FINAL
CONTRACT REPORT

FACTORS AFFECTING STRENGTH GAIN IN LIME-CEMENT COLUMNS AND DEVELOPMENT OF A LABORATORY TESTING PROCEDURE

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16. Abstract

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Key findings from the research were that (1) drying and subsequent restoration of soil moisture prior to treatment can decrease the strength of the mixture, (2) the mixture strength decreases as the ratio of soil water content to cement content increases for 100 percent cement-soil mixtures, (3) the addition of lime can increase the mixture strength for some soils and decrease the strength for others, and (4) presenting the test results in the form of contour plots of unconfined compressive strength can be very useful. The reasons for the different results from the two private firms are explained by differences in the test procedures that were used.

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ABSTRACT

Lime-cement columns were constructed to improve soft ground as part of a test embankment program at the I-95/Route 1 interchange in Alexandria, Virginia. Two different commercial laboratories performed tests on treated soil, and they produced very different measurements of unconfined compressive strength. Further, both sets of results are different from test results available in the published literature for similar soils. This situation created uncertainties and a conservative design philosophy. The goals of this research project were to assess factors that influence strength gain of lime-cement-soil mixtures, to develop a detailed laboratory test procedure that produces consistent results, and to determine the reasons that the strengths measured by the private firms were so different. A suitable laboratory procedure was developed and applied to three soils: one from the I-95/Route 1 interchange site and two from the site of a potential future application of lime-cement columns in West Point, Virginia, at State Route 33.

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INTRODUCTION

The supporting capacity of very soft clay or silt can be improved with lime-cement columns, which is a soil stabilization technique that creates strong columns in the ground by dry mixing lime and cement with the in-situ clay. Lime-cement columns are used primarily to reduce settlement and improve the stability of embankments. This technology has been used for decades in Scandinavia, but it is a relatively unexploited procedure in the United States. The Virginia Department of Transportation (VDOT) recently undertook its first project utilizing this technology by installing lime-cement columns beneath a test embankment at the I-95/Route 1 interchange, just outside of Washington, D.C. This project is part of the peripheral ground improvement associated with reconstruction of the Woodrow Wilson Bridge and connecting highways. The bridge and adjoining highway are to be widened, requiring an additional 15 meters of lane width that will be provided by an adjoining embankment. The underlying soil conditions were considered feasible for implementation of lime-cement columns: a soft saturated clay with pockets and seams of high organic content. Both wet and dry mix columns were installed during the test program, and although wet mix columns were ultimately selected for this particular project, dry mix methods may be more economical in some circumstances, so there is interest in developing dry mix technology further. Two consulting firms were hired by VDOT to determine the strength gain of lime-cement-soil mixtures using laboratory testing procedures. The results from the two independent studies were very different, and thus questions arose concerning the laboratory procedures employed and the validity of the results. Virginia Tech was asked to study the laboratory procedures and results from the consulting firms and to conduct an independent investigation in order to gain a better understanding of the factors that influence strength gain in lime-cement columns.

PURPOSE AND SCOPE

The purpose of this research was to identify factors that influence the strength of lime-cement-soil mixtures, to develop a recommended test protocol for mix design testing, and to determine the reasons that the two private firms produced such different strength measurements. The scope of the research included the following activities:

- Literature pertaining to laboratory testing methods for lime-cement-soil mixtures was examined. Altogether, over 70 papers and 20 reports were collected, including final reports summarizing the laboratory tests for the I-95/Route 1 project performed by two private consulting firms. Experts in the field, including Mr. Mel Esrig, a geotechnical engineering consultant, and Dr. Magnus Ruin of Hercules Grundlaggningg, were interviewed to obtain their insights.

- A laboratory test procedure was developed for lime-cement-soil mixtures. This procedure was modeled after the procedure in the Swedish Geotechnical Society (SGS) Report 4:95E (Carlsten and Ekrstrom 1995), in which strengths are measured by unconfined compressive strength tests.

- Soils from two sites were studied: the I-95/Route 1 interchange site, at which lime-cement columns were installed beneath a test embankment, and Virginia State Route 33, which is another potential site for lime-cement column application. Soil from the I-95/Route 1 site was extensively tested. Once the I-95/Route 1 study was completed, the laboratory procedure was used to perform abbreviated studies of two soils from the State Route 33 site.

- The results of the laboratory test program were analyzed to identify important factors affecting the strength of lime-cement-soil mixtures using three Virginia soils, determine the reproducibility of the test results using the laboratory procedure that was developed, identify differences in the commercial laboratory test procedures that would explain the differences in measured strength, and assess the suitability of the recommended laboratory test procedure for lime-cement column mix design.

LITERATURE REVIEW

The literature review focused on important factors affecting the strength of lime-cement-soil mixtures and on laboratory procedures for preparing test specimens and measuring strength. The following topics are summarized here: properties of the base soil, soil storage and preparation prior to mixing, stabilizing agents, dose rates and proportions of stabilizer, mixing of the soil and stabilizer, sample production, curing, sample extraction, and strength testing.

Base Soil Properties

According to Ahnberg and Holm (1999), laboratory test results show that most fine-grained soils have the potential for improvement given the right combination of lime and cement. The influence of base soil properties is discussed in the following.

Soil Type

Laboratory test results indicate that clays, quick clays, and clayey silts are readily improved soils, while organic clays and peat are less likely to attain the same degree of improvement for a given amount of stabilizer (Ahnberg et al. 1994).

Particle Size Distribution

Lime-cement stabilization is generally implemented in deposits of predominantly fine-grained soils. After treatment, the particle size distribution is altered because larger particles are formed as a result of bonding of the smaller particles together to form friable silt and sand size particles.

Soil Chemistry

Strength gain in lime-cement-soil mixtures is due to chemical reactions that take place among the mixture constituents.

Cation Exchange

Cation exchange and flocculation of clay particles in the presence of lime and/or cement are responsible for immediate improvements in soil plasticity, workability, uncured strength, and load-deformation properties. The added binder produces free calcium (Ca^{++}) cations, which replace dissimilar adsorbed cations on the colloidal surface. Practically all fine-grained soils display rapid cation exchange and flocculation-agglomeration reactions when treated with lime and/or cement in the presence of water (Eades and Grim 1960).

Pozzolanic Reactions

Pozzolans are materials that react with water and calcium to produce a cementing effect. A pozzolan is defined in ASTM C340 as "a silicious or aluminous material, which in itself possesses little or no cementation value, but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties." Clays are pozzolans that provide silica as a result of mineralogical breakdown in a high pH environment. With the addition of lime, aluminous and silicious minerals in clay react with the lime to produce calcium silicates and aluminates that bond the particles together. Cement, however, provides its own pozzolans and therefore requires only a supply of water. Pozzolanic reactions are time and temperature dependent, with lime requiring more reaction time than cement. The development of ultimate cured strength for lime-treated soil is gradual and continues for several years (Eades and Grim 1960).

Carbonation

Carbonation is produced by a reaction of lime with carbon dioxide from the atmosphere and soil to form relatively insoluble calcium carbonate. This chemical reaction should be avoided prior to stabilization by proper handling of the lime and expedited construction procedures that prevent prolonged exposure of lime to air (Chou 1987). After mixing, a slow process of carbonation and formation of cementitious products can lead to long-term increases in strength (Arman and Munfakh 1970).

pH

When a significant quantity of lime is added to a soil, the pH of soil-lime mixtures is elevated to approximately 12.4, which is the pH of saturated limewater. This is a substantial pH increase for natural soils. The solubilities of silica and alumina are greatly increased at elevated pH levels, which can lead to an increase in pozzolanic reactions (Chou 1987). Eades and Grim (1960) suggested that the high pH causes silica from the clay minerals to dissolve and, in combination with Ca^{++}, to form calcium silicate. This reaction will continue as long as $Ca(OH)_2$ exists in the soil and there is available silica. Elias et al. (2001) suggest that the soil pH prior to lime treatment should be 5 or greater for lime treatment to produce sufficient strength gain.

Sulfates

When lime and/or cement are mixed with soil containing sulfates, the minerals ettringite and thaumasite may form (Maclean and Lewis 1963, Mitchell 1986, Hunter 1988). Formation of these minerals has been associated with expansion of the cured mixture, breaking of cementitious bonds, loss of strength, and heave of overlying pavements. According to Hunter (1988), lime-induced heave of compacted lime-soil mixtures is likely when the soluble sulfate concentration in the soil approaches 1% (10,000 mg sulfate per 1 kg of dry soil), at least 10% of the dry soil consists of clay minerals, and the lime-soil mixture is frequently saturated. If no sulfates are present, lime-induced heave will not occur. In other conditions, the potential for lime-induced heave can be difficult to predict.

Organics

Organic material can interfere with strength gain in soil stabilized with lime or cement (Maclean and Lewis 1963, Arman and Munfakh 1970). When lime and/or cement is added to an organic soil, some of the calcium ions satisfy the exchange capacity of the organic material and reduce the calcium ions available for pozzolanic reactions (Arman and Munfakh 1970). According to Ahnberg and Holm (1999), it is essential to use a large proportion of cement in combination with lime additive for clays with high organic content. Hebib and Farrell (2002) indicate that a general statement cannot be made regarding the appropriate binder or required amount of binder for organic soils, as the degree of improvement is very dependent on the particular organics involved. Five types of organic material occur in soils: carbohydrates; proteins; fats, resins, and waxes; hydrocarbons; and carbon (Mitchell 1993). Organic deposits are highly erratic, which further complicates stabilization of these materials.

Soils containing organics can be categorized based on the amount of organic material, which is determined by placing an oven-dried soil in a muffle furnace at 440° C until a constant mass of ash is achieved. The ash content is defined as 100% times the weight ratio of the ash to the total oven-dried soil. The organic content is 100% minus the ash content. ASTM D2974-87 designates soils with an ash content of 25% or less as peat and soils with an ash content above 25% as organic soils. Landva et al. (1983) recommend that soils with ash content less than 20% be classified as peats, 20% - 40% be classified as peaty organic soils, 40% - 95% be classified as organic soils, and 95% - 99% be classified as soils with organic content.

Two other classification systems sometimes used by engineers for organic soils are the von Post system and the Radforth system (Landva et al. 1983). The von Post system is oriented toward horticulture, agriculture, and forestry requirements; the Radforth system was developed for engineering use. An important difference between these methods is that the von Post method includes all organic soils that can support plant growth while the Radforth method strictly addresses peat, which is composed primarily of vegetable tissue in various stages of decomposition and having a fibrous to amorphous texture, a dark brown to black color, and an organic odor. Peat differs from organic soils due to its low specific gravity, low wet density, very high water content, and very high void ratio.

The degree of humification, or decomposition, can greatly affect strength development. Hampton and Edil (1998) state that as humification progresses, the soil's pH, mineral content, bulk density, and cation exchange capacity increase. Generally speaking, as humification increases, strength gain decreases. Pousette et al. (1999) found that peats from northern Sweden were detrimentally affected by a high degree of humification while those from southern Sweden were not. The degree of humification is classified by the von Post method.

Much of the variability of organic soils stems from the wide range of age and type of organics and differences in geologic source material. According to Landva et al. (1983), the effects of the origin of organic matter cannot be quantitatively analyzed, but must be studied on a case-by-case basis.

Organics can produce counteracting effects of lime and sulfates on the strength of soil-cement mixtures. Laguros and Davidson (1963) studied the impact of lime, sulfates, and other chemicals on the unconfined compressive strength of compacted soil-cement mixtures. For one organic soil referred to as Iowa silt, the addition of lime was detrimental to strength and the addition of sulfates produced an increase in strength. It was hypothesized that, because lime tends to increase the solubility of organics, they became more uniformly distributed throughout the soil-cement mixture, producing increased interference with strength development. Conversely, because sulfates tend to decrease the solubility of organics, the organics interfered less with strength development when sulfates were added to mixtures of cement and Iowa silt.

Moisture Content

After the addition of lime and/or cement, hydration begins by consuming water, which produces an increase in the undrained shear strength of the soil. As the natural moisture content increases past the optimum amount required for hydration, the ultimate cured strength decreases. Cement consumes 25 g of water per 100 g of cement while quicklime consumes 32 g of water per 100 g of CaO. Thus, the quantity of water required to hydrate portland cement is about 80% of that required to hydrate quicklime (Esrig 1999).

Miura et al. (2002) suggest that the prime factor governing the engineering behavior of cement-stabilized soil is the clay-water to cement ratio, w/c. This is defined as the ratio of the water content of the soil, w, to the cement content, c. The cement content is the ratio of cement to soil by dry weight. For the wet-mixing process, the additional water input to the mixture is included in the numerator of the w/c ratio. Thus, w/c is equal to the weight ratio of water to cement in the soil-cement mixture. As the *w/c* ratio increases, the strength of the mixture decreases. For Hong Kong clay, Miura et al. (2002) found that the 28-day unconfined compressive strength, q_u, could be related to the *w/c* ratio by $q_u = (2461 \text{ kPa})/1.22^{w/c}$.

Storage and Preparation Prior to Admixing

The following points apply to the storage and preparation of the soil samples prior to laboratory mixing with lime and cement:

- The Swedish Geotechnical Society (Carlsten and Ekstrom 1995) states that samples should be stored at a constant ambient temperature similar to that in-situ.

- Samples should be sealed in airtight containers that are free of excess air and stored at 100% humidity to prevent the samples from drying (Carlsten and Ekstrom 1995).

- Thorough soil mixing is required to obtain representative samples prior to admixing lime and cement. The mixer should be of an appropriate size to thoroughly and completely mix the bulk samples (den Haan 2000).

- Haley & Aldrich Inc. (2001) recommends a 16-hour waiting period after soil mixing but before the addition of stabilizers to allow for moisture equalization within the homogenized sample. If oxidation, aging, and/or aerobic reactions alter physical and chemical characteristics of the soil, it would be important to minimize exposure time by significantly reducing or eliminating the moisture equalization time period.

Stabilization Agents

Lime

Lime is produced from natural limestone. The particular type of lime formed depends on the parent material and the production process (Lambe 1962). The five basic types of lime include:

1. High-calcium quicklime, CaO
2. Dolomitic quicklime, $CaO + MgO$
3. Hydrated high-calcium lime, $Ca(OH)_2$
4. Normal hydrated dolomitic lime, $Ca(OH)_2 + MgO$
5. Pressure-hydrated dolomitic lime, $Ca(OH)_2 + Mg(OH)_2$

The most widely used and best performing limes in soil stabilization are the high-calcium quicklimes and hydrated (slaked) limes. Of these two, research has shown that quicklime usually produces a better stabilization effect. Quicklime generates higher curing temperatures and consumes more water than hydrated lime, which results in a higher and faster strength gain in the columns (Ahnberg et al. 1994).

Cement

Ahnberg et al. (1994) tested four types of portland cement as follows:

1. Standard cement
2. SH cement, more rapidly hardening cement
3. Anlaggnings cement, sulfate resistant cement
4. Klinker cement, cement without gypsum

Of these, the SH cement yielded the most rapid and highest strength gain, followed by the standard, Klinker, and Anlaggnings cements, successively. The soils that were studied ranged from clayey silt through different types of clay, organic clay, clayey gyttja, gyttja (a nutrient-rich sedimentary peat consisting mainly of plankton, other plant and animal residues, and mud), and peat. The soils were normally consolidated and soft, with undrained shear strengths of 5 to 30 kPa. When using cement in the additive, a more rapid and higher strength increase was obtained than when using lime alone.

Dosage Rates and Proportions of Stabilizer

Ahnberg et al. (1994) found that, for most soils, the mixture strength increased as the amount of added stabilizer increased. Their test results agreed with theoretical studies of chemical reactions, which indicated that the optimal proportion of quicklime would probably be 10% to 25% of the total stabilizer added. Eades and Grim (1966) found that, for 100% lime mixes, the optimum lime content for most soils is between 2% and 5% of the dry soil by weight. As one example of a mix design study, Ahnberg and Holm (1999) used the binder types and ratios listed in Table 1, with dosage rates ranging from 70 to 300 kg/m^3.

Table 1. Typical Binder Types and Proportions

Binder 1	Binder 2	Binder 3	Binder Ratio
Cement Std	Lime		80:20
Cement Std	Lime		50:50
Cement SH	Lime		50:50
Cement Std	Slag		50:50
Cement Std	Fly Ash		50:50
Cement Std	Fly Ash	Gypsum	40:40:20
Slag	Fly Ash	Gypsum	40:40:20
Cement Std	Slag	Gypsum	40:40:20
Cement Std	Slag	Silica Dust	45:45:10

Mixing of the Soil and Stabilizer in the Laboratory

Different soil types require different mixing devices to achieve homogeneity. Typical laboratory-scale mixing devices include ordinary kitchen mixers and dough mixers; however, specialized (and more expensive) equipment can be used to more closely imitate deep-mixing techniques used in the field.

According to den Haan (2000), mixing should continue until the soil is visually homogenous, which produces good reproducibility of test results. Most publications, however, recommend that a particular mixing time be set between 2 and 5 minutes and sustained throughout the test series. Pousette et al. (1999) suggest mixing time be limited to 5 minutes for peaty soils, due to the breakdown of fibers during prolonged mixing.

Sample Production

Samples must be placed into the molds no more than 30 minutes after mixing (den Haan 2000). If a large set of samples at a particular dosage is required, several batches should be prepared to minimize the time between mixing and placing the samples in the molds.

One of the most noticeable differences in the laboratory procedures that were reviewed is the required degree of compaction and the method of placement. First the soil/binder mix is placed into an appropriately sized mold in lifts approximately 1 inch thick. Each lift is compacted by hand using a rodding tool (URS 2001), by tapping against a hard surface (Haley & Aldrich 2001), or by using a 45-mm-diameter compaction tool (Carlsten et al. 1995). These methods can produce widely varying results, indicating that compaction is an important aspect of sample preparation and that standardization is necessary (den Haan 2000).

The most frequently required pressure is 100 kPa applied over a 45-mm-diameter compaction tool (Carlsten and Ekstrom 1995, den Haan 2000). Other packing methods have no specified pressure and simply require that the mixture be compacted sufficiently (URS 2001, Haley & Aldrich 2001).

Typical samples have a diameter of 50 to 75 mm, depending on how easily the soil can be homogenized. Difficult clay mixing and large organic fibers tend to make homogenizing the sample difficult, and larger samples are required in order to minimize the effect of discontinuities. Larger samples also reduce scatter in test results (Sehn 2001). Most lab procedures call for a height-diameter ratio of 2. Ahnberg and Holm (1999) found that as sample diameter increased, unconfined compressive strength decreased. Hampton and Edil (1998) found the opposite.

Curing Conditions

Curing Time

Esrig (1999) states that most strength gain occurs within the first 28 days after mixing, and strength continues to increase at a slower rate thereafter. Esrig's test results show that, when normalized by the 28-day strength, all binder mixtures produced essentially the same rate of strength gain.

Curing Temperature

As curing temperature increases, the rate of pozzolanic reactions also increases, resulting in an increased rate of strength gain. According to Ahnberg et al. (1989), lime-cement column curing reactions can produce temperatures ranging from about 10°C to 100°C or more, depending on ambient temperature, soil thermal conductivity, configuration and density of columns, stabilizer type and amount, etc. If the field temperature is not reproduced in the laboratory, very different rates of strength gain can result. Den Haan (2000) suggests that the samples should be insulated using polystyrene casings in order to achieve temperatures similar to those experienced in-situ. Due to the many variables affecting the curing temperature, proper curing temperature for site-specific samples is quite uncertain, resulting in variable laboratory test procedures, typically ranging from 20°C (room temperature) to 75°C. Curing temperatures less than 15°C retard reactions, while higher temperatures accelerate reactions in lime-soil mixtures (Chou 1987). Ahnberg et al. (1999) also found that excessively high curing temperatures degrade humic materials in highly organic soils, detrimentally affecting strength gain. Whatever curing temperature is used, the specimens should be properly spaced and fans or pumps should be used to ensure that all specimens cure at the same temperature (Sehn 2001).

Curing Humidity

Although humidity control is not standardized, den Haan (2000) recommends several methods for controlling humidity in the curing environment: curing samples in sealed, airtight tubes; curing underwater; or placing samples inside an insulating jacket. Hampton and Edil (1998) found that providing the samples access to water while applying a confining pressure during curing, which may imitate field conditions more accurately, reduces strength.

Confining Pressure

Confining pressure is sometimes applied to samples during curing in order to mimic overburden stresses. The effect of confining pressure is usually more dramatic in peat samples (Hebib and Farrell 2002). Pousette et al. (1999) found that for peat samples, increasing the load during curing time from 10 to 40 kPa increased strength by 85%. The density of the peat samples after consolidation increased significantly, indicating that higher load leads to more consolidation, a higher density, and a more stable sample.

Freeze/Thaw Cycles

Pousette et al. (1999) report that freeze/thaw cycles detrimentally affect strength for several types of peat with moisture contents in the range of 200%. In their investigation, stabilized peat samples exposed to eight freeze/thaw cycles (-10 C°/+20 C°) lost 30% of their strength compared to those that were not exposed.

Sample Extraction

Extraction of the sample from the mold is primarily a function of the mold type, variations of which include plastic tubes, cardboard molds, and plastic molds. The extraction method varies with each type, and no standardized procedure has been established. After extraction, the sample ends must be prepared such that they are smooth, flat surfaces perpendicular to the length of the sample. Trimming the ends of the samples might be necessary to produce correct and reproducible strength test results.

Load Testing

Ahnberg et al. (1994) noted that the unconfined compression test does not simulate surrounding soil conditions and applied stresses, and they reported that an increase in confining pressure produced an increase in the drained shear strength. After analyzing unconfined and triaxial test results, Ahnberg et al. (1994) concluded that triaxial tests were more suitable for simulating in-situ conditions. Unconfined tests are, however, still the most commonly used test type due to their ease and low cost.

The compression of ground improved with lime-cement columns under an axial load is governed by the stiffness, or modulus of elasticity, of the columns and of the base soil between the columns (Kivelo 1998). The modulus of elasticity of lime-cement columns has been investigated by unconfined compression tests, triaxial tests, and in-situ load tests. The trend of data compiled by Ekstrom (1994), as reported in Baker (2000), shows that the undrained secant modulus evaluated at one half the unconfined compressive strength, E_{50}, is about 75 times the unconfined compressive strength.

METHODS AND MATERIALS

This section summarizes the procedures and materials used in performing the investigation, including soil characterization methods, standard methods for preparing and testing lime-cement-soil specimens, and methods used for special investigations.

Soil Characterization

Moisture Content (ASTM D2216-98)

Small soil specimens obtained from large bulk samples were weighed as received, then oven-dried at 105° C for 24 hours and weighed again. The difference in weight is assumed to be the weight of the water driven off during drying. The difference in weight is divided by the weight of the dry soil, giving the water content on a dry weight basis. To expedite the testing program, moisture contents were often determined using the microwave drying method as described by Hagerty et al. (1990). Correlation studies between oven and microwave water contents are provided in Appendix C.

Particle Size Analysis (ASTM D422-63)

Fifty grams of dry soil were treated with a dispersing agent for 18 hours. A hydrometer analysis was then performed to measure the amount of silt and clay size particles. Next, the sample was washed through a series of sieves with progressively smaller screen sizes to determine the gradation of sand-sized particles in the specimens.

Atterberg Limits (ASTM D4318-98)

In order to quantify the plasticity of the soils, the liquid limit and plastic limit values were determined. The Atterberg limits device was used to determine the liquid limit, and the plastic limit was determined by rolling 3-mm-diameter threads of soil until they began to crack. Atterberg limits were used to classify the soils.

Classification (ASTM D2487-98 and ASTM D2488-93)

All soils were classified using the Unified Soil Classification System (USCS). The USCS designates a two-letter symbol to represent a particular soil type based on the particle size analysis and the Atterberg limits. There are two types of classification procedures: the visual-manual procedure and the more rigorous testing-based procedure. The visual-manual procedure is a means of identifying soil types quickly and easily in the field. The laboratory testing-based procedure was used in this research.

Organic Content (ASTM D2974-87)

The organic contents of these soils were determined by first oven drying a sample at 105°C for 24 hr and recording the moisture content. The sample was then placed in a muffle furnace, heated to 440°C, and when constant mass was achieved, the sample was weighed. Weight loss due to ignition divided by initial dry weight produces the ash content. The organic content is calculated as 1 minus the ash content.

Specific Gravity (ASTM D854-98)

Values of the specific gravity of the soil solids were determined by first weighing a 150-ml flask empty and then full of water. A known weight of oven-dried soil was placed in the flask, which was then filled and weighed again. The weight of water displaced by the soil can then be determined. The specific gravity can be calculated as the weight of dry soil divided by the weight of displaced water.

pH (ASTM D4972-95a)

Air-dried soil samples were adjusted to 100% water content by adding distilled water, and pH values were measured using a calibrated pH probe.

Sulfate Content (AASHTO T290-95)

The water-soluble sulfate content was determined by mixing oven-dried soil samples with a known amount of water, centrifuging the mixtures, measuring the sulfate ion concentration in the supernatant, and reporting the result in mg of sulfate per kg of dry soil.

Mineralogical Analysis

Mineralogical analysis consisted of x-ray diffraction (XRD) and thermal analysis on the clay fraction (<2 micrometers). Pretreatment of the whole sample for mineralogical analysis included removal of organic matter with 30% H_2O_2 buffered at a pH of 5 with 1 M NaOAc (Kunze, 1965). Sand was separated by retention on a #300 mesh wet sieve. The suspension passing through the sieve included the silt and clay fractions, which were separated by centrifugation and decantation using 1 M Na_2CO_3 (pH 9.5) as a dispersant. X-ray diffraction was used to determine clay-mineral suites present by analyzing oriented, magnesium-saturated, glycerol-solvated samples both with no heat treatment and after 4 hours of heating at 110°C. A similar analysis was performed on potassium-saturated samples both with no heat treatment and after heating for 4 hours at 110, 300, and 550°C. Samples were scanned at a fixed counting time of 4 seconds at 0.075° of 2θ per step using CuKα radiation (20 mA, 40 kV). Mineral quantities were estimated as integrated intensities of their respective x-ray diffraction peaks. Sub-samples of the potassium-saturated clay fractions were also analyzed by thermogravimetric (TGA) analyses. Samples were heated from 50 to 1000°C in a nitrogen atmosphere at a rate of 20°C per minute. Kaolinite and gibbsite quantities were verified by mass-equivalent calibration of weight loss using poorly crystalline Georgia kaolinite and Reynolds synthetic gibbsite as standards.

Standard Methods for Preparing and Testing Lime-Cement-Soil Mix Specimens

The basic format of the specimen-forming process was modeled after the procedure given by the Swedish Geotechnical Society (SGS) Report 4:95E (Carlsten and Ekstrom 1995). The following is a brief discussion of the procedures used for preparing and testing the lime-cement-soil specimens. For the complete step-by-step laboratory procedure, see Appendix A.

Pretreatment

Sample Care and Pre-treatment Storage Environment

I-95/Route 1 bulk samples were placed inside thick gauge plastic bags and into 5-gallon buckets. A vacuum was used to remove excess air from the plastic bags, and de-ionized water was poured into the space between the bucket and the plastic bag. Lids were then placed on the buckets. State Route 33 samples were delivered to Virginia Tech in Shelby tubes, where they were immediately extruded to minimize the potential for cation exchange between the soil and the tube. The samples were then cut into thirds, wrapped in a thin plastic film, and placed into plastic storage bags. All bulk samples were kept sealed and stored in a moist room that was kept at 100% relative humidity and at 20°C.

Initial Moisture Conditions

For the purposes of the I-95/Route 1 study, it was important to standardize test conditions, including the initial moisture, so that each variable could be studied independently. Since most of the data indicated that the in-situ water contents of each bulk sample was just under or right at the liquid limit, a small amount of water could be added to the batch sample after the homogenization process if necessary to raise the moisture content to 67%, which corresponded to a liquidity index (I_L) of about 1.0.

Obtaining a Representative Sample

For the I-95/Route 1 soil, approximately 500 g of wet soil was obtained from each of six bulk samples, totaling about 3000 g in all, and placed in the mixer. For the State Route 33 soil, equal amounts of soil were taken from four different Shelby tube samples, equaling about 3000 g as well. The conglomerate batch was mixed until a uniform consistency was achieved, but allowing no more than 5 minutes to elapse from the initiation of the mixing. The homogenization procedure was developed so that inherent soil characteristics would remain approximately constant from batch to batch throughout the research project.

Mixing of Soil & Stabilizer

Mixing Device

A 250-watt KitchenAid™ stand mixer with a 4-liter-capacity mixing bowl was used for mixing. This size mixer allowed production of eight specimens per batch so that two specimens could be tested for each of four curing times. The soil and the soil-stabilizer mix had a thick consistency, requiring use of a dough hook to sufficiently blend the soil and stabilizer together.

Mixing Procedure

Once the soil had been homogenized, the batch was weighed and two moisture samples were taken. In order to minimize exposure to air prior to stabilization, a microwave oven was used to expedite the time required to dry the moisture samples. After moisture contents were obtained, the amount of lime, cement, and water to add were calculated, as discussed in a later section. If necessary to achieve an initial desired water content, water was added and blended into the soil before the lime and cement were added. The appropriate amounts of lime and cement were then dry mixed together in a separate container and sprinkled over the soil in the mixer during the first minute of mixing. The mixer was set at the lowest speed (approximately 68 rpm for the outer spindle and 155 rpm for the inner spindle), and the soil and stabilizer were mixed for 5 minutes. At three evenly spaced times, the mixer was stopped and a spatula was used to scrape soil from the sides and bottom of the bowl, placing it back into the mix.

Dosage Rates

The dosage rate is the amount of stabilizer added to the soil. There are two methods of defining the dosage rate: kg of stabilizer per m^3 of *treatable* soil and kg of stabilizer per m^3 of *treated* soil. The prior method bases the amount of stabilizer on the volume of soil that is to be treated, and the latter method bases the amount of stabilizer on the volume of soil after treatment. Calculating stabilizer amounts based on treated soil is slightly more difficult and leads to a slightly larger amount of stabilizer to be added than does the other method for the same nominal dosage rate. For the purposes of this investigation, dosage rates were calculated based on kg of stabilizer per m^3 of *treatable* soil. In practice, typical dosage rates range from 80 to 150 kg/m^3, which corresponds to about 5% to 10% by weight of dry soil. In order to test the effects of different additives and proportions effectively, it was important that large dosages be tested. For this reason, the range of dosage rates studied extended above the normal range of dosage rates often used in practice. In all, four dosage rates were investigated: 100, 150, 200, and 250 kg stabilizer per m^3 treatable soil.

Proportions of Stabilizer Used

Four proportions of lime and cement were studied, ranging from 0:100 (lime:cement) to 100:0. The most predominantly tested proportions were 0:100 and 25:75, since that is the range of proportions at which most columns are mixed. Table 2 illustrates the combinations of dosage rates and proportions that were tested for each soil.

Table 2. Dosage Rates and Proportions Tested

Dosage Rate (kg/m^3)	Proportions of Stabilizer (L:C)			
	0:100	25:75	50:50	100:0
100	SR 33	I-95/Route 1	I-95/Route 1	
150	SR 33 I-95/Route 1	SR 33 I-95/Route 1	I-95/Route 1	
200	SR 33 I-95/Route 1	SR 33 I-95/Route 1	I-95/Route 1	I-95/Route 1
250	I-95/Route 1	I-95/Route 1	I-95/Route 1	

Specimen Forming Procedure

Using appropriately labeled, 50-mm-diameter and 100-mm-tall plastic molds, specimens were formed by filling the molds with 25-mm-thick lifts of the lime-cement-soil mixture. After each lift was placed in the mold, a 5-mm-diameter brass rod was used to rod the lift 25 times. Next, a 100 kPa pressure was applied to the top of the lift for approximately 10 seconds. The pressure was applied with a 48-mm-diameter aluminum piston. This process was repeated three more time until the mold was full. Using a spatula, the top of the specimen was then screeded level with the top of the mold, and a lid was placed on the mold. No more than 30 minutes were allowed to elapse between the end of mixing and the forming of specimens.

Curing

Curing Humidity

Curing humidity remained constant throughout the investigation, and in most cases, samples were taken to the moist room and allowed to cure at 100% humidity. In cases where the curing temperature was being studied, specimens were tightly sealed and submerged in a temperature-controlled water bath.

Curing Temperature

Because curing temperature affects strength gain, four curing temperatures were investigated: 5, 10, 20, and 40°C. The 20° C cure test was performed by placing the specimens in the moist room at 100% relative humidity as previously mentioned. The 5° C and 10° C cure tests were performed by submerging tightly sealed samples in a water bath and placing them inside a refrigerator regulated to the required temperature. The 40° C cure tests were performed by again submerging tightly sealed samples in a water bath and then placing a temperature-regulated heating element into the bath. In all the water bath setups, a small pump was submerged in the baths to provide circulation, and thus an evenly distributed temperature was provided from specimen to specimen as well as from the top of the bath to the bottom. With all curing conditions, specimens were placed approximately 3 inches apart to provide for uniform curing temperatures.

Curing Time

The curing times were 7, 14, 28, and 56 days. Each batch mix generated eight samples, allowing strengths to be measured in duplicate for each of the four curing times. If strength could not be tested on the particular day required, the cure time was simply recorded and graphed as such.

Sample Extraction Technique

A major concern during this part of the procedure was to prevent the specimen from undergoing detrimental stress prior to testing. After trying several techniques, the best method for sample extraction made use of an aluminum tube with a diameter slightly larger than the specimen mold, as shown in Figure 1. The specimen and surrounding mold were inserted into the tube, which had slots that ran the length of the mold. Using a carpet-cutting knife with the blade length adjusted to the thickness of the surrounding pipe and mold, incisions were made along the length of the mold. The extraction procedure was done in such a way that the blade did not cut into the specimen and did not apply pressure to the side of the specimen. Portions of the mold were then peeled back, allowing the mold to be removed from the specimen.

Figure 1. Cutting the Plastic Mold for Sample Extraction

Unconfined Compressive Strength Test (ASTM D2166-98a)

Unconfined compressive strength tests were performed on all specimens. Using a strain rate equal to 1% of initial specimen length per minute (equaling 1.0 mm/min), a data acquisition system was used to record the applied load and measured deflection. The test proceeded until failure occurred. The data were then loaded into a spreadsheet so that area corrections could be made and the unconfined compressive strength calculated. Failure was defined as the peak stress, which typically occurred at 2% to 8% strain.

Methods for Special Investigations

The standard methods for preparing lime-cement-soil mix specimens were modified to investigate additional variables. These methods were performed on the I-95/Route 1 soil only. The following conditions were varied in order to study their effects on specimen strength gain.

Drying Conditions

It was recognized early in the investigation that the drying of soil prior to stabilization with lime and cement might influence the degree of strength gain. Samples taken from the I-95/Route 1 site underwent a dramatic discoloration from gray to rust-brown upon drying. As discussed in the Results section, drying produced a decrease in pH and Atterberg limits. Since one of the consulting firms allowed the bulk samples to dry out prior to testing, it was important to investigate the effect this could have on strength gain. Three drying conditions were tested for pH, Atterberg limits, and strength gain: sealed, air dried, and oven dried. For the sealed condition, specimens were taken from the sealed bucket samples and immediately tested for pH as per ASTM D4972-95a, and Atterberg limit specimens were not allowed to dry as per ASTM D4318-98, but were tested immediately after removal from the stored environment. For the oven- and air-dried conditions, the moisture content was restored after drying and prior to running the pH and limits tests.

Initial pH Conditions

As discussed in the Results section, drying of the I-95/Route 1 soil decreased the soil's pH and Atterberg limits. In order to investigate the effect of these two reactions separately, the pH of two batch mixes, one air dried and one oven dried, was adjusted back to the pH of the original (sealed) condition using calcium hydroxide ($Ca(OH)_2$). A very small amount of $Ca(OH)_2$ was required to raise the pH to the target value. The strength of these batches was compared with dried batches whose pH was not adjusted.

Initial Moisture Conditions

The effects of variation in initial moisture were studied by adjusting two batches to initial water contents of 52% ($I_L = 0.5$) and 82% ($I_L = 1.5$). The latter case was achieved by simply adding water to reach 82%. The prior case, however, was more difficult. Due to the recognized effect of air exposure, the sample was not allowed to air dry. Instead, the soil batch was placed in a large consolidation device and allowed to consolidate until the moisture had dropped below 52%. This allowed the moisture to be reduced without allowing exposure to air to take place.

Lime Type

Two types of lime were studied: high calcium quicklime (CaO) and hydrated lime ($Ca(OH)_2$). Both were donated by Chemical Lime, a local lime manufacturing plant. Lime types were studied using a 200 kg/m^3 dosage rate at a lime-cement proportion of 50:50. For the characteristics of the lime used, refer to Appendix B.

Cement Type

Two common types of cement were used for comparison during the investigation: portland cement Type I/II and portland cement Type II. Both were purchased at a local hardware store. Type I cement is used for general purposes. A low alkali mix, Type I meets all requirements of ASTM C150-02a. Type II cement is used for moderate sulfate resistance and when a lower heat of hydration is required. Type I/II provides the basic performance characteristics of Type I while also offering Type II characteristics of moderate sulfate resistance and a lower heat of hydration (Kosmatka and Panerese 1994). Cement types were studied using a 200 kg/m^3 dosage rate at a lime-cement proportion of 25:75. For the characteristics of the cement used, refer to Appendix B.

RESULTS

This section presents the results of tests performed on samples obtained from two different sites: the I-95/Route 1 interchange site and the State Route 33 site in West Point, Virginia. For each site, the results of soil characterization tests are presented first, and the results of the unconfined compression tests performed on lime-cement-soil mixtures are presented second.

I-95/Route 1

This site, which is located adjacent to marshlands of the Potomac River, is underlain by soft to very soft, normally consolidated gray clay deposits. Organic contents vary from 1.8% to 46.4%, with an average of about 10.5%. In some areas, the clay was overlain by several feet of various types of fill material.

Soil Characterization

Soil characterization tests were performed on specimens from each of the six bucket samples, and the results are presented in Table 3. According to the USCS, the soils classify as organic silt (OH). It can be seen in Figure 2 and Table 3 that natural moisture contents are generally close to the values of the liquid limit, with the average value of natural moisture content being 65%, and the average value of liquid limit being 67. The organic content is about 6%, which is lower than the site average value of 10.5%, and the pH is about 6.6, indicating a nearly neutral condition. Essentially all the soils pass through the No. 200 sieve, and the percent finer than 2 μm is 36 to

39, according to hydrometer tests performed on two specimens. The activity, which is the plastic index divided by the percent finer than 2 μm, is 0.8 to 0.9 for these two specimens.

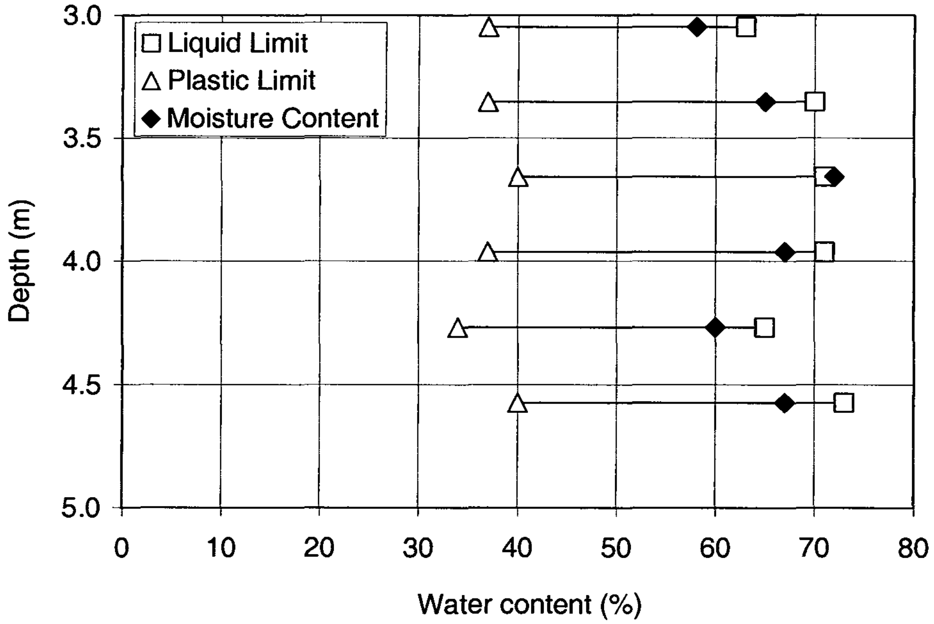

Figure 2. I-95/Route 1 Atterberg Limits and Moisture Content versus Depth

Table 3. Soil Characterization Test Results on Sealed Specimens for the I-95/Route 1 Soil

Nominal Depth (m)	Sample No.	pH	Moisture Content (%)	Atterberg Limits			< 2 μm (%)	Organic Content (%)	G_s
				LL	PL	PI			
3.0	1	6.5	58	63	37	26		7.1	2.65
3.4	2	6.7	65	70	37	33		6.3	
3.7	3	6.6	72	71	40	31	39	6.2	2.58
4.0	4	6.6	67	71	37	34		5.6	
4.3	5	6.6	60	65	34	31		5.9	2.71
4.6	6	6.8	67	73	40	33	36	5.5	

The measured sulfate content for the I-95/Route 1 soil is 730 mg/kg.

As shown in Table 4, the mineralogical analyses indicate that the clay fraction (<2μ) is dominated by montmorillonite, with some kaolinite, vermiculite, and mica present, and traces of quartz and chlorite. Carbon was analyzed with a carbon analyzer, and no significant difference was observed between an untreated sample and an acid washed sample, indicating that no carbonates are present. An estimate of organic matter can be obtained from the whole carbon of the acid treated sample by multiplying by 2, a conversion factor that relates the acid-treated carbon analysis to the organic content. The result is an estimated organic content of 6.6%, which is in good agreement with the results in Table 3.

Table 4. I-95/Route 1 Mineralogical Analysis Results

Carbon Analysis		Clay Fraction (< 2μ)					
Untreated (%)	Acid Treated (%)	Montmorillonite (%)	Vermiculite (%)	Mica (%)	Chlorite (%)	Kaolinite (%)	Quartz (%)
3.3	3.3	55	15	10	5	15	trace

As mentioned previously, the I-95/Route 1 soil changed color from dark gray to rust-brown upon exposure to air. In order to investigate whether drying affected soil properties, the values of pH and Atterberg Limits were determined for specimens subjected to three different degrees of drying: sealed condition, i.e., no drying; air drying; and oven drying. Table 5 provides the results, which show that, compared to the sealed condition, air drying produces a significant drop in pH and a slight drop in liquid limit and plastic index, and oven drying produces a further drop in pH and a very significant drop in liquid limit and plastic index. Thus, drying makes the soil more acidic and less plastic.

Table 5. Comparison of Atterberg Limits and pH for Three Exposure Conditions

Bulk Sample	Sealed Condition (pH = 6.6)			Air-Dried Condition (pH = 5.7)			Oven-Dried Condition (pH = 4.8)		
	LL	PL	PI	LL	PL	PI	LL	PL	PI
1	63	37	26	66	41	25	48	30	18
2	70	37	33	66	44	22	48	31	17
3	71	40	31	71	38	33			
4	71	37	34	65	37	28			
5	65	34	31	64	39	25			
6	73	40	33	65	40	25			
Average	69	38	31	66	40	26	48	31	18

Sample Identification System

Due to the large number of batch mix designs, the testing procedure was separated into phases and a system was developed to assign each batch mix with an identifying label. Table 6 illustrates the sample identification system used, conditions studied, and the way the investigation was divided into phases.

Table 6. Phased Investigation of I-95/Route 1 Soil

Phase	Variable	Range of Values Investigated
I	Lime Type	Quicklime, Hydrated Lime
II	Cement Type	Type **I/II**, Type **II**
III	Exposure Condition	Sealed, Air-Dried, Oven-Dried
IV	Stabilizer Amount and Proportion	**100, 150, 200, 250** kg/m^3
		0:100, 25:75, 50:50, 100:0 L:C ratio
V	Curing Temperature	**5, 10, 20, 40** °C
VI	Initial Moisture	**52, 67, 82** percent

The batch ID for a particular mix is labeled in the order shown above; for example, **Q-I/II-S-200-25:75-20-67** identifies the batch as having been prepared under the following conditions:

Q – **Q**uicklime used
I/II – Portland type **I/II** cement used
S – **S**ealed condition prior to treatment
200 – **200** kg of stabilizer per m^3 of treatable soil added
25:75 – **25**% of stabilizer is lime, **75**% of stabilizer is cement
20 – Cured at **20**° C temperature
67 – Moisture content adjusted to **67**% prior to mixing

Several of the identifiers in the batch IDs, such as curing temperature, initial moisture, and curing time, are nominal values. The actual values varied slightly from the nominal values.

Reproducibility Study

The first step in applying the laboratory procedure was to carry out a reproducibility study on the I-95/Route 1 soil. Eight specimens were created using the standard procedure, with the exception that all eight specimens were tested for 7-day strengths. The purpose was to study the variability in measured strength of several specimens that were prepared and cured in exactly the same way. Table 7 is the batch sheet, which is typical for all batches produced, for the reproducibility study. The average, standard deviation, and coefficient of variation of unconfined compressive strength can be seen at the bottom right-hand corner of the batch sheet. This reproducibility study produced a coefficient of variation of about 5%, which indicates a small variation in strength from specimen to specimen.

Strength Test Results for Lime-Cement-Soil Mixtures

Twenty-three batches were mixed using the I-95/Route 1 soil, each with a different mix design. Table 8 lists the strength test results. The first column is the batch number. The second column is the batch ID, identifying the conditions under which the batch mix was prepared. The third column shows the initial moisture content of the soil prior to adding the binder. The remaining columns provide the actual cure time, the peak unconfined compressive strengths, and the average strain at failure for each nominal cure time. These test results are discussed in detail in the Discussion section.

Clay-Water to Cement Ratio

Table 9 provides the 28-day strengths and the values of the clay-water to cement ratio (*w/c*) as defined by Miura et al. (2002) for the I-95/Route 1 soil for batches mixed with 100% cement.

Table 7. Reproducibility Test Results*

Batch Mix Sheet

Project	Lime Cement Column Study			Batch No.	1	Sample ID	Q-I/II-S-200-25:75-20-67
Location	I-95/Route 1 Interchange			Weight of Lime (g)	92.5	Lime Type	Quicklime
Job No.	437-737	Total Weight (g)	3605.0	Weight of cement (g)	277.6	Cement Type	I/II
Wet weight of soil, W_T (g)	2949.3	Gs	2.65	Weight of water (g)	0.0	Dosage Rate	200
Dry weight of soil, W_s (g)	1766	γ_T (pcf)	99.50	Soil Volume (ft^3)	0.0654	L:C Ratio	25 75
Mixer	Kitchen Aid Stand Mixer			Initial Moisture %	67	Exposure Condition	sealed
Conducted By	Jesse Jacobson			Mix Date	10/29/2001	Cure Temp (C°)	20
Research Professors	G. Filz & J. Mitchell			Applied Load (lb) & Pressure (psi)	45 14.3	Target Moisture %	67

Sample ID	Cure Time	Projected Test Date	Actual Test Date	Specimen wt after cure (g)	γ_{wet} (pcf)	Specimen Height (in)	Specimen Diameter (in)	Moisture after load test (%)	Peak q_u (psi)	Strain @ Failure, %
B1-A	7	11/5/2001	11/6/2001	334.0	101.60	3.98	2.00	53.58	16.26	5.32
B1-B	7	11/5/2001	11/6/2001	334.0	101.31	3.98	2.01	52.75	17.59	6.04
B1-C	7	11/5/2001	11/6/2001	333.0	101.18	3.96	2.01	51.12	16.80	5.60
B1-D	7	11/5/2001	11/6/2001	331.0	101.10	3.95	2.01	52.12	16.89	5.20
B1-E	7	11/5/2001	11/6/2001	337.0	102.41	3.97	2.01	51.12	17.24	5.63
B1-F	7	11/5/2001	11/6/2001	336.0	102.69	3.96	2.00	50.68	18.12	7.16
B1-G	7	11/5/2001	11/6/2001	337.0	102.50	3.97	2.00	50.16	17.33	5.98
B1-H	7	11/5/2001	11/6/2001	338.0	102.99	3.96	2.00	48.13	19.06	5.31
								Average	17.41	5.78
								Standard Deviation	0.87	0.64
								Coeff. of Variation	0.0498	0.1103

* Typical batch sheet used in the laboratory (note that data were collected and reported in both U.S. customary and SI units on this sheet).

Table 8. I-95/Route 1 Lime-Cement-Soil Mixture Test Program

Batch No.	Batch ID	Initial Moisture Content (%)	Nominal Curing Time (days)															
			7				14				28				56			
			Actual Cure Time (days)	Peak Strength (kPa)		Ave. Strain at Failure (%)	Actual Cure Time (days)	Peak Strength (kPa)		Ave. Strain at Failure (%)	Actual Cure Time (days)	Peak Strength (kPa)		Ave. Strain at Failure (%)	Actual Cure Time (days)	Peak Strength (kPa)		Ave. Strain at Failure (%)
1	Q-I/II-S-200-25:75-20-67	67	7	120		5.8	-	-		-	-	-		-	-	-		-
4	Q-I/II-S-200-50:50-20-67	67	7	98	114	7.6	14	140	135	7.5	28	144	132	4.5	63	281	292	3.5
5	H-I/II-S-200-50:50-20-67	66	7	115	91	5.7	14	142	145	5.1	29	179	198	4.6	62	171	-	2.8
6	Q-I/II-S-200-25:75-20-67	68	7	150	132	5.1	14	203	185	5.2	28	288	305	4.5	64	416	412	3.1
7	Q-II-S-200-25:75-20-67	67	7	156	135	5.8	14	205	213	4.2	28	223	257	3.5	60	329	325	3.2
8	Q-I/II-A-200-25:75-20-67	67	10	121	140	3.6	12	100	-	3.1	28	130	184	2.9	56	505	-	2.8
9	Q-I/II-O-200-25:75-20-67	69	6	52	47	8.9	14	45	47	6.4	28	69	-	7.8	55	157	176	4.0
12	Q-I/II-S-100-25:75-20-67	67	7	74	69	7.7	28	79	79	7.3	28	74	71	7.3	56	81	72	7.7
13	Q-I/II-S-100-50:50-20-67	69	7	57	-	9.2	9	67	66	11.0	28	68	72	12.0	54	75	78	9.0
16	Q-I/II-S-150-0:100-20-67	67	9	318	316	3.4	14	350	358	3.1	28	432	407	2.7	54	430	525	2.1
18	Q-I/II-S-150-25:75-20-67	67	7	83	87	7.7	14	88	88	7.0	29	129	115	6.2	56	174	-	4.9
19	Q-I/II-S-150-50:50-20-67	67	7	70	131	9.2	14	94	103	10.8	29	94	105	9.0	57	123	-	7.4
22	Q-I/II-S-200-0:100-20-67	75	7	573	598	1.9	14	821	-	1.9	28	864	1046	1.6	56	1075	1075	1.4
25	Q-I/II-S-200-100:0-20-67	70	8	190	-	6.6	14	232	227	7.7	28	234	236	4.2	56	279	-	3.7
26	Q-I/II-S-250-0:100-20-67	69	7	556	453	2.2	21	1075	1064	1.6	39	1070	862	1.7	56	1076	1071	1.6
28	Q-I/II-S-250-25:75-20-67	67	7	114	119	5.8	14	214	113	5.5	27	427	381	3.1	55	682	686	2.1
29	Q-I/II-S-250-50:50-20-67	67	7	141	141	7.6	15	169	168	6.1	38	354	354	4.8	56	395	344	3.3
32	Q-I/II-S-200-25:75-5-67	68	7	122	137	4.0	14	212	239	3.3	28	309	318	2.8	59	276	403	2.6
33	Q-I/II-S-200-25:75-40-67	67	7	59	81	5.9	14	94	68	5.7	30	798	778	1.6	52	1075	1068	1.8
34	Q-I/II-S-200-25:75-20-52	57	7	245	254	4.0	14	338	-	3.0	28	354	352	2.4	55	612	-	3.1
35	Q-I/II-S-200-25:75-20-82	68	7	39	45	8.5	14	48	57	6.9	28	154	152	4.1	54	254	222	3.1
36	Q-I/II-S-200-25:75-10-67	68	7	121	125	6.1	13	131	138	5.2	27	158	203	4.7	48	167	226	4.0
37	Q-I/II-A*-200-25:75-20-67	67	7	55	50	6.4	14	59	45	6.4	28	65	63	7.5	-	-	-	-
38	Q-I/II-O*-200-25:75-20-67	69	6	59	53	6.9	13	65	68	8.2	25	96	104	6.8	-	-	-	-

Table 9. Clay-Water Cement Ratio and 28-Day Strengths for I-95/Route 1

Batch No.	Dose Rate (kg/m^3)	Dry Weight of Soil (g)	Cement Added (g)	Initial Moisture (%)	Amount of Water (g)	*w/c* Ratio	28-Day q_u Strength (kPa)
26	250	1568	419	67	1051	2.51	965
22	200	1356	306	75	1017	3.33	938
16	150	1538	242	67	1030	4.26	414

Secant Modulus of Elasticity

The secant modulus of elasticity was calculated by determining the unconfined compressive strength, q_u, of a specimen from the stress-strain plot of a lime-cement-soil mix specimen, dividing it by 2, and drawing a straight line from the origin to the stress-strain curve at $q_u/2$. The slope of this line is the secant modulus, E_{50}, which is a measure of stiffness. Table 10 provides the 28-day secant modulus results for four batches. The results show that lime greatly decreases the mixture stiffness.

Table 10. 28-Day Secant Modulus Results for I-95/Route 1

Batch No.	Dose Rate (kg/m^3)	Proportion (L:C)	E_{50} (MPa)
16	150	0:100	29.2
18	150	25:75	3.7
22	200	0:100	74.9
6	200	25:75	11.5

State Route 33

The State Route 33 project is located in West Point, Virginia, where the Pamunkey River and Mattaponi River run together to form the York River. The subsurface profile consists primarily of marsh deposits of soft, organic clays, with moisture contents ranging from 15% to 200% and organic contents from 0% to 40%. The soft clay deposit is overlain by a varying amount of fill material and underlain by 3 to 6 m of loose to firm sand, which is underlain by moderately stiff silty clay.

Soil Characterization Test Results

Soil characterization tests were performed on specimens taken from Shelby tube samples. Moisture contents and organic contents were measured immediately after the samples were extruded from the tubes. Figure 3 illustrates the results of moisture content and organic content determinations with depth. The State Route 33 soils did not exhibit discoloration after being exposed to air.

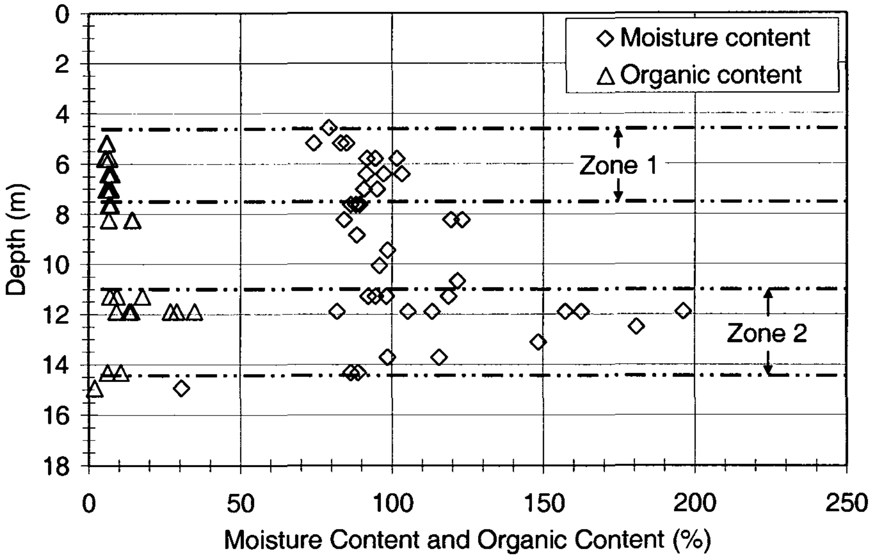

Figure 3. Moisture Content and Organic Content with Depth for State Route 33

For depths ranging from 4.5 to 7.5 m, the moisture and organic contents remain at fairly constant values of about 92% and 7%, respectively. In the zone from 11.0 to 14.5 m in depth, however, both water content and organic content vary greatly, averaging much higher values of 120% and 15%, respectively. For this reason, the State Route 33 soil was separated into two zones: Zone 1, a more uniform and better zone, and Zone 2, a more variable and worse zone. These were treated as two separate soil types throughout the investigation, each having its own index tests and batch mix tests performed independently.

According to the USCS, Zone 1 soils classify as organic silt (OH). It can be seen in Table 11 that natural moisture contents have an average value of about 92%, with the average value of plasticity index being 57. The organic content is about 7% and the pH is about 4.8, indicating a very acidic condition. Essentially all the soils pass through the No. 200 sieve, and the percent finer than 2 µm is about 65, according to the hydrometer tests performed. The activity is about 0.9.

According to the USCS, Zone 2 soils classify as organic silt (OH). It can be seen in Table 11 that natural moisture contents have an average value of about 120%, with the average value of plastic index being about 80. The organic content is about 15% and the pH is about 3.7, indicating a very acidic condition. Essentially all the soils pass through the No. 200 sieve, and the percent finer than 2 µm is about 52, according to the hydrometer tests performed. The activity is about 1.5.

Table 11. State Route 33 Soil Characterization Test Results

Zone	USC	pH	Ave. w (%)	Ave. Organic Content (%)	LL	PL	PI	<2µ (%)
1	OH	4.8	92	7	109	52	57	65
2	OH	3.7	120	15	209	129	80	52

The measured sulfate content was 10400 mg sulfate per kg of dry soil from Zone 1 and 10000 mg sulfate per kg of dry soil from Zone 2.

As shown in Table 12, the mineralogical analysis showed that the clay fraction (<2μ) was dominated by montmorillonite, with some kaolinite, vermiculite, and mica present, and traces of quartz and chlorite. A semi-quantitative analysis is provided based on peak area ratios of known minerals and weight loss after heating from 100 to 1000°C. Carbon was also analyzed with a carbon analyzer, and no significant difference was observed in Zone 1 between an untreated sample and an acid-washed sample, indicating no carbonates were present. In Zone 2, there was a 1% difference. The results of the mineralogical analysis are shown in Table 12. An estimate of organic matter can be obtained from the whole carbon of the acid-treated sample by using a conversion factor of about 2. The results are an estimated organic content of 5.2% in Zone 1 and 13.6% in Zone 2, which are in reasonably good agreement with the results in Table 11.

Table 12. State Route 33 Mineralogical Analysis Results

Zone	Carbon Analysis		Clay Fraction (< 2 μm)					
	Untreated (%)	Acid Treated (%)	Montmorillonite (%)	Vermiculite (%)	Mica (%)	Chlorite (%)	Kaolinite (%)	Quartz (%)
1	2.7	2.6	55	15	10	-	20	trace
2	7.8	6.8	60	3	15	2	20	trace

Strength Test Results for Lime-Cement-Soil Mixtures

A much smaller investigation was carried out on the soil from State Route 33 than from the I-95/Route 1 soil, totaling 10 batches in all. Five batch mixes were prepared using Zone 1 soil, and five identical mix designs were completed using Zone 2 material. Table 13 provides the test results in the same format as for I-95/Route 1 (Table 8). In the State Route 33 study, no attempt to normalize soil characteristics was made: initial moistures and pH were not adjusted prior to treatment. Only dosage rates and proportions were studied in this abbreviated investigation.

Modulus of Elasticity

The modulus of elasticity was calculated using the method described for the I-95/Route 1 soil. Table 14 provides the 28-day secant modulus results for eight batches, four from Zone 1 and four from Zone 2. As shown, lime had essentially no impact on stiffness, which is quite different from the response of the I-95/Route 1 soil.

Table 13. State Route 33 Lime-Cement-Soil Mixture Test Program

Zone	Batch No.	Batch ID	Initial Moisture Content (%)	Nominal Curing Time (days)															
				7				14				28				56			
				Actual Cure Time (days)	Peak Strength (kPa)		Ave. Strain at Failure (%)	Actual Cure Time (days)	Peak Strength (kPa)		Ave. Strain at Failure (%)	Actual Cure Time (days)	Peak Strength (kPa)		Ave. Strain at Failure (%)	Actual Cure Time (days)	Peak Strength (kPa)		Ave. Strain at Failure (%)
1	1	Q-I/II-S-100-0:100-20-NM	91	7	358	305	2.2	14	434	480	1.4	28	385.33	401.88	1.9	56	546.63	0	1.7
	5	Q-I/II-S-150-0:100-20-NM	95	7	380	565	2.2	14	592	620	1.4	28	730	709	1.5	54	698	499	1.7
	6	Q-I/II-S-150-25:75-20-NM	96	7	473	414	2.0	14	554	489	1.9	28	488	772	1.8	54	610	491	1.4
	9	Q-I/II-S-200-0:100-20-NM	86	7	598	556	2.0	14	675	539	1.9	28	784	1072	1.8	54	1073	566	2.0
	10	Q-I/II-S-200-25:75-20-NM	86	7	453	549	2.0	14	669	635	2.0	28	695	665	1.6	56	1068	959	1.7
2	17	Q-I/II-S-100-0:100-20-NM	150	7	226	215	3.2	14	241	192	2.8	28	225	300	2.8	56	246	196	2.5
	21	Q-I/II-S-150-0:100-20-NM	150	7	276	416	2.7	14	284	487	2.4	28	433	586	2.8	56	540	369	2.1
	22	Q-I/II-S-150-25:75-20-NM	120	7	403	403	2.9	14	420	469	2.8	28	398	-	2.8	56	496	517	2.6
	25	Q-I/II-S-200-0:100-20-NM	138	7	558	423	2.8	14	602	604	2.7	27	615	769	2.6	55	726	543	2.5
	26	Q-I/II-S-200-25:75-20-NM	120	7	520	472	2.8	14	514	547	2.7	26	480	558	2.6	54	558	449	2.5

NM = Natural Moisture Content

Table 14. 28-Day Secant Modulus Results for State Route 33

	Batch No.	Dose Rate (kg/m^3)	Proportion (L:C)	E_{50} (MPa)
SR 33 Zone 1	5	150	0:100	44.1
	6	150	25:75	43.6
	9	200	0:100	37.6
	10	200	25:75	50.2
SR 33 Zone 2	21	150	0:100	29.4
	22	150	25:75	28.5
	25	200	0:100	30.5
	26	200	25:75	27.3

Clay-Water/Cement Ratio

Tables 15 and 16 provide the 28-day strengths and the values of the clay-water to cement ratio (*w/c*) as defined by Miura et al. (2002) for the State Route 33 Zone 1 and Zone 2 soils for batches mixed with 100% cement.

Table 15. Clay-Water Cement Ratio and 28-Day Strengths for State Route 33 Zone 1

Batch No.	Dose Rate (kg/m^3)	Dry Weight of Soil (g)	Cement Added (g)	Initial Moisture (%)	Amount of Water (g)	*w/c* Ratio	28-Day Strength (kPa)
1	100	1273	164	91	1158	7.06	450
5	150	1232	246	95	1170	4.77	625
9	200	1266	314	86	1089	3.47	790

Table 16. Clay-Water Cement Ratio and 28-Day Strengths for State Route 33 Zone 2

Batch No.	Dose Rate (kg/m^3)	Dry Weight of Soil (g)	Cement Added (g)	Initial Moisture (%)	Amount of Water (g)	*w/c* Ratio	28-Day Strength (kPa)
17	100	935	176	150	1403	7.99	250
21	150	1011	285	150	1517	5.32	450
25	200	1014	357	138	1399	3.92	640

DISCUSSION

The test program for the I-95/Route 1 soil included investigation of the influence of several variables on mixture strength, including lime type, cement type, soil exposure condition, dose rate, lime-cement ratio, curing temperature, and initial water content. The test program for State Route 33 included only investigation of dose rate and lime-cement ratio. The test results are discussed using plots of unconfined compressive strength versus curing time. To facilitate comparisons between plots, the strength scales generally span from 0 to 1200 kPa, and the time scales generally span from 0 to 70 days. In most cases, two specimens were tested at each cure time, and both results are plotted on the graphs. For each test condition, a logarithmic trend line of the form $q_u = q_{u\,0} + a \ln (t - t_0)$ was fitted to the data where q_u= the unconfined compressive strength; t = time; and $q_{u\,0}$, a, and t_0 are coefficients obtained by least-squares regression. Logarithmic trend lines provide a good fit to the cure time vs. unconfined compressive strength data from this research, and they are in good agreement with the normalized relationship described by Esrig (1999). Batch identifications, as described in the Methods section, are provided in the title below each plot. The letter X in these batch identifications indicates the variable being compared in the plot, while other variable values are held constant. For example, Q-I/II-S-X-25:75-25-67 indicates a comparison of batches for which the dose rate varied, but for which all batches were mixed with quicklime, type I/II cement, a sealed soil exposure condition, 25:75 lime-cement ratio, a curing temperature of 25°C, and an initial water content of 67%.

I-95/Route 1

Lime Type

Figure 4 illustrates the strength gain with time for quicklime and hydrated lime. No appreciable distinction in strength gain was observed. It was expected that quicklime would produce faster cure times and higher strengths due to its higher heat of hydration and its ability to consume more water, but this behavior was not observed. In the field, the effect of higher heat of hydration may be more significant due to the large diameter of the columns.

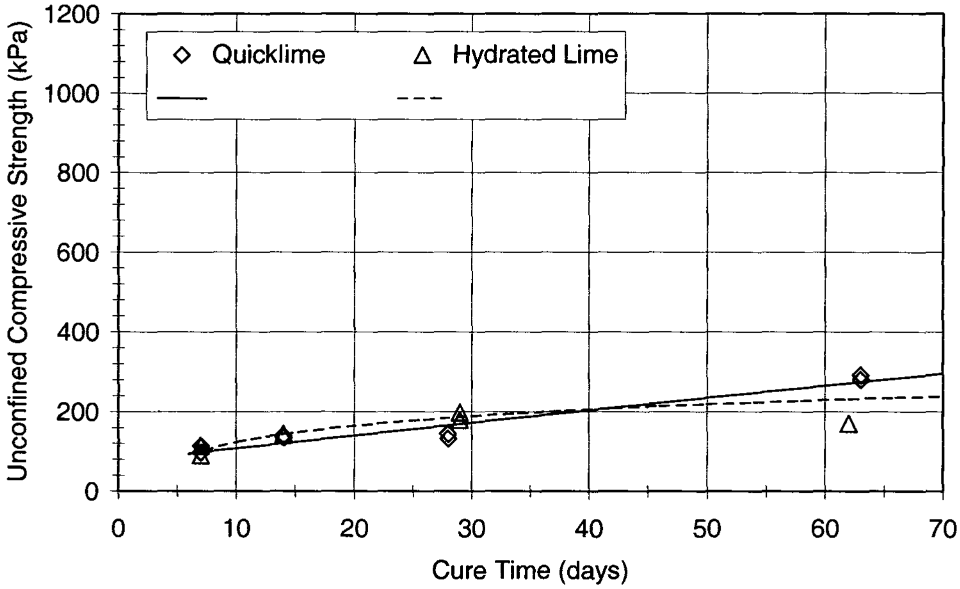

Figure 4. Quicklime vs. Hydrated Lime (X-S-200-50:50-20-67)

Cement Type

Figure 5 illustrates strength gain with time for portland cement Type I/II and Type II. It appears that Type I/II produces slightly higher strength than does Type II, although the difference is small. Type I/II generates a slightly higher and more rapid heat of hydration (Kosmatka and Panarese 1994).

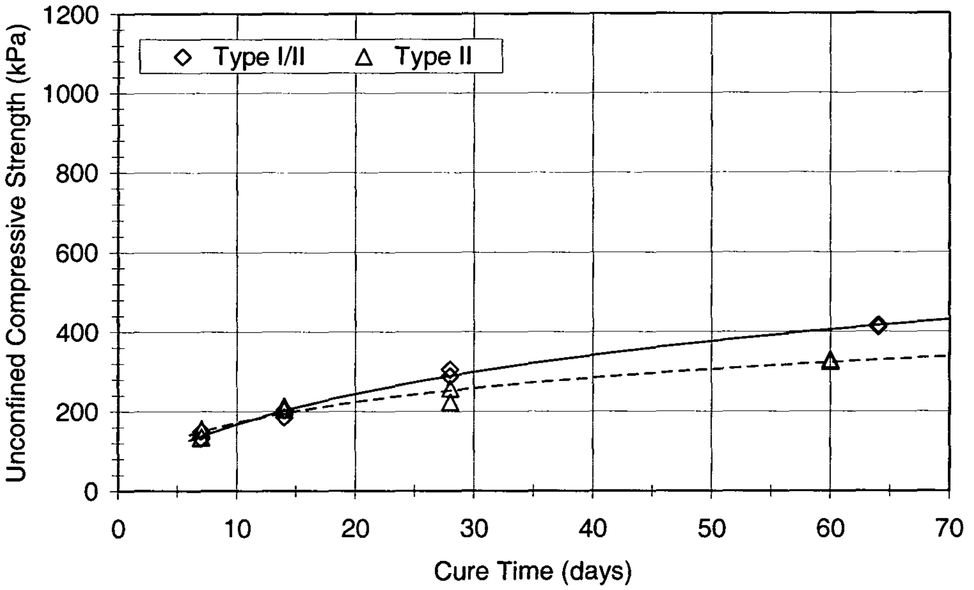

Figure 5. Type I/II Cement vs. Type II (Q-X-200-25:75-20-67)

Exposure Condition

Figure 6 illustrates strength gain with time for the sealed, air-dried, and oven-dried exposure conditions. Drying of the soil, with subsequent restoration to natural water content, had a significant detrimental impact on the strength of the lime-cement-soil mixtures.

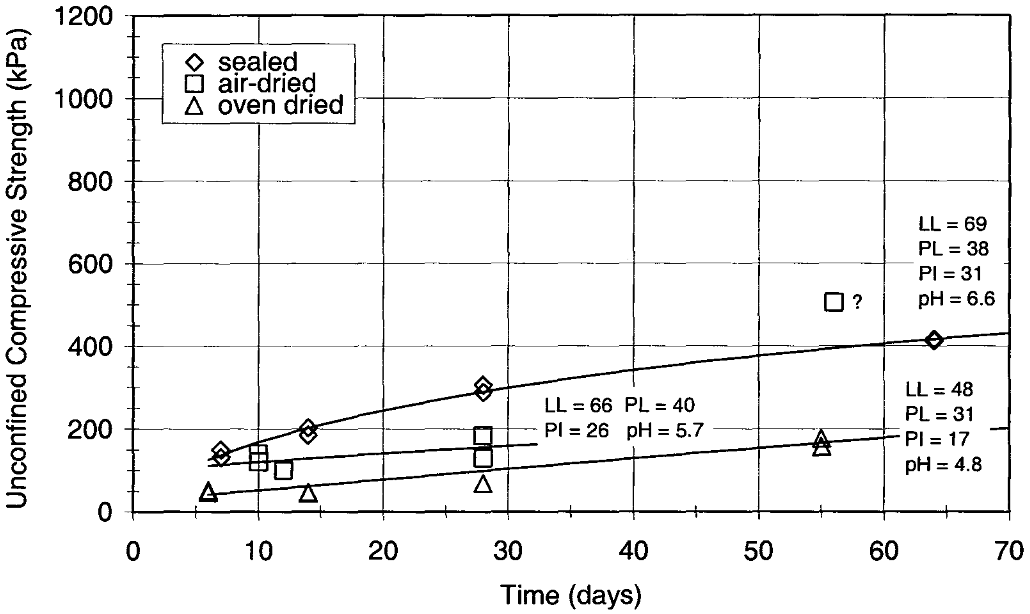

Figure 6. Sealed, Air-Dried, and Oven-Dried Conditions (Q-I/II-X-200-25:75-20-67)

The soil characterization tests performed for the specimens exposed to three degrees of drying showed that drying reduces the soil's plasticity and pH. In order to investigate the effects of these two reactions separately, the pH of two batch mixes, one air dried and one oven dried, were adjusted back to the pH of the sealed condition (pH ≈ 7) using calcium hydroxide (CaOH). Atterberg limits testing was then performed on the pH-adjusted soil. As shown in Table 17, the

Atterberg limits of the pH-adjusted air-dried soil were lower after adjustment than before, and the Atterberg limits of the pH-adjusted oven-dried soil were higher after adjustment than before, but in neither case were the Atterberg limits restored to the sealed condition by pH adjustment.

Table 17. Variation of Atterberg Limits with pH

Exposure Condition	Original				Post pH adjustment			
	pH	*LL*	*PL*	*PI*	*pH*	*LL*	*PL*	*PI*
Sealed	6.6	69	38	31	n/a	n/a	n/a	n/a
Air-Dried	5.7	66	40	26	7.0	61	37	24
Oven-Dried	4.8	48	31	17	7.0	53	34	19

Unconfined compressive test samples of the two pH-adjusted soils were then formed using the standard mixing procedure and the same mix design as used for the results in Figure 6. Figure 7 shows the sealed case, the air-dried case for both pH conditions, and the oven-dried case for both pH conditions. For this figure, the vertical scale was changed to show more detail. Together, the data in Table 17 and the results in Figure 7 indicate that the low strength gain for the dried soil is attributed primarily to a decrease in Atterberg limits values and not to a change in pH.

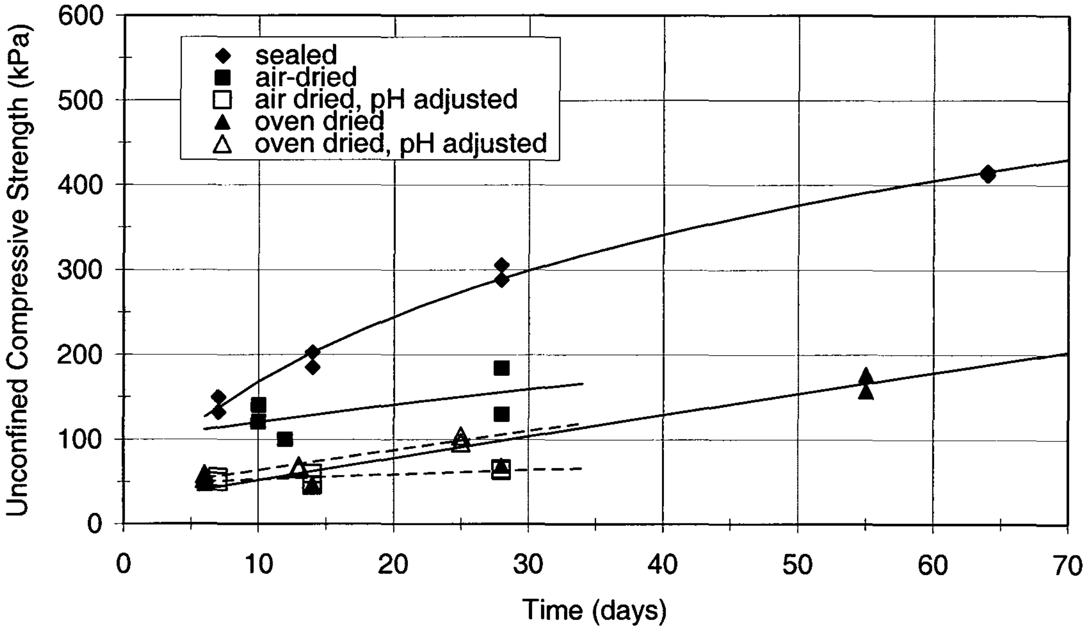

Figure 7. Sealed, Air-Dried, and Oven-Dried Conditions With and Without pH Adjustment.

Dose Rates and Proportions

Due to the large amount of data, this discussion is presented in three ways. The first sub-section discusses strength gain with time while holding proportions of lime and cement constant and changing the dose rate. The second sub-section discusses strength gain with time while holding dose rate constant and changing the proportions of lime and cement. The third sub-section discusses the effects of different amounts of lime and cement based on the 28-day strengths of the mixtures.

Dose Rates

Figure 8 illustrates strength gain with time for dosage rates of 150, 200, and 250 kg/m^3 using 0% lime and 100% cement.

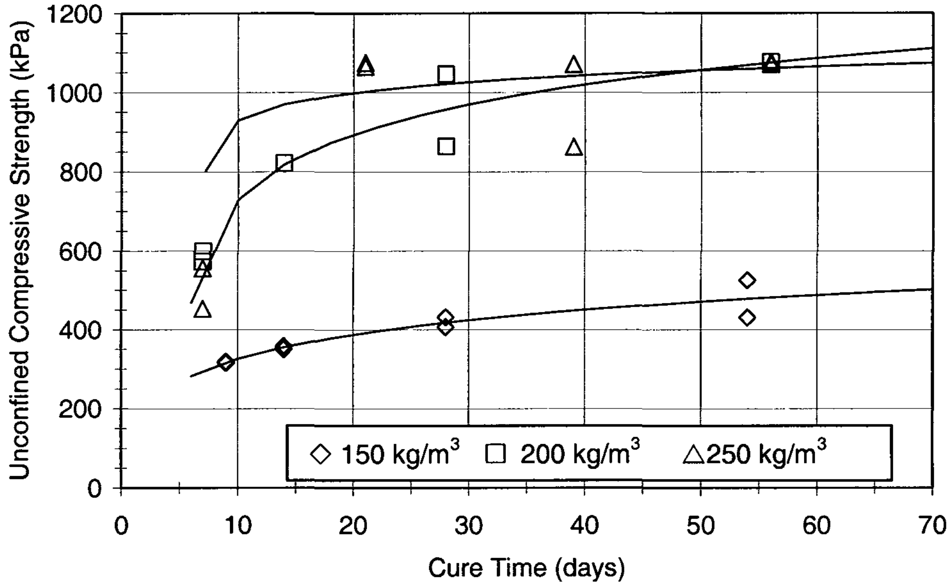

Figure 8. Effect of Dose Rate at L:C = 0:100 (Q-I/II-S-X-0:100-20-67).

Figure 9 illustrates strength gain with time for dose rates of 100, 150, 200, and 250 kg/m^3 using 25% lime and 75% cement.

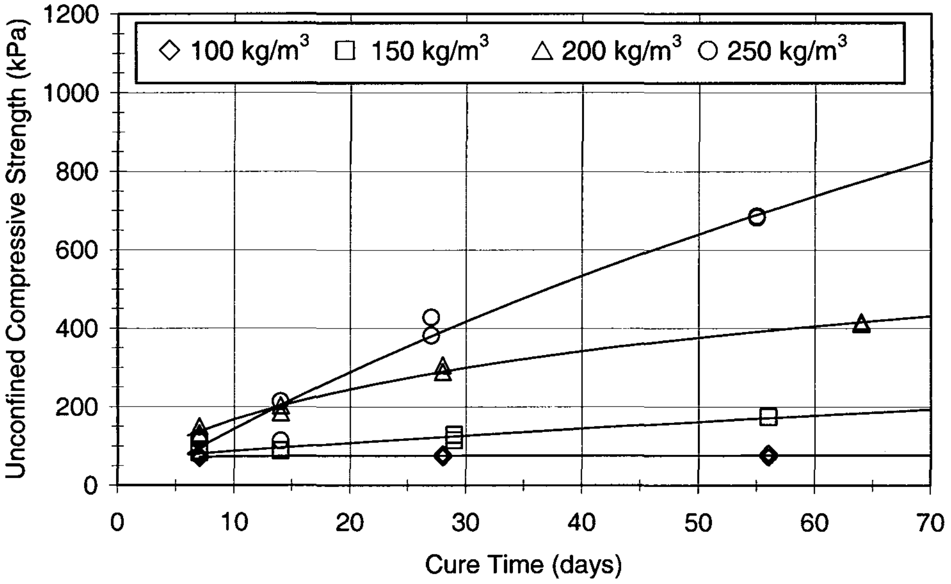

Figure 9. Effect of Dose Rate at L:C = 25:75 (Q-I/II-S-X-25:75-20-67)

Figure 10 illustrates strength gain with time for dose rates of 100, 150, 200, and 250 kg/m^3 using 50% lime and 50% cement.

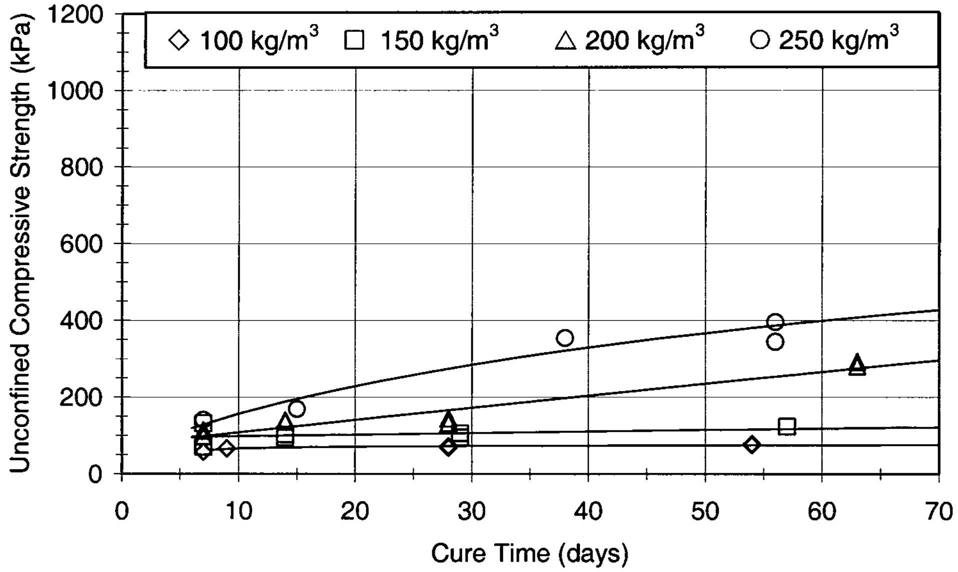

Figure 10. Effect of Dose Rate at L:C = 50:50 (Q-I/II-S-X-50:50-20-67)

From these three plots of dosage variation, several trends can be observed:

- There is a general trend of increasing strength with curing time. Exceptions occur for the low dosage rate mixtures that include lime.
- Strength gain with dosage appears nonlinear for the ranges of cement studied. The higher the percentage of cement, the more nonlinear the increase in strength with dosage rate becomes, as seen by comparing Figures 8 and 10.
- Cement dosages above 200 kg/m^3 had essentially no effect on strength gain. As seen in Figure 8, a 500-kPa increase in 28-day strength can be attributed to the change in dosage rate from 150 to 200 kg/m^3. From 200 to 250 kg/m^3, however, the additional strength gain was very small.
- Higher strengths resulted in more scatter in the data. This may be due to the effects of sample imperfections being amplified at higher stresses.

Proportions

The curves in Figures 11 through 13 are for the same data as in Figures 8 through 10, except that one additional batch outside the range of the dose-rate discussion is included. Figure 11 illustrates strength gain with time for lime-cement proportions of 0:100, 25:75, and 50:50 at a dose rate of 150 kg/m^3.

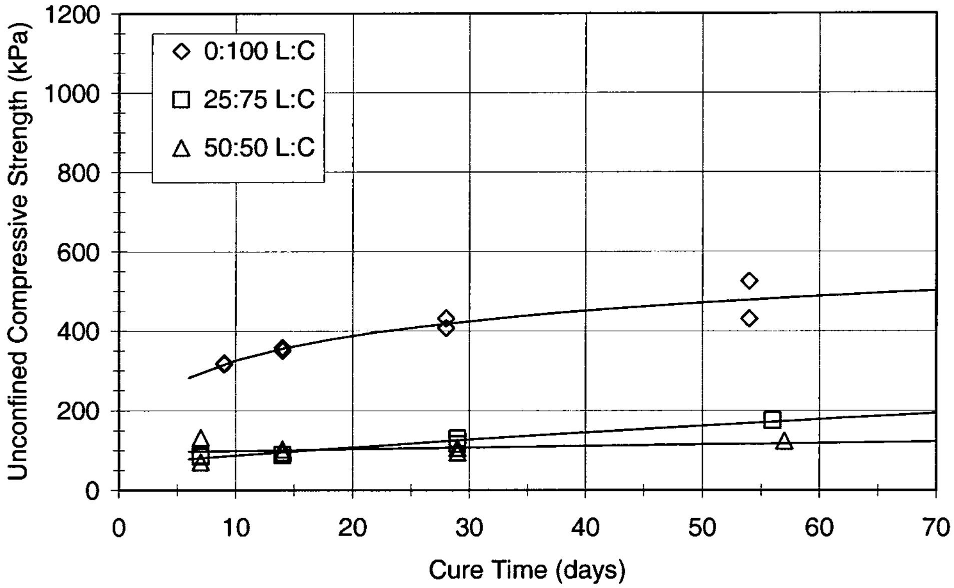

Figure 11. Effect of Proportions at a Dose Rate = 150 kg/m^3 (Q-I/II-S-150-X-20-67)

Figure 12 illustrates strength gain with time for lime-cement proportions of 0:100, 25:75, 50:50, and 100:0 at a dose rate of 200 kg/m^3.

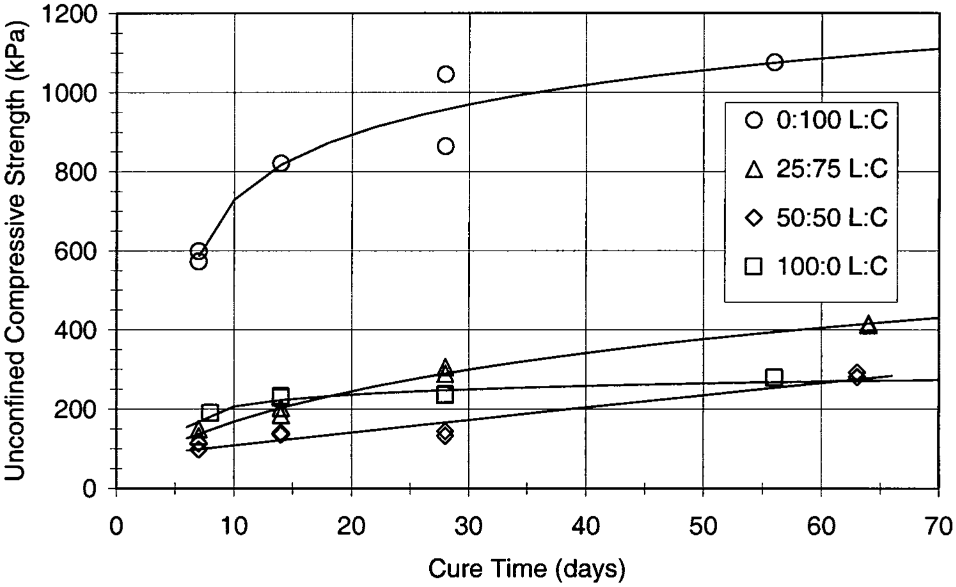

Figure 12. Effect of Proportions at a Dose Rate = 200 kg/m^3 (Q-I/II-S-200-X-20-67)

Figure 13 illustrates strength gain with time for lime-cement proportions of 0:100, 25:75, and 50:50 at a dose rate of 250 kg/m^3.

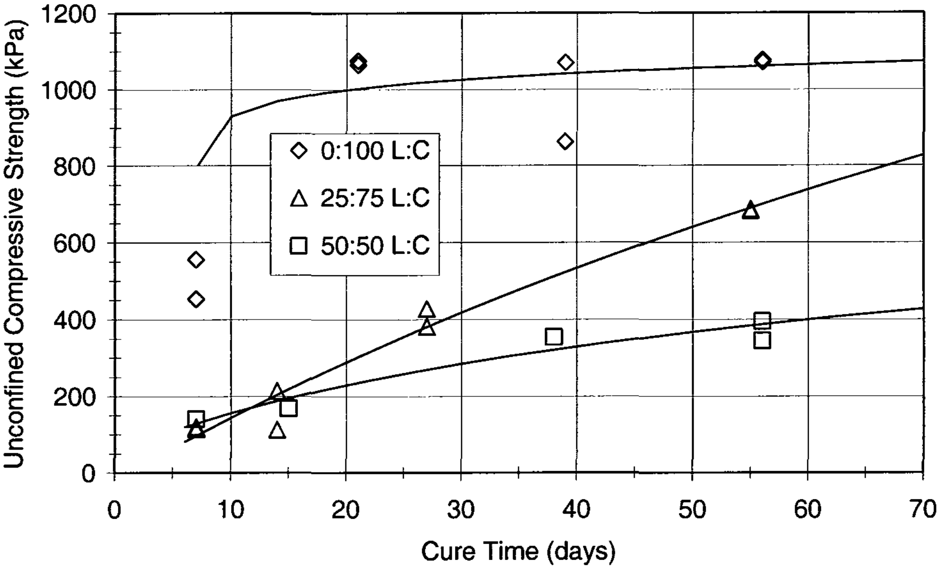

Figure 13. Effect of Proportions at a Dose Rate = 250 kg/m^3 (Q-I/II-S-250-X-20-67)

From these three plots of proportion variations, the following trends can be observed:

- One hundred percent cement mixes produced much higher unconfined compressive strengths than any other proportion at the same dose rate. The 28-day strengths for 200 and 250 kg/m^3 were approximately 1000 kPa.
- The impact of lime is not completely consistent. As shown in Figure 12, 100% lime performed slightly better than did the 50:50 mix at the same dose rate. The general trend, however, is the opposite; the addition of lime over most ranges of dose rate studied is detrimental to strength. Figure 14 illustrates this point. One batch mixed with 150 kg/m^3 of cement and no lime was much stronger than a batch mixed with 150 kg/m^3 of cement plus an additional 50 kg/m^3 of quicklime.

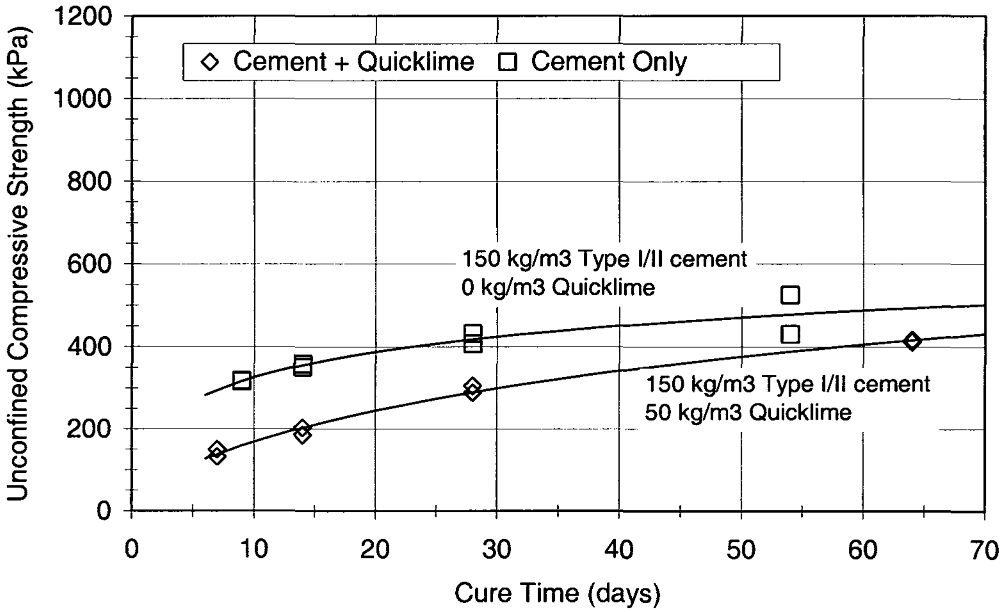

Figure 14. Impact of the Addition of Lime to 150 kg/m^3 of Cement-Treated Soil

28-Day Strength Contours

Typically, strength test results are presented as shown in the preceding figures, with the strength plotted versus curing time and comparisons made in terms of total dose rates and stabilizer proportions. Such presentations, however, may not be the best way to present the effect of each stabilizer or select the optimum stabilizer amounts. Another method of presenting strength data is to use 28-day strengths to plot a contour map of strength as a function of lime and cement dosages, as shown in Figure 15. Cement dosage is on the horizontal axis, and lime dosage is on the vertical axis. The hatched squares indicate the position of the batch mixes. Points falling on the horizontal axis are for 100% cement mixes; the point on the vertical axis is for a 100% lime mix. The three points falling on the 1:1 line are for lime-cement proportions of 50:50, and the four underneath are representative of 25:75 mixtures. A 0,0,0 point was also added to the plot, because the soft soil undergoing the standard procedure without the addition of stabilizer produced a very weak material. The very soft remolded soil without additives could not be extracted from the mold without destroying the specimen. Strengths were taken from the trend lines in order to incorporate the data obtained from all four cure times. The 12 points in Figure 15, with assigned 28-day strengths from the logarithmic trend lines, allowed for the interpolation of the strength contours as shown. Note that contours lines have no value in the upper right-hand portion of the figure, as there are no data for interpolation in this region.

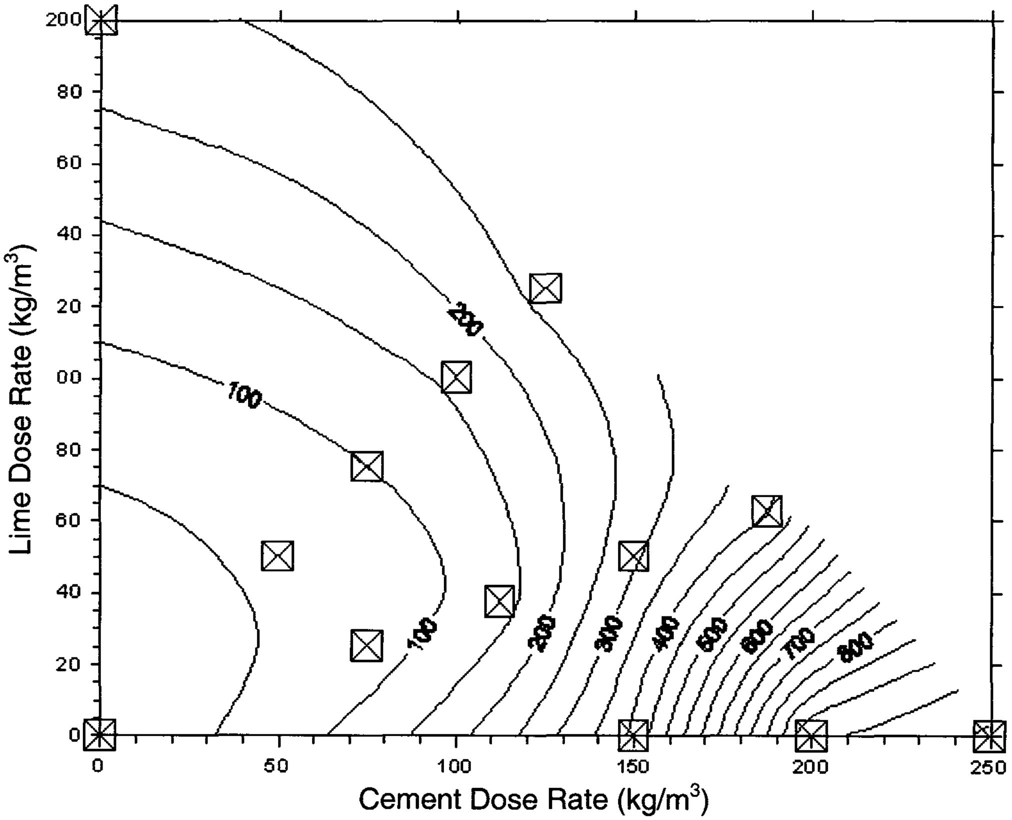

Figure 15. I-95/Route 1 28-day Strength Contours (kPa)

Several observations can be made from this style of presentation that could not be seen very easily with the prior methods:

- The addition of cement provides a continual increase in strength for all ranges of dose rates studied. Starting at any point on the vertical axis and moving horizontally across the figure, strength always increases.
- For cement dose rates of 150 to 250 kg/m^3, strength increases rapidly. This is shown by the high density of contour lines along the horizontal axis in the range from 150 to 250 kg/m^3.
- Lime appears to be much less effective than cement. This is shown by the low density of contour lines along the vertical axis.
- The addition of lime is detrimental for many of the possible combinations. Where the slope of the contour is positive, the effect of lime is negative. Drawing a line through the apex of each contour can delineate two zones, as shown in Figure 16: the zone to the upper left of the line reacts favorably to the addition of lime (Zone A), and the zone to the lower right reacts negatively to the addition of lime (Zone B).
- Optimal dose rates of lime and cement can be determined. For example, if the target value of 28-day unconfined compressive strength is 600 kPa, the optimal dose rates are 0 kg/m^3 of lime with 170 kg/m^3 of cement, as shown in Figure 15.

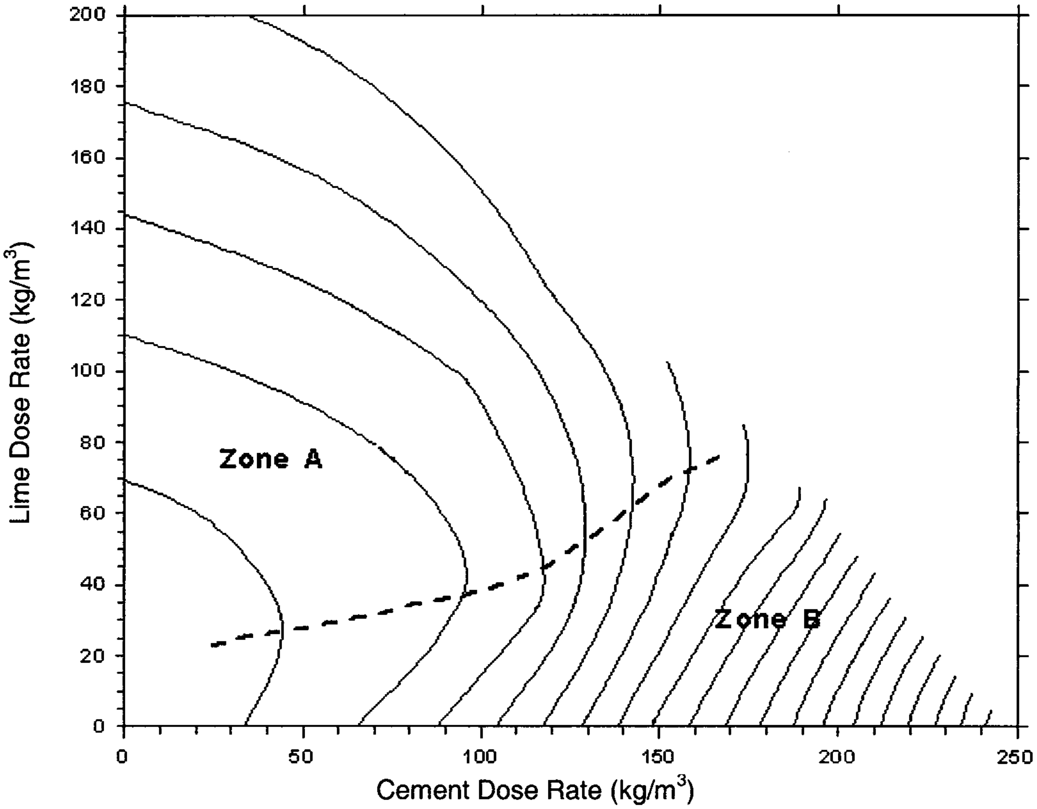

Figure 16. Zones of Influence for the Addition of Lime

Benefits of plotting the test results as strength contours in this format include the ability to:

- Determine if the 28-day design strength can be achieved.
- Determine the amounts of stabilizers required to achieve the design strength.
- Determine the most cost-efficient combination of stabilizer types to use.

- Incorporate in-situ soil characteristics in batch mix design, and produce design curves that are site specific.

Drawbacks include:

- No information about time-rate of strength gain is provided in a single contour plot.
- A number of batches must be produced in order to create contours.
- Variable soils might not provide consistent results.

The moisture contents after 28 days of curing can be plotted in the same manner as the 28-day strengths, as shown in Figure 17. The initial moisture content of the soil was about 67%, but the lime and cement consume water, producing 28-day moisture contents below 67%. The slope of the contour lines shows that quicklime consumes more water than cement. For example, about 160 kg/m^3 of quicklime without any cement reduces the 28-day moisture to 50%, but about 220 kg/m^3 of cement without any quicklime is necessary to reach the same water content.

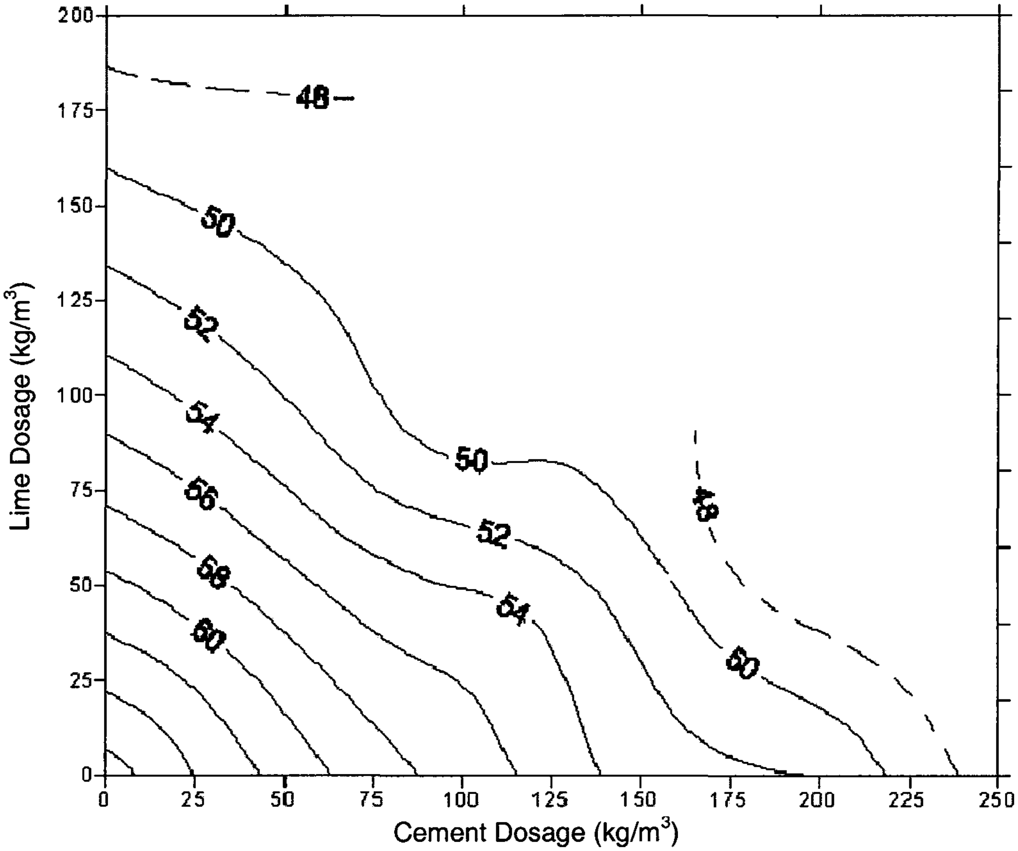

Figure 17. 28-day Moisture Content Contours

Curing Temperature

The effect of curing temperature after mixing was studied using temperatures of 5, 10, 20, and 40°C. Figure 18 illustrates strength gain with time for the selected curing temperatures.

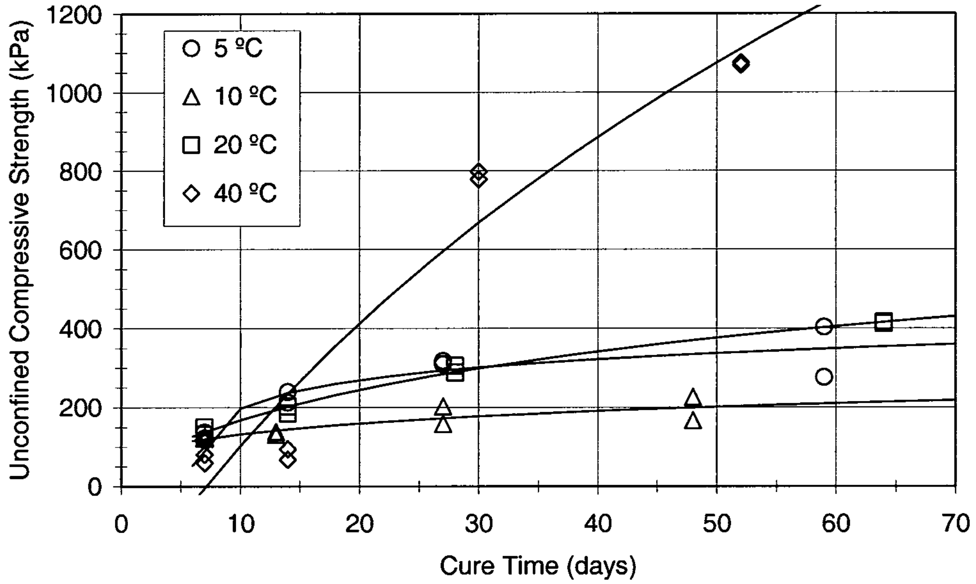

Figure 18. Effect of Curing Temperature (Q-I/II-S-200-25:75-X-67)

The 28-day strengths are plotted versus cure temperature in Figure 19. Except for the strength at 5°C, the strengths exhibit the expected increase in strength with increasing curing temperature. In-situ curing temperatures are discussed in the Literature Review section of this report.

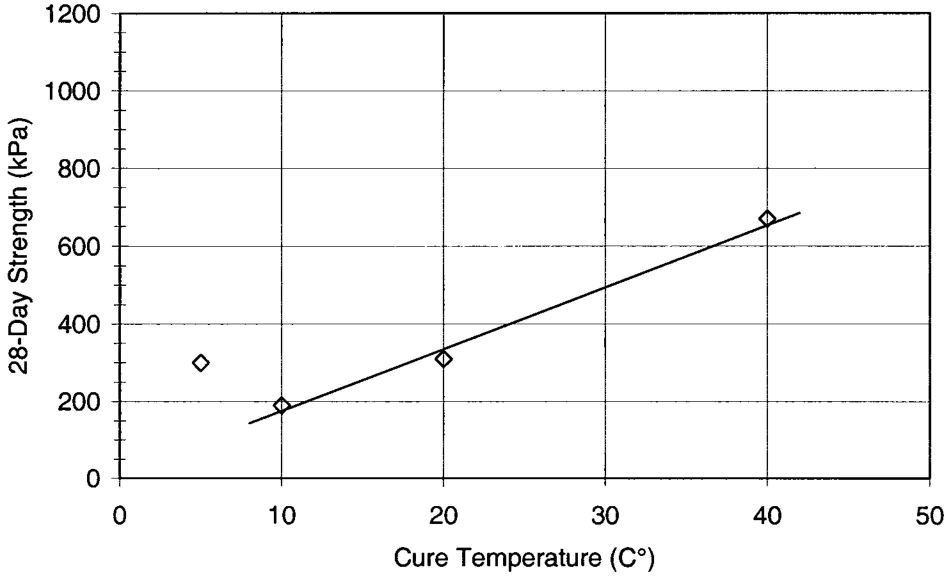

Figure 19. Curing Temperature vs. 28-Day Strength Gain

Initial Moisture

The effect of moisture conditions prior to stabilization was studied using initial moisture values of 52%, 67%, and 82%. These moistures corresponded to liquidity indices of approximately 0.5, 1.0, and 1.5, respectively. Figure 20 illustrates strength gain with time for all three initial moisture conditions. Figure 21 shows that the 28-day strength decreases as the liquidity index increases.

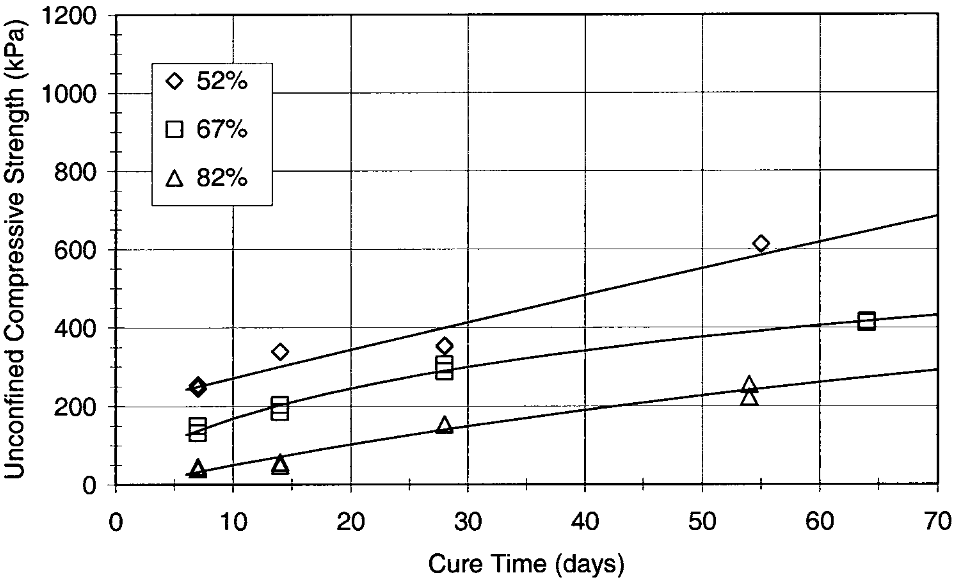

Figure 20. Effect of Initial Moisture (Q-I/II-S-200-25:75-20-X)

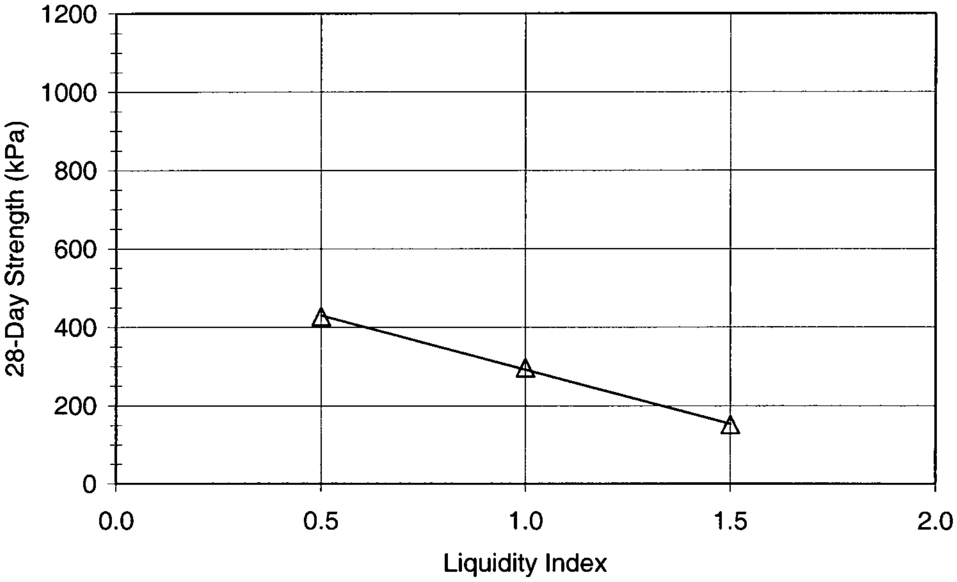

Figure 21. Liquidity Index vs. 28-Day Strength

State Route 33

Five batch mixes were prepared for Zone 1 and Zone 2 of State Route 33. Each zone is presented separately and in a manner similar to the I-95/Route 1 presentation. For each zone, the first sub-section discusses strength gain using conventional cure time vs. unconfined compressive strength plots. The second sub-section discusses the effects of different amounts of lime and cement based on 28-day strength contours. Batch IDs use the same system as the I-95/Route 1 soil, with the exception of the moisture identifier. All of the State Route 33 soil was tested at its natural moisture, which is expressed as NM in the batch ID. The values of natural moisture content for each batch are given in the Results section. The natural moistures for Zone 1 batches ranged from 86% to 96%, and averaged 91%. The natural moistures for Zone 2 batches ranged from 120% to 150% and averaged 136%.

Zone 1

Dosage Rates and Proportions

Figure 22 illustrates strength gain with time for dosage rates of 100, 150, and 200 kg/m^3 using 0% lime and 100% cement.

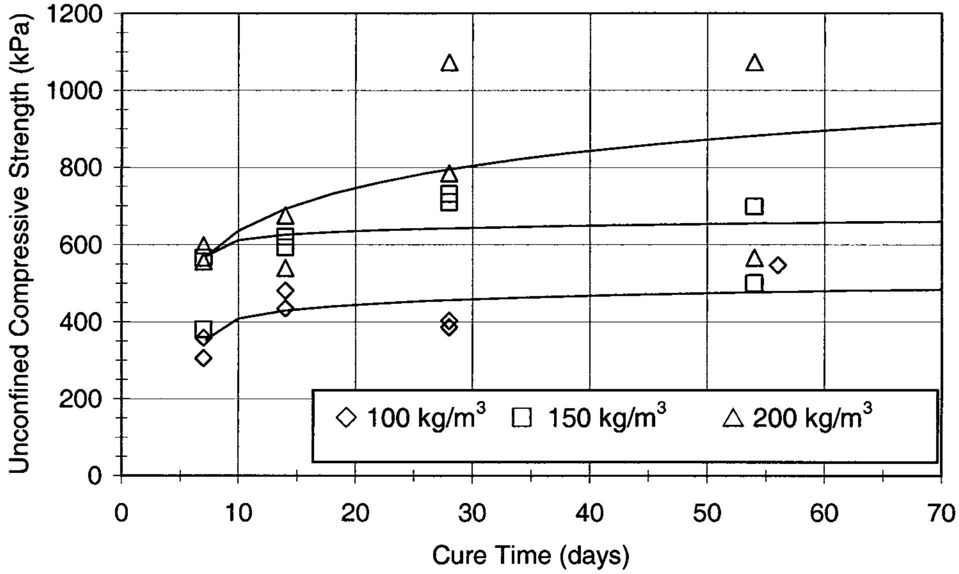

Figure 22. SR 33 Zone 1 Effect of Dose Rate (Q-I/II-S-X-0:100-20-NM)

Figure 23 illustrates strength gain with time for dosage rates of 150 and 200 kg/m^3 using 25% lime and 75% cement.

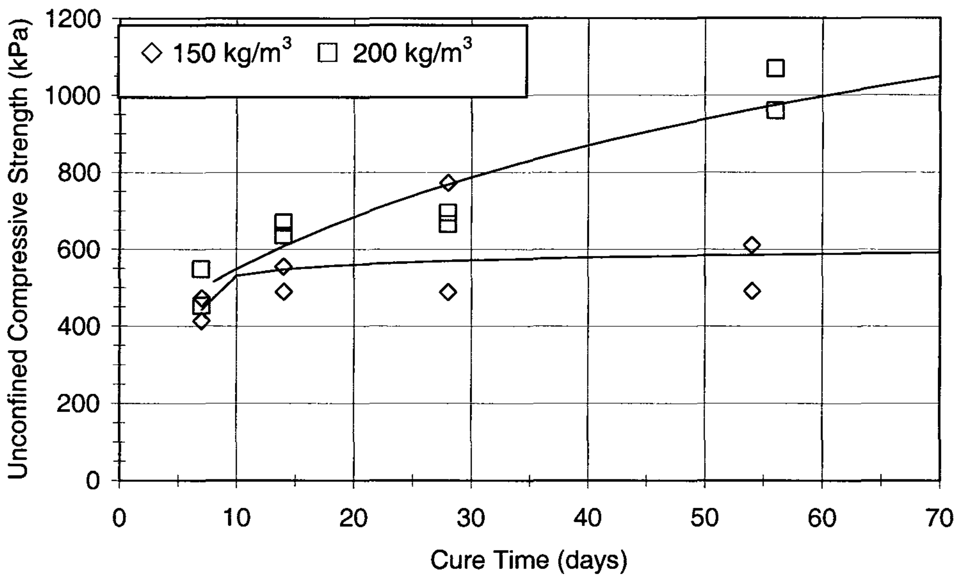

Figure 23. SR 33 Zone 1 Effect of Dose Rate (Q-I/II-S-X-25:75-20-NM)

From these two plots, several trends can be observed:

- As dosage rate increases, strength increases. A continual increase in strength was observed over the dose rates studied, regardless of proportions used.
- One-hundred-percent cement mixes do not produce dramatically greater strengths than 25% lime and 75% cement mixes, in contrast to the I-95/Route 1 soil.
- The addition of lime is beneficial for State Route 33 Zone 1 soil, as shown by comparing the 28-day strengths of the 150 kg/m^3, 100% cement mix with the 200 kg/m^3, 25% lime and 75% cement mix.
- More scatter was evident in the data than for the I-95/Route 1 soil. This may be due to the variability of the base soil.

28-Day Strength Contours

Twenty-eight-day strength contours were plotted in a manner similar to that previously shown and discussed for the I-95/Route 1 soil. The State Route 33 Zone 1 results are shown in Figure 24 below. The hatched squares indicate the position of the batch mixes, and a 0,0,0 point was again added to the plot. These points, with assigned 28-day strengths from the logarithmic trend lines, allowed for the interpolation of strength contours, as shown.

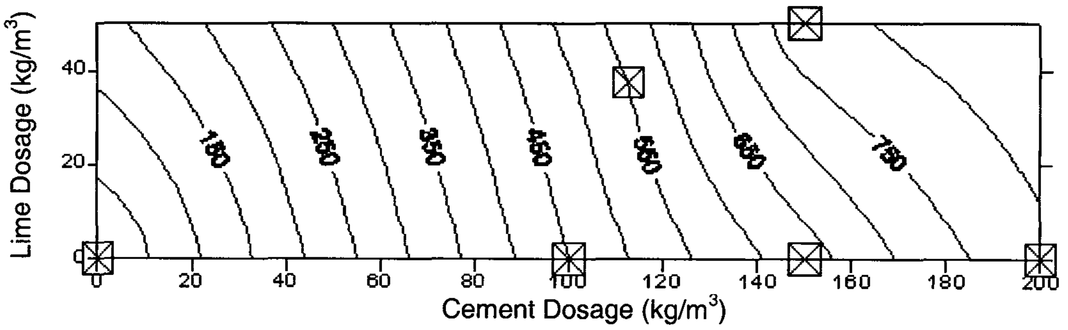

Figure 24. State Route 33 Zone 1 28-day Strength Contours (kPa)

Several observations can be made from this figure, as follows:

- The addition of cement provides a continuing increase in strength for all ranges of dose rates studied. Starting at any point on the vertical axis and moving horizontally across the figure, strength always increases.
- The addition of lime provides a continuing increase in strength for all ranges of dose rates studied. Starting at any point on the horizontal axis and moving vertically up the figure, strength always increases.
- For the same change in dose rate, lime appears to be less effective than cement. This can be seen by counting and comparing the number of contours crossed when moving equal distances vertically and horizontally across the plot.

Zone 2

Dosage Rates and Proportions

Figure 25 illustrates strength gain with time for dosage rates of 100, 150, and 200 kg/m^3 using 0% lime and 100% cement.

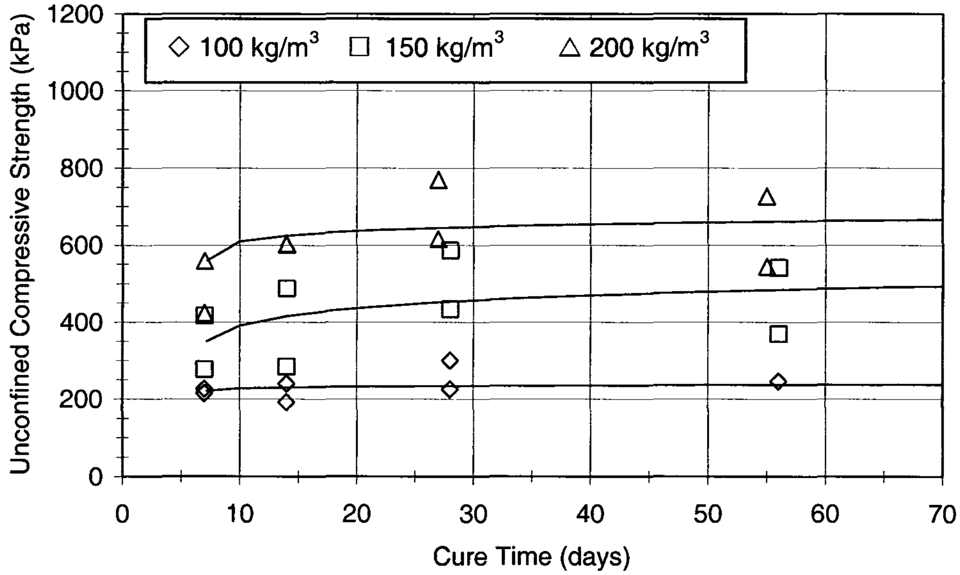

Figure 25. SR 33 Zone 2 Effect of Dose Rate (Q-I/II-S-X-0:100-20-NM)

Figure 26 illustrates strength gain with time for dosage rates of 150 and 200 kg/m^3 using 25% lime and 75% cement.

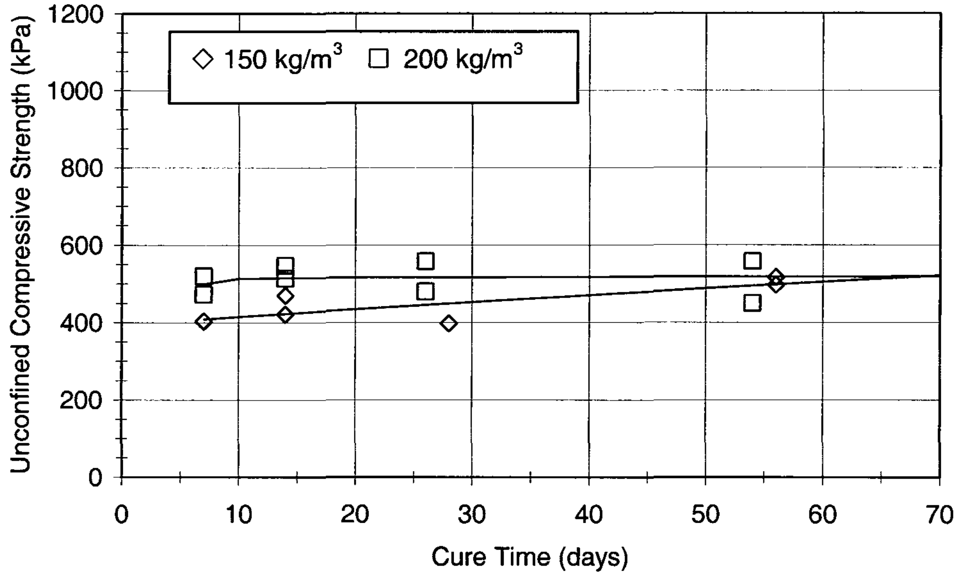

Figure 26. SR 33 Zone 2 Effect of Dose Rate (Q-I/II-S-X-25:75-20-NM)

Trends observed from these two plots are similar to those observed with Zone 1:

- As dosage rate increases, strength increases. A continual increase in strength was observed over the dose rates studied, regardless of proportions used.
- One-hundred-percent cement mixes do not produce dramatically greater strengths than mixtures prepared with a proportion of lime, in contrast to the I-95/Route 1 soil.
- The addition of lime is beneficial here, in contrast to the I-95/Route 1 soil.
- There is more scatter in the data, which may be due to inherent variability in the Zone 2 soil.

28-Day Strength Contours

State Route 33 Zone 2 results are shown in Figure 27. The hatched squares indicate the position of the batch mixes, and a 0,0,0 point was again added to the plot. These points, with assigned 28-day strengths from the logarithmic trend lines, allowed for the interpolation of strength contours, as shown.

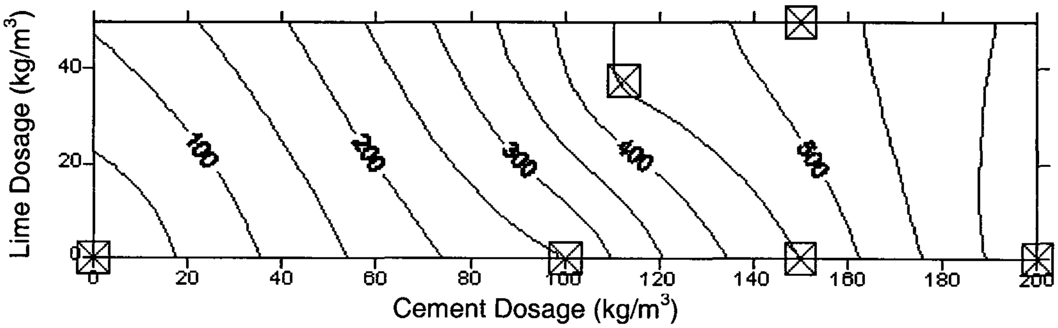

Figure 27. State Route 33 Zone 2 28-day Strength Contours (kPa)

Several observations can be made from this figure, as follows:

- The addition of cement provides a continuing increase in strength for all ranges of dose rates studied. Moving horizontally across the figure, strength always increases.
- The addition of lime provides a continuing increase in strength for all ranges of dose rates studied. Starting at any point on the horizontal axis and moving vertically up the figure, strength increases (the slopes of the contour lines are negative).
- For the same change in dose rate, lime appears to be less effective than cement. This can be seen by counting and comparing the number of contours crossed when moving equal distances vertically and horizontally across the plot.

Comparison of I-95/Route 1 and State Route 33 Results

Comparison of Base Soil Characteristics

Table 18 shows the base soil characteristics for each of the soil types tested. All three soils had roughly the same mineralogical composition in the clay fraction. The clay fraction was smaller for the I-95/Route 1 soil than for the two State Route 33 soils. The I-95/Route 1 soil and the State Route 33 Zone 1 were similar in their activity and organic content, but the State Route 33 Zone 2 soil had much higher activity and organic content. Each soil had a significantly different pH, and the I-95/Route 1 soil was the only soil to undergo discoloration when being exposed to air. The concentration of water-soluble sulfates was much higher for the State Route 33 soils than for the I-95/Route 1 soil.

Table 18. Base Soil Characteristics for the Three Soil Types Tested

	I-95/Route 1	State Rte. 33, Zone 1	State Rte. 33, Zone 2
Sample depth (m)	2.4 - 4.6	6.1 - 6.7	11.6 - 12.2
Organic content (%)	6	7	15
Carbon analysis:			
Untreated (%)	3.3	2.7	7.8
Acid treated (%)	3.3	2.6	6.8
pH	6.6	4.8	3.7
Sulfate content (mg/kg)	730	10,400	10,000
Clay fraction (%)	37	65	52
Composition of clay fraction:			
Montmorillonite (%)	55	55	60
Vermiculite (%)	15	15	3
Mica (%)	10	10	15
Chlorite (%)	5	--	2
Kaolinite (%)	15	20	20
Quartz (%)	trace	trace	trace
Atterberg Limits			
Liquid Limit	67	109	209
Plastic Limit	37	52	129
Plastic Index	30	57	80
Activity	0.8	0.9	1.5

Strength Comparison

Table 19 and Figure 28 present the comparable 28-day strength results for each of the three soils tested. Four batches with the same dose rate and lime to cement proportions were mixed for each soil type, allowing direct comparisons to be made for these cases. Note that initial moisture contents differ for each soil.

Table 19. Comparison of 28-day Strengths for the Three Soil Types Tested

Soil	Initial Water Content (%)	Initial Liquidity Index	q_u (kPa)			
			Total Dose Rate 150 kg/m^3		Total Dose Rate 200 kg/m^3	
			0L:100C	*25L:75C*	*0L:100C*	*25L:75C*
I-95/Route 1	67	1.0	414	117	938	297
SR 33 Zone 1	92	0.7	625	550	790	790
SR 33 Zone 2	120	~0.0	450	460	640	525

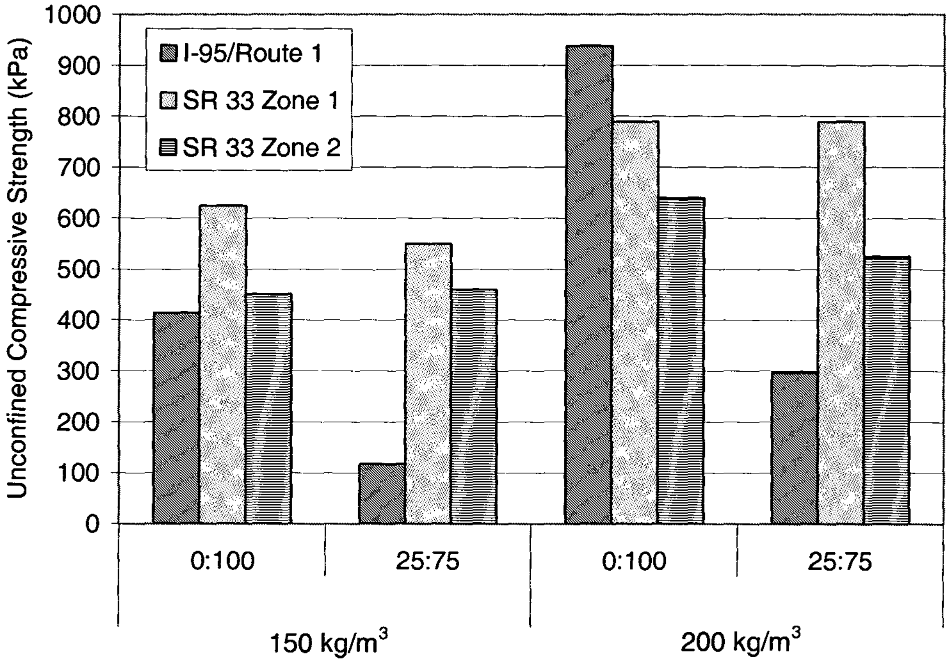

Figure 28. 28-Day Strength Comparison for the Three Soil Types Tested

From Table 19 and Figure 28, the following general observations can be made:

- As dose rate increases, strength increases for all three soils.
- Substituting 25% lime for cement appears to have relatively little impact on the State Route 33 soils, but a big impact on the I-95/Route 1 soil, re25:75.
- One-hundred-percent cement mixes produced the highest strengths in every case.
- Both the highest and the lowest strengths were produced using I-95/Route 1 soil.

- General trends in strength gain were similar for both of the State Route 33 soils, but the Zone 2 soil, which had a higher organic content, produced lower strengths on average.

One reason for the difference between the impact of lime on the I-95/Route 1 soil and the State Route 33 soils may be due to complex interactions among lime, sulfates, and organic material. According to Laguros and Davidson (1963), lime tends to increase the solubility of organics, so that the organics can become more dispersed throughout the lime-cement-soil mixture and more readily interfere with pozzolanic reactions, thereby reducing strength gain in the mixture. Further, Laguros and Davidson (1963) indicate that sulfates tend to decrease the solubility of organics, which can lead to an increase in the strength of stabilized organic soils. Both the I-95/Route 1 and the State Route 33 soils are organic, but the State Route 33 soils have much higher sulfate content. Addition of lime to the I-95/Route 1 soil may have increased the solubility of organics and caused the observed strength reduction. The high sulfate content of the State Route 33 soil may have kept the solubility of organics low, thereby permitting pozzolanic reactions between the lime and clay to increase the mixture strength.

An additional factor is that sulfate anions place a demand on added calcium cations, reducing the amount of calcium available for pozzolanic reactions (Arman and Munfakh 1970). Thus, added lime could contribute to strength gain for the State Route 33 soil by helping to satisfy the demand for calcium produced by the high sulfate content. Further, the State Route 33 soils have a higher clay fraction, so more pozzolanic material is available for reaction with added lime.

Clay-Water to Cement Ratio

Figure 29 shows the results of the unconfined compressive strength tests as a function of clay-water to cement ratio for 100% cement-soil mixes. The clay-water to cement ratio is defined as the ratio of initial water content of the soil to the cement content. The cement content is the ratio of cement to clay by dry weight. The upper trend line shown in the figure was suggested by Miura et al. (2002), in which an exponential curve of the form $q_{u\,(28\text{ day})} = a / b^{(w/c)}$ was fitted to the data where q_u = the unconfined compressive strength, w/c = clay-water to cement ratio, and a and b are coefficients obtained by least-squares regression. The lower trend line uses the same form, with the coefficients produced by fitting the data from three Virginia soils obtained from two sites. These soils have organic contents ranging from 6% to 15% and a pH ranging from 3.7 to 6.6. The relationship for Virginia soils is for 100% cement-soil mixtures prepared by the dry method. Using this trend line, it may be possible to estimate the amount of cement required to reach a specified unconfined compressive strength, based solely on the initial moisture content of the base soil. It would be interesting to test other Virginia soils to determine whether they provide results close to the trend line shown.

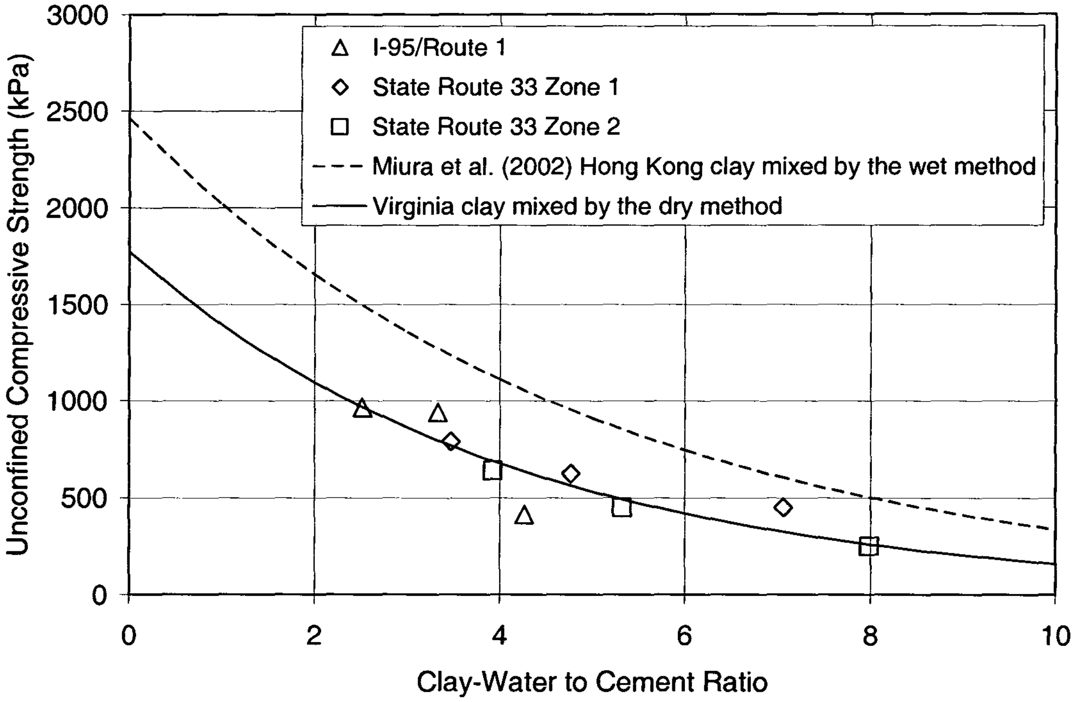

Figure 29. Relationship between 28-Day Unconfined Compressive Strength and Clay-Water/Cement Ratio for Cement-Stabilized Soil

Comparison of Secant Modulus of Elasticity

Figure 30 presents the 28-day secant modulus results for each of the soils investigated. All three soils show relatively good agreement with the dashed line, which is the trend line suggested by Ekstrom (1994). Thus, the trend is that E_{50} is approximately 75 times the unconfined compressive strength.

Comparison of Firm A, Firm B, and Virginia Tech Test Results

As mentioned earlier, two private consulting firms were retained by VDOT prior to this research to determine the strength gain of the dry mix lime-cement columns using laboratory-testing procedures. The results from the two private firms proved to be very different, and thus questions arose concerning the various laboratory procedures that were used. Table 20 illustrates the major differences in the laboratory techniques. The first column is a list of major variables that were found to have differed from one testing program to the next. The second column is a list of specifications recommended by the Swedish Geotechnical Society (SGS), and the remaining columns are the procedures used by the private firms and the procedures used in this investigation.

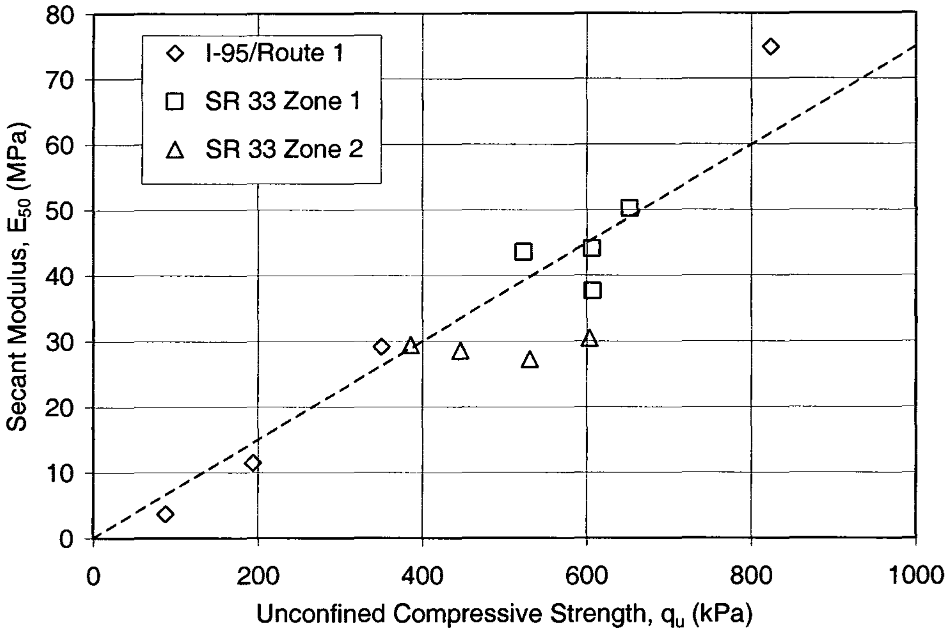

Figure 30. 28-Day Secant Modulus for the Three Soils Studied

Table 20. Comparison of SGS, Firm A, Firm B, and Virginia Tech Test Procedures

	SGS	Firm A	Firm B	Virginia Tech
Storage temp (°C)	constant	?	?	20°
Storage humidity (RH)	?	?	?	100%
Lime type	as specified	quicklime	quicklime	quicklime and hydrated lime
Cement type	as specified	Type I	Type I	Type I/II and Type II
Initial moisture	as specified	75 – 85%	75 & 100%	52, 67, and 82%
Dose rate defined as:	kg stabilizer / m^3 *untreated* soil	kg stabilizer / m^3 *treated* soil	kg stabilizer / m^3 *untreated* soil	kg stabilizer / m^3 *untreated* soil
Mixing device	dough mixer	dough mixer	dough mixer	dough mixer
Mixing time (min)	5 to 6	3 or 4	?	5
Compaction method	circular steel stamp	tapped against solid surface	rodding	rodding and circular steel stamp
Compaction pressure (kPa)	100	n/a	n/a	100
Mold size (mm)	50 dia., 180 tall	50 dia., 100 tall	?	50 dia., 100 tall
Mold type	piston sample cylinders	plastic molds	plastic molds	plastic molds
Cure temp (°C)	>15°	25°	15°	20°
Cure humidity (RH)	as specified	96%	?	100%

Figure 31 shows the trend lines of strength gain versus time for each of the three investigations using a dosage rate of 150 kg/m^3 (defined as kg stabilizer/m^3 of *untreated* soil for Virginia Tech's and Firm B's investigations, and kg stabilizer/m^3 of *treated* soil for Firm A's

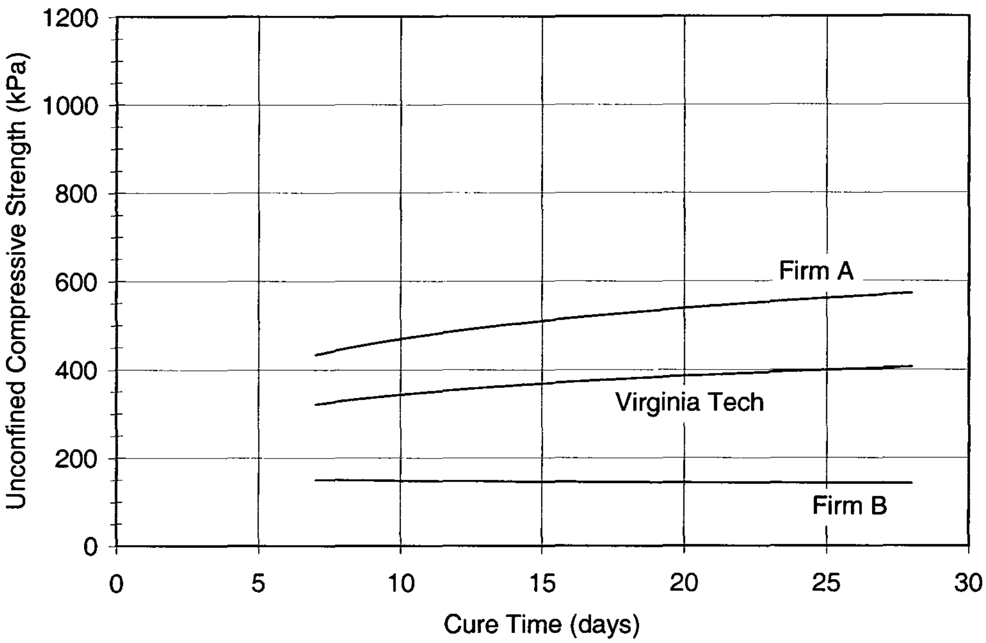

Figure 31. Comparison of Firm A, Firm B, and Virginia Tech Results

investigation) with a lime-cement proportion of 0:100. Firm A measured the highest strengths, Firm B measured the lowest strengths, and Virginia Tech's results were intermediate.

There are several factors that could have contributed to the variations of strengths measured by Firm A, Firm B, and Virginia Tech:

- Firm A and Virginia Tech cured specimens at a temperature 5 to 10 °C higher than did Firm B. As shown earlier, the general trend is that strength increases with increasing temperature.
- Firm B changed quicklime types during its investigation due to low reactivity of the first type of quicklime used. It is not known exactly when the lime type was changed or what data were presented using the first batch of quicklime. Quicklime that had been allowed to hydrate before being used may have reduced its effectiveness.
- Firm B and Virginia Tech used a dosage rate defined as kg stabilizer/m^3 of *untreated* soil; Firm A used a dosage rate in kg stabilizer/m^3 of *treated* soil. At a nominal dose rate of 150 kg/m^3, this results in Firm A adding slightly more stabilizer.
- Firm B soil samples were left unsealed and unattended for a period of time, and they eventually dried out. The water content was restored at a later time. As previously discussed, drying of the I-95/Route 1 soil, with subsequent restoration to natural water content, has a significant detrimental impact on the strength of the lime-cement-soil mixtures.
- Firm B tested the strength of lime-cement-soil mixtures at initial moistures of 100% in the first phase of testing and 75% in the second phase of testing. This was much higher than the range of moistures tested by Firm A and Virginia Tech. This research shows

that as the initial moisture increases, strength gain decreases, which may account for some of the difference in strength gain.

- Some variation in reported strength may be due to variation in the base soil used in forming the lime-cement-soil specimens.

The trends in strength variation among Firm A, Firm B, and Virginia Tech can be understood based on these points. Firm B's measured strengths are lower than Virginia Tech's because the initial moisture contents were higher, curing temperatures were lower, and the soil dried prior to testing. Firm A's measured strengths are higher than Virginia Tech's because more stabilizer was added at the same nominal dose rate and because the curing temperature was 5° C higher. Variations in base soil characteristics probably also contributed to the variation in measured strength.

CONCLUSIONS

I-95/Route 1 Study

- Quicklime and hydrated lime produced similar results.
- Type I/II cement produced slightly higher strength than did Type II cement.
- When soil samples were dried and the natural moisture contents were subsequently restored, the strength of the lime-cement-soil mixtures was reduced compared to mixtures using soil samples that were not dried.
- As dosage rate increased, strength increased for the range of dose rates studied.
- Soil-cement mixtures without lime produced the highest strengths.
- For lime-cement-soil mixtures with typical proportions, the addition of lime caused a decrease in the strength of the cured mixtures. This may be due to increased solubility of organics in the presence of lime. Dissolved organics may have interfered with strength gain during curing of the mixtures.
- As curing temperature increased, strength increased in most cases.
- As initial moisture increased, strength decreased.
- Higher strengths tended to produce more scatter in the data.

State Route 33 Zone 1 and Zone 2 Study

- As dose rate increased, strength increased.
- One-hundred-percent cement mixes produced only slightly greater strengths than the 25% lime and 75% cement mixes, contrary to the response of the I-95/Route 1 soil, for which much higher strengths were obtained with 100% cement mixes.

- Adding lime consistently increased the mixture strength, in contrast to the response of the I-95/Route 1 soil. This may be due to the high sulfate content of the State Route 33 soil. Sulfates tend to decrease the solubility of organics, which may have reduced their interference with strength gain, even in the presence of lime. Thus, the strength gains produced by pozzolanic reactions between lime and clay may not have been counteracted by detrimental effects of dissolved organics.
- There was more scatter in the strength data than for the I-95/Route 1 soil. This may be due to the variability of the State Route 33 soil.

General Findings

- For 100% cement mixes, a trend line was established relating the clay-water to cement ratio to the unconfined compressive strength for Virginia soils from two different sites.
- For a given lime-cement proportion, strength increases as dose rate increases.
- Adding lime to a soil-cement mixture produces a slight increase in strength for the State Route 33 soils. The strength of the I-95/Route 1 soil was detrimentally affected by lime, with 50 kg/m^3 of lime added to a 150 kg/m^3 cement-soil mixture producing a 50% strength reduction. The reason for this dramatic drop in strength is thought to be due to increased solubility of organics caused by addition of lime. For the State Route 33 soil, the high sulfate concentration reduces the solubility of organics, so that the effect of lime on organic solubility may be small. This may permit pozzolanic reactions between the clay and added lime to increase the strength of lime-cement-soil mixtures for the State Route 33 soil.
- One-hundred-percent cement mixes produced the highest strengths for soils tested in almost every case.
- The highest and lowest strengths were produced using I-95/Route 1 soil.
- For the State Route 33 soils, Zone 1 produced significantly higher strengths than did Zone 2, which had a higher organic content.

Reasons That the Strength Results of Firm A and Firm B Differed

- Firm A and Virginia Tech cured specimens at temperatures 5 to 10 °C higher than did Firm B. The general trend is that strength increases with increasing temperature.
- Firm B changed quicklime types during its investigation due to the low reactivity of the first type of quicklime used. It is not known exactly when the lime type was changed or what data were presented using the first batch of quicklime. Quicklime that had been allowed to hydrate prior to mixing may have reduced its effectiveness.
- Firm B and Virginia Tech used a dosage rate defined as kg stabilizer/m^3 of *untreated* soil; Firm A used a dosage rate in kg stabilizer/m^3 of *treated* soil. At a dosage rate of 150 kg/m^3, this results in Firm A adding about 7% more stabilizer.

- Firm B soil samples were left unsealed and unattended for an unknown amount of time, and eventually they dried out. The water content was restored at a later date. As previously discussed, drying of the I-95/Route 1 soil, with subsequent restoration to natural water content, has a significant detrimental impact on the strength of the lime-cement-soil mixtures.
- Firm B tested the strength of lime-cement-soil mixtures at initial moistures of 100% in the first phase of testing and 75% in the second phase of testing. This was much higher than the range of moistures tested by Firm A and Virginia Tech. As the initial moisture increases, the strength of the mixture decreases.
- Some of the variation in reported strength may be due to variation in the base soil used in forming the lime-cement-soil specimens.

Laboratory Procedures

- The laboratory procedure, given in Appendix A, resulted in the production of high-quality samples that generally yielded reliable and reproducible results.

Presentation of Data

- The logarithmic trend line $q_u = q_{u\,0} + a \ln (t - t_0)$ provided a good fit to the laboratory data of the cure time versus unconfined compressive strength relationship.
- The 28-day strength contour plots offer an effective way to present results. They can provide a simple way of determining whether the desired 28-day strength can be achieved, the amounts of stabilizers required to achieve design strength, and the most cost-efficient combination of stabilizer types to use.

RECOMMENDATIONS

Recommended Laboratory Procedure

It is recommended that the laboratory procedure in Appendix A be used by VDOT materials laboratories and outside consultants for preparing specimens and determining the unconfined compressive strength of lime-cement-soil mixtures prepared in the laboratory. This procedure offers a step by step process for the following:

1. Storing and handling the base soil.
2. Preparing the base soil for mixing with lime and cement.
3. Preparing the lime and cement for mixing.
4. Mixing the soil, lime, and cement.
5. Placing the mixture into the molds.

6. Storing the specimens during curing.
7. Strength testing the lime-cement-soil mixtures.
8. Reducing and presenting the data obtained.

This procedure can be used to investigate the impact of the following variables, which are commonly considered during laboratory mix design studies: type of stabilizer, amount of stabilizer, and proportions of stabilizer. If desired, the procedure can accommodate the investigation of many other variables as well.

Tentative Dose Rate Correlation

For coastal Virginia soils treated with 100% cement in the dry mix method, the relationship $q_{u\,(28\,day)} = 1700\ kPa / 1.27^{(w/c)}$ can be used to estimate the amount of cement required to reach a desired 28-day strength where *w/c* is the clay-water to cement ratio.

AREAS FOR FURTHER RESEARCH

- **Development of a Screening Procedure** A comprehensive screening procedure was not developed during this research; however, the recommended laboratory procedure could be applied to a variety of soils with different characteristics, such as organic content, pH, liquidity index, mineralogy, sulfate content, etc. It may then be possible to establish a correlation between base soil characteristics and unconfined compressive strength of lime-cement-soil mixtures. Such a correlation would be useful to assess the feasibility of lime-cement column application in a particular base soil. The correlation developed in this research between $q_{u\,(28\,day)}$ and the *w/c* ratio for 100% cement mixtures may serve as a good starting point for such a correlation.

- **Correlation between Laboratory Strength and In-situ Column Strength** There are many factors influencing the relationships among the laboratory strength of laboratory-mixed samples, the laboratory strength of cored samples, and in-situ column strength. Soil mixing equipment varies in the number of paddles, paddle configuration, speed of rotation, penetration/withdrawal speeds, dosage during penetration/withdrawal, etc. Mixing energy formulas are an attempt to quantify the column installation variables, but the coring variables are more difficult to quantify. It would be useful to compare the strengths of laboratory-prepared specimens with the actual strength developed in the field. In-situ columns could be cored using specified methods, tested for unconfined compressive strength, and compared to the strength of specimens prepared in the laboratory. Another factor is the influence of confining pressure on column strength, and this could be investigated with triaxial compression tests.

- **Field Quality Control/Quality Assurance** Much work is needed to develop and optimize quality control and quality assurance procedures for lime-cement column construction in the field. Such procedures could include observations of column construction, laboratory testing of specimens formed from grab samples, laboratory testing on core samples, direct penetration tests, reverse penetration (pull-out) tests, pressuremeter tests, column load tests, and geophysical tests.

- **Drained Strength Behavior** Some stability analysis procedures for ground stabilized with lime-cement columns require values of effective stress strength parameters. Drained triaxial compression tests or undrained tests with pore water pressure measurements could be performed for this.

ACKNOWLEDGMENTS

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URS Greiner Woodward Clyde transmittal to Dr. James K. Mitchell, URS Protocol, dated September 7, 2000.

Appendix A

Laboratory Procedure for Preparing Specimens and Determining the Strength of Lime-Cement-Soil Mixtures[1]

Equipment

1. 50 mm diameter, 100 mm tall plastic molds with lids
2. 5 mm diameter brass rod
3. 20 kg packing load
4. Calipers
5. Camera
6. Household vacuum
7. KitchenAid stand mixer; 4 liter capacity, 450 watt, model K455 with dough hook and flat beater
8. Mixing bowls
9. Moisture tins
10. Quicklime
11. Razor blade
12. Sandpaper
13. Scale
14. Spatula
15. Straight edge
16. Tape measure
17. Type I/II cement
18. Unconfined compression apparatus

Base Soil Storage and Handling

1. Immediately upon obtaining the base soil, place the samples in airtight containers in order to minimize exposure to air. If samples are obtained in blocks suitable for storage in five gallon buckets, first place a thick gauge plastic bag into the bucket, place the bulk sample inside the bag, and pour a small amount water between the bag and the bucket to create a humid atmosphere inside the bucket. Using a household vacuum, remove the excess air from the bag, seal the bag tightly, and place the lid on the bucket. If samples are retrieved in Shelby tubes, extrude the samples as soon as possible. Cut the samples into pieces, wrap each in a thin plastic film, and place the pieces into plastic storage bags. All samples should then be kept sealed and stored in a moist room at 100% relative humidity and at 20° C, or other conditions as specified by the engineer.

Soil Preparation

2. Obtain approximately 3000 g of wet soil from the bulk samples. This much soil will produce eight specimens, allowing two specimens to be strength tested at each of the four cure times. Depending on the purpose of the testing, it may be desirable to group bulk samples to represent various zones in the subsurface. If several bulk samples represent a single zone, then equal amounts of soil can be taken from each of these bulk samples to make up the 3000 g of wet soil needed to make a batch of eight specimens. Remove excess air from the plastic bags containing the samples and re-seal them.

---

[1] This procedure is adapted from and is very similar to the procedure described in the Swedish Geotechnical Society (SGS) Report 4:95E.

3. If the batch mix uses soil from more than one bulk sample, mix the conglomerate soil thoroughly for 3 – 4 minutes using the kitchen mixer with the dough hook.

4. Take two representative 20 g samples for moisture content analysis. In order to reduce the time of air exposure, a microwave oven drying method (Hagerty et al. 1990) may be used for soils with low organic content.

5. Weigh remaining soil to the nearest gram.

6. If the influence of initial moistures is being studied or standardization of initial water content is desired, calculate, add, and blend the amount of water required to raise the water content to the desired value.

Lime & Cement Preparation

7. Determine the amount of lime and cement to add to the nearest g, based on kg stabilizer per cubic meter of soil to be treated:

$$\text{Amount of Cement to Add (g)} = \frac{W_{TOT}\left(S + wG_s\right)}{G_s S \gamma_w \left(1 + w\right)}\left(DR\right)\left(\text{Cement Proportion}\right)$$

$$\text{Amount of Lime to Add (g)} = \frac{W_{TOT}\left(S + wG_s\right)}{G_s S \gamma_w \left(1 + w\right)}\left(DR\right)\left(\text{Lime Proportion}\right)$$

Where:
W_{TOT} = Wet weight of batch prior to the addition of stabilizer (g)
w = Moisture content of batch prior to the addition of stabilizer
G_S = Specific gravity of the soil solids
S = Degree of saturation of the soil, which is often assumed to be 1.0 for clays below the water table
γ_w = Unit weight of water (kg/m^3)
DR = Dose rate in kg of stabilizer / m^3 of soil to be treated
Proportion of Cement = Weight of cement / weight of cement and lime
Proportion of Lime = Weight of lime / weight of cement and lime

8. After weighing out the appropriate amount, use a separate bowl to dry mix the lime and cement together.

Soil-Stabilizer Mixing

9. The mixer used in this research has an inner and outer spindle. When the mixer was set at its slowest speed, the outer spindle rotated at about 68 rpm and the inner spindle rotated at about 155 rpm. The dough hook was used as the mixing tool. Sprinkle the lime-cement mixture over the soil within the first minute of mixing. Mix for a minimum of 3 minutes, and continue mixing until uniform in color and consistency, but do not mix for more than 5

minutes. At some point(s) during the mixing process, it might be necessary to stop the mixer and, using a spatula, scrape the unmixed soil on the sides and bottom of the mixing bowl into the mixed portion, and resume mixing.

Placement of Mixture in Molds

10. Appropriately label clean dry molds (this can be done at an earlier time).

11. If the sample is of such a consistency that it can be poured, fill the mold to the top and tap against a hard surface, releasing air bubbles, and skip Steps 12 – 15. Otherwise continue with Step 12.

12. Spoon in a 25 mm thick lift (1/4 of the mold height) of the mixture into the mold.

13. Using a 5 mm diameter brass rod, rod the lift evenly 25 times.

14. Using a 48 mm diameter aluminum piston, apply a pressure to the top of the lift for 5-10 seconds. The pressure should be the maximum pressure that does not cause extrusion of the mixture between the piston and the plastic mold, while also not exceeding 100 kPa.

15. Repeat Steps 12 – 14 three additional times, until the mold is full.

16. Screed the top of the specimen flush with the top of the mold using a straight edge and put on the lid.

17. Repeat Steps 11 – 16 for each specimen within 20 minutes of mixing. A total of eight specimens should be produced.

Storage

18. Place samples in a moist environment at the specified temperature for the specified times.

19. Remove two of the specimens from the moisture room at 7, 14, 28, and 56 days after mixing and prepare for unconfined compression testing.

UU Preparation & Testing

20. Using a fabricated mold holder, cut through the mold from top to bottom along four equally spaced lines, being careful not to damage the specimen. The mold holder shown in Figure A-1 is a 130 mm long section of steel tube with a 54 mm ID and a 12 mm wall thickness. The mold holder has a 110 mm long slot to serve as a guide for cutting through the mold. The knife blade is set to cut through the mold but not penetrate into the specimen. After cutting four slots through the mold, it can be easily peeled off of the specimen.


Figure A-1. Cutting the Mold for Sample Extraction

21. For specimens of stiff to hard consistency, it may be necessary to sand the specimen ends and edges with sandpaper such that the ends are planar and parallel.

22. Measure and record each specimen height and diameter at 2 locations, and weigh.

23. Record the time and date.

24. Run unconfined compression tests as per ASTM D2166-98a at a strain rate of approximately 1 percent per minute.

25. Record the load versus deformation data so that a plot of stress versus strain can be prepared.

26. Record the mode of failure and photograph the failed specimen.

27. Determine the moisture content of specimen fragments after performing the unconfined compression test.

Data Reduction

28. After recording 7, 14, 28 and 56 day strengths, plot all eight values of unconfined compressive strength versus curing time.

29. Fit the logarithmic trend line $q_u = q_{u0} + a \ln (t - t_0)$ through the data, where
    q_u = unconfined compressive strength
    t = cure time
    q_{u0}, a, and t_0 = coefficients obtained by least-squares regression.

30. Determine the 28-day strength from the trend line.

31. Determine the dose rate of each proportion of stabilizer in the batch mix; e.g., a batch mixed at 200 kg/m^3 at a lime cement proportion of 25:75 equals 50 kg/m^3 of lime, and 150 kg/m^3 cement. See the examples in Table A-1.

Table A-1. Lime Proportions, Cement Proportions and 28 Day Strength Values

Batch No.	Dose Rate (kg/m^3)	Lime Proportion (%)	Cement Proportion (%)	Lime Dose (kg/m^3)	Cement Dose (kg/m^3)	28-Day Strength (kPa)
1	100	0	100	0	100	450
5	150	0	100	0	150	625
6	150	25	75	37.5	112.5	550
9	200	0	100	0	200	790
10	200	25	75	50	150	790

32. Repeat steps 2 through 31 for at least four other batch mix designs. Typical ranges of dose rates vary from 70 to 300 kg/m^3 (Ahnberg and Holm 1999). A smaller range might be specified for a particular project, in which cement dose rates might range from 100 to 200 kg/m^3 and lime dose rates from 0 to 50 kg/m^3.

33. Locate the batches on a plot with cement dose on the horizontal axis and lime dose on the vertical axis. In many cases, the remolded base soil has a very soft consistency, and the strength is approximately zero when compared to the strength of lime-cement-soil mixtures. If this is the case, it may be reasonable and useful to assume a 0, 0, 0 point for the purpose of drawing contour lines.

34. Draw 28-day strength contours, as shown in Figure A-2. This example was created using the data shown in Table A-1.

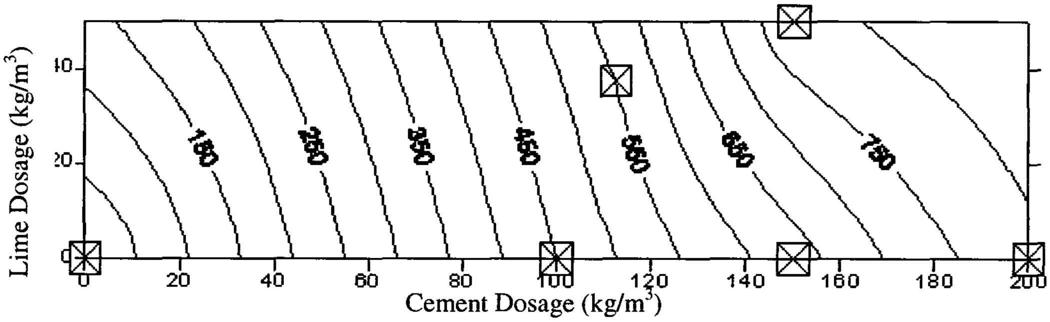


Figure A-2. 28 Day Strength Contours (kPa)

35. After the initial batches have been tested and the contour plot is created, an estimate of the amounts of stabilizer necessary to reach the desired strength can be made. It might be necessary to mix and test additional batches and plot the results on the same contour plot to extend and/or refine the region of interest.

Appendix B

Lime and Cement Physical Characteristics

Chemical Lime
A Lhoist Group Company

CHEMICAL GRADE HYDRATED LIME

Typical Chemical Analysis

	Percentage
$Ca(OH)_2$ (Available)	93.00
CaO (Total)	73.70
MgO (Total)	
SiO_2	1.25
Fe_2O_3	0.14
Al_2O_3	
Sulfur (S)	0.015
Manganese (Mn)	0.005
Chloride as NaCl	0.011
Free Moisture	0.65
Loss on Ignition	23.15
CO_2	
Calcium Carbonate Equivalent	

Typical Screen Analysis (Wet)

		Percentage
Through #100 Mesh (US Sieve)		95.0
Through #200 Mesh (US Sieve)		91.0
Through #325 Mesh (US sieve)		90.0
Bulk Density-Loose	25.0 lbs/Ft^3	
-Compact	45.0 lbs/Ft^3	
Specific Gravity	2.3	

Shipments in Bulk: Truck (Pneumatic); 50# Bags minimum order 4 pallets @ 45 Bags per pallet; Truck (Flatbed or Van).

Guaranteed by CLC to meet AWWA B202-83 standards for hydrated lime.

Chemical Lime Company
2093 Big Stony Creek Road
Ripplemead, VA 24150
Phone: (540) 626-8731 Fax: (540) 626-7234

Chemical-Hyd rev. 3-8-01

Chemical Lime
A Lhoist Group Company

HIGH CALCIUM QUICKLIME
(Oxide)

Typical Chemical Analysis

	Percentage
CaO (Total)	95.50
CaO (Available)	92.00
MgO (Total)	1.60
SiO_2	1.65
Fe_2O_3	.16
Al_2O_3	0.50
Sulfur (S)	0.025
Loss on Ignition	0.60
Calcium Carbonate Equivalent	172

Typical Physical Analysis

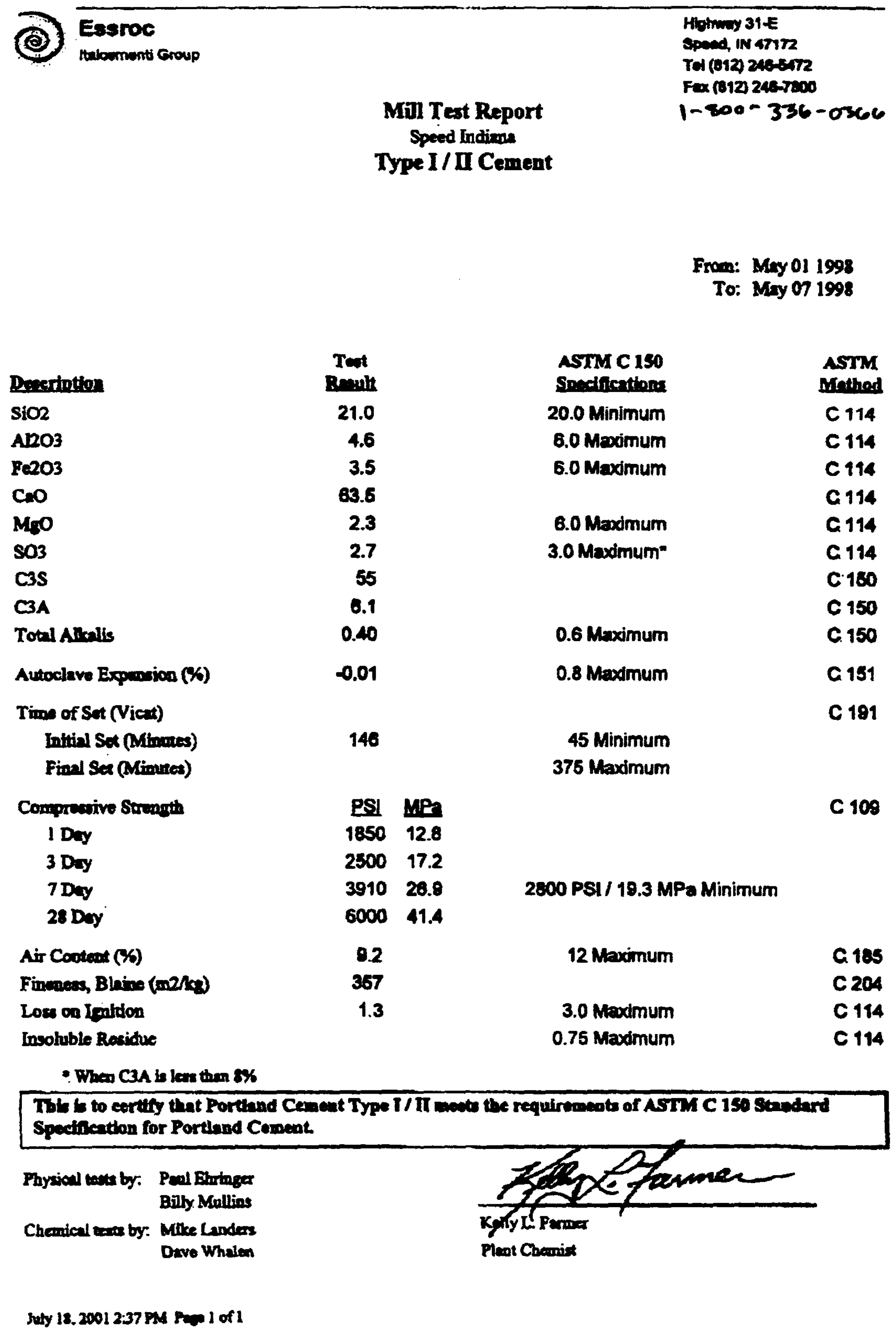
Temperature rise in 30 seconds	
Total active slaking time	3.0 min
Total temperature rise	
Slaking residue (on 100 Mesh sieve)	3.2

	Sizing Range
Rice	1/16" - 1/4"
Small	1/4" - 1"
Large	1" - 2"
Fines	0" - 1/16"

Shipment in Bulk: Rail (Hopper Cars); Truck(Dump or Pneumatic)

Chemical Lime Company
2093 Big Stony Creek Road
Ripplemead, VA 24150
Phone: (540) 626-8731 Fax: (540) 626-7234

Hi-Cal QL rev. 3-8-01



Essroc
Italcementi Group

Highway 31-E
Speed, IN 47172
Tel (812) 246-5472
Fax (812) 246-7800
1-800-336-0366

Mill Test Report

Speed Indiana

Type I / II Cement

From: May 01 1998
To: May 07 1998

Description	Test Result		ASTM C 150 Specifications	ASTM Method
SiO2	21.0		20.0 Minimum	C 114
Al2O3	4.6		6.0 Maximum	C 114
Fe2O3	3.5		6.0 Maximum	C 114
CaO	63.6			C 114
MgO	2.3		6.0 Maximum	C 114
SO3	2.7		3.0 Maximum*	C 114
C3S	55			C 150
C3A	6.1			C 150
Total Alkalis	0.40		0.6 Maximum	C 150
Autoclave Expansion (%)	-0.01		0.8 Maximum	C 151
Time of Set (Vicat)				C 191
Initial Set (Minutes)	146		45 Minimum	
Final Set (Minutes)			375 Maximum	
Compressive Strength	PSI	MPa		C 109
1 Day	1850	12.8		
3 Day	2500	17.2		
7 Day	3910	26.9	2800 PSI / 19.3 MPa Minimum	
28 Day	6000	41.4		
Air Content (%)	9.2		12 Maximum	C 185
Fineness, Blaine (m2/kg)	357			C 204
Loss on Ignition	1.3		3.0 Maximum	C 114
Insoluble Residue			0.75 Maximum	C 114

* When C3A is less than 8%

This is to certify that Portland Cement Type I / II meets the requirements of ASTM C 150 Standard Specification for Portland Cement.

Physical tests by: Paul Ehringer
Billy Mullins

Chemical tests by: Mike Landers
Dave Whalen

Kelly L. Farmer

Kelly L. Farmer
Plant Chemist

July 18, 2001 2:37 PM Page 1 of 1

CAPITOL CEMENT CORPORATION
POST OFFICE BOX 885
MARTINSBURG, WV. 25401
TELEPHONE: (304) 267-8966

ISSUE DATE FOR REPORT

Cement Laboratory Report

Customer: THIS IS A MILL TEST
STANDARDS SHEET FOR THE
PRODUCT LISTED BELOW.

Product: Type II Paper

SILO NUMBERS: 31

TEST DATA

Chemical Analysis

SIO2.............	20.00	(%)
AL2O3............	4.72	(%)
FE2O3............	2.79	(%)
CAO..............	60.47	(%)
MGO..............	2.31	(%)
SO3..............	2.50	(%)
Ignition Loss....	1.12	(%)
Free CAO.........	.09	(%)
NA2O Equivalent..	.64	(%)

Physical Analysis

Fineness:		
Blaine..........	3795	(CM2/GM)
Passing #325....	90.70	(%)
Normal Consis...	25.00	(%)
Gilmore Set:		
Initial.........	170	(MINS)
Final...........	280	(MINS)
Vicat Set:		
Initial.........	111	(MINS)
Final...........	190	(MINS)
Air Content..........	6.50	(%)
Autoclave Exp........	.04	(%)

POTENTIAL COMPOUNDS

C3S..............	51.30	(%)
C2S..............	18.70	(%)
C3A..............	7.80	(%)
C4AF.............	8.50	(%)

COMPRESSIVE STRENGTH

1 Day.................	2290	(PSI)
3 Days................	3420	(PSI)
7 Days................	4280	(PSI)
28 Days...............		(PSI)

Meets Latest Requirements of ASTM
C-150 and AASHTO M-85 Standards

FRANK SOWERS 4/15/2002
Quality Assurance Manager

Appendix C
Laboratory Procedure for Microwave Drying of Soils

Drying of soil specimens in microwave ovens can permit rapid determination of moisture content. A laboratory study was performed by Hagerty et al. (1990) to investigate the difference between soil moisture contents based on microwave oven drying and moisture contents developed by conventional drying procedures. For nine materials ranging from dense-graded aggregate to highly plastic clays, differences between moisture contents obtained by the two methods were very small, in many cases not exceeding the variability among values obtained from multiple specimens of the same soil dried in a conventional oven. A similar study was performed at Virginia Tech on the I-95/Route 1 soil, and good agreement between microwave and oven dried moisture contents was also found, as shown in Figure C-1.

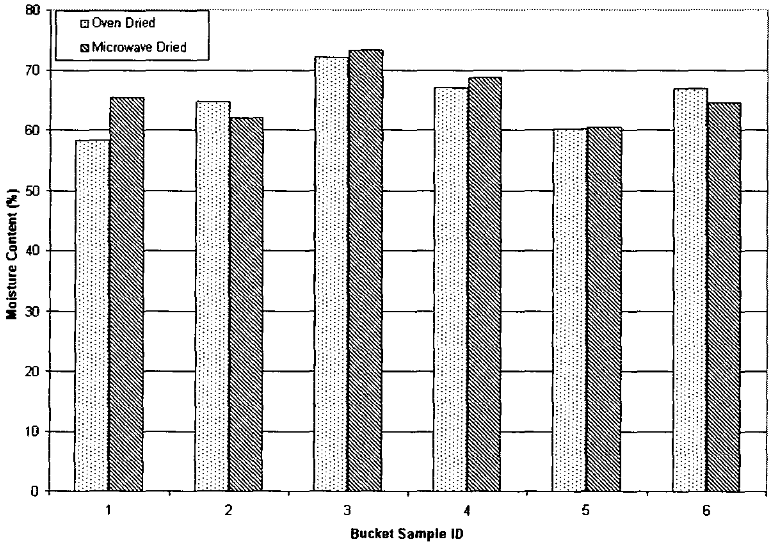


Figure C-1. Microwave versus Oven-Dried Moisture Content

The length of time required to microwave dry the specimens was determined by drying a specimen until constant mass was achieved, which was 3 minutes, as shown in Figure C-2.

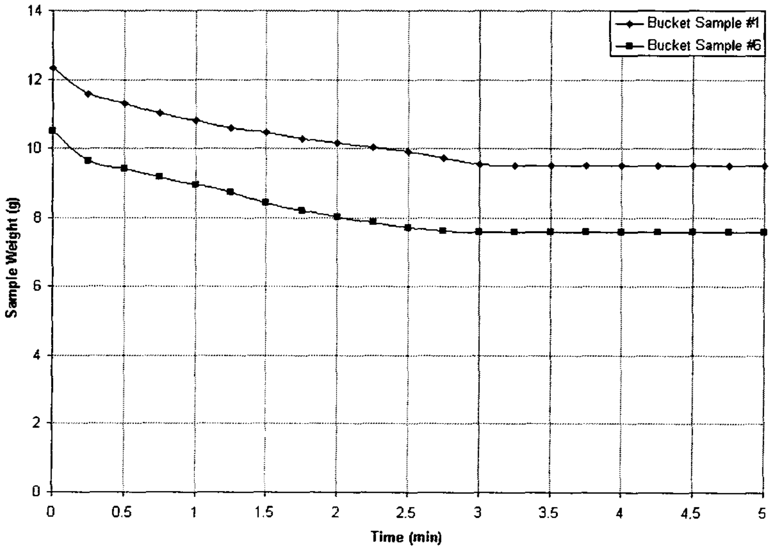


Figure C-2. Weight versus Time for the Microwave Drying Procedure