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LIME APPLICATION METHODS

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16 Abstract

High calcium lime is widely used for the modification and stabilization of subgrades composed of fine-grained soils. Lime is available in a variety of forms and may be applied using several methods. This report contains the results of a study on the mixing of different forms of lime with two soils in a laboratory and field settings. The forms of lime used in the lab were quicklime, dry hydrated lime, and slurries made from each of these dry products. For the field evaluation two sites with two different soils were selected. At each site quicklime was applied using a vane spreader (best technology) and spreading of a windrow of dumped lime with a blade (oldest technology). Slurry produced on site from slaked quicklime was used for the third subsection.

Results from the laboratory evaluation showed the form of lime added to the soil (quicklime, dry hydrated lime and slurry) appears to have little effect on the moisture-density relationship under completely mixed conditions. Swelling was minimal for all lime treated samples however pH testing showed the amount of lime added to the Paola South test section was too low to achieve true stabilization, based on low unconfined strengths and pH testing. This is likely a result of the use of a single statewide specification for the amount of lime to be used.

Field results showed that changes in the lime application method (slurry, vane spreader and blade) appeared to have a limited to negligible affect on the strength of the subgrades. Proper control of moisture and mixing, and adding sufficient lime for stabilization, had a greater impact on subgrade properties. The results suggest that long term strengths are similar, if not greater for lime treated soils compacted well above optimum than those soils compacted at or near optimum moisture.

The number of passes made over the subgrade during the mixing process made a substantial difference in the unconfined compressive strength of the samples, even after four passes. Remixing and re-compaction after mellowing also resulted in a significant improvement in strength and contributed to the breakdown of remaining soil lumps.

During application and mixing of the quicklime it was observed that significant amounts of lime dust were blown into the surrounding environment. Blowing lime presents some health and visibility risks to construction personnel and nearby traffic, and represents the loss of some product. No blowing dust was produced during the application of slurry. Due to the potential hazards presented by blowing lime dust, it is recommended that slurry be specified for projects in sensitive areas.

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PREFACE

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

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ABSTRACT

High calcium lime is widely used for the modification and stabilization of subgrades composed of fine-grained soils. Lime is available in a variety of forms and may be applied using several methods. This report contains the results of a study on the mixing of different forms of lime with two soils in a laboratory and field settings. The forms of lime used in the lab were quicklime, dry hydrated lime, and slurries made from each of these dry products. For the field evaluation two sites with two different soils were selected. At each site quicklime was applied using a vane spreader (best technology) and spreading of a windrow of dumped lime with a blade (oldest technology). Slurry produced on site from slaked quicklime was used for the third subsection.

Results from the laboratory evaluation showed the form of lime added to the soil (quicklime, dry hydrated lime, slurry) appears to have little effect on the moisture-density relationship under completely mixed conditions. Swelling was minimal for all lime treated samples, however pH testing showed the amount of lime added to the Paola South test section was too low to achieve true stabilization, based on low unconfined strengths and pH testing. This is likely a result of the use of a single statewide specification for the amount of lime to be used.

Field results showed that changes in the lime application method (slurry, vane spreader, blade) appeared to have a limited to negligible affect on the strength of the subgrades. Proper control of moisture and mixing, and adding sufficient lime for stabilization, had a greater impact on subgrade properties. The results suggest that long term strengths are similar, if not greater, for lime treated soils compacted well above optimum than those soils compacted at or near optimum moisture.

The number of passes made over the subgrade during the mixing process made a substantial difference in the unconfined compressive strength of the samples, even after four passes. Remixing and recompaction after mellowing also resulted in a significant improvement in strength and contributed to the breakdown of remaining soil lumps.

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Chapter 1

Introduction

Clay soils have a long history of poor subgrade performance if left untreated. Performance of clay soils can be substantially improved through soil modification and stabilization with lime. The benefits of lime treatment include the reduction or elimination of swelling, increased strength and improved workability.

High calcium lime is available in four different forms: pebble quicklime, slaked lime slurry from quicklime, hydrated lime and hydrated lime slurry. The most common forms of lime used in Kansas as of 2004 are pebble quicklime and slaked lime slurry. The laboratory performance of soils treated with lime in each of these four forms was evaluated as a part of this study. The two most common forms of lime were also compared in field testing.

In addition to the different forms of lime, industry has developed multiple methods of lime application. The benefits of each of three methods of application were compared as a part of this study. This study focused on three commonly used application techniques. The three methods were: slaked lime slurry spread with a distributor, pebble quicklime distributed with a spreader, and pebble quicklime placed in windrows and spread with a blade prior to mixing. These application methods were evaluated based on subgrade uniformity, the amount of effort required to completely mix the subgrade, and improvement in subgrade properties related to performance.

The slaked lime slurry application method requires specialized equipment, so costs associated with this method are usually higher then the other two methods. For this method lime and water are mixed in a large tank located on or near the jobsite before the mixture is applied over the subgrade. The tank is filled with enough water to create a slurry mixture with about 30

to 35% solids. Quicklime is then added to the tank and a paddle system stirs the water and lime together. The lime and water react and the final product is hydrated lime slurry with very fine particles that have a high surface area. The entire slaking process can be completed within an hour. After the slurry is made, it is dumped into trucks that spread the slurry over the subgrade by rear spreaders. The application rate may be slightly slower with the slaked lime slurry procedure as compared with the other two procedures (Little 1995).

Advantages of using the slaked lime slurry technique include reducing the amount of additional subgrade watering required for effective mixing and the elimination of blowing lime dust. The elimination of blowing dust prevents the development of a potential safety hazard for workers and drivers and reduces the potential for impacting the surrounding environment.

The second application method evaluated in this project was pebble quicklime distributed over the subsection by a truck with a rear-mounted spreader. Lime may be spread more quickly using this method than the lime slurry method. However, spreading of quicklime by this method generates significant amounts of dust and there is a greater chance of workers getting skin and eye burns. More extensive watering is also generally required to reach the target moisture content.

The final application method involved dumping the lime in windrows and then spreading the windrows over the subsection with a blade. The application rate using this method is also faster than application of lime in a slurry form. However, it has the same disadvantages as the spreading of dry lime with a spreader, and the lime is not distributed as evenly as with a spreader.

For this project two test strips with two different types of soils on highway US-169 near Paola, Kansas, were constructed in consultation with Kansas Department of Transportation

(KDOT). The strips are referred to throughout this project as Paola North and Paola South. Samples of the native soils were collected after the test sections had been trimmed to grade and were transported back to The University of Kansas (KU) where grain size analysis, Atterberg limits, Proctor, unconfined compression, pH and CBR tests were performed on both soils. Samples from the test sections were collected during the lime application and mixing process for lab testing. Dynamic cone penetrometer and soil stiffness readings were taken on both test strips after the lime application and final compaction were complete. Tests were conducted periodically during a 28 or 33-day period. Tests were performed in accordance with American Society of Testing Materials (ASTM) standards.

The information provided in this study has been organized into seven chapters. Chapter 1 contains an overview of the project. Chapter 2 is a review of literature relevant to this project. In Chapter 3, a discussion of the testing plan and procedure is presented. The results of all of the tests are included in Chapter 4 with a discussion of these results presented in Chapter 5. Chapters 6 and 7 contain the conclusions and recommendations developed based on the results of this research.

Chapter 2

Literature Review

The available literature on the types of lime, lime application methods, and testing of lime treated soils was reviewed and summaries of this information are presented in the following sections:

2.1 Types of Lime

Lime used for soil stabilization may be applied in any of several forms. The Handbook for the Stabilization of Pavement Subgrades and Base Courses with Lime (Little, 1995) defined the different forms of lime, which are reported below.

1. Quicklime (CaO): This is lime oxide formed by calcining limestone so that the carbon dioxide is freed. Quicklime comes in many particle sizes from quite fine to very coarse. This lime is very reactive and gives off heat when it comes into contact with water. This type of lime was used in about 25% of nationwide projects in 1995.
2. Hydrated Lime ($Ca(OH)_2$): This is the dry powder obtained by hydrating quicklime with sufficient water to satisfy the chemical affinity, forming calcium hydroxide. Both hydrated lime and quicklime may contain significant amounts of magnesium (dolomitic lime). Hydrated lime is considered to be safer to handle than quicklime because it is not as reactive when mixed with water.
3. Lime Slurry: This is a general term used to describe a thick water based liquid with lime hydrate in suspension.
4. Quicklime Slurry (Slaked Lime): Quicklime slurry is hydrated lime slurry created by mixing quicklime and water, which generates hydrated slurry with very fine lime particles as part of an exothermic reaction. It is often prepared near the jobsite in a batch tank.

2.2 Quicklime vs. Hydrated (dry)

Although hydrated lime is safer, the use of quicklime has been increasing over the years. This is because a smaller quicklime percentage can be used on a subgrade to achieve stabilization when compared to hydrated lime. This saves money on the cost of stabilization/modification in both materials and shipping. When spread over a subgrade by the dry method, quicklime reduces dusting because it is nearly twice as heavy as hydrated lime and will not be blown away as easily with a light wind (Lime Stabilization and Construction Manual 1991).

2.3 General Procedure for Stabilizing Subgrade Soils

There are many different techniques that are used to mix and design a stabilized subgrade, and many states and other organizations have their own set of standards for this procedure. These standards have many steps in common. Summaries of these different standards are outlined in TRB State of the Art Report 5 (1987). The Lime Stabilization Construction Manual outlines the general steps used to construct a stabilized subgrade. These steps are as follows:

1. Scarify – In this step, the soil is trimmed to grade, stumps and roots are removed and then the soil is scarified to a specified depth.
2. Lime Spreading – Lime is uniformly spread at a specified percent either in dry or slurry form.
3. Mixing and Watering – The soil is mixed to a proper depth and enough water is added to bring soil to at least 5% above the optimum moisture level. Soil should be lightly compacted before curing to minimize evaporation losses.
4. Curing – The mix is cured for 0-48 hours to allow the soil to mellow. The lime reacts with the clay during this mellowing period.
5. Final Mixing – The clay clods are broken down so all pass a one-inch screen and at least 60% pass the No. 4 sieve. Water can again be added to achieve optimum moisture content before compaction.
6. Compaction – The soils are then compacted to 95% optimum density.

7. Final Curing – The compacted subgrade is cured for at least seven days to allow the layer to harden before placing the subbase layer on top of it. This final curing is done through either moist curing or a membrane cure, which will keep water from evaporating and the soil from drying out.

2.4 Application of Dry Lime

For this method dry quicklime is generally applied in bulk for stabilization projects. The quicklime can be spread over the subgrade by a self-unloading auger or a pneumatic transport truck. Since quicklime is heavier and coarser than hydrated lime it can be tailgated by a regular dump truck with tailgate opening controls. After the lime is spread over the subgrade it is mixed and watered to achieve the final product (TRB State of the Art Report 5, 1987).

2.5 Slurry Method

The Porta-Batch slurry method was developed to address the many limitations regarding the spreading of bagged hydrated lime. The first successful Porta-Batch system was used in 1983 in Texas and is very similar to the Porta-Batch used today. It consisted of a 10-foot diameter and 40 foot long cylindrical tank with paddles attached to a center shaft. The system is powered by a heavy-duty hydraulic system. Before the slaking process begins the tank is filled with about 15,000 gallons of water. Quicklime is then added below the water level. The water acts like a wet scrubber for the lime dust. The lime then slakes and a slaking temperature of about 200° F is maintained in the tank. The final product is a small hydrated lime particle with a high surface area. There are no unhydrated lime particles remaining after this process is completed. This slaking process takes about one hour total, and produces lime slurry that is about 30 to 35% solids (McKennon 1992).

Figure 2.1: Porta-Batch Lime-Slurry Tank (McKennon 1992)

2.6 Calculation of Quantities for Payment

Lime is measured for payment based on available CaO using the Calculated Method, which is based on the principle that pure hydrated lime weighs 1.32 times quicklime with an equivalent amount of calcium. For the Calculated Method the available CaO is checked at the plant. The conversions used to convert quicklime of a given purity to an equivalent amount of hydrated lime were calculated by McKennon (1992) and are presented in Table 2.1. The increase in weight is determined by multiplying the weight of the available CaO by a factor of 1.32 and assuming the remaining material is inert.

Table 2.1: Weight Conversion of Quicklime to Hydrated Lime

Available CaO in quicklime	Quicklime		Weight of Equivalent Dry $Ca(OH)_2$
90.0%	100g	is equivalent to	128.8g
93.0%	100g	is equivalent to	129.7g
95.0%	100g	is equivalent to	130.4g

2.7 Comparison of Application Methods

According to the Lime Stabilization Construction Manual (1991), each application method has certain advantages. The slurry method eliminates the dusting problem caused by spreading dry lime and distributes lime more uniformly. The dry methods do not incur the costs of slurry plants and have a higher production rate per day. A visual representation of the differences is listed below.

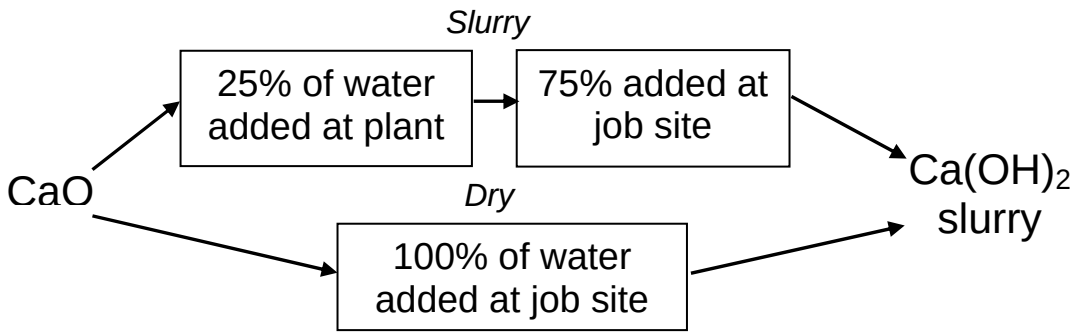


Figure 2.2: Comparison of the Porta-Batch Slurry System and the Dry Method
(adapted from *Lime Stabilization Construction Manual* 1991)

2.8 Mixing

Thorough mixing of the lime and subgrade is essential to ensure the even distribution of the lime and so the clay clods are sufficiently pulverized to maximize the surface area and available to react with the lime. With better mixing the lime particles and reactive mineral particles can have more complete reactions (Locat et al. 1990). Moisture content and degree of pulverization are critical to achieve the desired stabilization effects (Petry & Little 2002). Lack of water can leave unreacted lime, while soil not pulverized correctly can lead to lime's pozzolanic cementing action taking too long to occur.

The degree of pulverization is an important step in the stabilization process. This was demonstrated by Davidson, Demiral, and Handy in 1965, who conducted many unconfined compression tests on samples consisting of soil clumps that had varying percentages of soil

passing the No. 4 and No. 1 sieve. All of the soil used in these tests was stabilized. The samples with the larger clods were found to have lower unconfined compressive strengths. Soils with larger clods were also found to take longer to react with lime. The samples made with the most finely pulverized soil were found to have the highest strength gains in less time. Field samples taken by Parsons et al. (2000) yielded similar results.

Both rotary mixing and blade mixing may be used when applying lime. Rotary mixing is conducted after the lime is spread evenly over the subgrade. The rotary mixer then mixes the soil from the top down. For blade mixing the lime is placed in two windrows and the lime is spread down the centerline. Soil is then bladed over the lime. Rotary mixing has been preferred over blade mixing because it results in more uniform mixing, is faster and does a better job breaking up the soil into smaller particles (TRB State of the Art Report 5, 1987).

2.9 Testing of Lime Stabilized Soils

In general, soil-lime mixtures have a lower maximum density and higher optimum moisture content then untreated mixtures. Adding lime to a soil tends to flatten the compaction curve so a certain density can be achieved over a much wider range of moisture contents. Higher temperatures in curing can produce higher strengths because curing is accelerated (Bell 1996).

The California Bearing Ratio test is used to measure the swell of a surcharged soil and can also be used as an indirect measure of the shear strength of a soil, particularly for uncured mixtures (Little 1995). CBR swell values for soil-lime mixtures vary, but in general a reduction in swell is observed. CBR values tend to increase for soil-lime samples in comparison with native soils. CBR values of 100 or more can be found when testing cured lime treated soil samples, but these high values have little practical significance (Little 1995). Using CBR tests to characterize the strength of cured soil-lime mixtures can give a relative indication of

performance, however tensile and compressive tests are believed to better indicate the strength of stabilized soils. There were 23 Illinois soils subjected to CBR tests and it was found that regardless of curing time and lime-reactivity, the CBR value increased (TRB State of the Art Report 5, 1987).

The dynamic cone penetrometer test (DCP) is a field test performed on subgrades to determine the bearing capacity of subgrades. Livneh (1989) conducted four studies in Israel on existing roads and airport runways to prove empirically the strong correlation between DCP and CBR. He tested many equations derived for this correlation and concluded that different equations should be used in different situations. He also found that DCP values could only be correlated to CBR numbers when the depth of the subgrade is less then 80 centimeters. The US Army Corps of Engineers (1994) has developed relationships between the DCP and CBR. The USACE equation for all soil was used for this research, as discussed in Chapter 3.

DCP testing has also been used in the United States. Two test strips selected in Texas were subjected to over 60 DCP tests. The results of these tests showed that in order to be within a 95% confidence interval, at least six DCP tests are needed to characterize a subgrade. This is especially important because subgrade layers can be more variable then base layers (Chen et al. 2001).

McElvaney and Djatnika (1991) explored the correlation between DCP and unconfined compressive strength on stabilized soils. He tested clays, silty clays, and sandy clays with differing lime percentages. He performed DCP tests and unconfined compression tests on all samples in the lab. The statistical analysis of this data led to the development of a model that correlates DCP to unconfined compressive strength. These models have been found to

reasonably estimate the unconfined compressive strength of a sample when only DCP test results are available.

Chapter 3

Testing Plan and Procedures

This chapter contains a discussion of the testing program used to evaluate the effect of lime application methods on subgrade properties. Tests were performed on native soils, lime treated soil mixed and compacted at two test strips by the contractor, lime treated soil mixed in the field but compacted under lab conditions, and samples mixed and compacted in the laboratory.

3.1 Materials Used

3.1.2 Selection of Soils

For this research, two test sections were selected in consultation with KDOT. The locations of these test sections were both a part of the reconstructed US-169 near Paola, Kansas. To differentiate between the two soils they were named Paola North and Paola South. The Paola North test strip ran from station 18+00 to 18+500 and the Paola South test strip ran from station 7+468 to 7+983. A map of the Paola, Kansas, area is presented in Figure 3.1.

The native soil samples to be tested in the lab were obtained after the test sections had been trimmed to grade, but before any lime treatment had occurred. The trimmings were taken from the side of the test sections and were shoveled into rubber trashcans and storage containers. The containers were then transported to the KU lab for testing.

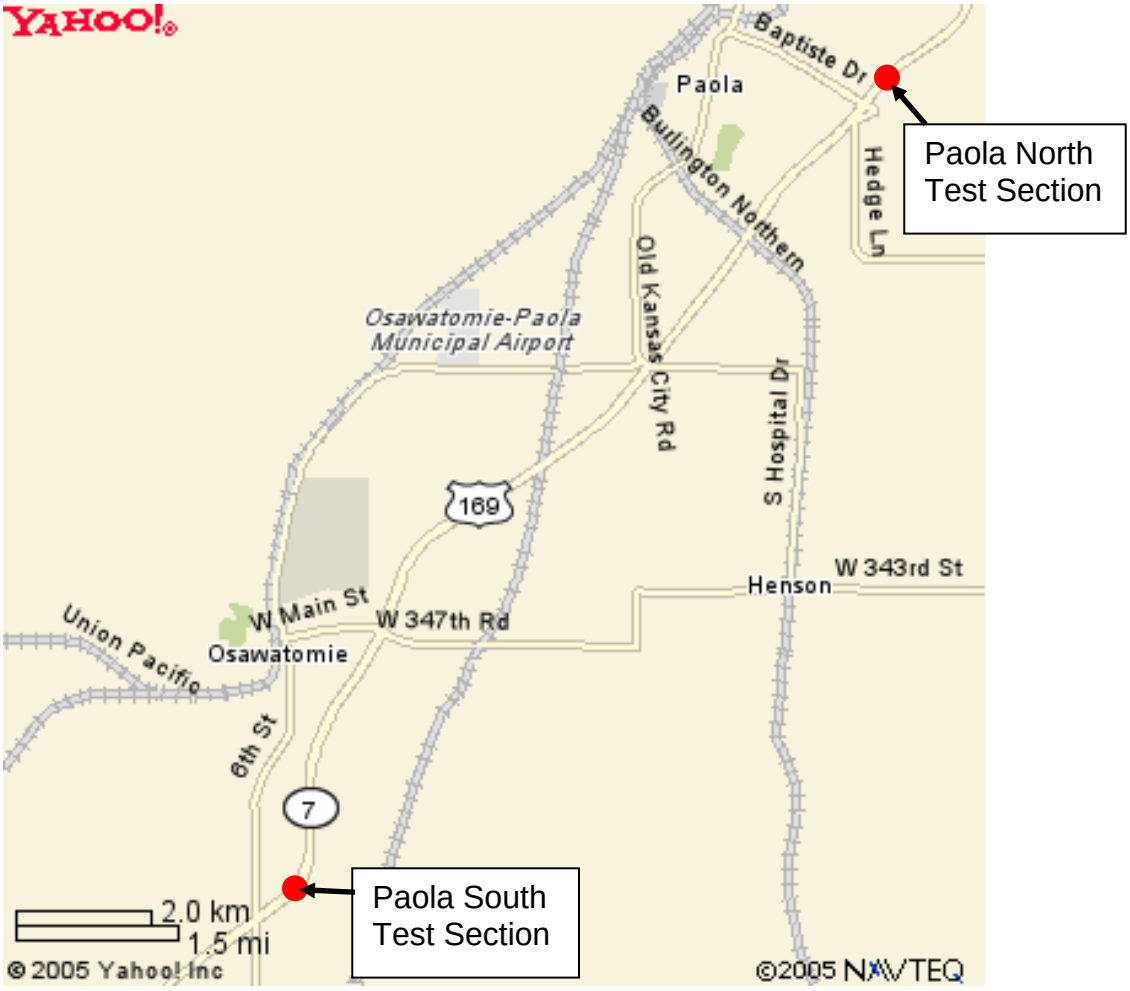


Figure 3.1: Approximate test section locations (Yahoo 2005)

Each test section was approximately 500 meters in length and was divided into three subsections. The three different lime spreading techniques were used within these subsections.

3.1.2 Lime Used for Laboratory Testing

Quicklime (CaO) was provided by Chemical Lime Company and the powdered hydrated lime ($Ca(OH)_2$) was ordered from Fisher Scientific. The pebble quick lime was approximately 90% pure and the hydrated lime was approximately 98% pure.

3.2 Field Mixing

The contractor generally followed the same mixing pattern and procedure for both test sections. This was partly due to the same hot and sunny conditions that were present during treatment of both test sections. Paola North was lime treated on June 25, 2002, and Paola South was lime treated on August 27, 2002. The first subsection mixed was the slaked lime slurry, the next subsection used a vane spreader to distribute the dry pebble quicklime and the final subsection placed the dry pebble quicklime in windrows and then spread it with a blade. Mixing passes were made with a CMS RS-550. Photos of the subsections and mixer are seen below.

Figure 3.2: Photo of Blade Subsection being mixed

Figure 3.3: Photo of Lime Slurry being applied

Figure 3.4: Photo of the Vane Subsection after one mixing pass

Figure 3.5: Photo of the Vane Subsection after three mixing passes

Figure 3.6: Photo of Mixer

Outlined below are the in-depth treatment procedures for each subsection of Paola North. Procedures for Paola South were similar. Water was added at the discretion of the contractor and varied in times and amounts for different sections.

- Slaked Lime Slurry: The slaked lime slurry sections were first scarified to loosen up the soil. Additional water was then added by water truck. Slurry was batched on site while the soil was being prepared. After the slaked lime slurry was thoroughly mixed it was then placed into a pump truck. The truck then spread the slurry through the truck's rear spreaders over the soil. The mixer then passed four times over the subsection. After mixing the section was sealed with a roller.
- Pebble Quick Lime Spread With a Vane: Lime was applied to the vane subsection by spreading the quicklime by truck. The subsection was then scarified to better mix the lime and soil. The water truck then made a pass over the subsection to moisten the soil. Two mixing passes were made and then two passes were made with the water truck. Two additional mixing passes were made prior to sealing the area with a roller.
- Pebble Quick Lime Placed in Windrows and Spread With a Blade: For the third subsection the procedure involved dumping the lime in a windrow and then spreading the pile over the area with a blade. The area was then scarified and heavily watered with the water trucks. Four passes were made with the mixer and then the roller sealed the area.

3.3 Field Sampling During Mixing

There were 68 grab samples were obtained for Paola North and 42 grab samples were collected over the Paola South test section. After each pass of the mixer grab samples were taken from the north, middle, and south area of each subsection and compacted into 4-inch (Proctor) samples. After the first pass two additional grab samples were collected and combined so CBR samples could be prepared. After each pass of the mixing truck, a one meter box was placed randomly

down on the subsection and the largest soil particles within the 1 m^2 area was retrieved. The grab samples were returned to the lab and compacted simultaneously with the test strips.

3.4 Field Testing

The soils were remixed and compacted by the contractor after a mellowing period of 24 hours. A series of in-situ tests were then conducted on the compacted soil. The in-situ tests performed were: dynamic cone penetrometer, soil-stiffness gauge (Humboldt GeoGauge), nuclear density gage, and drive tube. The goal was to test the sections over a 28-day span, however this was not possible with Paola North, as a drainable subbase had been laid over the section sometime after day 15.

3.4.1 Dynamic Cone Penetrometer

The dynamic cone penetrometer test was used on the two test sections to measure the in-situ strength of the soils. The soils were tested on many days throughout the 28-day span. DCP tests were performed at eighteen different locations on each test strip. The DCP data was then entered into a spreadsheet and converted to CBR using the Army Corps of Engineers (1994) formula shown in Equation 3.1.

$$CBR = 292/ (DCP)^{1.12} \qquad \text{DCP in mm/blow} \qquad \textbf{Equation 3.1}$$

3.4.2 Soil Stiffness Gauge (Humboldt Geogauge)

The soil stiffness gauge was used at each DCP location. Three readings were taken using this piece of equipment and then averaged. The soil stiffness gauge was also used in the lab on the field-mixed, lab compacted samples at 28 days. On all lab-mixed, lab compacted samples the soil stiffness was measured at 14 and 28 days.

3.4.3 Drive Tube

Two drive tube tests were performed on Paola North right after the soil had initially been trimmed to grade. These tests were performed the same day the soil was collected and brought back to the lab. The tests were conducted according to ASTM D-2937, Standard Test Method for Density of Soil in Place by the Drive Cylinder Method.

3.4.4 Nuclear Density Gauge

Nuclear density gauge testing was conducted at eighteen locations on the Paola North test strip. All tests were conducted by KDOT approximately one to two hours after the final compaction was finished.

3.5 Lab Mixing

Paola North and Paola South were both mixed in the lab with dry hydrated lime, slurry from dry hydrated lime, dry pebble quicklime, and a pebble quicklime slurry. The samples were mixed in accordance to ASTM D-3551, Standard Practice for Laboratory Preparation of Soil-Lime Mixtures Using a Mechanical Mixer. The two dry lime mixtures were mixed in the same manner, as were the slurries. The quicklime mixtures contained 3.75% lime (CaO) by weight and the hydrated lime ($Ca(OH)_2$) mixtures contained 5%. These mixtures contain equivalent amounts of calcium. For the dry lime mixtures, each soil was weighed out and then the proper proportion of lime was added and mixed in the mechanical mixer for one minute. After one minute, additional mixing water that was already weighed out was poured slowly and evenly from a beaker into the mixture. Then the water, soil, and lime were mixed for five minutes. After mixing, the mixture was placed in a resealable plastic bag to mellow for 24 hours.

The slurry mixing procedure was similar. Field slurry contains approximately 35% solids, and the lab slurries were mixed accordingly. The dry soil and lime were first weighed out. The

total amount of water needed was then calculated and weighed out in two separate beakers. One contained the amount of water added to the lime to make slurry, and the other beaker contained the rest of the water needed to bring the mixture to the desired moisture content. The slurry was stirred in a metal bowl for one minute and 45 seconds. The slurry was scooped over the soil into the mechanical mixer and mixed for two minutes. The excess water was then poured slowly over the mix, and the sample was mixed for four additional minutes. The slurry samples were then placed in resealable bags and allowed to mellow for 24 hours prior to compaction.

3.6 Lab Testing

A series of lab tests were conducted on the soils from each test section. These tests included: moisture contents, grain size analysis, Atterberg limits, moisture-density relationships, unconfined compression, soil-stiffness gauge, CBR, and pH.

3.6.1 Moisture Contents

The moisture contents of all samples were determined in accordance with ASTM D-2216, Standard Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass.

3.6.2 Grain Size Analysis

Grain size distributions were determined in accordance with ASTM D-422, Standard Test Method for Particle-Size Analysis of Soils, except that the soils were wet sieved over the No. 40 sieve, rather then the No. 10 sieve. The particle size distribution for the retained material was determined by dry sieving, while the finer material was dried out and broken up with a mortar and pestle. A hydrometer analysis was performed on this broken material. The excess material that passed the No. 40 was then used for the Atterberg Limits Test.

3.6.3 Atterberg Limits

The liquid limit, plastic limit, and plasticity index for Paola North and Paola South were determined according to ASTM D-4318, Standard Test Method for Liquid Limit, Plastic Limit and Plasticity Index of Soils. The three point method for finding liquid limit was used on both soils.

3.6.4 Moisture-Density Relationships

Standard Proctor compaction relationships were determined for both Paola North and Paola South. Relationships were determined for the native soils, hydrated lime spread dry, hydrated slurry, pebble quick lime spread dry, and slurry produced near the jobsite from quicklime. The curves were developed according to ASTM D-698, Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort. The two soils were first sieved over a 9.5 mm sieve, lime was then mixed for the lime treated samples, and the soil was then compacted in a 4-inch mold. Moisture contents were taken from excess material immediately after compaction. The lime treated samples were stored for 28 days in a moisture room, while the native proctors were stored for one day and then tested for strength.

3.6.5 Unconfined Compression Strength

Unconfined compression tests were performed on field-mixed and lab compacted soil lime samples, native lab compacted samples, and lab-mixed and lab compacted soil lime samples. There were 73 proctors from grab bag samples collected from Paola North and 36 proctors were made from Paola South. The grab bag samples were brought back to the lab from the field and allowed to mellow for 24 hours at room temperature. After the mellowing period, the samples were compacted in 4-inch molds according to ASTM D-698. The moist density was obtained and the moisture content was then taken so the dry density could be determined. Each

sample was extruded from the mold, placed in a sealed resealable bag, and cured for 28 days in a moisture room. The samples were tested according to ASTM D-5102 Procedure B, Standard Test Method for Unconfined Compressive Strength of Compacted Soil-Lime Mixtures at the end of 28 days. The moisture content of the sample determined again after this test was performed. Native lab-compacted samples were also made in accordance with ASTM D-698. After the samples were compacted, they were extruded immediately and stored in the moisture room for 24 hours. At the end of 24 hours, the samples were subjected to ASTM D-2166, Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. Moisture contents were not taken after this particular test because the moisture content of the soil was assumed to have not changed in a 24-hour period.

Lab-mixed and lab compacted soil lime samples were compacted according to ASTM D-698 and then extruded from the mold. The samples were also cured for 28 days in the moisture room. Strengths of these samples were determined in accordance with ASTM D-5102. The moisture content was determined after the test was completed. The results are reported in Chapter 4.

3.6.6 California Bearing Ratio (CBR)

CBR tests were performed on native-lab mixed samples and field-mixed soil lime samples. Eight samples of Paola South and eight samples of Paola North were compacted into CBR molds. These tests were performed in accordance with ASTM D-1883, The Standard Test Method for CBR of Laboratory-Compacted Soils. All samples were compacted to the standard compactive effort in accordance with ASTM D-698. The native CBR samples were prepared at the maximum dry density and optimum moisture content as determined from the moisture density curve. All samples were soaked for 96 hours and carried a 4.54 kg (10 lb) surcharge.

The change in volume was determined over this 96-hour period. After each 24-hour period, any change in volume was recorded from dial gauges placed on top of the molds. At the end of 96 hours, the samples were placed on the Load Trac II machine and the piston was inserted one inch into the soil at a constant rate and the CBR was determined. The final moisture content was taken from the middle of the sample after the test was finished.

3.6.7 pH

Two pH tests were performed on soils Paola North and Paola South. The results were determined in accordance to ASTM D-6276, Standard Method for Using pH to Estimate the Soil-Lime Proportion Requirement for Soil Stabilization. Pebble quicklime was used for both of these procedures.

Chapter 4

Results

4.1 Native Soil Properties

The native soil characteristics for this project were determined from grain size analysis tests, Atterberg limits tests, CBR tests, Proctor and unconfined compression tests. Paola South was classified a CH clay and Paola North was classified a CL clay by the Unified Soil Classification System. Additional native soil properties are presented in Table 4.1.

Table 4.1: Native Soil Properties

Soil Properties	Paola North	Paola South
% Sand	17	7
% Fines	83	93
Liquid Limit	49	59
Plasticity Index	26	33
Classification (USCS)	CL	CH
Classification (AASHTO)	A-7-5	A-7-6
Max Dry Unit Weight (lb/ft^3)	104.1	93.7
Optimum Moisture (%)	19.8	26.8
Swell Potential by CBR (%)	0.95	1.10
KDOT Swell Test (%)	1.6	1.8
Unconfined Compressive Strength (UC) at Optimum Moisture Content (psf)	2100	1510
Max UC (psf)	2654	2092
Moisture at Max UC (%)	18.3	20.3
California Bearing Ratio (Soaked)	2	4

4.2 Maximum Unit Weight (Density) and Optimum Moisture Content

The maximum unit weight and optimum moisture content were determined for each native soil along with the soils mixed with the four different lime additives. Samples were prepared in 102 x 117 mm molds in accordance with AASHTO T-99 and ASTM D 698. The results are presented in Table 4.2 and the Proctor curves are shown in Figure 4.1a and 4.1b. All samples were cured for 28 days prior to testing in unconfined compression. The UC strength results corresponding to the optimum moisture for density are presented in Table 4.2 and in Figures 4.2a and 4.2b.

These figures show that maximum density decreased with the addition of lime, particularly for Paola North. The strength of Paola North increased substantially with the addition of lime at water contents well above optimum, while moderate increases in strength were observed with the addition of lime for Paola South.

Table 4.2: Optimum Moisture, Density, and Unconfined Compression Strengths (Mixed in the Lab)

	Dry Pebble Quicklime			Slaked Lime Slurry			Dry Hydrated Lime			Hydrated Lime Slurry		
	w%	Max Density (lb/ft3)	UC (psf)	w%	Max Density (lb/ft3)	UC (psf)	w%	Max Density (lb/ft3)	UC (psf)	w%	Max Density (lb/ft3)	UC (psf)
Paola North	16.5	96.0	2700	17.0	97.2	4000	17.7	95.1	6400	18.1	96.0	6400
Paola South	20.5	91.7	3500	21.5	92.4	2700	20.3	91.9	7000	26.2	90.4	4800

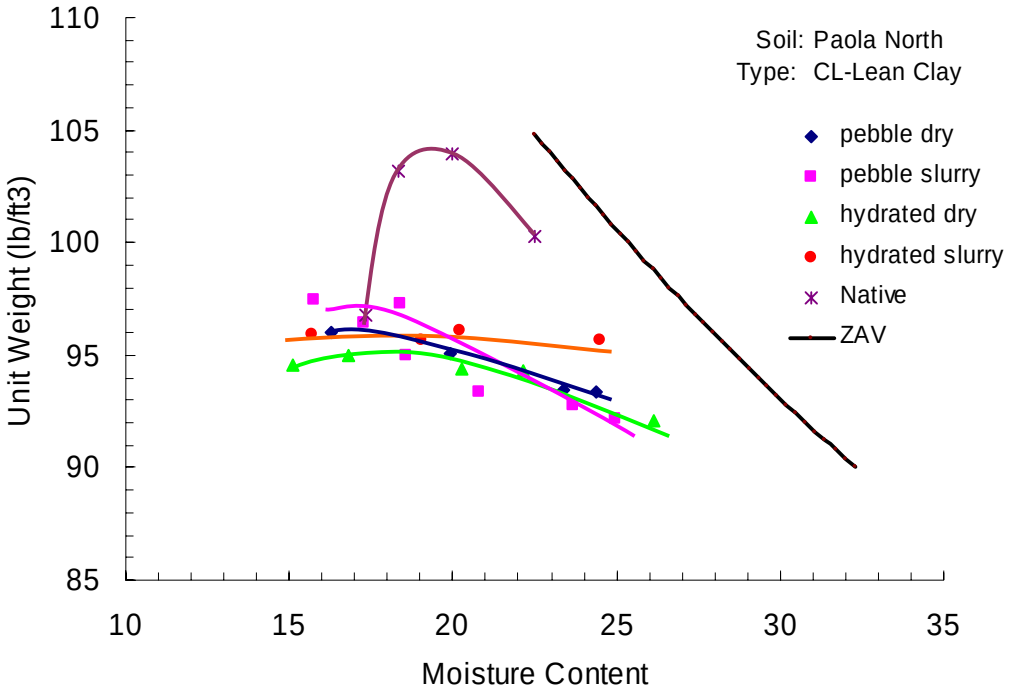
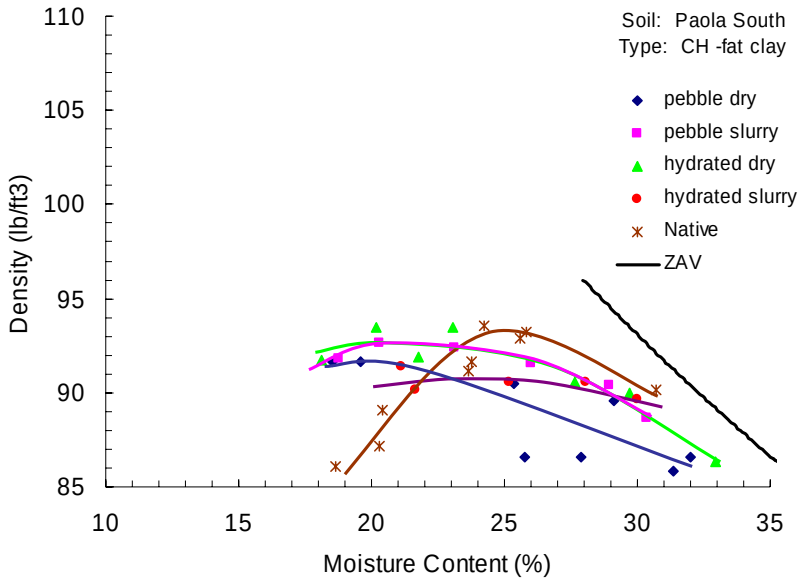
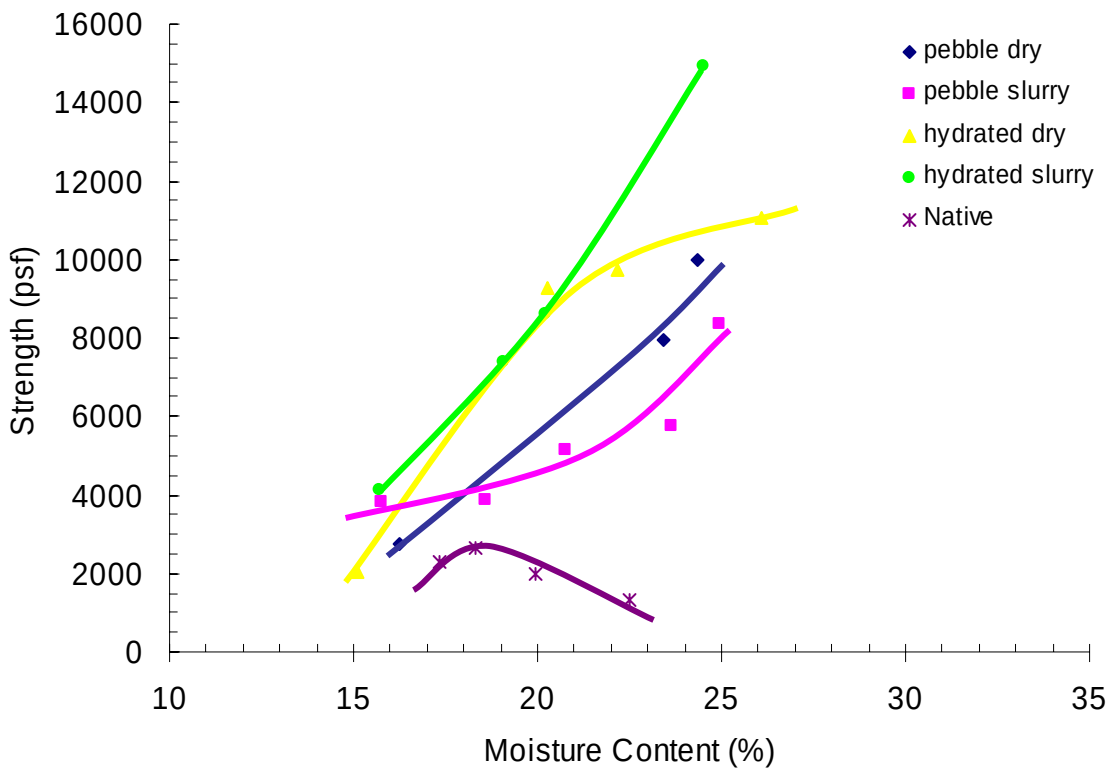


Figure 4.1a: Paola North Density Curves



4.1b: Paola South Density Curves



4.2a: Paola North Unconfined Compressive Strength Curves

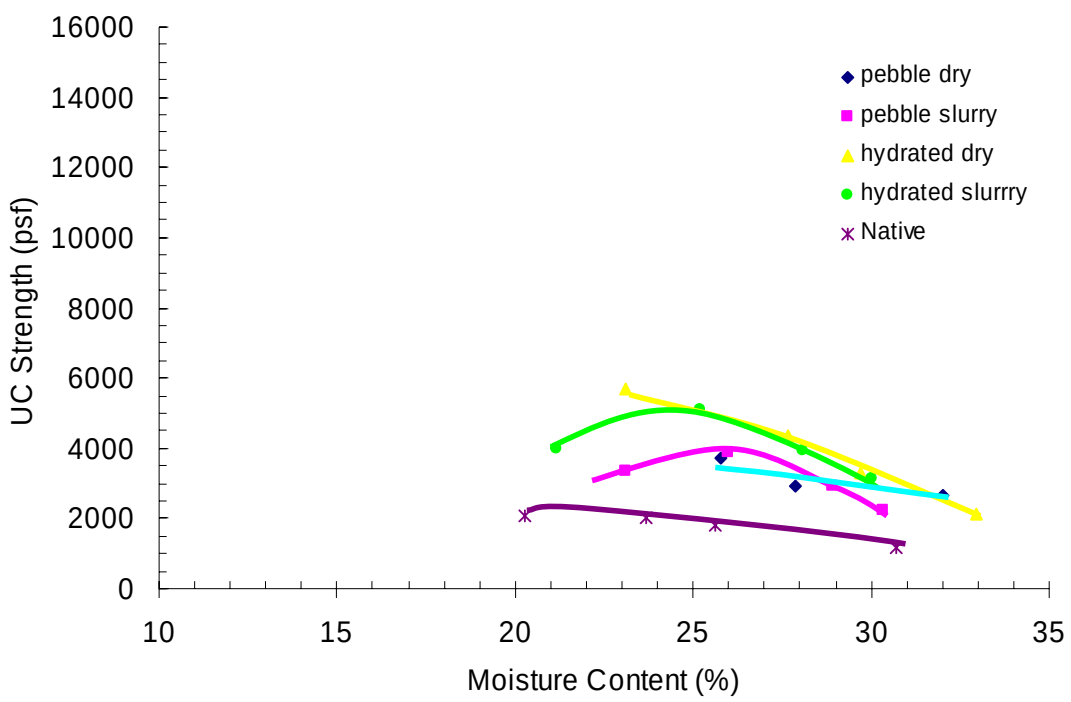


Figure 4.2b: Paola South Unconfined Compressive Strength Curves

4.3 Soil Stiffness With Time

The lime treated samples mixed in the lab were tested at 14 and 28 days using the soil stiffness gauge. Three soil stiffness gauge readings were taken for every lime treated sample. These readings were then averaged and the averages were plotted and are presented in Appendix A. A typical graph is presented in Figure 4.3. These graphs illustrate how the samples increased in stiffness with time.

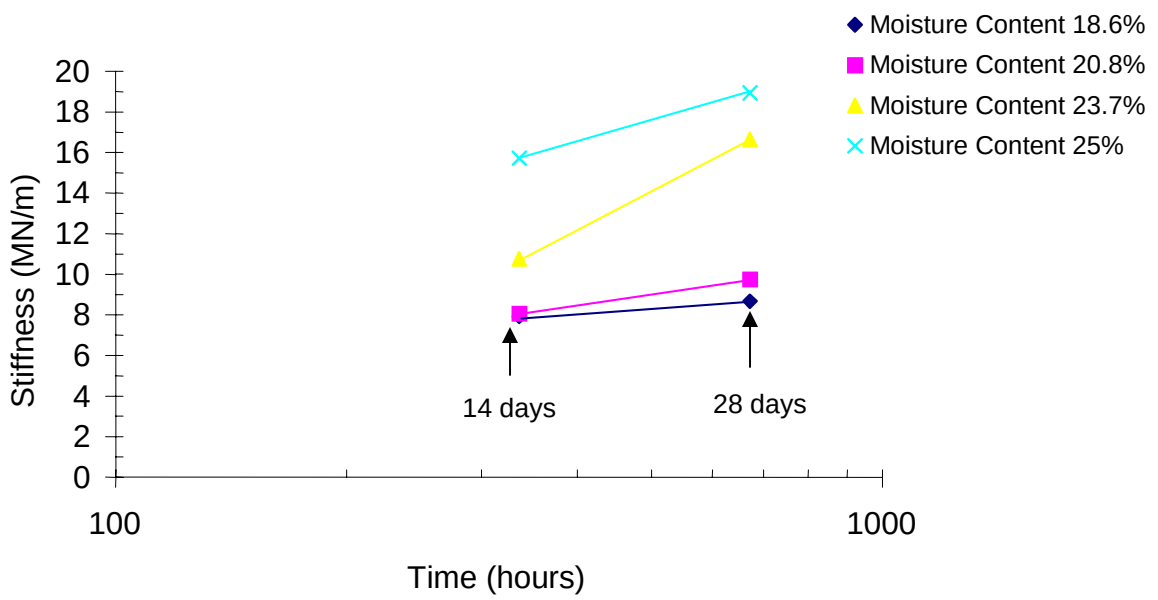


Figure 4.3: Soil Stiffness with Time Graph for Paola North Slaked Lime Slurry

The soil stiffness gauge was also used on the two test strips. Six stiffness gauge measurements were taken on each of three subsections of each test section. Measurements were taken on the same days and at the same locations as the dynamic cone penetrometer tests. Reported stiffness values represent an average of the three stiffness gauge readings from each area. The KDOT stiffness gauge and the KU stiffness gauge were both used for the first set of measurements to evaluate the consistency between instruments. The results of the soil stiffness

gauge readings on the test strips are presented in Tables 4.3a and 4.3b and discussed in detail in Section 5.2.

Table 4.3a: Paola North Soil Stiffness Gauge Readings (KDOT and KU Gauges, MN/m)

		KDOT	KU	KU	KU	KU	KU
	Station	Day 0	Day 0	Day 2	Day 4	Day 14	Day 28
Slurry	18+430	13.27	12.66	11.15	13.93	7.31	8.87
	18+410	12.62	12.16	14.5	8.05	7.07	8.57
	18+380	9.8	9.81	10.26	7.05	13.03	9.28
	18+365	10.03	11.48	11.69	10.3	11.14	7.47
	18+355	7.52	8.53	10.7	12.86	12.29	6.33
	18+305	11.61	17.98	17.78	18.63	8.75	6.6
	Average	10.81	12.10	12.68	11.80	9.93	7.85
	Std. Dev	2.12	3.26	2.91	4.27	2.57	1.23
Vane	18+275	11.4	14.37	14.88	13.62	9.57	7.34
	18+260	11.54	13.03	15.67	12.79	7.67	5.94
	18+230	11.57	14.84	15.63	14.17	10.69	10.75
	18+200	12.92	13.57	14.43	16.23	11.32	6.04
	18+170	14.42	15.87	14.65	12.69	9.93	-
	18+135	15.68	14.74	17.2	16.73	12.21	-
	Average	12.92	14.40	15.41	14.37	10.23	5.01
	Std. Dev	1.78	1.00	1.01	1.73	1.57	2.25
Blade	18+110	13.58	13.89	19.14	15.09	9.33	-
	18+95	20.69	18.59	23.46	20.94	11.66	-
	18+70	16.03	15.72	23.77	20.53	12.09	-
	18+50	12.84	15.09	21.08	15.49	9.27	-
	18+25	15.61	22.27	24.65	25.02	10.36	-
	18+5	10.14	11.19	15.1	13.64	7.64	-
	Average	14.82	16.13	21.20	18.45	10.06	0
	Std. Dev	3.58	3.86	3.61	4.40	1.66	0

Table 4.3b: Paola South Soil Stiffness Gauge Readings (KU Gauge, MN/m)

	Station	Day 1	Day 5	Day 12	Day 15	Day 33
Blade	7+ 470	12.19	6.82	8.12	4.86	7.8
	7+ 500	8.99	13.52	9.51	9.7	7.87
	7+ 530	15.56	12.81	7.92	6.63	6.75
	7+ 560	-	10.87	8.64	7.65	7.39
	7+ 590	14.31	11.55	7.73	7.75	5.48
	7+ 620	-	12.24	13.2	10.52	6.66
	Average	12.76	11.30	9.19	7.85	6.99
	Std. Dev.	2.87	2.38	2.07	2.05	0.90
Vane	7+ 650	14.86	9.19	11.66	10.42	8.14
	7+ 665	-	12.03	11.13	8.76	9.28
	7+ 680	13.75	10.6	8.69	10.63	9.22
	7+ 710	-	11.42	8.77	10.05	7.49
	7+ 740	14.29	12.19	11.79	10.61	7.99
	7+ 770	15.86	12.41	11.59	11.47	10.11
	Average	14.69	11.31	10.61	10.32	8.71
	Std. Dev.	0.90	1.23	1.47	0.90	0.99
Slurry	7+ 796	13.42	11.29	9.94	7.82	8.14
	7+ 830	10.56	9.53	6.99	7.74	6.89
	7+ 863	-	11.45	8.68	6.57	6
	7+ 890	12.84	10.86	7.98	5.61	5.18
	7+ 920	11.22	10.71	7.57	5.91	5.76
	7+ 965	10.36	11.53	9.14	8.04	6.44
	Average	11.68	10.90	8.38	6.95	6.40
	Std. Dev.	1.38	0.74	1.08	1.06	1.03

4.4 pH

The optimum pebble quicklime percentages for Paola North and Paola South were determined in accordance with ASTM D-6276, which defines the lime content required for stabilization is that which causes the pH to reach 12.4 or the content at which the pH stabilizes. By this standard Paola North required approximately 3% quicklime for stabilization. Paola South required 4.0% pebble quicklime to achieve stabilization, which was more than the 3.75% used in the field for both locations. Plots of these tests are presented in Figures 4.4a and 4.4b.

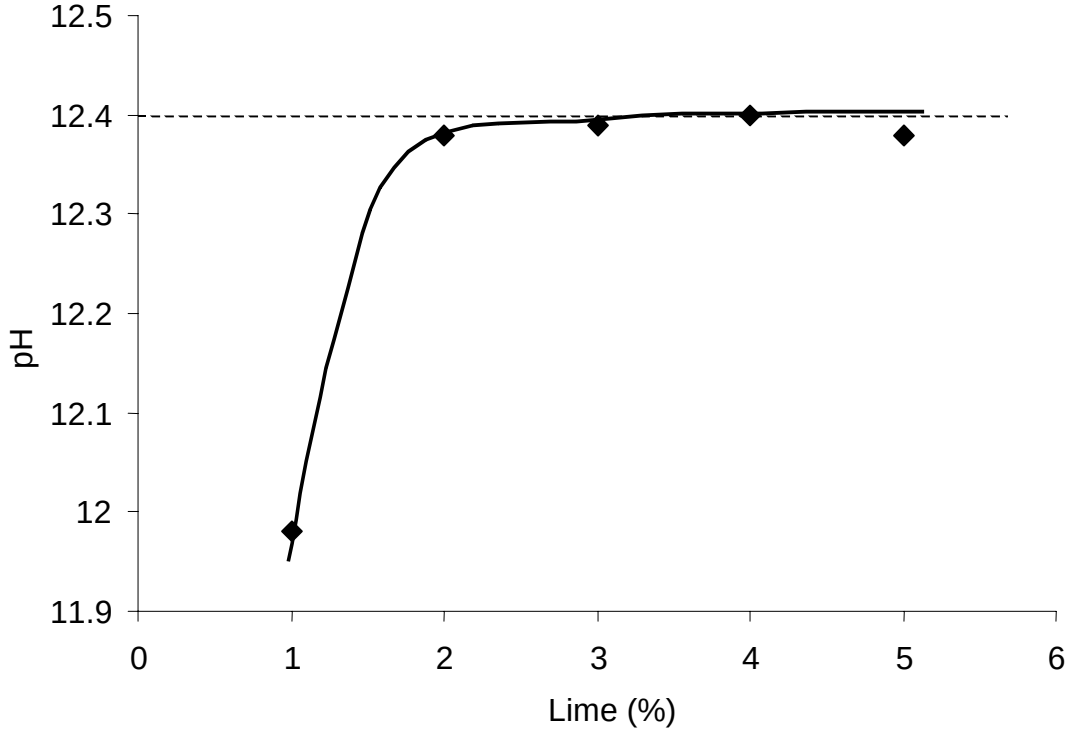


Figure 4.4a: Paola North pH plot (CL soil)

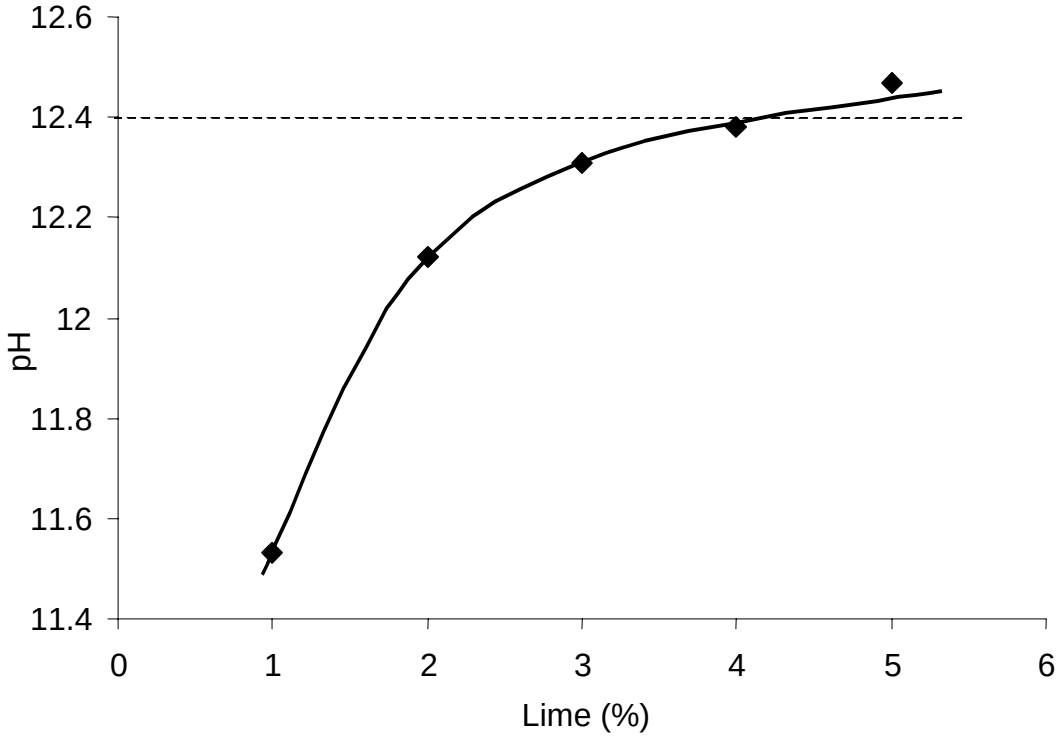


Figure 4.4b: Paola South pH plot (CH soil)

4.5 California Bearing Ratio

The California Bearing Ratio number was determined for the native samples and for samples collected in the field, but compacted in the lab. This test was also used to determine the swell percentages for the native and lime treated samples. The results of these tests are presented in Table 4.4.

Table 4.4: California Bearing Ratio and Swell Percentages

		Paola North		Paola South	
		CBR	Swell (%)	CBR	Swell (%)
Native	Sample 1	1	0.97	4	1
	Sample 2	2	0.92	4	1.2
Slurry	Sample 1	51	0.14	2	0.28
	Sample 2	46	0.19	6	0.44
Vane	Sample 1	60	0.17	16	0.13
	Sample 2	54	0.15	9	0
Blade	Sample 1	51	0.15	20	0
	Sample 2	36	0.2	11	0

4.6 Dynamic Cone Penetrometer

Dynamic Cone Penetrometer tests were performed on both test strips. Test data was entered into a spreadsheet and graphs were produced similar to the one in Figure 4.5. CBR values were calculated from the DCP data using the Army Corps of Engineers equation for the lime treated layer (top 6 inches) and for the untreated soil below. The CBR values for each station and day are presented in Table 4.5a and 4.5b. CBR results and the significance of changes in soil strength are discussed in Section 5.3

No. of Blows	Accumulative Penetration (mm)	Type of Hammer
0	0	2
1	5	2
2	15	2
3	25	2
4	37.5	2
5	50	2
6	65	2
7	80	2
8	95	2
9	110	2
10	125	2
11	140	2
12	157.5	2
13	182.5	2
14	210	2
15	235	2
16	272.5	2
17	312.5	2
		2
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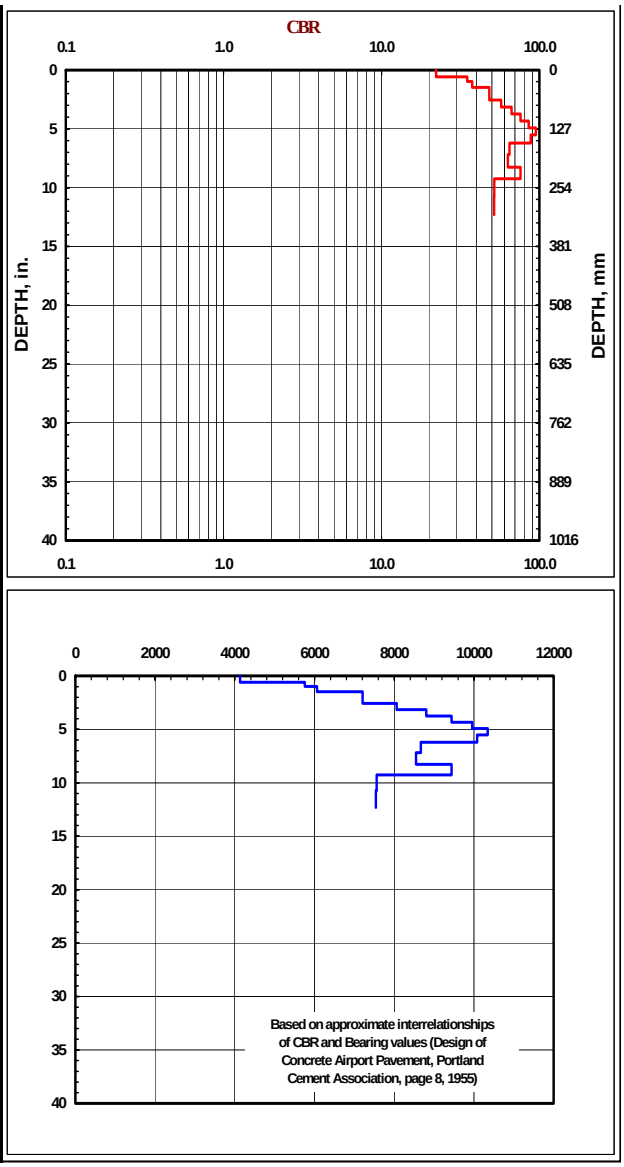

Figure 4.5: Example Dynamic Cone Penetrometer Spreadsheet

Table 4.5a: Paola North Dynamic Cone Penetrometer Data Correlated to CBR

		Day 0		Day 2		Day 4		Day 15		Day 28	
	Layer	Stabilized	Lower	Stabilized	Lower	Stabilized	Lower	Stabilized	Lower	Stabilized	Lower
	Station										
Slurry	18+430	5.7	6.5	8.9	9.7	20.1	14.3	18.2	12.9	22.2	14.3
	18+410	8.4	9.6	9.8	9.3	12	10.2	20.8	14.7	29.4	18.8
	18+380	7.7		10.4	8.3	16.6	12.6	30	19.4	24.6	17.1
	18+365	7.7	12.4	-	-	18.9	16.9	22.5	20	16.6	15.4
	18+355	6	9.3	-	-	19.6	16.5	16.9	12.7	-	-
	18+305	8.9	10.4	-	-	11.4	11	21.4	16.6	-	-
	Average	7.4	9.6	9.7	9.1	16.4	13.6	21.6	16.1	23.2	16.4
	Std. Dev.	1.3	2.1	0.8	0.7	3.9	2.8	4.6	3.2	5.3	2.0
Vane	18+275	11.4	9.8	-	-	12.5	10.9	26.5	17.1	-	-
	18+260	7.9	7.9	-	-	12.1	10.2	19	15.1	-	-
	18+230	5	6.2	-	-	10.4	10.2	18.6	12.6	-	-
	18+200	4.9	4.9	-	-	11.6	7.2	22.2	13.2	-	-
	18+170	5.1	6.6	-	-	16.6	15.7	17.9	15.1	-	-
	18+135	6.7	8.9	-	-	7.9	9.1	16.9	11.2	-	-
	Average	6.8	7.4	-	-	11.9	10.6	20.2	14.1	-	-
	Std. Dev.	2.5	1.8	-	-	2.9	2.8	3.6	2.1	-	-
Blade	18+110	5.8	8.4	-	-	15.9	13.6	13.2	12.2	-	-
	18+95	7.3	8.8	-	-	10.2	10.2	17.9	15.5	-	-
	18+70	7.3	11.5	-	-	10.6	13.3	15.4	13.9	-	-
	18+50.	8.4	9.4	-	-	13.6	10.9	21.3	ROCK	-	-
	18+25	9.6	10.7	-	-	13.6	12.2	20	18.6	-	-
	18+5	8.4	7.6	-	-	16.3	11.4	19.2	13.6	-	-
	Average	7.8	9.4	-	-	13.4	11.9	17.8	12.3	-	-
	Std. Dev.	1.3	1.5	-	-	2.6	1.3	3.0	2.4	-	-

"Stabilized" refers to the 6" lime treated layer

"Lower" refers to the untreated compacted clay beneath the stabilized layer

Table 4.5b: Paola South Dynamic Cone Penetrometer Data Correlated to CBR

		Day 1		Day 5		Day 12		Day 15		Day 33	
	Layer	Stabilized	Lower	Stabilized	Lower	Stabilized	Lower	Stabilized	Lower	Stabilized	Lower
Blade	Station										
	7+470	15.2	19.1	22.2	24.6	30	29.7	19.2	18.4	12.5	12.9
	7+500	9.6	13.3	13.6	16	17.9	20.7	11.6	11.7	13.8	11.4
	7+530	13	16.9	15.7	15.9	23	25.2	25	21.1	19.6	15.7
	7+560	-	-	8.2	8.6	23.8	18.1	18.2	13.8	17.9	11.4
	7+590	13.3	16.1	9.3	10.3	23	21.3	9.4	9.3	13.4	9.4
	7+620	-	-	9.8	16.8	18.9	21.1	14.6	ROCK	7.5	11
	Average	12.8	16.4	13.1	15.4	22.8	22.7	16.3	12.4	14.1	12.0
	Std. Dev.	2.3	2.4	5.3	5.6	4.3	4.1	5.7	4.8	4.3	2.1
Vane	7+650	10.6	14.1	12	13.4	28.9	26.3	20.1	18.7	16.3	9.5
	7+665	-	-	9.1	9.4	20.4	17.3	21.3	15.7	13.1	9.9
	7+680	9.4	9.1	11.8	11.4	27.7	19.9	12.5	12.2	16.3	9.4
	7+710	-	-	13	9.6	17.9	12.2	19.6	13.2	12.3	9.2
	7+740	13.8	11.1	9.4	10	13.8	13.3	17.9	16.7	17.3	12.8
	7+770	15.7	13.3	14.1	10.8	24.6	16.7	20.1	14.7	20.4	10
	Average	12.4	11.9	11.6	10.8	22.2	17.6	18.6	15.2	16.0	10.1
	Std. Dev.	2.9	2.3	2.0	1.5	5.9	5.1	3.2	2.4	2.9	1.3
Slurry	7+796	12.3	13	14.9	11.7	14.3	11.8	19.2	15.5	21.7	11.6
	7+830	15.2	21.1	15.7	16.2	14.1	16.1	17.3	16.4	9.8	8.4
	7+863	13.5	11.5	11	11.9	17.3	16.4	17.9	17.3	10.4	7.7
	7+890	-	-	16.6	18.5	22.2	23.8	11.4	12.5	3.3	4.9
	7+920	12.3	13.3	-	-	16.3	20.3	11.6	15.1	15.1	12.5
	7+965	12	11	-	-	13	11.3	7.9	9.4	7.3	7.3
	Average	13.1	14.0	14.6	14.6	16.2	16.6	14.2	14.4	11.3	8.7
	Std. Dev.	1.3	4.1	2.5	3.3	3.3	4.8	4.5	2.9	6.4	2.8

4.7 Nuclear Density Gauge

KDOT conducted multiple nuclear density gauge readings on Paola North on June 27, 2002.

The tests were conducted in the afternoon, approximately 1 to 2 hours after the final compaction.

The results from the nuclear density gauge are presented in Table 4.6.

Table 4.6: Nuclear Density Gauge Data for Paola North

	Location	Dry Density (pcf)	Wet Density (pcf)	% Moisture	Location on Test Strip
Slurry	1	87.9	113.4	29	North
	2	86.3	111.5	29.2	North
	3	84.7	108.4	28	Middle
	4	89.2	111.8	25.3	Middle
	5	83.6	104.6	25.1	South
	6	95.2	117.6	23.5	South
	Average	87.8	111.2	26.7	
	Std.Dev.	4.2	4.4	2.4	
Vane	7	90.4	113.5	25.6	North
	8	83.5	106.7	27.8	North
	9	89.5	111.1	27.7	Middle
	10	82	107.4	30.9	Middle
	11	80.3	104.5	30.2	South
	12	91.4	112.4	23	South
	Average	86.2	109.3	27.5	
	Std.Dev.	4.8	3.6	2.9	
Blade	13	88.8	110.4	24.4	North
	14	99.1	122.1	23.2	North
	15	101.8	124.1	22	Middle
	16	92.8	115.8	24.8	Middle
	17	97.3	118.9	22.2	South
	18	90.2	110.5	22.5	South
	Average	95.0	117.0	23.2	
	Std.Dev.	5.2	5.8	1.2	

4.8 Statistical Data

The results of a statistical analysis will be discussed in Chapter 5, however a summary of the data is presented in Table 4.8a and 4.8b and the raw data used are presented in Table 4.9a and 4.9b. The abbreviation “P1” in the spreadsheet for example represents pass one of the mixer, and “S1” stands for sample one. “MC-1” and “MC-2” are short for the moisture content taken immediately after compaction and the moisture content after an unconfined compression test was

performed. The abbreviation "SI-Y" stands for Young's modulus in SI units and "SI-S" stands for the stiffness measurement in SI units as determined by the SSG.

Table 4.8a: Paola North Summary Table of Averages of All Field Collected, Lab Compacted Samples

				SSG stiffness				
		n (# of samples)	UC (psf)	SI-S	SI-Y	MC-1 (%)	Density (pcf)	MC-2 (%)
Slurry	Pass1	6	8127	11.25	97.60	29.24	88.86	27.05
	Pass2	6	9361	10.56	91.60	36.45	83.20	30.83
	Pass3	6	8616	9.10	78.95	31.57	85.62	26.08
	Pass 4	6	14240	12.40	107.51	29.69	87.21	25.90
Vane	Pass1	6	6444	6.54	56.78	25.65	91.34	23.17
	Pass2	6	6968	7.57	65.66	24.82	90.62	23.34
	Pass3	6	10033	9.18	79.64	26.80	90.37	24.06
	Pass 4	6	10509	9.31	80.77	29.20	87.46	24.19
Blade	Pass1	6	7152	9.13	79.25	24.46	98.34	23.18
	Pass2	6	9642	10.97	95.17	24.19	96.06	22.35
	Pass3	6	13481	14.11	122.41	21.07	100.64	19.79
	Pass 4	6	16843	14.47	125.51	24.08	95.91	21.82

Table 4.8b: Paola South Summary Table of All Field Collected, Lab Compacted Samples

				SSG stiffness				
		n (# of samples)	UC (psf)	SI-S	SI-Y	MC-1 (%)	Density (pcf)	MC-2 (%)
Slurry	Pass 1	3	5024	4.80	41.64	18.15	90.16	20.54
	Pass 2	3	4267	5.71	49.57	22.85	90.20	23.58
	Pass 3	3	4112	4.00	35.24	23.28	88.82	22.37
	Pass 4	3	4673	4.69	40.70	23.07	90.68	22.85
	Remixed Pass 4	3	4588	6.97	60.48	20.46	90.87	20.77
	Remixed Pass 2	3	10744	11.77	102.12	24.47	91.66	24.41
Vane	Pass 1	3	4030	3.27	28.39	27.42	86.83	26.62
	Pass 2	3	5510	7.70	66.84	32.43	86.24	32.76
	Pass 3	3	5762	7.40	64.22	29.08	90.14	28.59
	Pass 4	3	7584	7.06	61.28	27.85	89.98	28.54
	Remixed Pass 4	3	9771	10.81	92.80	29.46	87.87	29.07
Blade	Pass 1	3	4571	5.00	43.36	22.53	88.47	22.55
	Pass 2	3	3625	5.18	44.98	32.49	85.11	33.42
	Pass 3	3	5922	6.89	59.81	31.06	88.60	29.61
	Pass 4	3	4968	5.14	44.59	29.83	89.11	29.01
	Remixed Pass 4	3	7602	9.59	83.19	27.39	91.36	27.62

Table 4.9a: Paola North Spreadsheet of Field Collected, Lab-Compacted Samples

Subsection	Location	Pass	Sample	Lab compacted UC (psf)	Stiffness Gauge SI-S	Stiffness Gauge SI-Y	MC-1	Lab compacted Density	MC-2
Slurry	North	P1	S1	6588.4	14.3	124.04	34.54	87.07	29.43
Slurry	North	P1	S2	5729.4	11.37	98.58	36.3	83.42	32.55
Slurry	North	P2	S1	6642.2	10.6	91.97	49.6	73.3	37.66
Slurry	North	P2	S2	6806.9	8.6	74.59	38.89	79.92	33.64
Slurry	North	P3	S1	7972	14.1	122.28	41.65	79.53	27.57
Slurry	North	P3	S2	10093	12.55	108.9	38.7	80.35	34.51
Slurry	North	P4	S1	15670	13.44	116.56	29.06	88.68	24.54
Slurry	North	P4	S2	19356	16.64	144.33	30.56	87.43	27.81
Slurry	Middle	P1	S1	12810	16.78	145.55	30.42	87.98	30.61
Slurry	Middle	P1	S2	12875	11.18	96.98	25.05	90.44	24.87
Slurry	Middle	P2	S1	11569	12.91	112.03	28.94	90.15	28.61
Slurry	Middle	P2	S2	9998.1	12.04	104.44	41.3	80.57	33.23
Slurry	Middle	P3	S1	13420	9.28	80.54	32.84	86.83	27.61
Slurry	Middle	P3	S2	10481	8.53	73.96	27	89.41	23.63
Slurry	Middle	P4	S1	17637	13.36	115.87	32.04	86	29.35
Slurry	Middle	P4	S2	14688	12.05	104.51	35.12	82.48	27.15
Slurry	South	P1	S1	4949.4	5.57	48.28	23	92.8	20.46
Slurry	South	P1	S2	5807.1	8.32	72.18	26.11	91.47	24.38
Slurry	South	P2	S1	13519	9.04	78.4	33.83	85.97	27.65
Slurry	South	P2	S2	7630.8	10.16	88.16	26.12	89.31	24.18
Slurry	South	P3	S1	5401.4	6.35	55.05	22.9	92.02	22.19
Slurry	South	P3	S2	4326.4	3.8	32.97	26.34	85.6	20.95
Slurry	South	P4	S1	8544.4	7.41	64.25	24.93	88.85	23.84
Slurry	South	P4	S2	9546.2	11.47	99.55	26.4	89.83	22.73
Vane	North	P1	S1	10715	9.49	82.33	33.78	83.64	30.34
Vane	North	P1	S2	4264.1	4.94	42.88	23.52	88.04	20.68
Vane	North	P2	S1	6863.8	7.73	67.02	29.35	87.55	23.69
Vane	North	P2	S2	4591	7.18	62.32	25.24	85.15	22.42
Vane	North	P3	S1	9640.1	11.51	99.88	24.88	92.01	22.77
Vane	North	P3	S2	6991.2	7.04	61.05	25.48	87.38	24.27
Vane	North	P4	S1	7039.1	8.52	73.88	22.35	89.87	19.74
Vane	North	P4	S2	7828.5	9.45	81.96	23.23	88.13	22.98
Vane	Middle	P1	S1	5874.2	7.81	67.77	24.67	93.13	22.43
Vane	Middle	P1	S2	4618.6	4.31	37.42	23.17	92.8	21.85
Vane	Middle	P2	S1	9576.9	8.41	72.95	26.76	91.59	24.11
Vane	Middle	P2	S2	6137.1	5.53	47.98	19.78	94.92	21.19
Vane	Middle	P3	S1	5368.8	6.91	59.97	28.38	90.79	21.98
Vane	Middle	P3	S2	8127.9	7.14	61.96	24.28	92.09	24.95
Vane	Middle	P4	S1	15029	8.42	73.04	27.77	89.93	26.93
Vane	Middle	P4	S2	8555.8	9.16	79.46	30.45	86.93	26.93
Vane	South	P1	S1	7228.7	7.33	63.64	25.39	95.58	21.7
Vane	South	P1	S2	5964	5.37	46.61	23.39	94.82	22.04
Vane	South	P2	S1	8403.8	9.72	84.34	23.9	92.62	25.06
Vane	South	P2	S2	6235.4	6.84	59.34	23.86	91.91	23.57
Vane	South	P3	S1	11537	12.31	106.83	28.52	89.52	23.68
Vane	South	P3	S2	18530	10.16	88.17	29.26	90.4	26.72
Vane	South	P4	S1	7703.5	7.96	69.1	35.78	83.95	22.86
Vane	South	P4	S2	16898	12.36	107.18	35.62	85.94	25.7
Blade	North	P1	S1	5077.8	5.29	45.92	26.36	93.07	23.56
Blade	North	P1	S2	7955.3	10.2	88.53	21.25	103.55	22.02
Blade	North	P2	S1	9046.3	11.16	96.84	26.74	96.81	20.88
Blade	North	P2	S2	7416.8	8.8	76.37	22.27	101.58	24.56
Blade	North	P3	S1	15607	13.35	115.79	20.85	101.28	19.16
Blade	North	P3	S2	12564	17.01	147.54	23.44	98.06	20.98
Blade	North	P4	S1	19313	14.92	129.39	25.83	95.37	24.13
Blade	North	P4	S2	21348	19.18	166.38	26.62	91.81	23.41
Blade	Middle	P1	S1	6078.2	6.54	56.74	27.11	93.82	24.93
Blade	Middle	P1	S2	9115.9	9.54	82.75	25.88	95.45	26.15
Blade	Middle	P2	S1	13608	13.04	113.12	25.28	92.19	23.49
Blade	Middle	P2	S2	11330	14.55	126.23	22.21	102.61	21.49
Blade	Middle	P3	S1	14364	16.72	145.06	19.6	102.59	19.21
Blade	Middle	P3	S2	15620	13.4	116.29	22.79	99.44	23.25
Blade	Middle	P4	S1	9917.9	11.48	99.52	25.55	89.49	22.91
Blade	Middle	P4	S2	19288	13.3	115.37	22.28	99.98	20.98
Blade	South	P1	S1	6868.5	10.92	94.73	24.7	100.56	21.57
Blade	South	P1	S2	7815.5	12.31	106.82	21.48	103.6	20.85
Blade	South	P2	S1	7812.7	10.53	91.35	24.05	90.93	20.66
Blade	South	P2	S2	8636.1	7.74	67.1	24.61	92.21	23.01
Blade	South	P3	S1	14539	13.81	119.82	20.09	102.05	18.93
Blade	South	P3	S2	8192	10.37	89.93	19.64	100.43	17.2
Blade	South	P4	S1	19620	16.59	143.93	21.83	100.34	18.96
Blade	South	P4	S2	11571	11.35	98.48	22.34	98.46	20.54

Table 4.9b: Paola South Spreadsheet of Field Collected Lab-Compacted Samples

Subsection	Location	Pass	Lab compacted UC (psf)	Stiffness Gauge SI-S	Stiffness Gauge SI-Y	MC1	Lab compacted Density	MC2
Slurry	North	P1	5023.8	4.8	41.64	20.57	93.31	20.04
Slurry	North	P2	4576.8	5.17	44.87	23.92	90.3	24.11
Slurry	North	P3	4459.7	3.87	33.55	22.68	89.38	22.07
Slurry	North	P4	5491.7	4.34	37.66	22.33	91.84	21.39
Slurry	North	4P	5663.4	7.87	68.23	21.75	90.18	21.64
Slurry	North	2P	12381	13.52	117.26	27.22	88.9	26.38
Slurry	Middle	P1	.	.	.	16.56	94.07	21.5
Slurry	Middle	P2	4673.7	4.92	42.64	21.34	91.97	22.62
Slurry	Middle	P3	3603.8	4.31	37.41	24.35	88.66	22.8
Slurry	Middle	P4	4553.2	5.04	43.74	23.64	89.41	24
Slurry	Middle	2P	4911.7	7.05	61.18	19.55	93.22	19.9
Slurry	Middle	4P	11819	12.37	107.33	22.72	95.58	22.66
Slurry	South	P1	.	.	.	17.32	83.11	20.08
Slurry	South	P2	3549.7	7.04	61.19	23.3	88.32	24.02
Slurry	South	P3	4271.9	3.83	34.75	22.82	88.42	22.23
Slurry	South	P4	3973.8	.	.	23.24	90.8	23.16
Slurry	South	2P	3187.8	6	52.04	20.07	89.2	.
Slurry	South	4P	8031.1	9.42	81.76	23.47	90.51	24.19
Vane	North	P1	5243.7	5.04	43.72	26.95	89.8	28.73
Vane	North	P2	7474.6	8.51	73.84	29.08	89.94	27.02
Vane	North	P3	6054.7	7.48	64.91	28.74	88.9	27.12
Vane	North	P4	9681	9.82	85.19	26.81	90.13	27.11
Vane	North	4P	12000	9.96	83.39	27.86	88.46	27.69
Vane	Middle	P1	2919.1	4.78	41.44	26.08	83.52	26.4
Vane	Middle	P2	4675	7.59	65.83	33.83	84.96	34.46
Vane	Middle	P3	5277	6.62	57.43	31.82	87.62	32.05
Vane	Middle	P4	6713.8	5.25	45.56	30.79	87.51	31.46
Vane	Middle	4P	8223.3	10	86.74	30.46	86.81	30.48
Vane	South	P1	3927.7	0	0	29.22	87.17	24.73
Vane	South	P2	4380.7	7.01	60.85	34.39	83.82	36.81
Vane	South	P3	5954	8.1	70.31	26.67	93.9	26.59
Vane	South	P4	6355.8	6.12	53.1	25.94	92.31	27.05
Vane	South	4P	9089.4	12.48	108.26	30.06	88.34	29.04
Blade	North	P1	3073.6	4.6	39.89	21.73	87.24	22.65
Blade	North	P2	6136	7.38	64.07	23.29	92.83	26.41
Blade	North	P3	7062.4	10.31	89.44	24.06	94.19	24.92
Blade	North	P4	4734	4.68	40.62	28.33	92.11	25.59
Blade	North	4P	6509.6	9.89	85.83	25.97	93.71	25.86
Blade	Middle	P1	5422.9	4.82	41.86	24.07	87.77	23.61
Blade	Middle	P2	3345.6	5.24	45.49	36.39	81.93	36.52
Blade	Middle	P3	5320.4	5.25	45.58	36.51	84.39	31.86
Blade	Middle	P4	6470.5	6.74	58.49	27.42	90.88	27.65
Blade	Middle	4P	9325.1	10.53	91.37	25.75	90.66	26.46
Blade	South	P1	5217.1	5.57	48.33	21.79	90.4	21.4
Blade	South	P2	1394	2.93	25.39	37.78	80.56	37.33
Blade	South	P3	5382.9	5.12	44.4	32.6	87.22	32.05
Blade	South	P4	3700.6	3.99	34.67	33.73	84.35	33.78
Blade	South	4P	6972.2	8.34	72.37	30.44	89.7	30.54

Chapter 5

Discussion

This chapter contains a discussion of the results of the various test results presented in Chapter 4.

5.1 Lab Mixed Soils

Paola North and Paola South samples mixed with the various forms of lime had lower dry unit weights and flatter Proctor curves as compared with their respective native soil (Figure 4.1a and 4.1b). The different Proctor curves for both the Paola North and Paola South soils were similar when treated with lime in the various forms, indicating that the form of lime had a negligible effect on the moisture unit weight relationship through mixing.

Unconfined compressive strengths for all of the Paola North and Paola South lime treated samples were higher than for the native soils. The highest strengths, by a slight amount, were recorded for the soils mixed with hydrated dry lime and slurry from hydrated lime (Figure 4.2a and 4.2b).

Soil stiffness values were recorded using the soil stiffness gauge for each of the lab mixed samples. Stiffness increased for nearly all samples with time (Figure 4.3 and Appendix A). Stiffness values also generally increased with increasing moisture for Paola North samples, which had moisture contents in the low to mid 20's, suggesting the better mixing promoted by conditions well above optimum facilitated lime stabilization. Stiffness values tended to decline with increasing moisture for the Paola South samples, which had moisture contents ranging from the mid 20's to the low 30's. As noted previously, stabilization was apparently not achieved for the Paola South soil, and these higher water contents reduced the soil stiffness.

5.2 Soil Stiffness in the Field

Changes in soil stiffness with time are presented in Figures 5.1a and 5.1b. A downward trend in stiffness was observed for both the Paola North and Paola South test sections over time. For the Paola North test section all three of the sections have an increase in stiffness between Days 1 and 3, but after that the stiffness continues to decline. This decline is most apparent for the blade section, and may be a partial function of the low moisture contents within that section immediately after compaction. This downward trend in stiffness is contrary to what would be expected as stabilization proceeded and may be a function of additional near surface moisture from minor rainfall events for Paola North and more significant events for Paola South. It may also be a near surface (top 1-3 inches) phenomenon resulting from construction traffic or other factors, as it is not consistent with the DCP results.

The variability between stiffness gauges was evaluated by taking readings at the same locations using both the KDOT gauge and the KU gauge. Results were reported in Table 4.3a. Based on a matched t-test analysis of these data pairs, the KDOT and KU stiffness gauges returned significantly different values ($\alpha = 0.05$). The average stiffness measured using the KU SSG was 14.2 and the average KDOT value was 12.8. A plot of the matched pair data is presented in Figure 5.2.

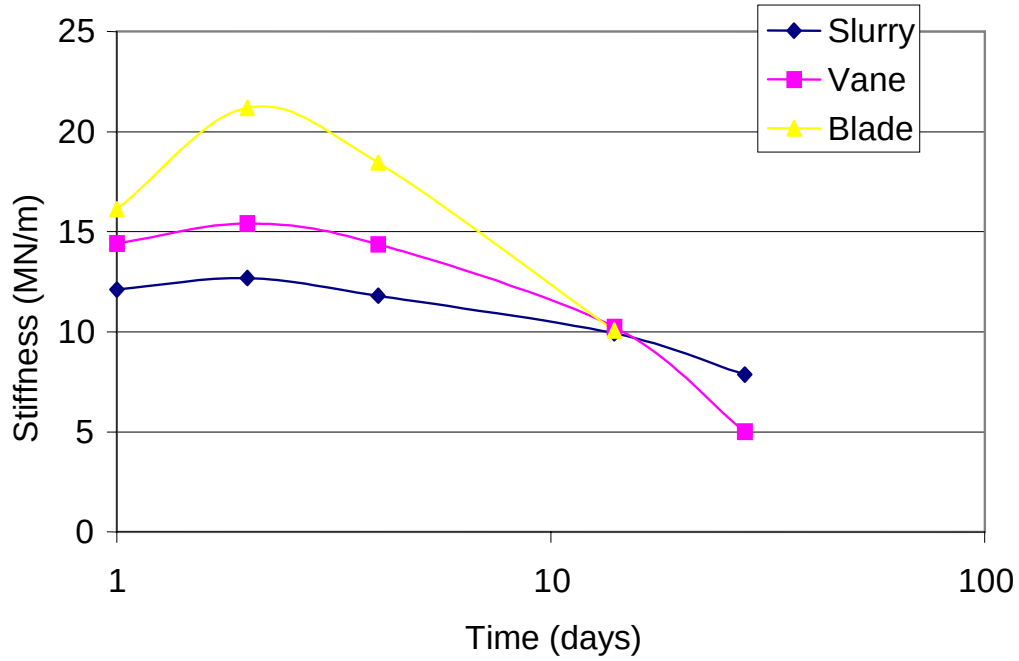

Figure 5.1a: Paola North Stiffness vs. Time Plot (Field Mixing)

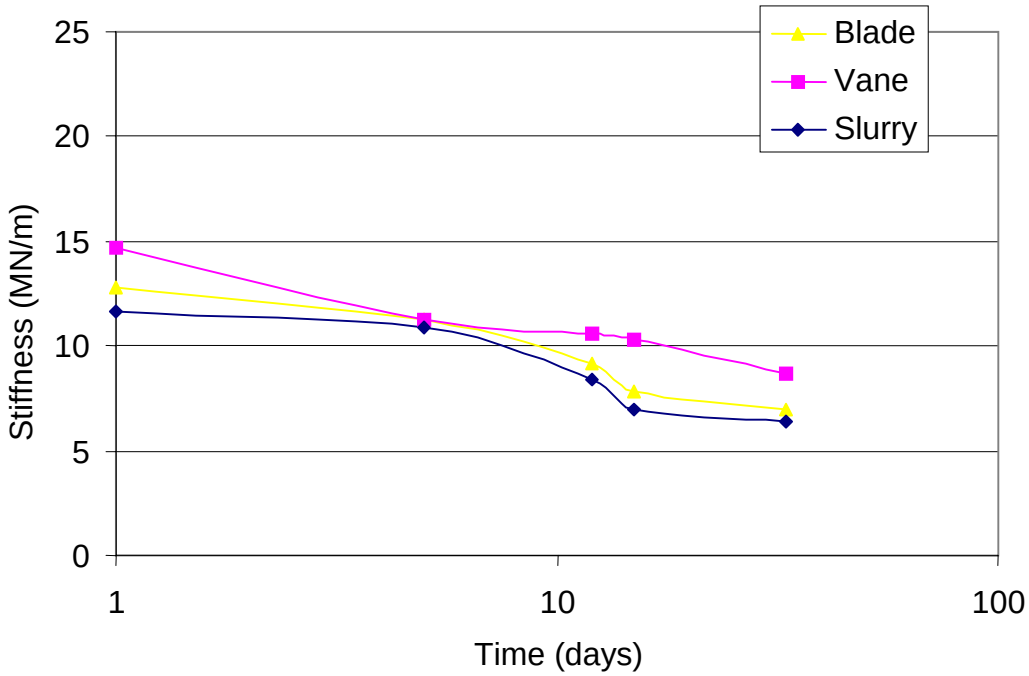

Figure 5.1b: Paola South Stiffness vs. Time Plot (Field Mixing)

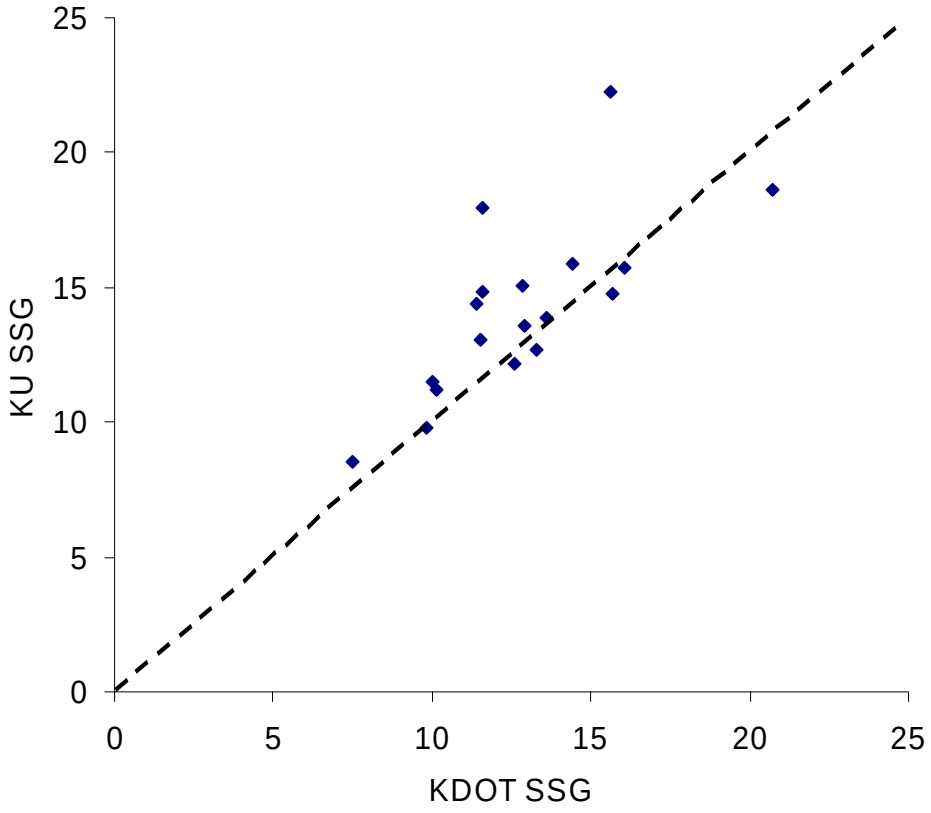

Figure 5.2: Comparison of KU and KDOT Soil Stiffness Gauges

5.3 Changes in Subgrade Strength (CBR from DCP) with Time

DCP data was obtained for a series of times (up to 33 days) afer compaction. An example DCP plot is presented in Figure 5.3 and the rest of the plots are found in Appendix C. Average penetration rate values were determined for the lime treated subgrade and the untreated subgrade. These values were then converted to CBR using the USACE correlation.

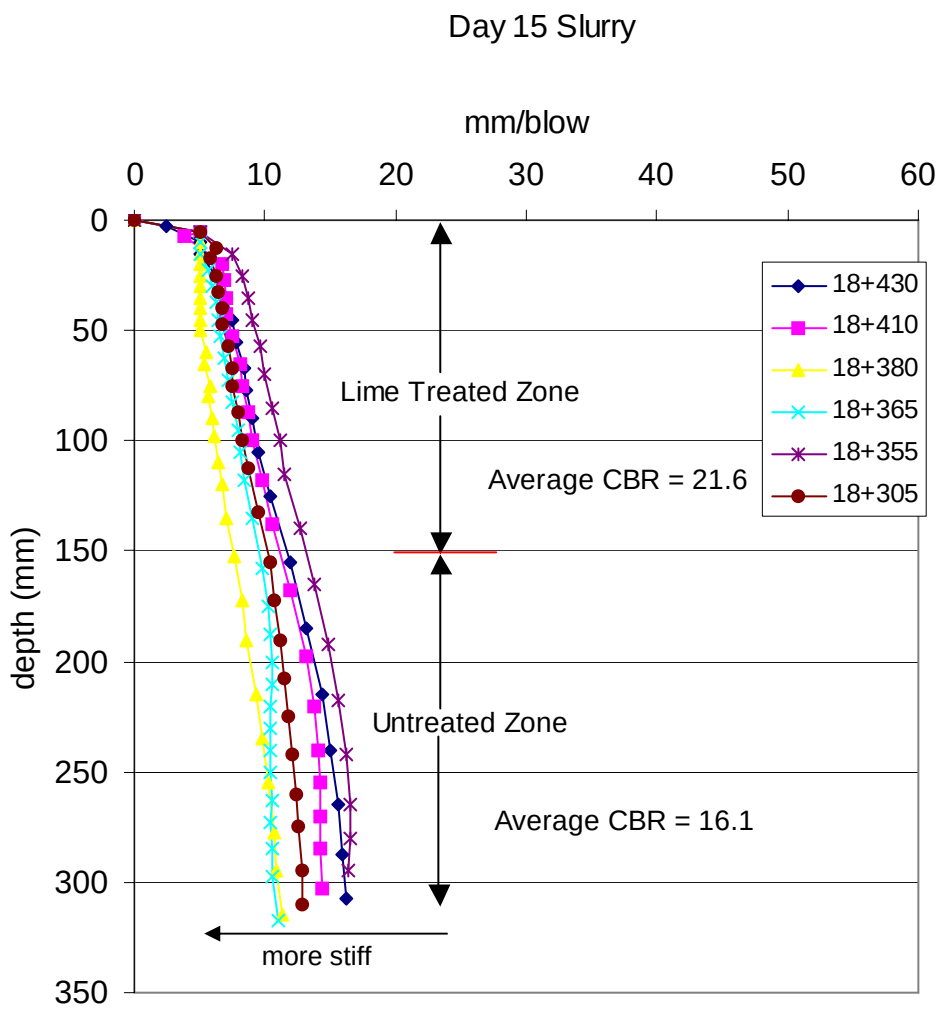

Figure 5.3: Paola North Day 15 (Slurry Section)

The CBR values determined from the DCP data were plotted against time in Figure 5.4a and 5.4b to evaluate changes in subgrade strength with time to evaluate the effects of curing.

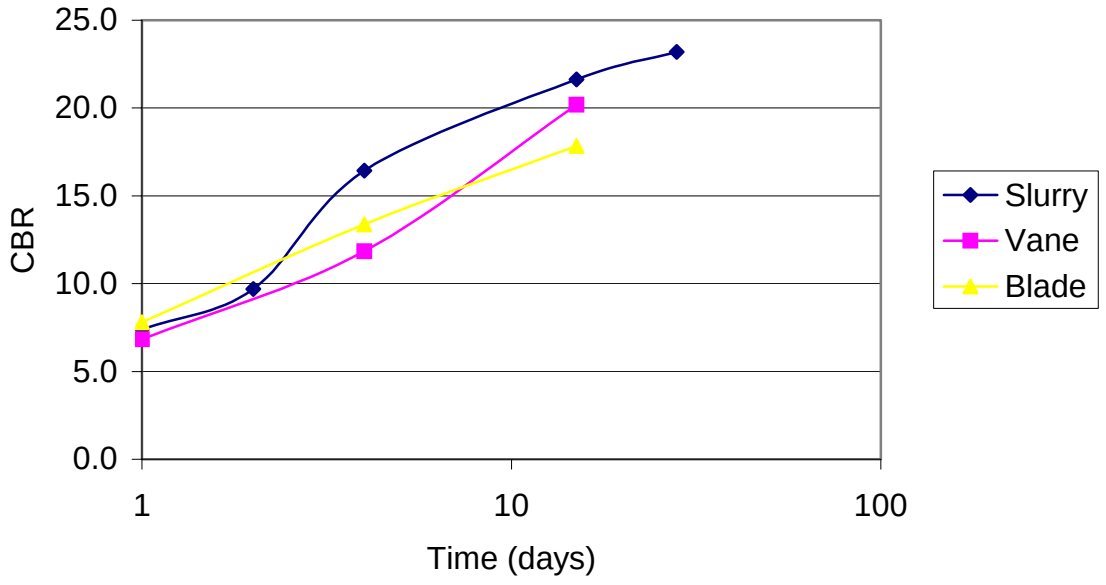

Figure 5.4a: Paola North CBR vs. Time

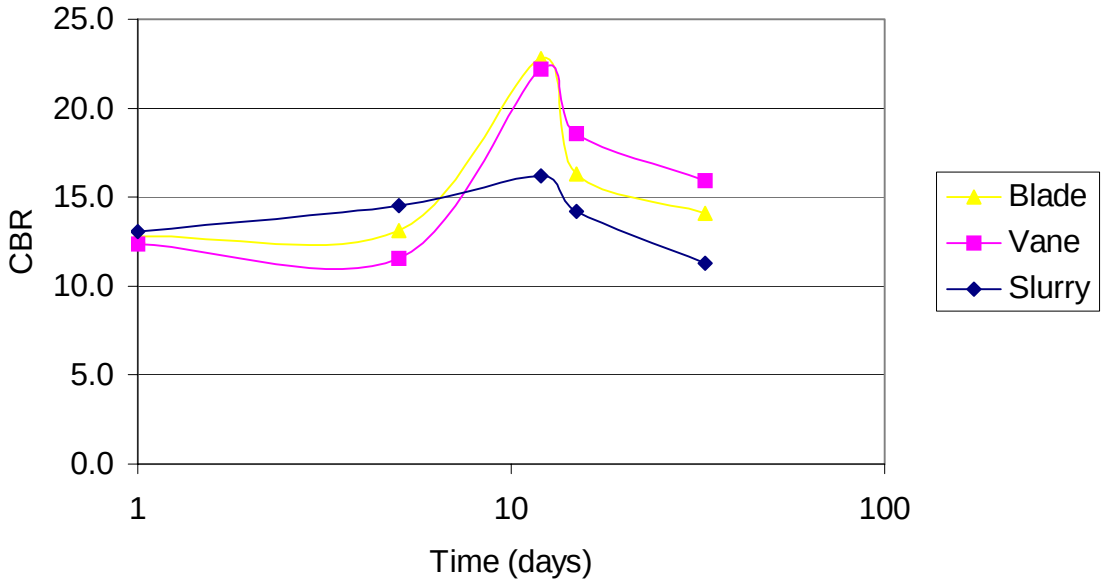

Figure 5.4b: Paola South CBR vs. Time

For the Paola North test section CBR values increased substantially with time, providing strong evidence that subgrade strength increased during the first 28 days. Average CBR values approached or surpassed 20 by the end of testing. There was not a substantial variation in CBR

values among the individual test sections, however the slurry section had the highest CBR and the blade section the lowest when testing was completed. These results reflect strength values throughout the stabilized section, which may explain the difference in trends between the DCP and the soil stiffness gauge.

CBR values for Paola South (Figure 5.4b) follow the same upward trend through Day 12, after which they decline substantially. It is believed this is at least partially a function of several rainfall events that occurred during the testing period. Rainfall data was obtained from the National Climatic Data Center (www.ncdc.noaa.gov) for a rainfall gauge located in Paola, Kansas approximately 1-1.5 miles from the test sites. Plots of the rainfall data for the sampling periods associated with DCP testing at Paola North and Paola South are presented in Figure 5.5a and 5.5b.

Rainfall data for the time period associated with the testing of Paola North shows several minor events occurred in the area (≤ 0.25 in). This would be consistent with some softening of the surface, which may have impacted the soil stiffness gauge readings. The data for the time period associated with the testing of Paola South shows two events with a magnitude greater than one inch occurring on Days 19 and 23. This is consistent with the large drop in strength observed in testing on Day 33. These particular rainfall events occurred 2-3 days after the testing on Day 15 and therefore cannot directly account for the decline in CBR on Day 15. However, the decline observed on Day 15 may have been caused by rain from a local thunderstorm that passed over the test site and not the rain gauge in Paola.

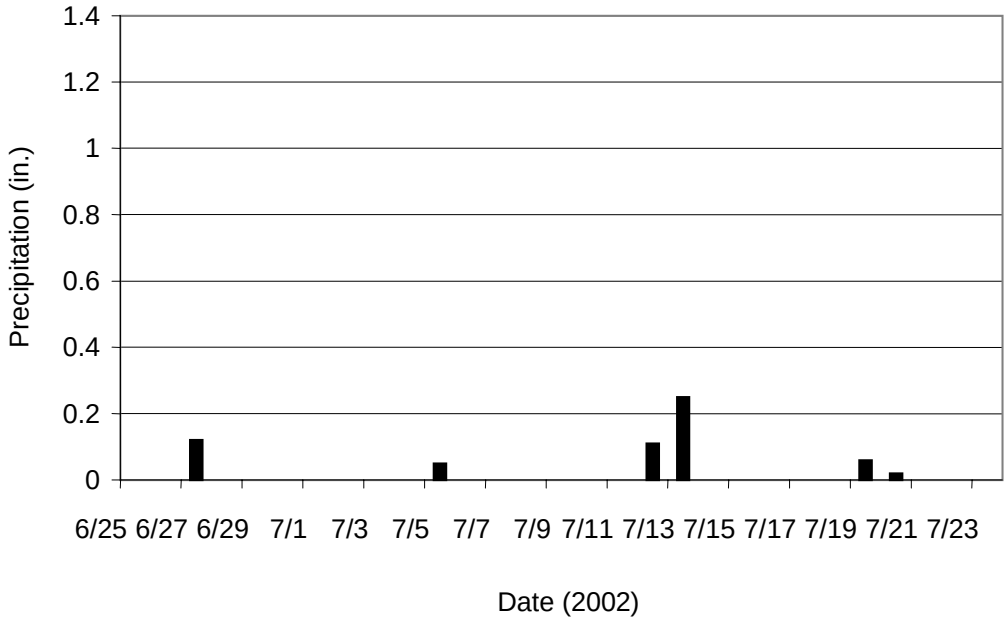

Figure 5.5a: Paola North Precipitation Data During the Test Period

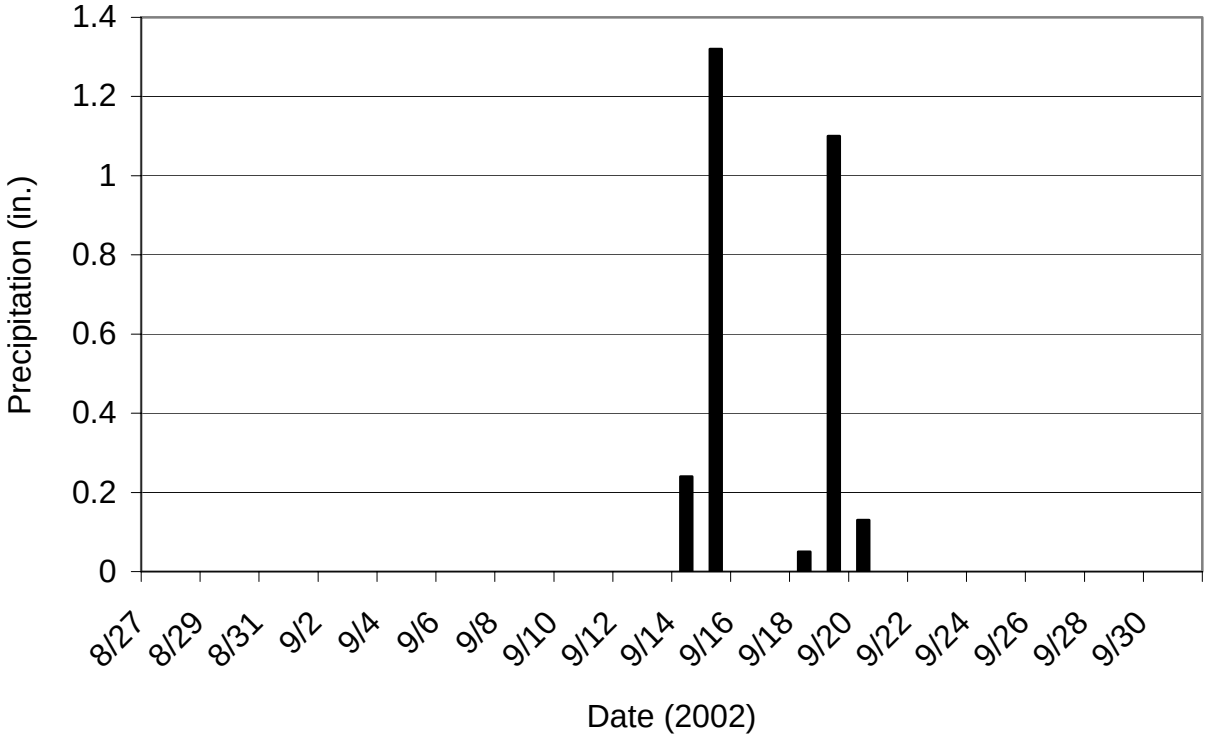

Figure 5.5b: Paola South Precipitation Data During the Test Period

5.4 Mixing

Areas of one square meter were selected by the random placement of a $1m^2$ form. The largest soil lumps observed within the $1m^2$ area were retrieved. Soil lumps were collected from each mixing pass, brought back to the lab and compared. The maximum soil lump size decreased with additional mixing and with greater average water content for the section. A substantial decrease in maximum lump size was observed upon remixing after the mellowing period was completed. A visual representation of the maximum lump size for each pass is shown in Figure 5.6a and 5.6b.

Figure 5.6a: Paola North Max Lump Size from Pass 1 to 4 (Slurry on Top, Vane Middle row, Blade lowest row)

Figure 5.6b: Paola South Max Lump Size from Pass 1 to 4 and a remixed pass one day after the first four (Slurry on Top, Vane Middle row, Blade lowest row)

Grab samples were collected and used to prepare samples for unconfined compression testing after each pass. Strengths increased with mixing for both sections. Plots of this data are presented in Figures 5.7a and 5.7b. This data shows that the strength of the soil increased as the number of passes increased, particularly after remixing (Figure 5.5b). A statistical analysis of the strength data conducted by Dr. Stephen Cross shows that Blade mixed samples were significantly ($\alpha = 0.05$) stronger than the Vane spreader samples for Paola North, while Slurry mixed samples were not significantly different from either. Vane spreader samples were significantly stronger than Blade and Slurry samples for Paola South, when six passes were considered, and were significantly stronger than slurry when only four passes were considered. It is believed these variations were caused by the variations in moisture content caused by variations in watering during mixing. Lower moisture contents typically result in stronger soils

under dry conditions, although for lime treated soils this behavior is complicated by the fact that higher moisture contents promotes interaction between lime and soil particles.

Increased mixing caused a statistically significant increase in strength for both Paola North and Paola South ($\alpha = 0.05$). Statistically significant increases were observed between Pass 1 and 3 and between Pass 3 and 4 for Paola North. For Paola South, a statistically significant improvement in strength was observed after mellowing and remixing ($\alpha = 0.05$), as well as between Pass 2 and 4 with a lower level of confidence ($\alpha = 0.1$).

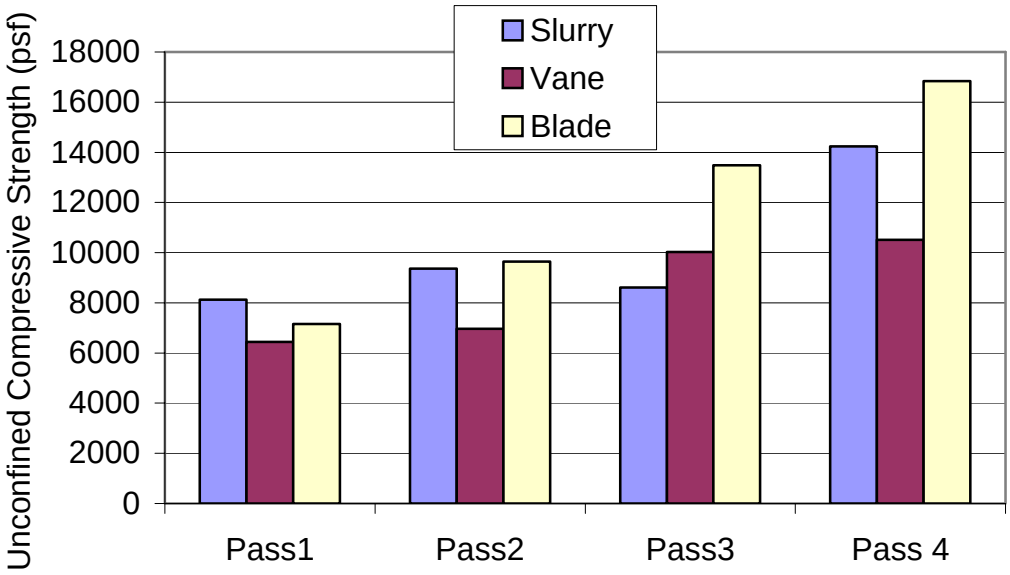

Figure 5.7a: Paola North UC vs. Pass Number

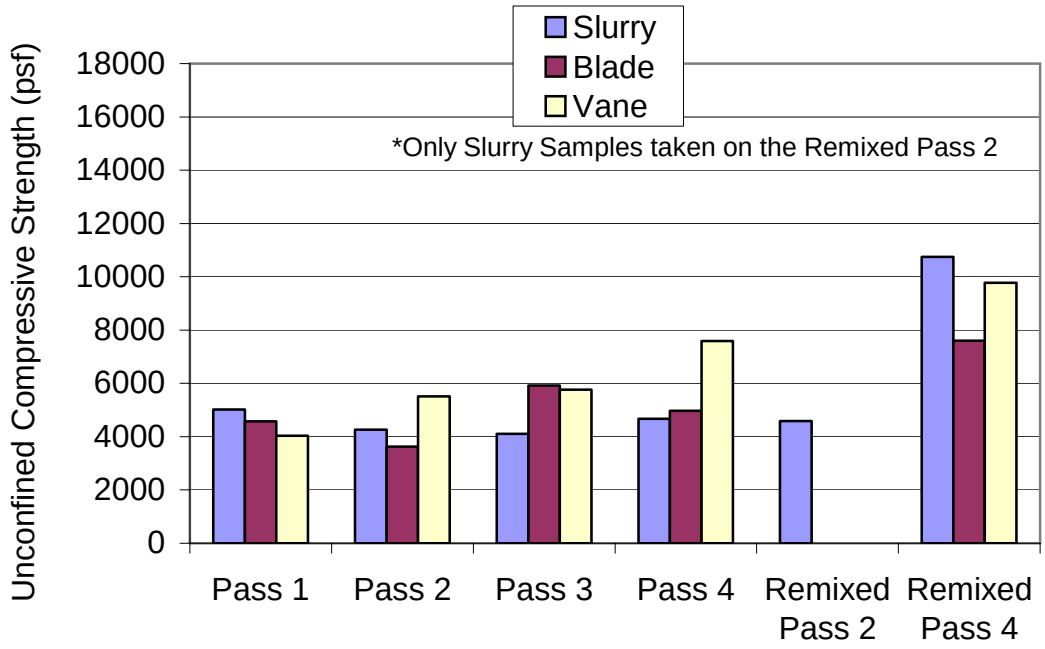

Figure 5.7b: Paola South UC vs. Pass Number

5.5 Unit Weight

The nuclear density gauge is often assumed to have limited value for testing lime treated soils. To test this assumption, 18 nuclear density gauge readings were taken by KDOT in Paola North after compaction. Results were presented in Table 4.6 and are summarized in Table 5.1. Also included within Table 5.1 are summaries of the unit weights and moistures of field mixed, lab compacted samples taken after Pass 4, and Proctor results for pebble quicklime.

Unit weight values for all three sections as measured by the nuclear density gauge were quite close to the unit weights for the field mixed, lab compacted samples taken after Pass 4, which by definition had 100% of the AASHTO T 99 energy applied during compaction. This indicated the compaction effort applied in the field was adequate. Unit weight values for the

slurry and vane sections as measured by the nuclear gauge were low when compared with the maximum density from the Proctor curves. This result is likely a function of the high moisture contents measured by the nuclear gauge and confirmed by the oven moistures determined from the samples taken after Pass 4. Unit weight values for the Blade section were 99% of maximum unit weight as determined from the pebble quicklime Proctor curve.

Table 5.1: Paola North Nuclear Gauge Unit Weights, Pass 4 Lab Compacted Unit Weights, and Maximum Unit Weight and Optimum Moisture

	Number of Samples	Nuclear density (pcf)	Nuclear moisture (%)	Number of Samples	Pass 4 lab compacted (pcf)	Moisture (%)	Max Unit Wt. (pcf)	Optimum Moisture (%)
Slurry	6	87.8	26.7	6	87.2	26.7	96.0	17.0
Vane	6	86.2	27.5	6	87.5	29.2	96.0	17.0
Blade	6	95.0	22.5	6	95.9	24.1	96.0	17.0

These results indicate that the nuclear gauge was at least a good indicator of the state of compaction for this soil, and that energy input from the compaction equipment was sufficient. Moisture contents were sufficiently high for the slurry and vane sections to prevent the achievement of a high compaction ratio. However, these high moisture contents had at most a limited impact on unconfined strength and stiffness, as indicated in Table 4.7a and Figure 5.5a. Field testing with the DCP showed higher strengths for the Slurry and Vane sections than for the Blade section as curing proceeded, despite their lower unit weights.

5.6 General Observations

A few general visual observations were noted on the days of mixing and compaction of the test sections. When the slurry subsection was being spread there was no blowing dust. When dry lime was spread on the blade and vane subsections there was a substantial amount of blowing dust that was sufficient to cause some breathing discomfort and hamper visibility.

Each mixing pass made a noticeable difference in the average size of the remaining clay clods and amount of unreacted lime that was still visible. It was also noted that after the 24-hour mellowing period the soil broke down very easily when remixed and it was apparent that the lime-soil reactions had occurred. This lack of resistance to breakdown is reflected in the maximum particle sizes retrieved after the remixing of Paola South (Figure 5.6b).

Chapter 6

Conclusions

This chapter contains a summary of the conclusions developed based on the test data and literature review.

6.1 Lab Samples

The form of lime added to the soil (quicklime, dry hydrated lime, slurry) appears to have little effect on the moisture-density relationship under completely mixed conditions. The proctor curves created were flatter and had similar optimum moisture contents and maximum unit weights. Swelling was minimal for all lime treated samples. Unconfined compressive strengths for the samples mixed with a dry hydrated lime or slurry from hydrated lime were slightly higher, particularly at lower water contents. This was likely due to the partial consumption of water by the hydration of quicklime.

The amount of lime specified for addition to the Paola South test section (3.75% quicklime) was too low to achieve true stabilization, based on low unconfined strengths and pH testing.

The soil stiffness gauge was effective for tracking stiffness when used in a controlled lab setting. Stiffness increased with time for the majority of samples, as would be expected as curing progressed. For the Paola North samples, stiffness tended to increase with additional moisture, while the stiffness of Paola South samples tended to decrease with additional moisture. These relationships reflect the balance required between having sufficient moisture to promote mixing and lime soil interaction, and avoiding adding to much water resulting in a softer subgrade. The loss of stiffness for the Paola South samples was also likely a function of the insufficient lime content.

6.2 Field Observations of Strength and Stiffness

Changes in the lime application method (slurry, vane spreader, blade) appeared to have a limited to negligible affect on the strength of the subgrades. Proper control of moisture and mixing, and adding sufficient lime for stabilization, had a greater impact on subgrade properties.

Unconfined compression testing of samples collected from Paola North showed that the Blade mixed section produced significantly stronger samples immediately after compaction, however DCP testing for Paola North showed the test sections continued to gain strength with time and at the end of the test period the strongest section was the Slurry section, with an equivalent CBR of 23. The initial higher strengths for the Blade mixed section were likely a function of a lower moisture content at the time of mixing. This lower moisture content may have inhibited the interaction between the soil particles and lime, resulting in a lower strength gain over time as measured by the DCP.

Strengths as measured by the DCP for Paola South increased through Day 12 before decreasing through the remainder of the test period. It is believed this is at least partially a function of rainfall events and the lack of sufficient lime to achieve stabilization of the soil. Final CBR values ranged from 11 to 16, which was similar to the initial values. CBR values were lowest for the Slurry section, even though it had relatively high strengths and low moisture contents at the time of compaction. These results, along with those from Paola North, suggest that long term strengths are similar, if not greater, for lime treated soils compacted well above optimum than those soils compacted at or near optimum moisture.

Stiffness as measured by the soil stiffness gauge declined for both Paola North and Paola South. Given the increases in DCP readings, it is proposed that this decline was a function of

construction traffic and minor rainfall events that may have disturbed the upper portion of the stabilized section and affected SSG readings but not significantly affecting the DCP results.

The number of passes made over the subgrade during the mixing process made a substantial difference in the unconfined compressive strength of the samples, even after four passes. Remixing and recompaction after mellowing also resulted in a significant improvement in strength and contributed to the breakdown of remaining soil lumps.

6.3 General Observations

Significant amounts of blowing lime dust were observed during the application of pebble/powdered quicklime. Blowing lime presents some health and visibility risks to construction personnel and nearby traffic, and represents the loss of some product. No dust was produced during the application of slurry.

Chapter 7

Recommendations

7.1 Application Method

Three methods for the application of lime were evaluated as a part of this study. This study focused on the mixing of the applied lime with the soil; the amount of lime added was assumed to be in compliance with KDOT specifications. Based on the results of this study, no application method produced a clearly superior subgrade; therefore no recommendation for the adoption or exclusion of an application method based on performance can be made. It is recommended that other factors be considered when determining if a particular application method should be specified. Given the potential health hazard and visibility problems associated with blowing quicklime, it is recommended that slurry be specified in areas where blowing lime may present a problem in either of these two areas.

7.2 Mixing

Proper mixing was a significant factor in performance. It is recommended that, at a minimum, two passes be made with a rotary mixer during initial mixing and additional mixing be conducted after a mellowing period. This is consistent with current specifications. Inclusion of a mellowing period makes it much easier for the contractor to meet the maximum lump size specification of Special Provision 90M-0141-R01 (95% < 37.5-mm, 40% < 4.75-mm). Additional mixing would likely improve performance further.

7.3 Lime Content

Use of the standard 3.75% quicklime for the Paola South test sections was insufficient to achieve stabilization. It is recommended that KDOT consider adoption of a pH-based test such as ASTM D 6276, possibly in combination with strength testing, for specifying the amount of lime to be

used if stabilization is desired for strength or to assure development of permanent bonds not susceptible to leaching (McAllister and Petry 1991). For modification purposes only, use of Atterberg limits or swell testing should be sufficient. Implementation of a mix design procedure would enable KDOT to more effectively match the appropriate amount of lime for the soil and objective desired.

7.4 Moisture

Moisture was a major factor if not the dominant factor in the strength gains observed. Standard practice is to mix soils at a moisture content several points greater than optimum. While this may result in lower initial unconfined strengths and lower unit weights, it also appears to promote soil-lime interactions as the soil cures, leading to equal or greater long term strengths than would be achieved under drier conditions. It is therefore recommended that compaction of soils well above optimum be continued. The National Lime Association recommends soils be compacted at optimum + 3 percent. (National Lime Association 2004).

7.5 Recommendations for Evaluating Variations in the Amount of Lime Added

The potential for variations in the amount of lime dispensed over the subgrade has been raised. The potential for variations would appear to be greatest for trucks that rely on gravity feed where the lime is under a varying amount of pressure that is greatest when the truck is full and decreases to zero when the truck is empty. Monitoring of changes in the application rate as the lime is applied could be achieved by requiring metering. When equipment without meters is used, it is recommended that lime be collected in pans placed evenly spaced over the length of lime application. The lime can then be dried (if in slurry form) and weighed to determine the variation in dispersal rate.

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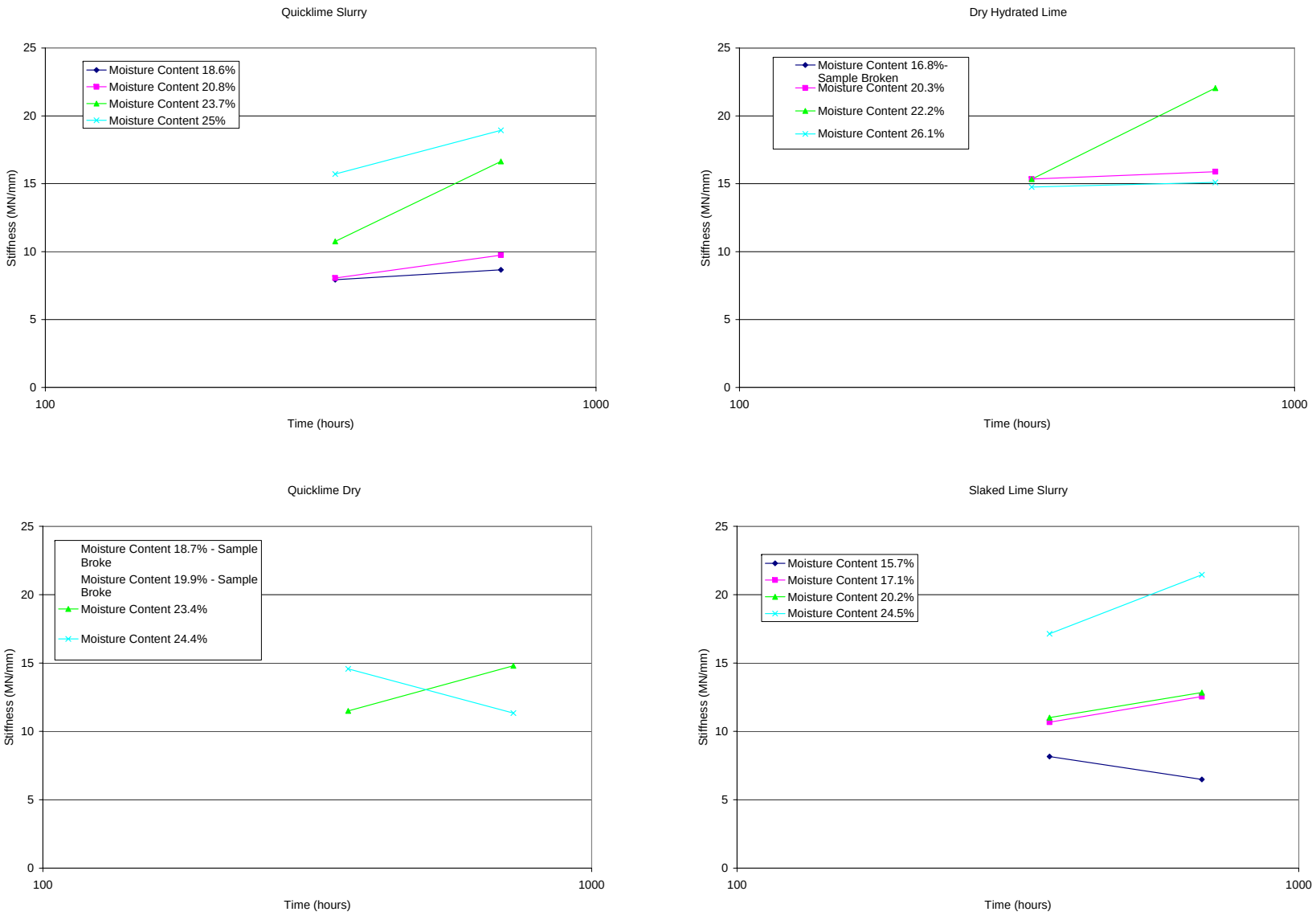
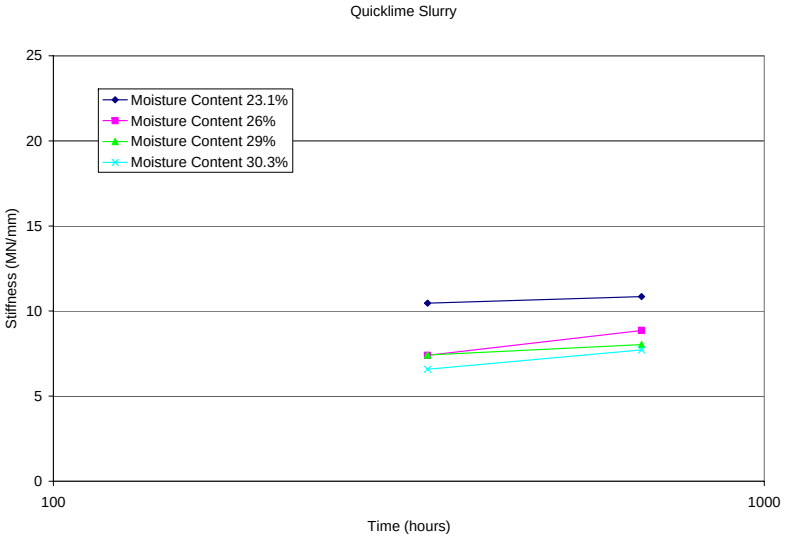
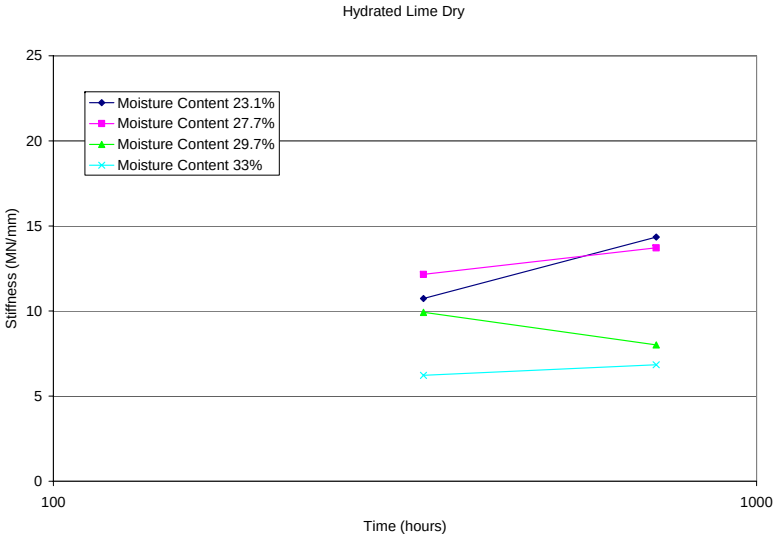
APPENDIX A

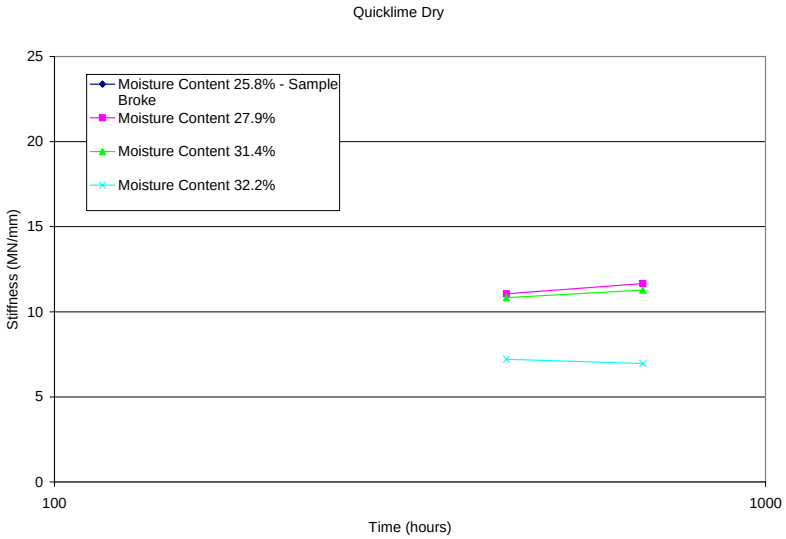
Soil Stiffness with Time Plots for Paola North and South - Lab Samples

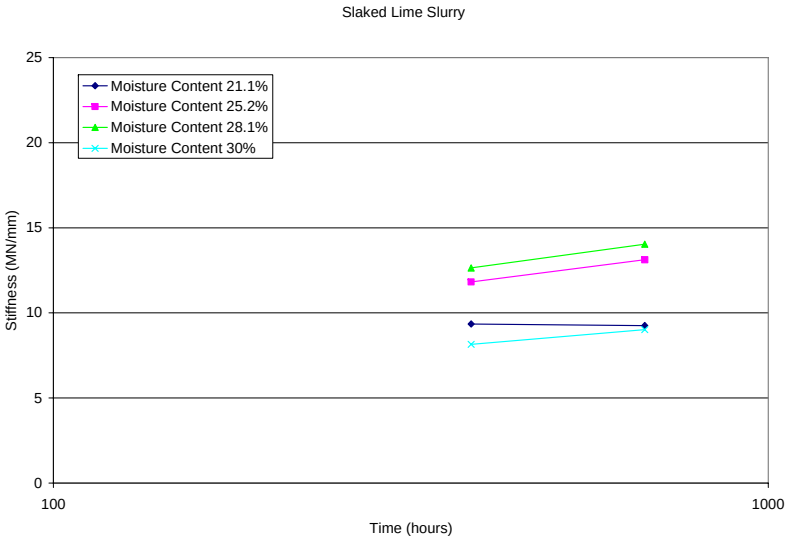


Soil Stiffness with Time Plots for Paola North
***Moisture Content is how samples were distinguished**









Soil Stiffness with Time Plots for Paola South
*** Moisture Content is how samples were distinguished**

APPENDIX B

Statistical Analysis

Unconfined Compression Statistical Analysis

Paola North

Factor	DF	SS	MS	F	Pr>F
Lime	2	1.3E+08	65001713	3.83	0.0269
Location	2	35092493	17546247	1.03	0.3614
Interaction	4	1.43E+08	35692195	2.10	0.0907
Error	63	1.07E+09	16962041		
Total	71	1.38E+09			

Grouping	Mean	N	Lime
A	11779	24	Blade
AB	10086	24	Slurry
B	8488	24	Vane

Paola South

Factor	DF	SS	MS	F	Pr>F
Lime	2	11615429	5807715	0.99	0.3801
Location	2	19467924	9733962	1.66	0.2032
Interaction	4	12647646	3161911	0.54	0.7068
Error	37	2.16E+08	5848730		
Total	45	2.6E+08			

Location Not Significant

Paola North

Factor	DF	SS	MS	F	Pr>F
Lime	2	1.3E+08	65001713	5.58	0.006
Pass	3	4.46E+08	1.49E+08	12.77	<0.0001
Interaction	6	1.01E+08	16873702	1.45	0.2115
Error	60	6.99E+08	11647785		
Total	71	1.38E+09			

alpha = 0.05	Grouping	Mean	N	Lime
	A	11779	24	Blade
	AB	10086	24	Slurry
	B	8488	24	Vane

alpha = 0.05	Grouping	Mean	N	Lime
	A	13864	18	P4
	B	10710	18	P3
	BC	8657	18	P2
	C	7241	18	P1

Paola South

Factor	DF	SS	MS	F	Pr>F
Lime	2	30484672	15242336	7.88	0.0019
Pass	4	53926259	13481565	6.97	0.0005
Interaction	8	32909087	4113636	2.13	0.0669
Error	28	54151695	1933989		
Total	42	1.71E+08			

alpha = 0.05	Grouping	Mean	N	Lime
	A	6531	15	Vane
	B	5338	15	Blade
	B	4457	15	Slurry

alpha = 0.05	Grouping	Mean	N	Lime
	A	7320	9	P6
	B	5742	9	P4
	B	5265	9	P3
	B	4467	9	P2
	B	4404	9	P1

Only LOOKING AT P1 - P4

Factor	DF	SS	MS	F	Pr>F
Lime	2	10260267	5130134	2.93	0.0745
Pass	3	12220409	4073470	2.33	0.1027
Interaction	6	15962623	2660437	1.52	0.2185
Error	22	38542415	1751928		
Total	33	76985714			

alpha = 0.1	Grouping	Mean	N	Lime
	A	5721.4	12	Vane
	AB	4771.7	12	Blade
	B	4417.8	10	Slurry

alpha = 0.1	Grouping	Mean	N	Lime
	A	5741.6	9	P4
	AB	5265.2	9	P3
	B	4467.3	9	P2
	B	4404	7	P1

Density Statistical Analysis

Paola North

Factor	DF	SS	MS	F	Pr>F
Lime	2	1656.4	828.2	53.65	<.0001
Location	2	161.4	80.7	5.23	0.0079
Interaction	4	112.2	28.05	1.82	0.1367
Error	63	972.5	15.43651		
Total	71	2902.5			

Alpha = .05	Grouping	Mean	N	Lime
	A	97.7	24	Blade
	B	89.9	24	Vane
	C	86.2	24	Slurry

Alpha = .05	Grouping	Mean	N	Lime
	A	92.9	24	South
	A	91.7	24	Middle
	B	89.3	24	North

Paola South

Factor	DF	SS	MS	F	Pr>F
Lime	2	47	23.5	2.80	0.0731
Location	2	62.8	31.4	3.74	0.0327
Interaction	4	106.7	26.675	3.18	0.0236
Error	39	327.5	8.397436		
Total	47	544			

Alpha = .1	Grouping	Mean	N	Lime
	A	90.4	18	Slurry
	B	88.5	15	Blade
	B	88.2	15	Vane

Alpha = .05	Grouping	Mean	N	Lime
	A	90.7	16	North
	AB	88.7	16	Middle
	B	88.0	16	South

Paola North

Factor	DF	SS	MS	F	Pr>F
Lime	2	1656.4	828.2	49.74	<.0001
Pass	3	112.3	37.43333	2.25	0.0919
Interaction	6	134.6	22.43333	1.35	0.2508
Error	60	999.1	16.65167		
Total	71	2902.4			

alpha = 0.05	Grouping	Mean	N	Lime
	A	97.7	24	Blade
	B	89.9	24	Vane
	C	86.2	24	Slurry

alpha = 0.1	Grouping	Mean	N	Lime
	A	92.8	18	P1
	AB	92.2	18	P3
	B	90.2	18	P4
	B	90.0	18	P2

Paola South

Factor	DF	SS	MS	F	Pr>F
Lime	2	32.3	16.15	1.34	0.2768
Pass	4	49.7	12.425	1.03	0.4065
Interaction	8	56.5	7.0625	0.59	0.7802
Error	30	360.8	12.02667		
Total	44	499.3			

alpha = 0.05	Grouping	Mean	N	Lime
	A	90.1	15	Slurry
	A	88.5	15	Blade
	A	88.2	15	Vane

alpha = 0.05	Grouping	Mean	N	Lime
	A	90.0	9	P6
	A	89.9	9	P4
	A	89.9	9	P3
	A	88.5	9	P1
	A	87.2	9	P2

Only LOOKING AT P1 - P4

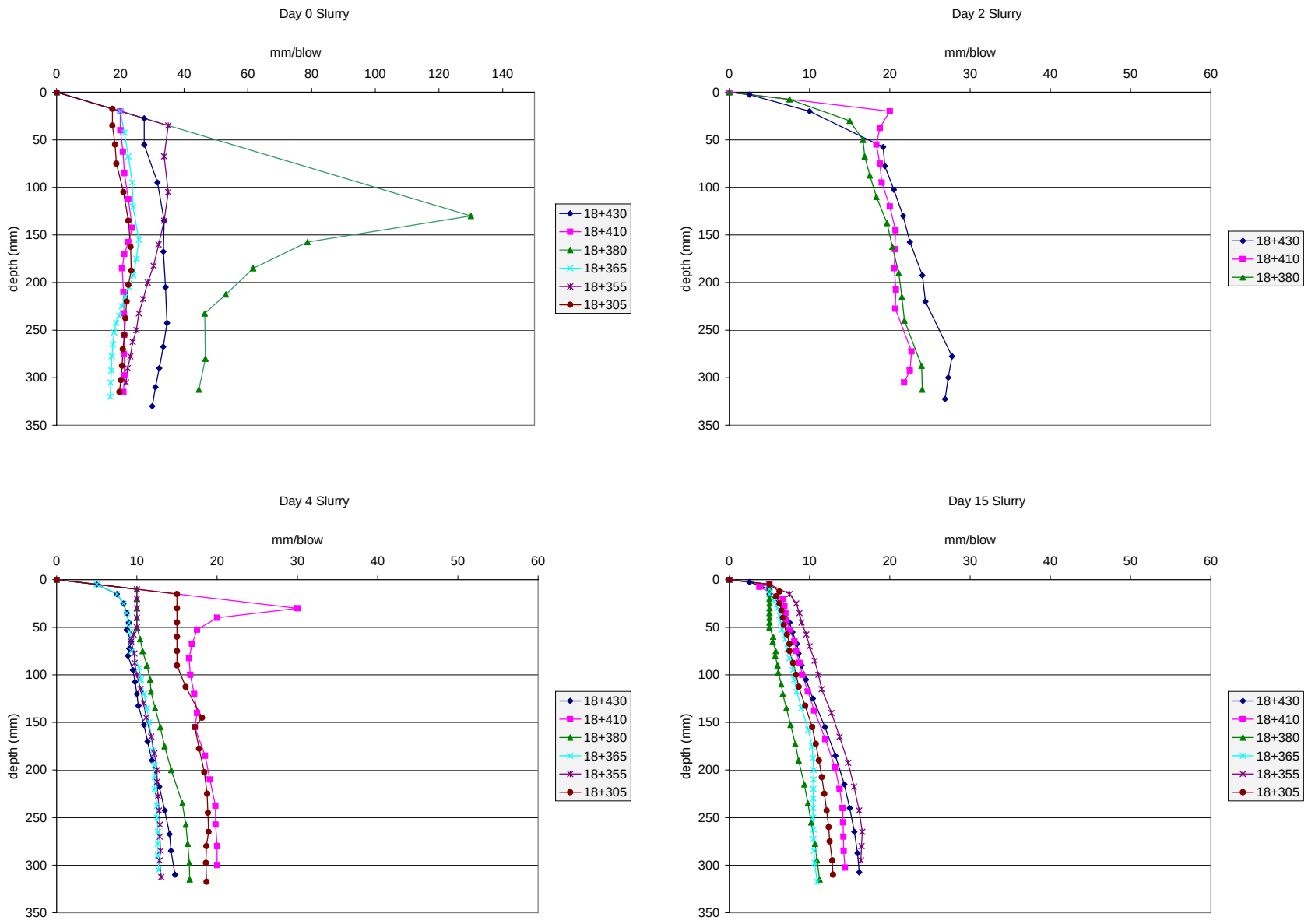
Factor	DF	SS	MS	F	Pr>F
Lime	2	30.4	15.2	1.07	0.3594
Pass	3	36.8	12.26667	0.86	0.4737
Interaction	6	37	6.166667	0.43	0.8494
Error	24	341.5	14.22917		
Total	35	445.7			

alpha = 0.05	Grouping	Mean	N	Lime
	A	90.0	12	Slurry
	A	88.3	12	Vane
	A	87.8	10	Blade

alpha = 0.05	Grouping	Mean	N	Lime
	A	89.9	9	P4
	A	89.2	9	P3
	A	88.5	9	P1
	A	87.2	7	P2

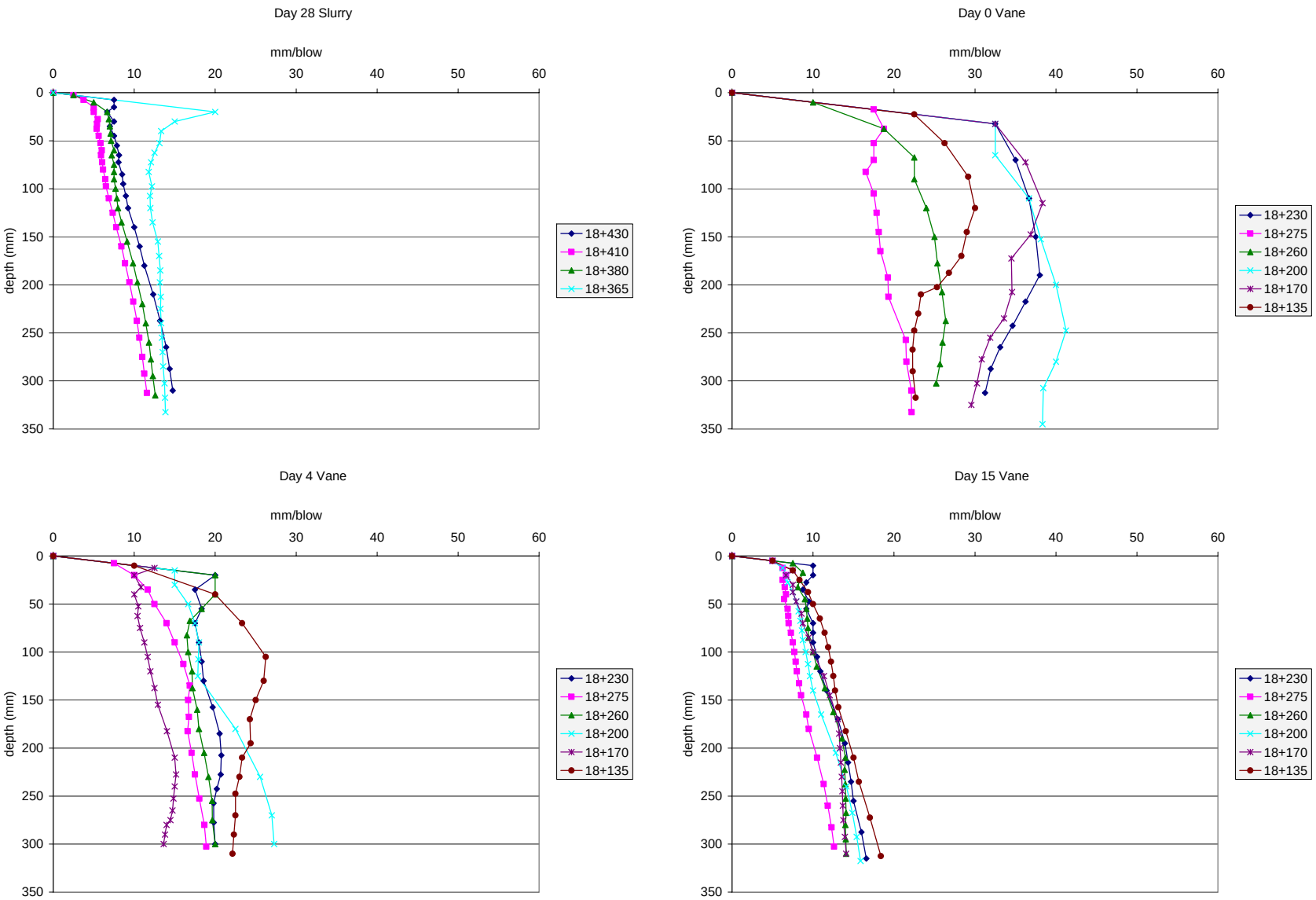
APPENDIX C

Paola North and South Plots of mm/blow vs. depth



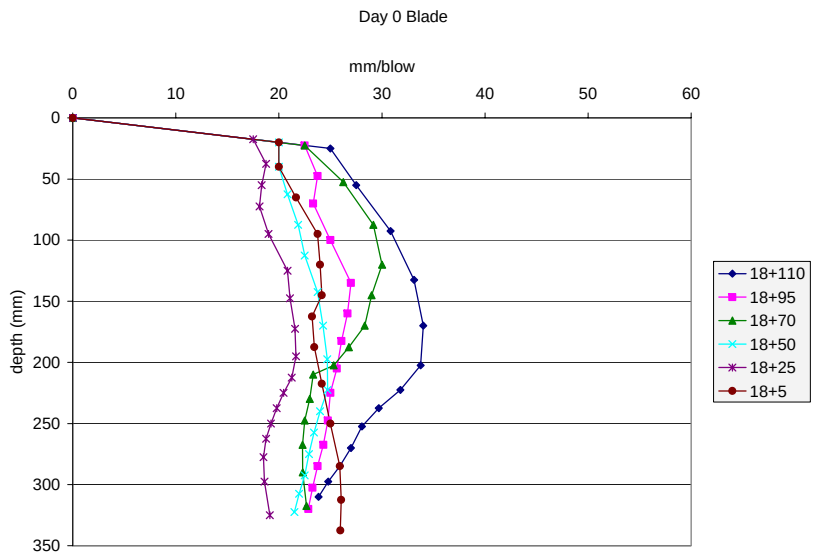
Paola North Plots of mm/blow vs. depth

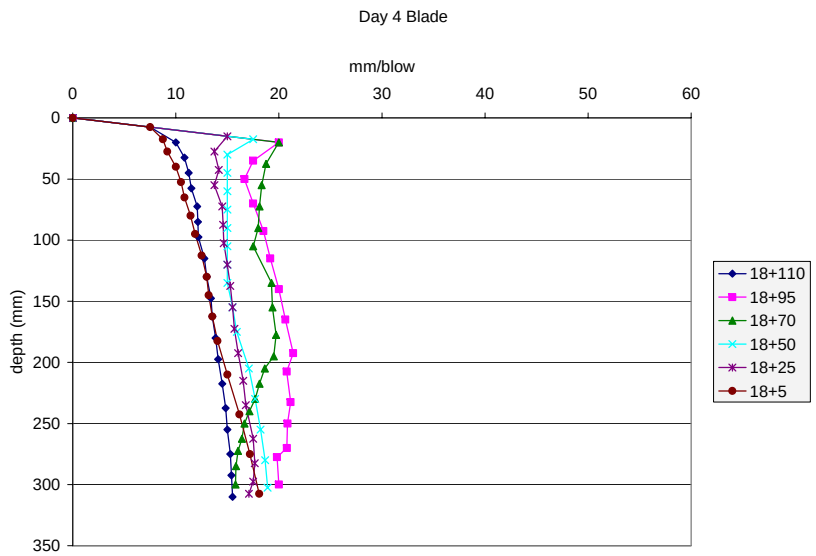
*Note: Smaller values represent a stronger subgrade

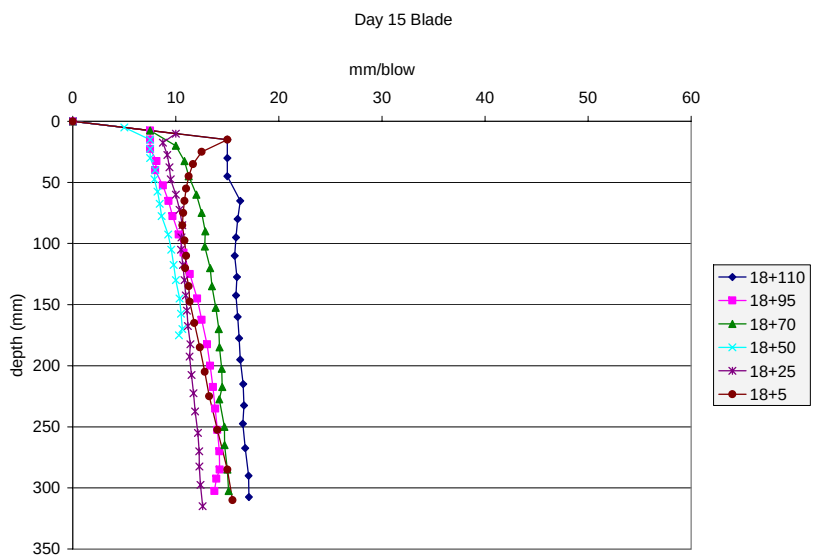


Paola North Plots of mm/blow vs. depth

*Note: Smaller values represent a stronger subgrade

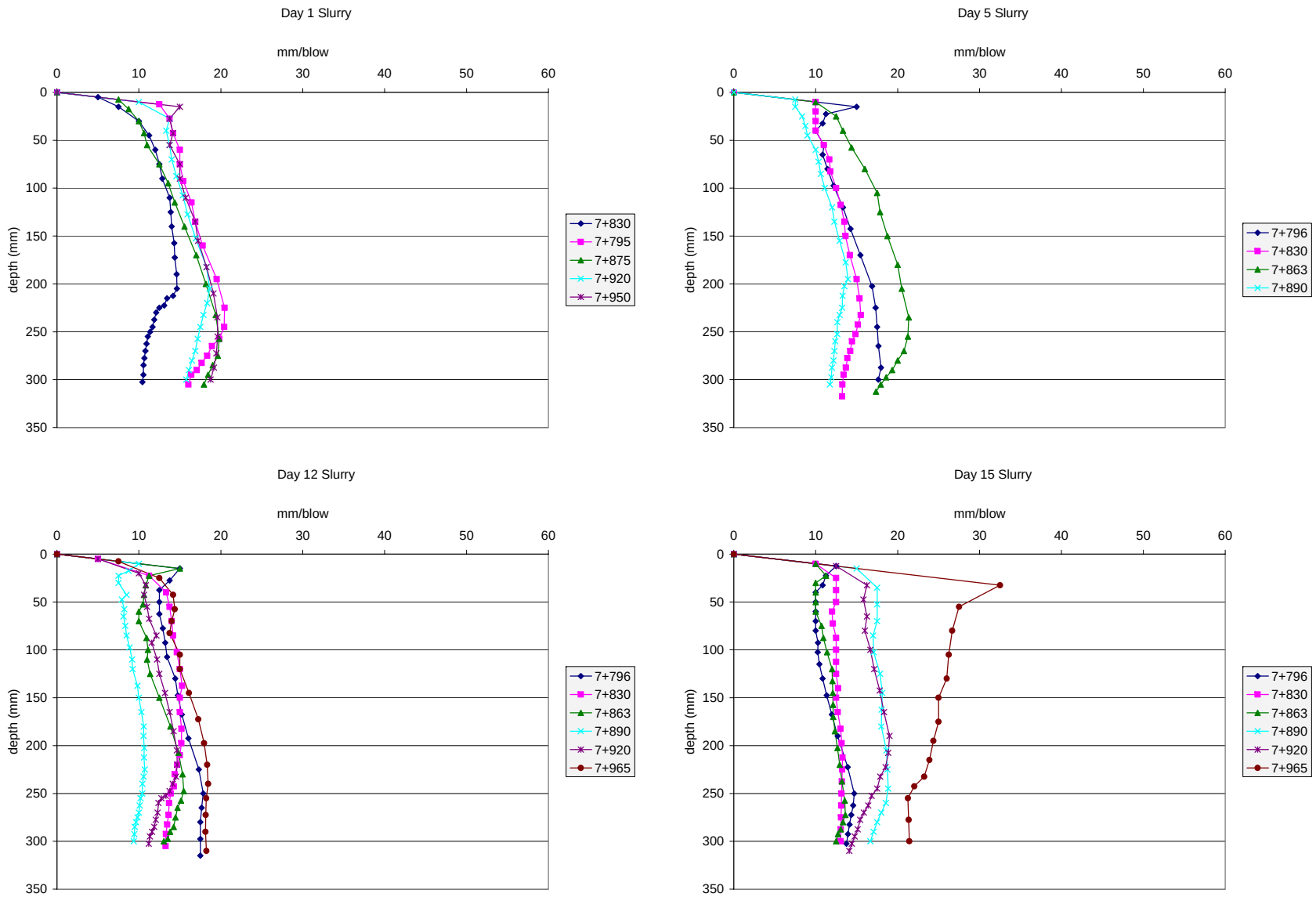






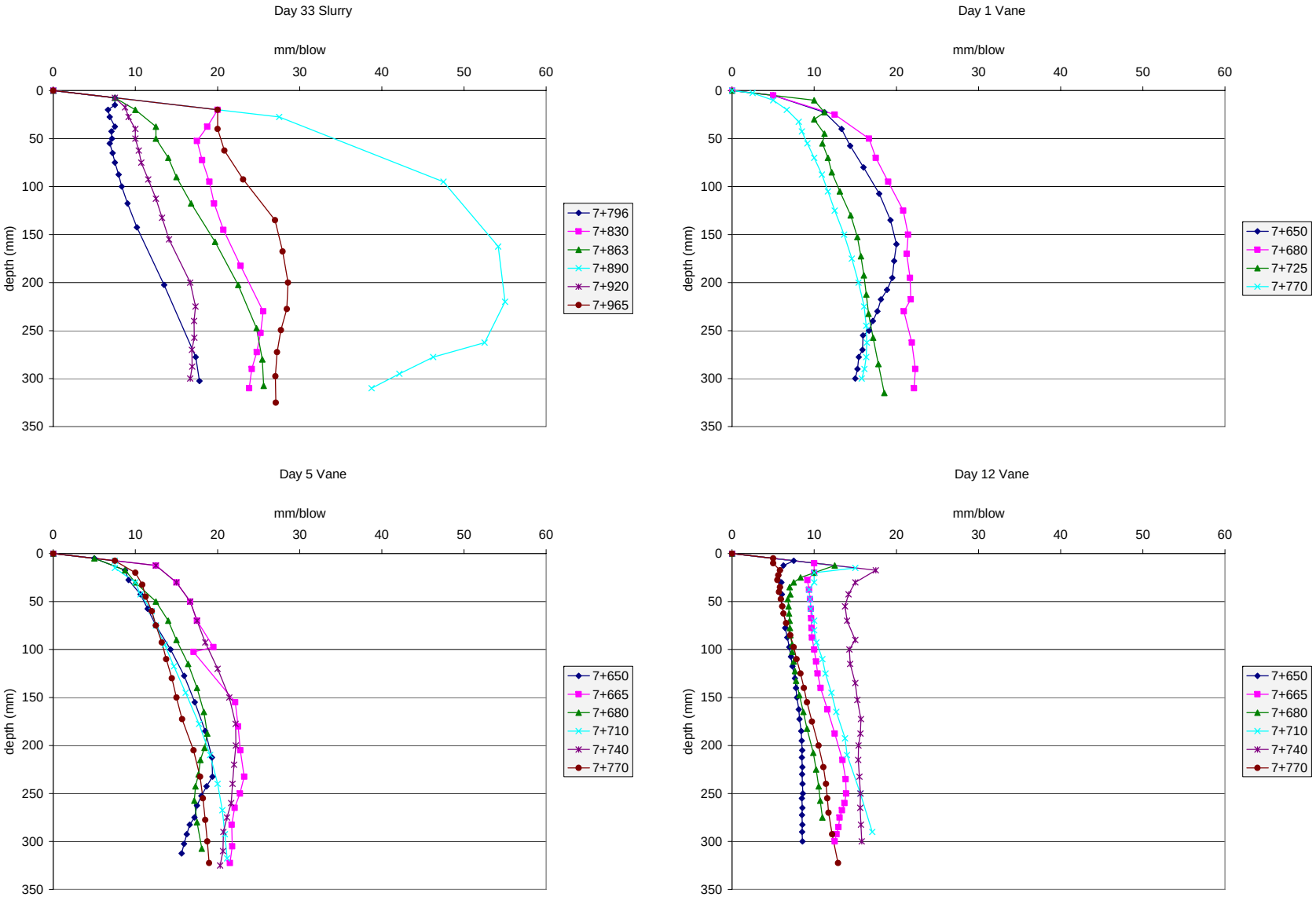
Paola North Plots of mm/blow vs. depth

*Note: Smaller values represent a stronger subgrade



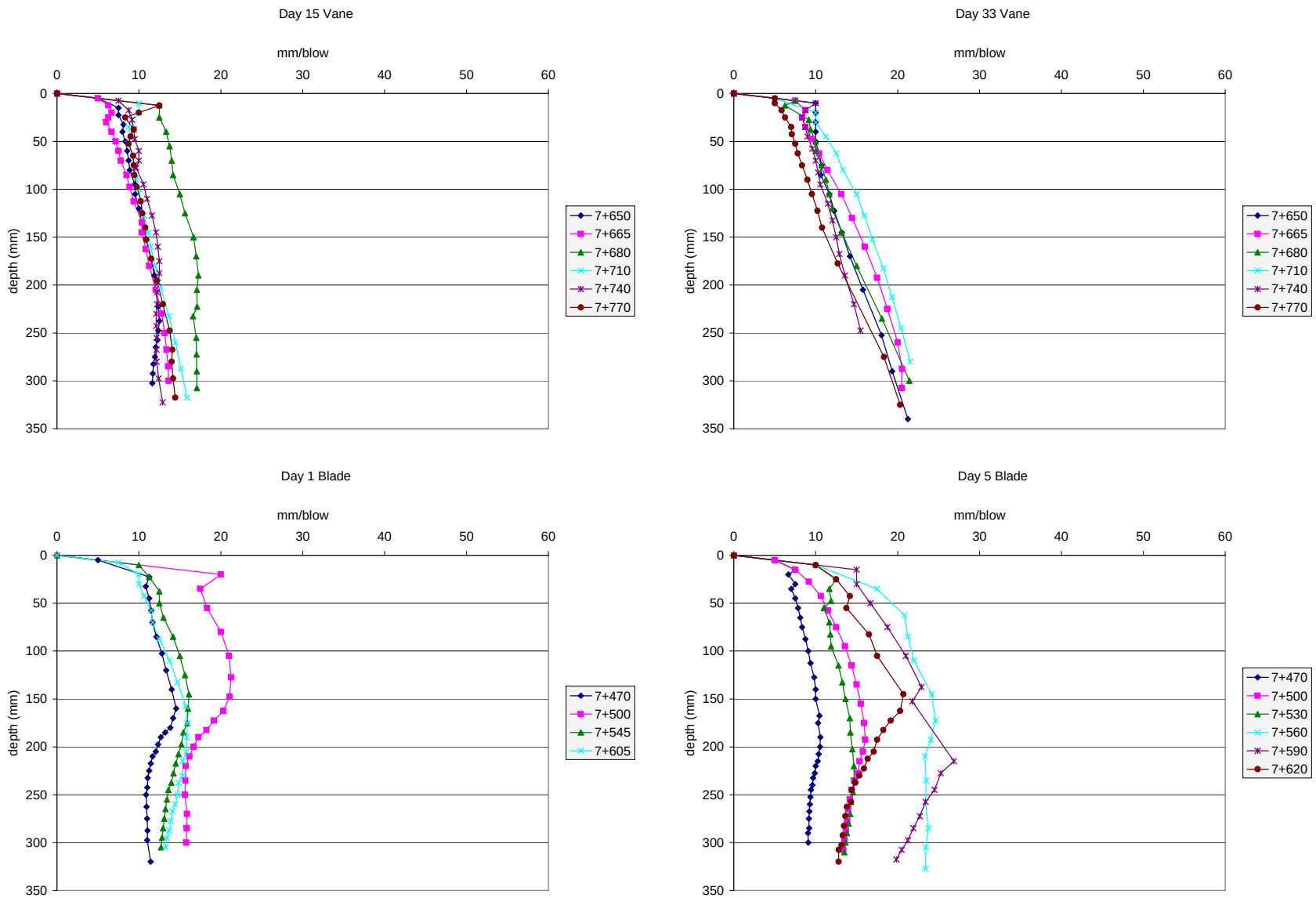
Paola South Plots of mm/blow vs. depth

*Note: Smaller values represent a stronger subgrade



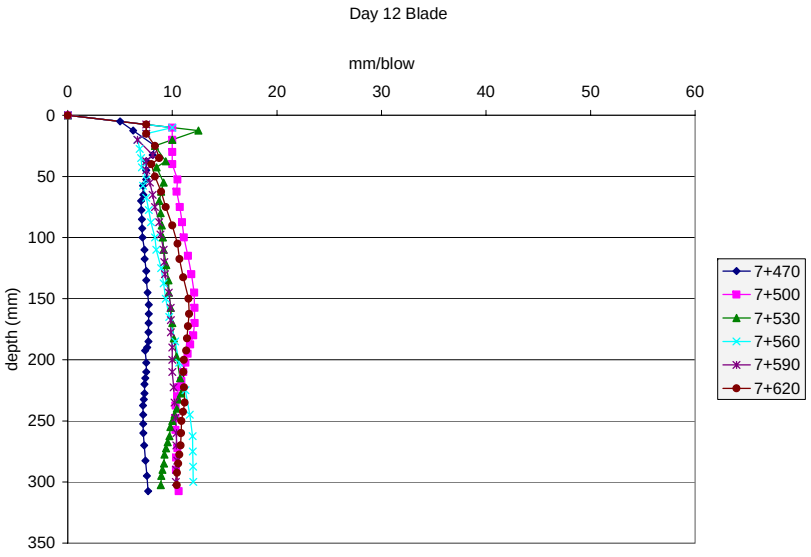
Paola South Plots of mm/blow vs. depth

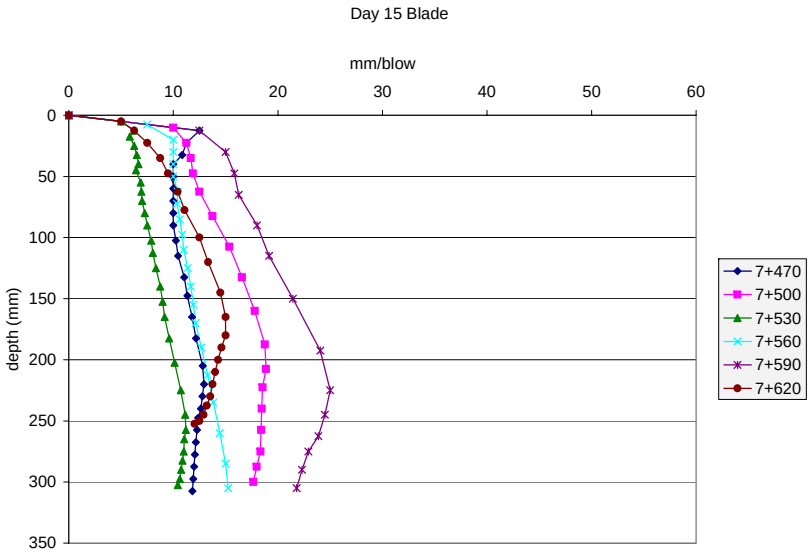
*Note: Smaller values represent a stronger subgrade

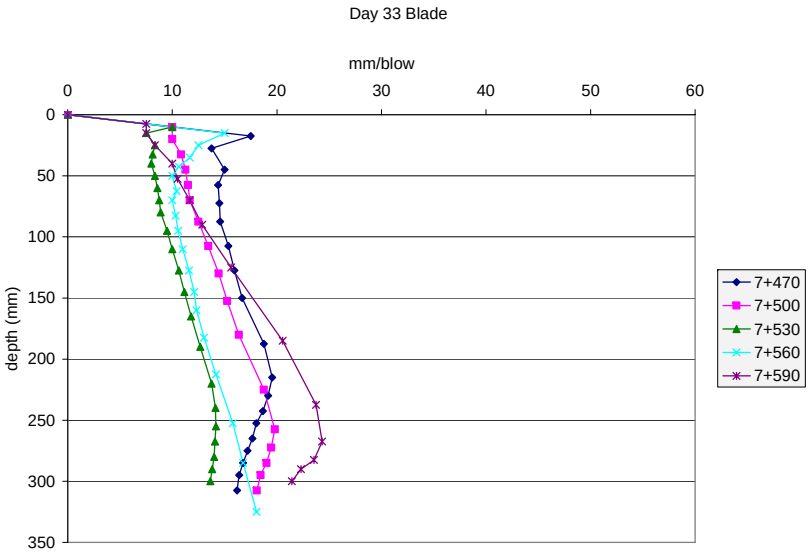


Paola South Plots of mm/blow vs. depth

*Note: Smaller values represent a stronger subgrade







Paola South Plots of mm/blow vs. depth

*Note: Smaller values represent a stronger subgrade

K - TRAN

KANSAS TRANSPORTATION RESEARCH
AND
NEW - DEVELOPMENTS PROGRAM

A COOPERATIVE TRANSPORTATION RESEARCH PROGRAM BETWEEN:

KANSAS DEPARTMENT OF TRANSPORTATION

THE UNIVERSITY OF KANSAS

KANSAS STATE UNIVERSITY