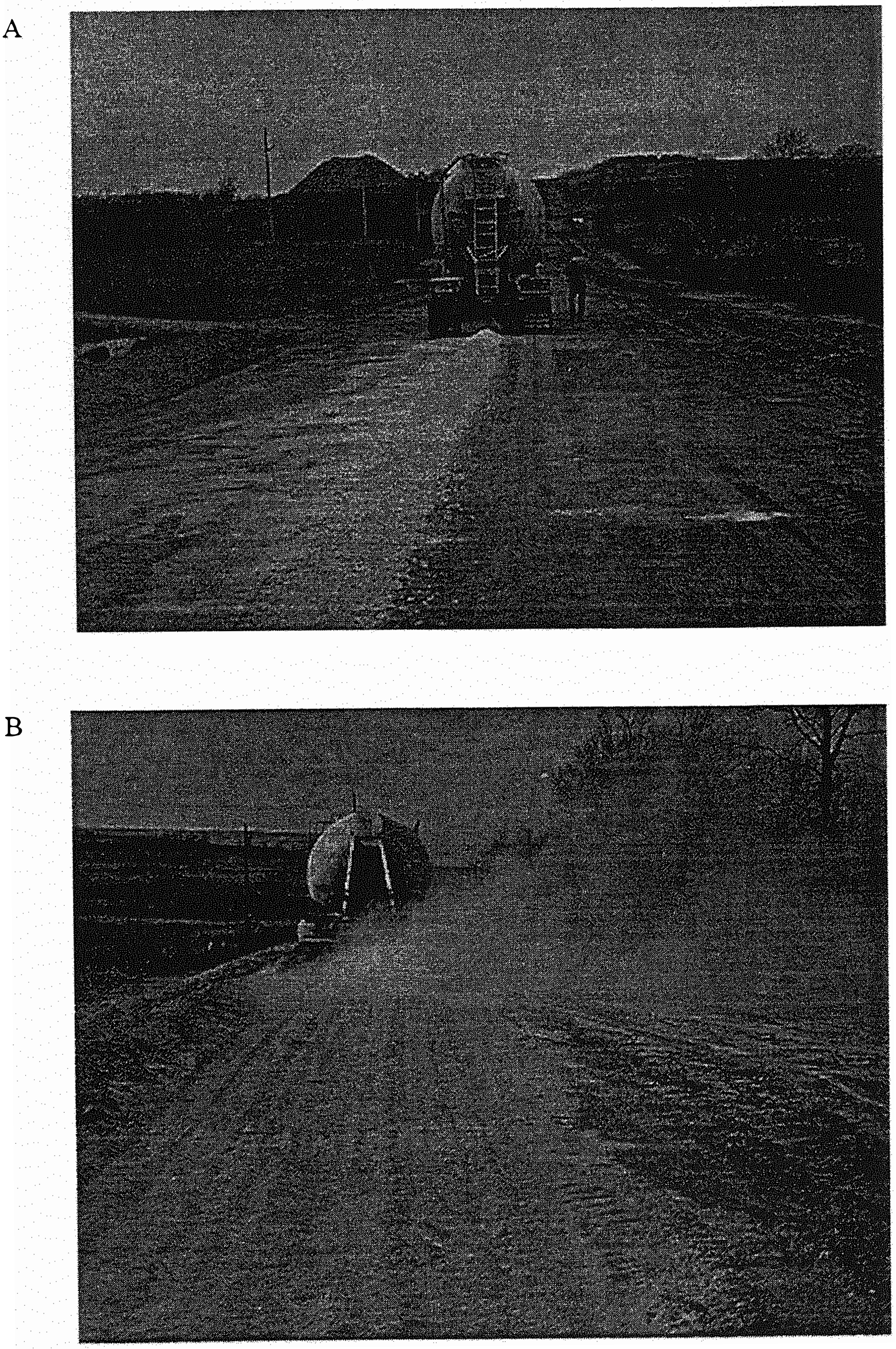


FIG. B–1 Belly Dumping: A) Lime and B) CKD

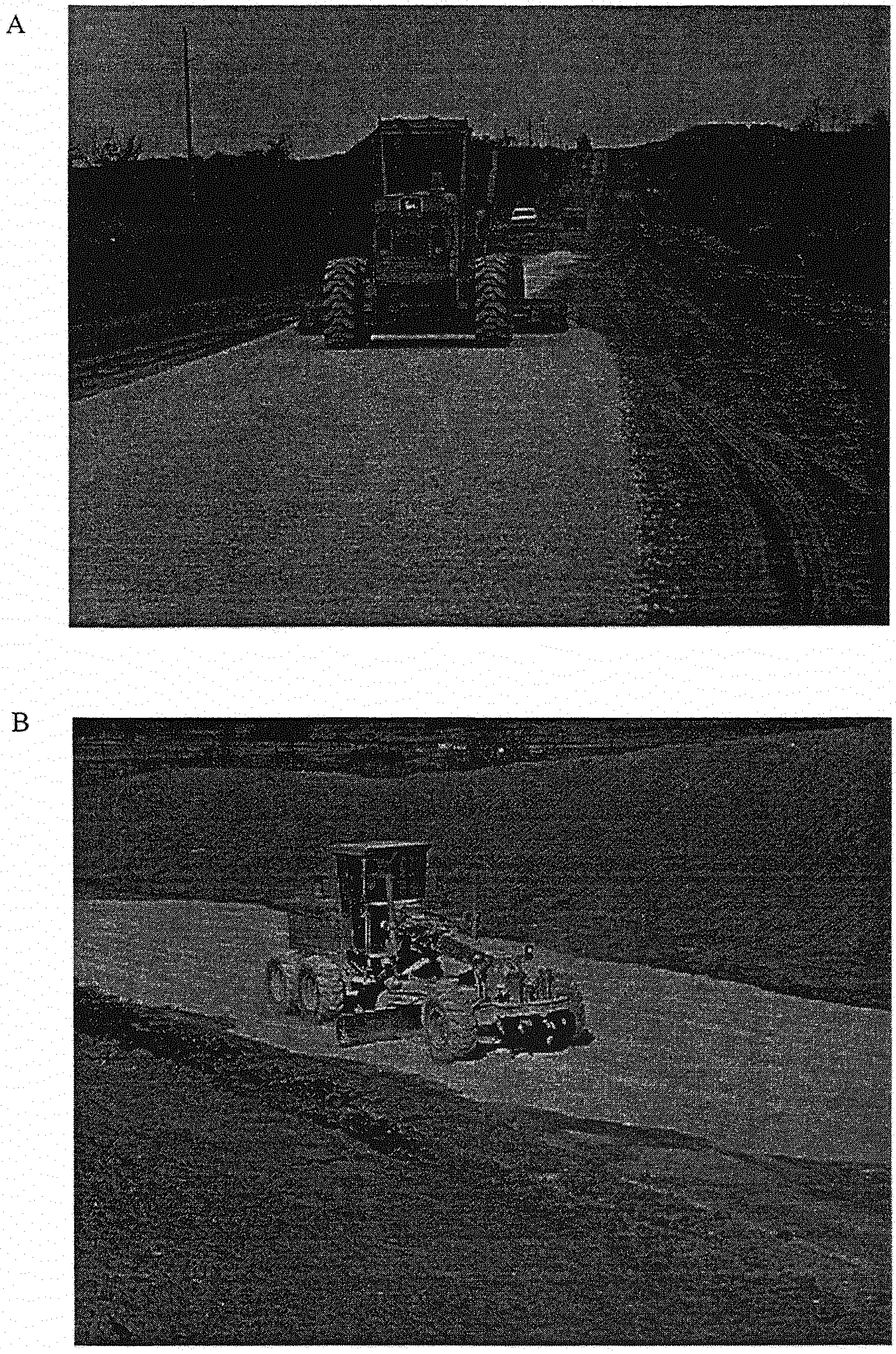


FIG. B–2 Spreading: A) Lime and B) CKD

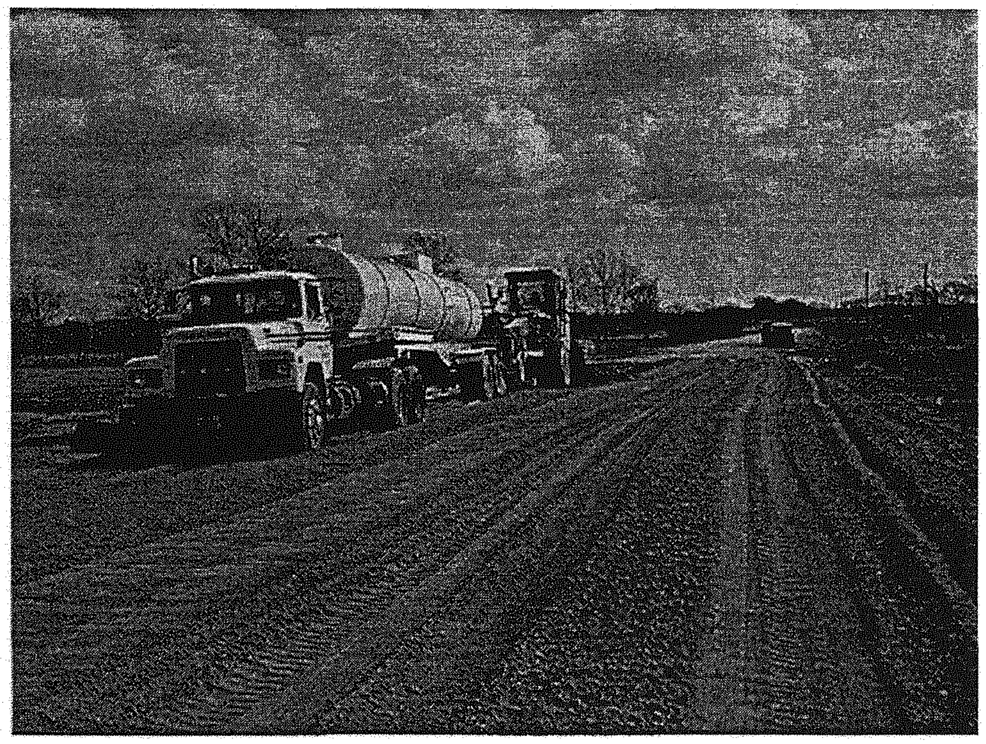


FIG. B–3 Adding Water

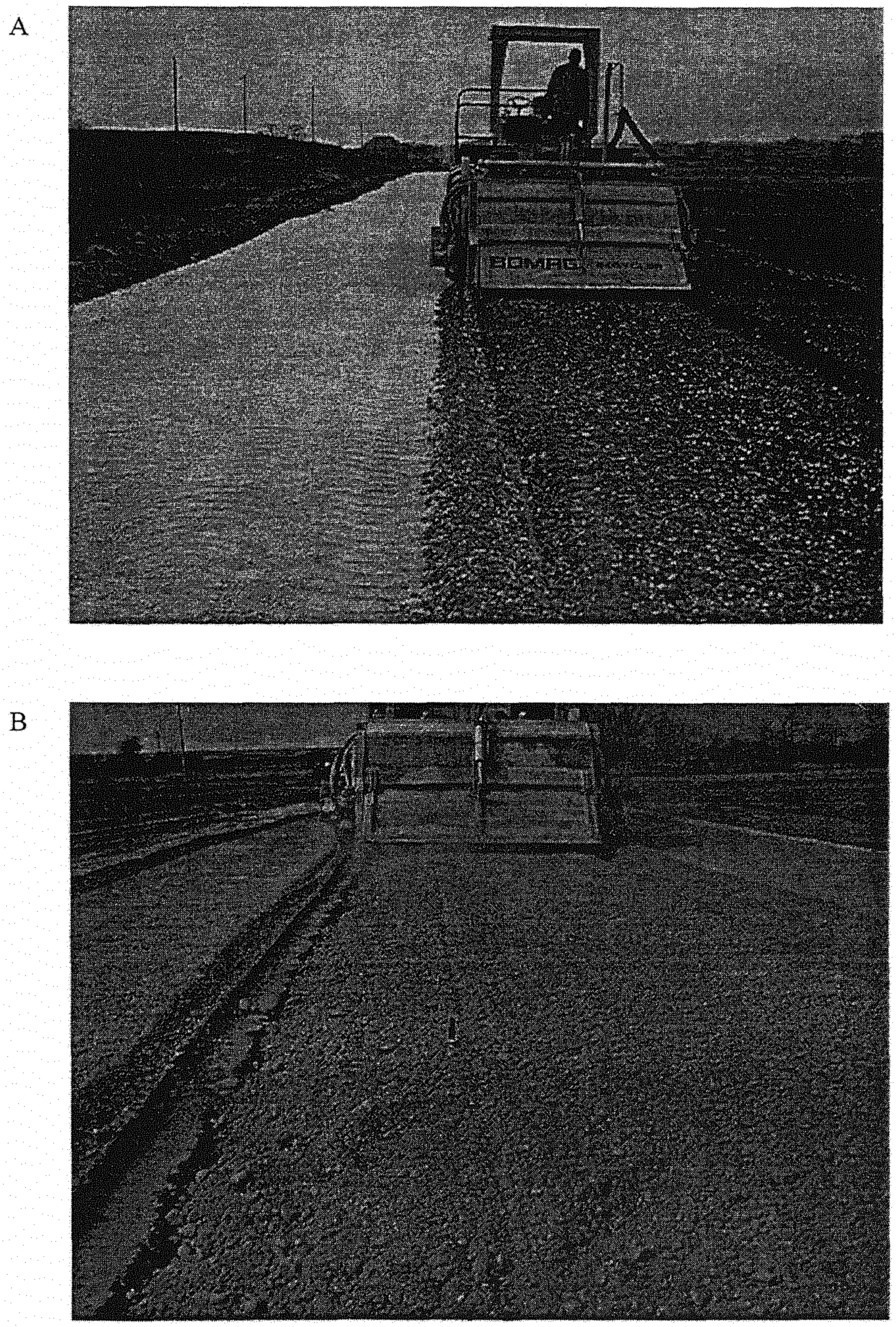


FIG. B–4 Mixing with Bomag Recycler: A) Lime and B) CKD

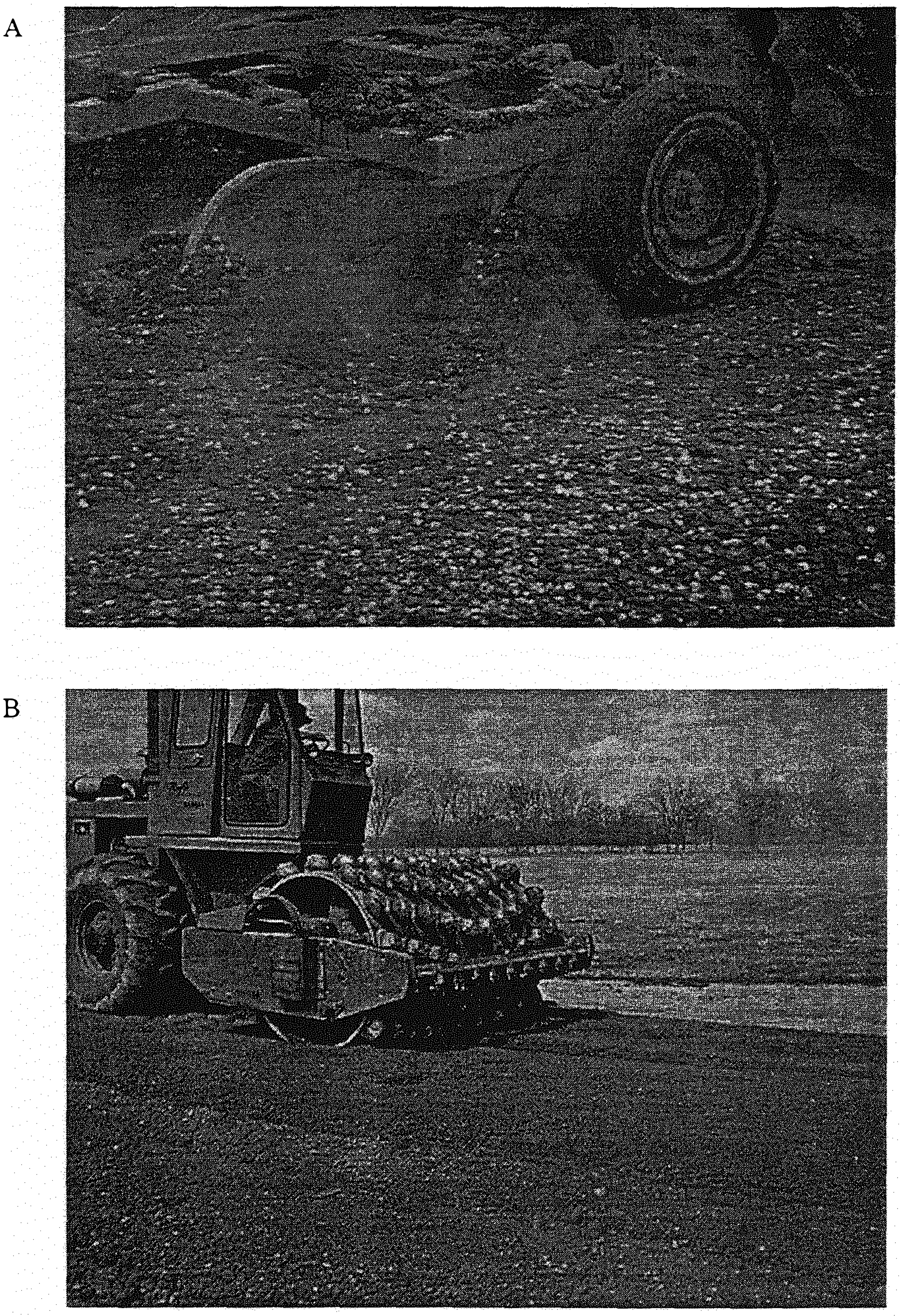


FIG. B–5 A) Mixing with Spring Tooth Harrow; B) Compacting with Sheep's Foot Roller

TABLE C-1 Unconfined Compression Test Data from Field Samples for 7- and 28-Day Curing

Chemical Additive	Station (ft.x100)	7-Day UCS (psi)	Avg. 7-Day UCS (psi)	7-Day[1] Sub. UCS (psi)	Avg. 7-Day Sub. UCS (psi)	28-Day UCS (psi)	Avg. 28-Day UCS (psi)	28-Day Sub. UCS (psi)	Avg. 28-Day Sub. UCS (psi)
Granular Quick Lime	142	27.9		45.0		45.6		41.8	
		32.3		37.4		49.4		48.1	
		43.7	34.6	31.7	38.0	54.5	49.8	49.4	46.4
	144	39.3				59.5			
		53.2				65.9			
		55.7	49.4			83.6	69.6		
	146	53.2				86.1			
		60.2				92.4			
		81.0	64.8			92.4	90.3		
	148	51.9				87.4			
		55.7				88.6			
		61.4	56.4			95.0	90.3		
	150	47.5		34.8		93.1		48.1	
		55.1		39.9		96.2		55.7	
		55.1	52.6	41.2	38.6	96.9	95.4	58.9	54.2
Holnam CKD	157	126.6				188.7			
		190.0				272.3			
		200.1	172.2			284.9	248.6		
	159	121.6				222.9			
		141.8				230.5			
		202.6	155.3			244.4	232.6		
Lone Star CKD	161	55.7				76.0			
		60.2				76.0			
		64.0	59.9			84.8	78.9		
	163	51.3				66.5			
		86.1				88.6			
		95.0	77.5			90.5	81.9		
	165	50.7		29.1					
		54.5		32.9					
		65.2	56.8	40.5	34.2				
	167	89.9				78.5			
		95.0				84.8			
		96.2	93.7			95.0	86.1		
Blue Circle CKD	169	22.8				32.9			
		24.1				34.2			
		27.9	24.9			35.5	34.2		
	171	31.7				62.1			
		45.6				70.9			
		46.9	41.4			74.7	69.2		
	173	0.0		20.9					
		0.0		23.4					
		0.0		29.1	24.5				
	175	19.6				30.4			
		20.9				32.3			
		22.8	21.1			36.7	33.1		
Holnam CKD	177	69.6				88.6			
		72.2				96.2			
		73.4	71.8			107.6	97.5		
	179	160.8		96.2					
		193.8		105.1					
		207.7	187.4	134.2	111.9				
	181	168.4				245.7			
		183.6				246.9			
		192.5	181.5			253.3	248.6		
	183	158.3		105.1					
		173.5		114.0					
		174.8	168.8	121.6	113.6				
	185	141.8				179.8		140.6	
		163.4				221.6		141.8	
		168.4	157.9			221.6	207.7	164.6	149.0

Notes: 1-Sub. indicates samples submerged in water for 2 days before UCS Test.

TABLE C-2 28-Day Dynamic Cone Penetration Test Results (0-8 inches)

Chemical Additive	Station (ft.x100)	CI (in./blow) for 0-4 in.	CI (in./blow) for 4-8 in.	CI (in./blow) for 0-8 in.	Average CI (in./blow) for 0-4 in.	Average CI (in./blow) for 4-8 in.	Average CI (in./blow) for 0-8 in.
Granular Quick Lime	140	0.20	0.30	0.25	—	—	—
	142	0.30	0.50	0.40	—	—	—
	144	1.20	0.65	0.93	—	—	—
	146	0.30	0.50	0.40	—	—	—
	148	0.30	0.50	0.40	—	—	—
Holnam CKD	159	0.21	0.29	0.25			
	159	0.25	0.33	0.29			
	159	0.31	0.40	0.36	0.32	0.42	0.37
Lone Star CKD	163	0.49	0.65	0.57			
	163	0.51	0.55	0.53			
	163	0.49	0.70	0.60	0.55	0.58	0.56
	165	0.70	0.40	0.55			
	165	0.70	0.30	0.50			
	165	0.41	0.45	0.43	0.59	0.42	0.51
Blue Circle CKD	171	0.54	0.54	0.54			
	171	0.53	0.53	0.53			
	171	0.54	0.51	0.53	0.55	0.50	0.52
	175	0.59	0.40	0.50			
	175	0.63	0.93	0.78			
	175	0.67	0.94	0.81	0.58	0.64	0.61
Holnam CKD	177	0.44	0.28	0.36			
	177	0.39	0.52	0.46			
	177	0.44	0.44	0.44	0.45	0.49	0.47
	179	0.53	0.70	0.62			
	179	0.45	0.78	0.62			
	179	0.40	0.64	0.52	0.45	0.69	0.57
	181	0.43	0.63	0.53			
	181	0.46	0.59	0.53			
	181	0.32	0.67	0.50	0.39	0.64	0.51
	183	0.33	0.66	0.50			
	183	0.36	0.56	0.46			
	183	0.42	0.82	0.62	0.35	0.71	0.53
	185	0.30	0.80	0.55			
	185	0.28	0.68	0.48			
	185	0.27	0.69	0.48	0.28	0.72	0.50

TABLE C-3 56-Day Dynamic Cone Penetration Test Results (0-24 inches)

Chemical Additive	Station (ft.x100)	CI (in./blow) for 0-4 in.	CI (in./blow) for 4-8 in.	CI (in./blow) for 0-8 in.	CI (in./blow) for 8-24 in.	Average CI (in./blow) for 0-4 in.	Average CI (in./blow) for 4-8 in.	Average CI (in./blow) for 0-8 in.	Average CI (in./blow) for 8-24 in.
Granular Quick Lime	140	0.36	0.39	0.38	0.27				
	140	0.33	0.35	0.34	0.32				
	140	0.30	0.26	0.28	0.32	0.33	0.33	0.33	0.30
	142	0.58	0.66	0.62	1.00				
	142	0.47	0.63	0.55	1.03				
	142	0.50	0.66	0.58	0.97	0.52	0.65	0.58	1.00
	144	0.60	0.70	0.65	1.96				
	144	0.63	0.92	0.78	2.05				
	144	0.55	0.63	0.59	1.65	0.59	0.75	0.67	1.89
	146	0.43	0.50	0.47	0.40				
	146	0.32	0.47	0.40	0.33				
	146	0.36	0.34	0.35	0.32	0.37	0.44	0.40	0.35
	148	0.44	0.55	0.50	0.61				
	148	0.41	0.63	0.52	0.56				
	148	0.40	0.70	0.55	0.52	0.42	0.63	0.52	0.56
Holnam CKD	157	0.13	0.18	0.16	0.21				
	157	0.16	0.25	0.21	0.16				
	157	0.14	0.25	0.20	0.21	0.14	0.23	0.19	0.19
	159	0.27	0.51	0.39	0.21				
	159	0.34	0.34	0.34	0.10				
	159	0.27	0.30	0.29	0.17	0.29	0.38	0.34	0.16
Lone Star CKD	163	0.86	1.70	1.28	0.91				
	163	0.70	1.23	0.97	0.69				
	163	0.70	1.27	0.99	0.67	0.75	1.40	1.08	0.76
	165	1.40	3.00	2.20	0.46				
	165	1.00	0.84	0.92	0.55				
	165	1.20	0.90	1.05	0.63	1.20	1.58	1.39	0.55
Blue Circle CKD	171	0.57	0.43	0.50	0.68				
	171	0.44	0.49	0.47	0.73				
	171	0.46	0.38	0.42	0.79	0.49	0.43	0.46	0.73
	175	0.59	0.65	0.62	0.79				
	175	0.50	0.61	0.56	0.60				
	175	0.59	0.65	0.62	0.79	0.56	0.64	0.60	0.73
Holnam CKD	177	0.36	0.56	0.46	0.26				
	177	0.29	0.42	0.36	0.33				
	177	0.33	0.40	0.37	0.31	0.33	0.46	0.39	0.30
	179	0.40	0.66	0.53	0.75				
	179	0.44	0.65	0.55	0.57				
	179	0.49	0.78	0.64	0.54	0.44	0.70	0.57	0.62
	181	0.27	0.34	0.31	0.59				
	181	0.23	0.33	0.28	0.65				
	181	0.27	0.36	0.32	0.61	0.26	0.34	0.30	0.62
	183	0.23	0.32	0.28	0.51				
	183	0.29	0.29	0.29	0.59				
	183	0.23	0.36	0.30	0.67	0.25	0.32	0.29	0.59
	185	0.29	0.44	0.37	0.59				
	185	0.23	0.42	0.33	0.63				
	185	0.24	0.42	0.33	0.54	0.25	0.43	0.34	0.59

TABLE C-4 Eastbound FWD Deflections and Modulus Calculations for Sensors D4 (at 24 in.), D5 (at 36 in.), and D6 (at 48 in.)

Chemical Additive	Station (ft.x100)	Sensor Deflections (mils)			Subbase/Subgrade Modulus (ksi)		
		D4	D5	D6	D4	D5	D6
Granular Quick Lime	140.00	3.34	2.53	1.91	21.0	18.5	18.5
	141.01	1.62	1.16	0.87	43.2	40.2	40.4
	142.01	2.27	1.61	1.16	30.8	29.0	30.3
	143.00	2.46	1.76	1.29	28.5	26.6	27.1
	144.00	3.94	3.03	2.25	17.8	15.5	15.6
	145.01	1.87	1.17	0.78	37.6	40.0	44.9
	146.02	1.90	1.42	1.06	36.9	33.0	33.1
	147.03	1.50	1.11	0.87	46.7	42.2	40.2
	148.00	1.48	1.17	0.94	47.4	40.2	37.4
	149.02	1.64	1.27	1.03	42.9	37.1	34.3
	150.01	1.91	1.36	1.06	36.7	34.4	33.3
	151.01	2.01	1.55	1.23	34.8	30.2	28.4
	152.00	1.78	1.26	0.92	39.4	37.1	38.2
	153.01	1.72	1.31	1.00	40.9	35.7	35.3
	154.00	1.60	1.27	1.03	43.8	36.8	34.2
	155.01	2.84	1.79	1.14	24.6	26.1	30.8
Holnam CKD	156.01	1.32	0.90	0.63	53.1	52.3	56.3
	157.01	1.10	0.58	0.39	63.7	80.7	90.2
	158.01	0.77	0.55	0.34	90.9	85.3	103.4
	159.10	1.06	0.67	0.45	66.6	70.7	78.8
Lone Star CKD	160.00	1.64	0.89	0.52	43.0	52.8	67.9
	161.00	1.47	0.72	0.34	47.7	65.4	103.9
	162.00	2.22	1.57	1.19	31.6	29.8	29.5
	163.00	2.65	1.79	1.32	26.5	26.2	26.6
	164.01	3.57	2.46	1.79	19.6	19.0	19.7
	165.00	4.13	3.00	2.29	17.0	15.6	15.4
	166.01	2.85	1.80	1.18	24.6	25.9	29.6
	167.01	2.49	1.58	1.11	28.2	29.8	31.6
Blue Circle CKD	168.01	3.33	2.12	1.36	21.1	22.1	25.8
	169.00	3.48	1.77	0.93	20.2	26.5	37.7
	170.00	3.78	2.71	1.97	18.5	17.2	17.8
	171.03	3.02	2.10	1.56	23.2	22.3	22.5
	172.02	2.64	1.85	1.39	26.7	25.4	25.4
	173.01	2.64	1.88	1.36	26.6	24.9	25.9
	174.03	2.72	1.84	1.31	25.8	25.5	26.7
	175.00	2.79	2.10	1.64	25.1	22.3	21.3
	176.02	3.10	2.34	1.85	22.7	20.0	19.1
Holnam CKD	177.06	2.56	2.08	1.65	27.4	22.5	21.3
	178.00	2.62	1.95	1.56	26.8	24.0	22.6
	179.00	2.53	1.93	1.54	27.7	24.2	22.8
	180.01	2.54	1.87	1.46	27.6	25.0	24.0
	181.01	2.31	1.80	1.42	30.4	26.0	24.8
	182.00	2.20	1.68	1.20	32.0	28.0	29.4
	183.02	2.37	1.85	1.40	29.8	25.4	25.2
	184.00	2.35	1.76	1.38	29.9	26.7	25.5
	185.00	2.32	1.69	1.39	30.3	27.7	25.3
	186.00	2.29	1.70	1.30	30.9	27.7	27.1

TABLE C-5 Westbound FWD Deflections and Modulus Calculations for Sensors D4 (at 24 in.), D5 (at 36 in.), and D6 (at 48 in.)

Chemical Additive	Station (ft.x100)	Sensor Deflections (mils)			Subbase/Subgrade Modulus (ksi)		
		D4	D5	D6	D4	D5	D6
Granular Quick Lime	140.00	3.84	3.02	2.28	18.3	15.6	15.4
	141.00	2.04	1.47	1.06	34.6	32.0	33.5
	142.03	2.32	1.61	1.18	30.3	29.0	29.8
	142.98	2.29	1.63	1.19	30.7	28.8	29.6
	144.00	3.37	2.63	1.99	20.8	17.8	17.7
	145.00	2.80	1.99	1.42	25.0	23.4	24.7
	145.99	1.68	1.28	0.92	42.0	36.8	38.5
	146.99	1.56	1.26	0.99	45.0	37.3	35.6
	148.00	1.50	1.24	0.98	46.9	38.0	35.9
	149.00	1.65	1.32	1.00	42.6	35.4	35.1
	150.00	1.64	1.27	0.97	43.1	37.2	36.5
	151.94	1.82	1.35	1.05	38.6	34.7	33.6
	153.00	1.71	1.23	0.94	41.2	38.2	37.7
	153.99	1.69	1.27	1.01	41.5	36.8	34.8
	154.99	2.00	1.51	1.10	34.9	30.9	31.9
Holnam CKD	156.00	1.27	0.85	0.58	55.0	55.0	60.4
	157.00	0.94	0.60	0.42	74.9	78.7	84.5
	157.99	0.91	0.56	0.33	77.2	84.4	106.2
	158.99	0.67	0.44	0.27	105.0	106.3	132.4
Lone Star CKD	160.00	1.63	0.92	0.54	43.1	51.1	65.4
	160.99	1.39	0.69	0.37	50.5	68.3	94.5
	162.00	3.04	2.10	1.54	23.2	22.4	22.9
	162.99	2.04	1.39	0.99	34.4	33.7	35.7
	164.01	2.73	1.97	1.49	25.8	23.9	23.6
	165.00	3.84	2.71	2.05	18.4	17.3	17.2
	165.96	4.12	2.48	1.48	17.0	18.9	23.7
	167.00	3.01	2.01	1.39	23.3	23.3	25.3
Blue Circle CKD	167.99	2.90	1.93	1.31	24.3	24.3	26.8
	168.99	2.94	1.61	0.91	23.9	29.1	38.6
	170.00	3.71	2.50	1.71	18.9	18.8	20.6
	171.00	2.92	2.06	1.60	24.1	22.8	22.1
	172.00	2.51	1.65	1.21	28.0	28.4	29.2
	172.98	2.31	1.59	1.17	30.6	29.6	30.2
	173.99	2.40	1.59	1.13	29.3	29.5	31.0
	175.00	3.36	2.47	1.97	20.9	19.0	17.9
	175.94	2.65	1.97	1.48	26.4	23.7	23.8
	176.93	2.52	2.01	1.62	27.8	23.2	21.7
Holnam CKD	177.99	2.43	1.91	1.51	29.0	24.7	23.4
	179.00	2.52	2.03	1.60	27.9	23.1	22.0
	179.99	2.19	1.77	1.41	31.9	26.4	24.8
	180.96	2.14	1.65	1.30	33.0	28.6	27.4
	181.99	2.26	1.79	1.41	31.3	26.3	25.1
	183.00	1.94	1.57	1.21	36.2	29.8	29.0
	184.00	2.14	1.68	1.31	32.9	28.0	26.9
	185.00	2.61	1.92	1.50	26.9	24.4	23.3
	185.92	2.03	1.54	1.16	34.6	30.4	30.3

TABLE D-1 Specific Gravity of Soil Solids

	Specific Gravity					
Trial	**1**	**2**	**3**	**4**	**5**	**Avg**
Sand	2.66	2.63	2.70	2.67	2.67	2.66
Shale	2.84	2.81	—	—	—	2.83

TABLE D-2 Grainsize Distribution Data

OU Sandstone Data		
Sieve Analysis		
Sieve No.	**Opening Size (mm)**	**Percent Finer (%)**
4	4.75	100.0
10	2.00	99.8
20	0.850	97.3
40	0.420	94.5
60	0.250	82.4
80	0.177	51.0
100	0.149	37.5
200	0.075	8.6

OU Shale Data		
Sieve Analysis		
Sieve No.	**Opening Size (mm)**	**Percent Finer (%)**
10	2.00	100.0
200	0.075	93.9
Hydrometer Analysis		
	0.0644	94.2
	0.0472	89.1
	0.0342	85.7
	0.0250	80.5
	0.0180	77.1
	0.0130	73.7
	0.0097	70.2
	0.0070	65.1
	0.0050	65.1
	0.0025	51.4
	0.0012	30.8

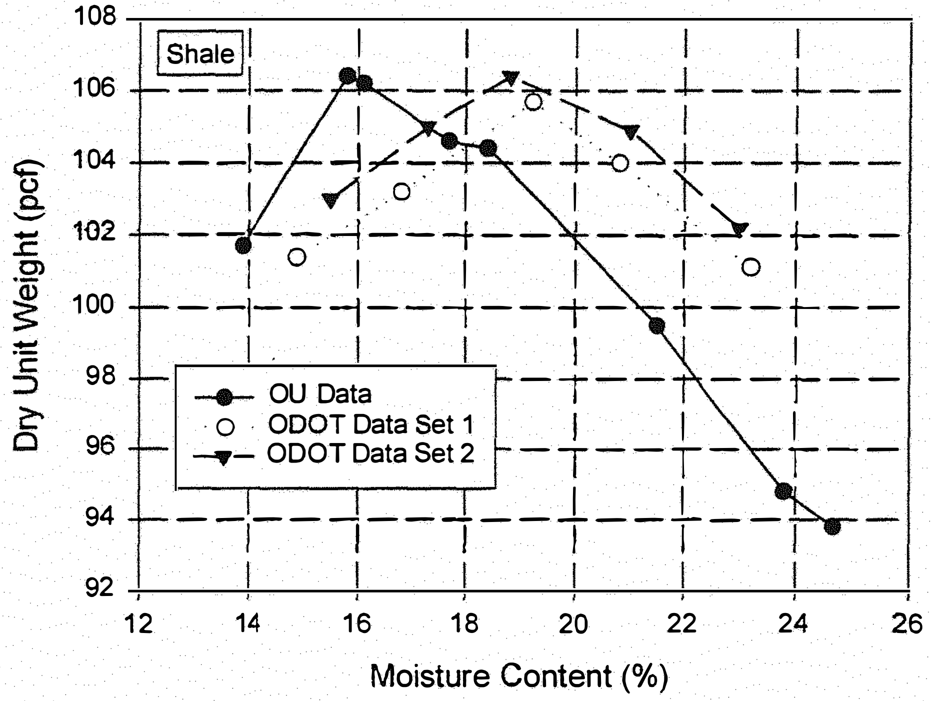
ODOT Shale Data		
Sieve Analysis		
Sieve No.	**Opening Size (mm)**	
10	2.00	100.0
12	1.70	100.0
16	1.18	99.9
20	0.850	99.8
30	0.600	99.7
40	0.420	99.5
50	0.355	99.3
60	0.250	99.1
70	0.212	98.8
80	0.177	98.7
100	0.149	98.0
140	0.106	97.1
170	0.090	96.6
200	0.075	95.8
270	0.053	93.4
Hydrometer Analysis		
	0.0261	78.9
	0.0168	74.9
	0.0099	68.9
	0.0071	65.9
	0.0052	59.9
	0.0026	52.9
	0.0011	40.0

TABLE D-3 Standard Proctor Effort Moisture-Density Test Data

OU Data	
Shale	
Water Content (%)	Dry Density (pcf)
13.9	101.7
15.8	106.4
16.1	106.2
17.7	104.6
18.4	104.4
21.5	99.5
23.8	94.8
24.7	93.8

ODOT Data Set 1		ODOT Data Set 2	
Shale		Shale	
Water Content (%)	Dry Density (pcf)	Water Content (%)	Dry Density (pcf)
14.9	101.4	15.5	103.0
16.8	103.2	17.3	105.0
19.2	105.7	18.8	106.4
20.8	104.0	21.0	104.9
23.2	101.1	23.0	102.2

OU Data	
Sand	
Water Content (%)	Dry Density (pcf)
5.5	103.3
6.9	103.1
8.5	103.7
9.8	103.9
10.9	104.6
13.2	107.1
15.1	106.9
16.6	107.6
17.9	107.0
18.1	106.7
18.6	108.1



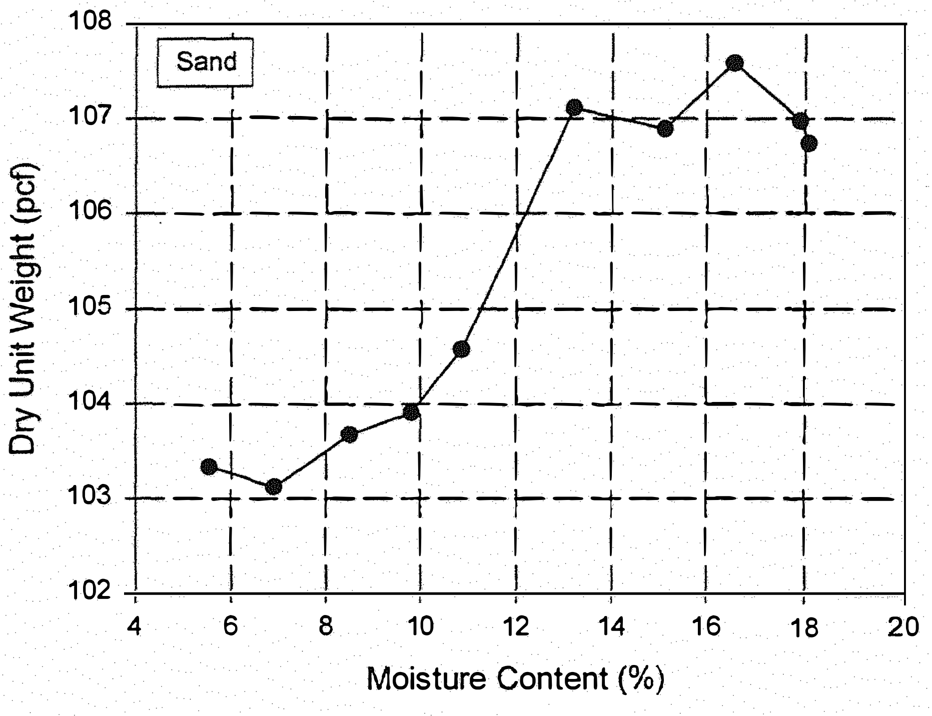


FIG. D-1 Standard Proctor Effort Moisture-Density Data

TABLE E-1 pH Data for CKD

	p H					
	SHALE			SAND		
% of CKD	Holnam	Lone Star	Blue Circle	Holnam	Lone Star	Blue Circle
0	7.55	7.60	7.58	5.82	5.35	5.23
2	10.75	9.42	9.45	11.85	11.32	11.11
4	11.51	10.10	10.16	12.16	11.72	11.68
6	11.79	10.17	10.96	12.30	11.93	11.89
10	12.06	11.41	11.44	12.42	12.17	12.12
15	12.23	11.76	11.77	12.49	12.33	12.27
20	12.30	11.93	11.90	12.52	12.43	12.35
100	12.52	12.65	12.48	12.67	12.75	12.59

TABLE E-2 pH Data for Lime

	pH	
	SHALE	SAND
% of Lime	Lime	Lime
0	7.42	5.18
1	12.00	12.37
2	12.37	12.43
4	12.44	12.46
5	12.45	12.46
8	12.46	12.47
10	12.49	12.47
100	12.51	12.48

TABLE E-3 UCT Data for Shale

	Unconfined Compression Strength, UCS (psi)				
	3 days	7 days	14 days	28 days	90 days
Raw Soil	---	51	---	---	43
	---	48	---	—	44
	---	49	---	—	47
Average	---	**49**	---	—	**45**
Granular Quick Lime + Soil	52	52	72	67	95
	51	58	58	73	91
	56	62	57	90	117
Average	**53**	**57**	**62**	**77**	**101**
Holnam CKD + Soil	125	233	184	246	306
	165	242	247	265	279
	152	265	247	253	301
Average	**147**	**247**	**226**	**255**	**295**
Lonestar CKD + Soil	94	147	146	149	139
	120	133	142	142	127
	76	99	185	139	138
Average	**97**	**126**	**157**	**144**	**135**
Blue Circle CKD + Soil	95	101	120	123	60
	77	115	104	103	113
	82	111	89	86	84
Average	**85**	**109**	**104**	**104**	**85**

TABLE E-4 UCT Data for Sand

	Unconfined Compression Strength, UCS (psi)				
	3 days	7 days	14 days	28 days	90 days
Raw Soil	---	1.3	---	1.9	2.5
	---	1.9	---	2.2	2.5
	---	1.3	—	1.9	2.5
Average	---	**1.5**	---	2.0	**2.5**
Granular Quick Lime + Soil	7	13	13	19	22
	8	11	15	18	25
	9	11	16	18	24
Average	**8**	**12**	**15**	**18**	**24**
Holnam CKD + Soil	33	139	219	252	342
	37	116	249	200	338
	43	113	241	248	339
Average	**38**	**123**	**236**	**233**	**340**
Lonestar CKD + Soil	43	70	94	106	149
	46	63	104	116	124
	44	77	113	96	135
Average	**44**	**70**	**103**	**106**	**136**
Blue Circle CKD + Soil	38	73	91	111	165
	46	75	92	108	163
	43	66	99	127	172
Average	**42**	**71**	**94**	**115**	**167**

TABLE E-5 Moisture Content and Density Data for UCT Shale Samples

	3 days		7 days		14 days		28 days		90 days	
	Water Content (%)	Dry Density (pcf)	Water Content (%)	Dry Density (pcf)	Water Content (%)	Dry Density (pcf)	Water Content (%)	Dry Density (pcf)	Water Content (%)	Dry Density (pcf)
Raw Soil	—	—	16.0	109.1	—	—	—	—	14.9	108.3
	—	—	15.8	108.2	—	—	—	—	15.0	107.1
	—	—	15.5	109.4	—	—	—	—	14.7	108.2
Average	—	—	**15.8**	**108.9**	—	—	—	—	**14.9**	**107.9**
Granular Quick Lime + Soil	20.1	101.0	20.1	98.3	21.6	101.4	20.1	97.5	20.2	97.5
	20.1	100.7	20.1	101.9	21.3	98.4	20.1	96.8	20.1	99.3
	20.7	99.2	20.1	98.5	21.6	99.4	21.0	97.9	20.0	96.8
Average	**20.3**	**100.3**	**20.1**	**99.6**	**21.5**	**99.7**	**17.3**	**97.4**	**20.1**	**97.9**
Holnam CKD + Soil	16.9	105.4	16.9	106.1	16.3	104.7	17.6	105.4	16.6	102.7
	17.4	103.9	17.0	107.6	16.0	103.2	18.1	104.2	17.4	103.2
	17.5	102.7	16.6	106.5	16.7	101.8	17.9	102.6	17.0	104.1
Average	**17.3**	**104.0**	**16.8**	**106.7**	**16.3**	**103.2**	**17.9**	**104.0**	**17.0**	**103.3**
Lonestar CKD + Soil	17.6	100.3	18.1	103.3	18.7	103.2	18.6	100.8	17.7	102.6
	19.9	103.3	17.4	102.0	19.1	101.0	17.8	102.4	20.2	102.7
	20.4	102.1	17.3	102.3	18.4	100.4	17.9	103.1	18.4	103.6
Average	**19.3**	**101.9**	**17.6**	**102.5**	**18.7**	**101.5**	**18.1**	**102.1**	**18.8**	**103.0**
Blue Circle CKD + Soil	17.8	103.7	18.2	105.2	17.4	105.5	18.6	103.7	17.5	100.1
	16.9	102.1	17.9	104.3	17.8	102.2	18.2	104.1	17.6	104.0
	16.9	104.8	17.9	103.8	17.4	103.4	18.3	99.2	18.1	102.9
Average	**17.2**	**103.6**	**18.0**	**104.4**	**17.5**	**103.7**	**18.4**	**102.3**	**17.7**	**102.3**

TABLE E-6 Moisture Content and Density Data for UCT Sand Samples

	3 days		7 days		14 days		28 days		90 days	
	Water Content (%)	Dry Density (pcf)	Water Content (%)	Dry Density (pcf)	Water Content (%)	Dry Density (pcf)	Water Content (%)	Dry Density (pcf)	Water Content (%)	Dry Density (pcf)
Raw Soil	—	—	14.7	101.0	—	—	11.8	103.1	11.7	104.4
	—	—	14.5	101.9	—	—	11.7	103.8	11.6	104.1
	—	—	14.0	101.0	—	—	11.9	104.0	12.0	103.8
Average	—	—	**14.4**	**101.3**	—	—	**11.8**	**103.6**	**11.8**	**104.1**
Granular Quick Lime + Soil	16.4	106.1	16.0	106.5	15.9	106.4	16.5	110.7	20.8	102.8
	18.4	103.8	15.7	106.6	15.6	106.8	16.0	110.8	17.9	104.5
	19.7	102.8	16.3	106.0	16.5	107.5	15.4	107.4	17.2	104.4
Average	**18.2**	**104.2**	**16.0**	**106.3**	**16.0**	**106.9**	**16.0**	**109.6**	**18.6**	**103.9**
Holnam CKD + Soil	15.7	109.5	14.8	112.5	15.0	109.2	14.7	108.7	16.4	108.6
	15.1	110.7	15.5	108.1	15.1	108.6	14.5	108.5	15.2	109.9
	15.0	109.6	15.3	108.3	15.1	108.5	15.2	108.3	17.0	106.9
Average	**16.9**	**109.9**	**15.2**	**109.6**	**15.0**	**108.8**	**14.8**	**108.5**	**16.2**	**108.5**
Lonestar CKD + Soil	15.6	112.1	15.6	111.9	16.2	111.8	15.0	112.3	16.8	110.8
	15.5	112.8	15.4	112.3	15.2	112.1	14.9	112.2	17.2	111.6
	15.8	113.3	15.3	112.5	14.9	113.8	15.6	112.1	15.5	113.5
Average	**15.6**	**112.7**	**15.5**	**112.2**	**15.4**	**112.6**	**15.2**	**112.2**	**16.5**	**112.0**
Blue Circle CKD + Soil	15.7	114.3	18.8	110.9	16.5	111.2	15.8	112.2	17.6	110.9
	15.6	114.4	15.9	112.8	13.8	113.8	15.9	112.5	17.1	111.2
	15.8	114.4	16.0	112.7	18.2	111.4	15.3	113.7	17.4	111.4
Average	**15.7**	**114.4**	**16.9**	**112.1**	**16.2**	**112.1**	**15.7**	**112.8**	**17.4**	**111.2**

TABLE E-7 Atterberg Limit Data for Shale for Moist Curing

Curing Time (days)	Lone Star CKD	Blue Circle CKD	Holnam CKD	Quick Lime
Liquid Limit				
0	57.1	54.2	54.9	58.8
3	63.4	60.4	69.4	68.6
7	64.4	59.1	72.2	72.1
14	67.6	62.5	76.4	74.6
28	68.5	61.6	79.5	79.6
90	66.5	62.5	88.7	91.5
Plastic Limit				
0	29.3	28.0	30.5	29.9
3	30.5	28.0	34.7	30.8
7	30.9	28.5	37.6	34.8
14	30.0	25.6	38.5	36.5
28	28.8	26.2	39.6	39.3
90	27.0	24.2	42.6	45.9
Plasticity Index				
0	27.8	26.3	24.4	28.9
3	32.9	32.4	34.7	37.8
7	33.5	30.6	34.6	37.4
14	37.6	36.9	38.0	38.1
28	39.8	35.5	39.9	40.3
90	39.5	38.3	46.2	45.6

TABLE E-8 Atterberg Limit Data for Shale for Dry Curing

Curing Time (days)	Lone Star CKD	Blue Circle CKD	Holnam CKD	Quick Lime
Liquid Limit				
7	46.1	40.1	51.6	55.4
14	46.6	45.7	52.1	54.0
28	49.7	48.0	57.1	50.3
90	45.5	45.0	55.4	49.0
Plastic Limit				
7	25.8	21.7	21.3	29.8
14	24.3	20.3	25.0	30.6
28	25.4	23.3	30.9	24.5
90	23.9	21.3	31.3	23.8
Plasticity Index				
7	20.3	18.4	30.3	25.7
14	22.4	25.4	25.0	23.4
28	24.2	24.8	26.2	25.8
90	21.6	23.7	24.1	25.2

TABLE E-9 Atterberg Limit Data for Atoka and Miller Clay for Moist Curing

	Atoka Clay		Miller Clay	
Curing Time (days)	Holnam CKD	Quick Lime	Holnam CKD	Quick Lime
Liquid Limit				
0	60.4	55.6	70.8	67.8
3	55.3	57.6	67.3	66.0
7	69.9	65.2	70.5	69.3
14	74.2	70.9	69.1	68.1
28	84.0	76.9	68.1	67.2
90	77.6	77.6	50.9	71.8
Plastic Limit				
0	27.4	35.2	44.9	49.5
3	34.7	37.4	46.1	49.1
7	37.0	41.2	47.6	50.2
14	49.4	42.7	46.8	49.5
28	49.7	45.1	49.5	50.5
90	49.4	49.4	73.4	52.5
Plasticity Index				
0	32.9	20.4	25.9	18.4
3	20.6	20.2	21.2	16.9
7	32.9	23.9	22.9	19.1
14	24.8	28.2	22.3	18.5
28	34.3	31.7	18.5	16.7
90	28.2	28.2	22.6	19.4

TABLE E-10 Atterberg Limit Data for Atoka and Miller Clay for Dry Curing

	Atoka Clay		Miller Clay	
Curing Time (days)	Holnam CKD	Quick Lime	Holnam CKD	Quick Lime
Liquid Limit				
7	69.9	65.2	62.1	52.1
14	74.2	70.9	57.4	54.8
28	84.0	76.9	56.7	53.8
90	77.6	77.6		
Plastic Limit				
7	37.0	41.2	41.2	39.9
14	49.4	42.7	40.1	32.9
28	49.7	45.1	39.2	33.9
90	49.4	49.4		
Plasticity Index				
7	32.9	23.9	20.9	12.2
14	24.8	28.2	17.3	21.9
28	34.3	31.7	17.5	20.0
90	28.2	28.2		

TABLE E-11 Durability UCT Data

	UCS for Wet-Dry Cycles (psi)			UCS for Freeze-Thaw Cycles (psi)		
Cycle	**Sand + Holnam CKD**	**Shale + Holnam CKD**	**Shale + Lime**	**Sand + Holnam CKD**	**Shale + Holnam CKD**	**Shale + Lime**
0	120	475	56	127	228	53
0	123	468	47	114	247	56
0	122	462	58	123	262	62
Avg.	**122**	**468**	**54**	**121**	**246**	**57**
1	228	522	40	165	249	68
1	209	570	35	176	241	55
1	171	518	41	146	254	51
Avg.	**203**	**536**	**39**	**162**	**248**	**58**
3	266	719	-	167	237	94
3	289	725	-	177	243	98
3	260	728	-	190	257	82
Avg.	**271**	**724**	**-**	**178**	**246**	**91**
7	352	-	-	147	272	91
7	449	-	-	152	222	105
7	390	-	-	157	238	108
Avg.	**397**	**-**	**-**	**152**	**244**	**101**
12	542	-	-	151	279	124
12	468	-	-	157	234	133
12	425	-	-	177	392	160
Avg.	**479**	**-**	**-**	**162**	**302**	**139**

TABLE E-12 Moisture Content and Density Data for Durability UCT Samples Subjected to Wet-Dry Cycles

	Sand + Holnam CKD		Shale + Holnam CKD		Shale + Lime	
Cycle	Water Content (%)	Dry Density (pcf)	Water Content (%)	Dry Density (pcf)	Water Content (%)	Dry Density (pcf)
0	0.53	107.2	0.29	104.1	0.43	100.1
0	0.00	107.8	0.40	103.9	0.35	98.9
0	0.29	107.8	0.30	105.9	0.41	98.2
Avg.	**0.27**	**107.6**	**0.33**	**104.6**	**0.40**	**99.1**
1	0.77	107.1	0.00	104.5	0.20	96.7
1	0.00	106.7	0.40	103.0	0.10	99.8
1	0.33	106.9	0.40	104.0	0.40	98.8
Avg.	**0.37**	**106.9**	**0.27**	**103.9**	**0.23**	**98.5**
3	0.54	107.4	0.29	105.6	—	—
3	0.42	108.8	0.38	103.2	—	—
3	0.40	108.0	0.62	102.1	—	—
Avg.	**0.45**	**108.1**	**0.43**	**103.6**	—	—
7	0.56	106.5	—	—	—	—
7	0.62	108.2	—	—	—	—
7	0.26	107.5	—	—	—	—
Avg.	**0.48**	**107.4**	—	—	—	—
12	0.36	110.0	—	—	—	—
12	0.30	109.9	—	—	—	—
12	0.46	109.3	—	—	—	—
Avg.	**0.38**	**109.7**	—	—	—	—

TABLE E-13 Moisture Content and Density Data for Durability UCT Samples Subjected to Freeze-Thaw Cycles

	Sand + Holnam CKD		Shale + Holnam CKD		Shale + Lime	
Cycle	Water Content (%)	Dry Density (pcf)	Water Content (%)	Dry Density (pcf)	Water Content (%)	Dry Density (pcf)
0	15.7	109.5	16.9	106.1	20.1	98.3
0	15.1	110.7	17.0	107.6	20.1	101.9
0	15.0	109.6	16.6	106.5	20.1	98.5
Avg.	**15.3**	**109.9**	**16.8**	**106.7**	**20.1**	**99.6**
1	14.5	107.6	16.2	106.6	18.9	96.5
1	14.3	107.8	16.0	110.4	18.5	96.0
1	14.5	107.7	15.2	106.9	19.5	97.9
Avg.	**14.4**	**107.7**	**15.8**	**107.9**	**19.0**	**96.8**
3	13.7	107.9	13.6	108.0	17.5	99.6
3	12.1	109.2	14.2	106.6	18.7	101.9
3	13.1	108.6	15.3	107.5	18.7	101.0
Avg.	**13.0**	**108.6**	**14.3**	**107.4**	**18.3**	**100.8**
7	11.1	109.6	14.8	106.9	16.6	99.9
7	11.0	110.1	14.8	105.5	18.3	101.0
7	10.3	109.3	14.0	106.0	17.8	100.7
Avg.	**10.8**	**109.7**	**14.5**	**106.1**	**17.6**	**100.5**
12	1.8	110.9	5.1	105.7	10.7	100.7
12	1.7	111.5	5.2	105.2	12.6	101.2
12	1.8	111.7	5.1	109.0	13.0	102.1
Avg.	**1.7**	**111.3**	**5.1**	**106.6**	**12.1**	**101.3**

TABLE E-14 One Dimensional Swell Test Data for Shale with No Curing Period

Shale + Lime		Shale + Holnam CKD		Raw Shale	
Elaspsed Time (min.)	Vertical Strain (%)	Elaspsed Time (min.)	Vertical Strain (%)	Elaspsed Time (min.)	Vertical Strain (%)
0	0.000	0	0.000	0	0.000
0.1	0.060	0.1	0.030	0.1	0.000
0.25	0.120	0.25	0.060	0.25	0.010
0.5	0.190	0.5	0.120	0.5	0.010
1	0.280	1	0.170	1	0.020
2	0.380	2	0.210	2	0.030
4	0.450	4	0.250	4	0.060
8	0.480	8	0.300	8	0.090
15	0.510	15	0.340	15	0.130
30	0.530	30	0.390	30	0.240
60	0.550	60	0.400	60	0.410
120	0.570	120	0.530	120	0.660
480	0.640	1330	1.050	1329	2.730
1100	0.700	1779	1.070	1744	2.850
1580	0.740	2881	1.080	2881	2.960
1880	0.760	7110	1.100	7110	3.080
2510	0.800	—	—	—	—
2630	0.840	—	—	—	—
3075	0.910	—	—	—	—
3570	0.910	—	—	—	—
4710	0.920	—	—	—	—
6060	0.930	—	—	—	—
7560	0.940	—	—	—	—

TABLE E-15 One Dimensional Swell Test Data for Shale with 14 Days of Curing

Shale + Lime		Shale + Holnam CKD		Raw Shale	
Elaspsed Time (min.)	Vertical Strain (%)	Elaspsed Time (min.)	Vertical Strain (%)	Elaspsed Time (min.)	Vertical Strain (%)
0	0.000	0	0.000	0	0.000
0.1	0.030	0.1	0.020	0.1	0.020
0.25	0.060	0.25	0.025	0.25	0.080
0.5	0.100	0.5	0.030	0.5	0.130
1	0.130	1	0.035	1	0.140
2	0.150	2	0.045	2	0.150
4	0.170	4	0.060	4	0.150
8	0.180	8	0.060	8	0.150
15	0.220	15	0.060	15	0.150
30	0.250	30	0.060	60	0.440
60	0.300	60	0.060	1445	0.830
120	0.390	120	0.060	2185	0.920
1329	0.510	480	0.060	4425	1.130
1744	0.530	1100	0.060	6180	1.170
2881	0.690	4425	0.070	13080	1.220
7110	0.700	6180	0.070	—	—
—	—	13080	0.070	—	—

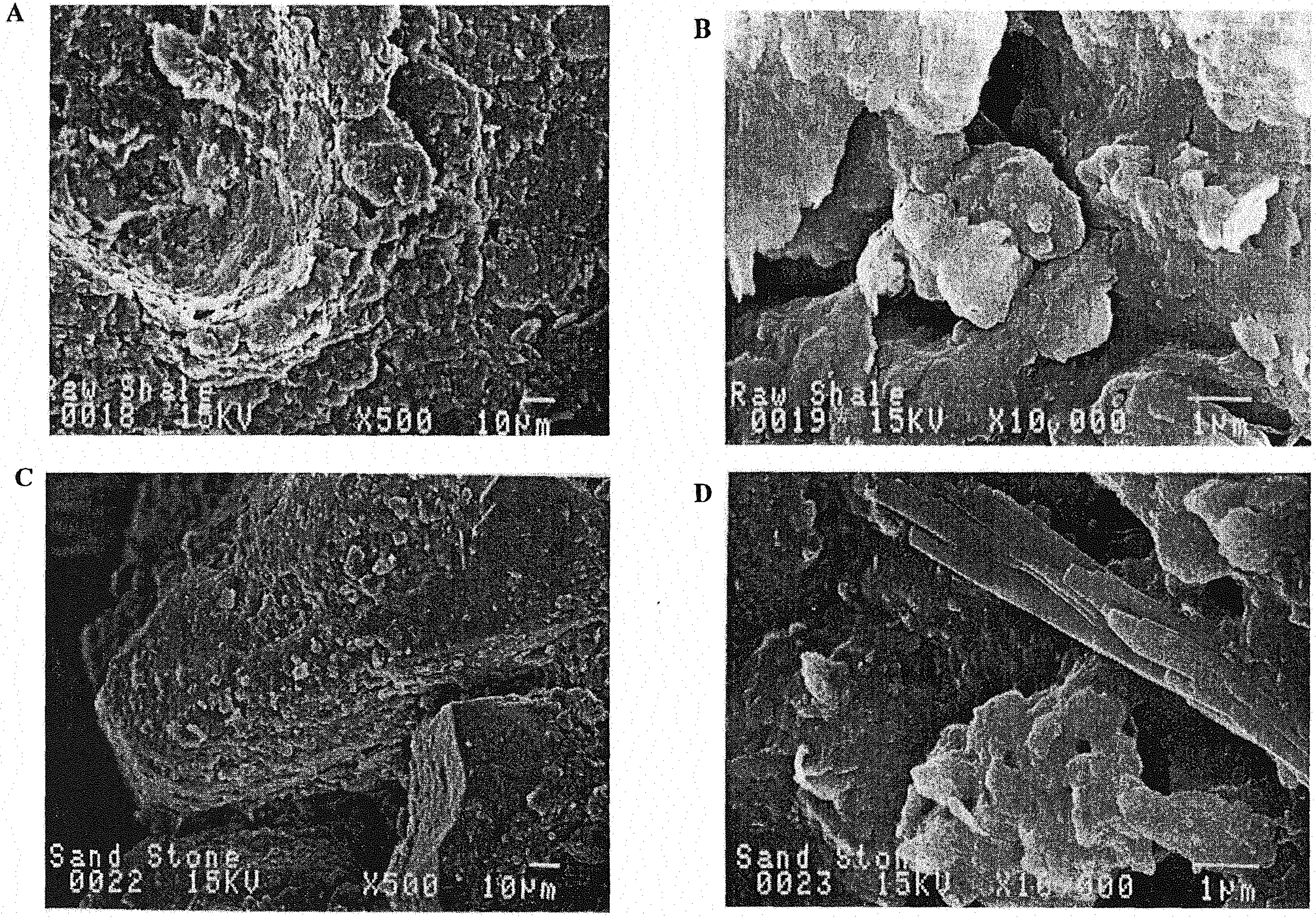


FIG. F-1 Scanning Electron Micrograph of A) Shale at 500x Magnification, B) Shale at 10,000x Magnification, C) Sand Stone at 500x Magnification, D) Sand Stone at 10,000x Magnification.

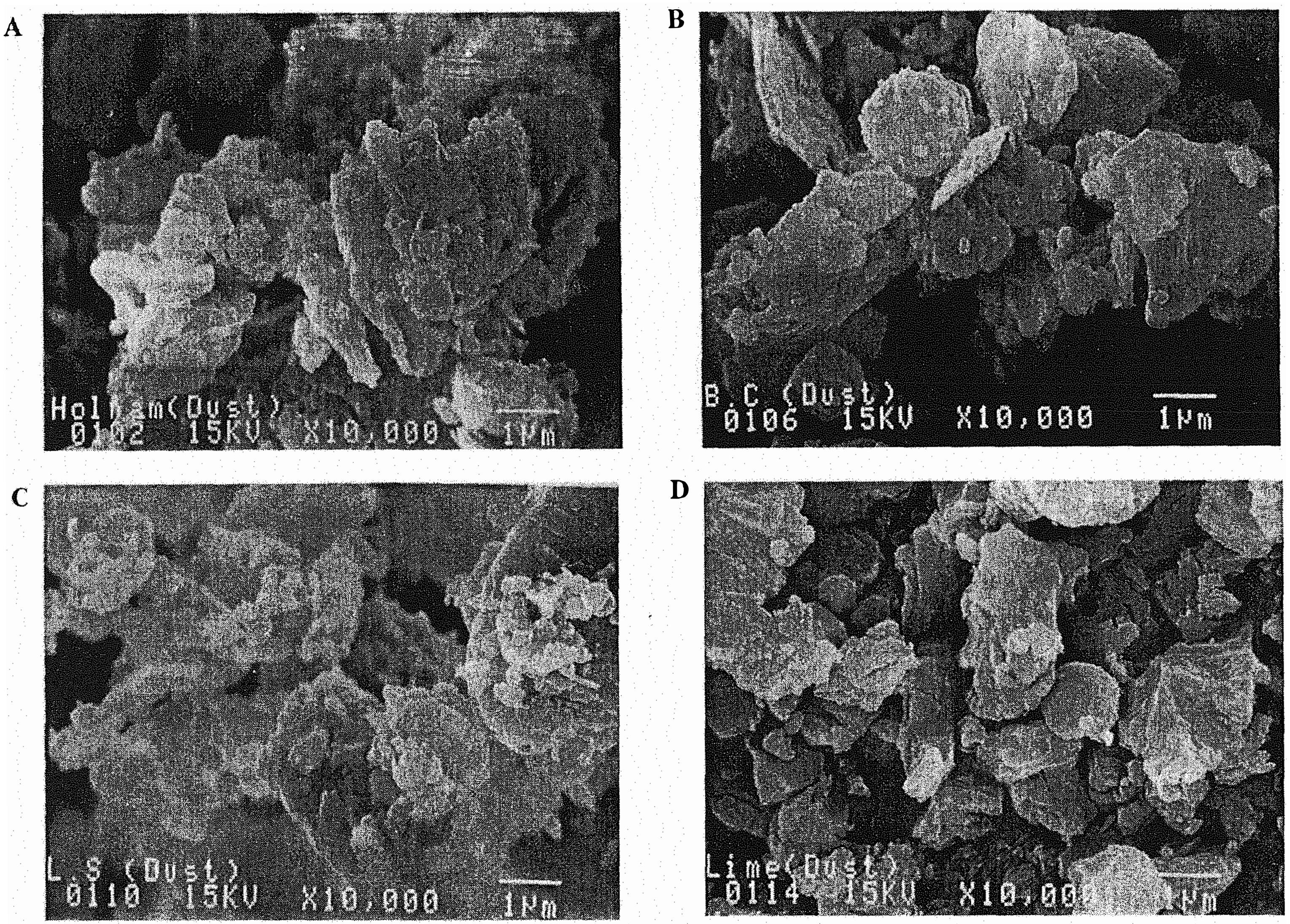


FIG. F-2 Scanning Electron Micrograph at 10,000x Magnification of A) Holnam CKD, B) Blue Circle CKD, C) Lone Star CKD, D) Lime

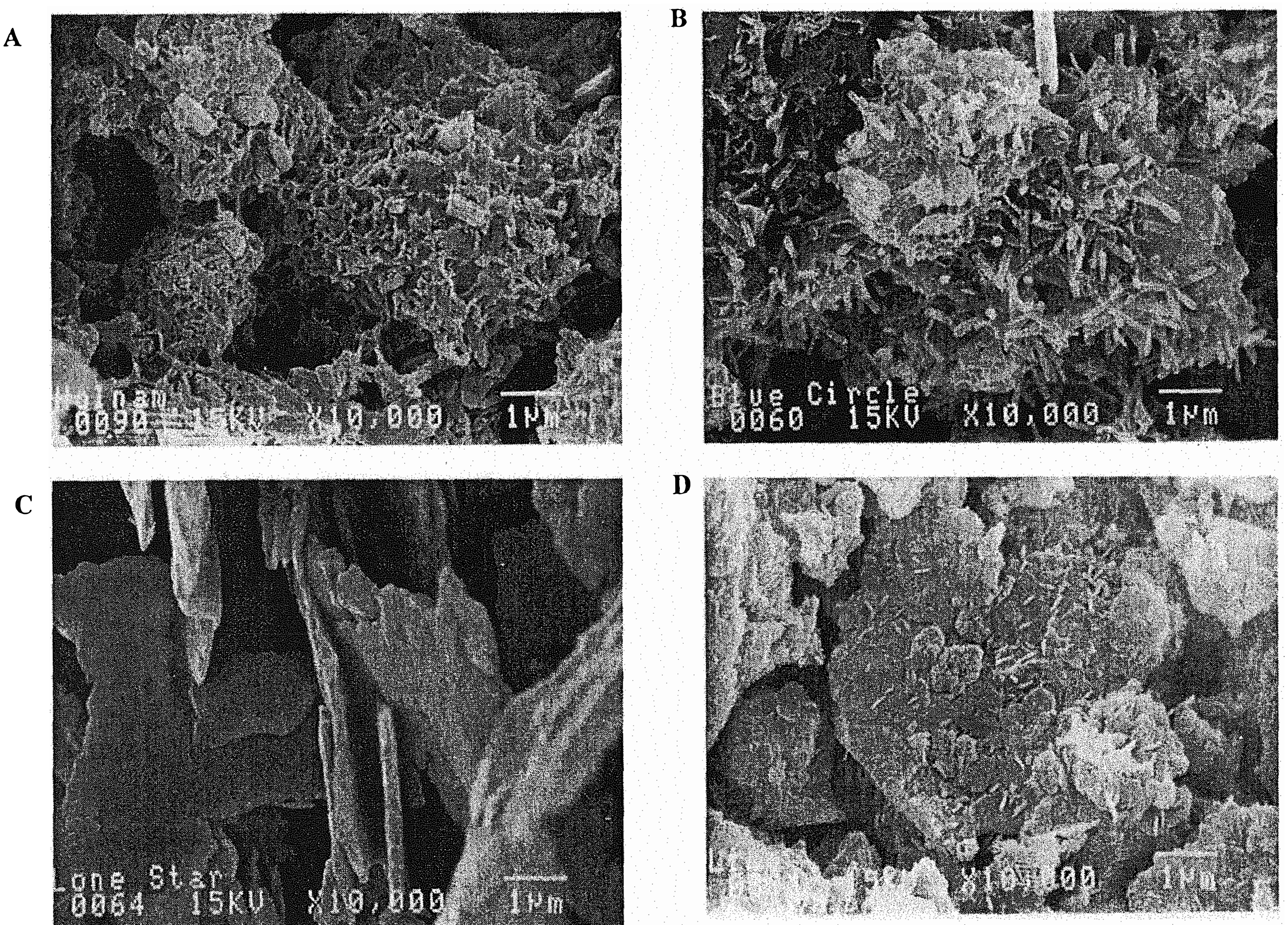


FIG. F-3 Scanning Electron Micrograph at 10,000x Magnification of A) Holnam CKD, B) Blue Circle CKD, C) Lone Star CKD, and D) Lime, after Mixing with Water and Curing

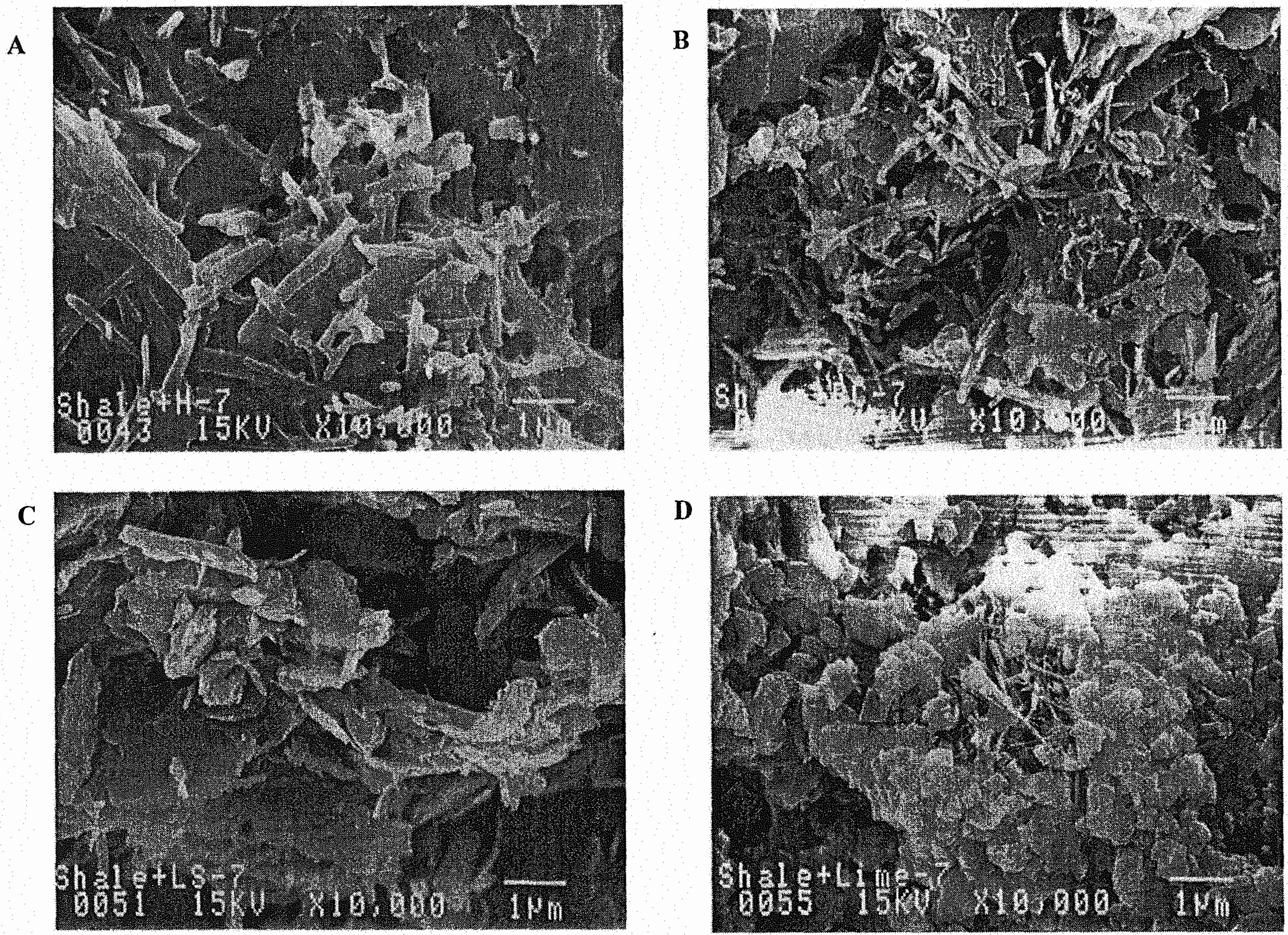


FIG. F-4 Scanning Electron Micrograph at 10,000x Magnification for 7-Day Cured Shale Mixed with A) Holnam CKD, B) Blue Circle CKD, C) Lone Star CKD, D) Lime

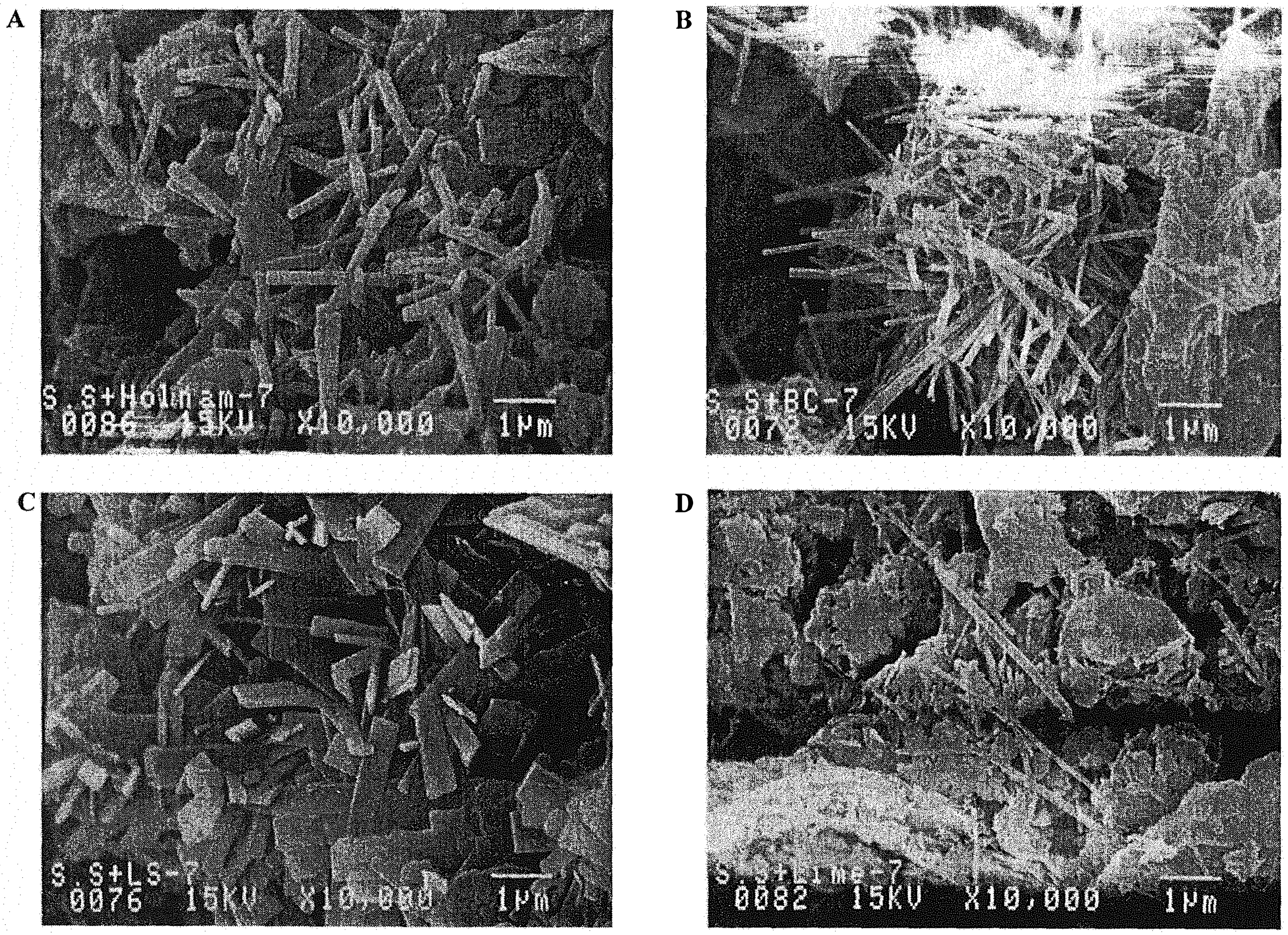


FIG. F-5 Scanning Electron Micrograph at 10,000x Magnification for 7-Day Cured Sand Stone Mixed with A) Holnam CKD, B) Blue Circle CKD, C) Lone Star CKD, D) Lime

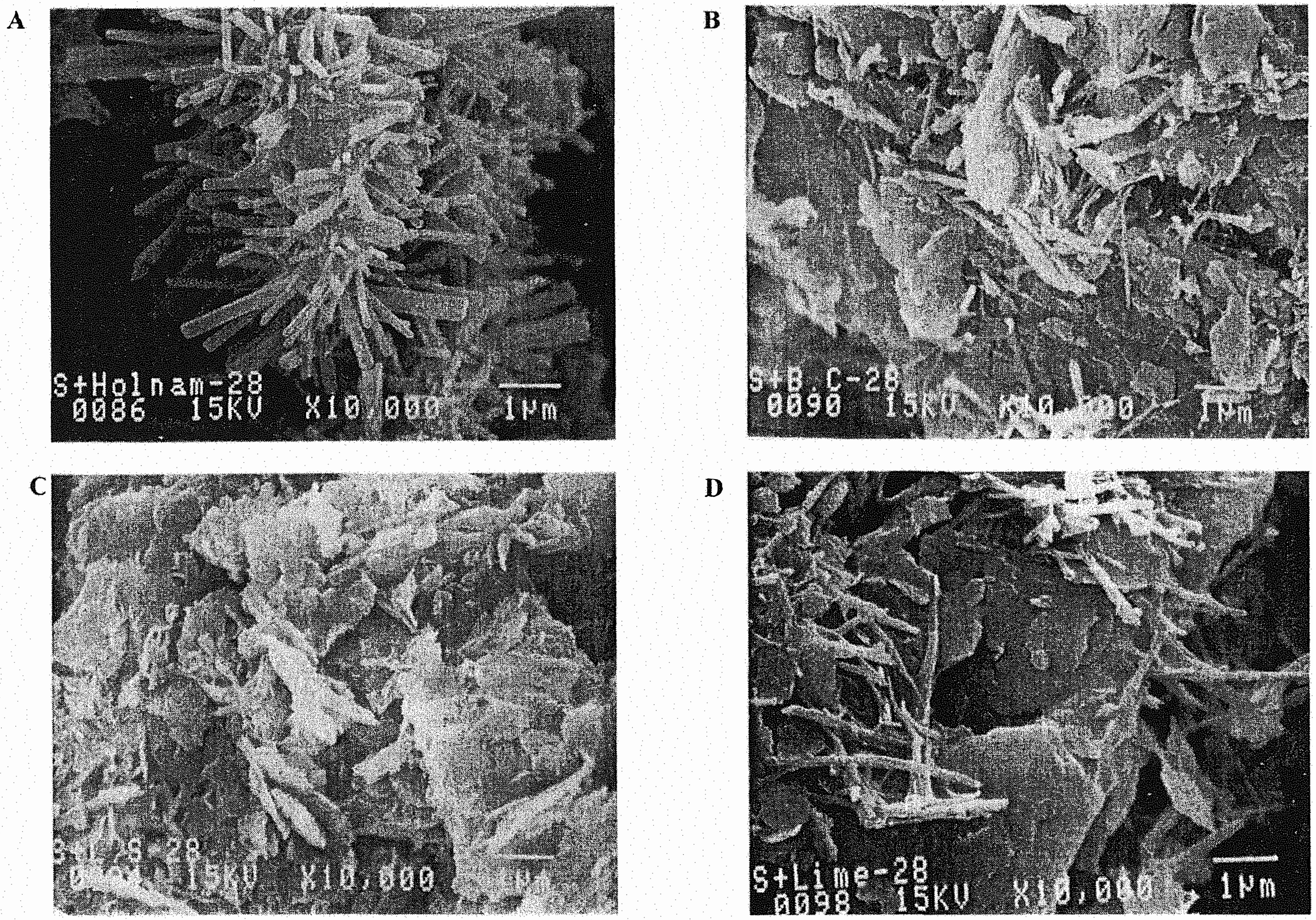


FIG. F-6 Scanning Electron Micrograph at 10,000x Magnification for 28-Day Cured Shale Mixed with A) Holnam CKD, B) Blue Circle CKD, C) Lone Star CKD, D) Lime

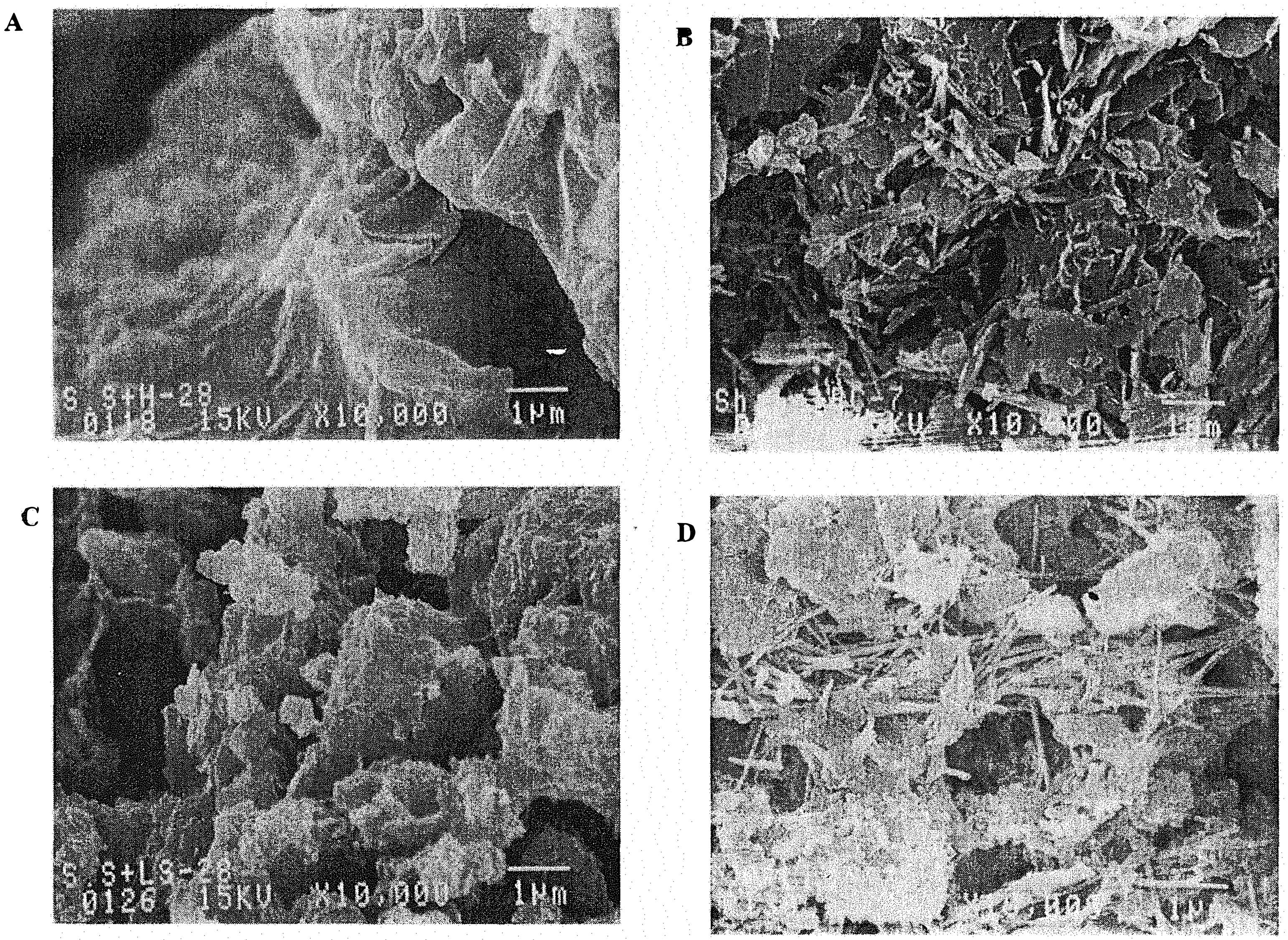


FIG. F-7 Scanning Electron Micrograph at 10,000x Magnification for 28-Day Cured Sand Stone Mixed with A) Holnam CKD, B) Blue Circle CKD, C) Lone Star CKD, D) Lime

SECTION 3XX
SUBGRADE STABILIZATION WITH CEMENT KILN DUST

3XX.01. DESCRIPTION. This work shall consist of furnishing and placing one or more courses of a mixture of soil, cement kiln dust (CKD), and water in accordance with these Specifications and in reasonably close conformity with the lines, grades, thickness and typical cross sections shown on the Plans or established by the Engineer.

In subgrade extents designated on the Plans or by the Engineer as having excessive rock; the dimensions or quantities of which 25% or more is greater than 63 mm, which makes full compliance impractical; the Engineer may waive certain portions of the Standard Specifications as described below. The Engineer may require exploratory scarifying by the Contractor before designation of extents for which the full compliance of Specifications is waived.

3XX.02. MATERIALS. Materials shall meet the requirements specified in the following Subsections of Section 700 – Materials.

Water	701.04
Cement Kiln Dust	7XX.XX

When CKD is stored, it shall be stored in a suitable weathertight building or compartment which will protect the CKD from dampness, and placed in such a manner as to permit easy access for proper inspection and identification of each shipment. Cement kiln dust, which for any reason has become partially set or which contains hard lumps or cakes shall not be used. Cement kiln dust from different sources, although tested, shall not be mixed in storage.

3XX.03. EQUIPMENT.

(a) **General.** All equipment necessary for the construction of CKD modified subgrade shall be furnished in accordance with requirements of Subsection 108.06 and the following:

(b) **Traveling Plants.** Traveling plants used for soil pulverization and mixing shall be approved in accordance with the requirements of Subsection 301.03(b).

(c) **Compactors.** Equipment for compaction shall meet the requirements of Subsection 301.03(c).

(d) **Sprinklers.** Sprinklers shall meet the requirements of Subsection 301.03(d).

3XX.04. CONSTRUCTION METHODS.

(a) **General.** It is the primary requirement of these Specifications to secure a completed course of treated material containing a uniform mixture of soil, CKD, and water, free from loose or segregated areas, of uniform density and moisture content, well bound for its full depth and with a smooth surface suitable for placing subsequent courses. It shall be the responsibility of the Contractor to regulate the sequence of his work, to use the proper amount of CKD, to maintain the work, and to rework courses as necessary to meet the above requirements.

(b) **Weather Limitations.** Cement kiln dust shall not be applied unless the air temperature is at least 4°C and rising. The air temperature shall be taken 1.2 m above the ground in the shade and away from artificial heat. Cement kiln dust shall not be applied when any portion of the ground is frozen. The Contractor shall be responsible for the protection and quality of the CKD-treated subgrade under any weather conditions.

(c) **Preparation of Existing Roadbed.** Prior to beginning any CKD treatment, the roadbed shall be compacted and shaped to reasonably close conformity with the typical sections, lines and grades as shown on the Plans or established by the Engineer. The Contractor shall be required to roll the subgrade as directed by the Engineer, and to correct any soft areas that this rolling may reveal.

(d) **Scarifying and Loosening.** Scarifying and loosening may be required prior to the application of CKD to achieve the desired results as determined by the Engineer. Precautions shall be taken to avoid forming furrows of loosened material below the depth specified for the bottom of the treated subgrade. Except by special permission from the Engineer, the length of roadway scarified and loosened at any time shall not exceed the length in which mixing with CKD (paragraph 3XX.04(f)) will be completed within two calendar days.

(e) **Application of CKD.** General. The proportion of CKD indicated on the Plans is approximate. CKD shall be applied at the rate as prescribed by the Engineer, based on tests of the subgrade soil and soil-CKD mixtures. Equipment necessary for proper control of application rate of the CKD shall be provided by the Contractor. Where tests indicate a significant change in subgrade soil, the Engineer will establish a new rate as deemed necessary for the section of road affected, and at the time of placing and spreading the CKD, will advise the Contractor of the final rate for the said section.

CKD shall not be applied when wind conditions are such that blowing CKD becomes objectionable to traffic and adjacent property owners. When CKD is applied ahead of a mixing plant, the CKD shall be placed only on that area where the mixing and compaction operations can be completed during the same working day. During the interval of time between application and mixing, CKD that has been exposed to weather conditions resulting in excessive wetting may not be accepted for payment. Payment will not be made for CKD loss due to excessive washing or blowing.

Dry methods of application shall be utilized for placement of the CKD onto the subgrade. Equipment for spreading the CKD shall be approved types, which demonstrate to the Engineer the ability to distribute the CKD uniformly.

Cement kiln dust shall not be applied by the slurry method. It shall not be applied on a subgrade with standing water or otherwise allowed to be exposed to free water during application.

(f) **Mixing.**

1. *General.* Mixing of CKD with the subgrade soil shall follow application and spreading as a continuous construction operation. Work areas for mixing shall not exceed 4000 m^2 unless otherwise authorized by the Engineer.

   The mixing procedure shall be as hereinafter described:

   1.1. *First Mixing.* The moisture content of the subgrade soil shall not exceed 80 percent of optimum as determined by AASHTO T-99 at the time of first mixing. The soil and CKD shall be mixed until a uniform mixture is obtained in which all clods and non-aggregate lumps are reduced to a maximum of 63 mm diameter in size. The addition of water will not be permitted during the first mixing. First mixing operations shall begin no later than four hours after application of the CKD.

   When deemed necessary by the Engineer, any portion of the work area shall be rescarified and additional CKD added to ensure adequate soil stabilization.

   The CKD and soil shall be thoroughly mixed prior to the beginning of final mixing operations.

   1.2. *Final Mixing.* After the soil and CKD have been satisfactorily mixed, additions of water shall be made in the final mixing operations to initiate the soil-CKD reaction. Water shall be sprinkled or sprayed as a mist onto the subgrade in a manner that produces a uniform coverage. The method of mixing shall be an approved procedure utilizing a traveling mixing plant that demonstrates uniform dispersion of CKD and water throughout the soil materials. The quantity of water necessary for the final mixing operations will vary with the nature of the materials, normally 2 to 5 percentage points above the optimum moisture content of the compacted soil-CKD mixture. In any case, sufficient water shall be added in the final mixing process to insure chemical action between CKD and soil.

   All clods shall be reduced in size by mixing until the soil-CKD mixture meets the following size requirements when tested with laboratory sieves:

SIEVE SIZE	PERCENT PASSING
37.5 mm	100
19.0 mm	50 minimum

(g) **Compaction.** Compaction of the soil-CKD mixture shall be performed immediately after final mixing, wherein the compaction operation shall be a continuation of the mixing operation. The target density shall be determined in the field by moisture-density tests on representative samples of the soil-CKD mixture obtained from the roadway when compaction is started. The test method for the target density will be as specified in Subsection 202.02(b) modified to provide one compacted specimen of the soil-CKD mixture as obtained from the roadway, and separate portions of the sample used for additional specimens with the moisture reduced or increased.

The soil-CKD mixture shall be compacted immediately and before any appreciable loss of mixing moisture occurs. Mixing and compaction operations shall be performed in such a manner that the mixture will be compacted within plus or minus 2 percentage points of optimum moisture content. However, during the course of construction, changes or adjustments in the specified moisture requirements to meet field conditions may be authorized by the Engineer.

Compaction shall continue until the entire depth of the mixture is uniformly compacted to no less than 95 percent of the target density. Field density will be determined in accordance with Subsection 202.02(b)(2). The rate of operation and number of rollers shall be sufficient to uniformly compact the section of roadway being processed within 2 hours of final mixing.

The material shall be sprinkled and rolled. All irregularities, depressions or weak spots which develop shall be corrected immediately by scarifying the areas affected, adding or removing material as required and reshaping and recompacting by sprinkling and rolling.

In addition to the requirements specified for density, the full depth of material shown on the Plans shall be uniformly compacted to the extent necessary to remain firm and stable under construction equipment. After each section is completed, density tests as necessary will be made by the Engineer for acceptance. Throughout this entire operation, the shape of the course shall be maintained and the surface upon completion shall be smooth and in conformity with the typical section shown on the Plans and to the established lines and grades. Should the material, due to any reason or cause, lose the required stability, density, or finish before the next course is placed or the work is accepted, it shall be replaced and refinished at the sole expense of the Contractor.

In areas designated by the Engineer as excessive rock areas, it is the intent that compaction be in substantial compliance with these Specifications. However, it is recognized that the soil-CKD mixture may not be uniform and some variation is to be expected in both the target density and optimum moisture dependent on the CKD content of a given sample. In the event that in-place density tests are not practical because of rock in the soil-CKD mixture, the Engineer may waive the density and moisture content requirements and approve compacting by visual observation in lieu of such tests.

(h) Finishing and Curing. After the final layer of the CKD stabilized subgrade has been compacted, it shall be brought within reasonable compliance to the lines, grades and typical sections. The completed section shall then be finished with a suitable roller sufficiently light to prevent hair cracking. The stabilized material shall be maintained at a moisture content satisfactory for proper curing by sprinkling or until a prime, seal, or other course is placed, whichever comes first.

(i) Surface Tolerance. The finished surface tolerance shall be in conformity with Section 301.

3XX.05. METHOD OF MEASUREMENT.

(a) Cement kiln dust will be measured by the metric ton.
(b) Cement kiln dust stabilized subgrade will be measured by the square meter.
(c) Water and rolling will not be measured for payment.

3XX.06. BASIS OF PAYMENT. Accepted quantities of CKD stabilized subgrade, measured as provided above, will be paid for at the contract unit price for:

(A)	CEMENT KILN DUST	METRIC TON
(B)	SUBGRADE STABILIZATION	SQUARE METER

which shall be full compensation for furnishing all materials, equipment, labor and incidentals to complete the work as specified.

SECTION 3XX
CEMENT KILN DUST FOR SUBGRADE STABILIZATION

7XX.01. DESCRIPTION. This Section covers the cement kiln dust (CKD) used as an admixture to stabilize soils. The CKD should be evaluated using ASTM D 4609. At a minimum, when mixed with soil to be stabilized, the selected percentage of CKD should increase the unconfined compressive strength of the soil by at least 350 kPa after a maximum of 7 days of curing. Soil-CKD mixtures used for unconfined compression tests should be compacted to the optimum moisture and density as determined by AASHTO T-99.

The product of only one plant shall be used on the project, unless otherwise approved by the Engineer. The contractor shall provide a suitable means of storing and protecting the CKD against contamination and dampness. Cement kiln dust that has become partially set, contains lumps of caked CKD or has been contaminated will be rejected.