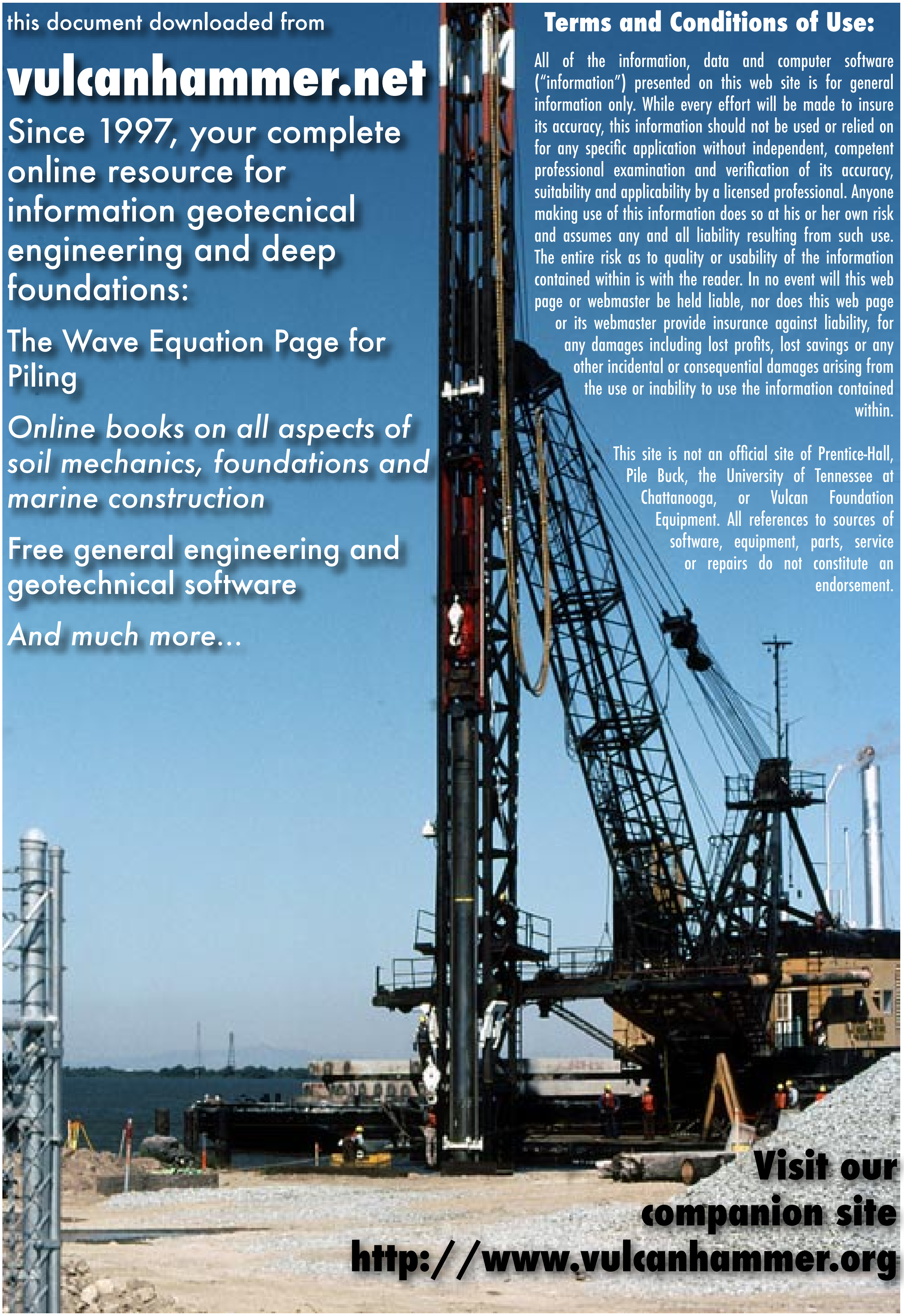

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Report No. K-TRAN: KU-00-6
Final Report

EVALUATION OF SOIL MODIFICATION MIXING PROCEDURES

Robert L. Parsons
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University of Kansas
Lawrence, Kansas

January 2001

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16 Abstract

Lime is routinely used as a soil modification agent in Kansas to improve the performance of subgrade soils with the primary goal of reducing volume change. Effective mixing of lime and soil is critical to ensuring that the expected improvements occur throughout the soil mass. The results are presented herein on the effectiveness of current soil-lime mixing and construction procedures for five soils treated with powdered quicklime or lime slurry. A series of tests was performed on each soil as part of the evaluation process. Test procedures included field density determination, dynamic cone penetrometer, unconfined compression, lime content, pH, Atterberg limits, swell testing, and determination of the maximum unit weights and optimum moisture contents for the native soil and lime treated soil.

The effect of significantly reducing the mellowing period for ease of construction was evaluated and determined to negatively affect subgrade compaction and strength due to high water contents remaining from the mixing process. Additionally, the results of the testing showed that two passes with a rotary mixer were sufficient to effectively pulverize and mix the soil and lime to achieve modification. However, the results also suggested that there was the potential for additional strength gains with additional mixing. The consistency of lime distribution on a larger scale was also evaluated and determined to be adequate at the locations observed, although there was some evidence that the mixing of soil with lime in a slurry form appeared to yield a more consistent final product than mixing with powdered quicklime.

Several recommendations were proposed for consideration by KDOT for soil modification procedures. These included moving from a specified percentage of lime for all projects to a lime percentage based on soil testing. Recommendations also included the introduction of a mellowing period after preliminary mixing to allow the lime more time to react with the soil to break down clay lumps and to give the soil time to dry to a water content closer to optimum. Also proposed for consideration was the adoption of National Lime Association specifications for final mixing, which include the use of AASHTO T-180 as the compaction standard and requiring rotary mixing during the final stage of mixing. Further evaluation of the performance of soils mixed with lime slurry compared with soils mixed with quicklime was recommended to determine if lime slurry yields a significantly better product.

Other recommendations proposed for consideration included an evaluation of the benefits of making soil stabilization a goal of soil treatment and taking advantage of the benefits of including the stabilized layer as a component in the pavement design. Construction costs beyond those already incurred for modification should be relatively small and the additional structural benefits could yield significant savings.

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Evaluation of Soil Modification Mixing Procedures

Final Report
K-TRAN Project KU-00-06

January 2001

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PREFACE

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Executive Summary

Lime is routinely used as a soil modification agent in Kansas to improve the performance of subgrade soils with the primary goal of reducing volume change. Effective mixing of lime and soil is critical to ensuring that the expected improvements occur throughout the soil mass. This paper contains the results of a study on the effectiveness of current soil-lime mixing and construction procedures for five soils treated with powdered quicklime or lime slurry. A series of tests was performed on each soil as a part of the evaluation process. Test procedures included field density determination, dynamic cone penetrometer, unconfined compression, lime content, pH, Atterberg limits, swell testing, and determination of the maximum unit weights and optimum moisture contents for the native soil and lime treated soil.

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AASHTO T-180 as the compaction standard and requiring rotary mixing during the final stage of mixing. Further evaluation of the performance of soils mixed with lime slurry compared with soils mixed with quicklime was recommended to determine if lime slurry yields a significantly better product.

Other recommendations proposed for consideration included an evaluation of the benefits of making soil stabilization a goal of soil treatment and taking advantage of the benefits of including the stabilized layer as a component in the pavement design. Construction costs beyond those already incurred for modification should be relatively small and the additional structural benefits could yield significant savings.

Chapter 1

Introduction

Maintenance and replacement of pavement consumes a large portion of the budgets of transportation departments throughout the United States. Methods for reducing the cost of constructing and maintaining pavements and lengthening pavement life can help transportation departments better maintain the road network on limited budgets.

Modern pavements are expected to provide a high level of safety and comfort for their users. Pavements are commonly designed using a combination of mechanistic and empirical approaches. These methods involve selecting the appropriate soil and pavement parameters and then calculating layer thicknesses for the subbase, base and the asphalt or concrete pavement as appropriate. With any method, a strength parameter is used to describe the subgrade or native material beneath the pavement layers. Subgrade materials vary from soft clays to rock. Variations in the subgrade, even over short distances, are inevitable and can occur abruptly or gradually, depending on the geologic history of the surface soils. A high variability in subgrade soil characteristics may dictate the use of conservative estimates that may lead to thicker pavements with higher construction costs or poor performance and higher maintenance costs. In order to alleviate these problems, methods have been developed to try and minimize the variability in subgrade characteristics.

Clay soils in particular can present great problems in pavement design due to uncertainty associated with their performance. They are often unstable beneath a pavement and they are the most susceptible to problems from changes in moisture content. Clay soils tend to swell and become soft when wetted and may shrink and become stiff when dried. Additives, including lime, fly ash, Portland cement, and more recently synthetics are available that will lessen these problems when mixed in the proper amounts with problem soils. These additives may be used separately or in combination and each has construction issues related to its performance. This study addressed the particular problem of variability in the placement and mixing of lime when performed in accordance with Kansas Department of Transportation (KDOT) specifications.

Lime is a product of crushing limestone and heating it to a high temperature to modify the chemical components. The chemistry behind this process will be discussed in further detail in Chapter 2. The resulting powder or pellets are sold commercially as lime. The new chemistry of the lime is often reactive with soil to provide both textural and chemical changes within the soil. Lime is generally used to treat clay soils, although not all clay soils are subject to significant changes in engineering properties when mixed with lime. The changes that can occur in a soil include soil modification and soil stabilization. Modification involves changing the texture and moisture sensitivity of a soil, which is correlated to a change in plasticity of the soil. Stabilization refers to a long-term strength gain of the soil that occurs with many soils in addition to modification when the soil is mixed with lime. Table 1.1 contains a summary of the characteristics of soil that has been modified or stabilized.

Table 1.1: Summary of the Characteristics of Lime Modified or Stabilized Soil

Modification	Stabilization
Reduces the Plasticity Index	Effects of modification
Causes clay soil to become friable	May significantly increase soil strength (up to 4000 percent)
Dries wet soils	
Significantly reduces volume change	

Lime has been used for many decades as an admixture in soils, and a significant amount of research has been performed to explain how lime works and the effects it has on soil properties. There are many different design methods available to determine the modification and stabilization potential, along with the necessary amount of lime to achieve the desired changes. Most involve mixing soils with lime in the lab and then performing strength or classification tests on these mixtures. Lime can be added to a soil in varying amounts to determine the optimum lime content for the desired results. Many Departments of Transportation (DOTs), such as the California DOT, Texas DOT, Illinois DOT, and others, determine a design lime percentage using lab procedures based on their regional needs (SOTAR, 1987). Others, like the KDOT, use a uniform percentage of lime for all soils to be treated and assume it will be sufficient for their needs.

Lab mixing and testing of lime treated soils is generally well controlled and documented. However, field mixing of lime with native soil can be more difficult to control and maintaining the correct proportions of lime, soil and water may become problematic. Field mixing can be accomplished using one of two methods. One method is to mix the soil and lime at a central plant location, and then haul the soil-lime mixture to be placed and compacted. The other method is to mix the lime and soil in-place (Lime Stabilization Construction Manual, 1991).

Regardless of the method used, several basic principles must be followed to ensure proper and uniform mixing. First, the soil to be mixed should be ground or pulverized and then lime is spread over the area to be treated. Lime application may be achieved by applying lime in a slurry or spreading out dry lime over the area to be treated. After spreading the lime and adding sufficient water to increase the water content to a level significantly above optimum, the soil, lime and water are mixed thoroughly. After proper mixing, the soil-lime mixture may be allowed to mellow. If mellowing is allowed, a final mixing is necessary before final compaction. The lime-soil mixture is then compacted as specified by the contracting agency. The mixture must then be kept moist for a period of time to facilitate the continuing reactions in the mixture (Lime Stabilization Construction Manual, 1991).

This study addressed the effectiveness of lime mixing procedures as performed in Kansas in accordance with the Special Provision 90M-141-R1. This Special Provision effectively amended the 1990 Standard Specifications for lime mixing and compaction by eliminating the preliminary mixing and mellowing requirements for ease of construction. A summary of the specifications is shown in Table 1.2. Problems reported with pavement performance since the adoption of the Special Provision led to the initiation of this study.

Table 1.2: Lime Mixing Specifications

1990 Standard Specifications	Special Provision 90M-141-R1
Apply lime	Apply lime
Add water (optimum of native soil + 8% for hydrated lime, +10% for quicklime)	Add water (optimum of native soil + 8% for hydrated lime, +10% for quicklime)
Preliminary mixing	Mixing (95% passing 37.5 mm, 40% passing 4.75 mm)
Seal and cure (48 hours)	Compaction
Final mixing, watering (+8%) and compaction	Protection and curing
Protection and curing	

This report will examine the variability of the mixing of lime and soil on several road projects in eastern Kansas. The projects studied were all KDOT projects where lime was added to subgrade soils for modification purposes, with the primary goal of reducing the potential for volume change. The soils were sampled from projects in the following areas:

1. US-169 bypass around Iola, KS (Soils A, B & D)
2. I-70 reconstruction (eastbound) east of Junction City, KS (Soil E)
3. I-70 reconstruction (eastbound) near the intersection with K-99 (Soil F)

Soil C, which was also from the Iola location, was very similar to Soil B and was therefore replaced with Soil F.

Samples of the mixed in place soils were taken at various stages in the mixing process. Several different tests were then performed on these soils, including natural moisture and density, Atterberg limits, unconfined compressive strength, lime content, pH, and swell tests. Dynamic cone penetrometer readings were taken of the field compacted final product. Samples of the native, unmixed soils were also brought back to the lab, where the soils were tested in their native form and with lime mixed in the lab. These tests on lab treated soil included Atterberg Limits, moisture-density curves, unconfined compressive strength, pH, lime content measurement, and swell tests. Procedures followed American Society of Testing and Materials (ASTM), American Association of State Highway and Transportation Officials (AASHTO), or KDOT specifications where applicable.

The results of this study have been organized in the following manner. Available literature on properties and procedures of the use of lime with soils was reviewed and is summarized in Chapter 2. Descriptions of the test procedures that were implemented are reported in Chapter 3. The results of tests performed on lab and field samples showed several trends, which will be discussed in Chapters 4 and 5. Comparisons were also made between lab and field values to ascertain the effectiveness of lime treatment procedures in the field. Chapter 6 contains the conclusions based on the analysis of the data and Chapter 7 contains recommendations for further research and improved lime treatment effectiveness.

Chapter 2

Lime Overview and Literature Review

The available literature on lime modification and stabilization was reviewed, and the pertinent information and similar studies are presented in this chapter. The production of lime and its chemistry are reviewed. The theoretical mechanisms and general reactions for soil-lime mixtures are reviewed and current mix designs for lime are mentioned. Several studies on the measurable effects of lime on soil properties are presented. Current construction practices and field control on lime treatment projects is discussed. Internet sources within this text are delineated by the text "WWW," for World Wide Web, followed by the name of the web site. The date the information was gleaned is also noted because content on web pages can change over time.

2.1 Lime Manufacturing

The main ingredient in lime commonly used in construction today is a compound of calcium and oxygen called calcium oxide, CaO. This type of lime is called high calcium quicklime. Dolomitic lime, which contains significant portions of magnesium oxide (MgO), is also available. For both compounds, the lime is formed by calcining crushed limestone (predominantly $CaCO_3$) at a temperature of 982EC. In order to maintain the purity of the end lime product, tests are conducted on the limestone before calcining begins to ensure there are not any major contaminants in the basic limestone chemistry (WWW-National Lime Association, Jan 2000). The high temperature boils off the carbon dioxide, as shown in the following reaction:

$$\mathrm{CaCO_3 + Heat} \;{}^{\circ}\; \mathrm{CaO + CO_2} \tag{2.1}$$

Commercially produced lime is sold from the kilns as either quicklime or hydrated lime. Quicklime is the calcium oxide (CaO) produced from calcining. Hydrated lime is quicklime that has been slaked (mixed with a small amount of water). Hydrated lime is formed by the following reaction:

$$CaO + H_2O \rightarrow Ca(OH)_2 + \text{Heat} \qquad (2.2)$$

This reaction happens quickly and produces a significant amount of heat. After slaking, the lime becomes a very fine powder. From their chemical formulas and the atomic weights for the elements found in Table 1, it can be seen that the molecular weight of quicklime is 56.08, and the molecular weight of hydrated lime is 74.09. From these weights, the ratio of hydrated to quicklime required to provide the same amount of calcium is 1.321. A ratio of 1.3 (hydrated to quick) is commonly used in design and construction (Little, 1995).

Table 2.1: Molecular Weights

Hydrogen (H)	1.00794
Oxygen (O)	15.9994
Calcium (Ca)	40.078
Calcium Oxide (CaO)	56.077
Calcium Hydroxide ($Ca(OH)_2$)	74.093

Quicklime is less expensive to ship because it weighs less, but it can be more dangerous to handle because of the high energy released when it is mixed with water. Both forms of lime need to be protected from the atmosphere until being mixed with the soil. Quicklime will react with atmospheric moisture and both forms of lime will react with carbon dioxide in the air to reform calcium carbonate. This carbonation is a reversal of the calcining reaction. It is a relatively slow reaction, but, once carbonated, lime is rendered ineffective for use in construction (Little 1995).

2.2 Lime-Clay Interactions

Lime mixed with soil causes immediate changes in the structure and stability of the clay matrix and in many clays it produces long term strength gains. The immediate changes in structure and moisture stability are often called modification, while the strength gain is often called stabilization. These changes in soil properties will be reviewed separately for clarity.

Soil modification is a function of the mineralogy and structure of fine grained soils. Clay structures are made up of long sheets of silica tetrahedra and aluminum octahedra (also called gibbsite). These structures are shown graphically in Figure 2.1. Kaolinite consists of alternating sheets of silica and alumina held together by hydrogen bonding. Illite is formed by an alumina sheet sandwiched between two silica sheets and illite layers are bonded together by potassium ions. Montmorillonite, a type of smectite mineral, also consists of an alumina sheet between two silica sheets. However, montmorillonite layers are held together by available cations and potassium is not present (Das 2000).

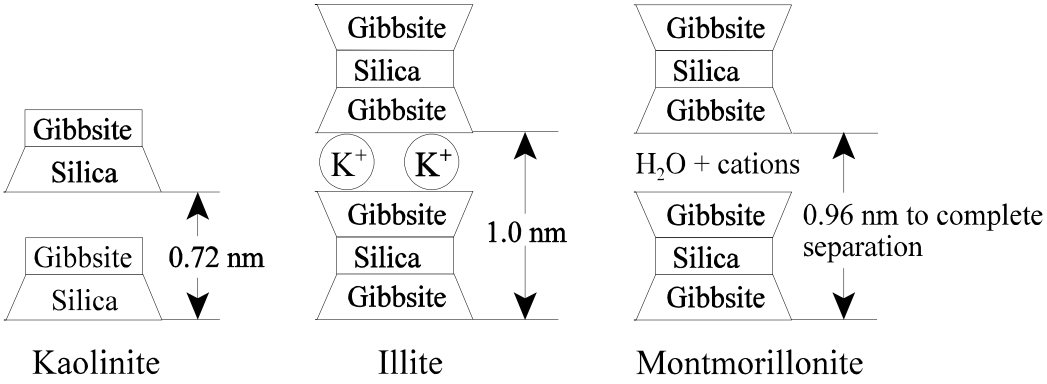


Figure 2.1: Structures of common minerals

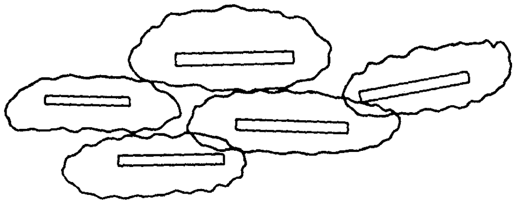
Each of these clay minerals has a net negative charge at the surface. Due to the net negative charge at the surface, cations and polar molecules (usually water) are attracted to the surface of the clay mineral. These minerals accumulate a layer of cations and water molecules around the particle called a diffused water layer. In a smectite, this diffused water layer can be several times thicker than the clay particle.

Modification involves decreasing the moisture sensitivity and plasticity of a soil. Lime achieves this primarily through cation exchange and a resulting flocculation-agglomeration of the clay particles. In a natural state, clay particles have a diffused water layer surrounding them which tends to orient the particles in a parallel fashion, as shown in Figure 2.2(a). When lime is mixed with the soil in the presence of water, calcium cations in solution do two things: replace cations at the clay surface and raise the pH of the mixture. Cations are replaced according to the Lyotropic series:

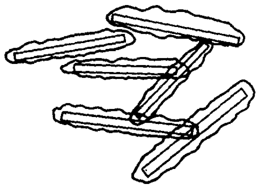
$$Li^{+} < Na^{+} < H^{+} < K^{+} < NH_4^{+} << Mg^{++} < Ca^{++} << Al^{+++} \tag{2.3}$$

where a cation will tend to replace one to its left. According to this series, calcium will replace the cations present in most clays. Little (1987) states, as an example, that given equal concentrations of cations in the pore water, there will be 17.5 times more calcium ions than sodium ions at the clay surface.

The calcium ions that result from adding lime replace many of the cations at the clay surface and this helps to reduce and stabilize the diffuse water layer. Raising the pH of the mixture also increases the cation exchange capacity (SOTAR 1987), encouraging further replacement of cations by the calcium. The reduction in the diffuse water layer allows the particles to align in a more edge-to-face alignment as shown in Figure 2.2(b). This new configuration increases the friction angle and shear strength of the soil and it improves the workability of the soil by decreasing plasticity and making it more friable (Hausman 1990).



(a) Parallel arrangement of clay particles with hydrated water layers.



(b) Edge - to - face attraction induced by thin water layer which allows attractive forces to dominate.

Figure 2.2: Clay particles in parallel and edge-to-face alignment (Little, 1996)

Stabilization of the soil refers to the long-term strength gain of a soil as measured by unconfined compression or other strength tests (CBR, R-value, etc). Although there is an immediate strength improvement due to textural changes, stabilization involves the formation of cementitious compounds within the clay structure over time. The compounds are formed by available calcium and the alumina and silica oxides dissolved from the clay structure at a high pH. The components react to form calcium silicate hydrates and calcium alumina hydrates, cementitious products that tend to form bonds between the clay particles. This process is dependent on ample free lime, available clay minerals, and conducive environmental conditions. Strength can continue to increase for several months or even years under the proper conditions (Little 1995). The definition of a strength threshold for determining stabilization is arbitrary and suggestions for a strength threshold vary from .34 MPa (50 psi) (Texas Procedure and Thompson Procedure, from SOTAR 1987) to .86 MPa (Hausman 1990). Those soils that, when mixed with lime, exhibit an unconfined compressive strength gain of sufficient magnitude are called reactive, while those that do not achieve this unconfined strength increase when mixed with lime are called non-reactive.

There is also evidence of different mechanisms that may be occurring within the soil-lime reactions. There are several references that explain in much greater detail the mechanisms and chemistry involved with soil-lime reactions. Although these go beyond the scope of the current paper, Little's "Stabilization of Pavement Subgrades and Base Courses with Lime" (1995) provides a good reference and lists many other papers on the subject.

2.3 Mix Design

There are many different mix designs for lime treatment of soils and they are commonly based upon the desired soil property changes. Some designs simply look for modification, often measured by the reduction in PI or swell potential from lime treatment. For example, Oklahoma and Illinois design for modification by comparing the effects of increasing lime content to plasticity index (PI). Optimum lime content is assumed to be the lime content past which there is no further appreciable decrease in PI. Others look for long term strength increases, often measured in cured unconfined compressive strength. California, Illinois, Texas, and Virginia all design lime content based on minimum strength increase or cost optimization from increased strength from adding lime (SOTAR 1987).

For either objective, the native soil is mixed with different amounts of lime in the lab, and the optimum lime content is that content where the PI reduction, swell reduction, strength gain, or other predetermined criteria meet the acceptable range for that project. The *State of the Art Report #5* (SOTAR) details several procedures from around the United States, including, among others, the California, Texas, and Virginia methods along with the Thompson procedure and the Eades and Grim Test. A good summary of each of these procedures is found there.

In reviewing mix design procedures, there are many factors that change the effectiveness of lime in modifying and stabilizing soil. Some of these conditions are lime percentage, clay mineralogy, moisture content at mixing, mellowing period, type of compaction, temperature during curing, and available moisture during curing (Little 1995).

2.4 Other Soil-Lime Characteristics

Previous studies have identified many trends and general characteristics of changes in soil properties due to the addition of lime. The universal effect of mixing lime with plastic soils is the reduction in plasticity of a soil when mixed with lime. Little (1995) states that lime treatment causes a substantial reduction in the plasticity of a soil and the soil often will become non-plastic. Laguros (1965) found that the plasticity index of a soil was reduced from 47 to 15 with the addition of 6% hydrated lime. Jan and Walker (1963) noted that the incremental reduction in plasticity decreases as the lime content increases. Others have found that after approximately 2 to 4% hydrated lime is added, the additional effect on the plasticity of the soil is minimal (Puppala, Mohammad, and Allen 1996; also Sweeney, Wong, and Fredlund 1988). Basma and Tuncer (1991) tested the plasticity of lime treated soils at cure times of 1 hour to 28 days and found that cure time had little effect on the plasticity of a lime treated soil.

Lime also decreases the apparent amount of fines in a soil by causing flocculation and agglomeration of the clay particles (Little 1995). This results in an increase in the percentage of sand and silt size particles as measured by standard grain size distribution methods (Basma and Tuncer 1991). Lime can also be used to reduce the dry gradation of a soil if there are significant amounts of large clay clods (Lime Stabilization Construction Manual 1991).

Lime also tends to reduce the swell potential of fine grained soils (Kennedy et al 1987). There is not agreement as to the time effects on swell potential. Sweeney, Wong, and Fredlund (1988) found that swell characteristics of a lime treated soil were unaffected by the cure time before testing, while Basma and Tuncer (1991) found that increased cure time tended to decrease the swell potential. Moisture content plays an important role in the swell potential of a lime treated soil; soils with a moisture content below optimum show a much greater swell potential than soils with a moisture content above optimum (Sweeney et al 1988).

The amount of fines and types of clay minerals affects the effectiveness of the lime in stabilizing a soil and causing long term strength gain. Ford, Moore, and Hajek (1982) used x-ray diffraction, thermogravimetric analysis, and a scanning electron microscope to examine the structural changes on a particle level to a Southeastern clay soil when lime is added. They found that soils with a significant amount of montmorillonite developed almost no increase in unconfined compressive strength. They concluded that most of the lime was used to break down the montmorillonite and the montmorillonite also had too great of a surface area for the cementitious compounds to significantly affect the strength.

There appear to be other criteria that affect the ability of lime to stabilize a soil. Moore and Jones (1971), using data from Illinois soils, found that surface area has an inverse correlation to the unconfined compressive strength of a lime stabilized soil, but their data suggest only a moderate correlation. They found that available silica appears to be more important to long-term strength gain than is available alumina. They also found that an inverse correlation exists between extractable iron in soils and their unconfined compressive strength after being stabilized with lime.

Epps, Dunlap, Gallaway, and Currin (1971) reviewed several criteria for stabilization and found that, in general, a soil should have a clay content of at least 7% and a plasticity index of at least 10 to be considered a candidate for stabilization using lime. They also found that low pH, high organic content, and high sulfate content are prohibiting factors in stabilizing soils with lime.

Lime tends to increase the strength of many soils; time and lime content appear to have a great effect on the amount of strength gain that occurs (Tuncer and Basma 1991).

Ford, Moore, and Hajek (1982) also found that for a lime treated soil compacted at two different moisture contents, the soil developed a minimal strength gain when compacted dry of optimum, while the soil had an unconfined compressive strength gain of over 344 kPa when compacted at optimum moisture. This indicates that moisture content at mixing can affect the strength gained from lime treatment.

Pulverization of the native soil has an effect on the ability of the lime to be effectively mixed with the soil. Petry and Wohlgemuth (1988) tested a fine-grained soil at 60%, 80%, and 100% of the dried soil passing a 4.75 mm sieve. They found that after a 28 day cure, the unconfined strength of the coarsest sample was 172 kPa, while the finest gradation had an unconfined compressive strength of 758 kPa.

Adding lime to some soils tends to reduce the maximum dry density and increase the optimum moisture (Wang et al 1963), but there are other soils that exhibit little change. Lockett and Moore (1982) found that, for soils in the southeastern United States, lime modification of clays dominated by montmorillonite increases the optimum moisture by as much as 20 points over the native soil. However, Tuncer and Basma (1991) found that there was no significant change in the maximum dry density and optimum moisture of a soil after adding lime. The change in Proctor values due to addition of lime appears to be different for each soil. However, longer mellowing of lime treated soils tends to reduce the maximum dry density in most soils (Sweeney et al 1988).

Compaction procedure appears to affect the strength of lime treated soils. Dry density and moisture control during construction are essential to obtaining adequate strengths (Jan and Walker 1963) and increasing compaction from standard to modified Proctor methods can double the strength of a soil (Kennedy et al 1987). Increased rolling of a lime treated soil in the field has been found to increase the strength of a soil (Jan and Walker 1963), but overcompaction can actually break up the soil and make it weak (Sweeney, Wong, and Fredlund 1988).

Although some studies have been done on the effectiveness of field operations, there is great variation in the properties measured using field samples and often only a moderate correlation to laboratory results. Stewart, Fletcher and Chu (1971), using soils from South Carolina, found that cores taken from a constructed base showed unconfined compressive strengths comparable to or greater than lab strengths. They did, however, have great difficulty in obtaining field cores that could be used in testing. They also found a wide variation in lime contents in the field mixed soil. Little (1995) also found great variations in the stiffness of in-situ field lime treated and compacted soils. McDowell (1966) found that lab determined strengths underestimated the actual strength of field lime treated soils.

Hoover (1965) compared strengths of lime treated soils mixed and compacted in the lab to the strengths of soils mixed in the field and compacted in the lab. He found that field mixed samples had an unconfined compressive strength of 724 kPa, while lab mixed soils had an unconfined compressive strength of 1585 kPa. He also found that field compaction of lime treated soils yielded dry density values above 100% of standard Proctor for the lime treated soil.

Much of the preceding discussion about strength was intended to show the tendencies of lime to affect strength and the possible variables that can affect strength in a soil-lime mixture. Strength measurements were used in this study as one method for evaluating the effectiveness of lime spreading and mixing operations.

2.5 Current Construction Practices

Lime is currently applied to and mixed with surface soils in two methods: plant mixing and in-place mixing. Plant mixing involves transporting the soil, lime, and water to a central batching plant to be mixed. The resulting mixture is then returned to the site for placement and compaction. In-place mixing requires less material transport because the soil is modified at the construction site. The soil, after being scarified, is mixed with lime in the presence of water and then the mixture is recompacted (SOTAR 1987).

All methods of mixing have some common procedures. First, the soil to be lime treated must be pulverized into clods that are generally less than 50.8 mm (2 inches) in diameter, although the exact specification varies. Generally, soils that are better pulverized will interact with the lime more effectively. The lime is added to the soil as either a powder or a slurry after pulverization. In some cases, the lime is spread on top of the clay before pulverization. The soil is then mixed with the lime. If necessary, water is added to the mix to facilitate mixing and reaction between the soil and lime. The water content is usually specified to be a minimum of 5 percent over optimum. This high moisture content is necessary to facilitate the essential chemical reactions to occur in the soil-lime mixture. Mixing is generally accomplished with a rotomixer. For thick clays or those with high plasticity, the procedure is usually repeated after a certain period. After all mixing operations are completed, the soil-lime mixture should have no clods above 25.4 mm (1 inch) in diameter. After all lime is added and mixed with the soil, the National Lime Association recommends that the soil be lightly sealed to promote runoff in the event of rain, followed by a 24-48 hour mellowing period. Once compacted, the material should be kept moist, by sprinkling or seal coat, for at least seven days. (Lime Stabilization Construction Manual 1991).

Quality control of spreading and mixing on the job site is essential to ensure that a uniform subgrade is produced. After mixing, the engineer must ensure that proper compaction and moisture control occurs. The lime, after spreading but before mixing, can be weighed from a small area to ensure that there is an appropriate amount of lime per unit area of soil surface. Another method is to take a field sample back to a lab and have the lime content tested through methods such as AASHTO Method T-232, “Determination of Lime Content in Lime-Treated Soils by Titration.” Depth can be measured by drilling a hand-augered core through the lime treated soil past the desired depth and spraying a solution of phenolphthalein on the core. The portion that is lime treated will turn a bright pink due to the presence of calcium ions, while the untreated portion will merely look wet in the presence of phenolphthalein (SOTAR 1987).

Proper mixing cannot be directly measured and it has been suggested by Little (1995) that the quality of mixing be tested by making a series of unconfined compression samples using field lime treated soils. Samples taken from the field to the lab can be halved, with one half being compacted as sampled, and the other half being well mixed in the lab and then compacted. The ratio of the unconfined strength of the field mixed, lab-compacted samples to the field and lab-mixed, lab compacted samples can be calculated. A higher ratio will indicate better mixing and a common standard is 60%-80%.

Compaction control may be achieved with a nuclear density gauge as on most other projects, although the presence of lime may affect the readings and necessitate the use of a correction factor. A potential difficulty with compaction control is selection of the maximum dry density and optimum moisture to be used for quality control. This can be difficult as the maximum dry density generally decreases and optimum moisture generally increases as the soil-lime mixture cures. In order to achieve reliable results, the appropriate Proctor curve should be prepared at the curing time corresponding to field conditions (SOTAR 1987).

Samples of field mixed and compacted soil may also be obtained using drive cylinders or grab samples and returned to the lab. Drive cylinder samples can be used to determine the unconfined compressive strength or, where possible, swell potential of in-place soil. In addition, drive cylinder or grab samples can be used to determine Atterberg limits, swell potential, gradation, or other desired soil properties. These are generally a more effective measure if the lime treated soil properties can be compared to the native soil properties. (SOTAR 1987)

Although use of lime continues to increase, there is still uncertainty in the proper design and use of lime in construction. The effectiveness of lime depends upon several factors, some of which are beyond the control of designers or construction workers. There are also many different methods of preparing and testing lime-soil reactions. This breadth of variation makes comparison between studies a sometimes questionable proposition (SOTAR 1987). Despite these difficulties, there are several identifiable trends in lime modification and/or stabilization of soils. Each soil needs to be evaluated as to the effectiveness of lime in remediating the undesirable properties of a specific soil. Once this is determined, care must also be shown in specifying proper construction techniques to achieve the desired results.

Chapter 3

Testing Plan and Procedures

This chapter contains a discussion of the testing program used to evaluate the effectiveness of the field mixing operations for soil modification. Tests were performed on lime treated soil mixed at the job site by the contractor, lime treated soil mixed in the lab, and native soil samples. The results of tests on the field mixed soils were evaluated in relation to results from the same tests performed on native soil samples and the lab prepared samples. Field samples were also obtained periodically during the mixing process and compacted in the lab to evaluate the benefits of additional mixing.

The testing performed as a part of this study focused on the uniformity of soil modification and on the uniformity of characteristics associated with volume change, as control of volume change is the primary goal of lime treatment in Kansas. Any accompanying strength gain in the subgrade is a desirable side-effect not included in the structural design of the pavement. Table 3.1 lists the type and number of tests performed on each soil.

3.1 Materials Used

3.1.1 Projects Selected for Study

For this study, five soils at three different projects where lime was mixed with the subgrade soil were chosen in consultation with the Kansas Department of Transportation. Three of the soils studied (Soils A, B, and D) were sampled near Iola, Kansas, along a bypass under construction on US-169 around Iola. Soil E was sampled along reconstruction of the eastbound lanes of I-70 near Kansas State Highway 177.

Table 3.1: Number and Type of Test on Each Soil

Test Method	Soil A	Soil B	Soil D	Soil E	Soil F
Dynamic Cone Penetrometer	16	20	20	5	4
Atterberg Limits	8	13	13	17	16
Unconfined Compressive Strength	15	13	22	27	21
Field Dry Density	1	2	10	0	4
Lab Dry Density	0	0	0	9	9
Lime Content	5	8	10	10	13
Swell	5	6	6	6	5
pH	5	9	10	14	13
Proctor Curves	3	3	3	3	3
Gradation	1	1	1	1	1

Soil F was sampled during reconstruction of the eastbound lanes of Interstate 70 near the interchange with Kansas State Highway 99.

Each of the native soil samples was obtained after the in-place subgrade had been compacted and trimmed to grade elevation prior to the addition of lime. Samples came from the trimmings that were furrowed along each side of the road by the construction equipment used to trim the native soil to the proper elevation. Native soil samples were obtained by shoveling the soil into cloth bags for transport back to the lab.

3.1.2 Lime

Lime needed for preparing lab samples of soil-lime mixtures was obtained from the contractors on-site. The lime used was sampled by the contractors and delivered in sealed containers for all soils but Soil E. For Soil E, samples of the lime were obtained in a powder form after it was spread on the subgrade soil and prior to mixing. The lime was placed in sealed bags and transported back to the lab. Within the lab, the lime was kept in sealed bags to protect it from moisture and carbon dioxide in the air.

The reactivity of the lime was qualitatively evaluated throughout testing by mixing small amounts of the lime being used with small amounts of water. During a typical reaction, unaltered quicklime will generate a significant amount of heat and the mix will return to a powder after the lime hydrated. This qualitative measure of purity was observed throughout testing in the quicklimes used with soils A, B, D, and F. Although the lime used with Soil E was reported to be quicklime, the powdered lime used with Soil E did not exhibit the typical behavior expected for quicklime so it was mixed with soil at the rate appropriate for hydrated lime (5 percent).

3.2 Field Mixing

For all projects visited as a part of this study, contractors generally followed the same pattern for mixing subgrade soils with lime. The subgrade soil was scarified and pulverized to the depth of lime treatment, specified by KDOT as a depth of 152 mm (6 inches) for each soil tested. After the soil was pulverized, the lime was spread evenly across the width of soil to be treated. After the lime was evenly distributed, a CMI 500 series rotomixer or equivalent was used to mix the soil and lime. If necessary, a water truck provided water for the mixture directly into the hopper of the rotomixer. The soil-lime mixture was then compacted using pneumatic or pad foot rollers and was in most cases sealed with a steel wheel roller.

Lime was applied as either quicklime slurry (Soils A and D) or dry quicklime (Soils B, E and F). When dry quicklime was used, the lime was hauled to the site by truck and placed directly onto the subgrade. Slurry was made by mixing known quantities of quicklime with water in a large, specially built tank. Quantities of each component were specified beforehand to meet the necessary lime requirements of the soil. Slurry was placed using pump trucks with rear spreaders. The lime was then evenly distributed over a predetermined area based on volumetric calculations for the lime-soil ratio. The weight of lime placed was known, and, knowing the depth of lime treatment, the appropriate surface area for one truckload was calculated. Sufficient water was added to the soil-lime mixture to raise the water content to 8-10 percent above the optimum water content for the native soil and a rotomixer was used for mixing.

Each soil was sampled using both drive cylinder and grab bag samples. The number and type of samples of each soil are summarized in Table 3.2. Drive cylinder samples were obtained according to ASTM D-2937, Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method, and the dry density of each intact sample was determined in general conformance to this specification, except as noted later in this chapter under field dry density. Samples of Soils A, B, and D were taken along a 30.5 meter (100 ft) length of the roadway being lime treated, while Soils E and F were taken along a 100 meter length of roadway. Samples for Soil A were taken within only a 5 meter length of road, although dynamic cone penetrometer tests were performed along a full 30.5 m (100 ft) length of roadway. The sampling pattern for each soil is shown in Figures 3.1 - 3.5.

Table 3.2: Types and Number of Field Samples Obtained of Lime Treated Soil

Method of Sampling	Soil A	Soil B	Soil D	Soil E	Soil F
Drive Cylinder Samples	1	2	10	5	4
Grab Samples-Compacted Soil	4	8	0	0	0
Grab Samples-Uncompacted Soil	0	0	0	9	9

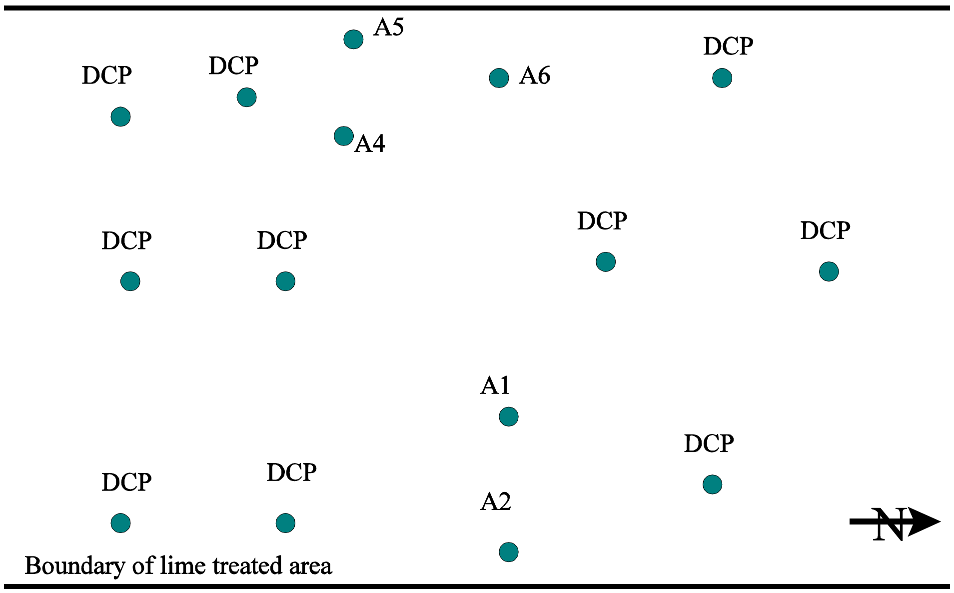


Figure 3.1: Sampling Pattern for Soil A

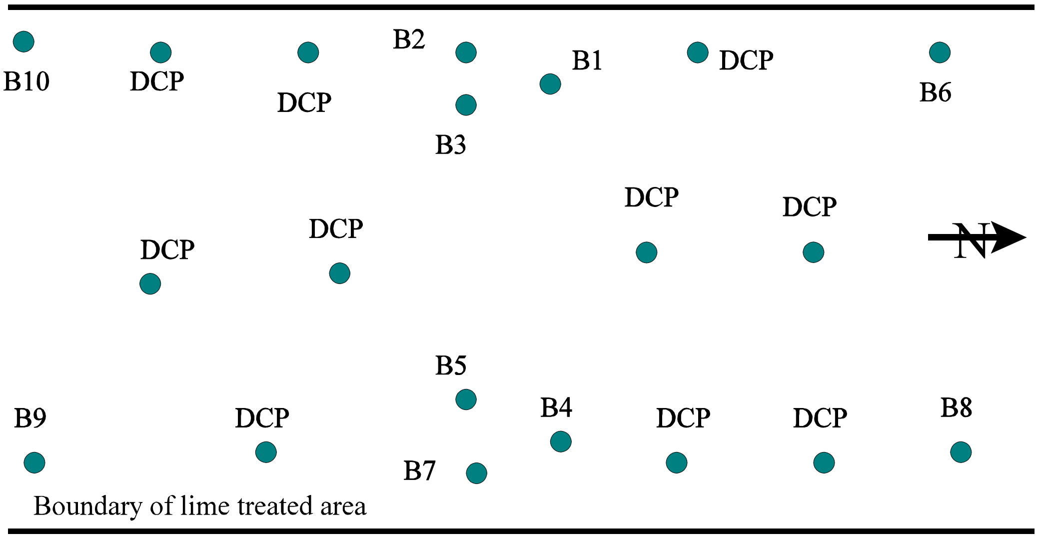


Figure 3.2: Sampling Pattern for Soil B

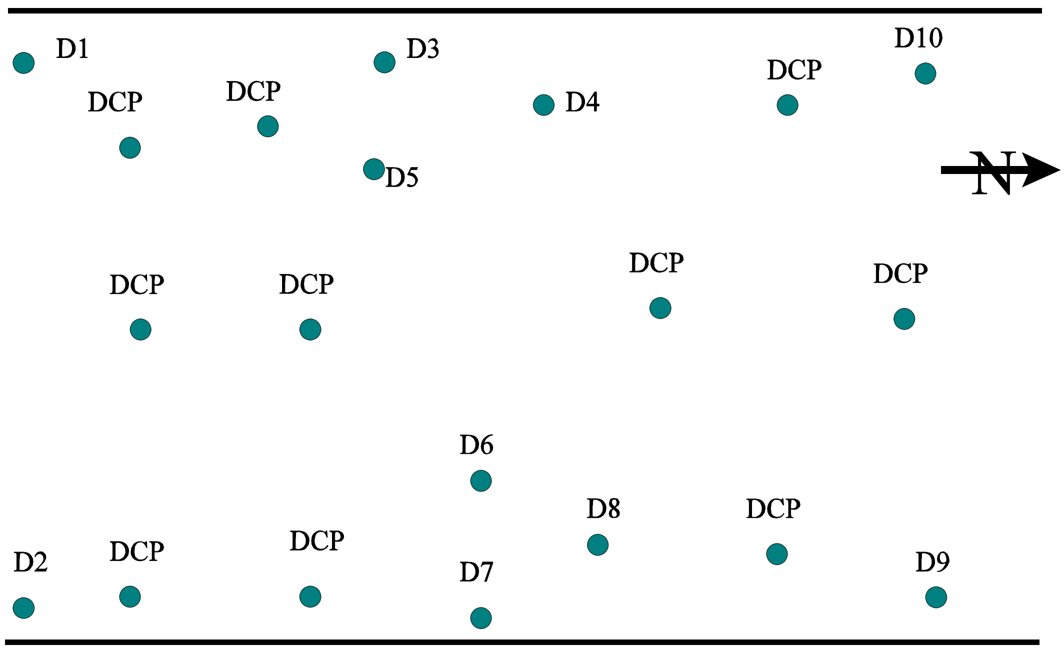
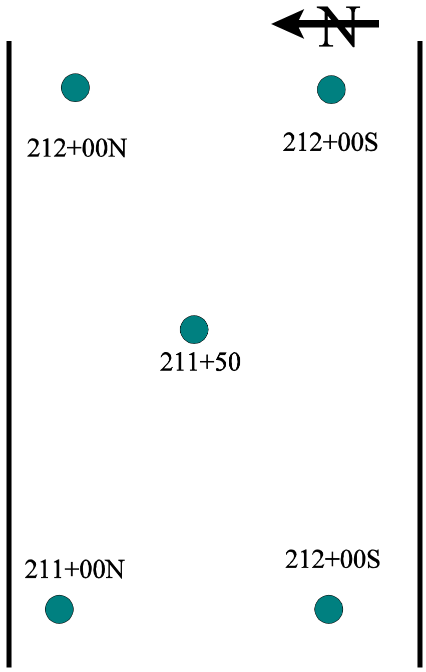


Figure 3.3: Sampling Pattern for Soil D



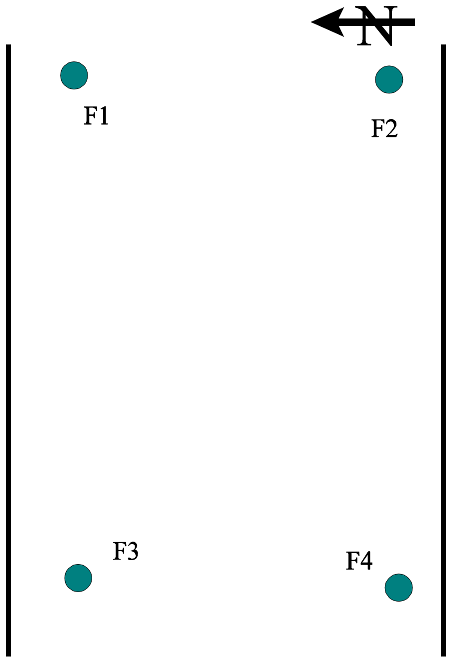


Figure 3.4: Sampling Pattern for Soil E

Figure 3.5: Sampling Pattern for Soil F

In order to determine the effects of the field mixing procedures, bag samples were taken of the mixed but uncompacted lime-soil mixtures for soils E and F. For Soil E, three bag samples were obtained after one pass by the rotomixer. For purposes of this report, a pass equals mixing at a particular location one time in one direction. After the second and final pass by the rotomixer, six more samples of the soil-lime mixture were taken. For Soil F, three bag samples were taken after the one and only pass by the rotomixer, and six more were taken after two passes of a pad foot roller. These bag samples were taken at the same location for each soil and were tested as described in the following sections.

3.3 Lab Mixing

Lime-soil mixtures prepared in the lab were mixed using standards set forth in ASTM D-3551, Standard Practice for Laboratory Preparation of Soil-Lime Mixtures using a Mechanical Mixer. Larger samples, such as those for the moisture-density curves and unconfined compressive strength, were mixed as shown in the standard using a mechanical mixer. The appropriate amounts of air dried soil and lime were mixed for one minute in the mixer. After one minute, water was weighed out and mixed in slowly from a squirt bottle. Each component was weighed before mixing to ensure the samples were mixed at the appropriate lime content and moisture content. The blend was mixed for five minutes after the introduction of water to the mix, after which the soil-lime mixture was placed in a bag to mellow for either one or 48 hour(s), as desired. Smaller samples, such as those for Atterberg limits and swell, were too small for the mixer to efficiently mix. For these samples, the soil and lime were mixed dry with a small spatula to a homogeneous state. Water was then added, stirring occasionally, until the appropriate amount of water had been added. The mixture was mixed using a spatula to a homogeneous consistency and it was allowed to mellow for the specified time.

3.4 Dynamic Cone Penetrometer Testing

The dynamic cone penetrometer test was used to measure the in-situ strength of the subgrade soil. Dynamic cone penetrometer tests were performed using a 7.9 kg mass dropped a distance of 585 mm. The displacement data was converted to a California Bearing Ratio (CBR) value using the KDOT Dynamic Cone Penetrometer (DCP) program. In nearly all cases, the lime treated soil was stiffer and exhibited a larger CBR value than the subgrade below it. It was therefore possible to indirectly determine to what depth the lime actually affected strength of the soil. Dynamic cone penetrometer tests were performed at each drive cylinder sample location for every soil. For Soils A, B and D, 10 additional DCP tests were performed within the 100 meter testing area in the roadway.

No literature was available with the software provided by KDOT to indicate the correlation used in obtaining CBR results. Therefore, artificial DCP data were entered and correlating CBR values were noted and compiled. The data were transferred into a Microsoft Excel spreadsheet and the following equation for the KDOT software was extracted:

$$CBR = 8.9526 * (DCP)^{\wedge} -1.1579 \qquad (3.1)$$

where

CBR = California Bearing Ratio (%)

DCP = inches per blow.

This correlation gives a coefficient of R^2=.9921. The KDOT software is written using English units, but the correlation using metric units (millimeters per blow) is:

$$CBR = 378.91 * (DCP)^{\wedge} -1.1579. \qquad (3.2)$$

Livneh et al (1995) looked through many correlations of DCP to CBR and concluded that the equation:

$$\log CBR = 2.46 -1.12 * (\log DCP), \qquad (3.3)$$

using mm/blow for DCP units, works best for converting DCP data to CBR values. Livneh concluded that this is a universal correlation that can be used for a wide range of materials, conditions, and technologies. The CBR values for the Livneh equation are about 8 to 20 percent lower than those obtained from the KDOT analysis for similar DCP data when used for CBR values of 1 to about 100. The two correlations are reasonably close for measuring lower CBR values (below 25). The correlations are shown in Figure 3.6.

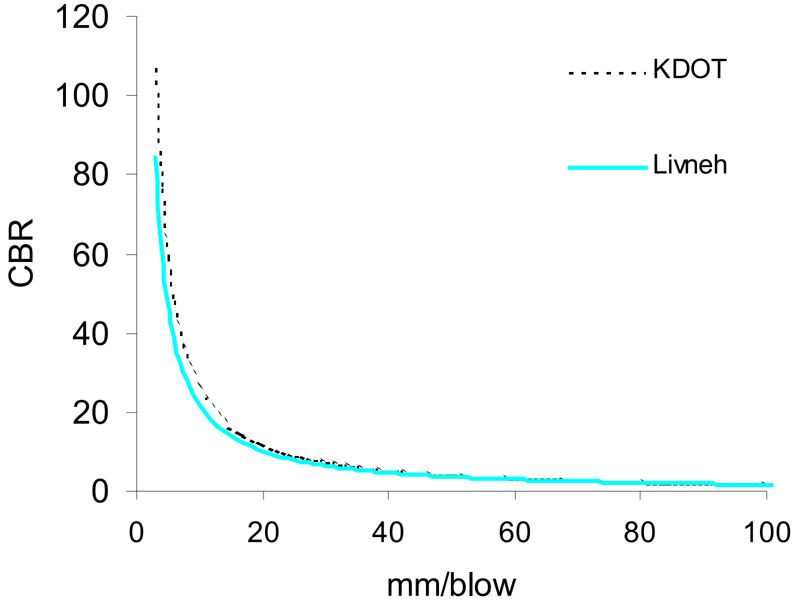


Figure 3.6: KDOT and Livneh correlations between CBR and DCP penetration rates

3.5 Lab Testing

A series of lab tests was conducted on the lime treated field samples that included moisture content, dry density determination, Atterberg limits, lime content, swell, and unconfined compressive strength. Lab prepared samples with and without lime were also tested. These testing procedures included Proctor curves, Atterberg limits, swell, and unconfined compressive strength. Grain size analysis was performed on the five native soils. These tests were performed according to established procedures, where applicable, and they are briefly described in the following sections.

3.5.1 Moisture Content

Moisture contents were determined according to ASTM D-2216, Standard Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. Moisture contents were performed on each field-mixed sample to determine field moisture content and lab samples were tested as appropriate. It should be noted from the hydration of quicklime that each molecule of CaO will chemically bind one molecule of H_2O when they come in contact. The temperature for determining moisture content (110° C) is not sufficient to drive off the hydroxyls in the hydrated lime, $Ca(OH)_2$, therefore the mass of solids is increased by the weight of the hydroxyls. However, the magnitude of this increase is minor because CaO only represents approximately 3.75% of the sample by weight.

3.5.2 Field Dry Density

Dry density values were obtained from drive tubes taken from the subgrades at the locations indicated in Figures 3.1 - 3.5. The drive tube samples were retrieved and tested according to ASTM D-2937. The drive tubes used were commercially available 126 mm in length by 97 mm in diameter with the same volume and similar dimensions to the standard Proctor mold. Due to the more brittle nature of the lime treated soil, development of surface irregularities on the ends occurred in many of the samples. In order to account for the irregular surfaces, sand with a known dry density in a loose state was used to fill in holes at the ends of the tube. The sample was weighed with and without the sand. With a known weight of sand, the volume of sand was calculated; this volume was then subtracted from the volume of the mold to obtain the actual volume of the soil sample.

3.5.3 Atterberg Limits

The liquid limit, plastic limit, and plasticity index of each sample was determined according to the specifications in AASHTO T-89 and AASHTO T-90. Liquid limits were performed using the one-point method described in T-89 Method B after verification of the accuracy of this method for lime treated samples by comparison with the three point method. The number of blows was restricted to a range of 22-28, and the actual liquid limit was obtained from the equation given, where:

$$LL= w_n*(N/25)^{0.121} \tag{3.4}$$

LL=liquid limit
w_n= actual water content
N= Number of Blows

Field samples of lime treated soil and native soil were tested as soon as possible after sampling. A representative portion of each sample was air dried and broken down to pass a .425 mm (#40) sieve. The soil passing the .425 mm (#40) sieve was then tested.

Samples of soil and lime mixed in the lab were prepared using the KDOT Lime PI procedure outlined at the end of the KDOT Specification for Determination of Volume Change of Soils. It specifies that the appropriate amounts of soil and lime be mixed at a moisture content 5% above the plastic limit of the native soil. The sample is then moist cured for 48 hours and oven dried at 71EC (160EF) before testing. This was accomplished by placing the soil-lime mixture in a bowl in a partially sealed Ziploc freezer bag. The locking end of the bag was folded under the bowl to only allow indirect exposure to moisture. The sample was cured in a moisture room at approximately 22EC for 48 hours. The sample was then oven dried as specified before testing.

3.5.4 Lime Content

Lime content was determined using AASHTO T-232, Determination of Lime Content in Lime-Treated Soils by Titration. “It is based on the continuous neutralization of an aqueous solution from the lime-treated specimen for a specified time period” (AASHTO T-232). The field samples were broken up over a 9.5 mm (3/8") sieve and then 300 g of moist soil was weighed out and placed in a plastic bowl. Addition of acids and other chemicals followed the amounts and timing listed in the specification. In each case, the amount of hydrochloric acid (HCl) necessary to titrate the solution to a neutral state was determined.

The only deviation from the specification is that the field samples were often tested several days or weeks after field lime treatment due to the timing of lime treatment, sampling, and testing. With regard to AASHTO T-232, it is apparent that the effect of time on free lime in the mixture decreases as the time from lime treatment increases. Due to the timing of sampling of the soils tested, the soils were not generally tested within the 48 hours specified in AASHTO T-232.

In order to determine lime content, the amount of hydrochloric acid necessary to neutralize a field sample was compared to the amount required for a lab mixed sample of known lime content. A curve of lime content as a function of HCl was established by testing at lime contents above and below the desired lime content. The lime content of a field sample was interpolated or extrapolated as necessary. Extrapolation was often necessary as the amount of HCl necessary for titration on many samples was outside the extent of the established lime content curves.

The lab lime content specimens for the lime content curve of each soil were prepared according to Table 1 listed in AASHTO T-232. The mixing water content was assumed to be 32% for each soil, as this represented an average mixing moisture content in the field. The curves developed are not only specific to the soil, but also to the mellowing time between mixing and testing. Due to the extended period between field mixing and lime content determination, a lime content curve was established for the curing period of each sample tested. The lab samples were cured in sealed plastic containers to help prevent moisture loss over the extended curing period. The sealed containers reduced exposure to the air, which may have reduced carbonation and potentially impacted the results.

3.5.5 Swell

Swell tests were performed according to the KDOT specification, Method of Test for Determination of Volume Change of Soils. This procedure appears to be based on a dated American Association of State Highway Officials (AASHO) procedure by a similar name that dates back to at least 1942 (AASHO 1942). The test is not found in the current AASHTO test methods.

Tests were performed on native soils, field mixed soil-lime samples, and lab mixed soil-lime specimens. The specification requires that a sample 50.8 mm (2 inches) high with a diameter of 101.6 mm (4 inches) be statically compacted in a confining mold to 92% of the maximum dry density at a given moisture content. The sample is then loaded with 7.24 kPa (151 psf) and the sample and mold are placed in a water bath. The base of the mold is perforated to permit the water to enter the sample and cause the soil to swell. Displacement is measured using a dial gage placed on top of the loaded sample over a period of 96 hours. Samples are tested at optimum moisture plus and minus 3% and a linear relationship between swelling and moisture content is developed. The amount of swell corresponding to optimum moisture is the reported swell potential.

The procedure was followed for each of the native soils, except that samples were compacted to a dry density equal to 95% of the maximum dry density as determined by ASTM D-698 (Standard Proctor). This higher dry density was used to correspond with the target compaction in the field.

For the field mixed soil-lime samples, each sample was compacted to the dry density and moisture content at sampling to simulate the prevailing field conditions. The samples were generally near the target water content for testing, so the oven drying and subsequent addition of moisture were not conducted. In order to obtain the desired moisture content, small amounts of moisture were added and mixed in or allowed to evaporate just before mixing. After several tests, it became apparent that virtually all swell for the lime treated soils occurred during the first 48 hours of testing. Testing was therefore discontinued after two successive readings were recorded with a difference of not more than .0051 mm (.002 in).

For the lab prepared samples, each soil was tested at a hydrated lime equivalent of 2.5% and 5% lime by weight. Native soil was dried in an oven as provided in the specification and the soil-lime mixtures were stirred while dry. Samples were prepared at 95% of standard proctor and at +3% and -3% from optimum moisture. With the exception of Soil E, the actual mixing moisture content was slightly higher than the target to allow for the hydration of quicklime and natural evaporation during mixing. These samples were only allowed to mellow for one hour after mixing, not the 16 to 24 hours provided in the specification, to better simulate the field conditions. The swell reported corresponds to the swell at optimum moisture.

3.5.6 Moisture-Dry Density Relationships

Proctor curves were established for native and lime treated soils using standard energy according to ASTM D-698, Standard Test Method for Laboratory Compaction Characteristics of Soil using Standard Effort. Soil to be tested was screened on a 9.5 mm sieve and method B of the test specification was followed. Soil-lime mixtures were mixed as detailed above. Each soil was mixed with 5% hydrated lime equivalent by dry weight, with each successive sample mixed at a higher moisture content. Two separate curves were established for the soil-lime mixtures, one for a 1-hour mellowing period and one for a 48-hour mellowing period. Moisture contents were taken from the soil left in the bowl after compaction and trimming, as the Proctor samples were saved for later unconfined compressive strength testing. Lab comparisons at the beginning of testing showed that this was an acceptable and reliable procedure for obtaining a moisture content without destroying the Proctor specimen.

3.5.7 Unconfined Compressive Strength

Unconfined compressive strength tests were performed on remolded native soils, field mixed and compacted soil-lime samples, field mixed and lab compacted soil-lime samples, and lab mixed and lab compacted soil-lime samples. For the native soil samples, unconfined tests were performed in accordance with ASTM D-5102, Standard Test

Method for Unconfined Compressive Strength of Compacted Soil-Lime Mixtures. Procedure B of the specification was followed because it calls for samples to be compacted in a Proctor mold, which allowed for a direct comparison between native and soil-lime unconfined compressive strengths. In addition to the stress strain relationship developed from the test, the moisture content at testing was measured for each specimen.

For unconfined compression tests on the remolded native soils, samples used in determining the moisture density curves were extruded from the 102 mm (4") mold and tested directly after compaction. These samples were left in their unchanged compacted state (instead of taking a moisture content directly from the compacted specimens), so the dry density of each sample was also known. These specimens were tested on the Loadtrac II testing machine. Strain rates were from 0.75%/min to 1.5%/min. The ratio of length to diameter was 1.15 for all specimens.

Nine loose samples of field mixed soil-lime mixtures were taken for soils E and F. These were taken to help evaluate the effectiveness of field methods for mixing the lime with the soil. Each sample was placed in a Ziploc bag in the field and brought back to the lab. The soil-lime mixtures were cured approximately 12 hours in the sealed bag at room temperature. They were each compacted in a 102 mm (4") proctor mold using the same energy specified in ASTM D-698. The wet density was determined and a moisture content was taken from the remaining sample so that a corresponding dry density could be found. This also allowed for an intact specimen for unconfined compression testing. Each sample was extruded, placed in a sealed plastic bag and cured for 28 days in a moist room at 22EC (72EF). After the curing period, the samples were tested using ASTM D-5102. Moisture contents were taken of each sample at testing.

Unconfined compression tests were also performed on field mixed and compacted soil-lime samples. These samples were taken using drive cylinders. The drive cylinders had a volume of 9.43×10^{-4} m^3 (1/30 ft^3) and a length/diameter ratio of 1.33. After recording the moist weight for dry density determination, the samples were placed in a sealed plastic bag, still in the cylinder. These samples were then cured for 28 days in a moisture room at 22EC (72EF). After the curing period, the samples were tested using the standard method for unconfined compression testing. Moisture contents were taken of each sample at testing.

3.5.8 Grain Size Analysis

A mechanical grain size analysis was performed to determine the amount of gravel, sand, and fines in each native soil as defined by the Unified Soil Classification System (USCS). This analysis was performed on soil that had previously been screened over a 9.5 mm sieve. However, it is estimated that there was less than 8% of any of the samples retained on the 9.52 mm (3/8") sieve, so the results were considered to accurately reflect field conditions. The soils were tested in accordance with ASTM D-1140, Standard Test Method for Amount of Material in Soils Finer Than the 0.075 mm (#200) Sieve.

A sample from each native soil (that portion passing the 9.52 mm (3/8") sieve) was dried to a constant mass. It was then washed through a 0.075 mm (#200) sieve and dried again. The redried material was passed through the 4.75 mm and 0.075 mm (#4 and #200) sieve sizes and shaken for a period of 3-4 minutes. The dry masses of material retained on each sieve were then recorded.

3.6 Long-Term Testing of Lime Treated Soils

In addition to the testing of lime-treated subgrades during the construction process, a lime treated subgrade soil that had been in service for approximately 25 to 30 years was sampled. This soil was from I-135 near Newton, KS and was reported to have been lime treated during the early 1970s. The dry density was determined using the sand cone method. Atterberg limits were determined for four locations and the DCP values were determined for seven locations on a one meter spacing across that portion of the subgrade that had not been removed.

Chapter 4

Results

This section contains the results of the testing program. Included are a discussion of the sampling procedures and the results of testing on the native soil, lime treated soil, and dynamic cone penetrometer testing conducted in the field.

4.1 Soil Sampling and Preparation Procedures

Native soils for this project were brought from the field as bag samples and were broken up and sieved over a 9.5 mm (3/8") sieve. All tests on native material were performed on the material passing a 9.5 mm sieve. The tests performed included grain size analysis, Atterberg Limits, swell, standard Proctor, and unconfined compression. The results reflect a slightly more granular material than indicated by KDOT on soils A, B, and D (KDOT Reports 57-02 K4421-01, 169-01 K-4419-01, 69-02 K-4420-01), even though the grain size analysis did not include the small amount of material retained on the 9.5 mm sieve. This was likely the result of some mixing in of a more coarse borrow material by the contractor. A summary of the results of the tests on native soil are presented in Table 4.1.

Lime treated soils that were mixed and compacted in the field were generally sampled within 24 hours of compaction using drive cylinders, with the exception of Soils A and B. These soils were sampled five and nine weeks after compaction, respectively. Soils D and E were sampled approximately six hours after compaction and Soil F was sampled approximately 24 hours after compaction. Dynamic Cone Penetrometer (DCP) tests were performed several weeks after compaction for soils A, B, and D. DCP testing was performed approximately four hours after compaction for Soil E and 24 hours after compaction for Soil F. Obtaining intact samples of soils A and B was nearly impossible due to the time interval between compaction and sampling. The reaction of the lime with soil had progressed to the point that the soils had almost no plasticity but were well compacted and lightly cemented. As a result, it was very difficult to penetrate the soil, and the energy required to obtain the sample tended to damage the sample to the point that it was unusable. For this reason the DCP was selected as the primary method used to evaluate the in-situ strength.

Table 4.1: Native Soil Properties

Soil Property	Soil A	Soil B	Soil D	Soil E	Soil F
% Gravel	17	3	1	4	11
% Sand	18	28	9	25	21
% Fines	64	69	91	71	69
Liquid Limit	56	44	44	43	38
Plasticity Index	32	21	27	25	21
Classification (USCS)	CH	CL	CL	CL	CL
Classification (AASHTO)	A-7-6	A-7-6	A-7-6	A-7-6	A-6
Swell Potential (%)	5.6	1.5	2.4	1.3	1.0
Maximum Dry Density (kg/m^3)	1600	1620	1670	1700	1820
Optimum Moisture (%)	22.0	21.0	20.1	18.4	15.8
Unconfined Compressive Strength (UCS) at Optimum Moisture (kPa)	200	190	150	140	280
Max UCS (kPa)	279	240	272	210	230
Moisture at Max UCS	18.6	17.6	18.0	16.0	13.7

The soil properties of the samples of lime treated soil mixed and compacted in the field are representative of an average for the entire depth of sampling (generally 150 mm) and possible variations of soil properties within that depth were not measured. These samples generally consisted of a drive cylinder sample and the surrounding soil. In the lab, the samples were placed in a separate bag and put in a moisture room to cure for 28 days, except where noted. The remaining soil from each sample was screened over a 9.5 mm (3/8") sieve before performing any lab tests. The lab tests performed on these samples included Atterberg Limits, swell, in-place density and moisture (from drive cylinder samples before curing), unconfined compressive strength (from the cured, extracted drive cylinder samples), lime content, and pH.

Samples of lime treated Soils E and F were collected in the field and returned to the lab for compaction. The samples were placed in sealed bags immediately after field mixing was complete. For Soil E, three samples were taken after one pass (once over in one direction) by the rotomixer and six samples were taken after the second pass (once over in each direction) by the rotomixer. For Soil F, three samples were taken after the one and only pass by the rotomixer and six samples were taken after the one rotomixer pass and two passes by a pad foot roller over the soil-lime mixture. The samples for each soil were taken from the same location to minimize the effects of spatial variability. The samples were then taken back to the lab and compacted in a 101.6 mm mold using energy for a standard Proctor. The lag time between mixing and lab compaction was approximately 12 hours.

Lab mixed and compacted lime treated soil samples were prepared in accordance with ASTM D-3551 to simulate complete mixing prior to testing. This provided a standard measure of the possible benefits of mixing lime with the soils studied. The mixing, and compaction where necessary, of soil and lime samples followed applicable specifications as set out in Chapter 3.

The lab tests performed included Atterberg limits, swell, Proctor curves, and unconfined compressive strength. In differentiating test data, Atterberg limits and swell tests were performed at 2.5% and 5% equivalent hydrated lime for each soil following the outlined procedures. Proctor and unconfined strength values were determined for a 1-hour and a 48 hour cure between mixing and compaction using 5% lime.

4.2 Strength Testing by Dynamic Cone Penetrometer and Unconfined Compression

Dynamic cone penetrometer testing was performed at each of the sampling locations to a depth of approximately 305 to 356 mm. Additional DCP testing was performed on soils A, B, and D between the locations of the test samples. These data were analyzed by two methods, one using software provided by the Kansas Department of Transportation and the other using a correlation developed by Livneh (1995). The DCP readings were correlated to CBR in accordance with the equations discussed in Chapter 3. The data from the dynamic cone penetrometer testing were utilized to establish an average CBR value for the in-situ subgrade below the lime treated layer of soil. The data also were used to establish the approximate depth to which the lime treatment effectively strengthened the soil. The average data and results for each soil are given in Table 4.2 and coefficients of variation for the lime treated layer and the untreated subgrade beneath are shown in Figure 4.1 for those soils for which at least 19 tests were performed. Soil E was tested almost immediately after compaction and this is reflected in the low strength values recorded. These low values also made it impossible to identify the depth at which lime treatment ended.

Soil F had the greatest amount of variability in CBR as measured by the standard deviation and coefficient of variation, followed by Soils B, D, and A, in that order. Known construction differences between these soils include the method of lime treatment and the amount of mixing. Soils B and F were both lime treated with quicklime while Soils A and D were treated with slurry. Soil F also had the highest variability in the untreated subgrade and was mixed only once with the rotary mixer.

Table 4.2: Dynamic Cone Penetrometer Average Data and Results

	Soil A	Soil B	Soil D	Soil E	Soil F
KDOT CBR	14.8*	20.5	17.4	2.0	12.7
Livneh CBR	12.5	17.2	14.7	1.8	10.8
Depth of Liming (cm)	15.7	16.3	16.0	----	----
KDOT CBR (untreated subgrade)	15.4	11.8	6.8	----	----
Standard Deviation	2.52	6.42	3.07	----	5.12
Coefficient of Variation (Lime treated layer)	17 %	31 %	18 %	----	40 %
Time after Liming	7 weeks	11 weeks	2 weeks	4 hrs	24 hrs

*All CBR values expressed in percent (%)

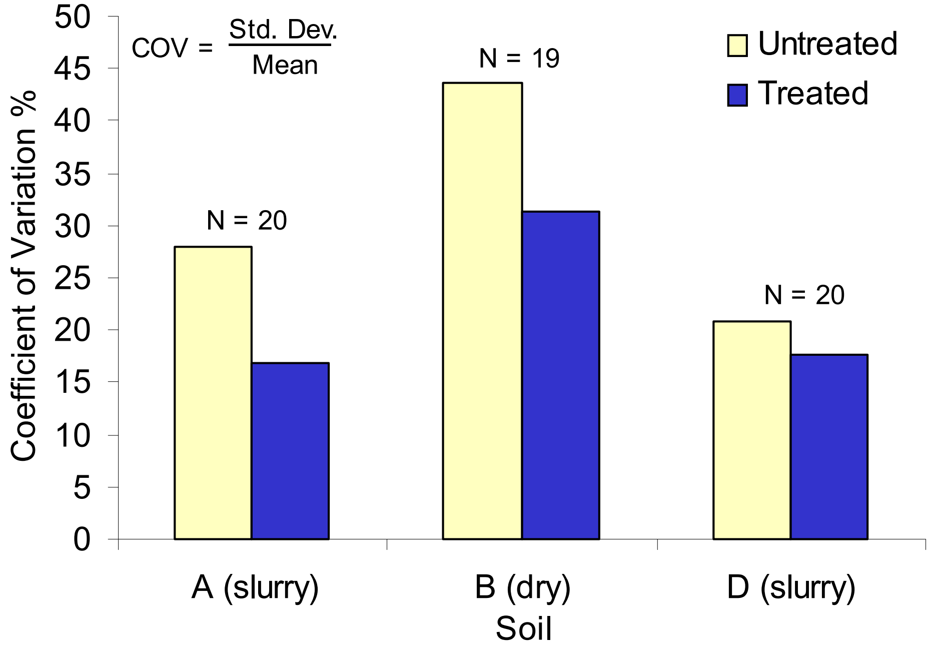


Figure 4.1: Variability of lime treated and untreated subgrade soils for Soils A, B and D

Unconfined compression testing was performed on drive cylinder samples taken from soils D, E, and F. These samples were tested 28 days after mixing and compaction, with the exception of two samples from Soil E which were tested at 100 days. The results of this testing are shown in Figure 4.2. This figure shows that Soil D was stronger than E and F, which is consistent with the strength tests on the lab compacted samples discussed later in this chapter. However, the strength values as a whole are much lower than the maximum compressive strengths recorded from the lab compacted samples. This outcome is addressed in more detail in Chapter 5.

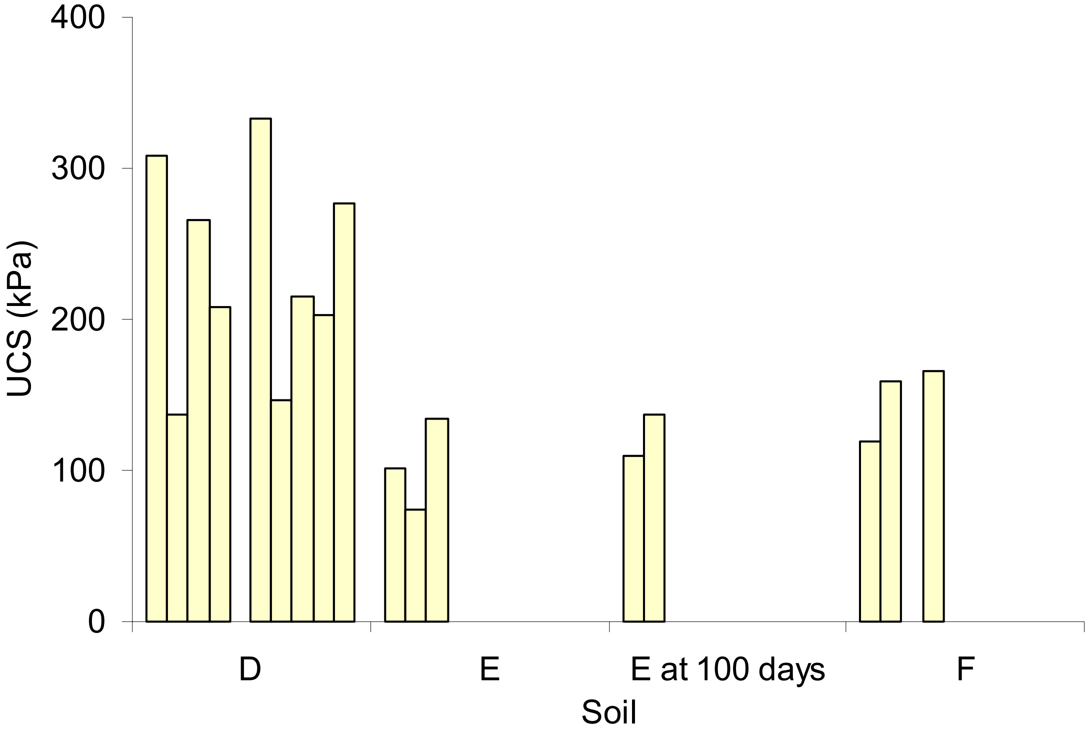


Figure 4.2: Results of unconfined compression testing on drive cylinder samples

4.3 Swell Testing

Swell tests on field samples were prepared at the prevailing moisture and density conditions at the time of sampling. Lime content values shown are in hydrated lime equivalent percentages. The hydrated lime equivalent percentages were obtained by multiplying the percentage of quicklime by 1.3 where necessary. This conversion was done because most of the research and specifications available are written in terms of hydrated lime. Figure 4.3 shows the results of lab tests on each of the soils with 0, 2.5, and 5 percent hydrated lime equivalent. These results demonstrate that lime is effective in reducing the swelling potential of each of the soils tested and that the final swelling potential was acceptable with the exception of Soil A, which still had a swell potential of 2.7% even with the addition of 5% hydrated lime. This is likely a function of the fact that Soil A was a CH soil and had the highest initial swelling potential.

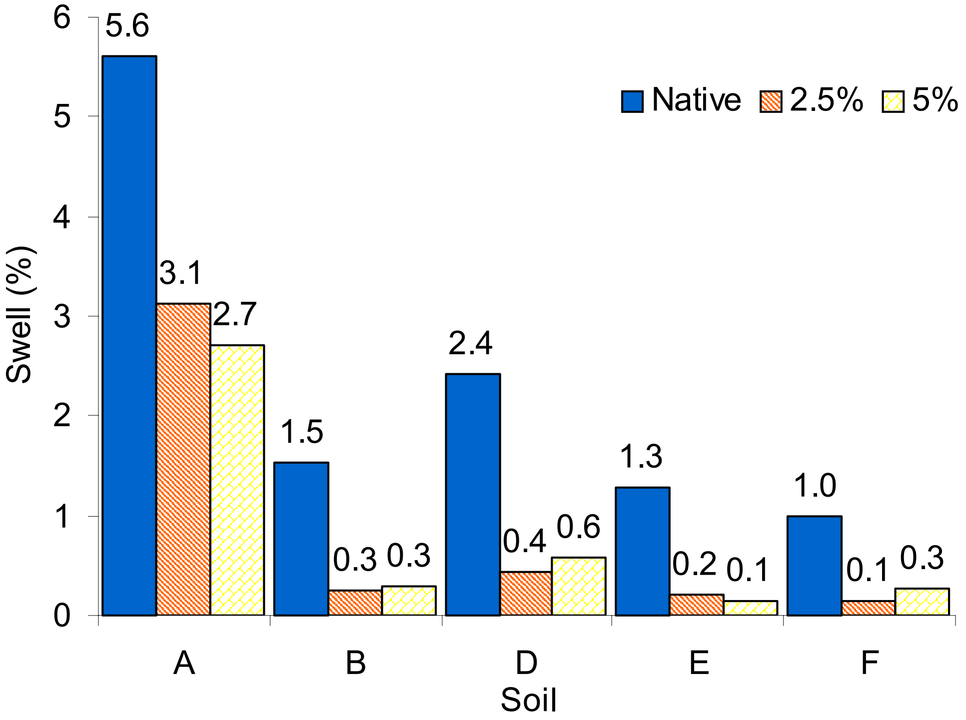


Figure 4.3: Swell testing results for lab mixed and lab compacted soil lime mixtures

Samples for swell testing were prepared from selected grab samples that had been mixed in the field. Results of swelling tests performed on field samples showed swell reductions equivalent to or better than results from the tests performed on the soil samples mixed and prepared in the lab. The probable reason for this improvement was the moisture content at the time of testing, which was left at the field moisture content to better simulate field conditions. This moisture content was well above optimum in each case. As the results in Figure 4.4 show, the swelling potential was well below one percent for all samples tested and Soil A again had the greatest amount of swell.

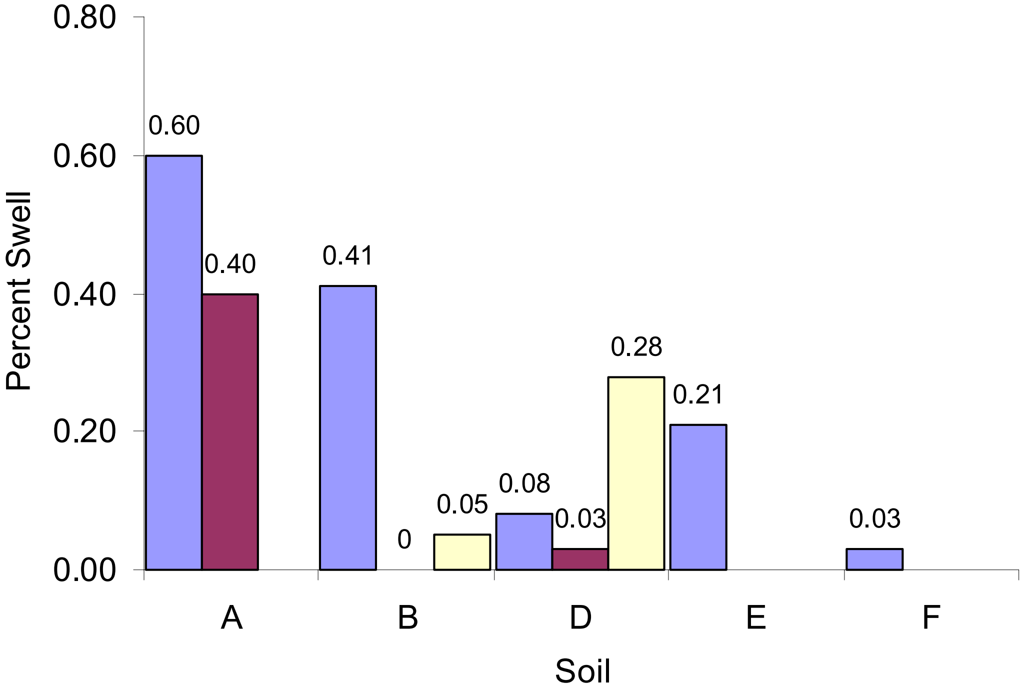


Figure 4.4: Swell of field mixed samples at the field moisture content

4.4 Atterberg limits based on lime content

Table 4.3 and Figure 4.5a shows the Atterberg limits for the native soil mixed with 0, 2.5, and 5 percent lime. This figure shows that the plasticity index was greatly reduced with the addition of 2.5% lime and four of the five soils became non-plastic with the addition of 5% lime. This was achieved by both reducing the liquid limit and increasing the plastic limit. These results correspond well with the swell data reported earlier, with only Soil A retaining a measurable PI after the addition of 5% lime. Figure 4.5b shows the plasticity index results for samples taken from the lime treated soils in the field. These also show a significant reduction in the plasticity index, although it was not as significant as that from the soil samples prepared in the lab.

Table 4.3: Atterberg Limits for Lime Treated Soils Mixed in the Lab

Soil@Lime %	Liquid Limit	Plastic Limit	Plasticity Index
Native A	56	24	32
A@2.5%	54	38	16
A@5%	43	39	4
Native B	44	23	21
B@2.5%	35	31	4
B@5%	---	---	NP
Native D	44	17	27
D@2.5%	36	29	7
D@5%	---	---	NP
Native E	43	18	25
E@2.5%	36	29	7
E@5%	---	---	NP
Native F	38	17	21
F@2.5%	35	30	5
F@5%	---	---	NP

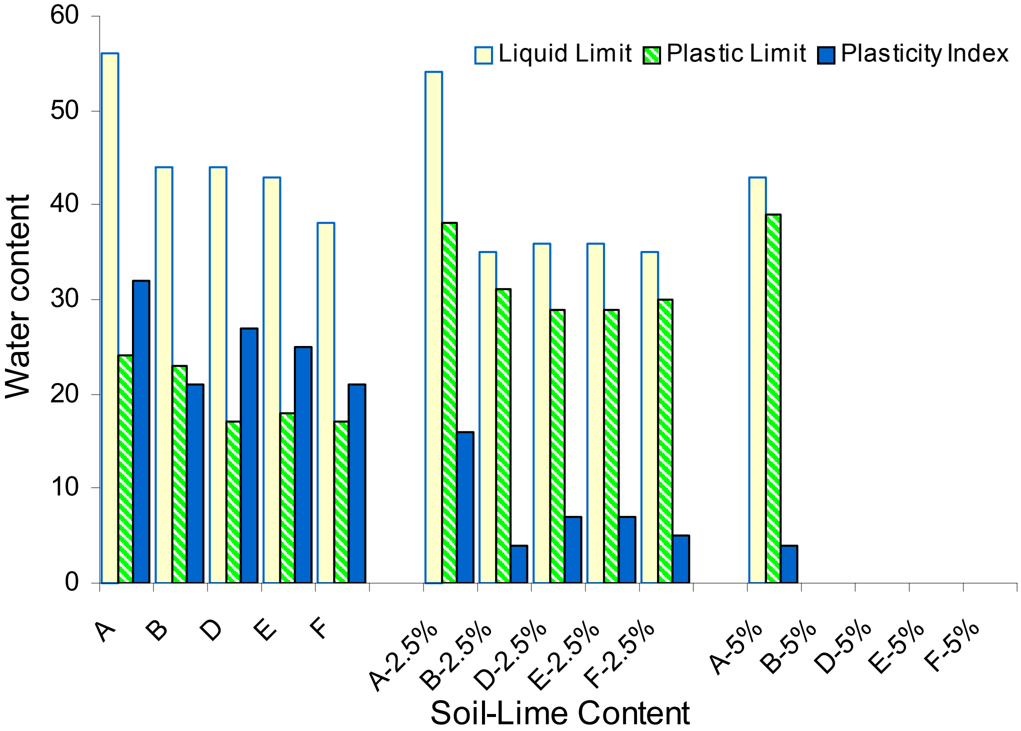


Figure 4.5a: Changes in Atterberg limits with changing lime content

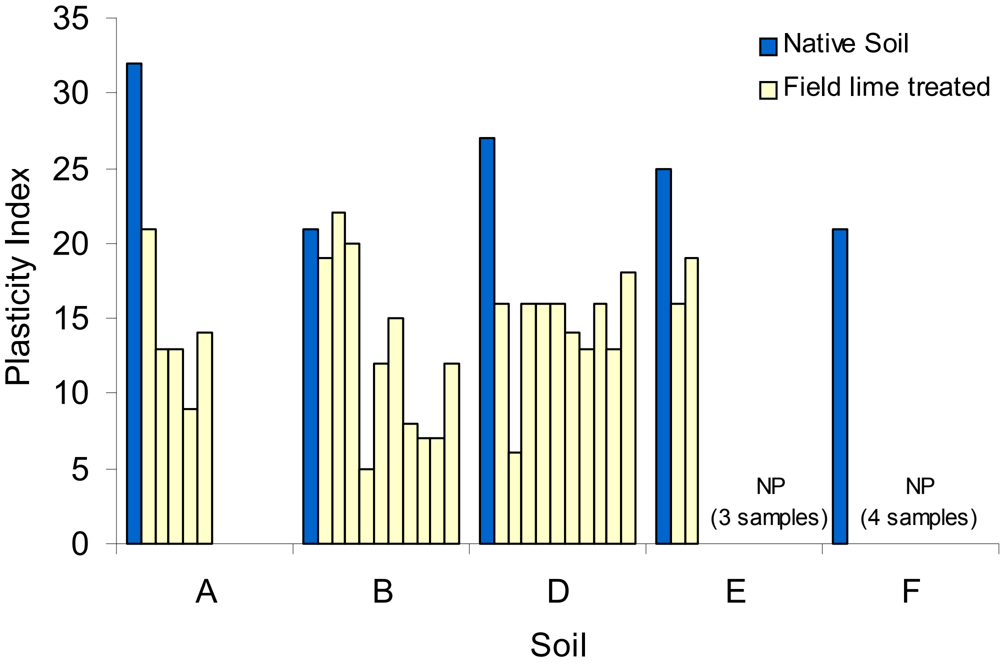


Figure 4.5b: Plasticity index for field samples of lime treated soil

4.5 Moisture-Dry Density and Moisture UCS Relationships

Maximum dry density and optimum moisture are functions of curing time. Figures 4.6 - 4.10 show the moisture-dry density and moisture-strength relationships. Results of a 1-hour and a 48-hour mellowing period are shown along with the native curves. A summary of the results of the Proctor and unconfined compressive strength data are shown in Table 4.4.

Table 4.4: Proctor and Unconfined Strength Data for Lime Treated Soils Mixed in the Lab

Soil@ Mellowing Time	Optimum Moisture Content after treatment (%)	Max. Dry Density (kg/m^3)	Maximum Unconfined Compressive Strength (kPa)	Moisture at Max UCS (%)
A @ 1 hr	18.0	1620	620	22.5
A @ 48 hrs	16.7	1580	420	16.0
B @ 1 hr	19.6	1600	650	20.5
B @ 48 hrs	19.5	1550	500	17.7
D @ 1 hr	18.0	1650	1610	19.5
D @ 48 hrs	18.0	1590	1280	24.0
E @ 1 hr	18.2	1700	1180	17.0
E @ 48 hrs	17.0	1630	860	15.0
F @ 1 hr	17.8	1700	1010	17.5
F @ 48 hrs	18.2	1620	730	18.4

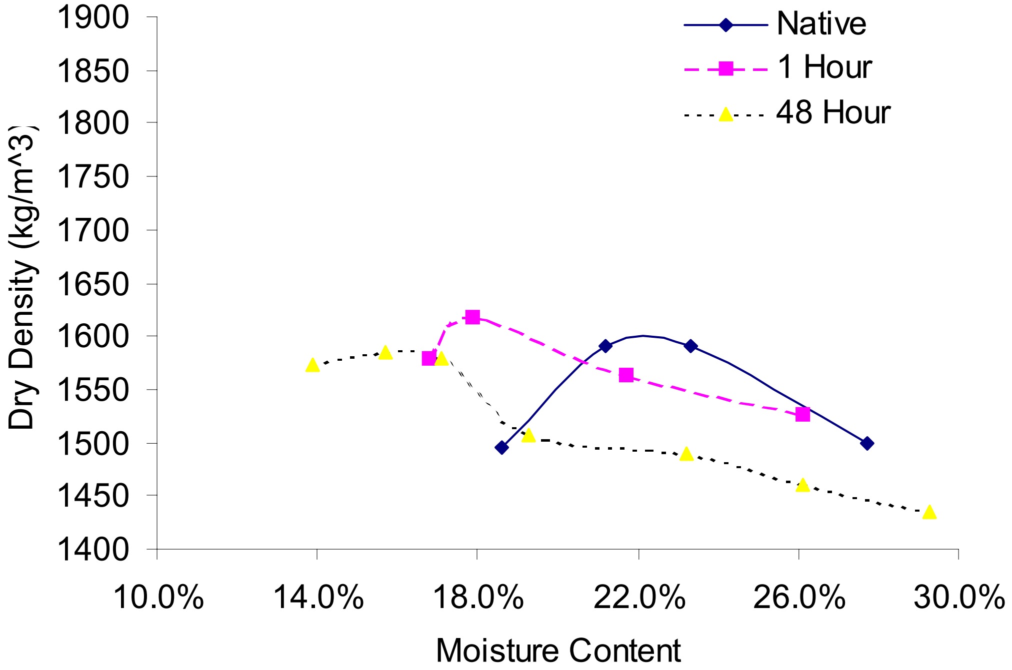


Figure 4.6a: Moisture-Dry density relationships for Soil A

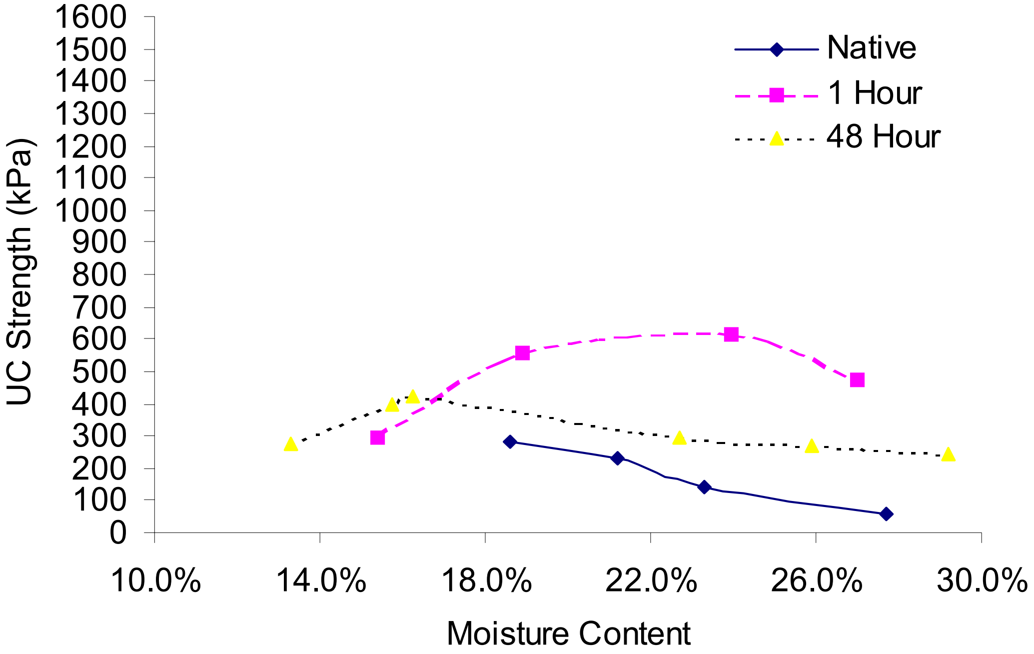


Figure 4.6b: Moisture-Strength relationships for Soil A

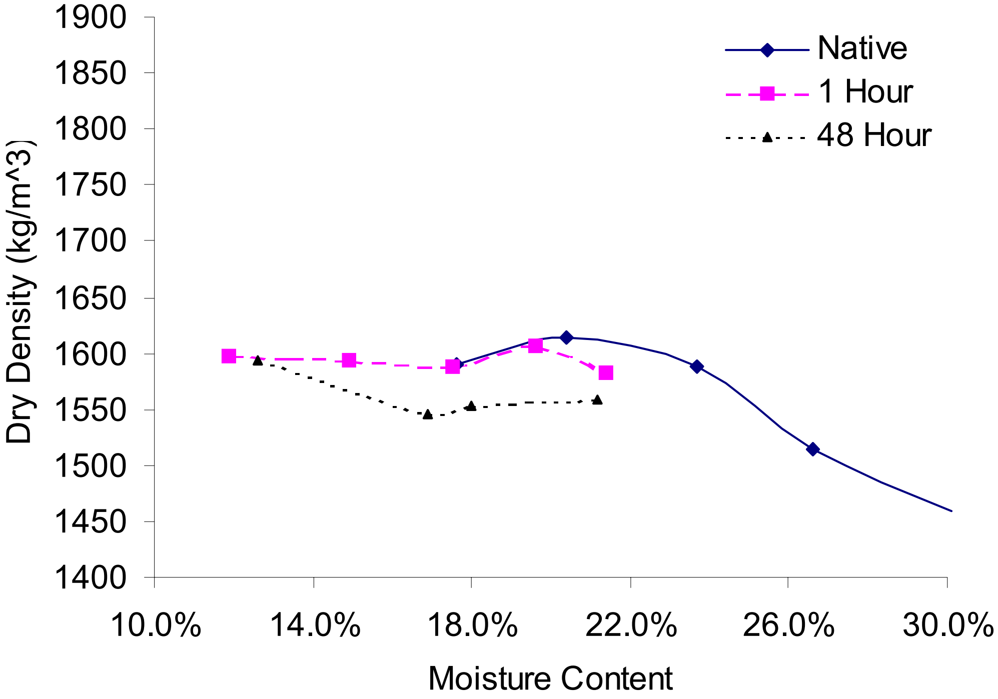


Figure 4.7a: Moisture-Dry density relationships for Soil B

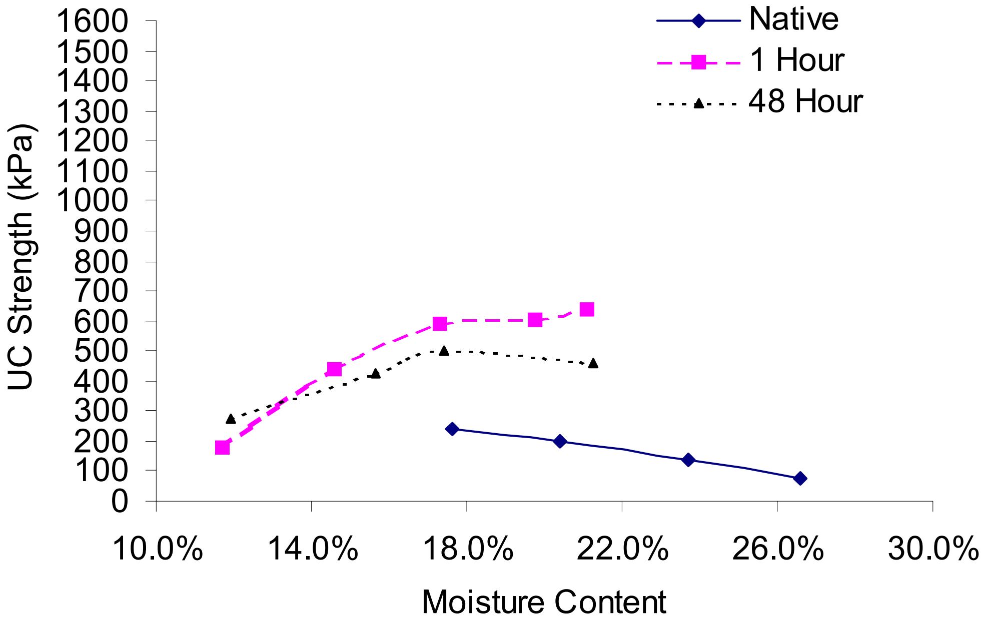


Figure 4.7b: Moisture-Strength relationships for Soil B

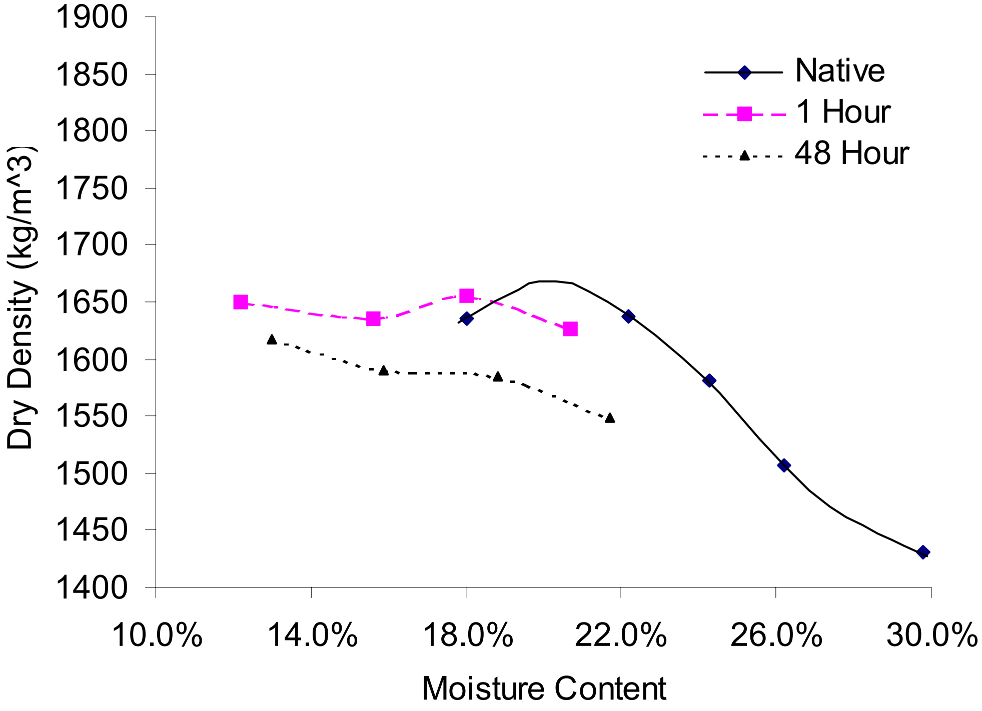


Figure 4.8a: Moisture-Dry density relationships for Soil D

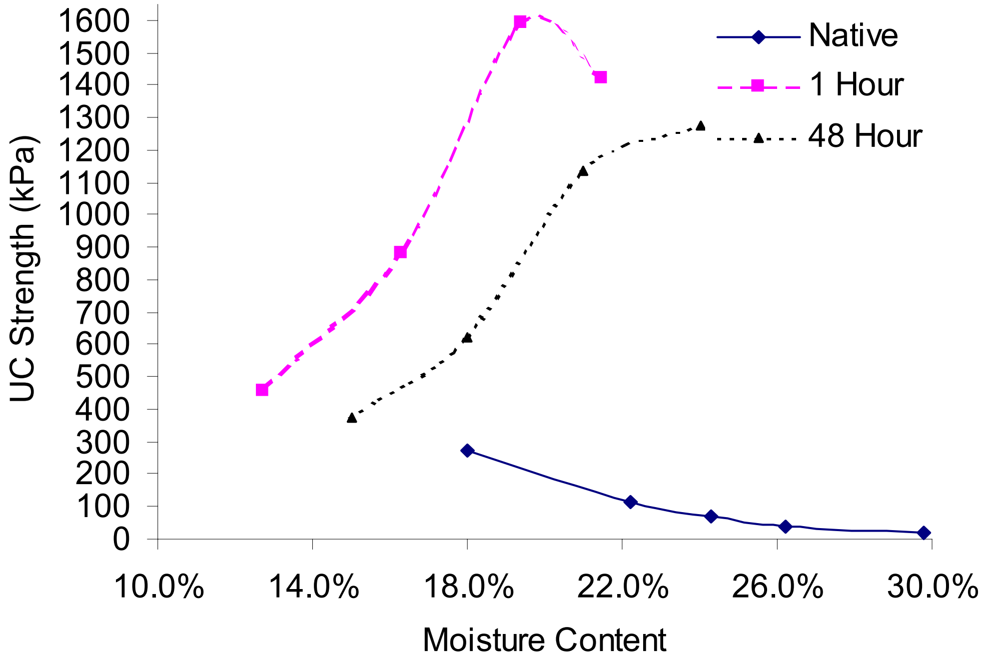


Figure 4.8b: Moisture-Strength relationships for Soil D

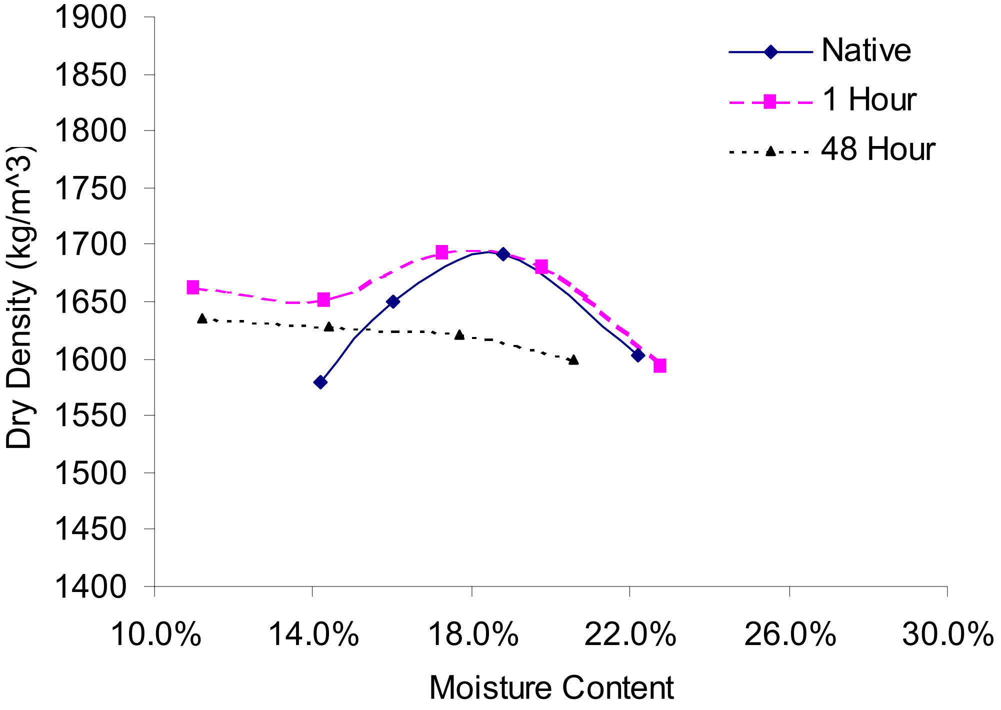


Figure 4.9a: Moisture-Dry density relationships for Soil E

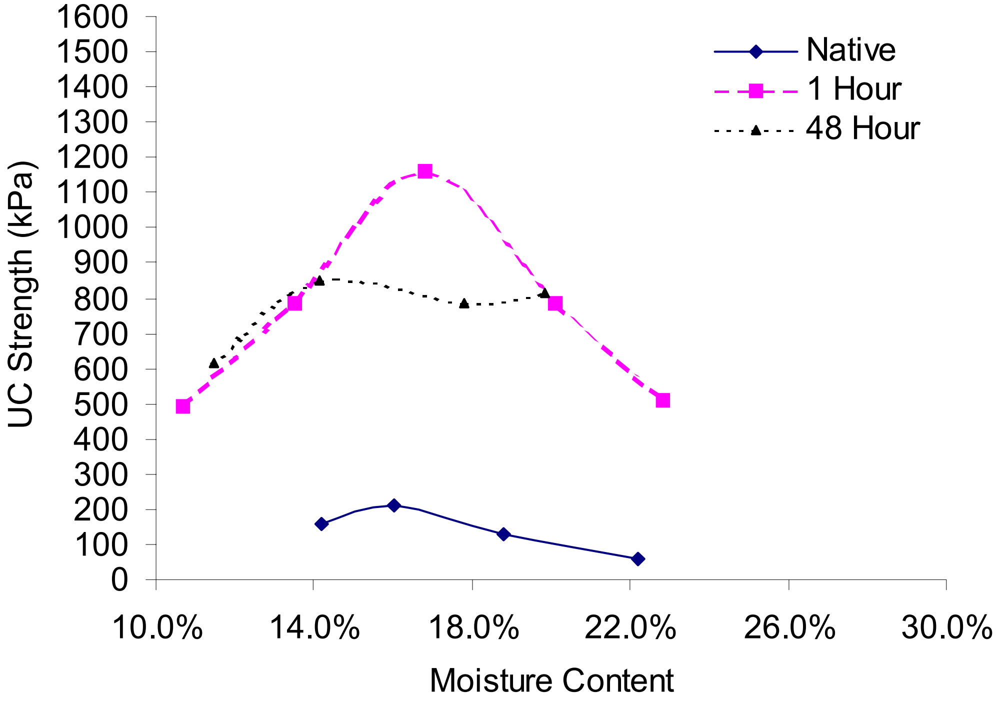


Figure 4.9b: Moisture-Strength relationships for Soil E

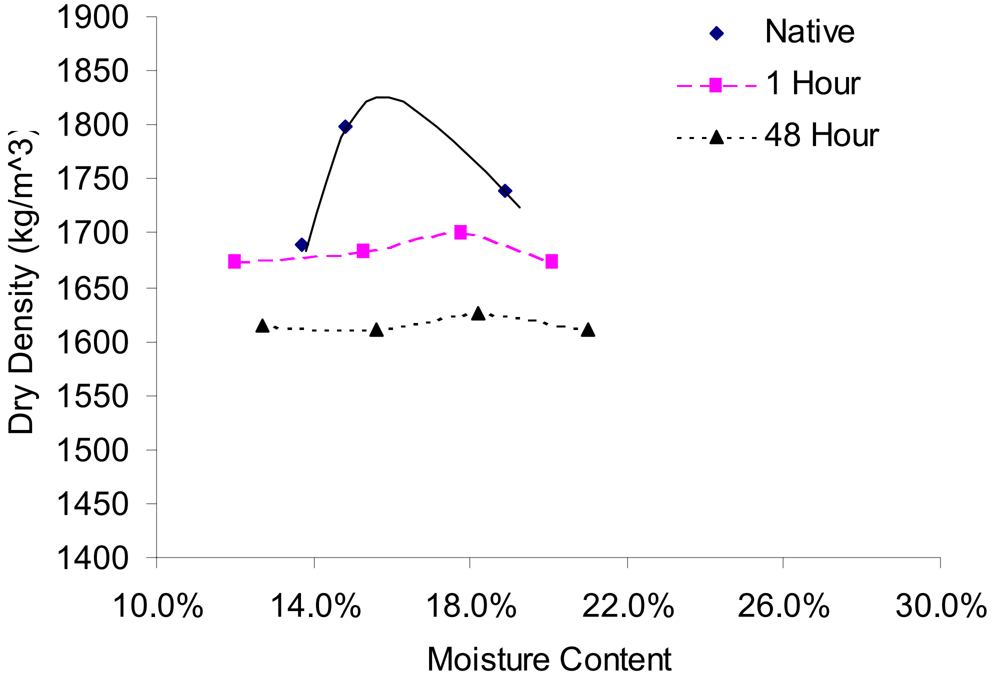


Figure 4.10a: Moisture-Dry density relationships for Soil F

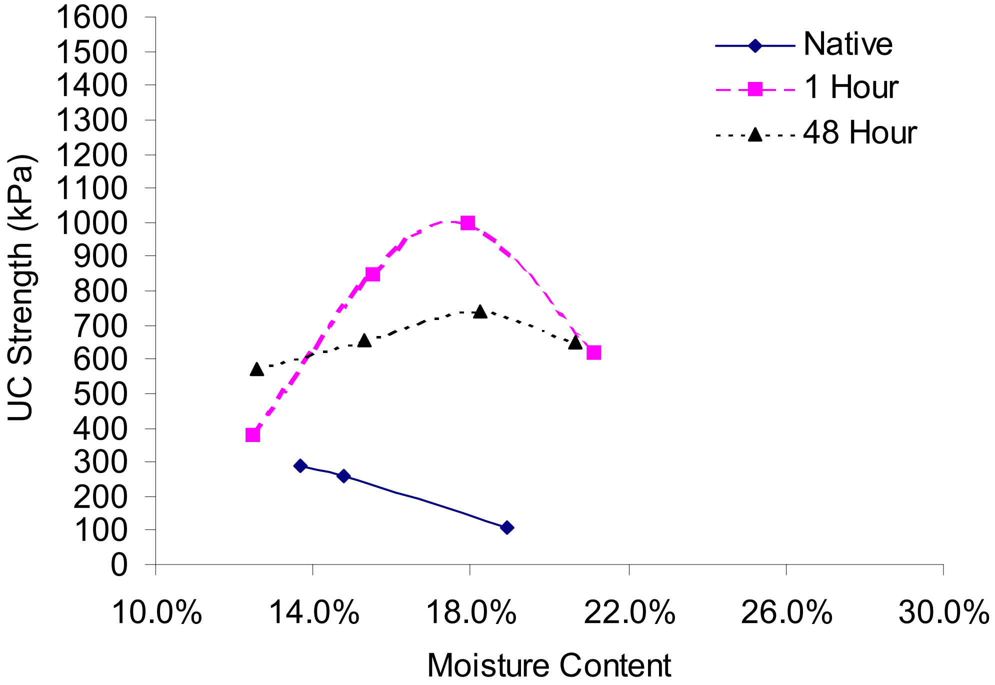


Figure 4.10b: Moisture-Strength relationships for Soil F

4.6 Measurement of Lime Content

Lime content was evaluated using three methods: evaluation of the actual lime content present by titration (AASHTO T 232-90), soil pH using the method described in ASTM C 977, and a qualitative method for determining if lime is present (phenolpthalein solution).

Measurement of the actual lime content proved to be difficult and of limited value with respect to evaluation of the quality of mixing. The test is based on the amount of lime that remains free to react with hydrochloric acid and therefore the test is subject to variations in the reactivity of the clay as well as the amount of lime. As with Atterberg limits testing, thorough mixing of the soil is required as a part of the sample preparation method, which causes unreacted lime particles to come in contact with the clay. Based on our review of the literature, this approach has not proven to be widely used.

Measurement of pH was more straightforward and had the advantage of being a direct measure of whether enough lime is present for stabilization, although it was subject to some of the limitations of measurement of lime content by titration. Figure 4.11 shows the results of pH measurements for field samples of the soils tested.

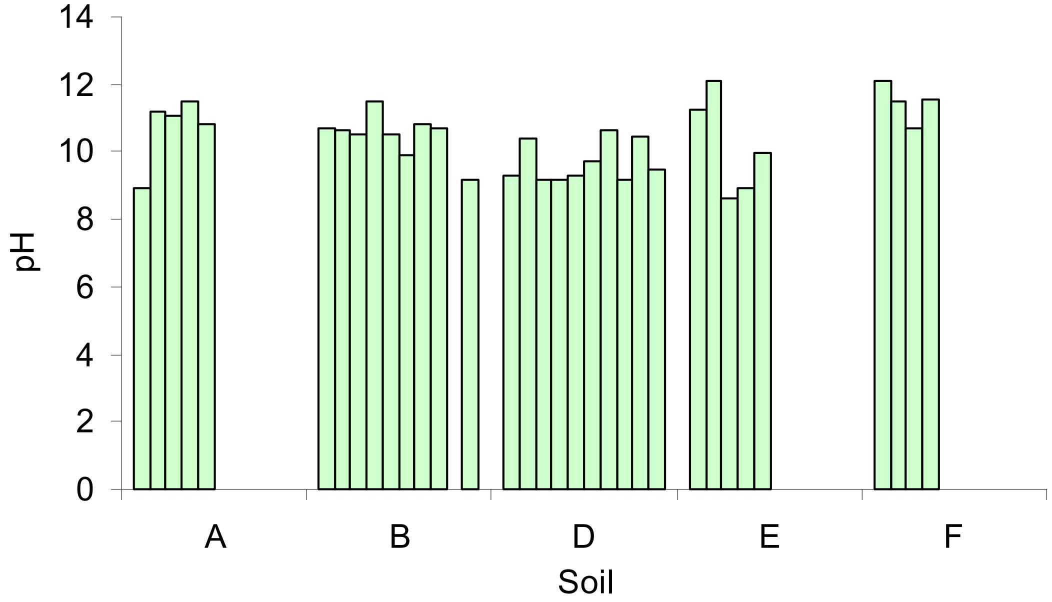


Figure 4.11: pH measurements for all field samples

Phenolphthalein proved to be very simple and effective indicator of the presence of lime. The only problem observed was that in attempting to evaluate the depth of mixing, a sample from beneath the treated soil would occasionally become coated with a film of treated soil during excavation. This film could give a false positive reading on the presence of lime if not scraped off of the sample.

4.7 Moisture Content

Recorded field moisture contents for drive cylinder samples are shown in Figure 4.12. These values show that the moisture content was generally well above optimum. This was true even for soils A and B, which had been exposed for several weeks prior to sampling. They also show a high variability for Soil F, which had both the highest and lowest individual moisture content measurements.

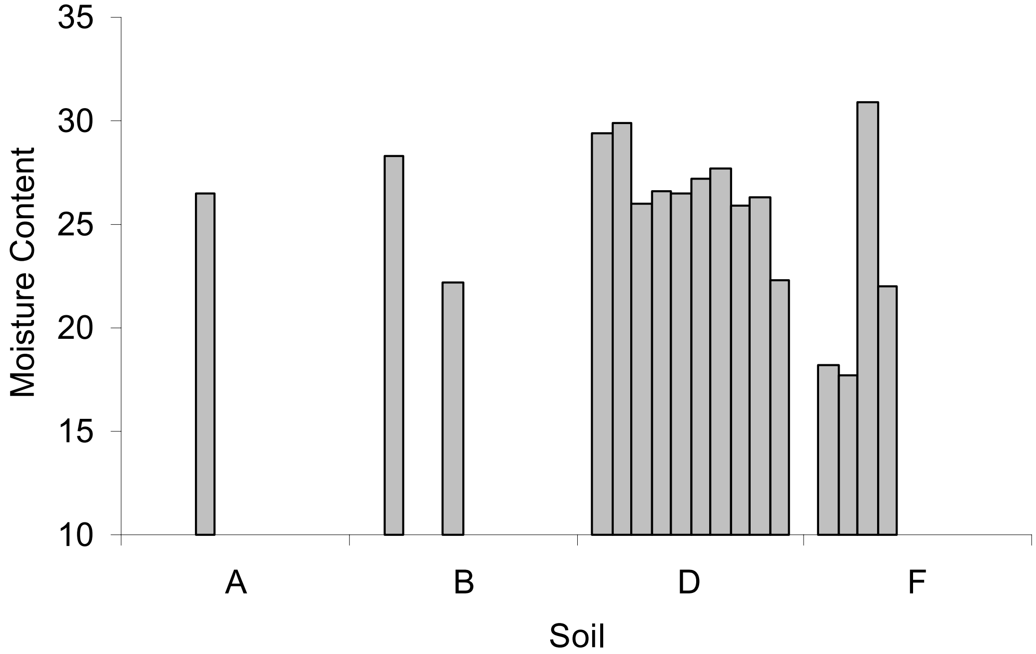


Figure 4.12: Field moisture content

4.8 Evaluation of the Depth of Lime Treatment Using the Dynamic Cone Penetrometer

Figure 4.13 shows the penetration resistance for all blows recorded for Soils A, B, D, and F with a moving average line superimposed. These averages reflect lower DCP penetration values (higher strength) than the average values reported in Table 4.2 because more blows are required to penetrate stiff soils than soft soils. This results in a moving average that is slightly biased in the direction of stiffer soils. Figure 4.13 shows that Soils A and D are the most consistent, with Soil B showing slightly more variable readings and Soil F the most variable. This figure also shows the effective depth of lime treatment and the magnitude of soil improvement can often be determined by penetration resistance. Soil D shows this most clearly with a large decrease (improvement) in penetration/blow for depths less than 150 mm. Soils A and B show very slight decreases in penetration/blow above this depth. Soil F shows a significant decrease in penetration/blow, however this increase begins at a depth of approximately 100 mm (4 inches), suggesting that a single pass by the rotary mixer may have been insufficient to evenly distribute the lime to the full depth of 152 mm (6 inches).

4.9 Effect of Additional Mixing

The field lime treated and lab compacted samples for Soils E and F were divided into three categories to evaluate the impact of additional mixing. The three samples of each soil taken after one pass were designated 1-mix and were compacted directly from the bag with no additional mixing. The other six samples taken after the second rotomixer pass (Soil E) or after compaction by the padfoot roller (Soil F) were divided into two groups. Three samples of each soil were compacted directly from the bag and labeled as 2-mix. The last three samples of each soil were mixed in the lab in an electric mixer for five additional minutes in accordance with ASTM D-3551 and labeled completely mixed. These samples were compacted in a standard 101 mm mold when mixing was complete.

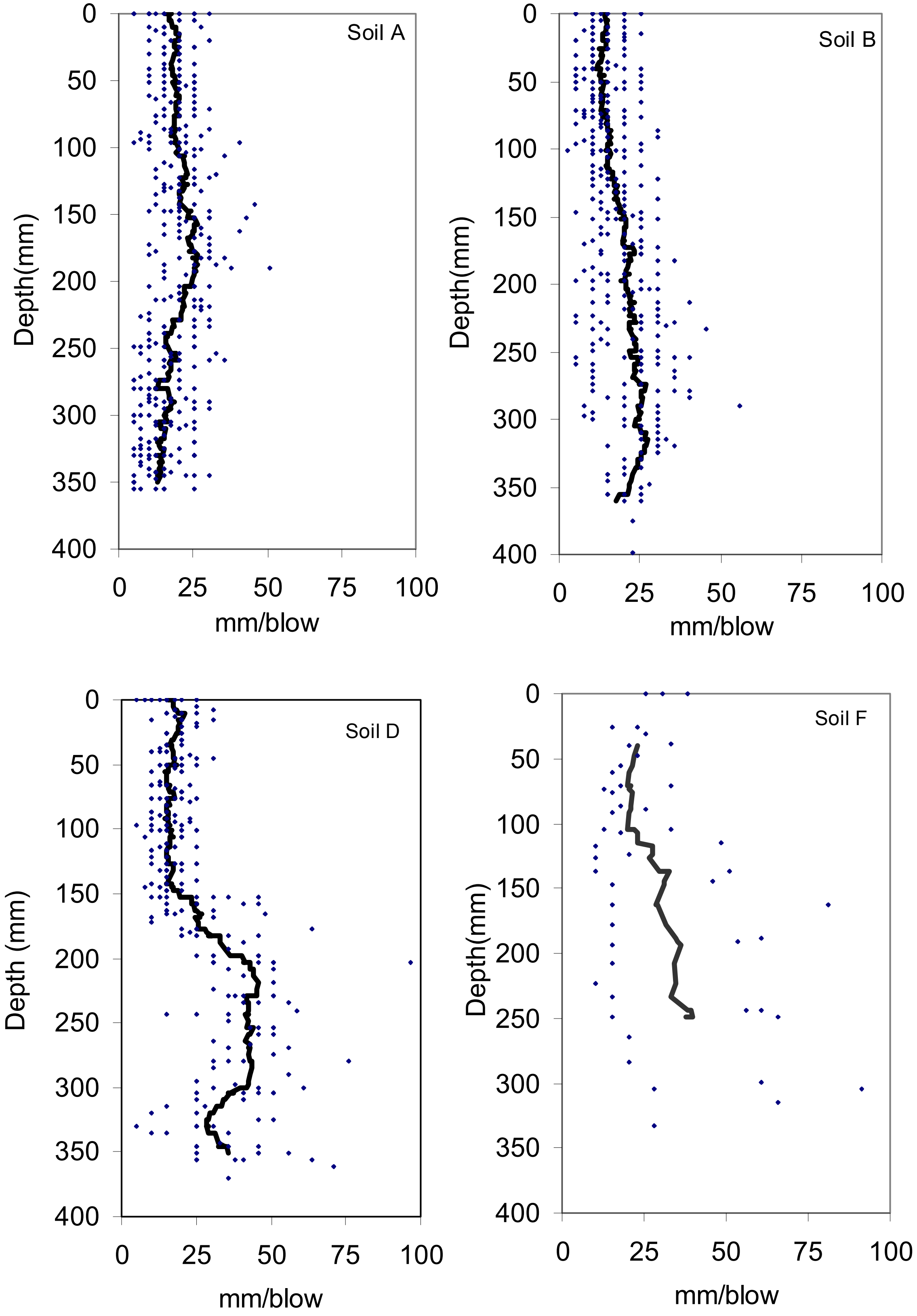


Figure 4.13: Penetration resistance vs depth

After compaction, the remaining soil for each sample was screened over a 9.5 mm sieve. Lab tests were then performed, including Atterberg limits, swell, lime content, and pH. The density and moisture of the compacted samples were measured at the time of compaction and were then cured for 28 days in a sealed bag in a moisture room. After curing, unconfined compression tests were performed on the samples.

Of particular interest were the unconfined compressive strength and the Atterberg limits after various levels of mixing. The strength of Soils E and F for each level of mixing are shown in Figure 4.14. Each value reported is the average of three test samples, with the exception of Soil F-1 mix, for which two samples broke apart prior to testing. This figure shows that the strength of each soil increased with additional mixing and continued to increase with additional mixing beyond that which was done in the field. This increase was not a function of either dry unit weight or moisture content, as these were relatively constant for all samples as shown in Figure 4.15.

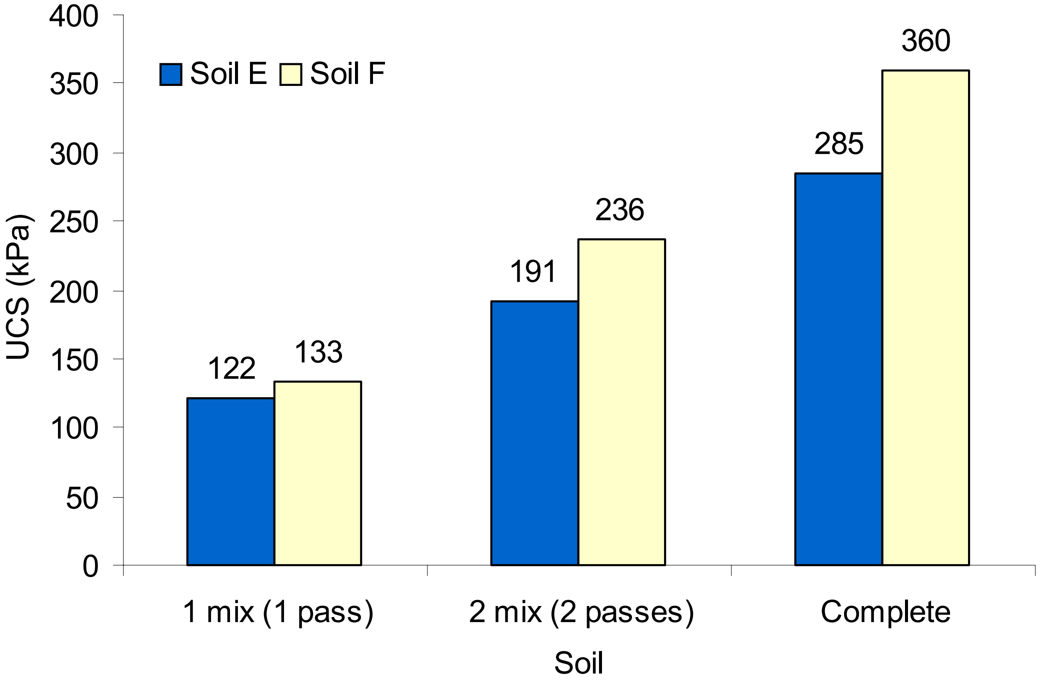


Figure 4.14: Relationship between strength and mixing

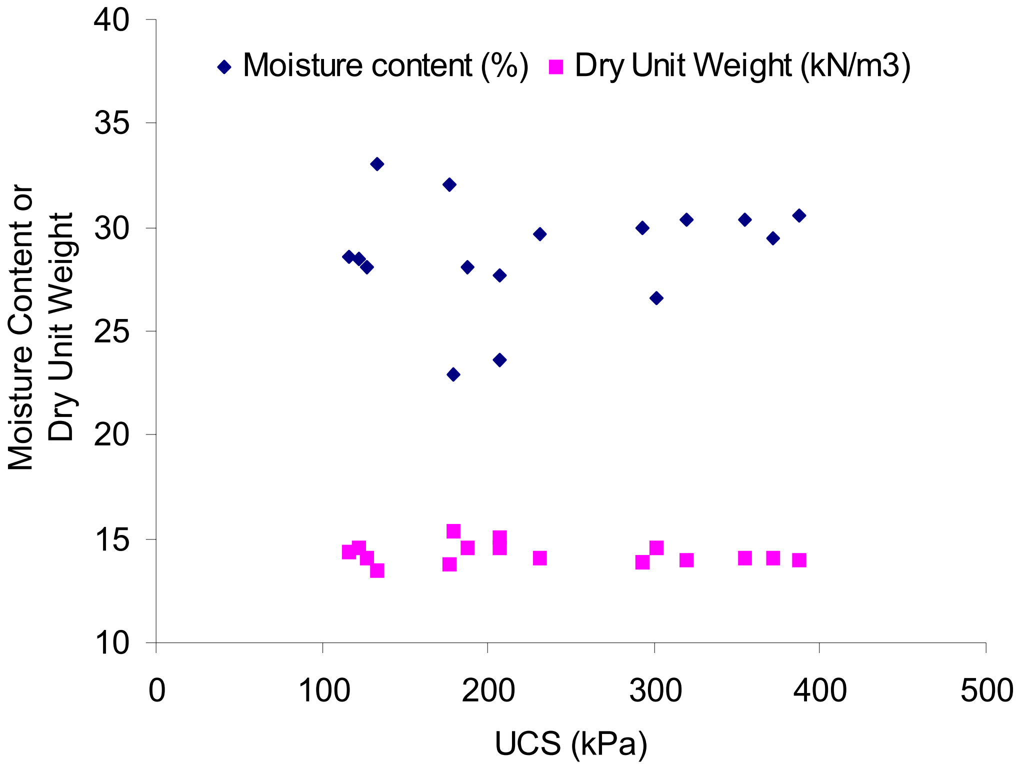


Figure 4.15: Moisture content and unit weight vs strength

The Atterberg limits were also determined for these samples to evaluate mixing on a medium scale (approximately 10 - 500 cm). As mentioned in the section on lime content, the effectiveness of mixing on a small scale is masked by the mixing done as a part of the test procedure.

Figures 4.16 and 4.17 show the relationship between the Atterberg limits and mixing. Values reported in this figure represent the average of three values, with the exception that samples that were non-plastic were not included in the average and are reported as non-plastic (NP). These figures show that the plasticity decreased with increased mixing, and that most of the decrease in plasticity occurred after two passes with the rotary mixer. This suggests that two passes with the rotary mixer is sufficient to get the lime distributed evenly throughout the soil. It does not necessarily indicate that this level of mixing is sufficient to adequately break up the clay lumps, as this was done to the samples as a part of the test procedure.

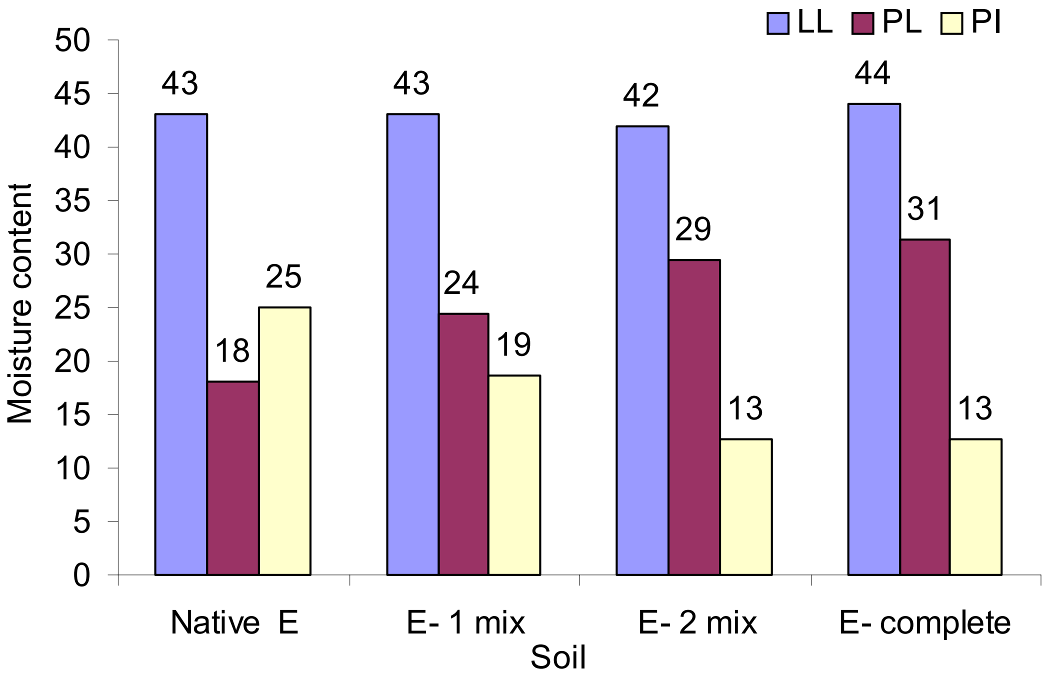


Figure 4.16: Change in Atterberg limits for Soil E with additional mixing

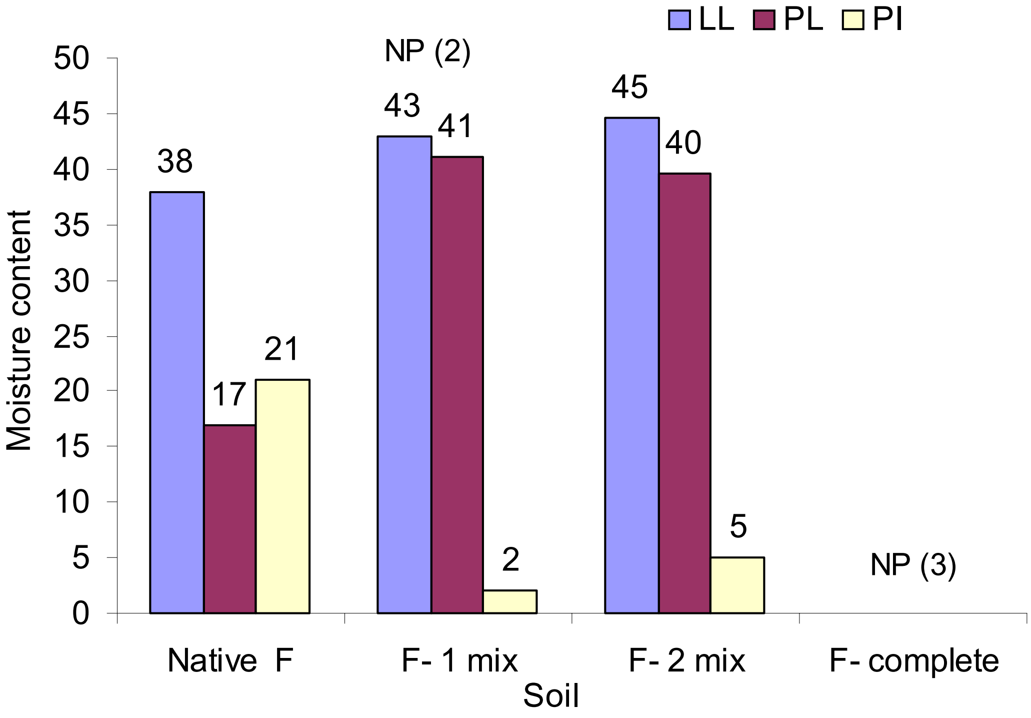


Figure 4.17: Change in Atterberg limits for Soil F with additional mixing

4.10 Newton Soil

An additional soil was added to the study to evaluate the long-term strength of a lime treated soil. The soil was part of a lime treated subgrade dating from the early 1970s and was from I-135 near Newton, Kansas. No native soil was available for investigation on this project. DCP tests were performed along a cross-section of the remaining subgrade at a spacing of approximately 1 meter. The DCP data, Atterberg limits and field dry density (by sand cone) were determined for selected samples and are shown in Figure 4.18 and Table 4.5.

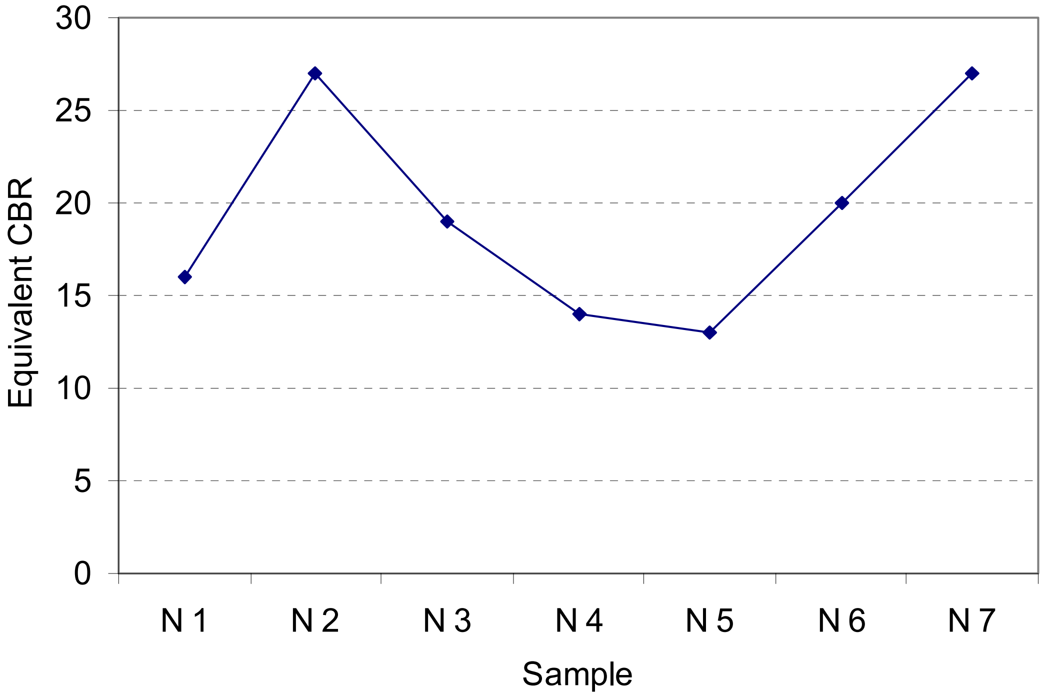


Figure 4.18: Newton DCP data for a subgrade cross-section (25+ years after treatment)

Table 4.5: Newton Subgrade Data

	N1	N2	N3	N4	N5	N6	N7
CBR by Kansas DOT Correlation from Dynamic Cone Penetrometer	16	27	19	14	13	20	27
Liquid Limit	----	32	32	32			
Plasticity Index	NP	8	11	12			
Dry Density (kg/m^3)		1560					
Moisture (%)		18.8					

Chapter 5
Discussion

5.1 Native Soils

All soils tested were fine grained with liquid limits between 38 and 56 and with PI values between 21 and 32. All of the native soils studied were classified as a lean clay (CL) under the Unified Soil Classification System, except for soil A which was a fat clay (CH). Each of the soils was classified as an A-7-6 soil using the AASHTO classification system, except for Soil F which was an A-6 soil. From the AASHTO classifications, all of these soils would be fair to poor subgrade materials in their native form (AASHTO M-145).

A swell potential of 2 percent is considered by KDOT to be the threshold of concern for samples at optimum moisture and compacted to 92 percent of the maximum dry density. Soils A and D exceeded the 2 percent threshold of concern for swell potential in their native state when tested at 95% of the maximum dry density. Soil B was near this level with a recorded swell potential of 1.7 percent. The swell potentials for Soils E and F were somewhat lower. Swell potential appeared to be correlated with the PI and liquid limit as would be expected. These correlations are shown in Figure 5.1.

Unconfined compression tests performed on the native soils exhibited the normal tendency for clay strength to be dependent on moisture content. For all soils, except Soil E, lower moisture content always correlated to higher strength (Figures 4.6 - 4.10). Peak unconfined strengths were between 200 and 300 kPa and corresponded to moisture contents several points below optimum. As the moisture content increased to 3% or more above optimum, strengths dropped at least 50%. The potential swell dropped by an average of approximately 75% when going from three points below optimum moisture to three points above optimum moisture. These results are consistent with traditional soil behavior and demonstrate the inherent conflict between achieving strength improvement and swell reduction by varying moisture content only.

In summary, the native soils demonstrated a reduction in strength and swell potential as they were wetted, indicating a moisture sensitivity that would be undesirable in a pavement subgrade. The unconfined compression results and the CBR values reported in Chapter 4 for these native soils (6.8 - 15.4, Table 4.2) indicate that they would provide moderate to poor support.

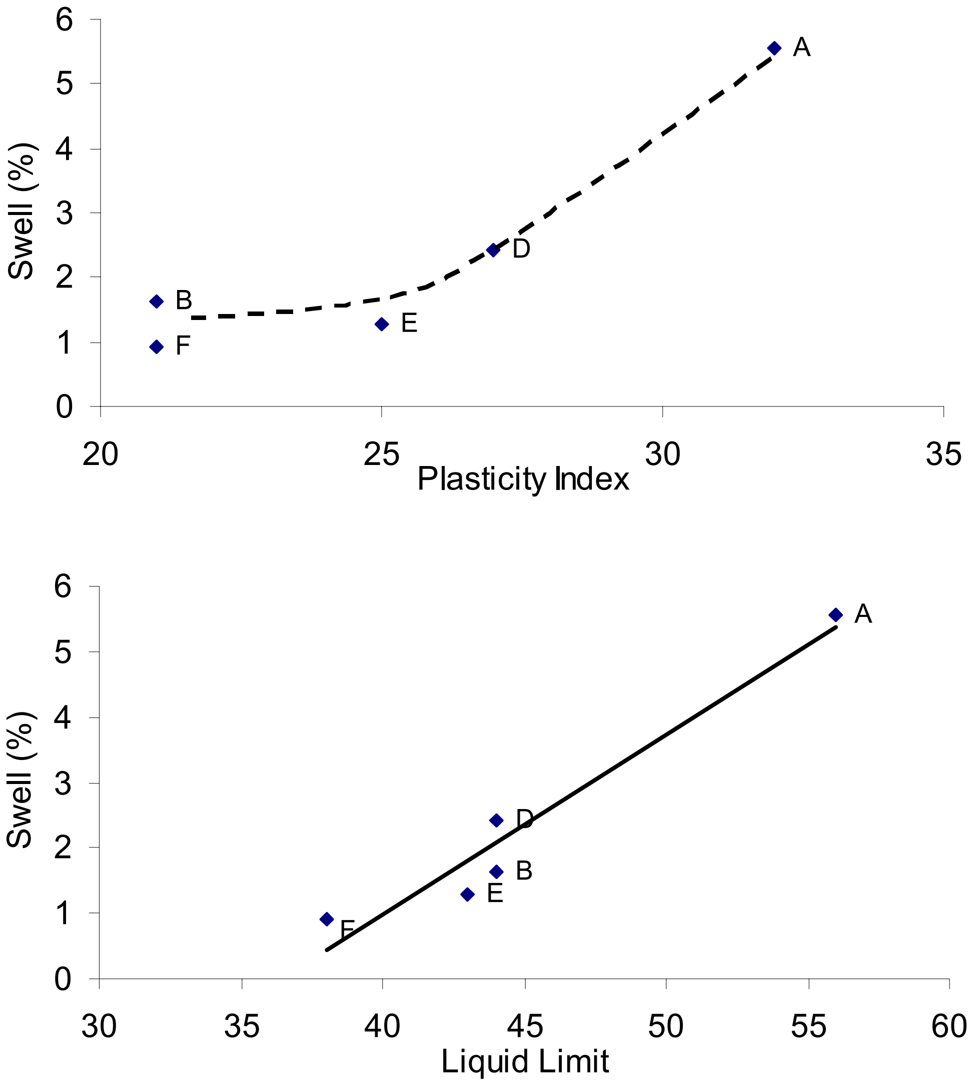


Figure 5.1: Swell vs PI and liquid limit

5.2 Dry Density

Soils compacted after a one hour mellowing period tended to have a moisture-dry density relationship that was similar to the untreated soil, except for Soil F which had a 7 percent reduction in maximum dry density. The moisture-dry density relationships for the soils mellowed for 48 hours had maximum dry densities that were typically 3 to 4 percent lower than those of the untreated soils with the exception of Soil F, which had an 11 percent reduction.

The Proctor curves for the 48-hour curves were much flatter that those of the native soils and generally flatter than the 1-hour curves. Proctor curves for the 48-hour cure had a tendency to rise at the dry end of the curve, whether or not they established a peak at higher moisture contents. This may have been a function of incomplete mixing/reaction of the lime with the soil at low moisture contents.

In addition to the maximum dry density changing with cure time, it may also be affected by the moisture content at mixing for longer cures. This changing of the maximum dry density with time could make selection of the maximum dry density for compaction specifications difficult, particularly if compaction is performed relatively quickly after treatment.

The energy necessary to achieve compaction also appears to increase with increasing lime content. The swell samples were compacted using static compaction, meaning the magnitude of compression necessary to achieve a desired density could be measured. In each soil, the average amount of energy necessary to achieve 95% of the maximum dry density increased with increasing lime content. The pressure necessary to compact samples with 5% equivalent hydrated lime was approximately 100 percent greater than was necessary to compact the native samples for the five soils tested. The lime treated samples used for swell testing were all compacted after a 1-hour cure, however two additional field mixed samples were compacted after six months of curing. These samples could only be compacted to approximately 90% of the maximum 48-hour dry density under a pressure of 4.9 MPa, the upper limit of the machine used.

5.3 Unconfined Compressive Strength of Lime Modified Soil

Compressive strength was significantly improved for all lab mixed soils with the addition of lime. Peak strength was highest for samples compacted after one hour and this peak strength generally corresponded with the optimum moisture content for the maximum dry density. However, this strength declined sharply as water content increased. Strength of soils mellowed for 48 hours had a lower peak strength, but maintained that strength better at water contents above optimum than samples compacted after one hour. This was significant because KDOT specifications require that the soil moisture be a minimum of 8 percent above optimum for hydrated lime (10 percent for quicklime) during mixing. Virtually all field moisture contents were in or near this range, including those samples taken several weeks after compaction. This suggests that field strengths may be well below the peak values recorded in the lab.

Drive cylinder sampling for dry density and strength determination was conducted for all sites. Samples were collected in accordance with ASTM D-2937 using thin walled cylinders with the same volume as a Proctor mold, but with slightly different dimensions (97 mm diameter, 127 mm height). This sampling procedure was only effective for those sites that had been lime treated within the previous 24 hours and preferably within six hours, as the soils became both less plastic and more resistant to penetration. Samples taken more than 24 hours after compaction tended to break up during removal from the ground or extrusion from the cylinder. Strength values for these samples had more variability than those determined with the dynamic cone penetrometer and were used only as indicator values. The samples that were recovered generally had relatively low strength, very high moisture contents (typically 5 – 10 points above optimum), and low relative compaction values.

The relative compaction for the drive cylinder samples was determined based on the lime moisture-dry density curves developed for samples with a mellowing time of one hour, which was the approximate delay between mixing and compaction in the field. Relative compaction values are presented in Figures 5.2 and 5.3 and show that the target of 95 percent relative compaction was only approached by Soil D. A review of the 1990

Standard Specifications and Special Provision 90M-141-R1 showed that low dry density values and strength values well below peak were likely under either specification due to the high moisture contents specified for the mixing stage immediately prior to final compaction.

Of the two soils for which more than two samples drive cylinder samples were obtained (Soils D and F), the relative compaction for Soil F was much more variable than for Soil D. Moisture content results were even more variable for Soil F, which had both the highest and lowest moisture contents (18.2 and 30.9 percent) recorded for any samples of the compacted product.

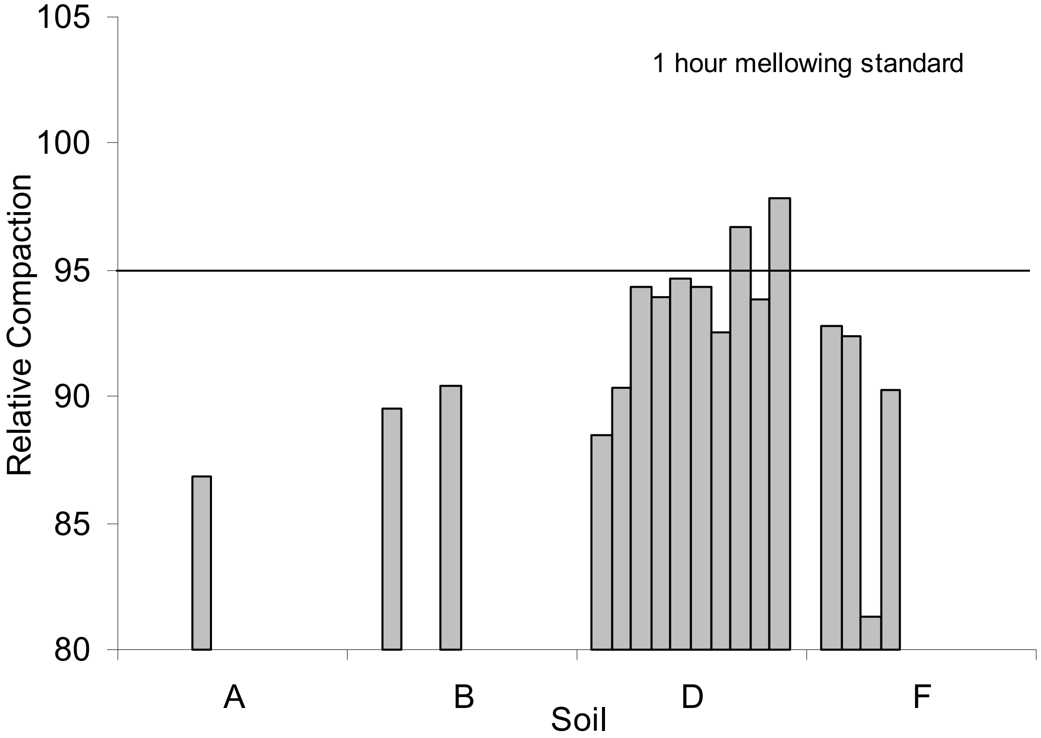


Figure 5.2: Relative compaction based on a 1-hour mellowing period

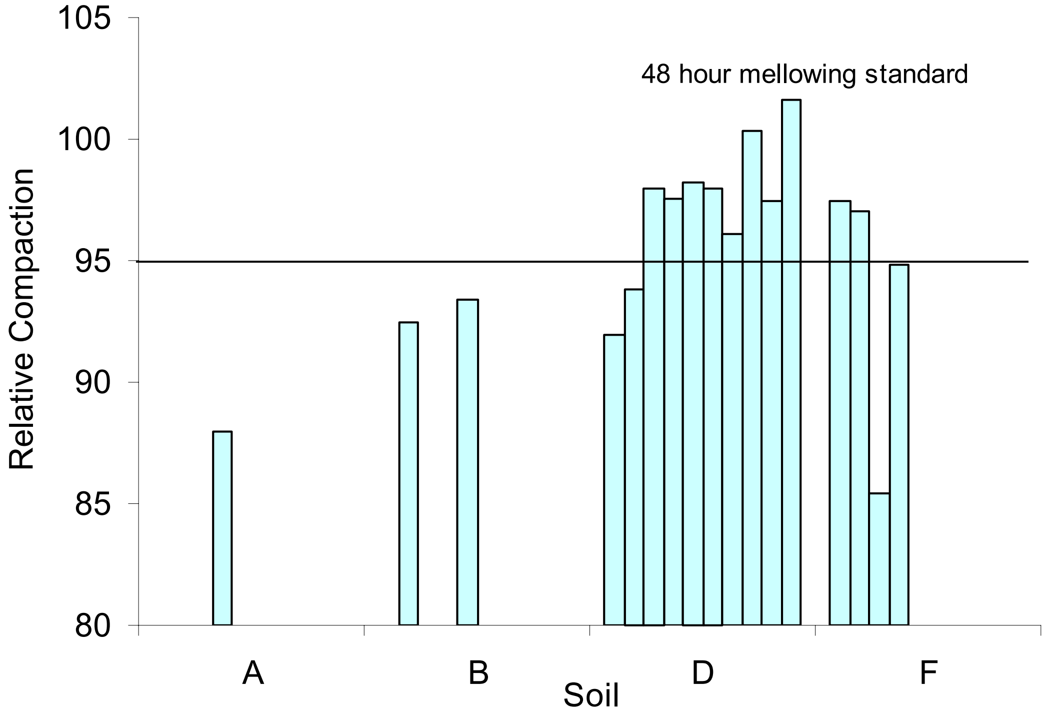


Figure 5.3: Relative compaction based on a 48 hour mellowing period

5.4 Dynamic Cone Penetrometer

Using the KDOT software described in Chapter 3, a pattern of two distinct CBR values generally emerged at each sampling location. Plotting the number of blows per mm compared to depth showed that there was usually a strength change at approximately 152 mm (six inches) in depth. This suggested that the target depth for lime treatment of 152 mm was generally met. In order to smooth out minor variations over the depths tested, average CBR values were determined for two depths coinciding with the upper and lower parts of the subgrade. In many cases a distinct change in strength was observed while in others the change was more gradual. In order to determine a break point for the sampling locations with a gradual change, the data point at a depth closest (greater or lesser) to 157 mm without exceeding 178 mm (7 inches) was accepted as the point where lime addition ended. It was evident that in most cases there was a distinct strength gain in the top 152 mm of the subgrade. The depth of lime treatment could also be determined from the depth at which the changes in strength occurred.

The CBR results derived from the DCP data and the apparent depth to the change were shown in Table 4.2. It can be seen that the CBR of Soil D increased approximately 150% above that of the untreated soil beneath, suggesting that some stabilization was taking place. Improvements were also observed in Soils B and F, while the CBR of Soil A did not improve. This may be related to the high plasticity of Soil A, which would be expected to require a higher percentage of lime to achieve stabilization. Soil A also had a higher initial strength based on penetration resistance values from below the depth of treatment. Soil E was tested approximately four hours after lime treatment and the high moisture contents resulted in low CBR values which were unrepresentative of final strength.

The average depth of lime treatment, magnitude of improvement, and uniformity of the subgrade were evaluated by plotting the penetration resistence vs depth as shown in Figure 4.13. While the absolute numbers were slightly biased because more blows were recorded in stiff layers than soft ones, the depth and relative improvement (or lack of improvement) in strength were readily apparent. This figure showed that Soils A and D were the most uniform with regard to penetration resistence, with Soil B showing slightly more variable readings and Soil F the most variable. Soil F did show a significant decrease (improvement) in penetration/blow. However, this increase extended only to a depth of approximately 100 mm (4 inches), suggesting that a single pass by the rotary mixer may have been insufficient to evenly distribute the lime to the full depth of 152 mm (6 inches).

5.5 Lime Content Determination and pH

Control of lime content on a large scale was based on relating the quantity of lime to an area to be treated. Determination of this area was based on a volume of soil with an assumed depth of mixing and dry density of soil. This appeared to be an effective approach as the area could be easily determined and the depth control for the rotary mixer appeared to be very good. As discussed in Chapter 4, direct determination of lime content by titration tended to yield erratic results. Similar problems have been reported in the literature (McAllister and Petry 1990). The test procedure and the variability of results yielded by this type of test suggest that its adoption for general use would add little information of value to the current procedure.

The variability in pH was determined from stored samples approximately four to eight months after lime treatment in accordance with ASTM C 977. This procedure calls for testing of the samples relatively quickly after preparation and it is unknown if the pH was reduced while the samples were in storage due to carbonation of the lime. However, all samples for the same soil were stored under similar conditions so it was assumed that the variability among the samples when tested could provide an indication of the variability at the time of mixing. The pH results from Soil E had the greatest variation (3.5 pH units) among all of the soils tested and it contained both the overall highest and lowest values obtained. Soil D was again the most uniform, with a range over only 1.43 pH units. There was also no apparent correlation between the unconfined compressive strength and sample pH.

5.6 Field Mixed and Lab Compacted Lime-Soil Mixtures

Samples of Soils E and F were selected with the intent of examining the effectiveness and efficiency of the mixing process. Bag samples were taken in three groups of three for each soil as explained in Chapter 3. Three of the samples were obtained after one pass with a rotary mixer and six were obtained after the second pass with the mixer or after compaction with the padfoot roller (Soils E and F, respectively). The three samples taken after one pass and three of the samples taken after the second pass were compacted immediately upon returning to the lab. The remaining three samples, taken after the second pass, were mixed in accordance with ASTM D 3551 to simulate complete mixing and then compacted. Delay times between sampling and compaction were approximately 8-12 hours for all samples. Unconfined compressive strengths for each group were compared as a measure of the effectiveness of the mixing process.

The unconfined compression test is useful in measuring the effectiveness of mixing because it is a measure of a larger sample of soil than the other tests performed. Effective mixing is a function of several variables, including clod size, depth of mixing, moisture content at mixing, and the mixing equipment used (Little, 1995). Tests such as the Atterberg limits, lime content, and swell require breaking down the soil, adding moisture, and essentially well-mixing it in the lab. As the soil is broken down and moisture is added, the lime is put into contact with greater surface area of soil, and the breaking up of the soil moves particles around. These other tests better reflect the properties of the soil-lime mixture under good mixing and curing conditions. The unconfined compression samples are formed and later tested in a state of mixing more representative of that present in the field.

Mixing efficiency was determined based on the percentage of the strength developed for the field mixed samples when compared to samples "completely" mixed in accordance with ASTM D 3551. Typical values of 60 to 80% are suggested as an acceptable range for mixing efficiency (Little 1995). Table 5.1 shows the mixing efficiency of Soils E and F for one pass, two passes and lab mixed samples. This is the same information reported in Figure 4.12.

Table 5.1: Mixing Efficiency Results

Soil	E	E	E	F	F	F
Mix Passes	1	2	Complete	1	2**	Complete
Avg. UCS (kPa)	122	191	285	133	236	360
Mixing Efficiency (%)	43	67	100	37	66	100
Number of Samples	3	3	3	1*	3	3

*The value for only one sample is reported as 2 of 3 samples broke apart during testing

**The second pass consisted of compaction with a padfoot roller

These results indicate that UC strength is related to the quality of mixing in the field and that two passes were required at a minimum to achieve the strength threshold recommended by Little. Additional mixing may have yielded additional improvements in strength, given the strength values were near the low end of the suggested range. All samples had dry density and strength values well below those from the lab testing, including those that were completely mixed. This appeared to be a function of the high moisture content of the soil after mixing. Figures 5.4 and 5.5 show the moisture-dry density curves with the moisture and dry density values of the field mixed and lab compacted samples for Soils E and F. As these figures show, many of the samples were so wet that it was not possible to achieve a relative compaction of 95%. Figure 5.5 includes both the field mixed, lab compacted samples and the moisture information for the drive cylinder samples of the soil compacted the previous day. The samples that were mixed just prior to sampling were very wet and as a result had very low dry density values when compacted. The samples obtained from the subgrade compacted during the previous day were generally drier and had a great deal of scatter, with one sample with a moisture content still in excess of 30 percent. These samples also had low dry density values when compared with the maximum dry density for the one hour mellowing curve.

5.7 Lab Mixed and Compacted Lime-Soil Mixtures

These samples were made from native soil taken from each site and mixed with lime taken from each site. These tests were performed to help evaluate the potential that existed for modification and stabilization of these soils and to provide a basis for comparison of the field samples. However, the lab mixed and compacted samples showed several trends that could be helpful in designing lime modification procedures in the future.

Figures 4.6 - 4.10 showed the difference in unconfined compressive strength between a 1 and 48-hour mellowing period. In each case, the soils showed a higher maximum strength from a 1-hour mellowing period than from a 48-hour mellowing period between mixing and compaction, which was probably a function of the higher dry

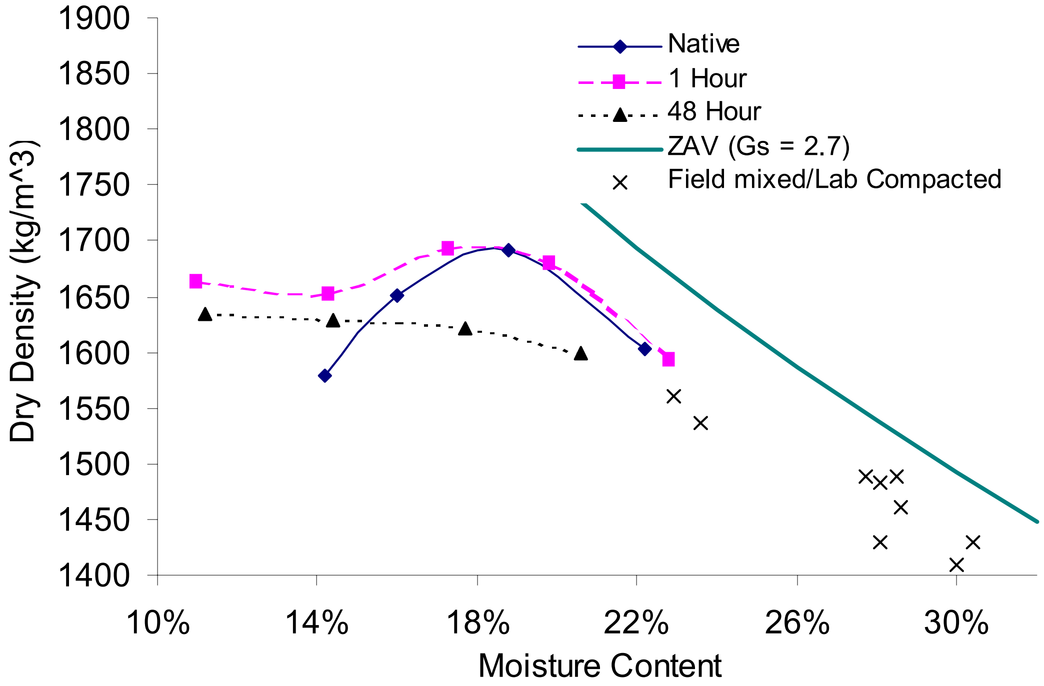


Figure 5.4: Dry density and Moisture Data for Field Mixed, Lab Compacted Samples of Soil E

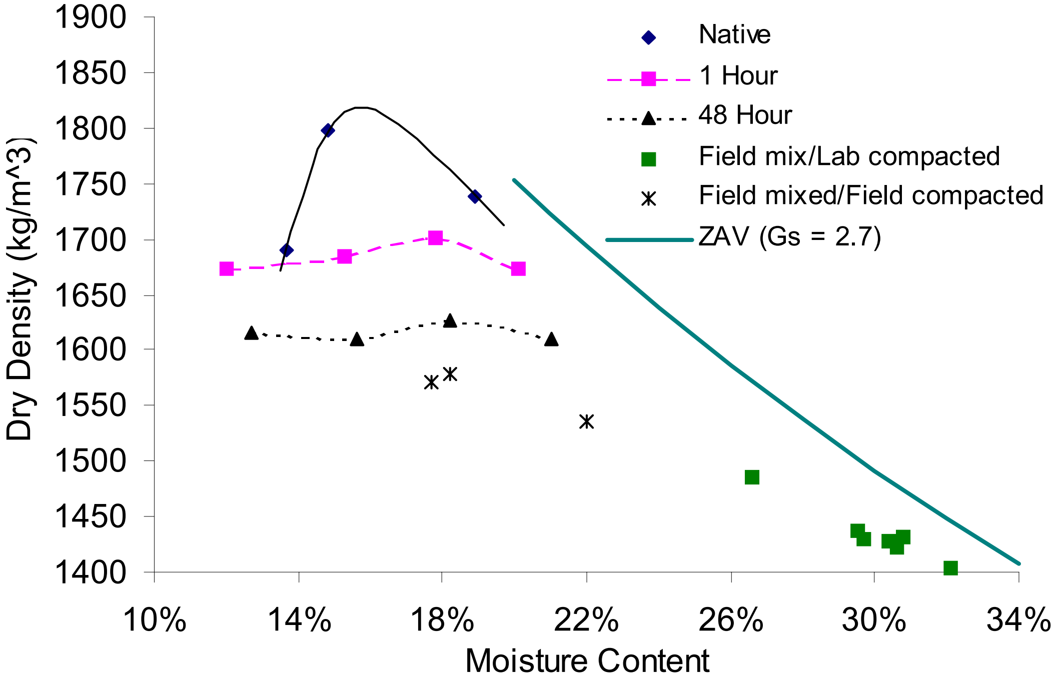


Figure 5.5: Dry density and Moisture Data for Field Mixed, Lab Compacted Samples of Soil F

density values recorded for the 1-hour specimens. However, strength values for the soils compacted with a 1-hour mellowing period tended to decline significantly as the moisture content increased beyond the optimum, particularly for Soils D, E, and F. Soils compacted with a 48 hour mellowing period tended to maintain strength better at these higher moisture contents.

The unconfined compression values obtained from these samples were significantly higher than UC values obtained from the field mixed samples. This is likely a function of the low dry density values and very high water contents of the field samples, which were beyond the range of moisture contents of lab prepared samples. Additional sampling factors that may have caused the lower field strengths include sample disturbance and a slightly larger length/diameter ratio of 1.3 as compared to 1.15 for a standard 101 mm (4 inch) mold.

5.8 Atterberg Limits and Swell Potential

Each of the soils tested showed a significant increase in the plastic limit with the addition of 2.5% equivalent hydrated lime. They also exhibited a moderate decrease in liquid limit. These factors served to dramatically reduce the plasticity index by 50-80% over the native PI. Each of the soils, except Soil A, became non-plastic with 5% equivalent hydrated lime.

The PI for the field samples was lower than that for the native soil for all samples, although not to the level predicted by the lab tests. PI reductions were generally between those observed for lab samples with 2.5 and 5 percent lime. Soils A and D, which were treated with slurry and mixed twice with the rotary mixer, had generally consistent PI values. Soil B was treated with quicklime and had a more variable plasticity index. Soil E was also quite variable, with a PI over 15 in two locations and nonplastic in three others. Soil F, which along with Soil B was the least plastic and had the lowest swell potential in an untreated state, was non-plastic in all locations.

5.9 Swell Potential

All of the soils showed significant swell potential reduction, although Soil A exhibited a much higher swell potential at 5% equivalent hydrated lime than would be expected for a plasticity index of four. This higher swell potential is primarily a function of a significant swelling for the sample prepared dry of optimum (4.55%) compared with the sample prepared wet of optimum (0.85%). Higher swell potentials for samples prepared dry of optimum were observed for all soils and may have been caused by a combination of the general tendency of dry soils to swell more and the incomplete interaction of the lime with the clay particles.

Lime also significantly decreased the time necessary for the soil to achieve its maximum swell. Native soils all continued swelling for the full 96 hours of the swell test, while the lime-soil mixtures achieved maximum swell at an average of about 13 hours. As Figure 4.3 showed, the swell potentials recorded for all samples taken from the field were well within the KDOT target of 2 percent for subgrades beneath rigid pavements and were generally better than results from the lab tests. While the addition of lime contributed to the swell reduction, it was difficult to assess the true effectiveness of the lime treatment because the field water contents were well above optimum during compaction and sampling for all soils, which would have limited swell. Soil A exhibited the most swell, which was consistent with the results from the lab tests.

5.10 Long Term Behavior

The soil obtained near Newton had been in place for approximately 25 years. It had relatively low PI values and CBR values that were consistent with or better than the soils tested as a part of this study. These results suggest that the lime treatment of the Newton soil was essentially permanent. There was an unusual variation in the CBR values across the tested section (see Figure 4.16). This variation may have been a function of lime distribution or mixing methods used at the time.

Chapter 6
Conclusions

6.1 Test Results

Lab testing on field mixed and compacted soil-lime mixtures showed that the plasticity index was always reduced and unconfined strength was always increased with the addition in lime. Four of the five soils tested showed a significant reduction in swelling potential with only 2.5 percent lime, while one soil still exhibited significant swelling potential with 5 percent lime. Plasticity and unconfined strength results showed that subgrade characteristics were relatively consistent when good mixing practices were followed. Results also showed that current field liming and mixing procedures did not reduce the PI or improve the strength of the subgrade as much as lab prepared samples using the same percentages of lime. Samples showed that the swelling potential was reduced to acceptable levels in the field, however, the high water contents at the time of compaction were likely to have been a contributing factor to this result. These high water contents also prevented the soils from being compacted to within 95 percent of the maximum dry density, as determined by ASTM D-698 (AASHTO T-99).

The soils tested exhibited a wide range in stabilization potential as measured by the unconfined compressive strength of the soils. While Soil A exhibited an increase of about 375 kPa, Soil D showed an increase of over 1300 kPa. Peak unconfined strength of the soil-lime mixtures was higher for compaction after one hour rather than 48 hours after mixing, however, mellowed samples appeared to retain their strength better as moisture increased.

6.2 Test Methods

The AASHTO procedure for determining lime content (T-232) yielded variable results. Similar problems have been reported by other researchers for this type of test (McAllister and Petry 1990). The information provided by this type of test would therefore not appear to be of great additional value for the following reasons:

- test variability
- the overall lime content is already known based on mass balance calculations and the dimensions of the mixing area which are easily controlled
- mixing of the sample is required as a part of the test, which may mask the limitations of field mixing

Determination of dry density using the drive cylinder method was effective when samples were taken on the day of compaction. Drive cylinders used to obtain samples more than one day after compaction were very difficult to drive and remove and many of the tubes were damaged during sampling. Samples taken the same day could be tested in unconfined compression as a relative indicator of soil strength.

The mixing efficiency procedure suggested by Little (1995) appears to be an effective method for evaluating the effectiveness of mixing operations. This method permits a larger sample to be tested that does not require the soil-lime mixture to be significantly altered from its as-mixed state. The results of the mixing efficiency for soils treated with powdered quicklime (Soils E and F) showed that adequate mixing efficiency was achieved with the equivalent of two passes with a rotomixer over the soil-lime-water mixture. Additional mixing may have yielded additional strength gains based on the testing of samples of the same soils compacted after additional mixing in the lab. Plasticity index values were reduced to values consistent with complete mixing after two passes for the two soils tested, however the additional mixing required as a part of Atterberg limits testing may have masked some of the impact of the field mixing on a very local scale.

Dynamic cone penetrometer testing also yielded valuable information on soil strength and variability. This information could be examined based on test location, depth, and the improvement in soil strength between the treated subgrade and the untreated subgrade below. The depth of treatment could usually be identified as well. As a field test that disturbs a very small area, the DCP test has the potential to provide subgrade performance data on a long term basis after the road has been placed into service.

6.3 Mixing Procedures

The high water contents specified under both the 1990 Standard Specifications and Special Provision 90M-141-R1 are sufficient to permit effective mixing of both slaked lime and powdered quicklime with the soil. However, these high water contents effectively prevent the achievement of good compaction if no mellowing period is permitted after the addition of water.

The current procedure of basing the quantity of lime on mass balance calculations appears to be effective at achieving the specified percentage of lime on a large scale.

Two passes with a rotary mixer resulted in significantly better mixing and smaller clod sizes based on visual observation. Two passes also appeared to be sufficient to achieve the minimum level of mixing based on unconfined compression testing as recommended by Little (1995). However, additional mixing may yield additional strength gains. Relatively uniform DCP and PI measurements were also obtained for soils mixed twice with the rotary mixer. Results were most uniform for those where lime slurry was applied. The most variable results were for Soil F where powdered quicklime was used and the mixing process consisted of only one pass with the rotary mixer and several passes with a pad foot roller as a part of the compaction process.

Chapter 7

Recommendations for the Implementation of Results

7.1 Construction Specification Adjustments

One of the primary conclusions of this study was that subgrades were not consistently compacted to 95% of the maximum dry density as determined by AASHTO T 99. This appeared to be a function of high water contents specified to facilitate the mixing process under both 1990 Standard Specifications and special provision 90M-141-R1. It is recommended that KDOT consider altering the lime mixing specifications by reinstating the mellowing period between preliminary and final mixing as called for in the 1990 specifications, with the option of a longer period for CH clays. By reinstating the mellowing period before final mixing, high water contents can still be used to facilitate interaction of the lime and clay during preliminary mixing while giving the soil some time to dry to a condition closer to optimum prior to final compaction. This mellowing period will also provide the lime a longer period of time to break down clay clods prior to final mixing, which should lead to a more uniform subgrade.

If the mellowing period is reinstated, it is recommended that KDOT change the requirement in Section 305.03(g) of the Standard Specifications. This section currently requires the moisture content be raised to eight points above optimum for the untreated soil (10 points for powdered quicklime) during final mixing. It is recommended that the moisture specification be changed to a requirement the soil be at or above optimum such that the density specification is achievable. It is assumed the lime will already be well distributed from the preliminary mixing step and that raising the water content to eight points above optimum will make the achievement of good compaction difficult, if not impossible. Changing these specifications will move KDOT specifications closer to the recommendations of the National Lime Association (NLA) shown in Table 7.1.

It is also recommended that KDOT consider moving from a specified percentage of lime for all projects to a lime percentage based on soil testing. Modification for several of the soils in this study could likely have been achieved with a lower percentage of lime, while additional lime may have been appropriate for Soil A, the CH clay. A number of lime mix design procedures have been developed and are published in the literature. These procedures include methods based on pH, PI, unconfined compressive strength, and other tests (see State of the Art Report #5, 1987). Evaluation of these design procedures to determine which are most appropriate for KDOT was beyond the scope of this project, but this may be an appropriate subject for future research. Specifying lime content based on soil testing could yield construction savings for many CL soils while demonstrating the need for a higher percentage of lime for heavier clays, thus preventing inadequate performance. This testing would likely be more beneficial if performed prior to the letting of construction contracts so that the percentage of lime required may be included.

The National Lime Association also recommends that subgrades be compacted to 95 percent of AASHTO T 180 using the lime treated soil. While the impact of compacting to different energy levels was not a focus of this study, greater compaction should lead to stronger subgrades. Adoption of specific targets for compaction would require testing in the field in addition to visual observation.

7.2 Mixing Procedures

It is recommended that KDOT encourage the use of rotary mixing equipment for the mixing of lime with soil. Rotary mixing equipment did appear to be very effective at mixing and maintaining good depth control based on visual observation and DCP data. Rotary mixing is mandatory for final mixing under the NLA (1990) recommendations for final mixing. It is also recommended that KDOT require at least two passes with mixing

Table 7.1 Specifications for Lime Treatment in Kansas

1990 Standard Specifications	Special Provision 90M-141	National Lime Association[1]	Recommendations
Apply lime	Apply lime	Apply lime	Consider requiring lime slurry
Add water (optimum + 8% for slurry or 10% for quicklime)	Add water (optimum + 8% or 10% for quicklime)	Add water (optimum + 5% or greater)	Consider adopting the NLA specification
Preliminary mixing	Mixing (95% passing 37.5 mm, 40% passing 4.75 mm)	Preliminary mixing (pulverize to 50 mm or smaller)	No change
Seal and cure (48 hours)	Type B compaction	Seal and cure for 0-48 hours, up to 7 days for heavy clays[2]	Consider returning to a curing period of 48 hours with a longer period for heavy clays
Final mixing (free of lumps greater than 25 mm in diameter), watering (optimum + 8%) and Type B compaction		Final mixing (100% passing 25.4 mm, 60% passing 4.75 mm). Rotary mixing is mandatory. Compact to 95% of T-180 at optimum moisture or above	Consider adopting NLA specifications
Protection and curing	Protection and curing	Protection and curing	No change

[1] This is a summary of the major specifications addressing mixing for lime stabilization. Additional specifications are included in the Lime Stabilization Construction Manual (1990)

[2] The seal, curing and final mixing steps may be skipped if pulverization requirements for final mixing are met during the preliminary mixing stage

equipment based on the visual improvement in pulverization and the improvement in mixing efficiency observed after two passes. Use of lime in a slurry form also appeared to promote subgrade uniformity when compared with powdered quicklime and it is recommended that KDOT consider funding a research project to further evaluate the two forms of lime to determine if lime slurry yields a significantly better product. This evaluation may be best performed by constructing test sections where both forms of lime are used. The improvement in properties related to performance such as unconfined compressive strength, DCP resistance, volume change, and other factors could be evaluated.

7.3 Recommendations Regarding Testing Procedures

The large majority of subgrade samples obtained with drive cylinders after final compaction did not have a unit weight corresponding to 95% of AASHTO T 99 or greater. Strength values for these samples were also very low when compared with the strengths of the Proctor samples. It is therefore recommended that KDOT consider moving from Type B compaction to a specified relative compaction level with field testing to confirm that the required compaction levels have been achieved. As previously mentioned, the NLA recommends a standard of 95% of AASHTO T 180 for compacted subgrades. Drive cylinders were used successfully for this purpose during this study when they were used within a few hours of compaction. Other methods for density determination could also be used.

It is recommended that KDOT reevaluate the current swell testing procedure for use with lime treated soils. This is not a widely used procedure and the moisture contents used in the preparation procedure are not consistent with the moisture content of the soil in the field. Mixing in the field is performed with a moisture content a minimum of 8 percent above optimum, while one of the two lab samples is mixed dry of optimum. It is possible that effective interaction between the soil and lime for a sample dry of optimum will not occur, which could result in an overestimation of the swell potential on the dry side of optimum. An ASTM procedure, *Standard Test Methods for One-Dimensional*

Expansion, Shrinkage, and Uplift Pressure of Soil-Lime Mixtures (D 3877), is an alternative test method that may be worthy of consideration.

The most effective techniques used in this study for evaluating the effectiveness of compaction were the DCP and the efficiency of mixing based on unconfined compression testing. It is recommended that KDOT consider wider use of these procedures. The DCP provided particularly useful information regarding uniformity, depth of treatment, and improvement compared with the subgrade below the treatment depth. There was also no delay between testing and availability of results. The DCP also has the potential to provide information on the performance of subgrades over time.

Other methods that were not evaluated as a part of this study include the nuclear gauge and the soil stiffness gauge (Humboldt GeoGauge). The stiffness gauge has significant potential for use as a quality assurance tool because it contains no nuclear material and can provide a measure of the subgrade modulus. It does have a very limited record of commercial use and it is recommended that KDOT consider funding a research project to evaluate its suitability for use as a quality assurance tool.

7.4 Potential for Stabilization

The amount of lime currently specified for lime treatment is sufficient to achieve stabilization for many soils. It is therefore recommended that KDOT consider making stabilization a goal of treatment and taking advantage of the benefits of stabilization by including the stabilized layer as a structural component in the pavement design. This will require additional testing using the ASTM C 977 procedure or an alternative prior to construction. However, it may significantly reduce the thickness and cost of the other structural layers for many soils with no increase in earthwork construction costs.

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