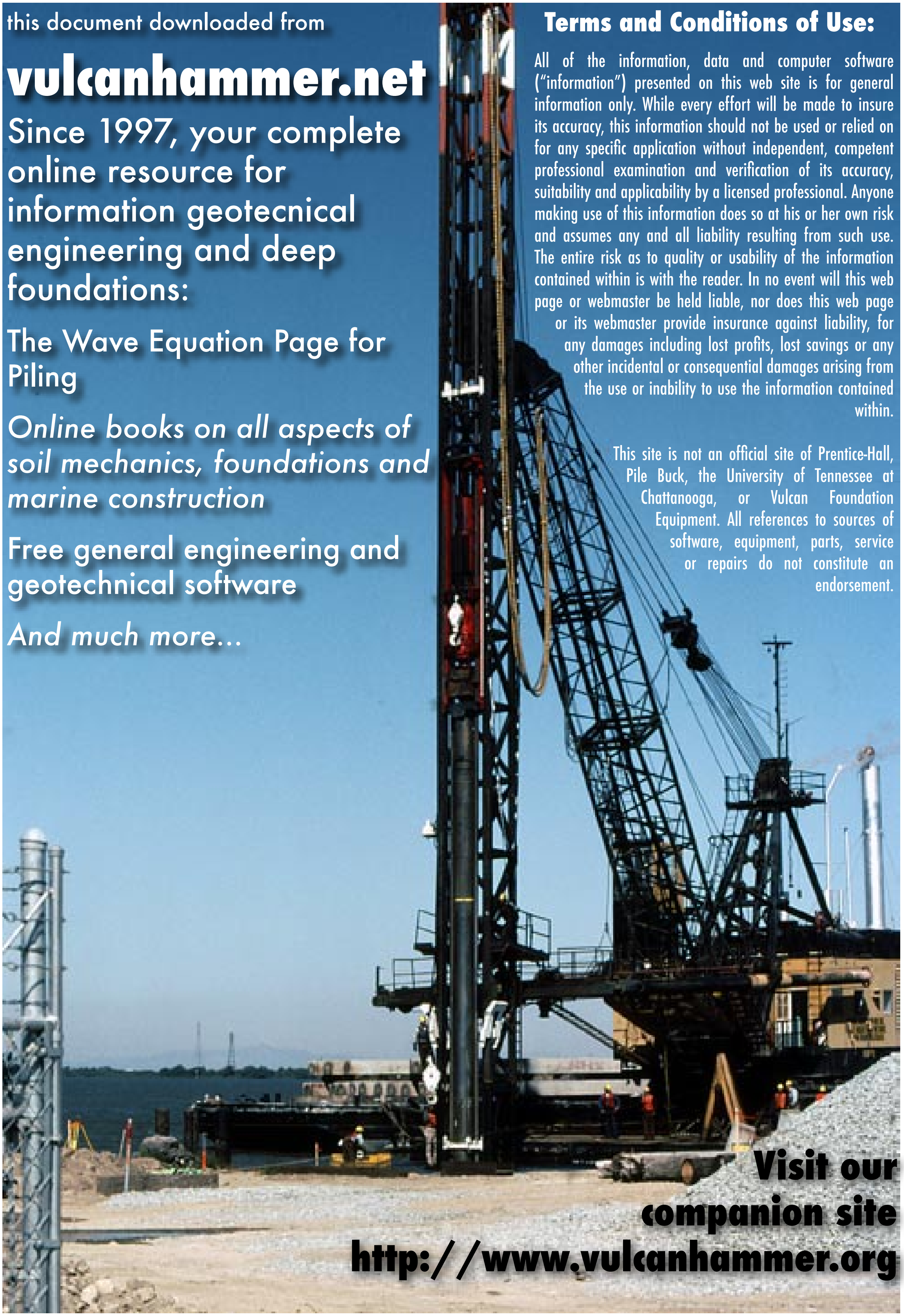

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Stabilization of Clay Soils with Nontraditional Additives

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Stabilization of Clay Soils with Nontraditional Additives

Abstract

A laboratory experiment was conducted to evaluate the stabilization of low- and high-plasticity clay soils with nontraditional chemical or liquid stabilizers. Clay soil specimens were mixed with various stabilization products and compacted using a gyratory compaction machine to approximate American Society for Testing Materials (ASTM) D 1557 moisture-density compaction. Each specimen was subjected to “wet” and dry testing following a 28-day cure period. Twelve nontraditional stabilizers were evaluated in this experiment including an acid, enzymes, a lignosulfonate, a petroleum emulsion, polymers, and a tree resin. Additional specimens were stabilized with Type I portland cement and hydrated lime to provide a comparison to traditional stabilizers under the same mixing, compaction, and curing conditions. The analysis of the test data consisted of determining the average strength, in terms of unconfined compression strength, of three replicate specimens of each mixture. The average strength of the three replicates of each additive was compared to the average strength results of the remaining nontraditional additives, the traditional stabilization results, and a series of control specimens that were not stabilized. The results of the experiment indicate increased strength of some nontraditionally stabilized specimens when compared to both the control series and the traditional stabilization alternatives. Other nontraditional stabilizers did not demonstrate significant increased strength compared to the control series for the conditions of this experiment. Many of the stabilized specimens were highly moisture susceptible indicating the potential for poor performance when exposed to adverse environmental conditions, while a few specimens demonstrated excellent performance when exposed to moisture. Specific product categories are recommended for stabilizing low- and high-plasticity clay soils.

INTRODUCTION

The design and construction of low-volume roads typically requires engineers to incorporate poor quality soil and aggregate into the pavement structure. This necessity is often dictated by the availability of quality materials, haul distances, economic considerations, and political concerns. The “poor quality” or “marginal” materials usually have the potential to demonstrate undesirable engineering behavior such as low bearing capacity, high shrink/swell potential, high moisture susceptibility, and poor freeze-thaw durability. These negative soil performance characteristics are generally attributed to the nature and quantity of the fines present in the material. Thus, fine-grained soils such as silts and clays tend to present the most problematic materials. Poor engineering performance of readily available materials has forced engineers to attempt to improve the engineering properties of poor quality soils and aggregates through soil stabilization. Traditional stabilization methods include the application of various combinations of lime, cement, fly ash, and bituminous materials. These traditional stabilization techniques often require lengthy cure times and relatively large quantities of additives for significant strength improvement. Calcium-based products such as cement, lime, and fly ash also have the potential to develop adverse chemical reactions in sulfate-bearing soils. These concerns have led industry and government agencies to seek alternative stabilization methods such as concentrated liquid stabilizers, waste byproducts, and geosynthetics.

Nontraditional concentrated stabilization additives have become increasingly available for commercial and military applications. For the purposes of this study, the products were divided into seven categories: salts, acids, enzymes, lignosulfonates, petroleum emulsions, polymers, and tree resins. Many of these stabilizers are advertised as requiring lower material quantities, reduced cure times, higher material strengths, and superior durability compared to traditional stabilization additives. Unfortunately, little research has been completed to distinguish between products that deliver enhanced performance and those that do not. The nature of soil stabilization dictates that products may be soil-specific and/or environment-sensitive. In other words, some products may work well in specific soil types in a given environment, but perform poorly when applied to dissimilar materials in a different environment. The rapid evolution of existing products and introduction of new stabilizers further complicate the process of defining the performance characteristics of the various nontraditional soil stabilization additives.

RESEARCH OBJECTIVES

The primary objective of the research described in this paper was to screen commercial off-the-shelf chemical stabilizers and determine the potential engineering benefits of these products for stabilizing low- and high-plasticity clay soils (CL and CH). This research focused upon increased load-bearing capacity as the basis of performance characterization as indicated by unconfined compression strength (UCS). The specific objectives included determining required additive quantities, the magnitude of strength improvement, the relative strength improvement compared to other additives, and moisture susceptibility. The experiment was designed to provide alternatives to traditional stabilization materials for improving the load-bearing capacity of CL and CH subgrade materials.

The research scope included the execution of an extensive laboratory test matrix including variations in soil type (CL or CH), additive type, and additive quantity. Six specimens of each mix design were molded using gyratory compaction and allowed to cure under controlled conditions for 28 days. Unconfined compression (UC) tests were used to provide an index of performance for all test specimens. A “wet” test procedure was developed to provide an indication of the moisture susceptibility of the stabilized specimens. Three of the six specimens for each mixture were tested under dry conditions, while the remaining three specimens were subjected to UC tests following the “wet” test procedure. Selected stabilizers were mixed with either CL soil only or each of the CL and CH soils. It is the intention of the authors to present this data as a limited and independent evaluation of the performance of selected nontraditional stabilization additives for stabilizing low- and high-plasticity clays. This study is limited in terms of the number of additives evaluated, the range of additive quantities used, the range of cure times, the limitations of laboratory testing versus field testing, and the absence of detailed soil testing to identify fundamental soil properties. However, the study does provide an unbiased comparison of selected stabilizers based upon controlled laboratory testing using an expedient index test.

LITERATURE REVIEW

A review of the literature indicates that there has been a large quantity of research completed regarding the application of traditional stabilization additives such as lime, cement, and fly ash (1-3). However, little independent research has been documented pertaining to the use of nontraditional stabilization additives. A large quantity of advertisements, pamphlets, and videos has been distributed testifying to the benefits of a particular stabilization additive. Unfortunately, most of the information disclosed in these media is subjective and traditional engineering properties are poorly documented. Due to the proprietary nature of the majority of these products, the mechanisms by which they interact with the soil are unknown. Another concern is the discontinuity of brand names resulting from frequent reformulations and changes in marketing strategies. Frequent brand changes result in a lack of product history and eventually poor user familiarity. One final barrier to the acceptance of nontraditional stabilization additives is the lack of standardized test procedures for evaluating product potential. Early attempts at standardizing testing protocol were too inclusive requiring an expensive array of laboratory tests or rationalized selection of specific tests based upon performance objectives (4). Thus, the procedures selected for product evaluation were still left to each agency’s discretion resulting in a poor basis for performance comparisons among different agencies. More recent standardized testing protocol established by the American Society of Testing and Materials (ASTM) in standard ASTM D 4609 provides more detailed guidance, but has yet to achieve widespread acceptance. Due to the lack of accepted evaluation procedures, individual agencies such as Texas Transportation Institute (5) and the U.S. Army Engineer Research and Development Center have developed their own.

The variety of nontraditional stabilization additives has led to various attempts to categorize products according to their active components. Oldham et al. (6) developed a synthesis of potential stabilizers identified by the Corps of Engineers and contract researchers from 1946 to 1977. Their report identified acids, asphalt, cement, lime, resins, salts, silicates, and other products as potential stabilizers demonstrating varying degrees of success. The results of their investigation divided performance by soil type and demonstrated that product performance differed for varying soil types. They also noted that the stabilization mechanisms for individual stabilizing agents, such as salts, were particularly suited for specific climates and environmental conditions. Unfortunately, most of the products evaluated under the research documented in this reference are no longer commercially available, have altered their formulas, or have changed trade names. Scholen (7) categorized nontraditional stabilizers into five groups: electrolytes, enzymes, mineral pitches, clay fillers, and acrylic polymers. The proprietary nature of many of the products hinders the categorization process.

Scholen (7, 8) also attempted to describe the reinforcement mechanisms for the electrolytes and enzymes. Scholen hypothesized that the electrolytes or ionic stabilizers served as catalysts to accelerate the weathering process of individual clay minerals. He proposed that the ionic stabilizers alter the electrolyte concentration of the pore fluid resulting in cation exchange and flocculation of the clay minerals. As the clay minerals attract stronger cations from the ionic electrolyte pore fluid, the higher valence cations collapse the clay structure into a more stable configuration exuding excess double-layer water in the process. The resulting clay material typically exhibits reduced plasticity, reduced swell potential, and reduced particle size. However, Scholen notes that a change in the quality of the environment from alkali to acidic or vice versa can result in a complete change in the material's molecular structure but usually over long periods of time (7). Scholen also hypothesized the mechanism by which enzymes could stabilize clay materials (7). He proposed that the enzymes could bond with large organic molecules that would be attracted to the clay minerals net negative surface charge. The large organic molecules would then surround the clay minerals neutralizing the negative charge and reducing the clay's affinity for moisture. The end result of both proposed mechanisms is a more stable clay lattice structure and a reduced affinity for moisture.

Numerous laboratory experiments have been conducted over the years with specific soil stabilizers. Although frequent brand changes and product reformulation have rendered specific product performance reports obsolete, performance trends and behavioral characteristics of individual product categories remain meaningful. Given this consideration, various research findings are presented focusing on the performance trends of individual product categories. For example, Scholen (7, 8) indicated that limited laboratory testing revealed only minor changes in grain size distribution and Atterberg limits for 10 clays gathered from construction projects stabilized with one of seven chemical stabilization additives including electrolytes, enzymes, mineral pitch, clay filler, and an acrylic polymer. Thus, no particular additive was recommended.

Ajayi-Majebi et al. (9) conducted an experiment designed to determine the effects of stabilizing clay-silt soils with the combination of an epoxy resin (bisphenol A/epichlorohydrin) and a polyamide hardener. The additive mixture was composed of a 1:1 ratio of epoxy resin to polyamide hardener. Reported soil properties included a liquid limit ranging from 37 to 45 and a plasticity index ranging from 13 to 18. Ajayi-Majebi et al. concluded that admixing up to 4 percent stabilizer into a clay-silt material produced large increases in the load-bearing capacity of the material in terms of its unsoaked California Bearing Ratio (CBR). They observed that increases in the temperature of the curing environment led to increased strength formation. Cure times for the stabilization agent were reported as low as three hours.

Katz et al. (10), Rauch et al. (11), and Rauch (12) conducted a series of laboratory experiments designed to measure the engineering property effects and mechanisms of three liquid stabilizers on five clay soils. The 3 liquid stabilizers included an ionic stabilizer (electrolyte), an enzyme, and a polymer product. The clay materials consisted of three relatively "pure" clay minerals (kaolinite, illite, and sodium montmorillonite) and two high-plasticity clays. The liquid limits of the two natural clay soils ranged from 60 to 68, and the plasticity indices ranged from 37 to 48. Katz et al. (10) performed various laboratory mineralogy tests on sodium montmorillonite clay samples stabilized with the ionic stabilizer at manufacturer recommended additive rates. Their results indicated only minor changes in the d-spacing between molecular layers and concluded that the application rates were much too low to effectively accelerate the clay's "weathering" process as proposed by Scholen (7, 8). A follow-on study was conducted by Rauch et al. (11) to measure changes in commonly reported engineering properties for the three stabilizers and five clay materials. The study concluded that the only effective reduction in plasticity occurred with the ionic stabilizer in sodium montmorillonite. They reported no significant effect of any stabilizer on the compacted density or optimum moisture content. Also, among the three products evaluated, there was no consistent reduction in swell potential. Further unpublished testing by Rauch (12) including the same three stabilizers and five clay minerals indicated only minimal changes in X-ray diffraction results, specific surface area, and alumina-silica ratios for very high additive quantities of 50 percent by dry weight of clay. However, the researchers noted that the minor changes in the properties of the clay minerals did tend to support Scholen's hypothesized mechanisms for the ionic and enzyme stabilization additives.

Laboratory testing conducted by Scullion (5) on a clay soil stabilized with two acid (ionic) stabilizers revealed no significant reduction in shrink/swell potential or strength improvement for either product. Analyses of treated and untreated samples failed to reveal any observable changes within the stabilized specimens using pH measurements, scanning electron microscope (SEM) imaging, and energy dispersive spectrometer (EDS) analyses.

Many manufacturers contend that common laboratory testing procedures do not provide adequate indicators of field performance. Scholen (7) reported 34 abbreviated citations of successful field use of 7 different nontraditional stabilization products. Unfortunately, these testimonials are poorly documented and do not include direct comparisons to untreated control sections. Indeed, the authors of this paper have found that a common tendency is to only report or publish successful projects making it difficult to discern the success rate of specific products. The authors have personal knowledge of at least two unsuccessful projects completed with the use of one of the ionic stabilizers reported by Scholen. Scullion (5) conducted field experiments during two highway construction projects in Texas to evaluate the potential for two ionic stabilizers and one polymer additive to stabilize an expansive clay subgrade. Scullion reported that none of the products provided an effective working platform. Dynamic cone penetrometer and falling-weight deflectometer results showed no substantial improvement in bearing strength or stiffness. It should be noted that the polymer experienced curing problems that resulted in its exclusion from further testing.

In summary, various researchers have divided nontraditional stabilization additives into broad categories dependent upon the stabilizer's primary active components. Attempts to define the reinforcement mechanisms have been limited, but laboratory experimentation has provided minimal support for the hypothesized mechanisms for ionic stabilizers and enzymes. The benefit of many of the commercial stabilization additives for stabilization of clay soils has not been conclusively shown in the laboratory experiments cited. Well-documented field studies are lacking with limited testimonials indicating success. The approach of the research program presented in this paper is to screen commercial products to identify those demonstrating the greatest potential for success. Once specific products are identified, additional studies will be conducted to define the reinforcement mechanisms and evaluate their performance under field conditions.

MATERIALS

The stabilization additives used in this experiment were grouped into seven categories: traditional additives, acids, enzymes, lignosulfonates, petroleum emulsions, polymers, and tree resins. The traditional stabilization additives included: Type I portland cement and a hydrated lime. The remaining additives consisted of one acid, four enzymes, one lignosulfonate, one petroleum emulsion, four polymers, and one tree resin. Generic product names were used in this paper to avoid the unintentional endorsement of any product. A total of 12 and seven nontraditional stabilizers at varying concentrations were used to stabilize the CL and CH materials, respectively. Due to the proprietary nature of the commercial stabilization additives used in this research, the chemical composition and reinforcement mechanism by which they stabilize are relatively unknown. A new effort stimulated by this research is currently being conducted to define the constitutive properties and fundamental stabilization mechanisms for selected products. A brief discussion of possible stabilization mechanisms for acids (ionic) and enzymes was provided in the literature review. Potential mechanisms include a) encapsulation of clay minerals, b) cation exchange of monovalent cations for covalent cations, chemical breakdown of the clay mineral structure resulting in the reduction of double-layer water, and d) interlayer absorption of organic molecules resulting in reduced moisture susceptibility. However, the intent of this paper is not to define individual stabilization mechanisms for specific additives, but to provide a performance comparison. Selected products from this investigation will be subjected to more fundamental testing during future research to identify specific reinforcement mechanisms. For the purposes of this paper, the stabilization mechanisms of individual stabilizer categories can be grouped into two general forms, mechanical and chemical bonding. Manufacturers and distributors of these additives claim widespread performance of these products for "most" soil types and stabilization environments. A detailed analysis of the chemical composition of these products and their reinforcement mechanisms is beyond the scope of this paper. Material data sheets can be obtained through solicitation from individual manufacturers.

Both the low-plasticity clay (CL) and high-plasticity clay (CH) materials used in this experiment were collected from natural deposits in Vicksburg, Mississippi. Pertinent properties of the two clay materials are shown in Table 1. Classification of each material was in accordance with ASTM D 2487. Approximately 21 percent and 10 percent of the worldwide surface soils are classified as CL and CH, respectively (13). As noted previously, these soil types represent two of the most problematic materials in the construction of low-volume roads.

SPECIMEN PREPARATION

Prior to the start of the experiment, soil compaction curves were developed for 102-mm-diameter by 152-mm-high cylindrical specimens of each clay material using a gyratory compaction machine. A detailed test matrix is shown in Table 2. The matrix required preparation of over 390 specimens, and the gyratory compaction method provided a simple, reproducible, and reduced-effort method of preparing the specimens for testing. Additionally, previous gyratory compaction experiments demonstrated the ability to approximate modified proctor compaction by varying the gyration angle, ram pressure, and number of revolutions (14). The angle of gyration was set at 1.25° (0.022 rad) based upon the previous gyratory compaction experiments. The ram pressure and number of revolutions were varied to generate different compaction energies. A ram pressure of 870 kPa and 90 revolutions were selected to approximate the same compaction energy as ASTM D 1557 moisture-density compaction for both clay materials. A comprehensive explanation of the compatibility between gyratory compaction and ASTM D 1557 compaction is beyond the scope of this paper. Pertinent compaction characteristics of each material are shown in Table 1.

The optimum water content measured from the gyratory compaction was used as the target moisture content for each soil. Based upon prior experience, the target moisture content for the cement-stabilized CL specimens was increased to 17 and 18 percent for the seven and nine percent additive rates, respectively. The target moisture content for the lime-treated specimens was increased to 24 percent for the CH soils based upon prior experiments. The target moisture content for the lime-treated CL specimens was increased to 18, 19, and 20 percent for additive rates of three, five, and seven percent, respectively. These increases in moisture content were necessary to counter the effects of hydration during sample molding. Prior experience with the nontraditional stabilization additives used in this experiment indicated that the optimum moisture content for nontraditionally-stabilized materials did not change significantly from that of the untreated material shown in Table 1.

Specimen preparation consisted of six steps: soil preparation, additive preparation, soil-additive mixing, molding, compaction, and curing. The soil was prepared by air-drying the material to a moisture content of two to three percent, pulverizing large clods to pass the No. 4 sieve, determining the free water requirements to obtain the desired moisture, and mixing the soil-water to obtain the desired moisture content. Since both materials were clay, each material was sealed in a plastic container overnight to achieve equilibrium of the free moisture. Additive preparation varied depending upon the commercial additive used. Many of the additives required dilution of the concentrated product prior to mixing. The weight of the water used for dilution was combined with free water weight to produce the desired specimen moisture content as noted previously. The Lignosulfonate 1 product was purchased in powder form, and a 30 percent powder-water solution was used to ensure proper mixing using part of the required free water. Once the soil and additive preparation procedures were complete, the additive was mixed with soil using a high-speed rotary mixing bit and an electric drill. The additive was mixed into the soil in increments to achieve uniform mixing. The material was mixed until a uniform product was achieved. A wide-blade puddy knife was used periodically during mixing to prevent materials from adhering to the sides and bottom of the mixing container.

A sample of the mixed material was taken to determine the initial moisture content of the composite material according to ASTM D 4643. An initial quantity of loose material was measured for each specimen that would produce a 152-mm-high compacted specimen. The quantity of material used to mold each specimen was altered slightly after compacting the previous specimen to improve the accuracy of the compacted specimen height. The material was molded using a 102-mm-diameter by 254-mm-high gyratory compaction mold. The material was placed in five layers, and each layer was hand-rodded 25 times with steel rod to reduce the loose height of the material. This was necessary to ensure that all of the loose material would fit within the gyratory compaction mold. The top of the loose material was leveled using 10 blows of a rubber mallet on a 102-mm-diameter steel plate. A 0.254-mm-thick circular polypropylene membrane was placed on each end of the specimen to prevent adherence to the top and bottom mold plates. Once placed in the mold, the specimens were inserted into the gyratory testing machine and compacted using the procedures described previously. The compacted specimens were extruded from the gyratory mold using the hydraulic jack extrusion device mounted on the machine. The height of the compacted sample was recorded by the gyratory machine's software, and the compacted sample was weighed to calculate the as-molded wet and dry densities. All six specimens of each test series were compacted within 1 hour of mixing to within a range of 32 kg/m^3. All specimens were compacted to within 90 percent of the maximum dry density for the untreated soil shown in Table 1 except the 7 percent lime mixtures.

The compacted specimen was then placed in a temperature-controlled room where it was allowed to cure at 22.2°C and 40 percent relative humidity for 28 days. The curing process could be considered an air-dried rather than a moist curing process. This method of curing was selected to represent field conditions during construction operations and was also preferred by the suppliers of the nontraditional stabilizers over a moist-cure process. The curing process primarily consisted of the evaporation of moisture from the specimens over time and the hardening or cementation of the additive-soil matrix.

TESTS AND RESULTS

Tests

Six specimens of each mixture were prepared in the manner described. Three of the six specimens were subjected to unconfined compression (UC) tests once the designated curing period was complete. Note that the height to diameter ratio of the specimens was 1.5 rather than the traditionally recommended value of 2.0 for UC testing. This was due to the limitations of the size of the mold. It should also be noted, however, that this investigation is a comparative study in which all additives were tested under the same conditions. Emphasis is placed upon comparative performance rather than the ultimate unconfined compressive strength (UCS) of the material. These specimens were tested according to the "dry" test procedure. The remaining three specimens were tested according to the "wet" test procedure. Since the probability of exposure to moisture during the stabilized materials performance life in a low-volume road is extremely high, a "wet" test procedure was developed to evaluate the stabilized material's moisture susceptibility. Several wet test procedures were evaluated, but were deemed to be either not representative of field conditions, too complicated for large numbers of repetitions, or too harsh to permit effective specimen evaluation. Thus, a simplistic "wet" test procedure was developed in which the cured specimen was placed on its side in 25.4-mm of water for a period of 15 minutes (Figures 1 and 2). The specimen was then removed from the water and allowed to drain for five minutes. The specimen was then subjected to UCS testing. This "wet" procedure permitted a visual observation of the susceptibility to moisture, as well as, a physical evaluation of structural strength loss. The time for exposure to moisture was selected as 15 minutes, based upon the deterioration rate of the control specimens. Full soaking of the specimens by complete immersion was not selected due to the inability to disintegration rate of the control specimens and some of the "stabilized" specimens.

The UCS tests were conducted using an Instron® 4208 testing system. The Instron® system consists of the test loading instrument and a computer for recording results. The test specimen was positioned in the test instrument, and a seating load of 0.45 kg was applied. This initial load was required to ensure satisfactory seating of the compression piston, and it was considered as the zero load when determining the load-deformation relationship. The load was applied to each stabilized specimen at a constant rate of 0.042 mm per second. Each specimen was compressed until it reached a preset axial strain of 0.08 or until it collapsed.

Results

Tables 3 and 4 show a tabulation of the results of testing the stabilized soil and the control specimens for the CL and CH soil types, respectively. The UCS results were used as an index of specimen performance. The performance of test specimens relative to the performance of the control specimen, and each other, provided a means of evaluating the effects of stabilizer type, stabilizer quantities, and durability in terms of wet and dry conditions. The control specimens were composed of untreated soil prepared at the target moisture contents without any stabilizer. For this experiment, significant strength improvement was defined as a minimum increase in the compressive strength of the stabilized specimen of 345 kPa over the strength reported for the control specimens. Effective moisture resistance for this experiment was defined as a maximum reduction in UCS for the average "wet" test results of 50 percent of the average dry strength results. The results are shown graphically in Figures 3 through 6 for the CL soil and Figures 7 through 9 for the CH soil. The dashed lines on the figures indicate the average performance of the control specimens as a benchmark for comparisons.

The results of the tests indicated that some of nontraditional stabilizers significantly improved the UCS of the clay materials, while others had no significant effect on the UCS. For the CL soil stabilized with traditional additives (Figure 3), only the 9 percent concentration of cement improved the dry UCS by more than 345 kPa compared to the control specimens. All traditionally stabilized specimens improved the wet UCS over the control specimens by at least 345 kPa except for the three percent lime mixture. Overall, the traditionally stabilized CL samples demonstrated significant strength improvement and resistance to moisture susceptibility. However, for the CH soil the lime-stabilized specimens failed to improve either the dry or wet UCS for all specimens (Figure 7). In fact, the lime-stabilized specimens disintegrated during the "wet" test procedure and could not be tested.

For the CL soil stabilized with nontraditional additives (Figures 4 through 6), Lignosulfonate 1 and Polymer 1 increased both the dry and wet UCS. Enzyme 2, Polymer 2, Polymer 3, and Petroleum Emulsion 1 demonstrated significant "wet" UCS improvement for the CL soil specimens. For the CH soil stabilized with nontraditional products (Figures 7 through 9), Acid 1, Enzyme 1, Enzyme 2, and Polymer 1 increased the dry UCS. The wet test results for the CH specimens show that Enzymes 1, 2, and 4 along with Polymers 1 and 3 significantly improved the wet UCS by at least 345 kPa. Effective resistance to moisture was defined as a wet UCS strength of at least 50 percent of the dry UCS strength. Lignosulfonate 1, Enzyme 2, Polymer 3, Petroleum Emulsion 1, and Tree Resin 1 demonstrated effective resistance to moisture degradation for CL soil specimens. For CH samples, only Polymers 1 and 3 provided significant resistance to moisture degradation. These results indicate varying performance by different stabilization additives dependent upon additive type, additive, quantity, soil type, and testing conditions (dry/wet).

Effect of Stabilizer Type

The effect of stabilizer type was evaluated by testing six control samples, 12 nontraditional stabilizer types, and three traditional stabilizer types (Table 2). The cement stabilized CL soil test results show improved UCS under both the dry and wet test conditions. However, the results of the lime-stabilized specimens show reduced dry UCS for both the CL and CH soils. The CL soil stabilized with lime did show increased wet UCS, but the CH specimens disintegrated under wet conditions. Thus, the cement was more effective than lime in stabilizing the CL soil for strength improvement. Lime was ineffective in improving the UCS of the CH soil probably due to a lack of moist curing.

The test results indicated that some nontraditional stabilizers significantly improved the UCS of the clay materials, while others had no significant effect on the UCS. Overall, Acid 1 was generally not effective in increasing the dry or wet UCS of either the CL or CH and demonstrated similar moisture susceptibility to the untreated specimens (Figures 4 and 7). Lignosulfonate 1 produced significant increases in both the dry and wet UCS in the CL soil and was considered effective (Figure 4). A review of Figures 5 and 8 shows that the enzymes, as a group, performed similar to the untreated specimens in both soil types. Enzyme 2 did appear to have some waterproofing effect as shown by slightly higher wet UCS, especially in the CL soil. Figures 6 and 9 show that only Polymer 1 increased the dry UCS of both soil types, but the remaining polymers, except Polymer 4, demonstrated some increase in wet UCS for the CL and CH specimens. In general, the lignosulfonate was the most effective nontraditional product for stabilizing the CL soil for strength, followed by the polymers. Enzyme 2 was the only enzyme product that demonstrated any potential performance enhancement in the CL soil. For the CH soil, the polymers were the most effective nontraditional additives with several enzymes demonstrating improved dry UCS but poor moisture susceptibility during wet testing.

Effect of Additive Quantities

Low, medium, and high additive quantities were used to evaluate each stabilizer against the untreated samples and between each other (Table 2). The lowest additive quantity was the amount of additive recommended by the manufacturer. The medium and high quantities were selected to see if an optimum quantity of stabilizer existed or if UCS could be increased with increased additive quantities. The stabilizer quantities for the cement and lime were based on recommendations provided in Army Technical Manual 5-822-14 (15). For the cement, increasing the amount of stabilizer did improve both the dry and wet soil strength. For the lime, the dry UCS increased in the CL and decreased in the CH soil with increasing additive amounts. Changes in the additive amount for Acid 1, the enzymes, and Tree Resin 1 revealed no clear trends in strength improvement or degradation for either soil type. For Lignosulfonate 1, a definite optimum additive quantity near five percent existed based upon both the dry and wet test results in the CL soil. The polymers appeared to demonstrate some improvement in wet UCS with increasing additive amounts in both soil types. Optimum amounts of polymer additive ranged from two to five percent depending upon the specific product. However, Petroleum Emulsion 1 showed a clear trend of decreasing dry and wet UCS with increasing additive amounts and an optimum amount of 2.5 percent for the CL soil (Figure 4). These results indicate that different categories of stabilizing agents respond differently to increasing additive quantities. Some categories had no distinguishable effect, while other demonstrated the existence of an optimum amount or clear trends. Individual categories and products must be studied in detail to define the appropriate additive quantity.

Effect of Wet and Dry Test Conditions

As discussed previously, the treated and untreated samples were tested using dry and wet test procedures to provide an indication of the material’s moisture susceptibility. Placing the specimens in 25.4 mm of water for 15 minutes provided an excellent indicator of the material’s durability under wet conditions. The deterioration of the specimens due to moisture exposure reduced the UC strength of all specimens tested (i.e. control and stabilized specimens). The UCS of the control specimens was reduced by an average of 72 and 78 percent for the CL and CH soils, respectively, when tested under the wet condition. In addition, the control specimen and all specimens stabilized with Acid 1, Enzyme 1, Enzyme 3, Enzyme 4, Polymers (at less than 2.0 percent), and Tree Resin 1 began to disintegrate once they were placed in the water in preparation for the wet UC test. The disintegration altered the cross sectional area of the specimens and ultimately reduced the wet UCS. Figures 1 and 2 show an Enzyme 2 sample and its disintegration during the 15-minutes soaking period. Moisture susceptibility of individual specimens was evaluated by considering the ratio of the wet UCS to the dry test results. Effective resistance to moisture degradation was defined as a maximum UCS strength reduction of 50 percent. Both traditional stabilization additives met this criterion for the CL soil, but the lime-stabilized CH specimens disintegrated during wet testing. Only Lignosulfonate 1 and Petroleum Emulsion 1 consistently provided good moisture resistance for the nontraditional stabilizing agents. Enzyme 2 and Polymer 3 met the criteria at a single additive quantity in the CL soil. For the CH soil, only Polymer 1 and Polymer 3 met the criteria at one additive quantity per product. In general, the polymer products tended to provide some resistance to moisture just below the 50 percent strength reduction criteria. The acid and enzymes demonstrated the highest susceptibility to moisture degradation. In summary, the results indicate that the wet test procedures used provided a range of performances ranging from sample disintegration to good performance. The results show significant decreases in the performance of many products when exposed to moisture over a relatively short duration.

Repeatability of Laboratory Tests

The ability to reproduce test results for specimens with similar compositions was evaluated during the laboratory experiment. The purpose of the replicate tests was to determine the variability of the mixing, test procedures, and materials. For each condition (i.e. wet and dry conditions, stabilizer type, and stabilizer quantities), three specimens were prepared and tested. The data indicated that the height of the CL specimens ranged from 150.7 mm to 158.7 mm with a mean of 153.0 mm and standard deviation of 1.19 mm. The data indicated that the CH specimens' height ranged from 149.2 mm to 161.3 mm with a mean of 152.9 mm and standard deviation of 1.57 mm. The average molded water content for the CL specimens excluding cement and lime mixtures was 14.9 percent with a standard deviation of 0.8 percent. The average molded water content for the CH soil specimens excluding lime mixtures was 23.2 percent with a standard deviation of 0.8 percent. The mean and standard deviation of the specimen dry density and UCS varied for each mixture and test condition (dry/wet). However, the specimen dry density for the six specimens of each mixture was within 32 kg/m^3. The individual mean UCS results for each additive in the CL and CH soils are presented in Tables 3 and 4. The average of the individual mixture standard deviations for the dry and wet UCS results of the CL specimens was 416 kPa and 184 kPa, respectively. The average of the individual mixture standard deviations for the dry and wet UCS results of the CH specimens were 273 kPa and 503 kPa, respectively.

CONCLUSIONS AND RECOMMENDATION

Conclusions

The results of the laboratory experiment produced several conclusions regarding stabilization of clay materials with traditional and nontraditional additives. The conclusions are based only on the test conditions presented.

1. Cement and lime were effective in stabilizing the low-plasticity clay under wet test conditions, but the lime was relatively ineffective in stabilizing the high-plasticity clay based upon strength improvement criteria.
2. The dry UCS was significantly greater than the wet UCS test results for all specimens tested.
3. Acid 1 produced variable UCS results, but was generally ineffective in improving the strength of the clay soils. No optimum quantity could be determined.
4. Lignosulfonate 1 provided excellent UCS improvement under both dry and wet test conditions with an optimum additive content of approximately 5.0 percent. Lignosulfonate 1 provided the greatest strength improvements for the CL soil.
5. Enzyme 2 showed a slight increase in the UCS for the CL and CH soils under both dry and wet test conditions. However, the enzymes as a group had minimal effect compared to the untreated specimens. No definitive conclusions regarding optimum additive rates could be reached.
6. The polymers showed variable dry UCS improvements, but good improvements in the wet UCS tests for both soil types, excluding Polymer 4. Optimum polymer additive rates ranged from two to five percent depending upon the specific product. Polymer 1 provided the greatest strength improvements for the CH soil, noting that Lignosulfonate 1 was not included in the matrix.
7. Lignosulfonate 1 provided the best resistance to moisture followed by Petroleum Emulsion 1 and the traditional additives. These products provided excellent waterproofing. The polymers as a group did not meet the 50 percent strength reduction criteria, but did provide some resistance to moisture degradation.
8. The significant strength improvement criterion of 345 kPa should be reconsidered for specific stabilization agents based upon the statistical variability of each agents UCS results.

Several of the products used in this experiment demonstrated excellent potential for stabilizing low quality materials for use in low-volume roads. These products could be used to stabilize existing subgrade materials to provide a stable working platform, to improve the properties of marginal materials for use as the load-bearing layer within the pavement system, and for improved erosion resistance or dust abatement. The conclusions presented above indicate a wide range of performance among commercially available nontraditional stabilization additives in clay soils. The rudimentary laboratory tests conducted appear to provide a valid means of screening these products for individual soil types. However, definitive results regarding optimum additive quantities and potential strength improvements must be ascertained for the specific soil to be stabilized through a detailed mixture design process. Ideally, field test sections under actual site conditions would be constructed prior to full-scale product application to verify performance.

Recommendation

The nontraditional stabilization products identified in this experiment as demonstrating significant performance improvement should be evaluated under actual field conditions and traffic loadings. The fundamental stabilization mechanisms for these products should be identified. In addition, other durability tests should be conducted or developed for these products to verify long-term performance of stabilized materials.

ACKNOWLEDGMENTS

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LIST OF TABLES AND FIGURES

FIGURE 1 Example of Enzyme 2 CL specimen being soaked for 15 minutes

FIGURE 2 "Wet" unconfined compression test on Enzyme 2 CL specimen after soaking

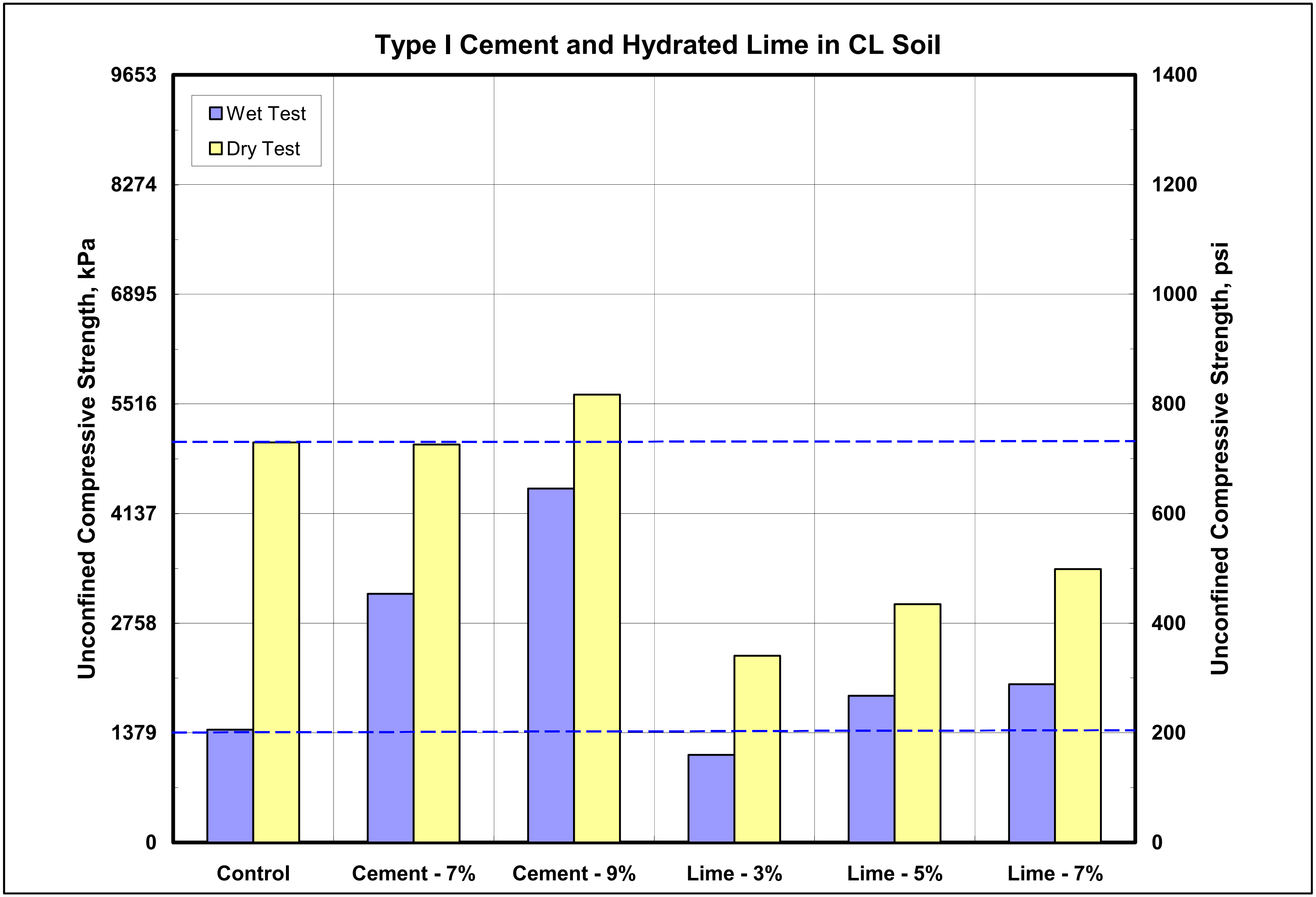

FIGURE 3 Test results for CL soil stabilized with Type I portland cement and hydrated lime versus control

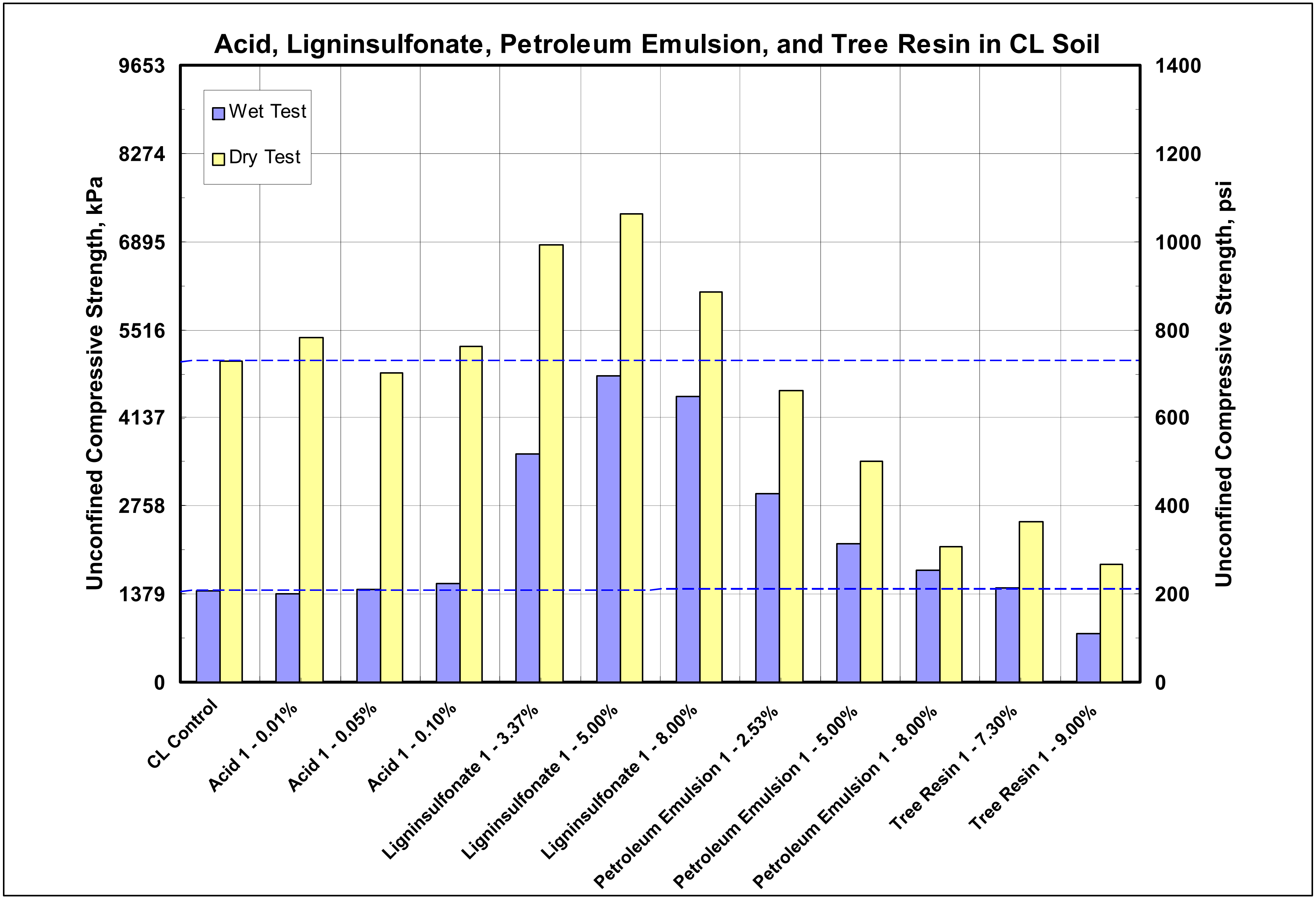

FIGURE 4 Test results for CL soil stabilized with acid, lignosulfonate, petroleum emulsion or tree resin versus control

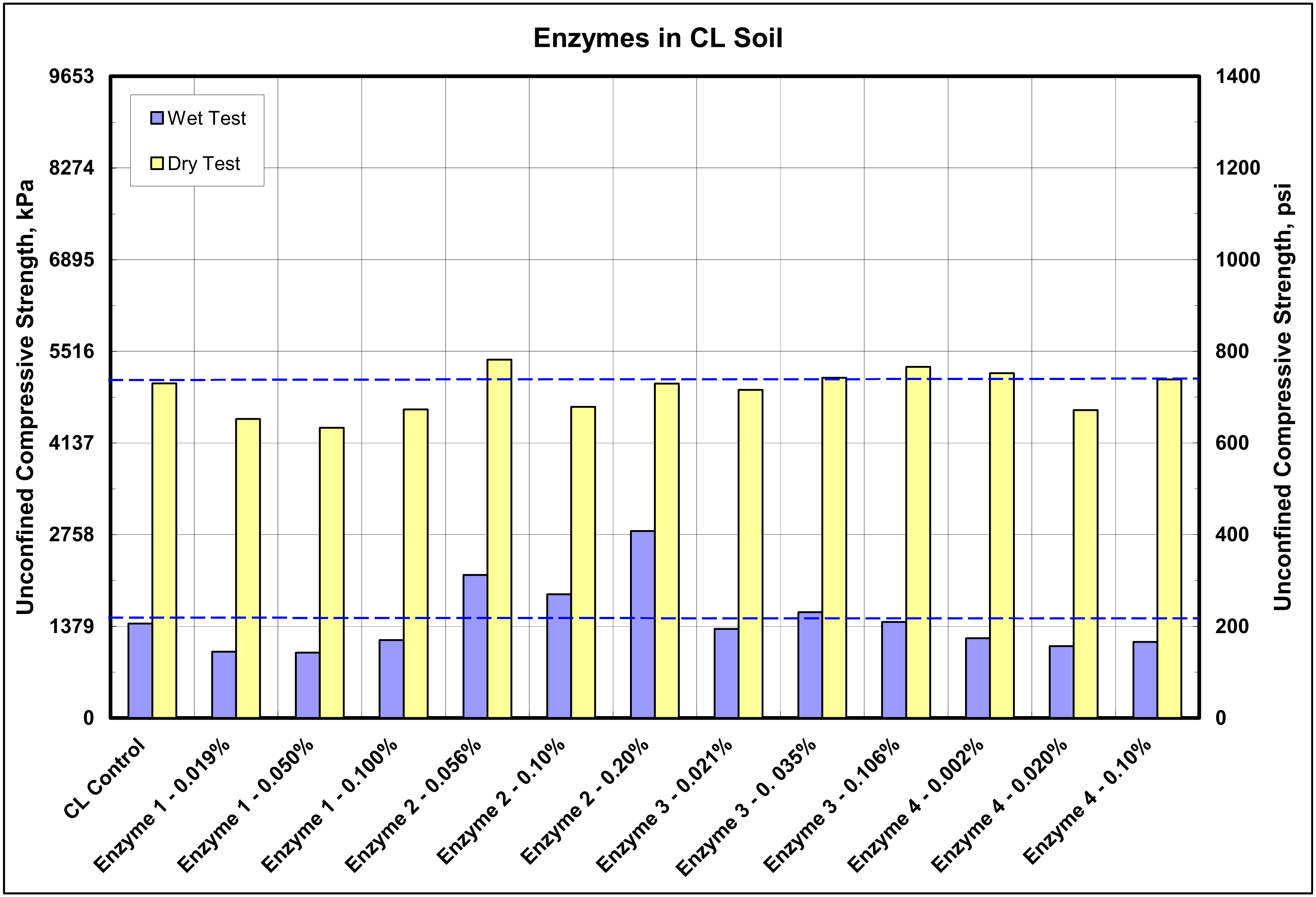

FIGURE 5 Test results for CL soil stabilized with enzymes versus control

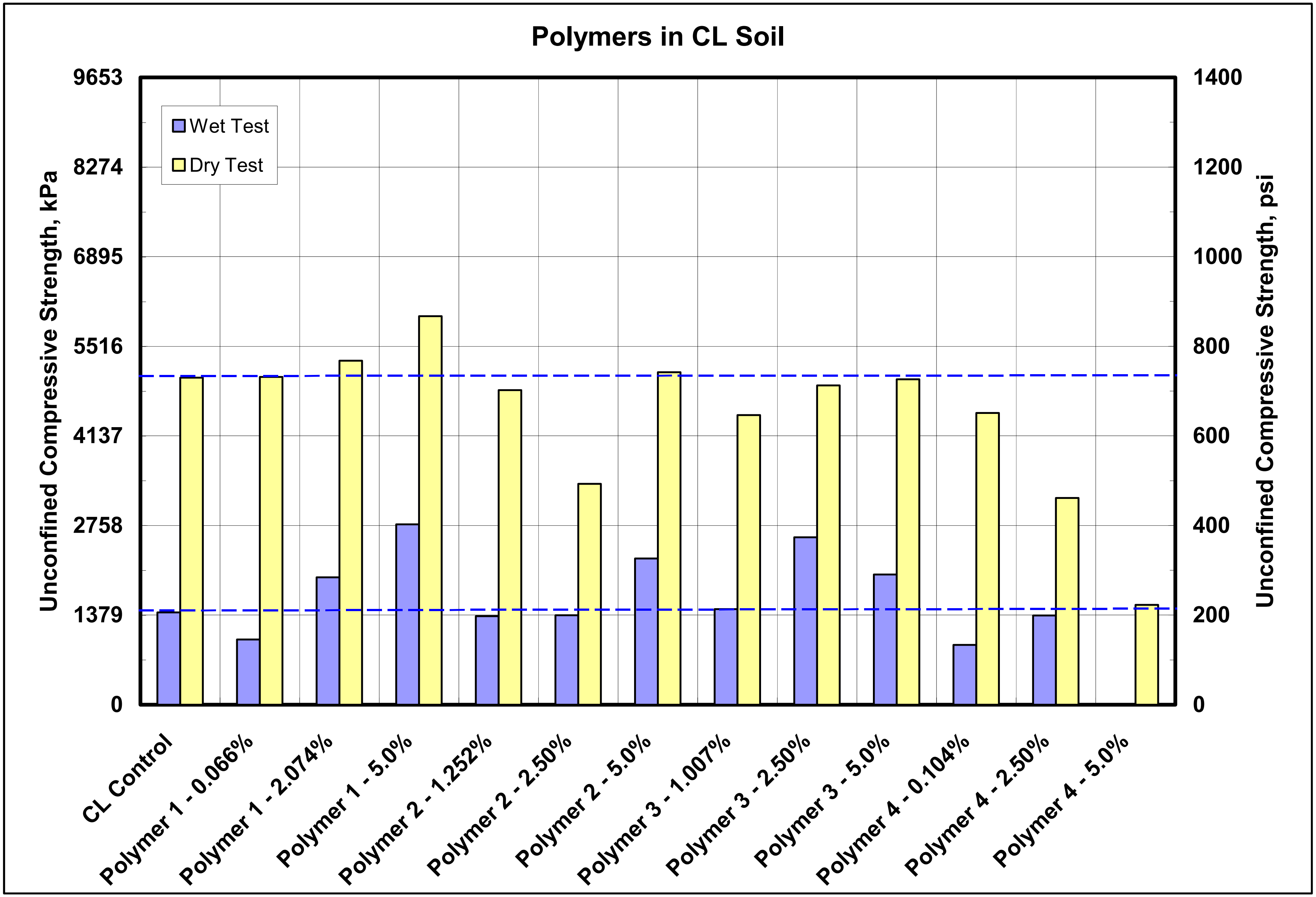

FIGURE 6 Test results for CL soil stabilized with polymers versus control

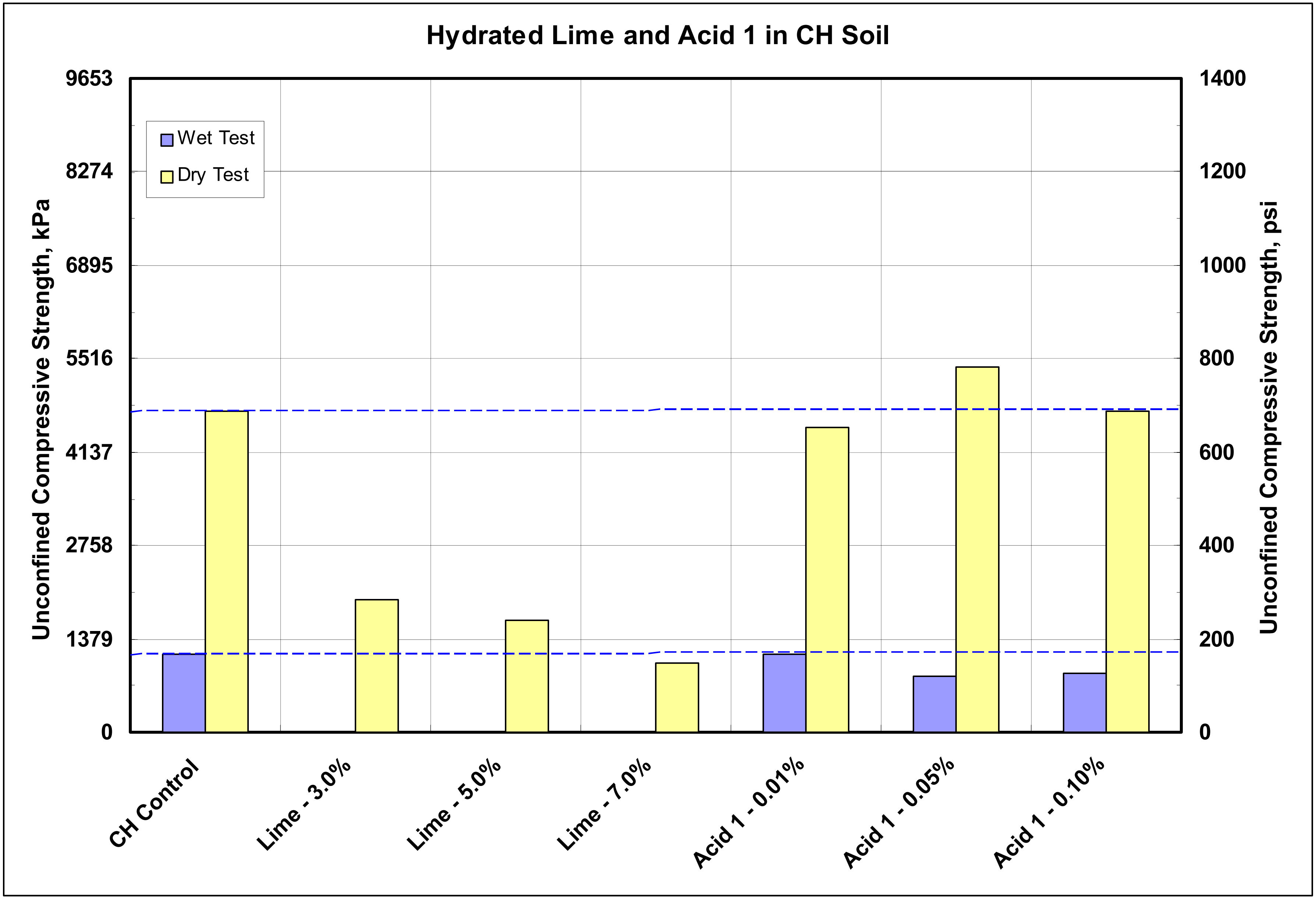

FIGURE 7 Test results for CH soil stabilized with hydrated lime or acid versus control

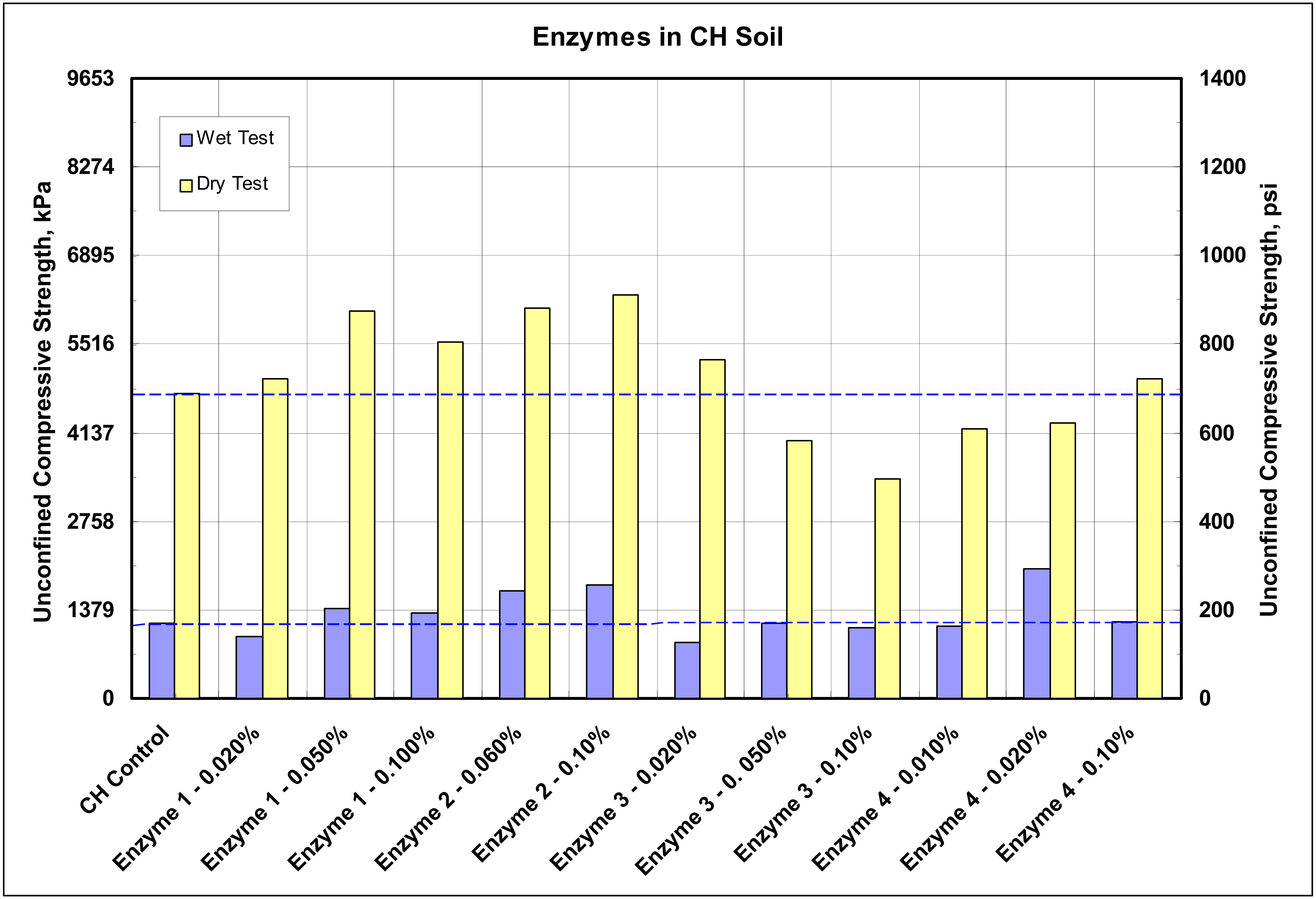

FIGURE 8 Test results for CH soil stabilized with enzymes versus control

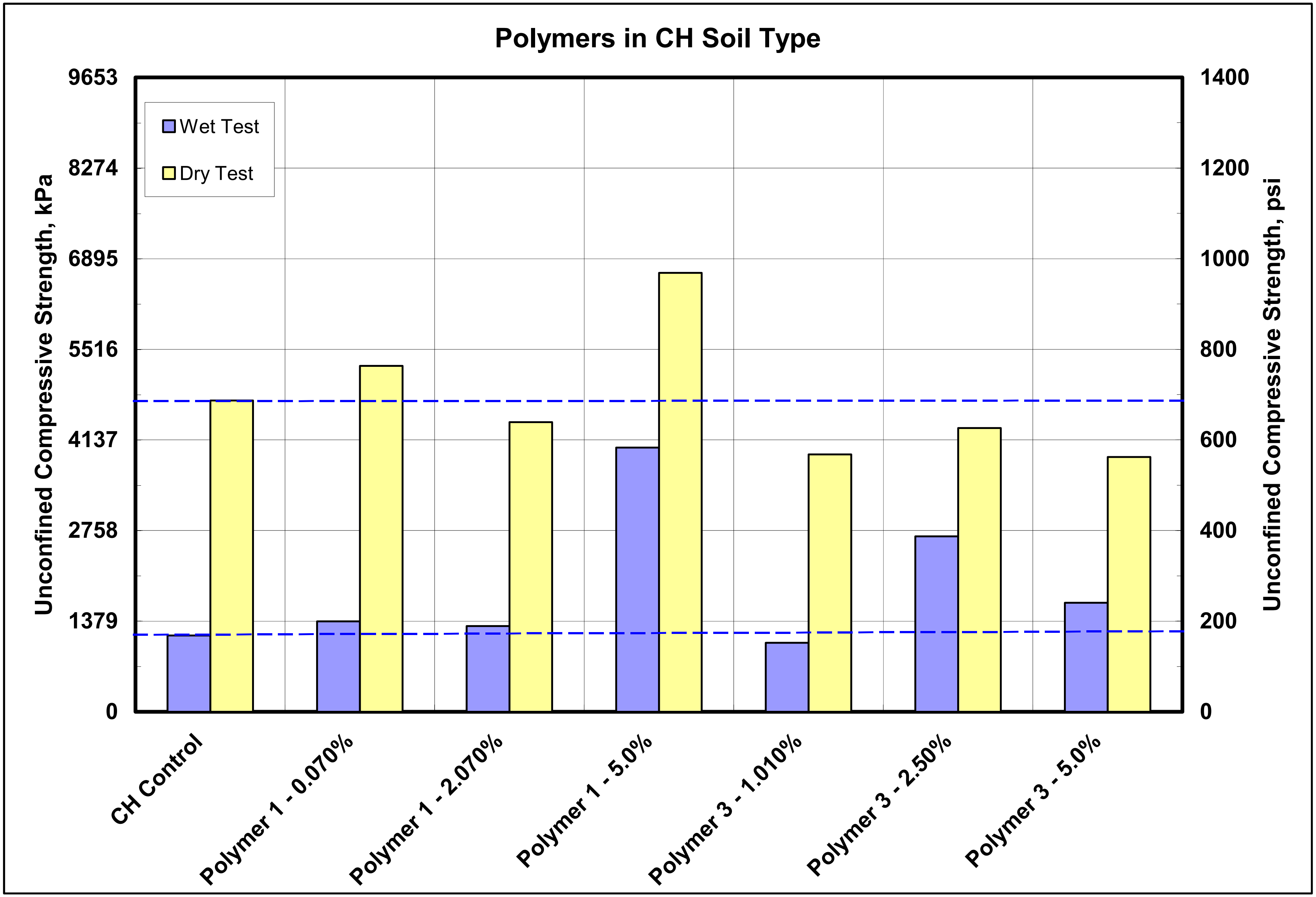

FIGURE 9 Test results for CH soil stabilized with polymers versus control

TABLE 1. Properties of Clays Used In The Experiment

Property	CL	CH	Test Procedure
Grain Size Distribution			
Percent Passing No. 40, %	99.8	98.7	ASTM D 422
Percent Passing No. 200, %	99.6	96.8	ASTM D 422
Percent Passing 0.005 mm, %	27.3	73.3	ASTM D 422
Specific Gravity	2.71	2.74	ASTM D 422
Soil Plasticity			
Liquid Limit, %	37	79	ASTM D 4318
Plastic Limit, %	24	28	ASTM D 4318
Plasticity Index, %	13	51	ASTM D 4318
Modified Proctor Compaction			
Maximum Dry Density, kg/m^3	1,858	1,664	ASTM 1557 Method A
Optimum Moisture Content, %	13.4	19.2	ASTM 1557 Method A
Gyratory Compaction			
Maximum Dry Density, kg/m^3	1,850	1,650	Author Developed[1]
Optimum Moisture Content, %	14.9	22.2	Author Developed[1]

[1] Gyratory compaction was conducted using a Pine® Gyratory Compaction Machine with a set angle of 1.25° at a ram pressure of 870 kPa for 90 revolutions.

TABLE 2. Experiment Test Matrix

Stabilizer	Stabilization Mechanism(s)	Soil Type	Additive Quantity[1]		
			Low	Medium	High
Control (No Additive)	None	CL and CH			
Type I Cement	Chemical/Mechanical	CL Only		X	X
Hydrated Lime	Chemical	CL and CH	X	X	X
Acid 1	Chemical	CL and CH	X	X	X
Lignosulfonate 1	Mechanical	CL Only	X	X	X
Enzyme 1	Chemical	CL and CH	X	X	X
Enzyme 2	Chemical	CL and CH	X	X	X[2]
Enzyme 3	Chemical	CL and CH	X	X	X
Enzyme 4	Chemical	CL and CH	X	X	X
Polymer 1	Mechanical	CL and CH	X	X	X
Polymer 2	Mechanical	CL Only	X	X	X
Polymer 3	Mechanical	CL and CH	X	X	X
Polymer 4	Mechanical	CL Only	X	X	X
Petroleum Emulsion 1	Mechanical	CL Only	X	X	X
Tree Resin 1	Mechanical	CL Only		X	X

[1] The "Low" additive quantity was based upon manufacturer recommendations. The "Medium" and "High" quantities were selected above and below the recommended quantity to identify performance trends.

[2] The "High" additive quantity was not tested for Enzyme 2 in the CH soil due to unavailability of sufficient materials.

TABLE 3. Unconfined Compression Test Results and Density Measurements for CL Test Series

Stabilizer Type	Application Rate By Dry Weight %	Primary Stabilization Mechanism	Dry Test			Wet Test		
			Water Content %	Dry Density[1] kg/m^3	Unconfined Compressive Strength, kPa	Water Content %	Dry Density[1] kg/m^3	Unconfined Compressive Strength, kPa
Control and Traditional Stabilizer Specimens								
None	0.00	None	15.9	1779.7	5033.2	15.9	1781.3	1420.3
Type I Cement	7.00	Both	16.9	1741.2	5005.6	16.8	1733.2	3123.3
Type I Cement	9.00	Both	17.2	1755.6	5633.1	17.9	1754.0	4447.1
Hydrated Lime	3.00	Chemical	17.9	1690.0	2351.1	17.9	1688.3	1103.2
Hydrated Lime	5.00	Chemical	18.5	1688.3	2999.2	18.5	1699.6	1847.8
Hydrated Lime	7.00	Chemical	19.0	1696.4	3440.5	19.0	1701.2	1985.7
Nontraditional Stabilizer Specimens								
Acid 1	0.010	Chemical	14.7	1787.7	5377.9	14.7	1778.1	1379.0
Acid 1	0.050	Chemical	14.9	1778.1	4840.1	14.9	1776.5	1454.8
Acid 1	0.100	Chemical	14.6	1789.3	5246.9	14.6	1789.3	1551.3
Lignosulfonate 1	3.370	Mechanical	15.0	1802.1	6839.6	15.0	1798.9	3564.6
Lignosulfonate 1	5.000	Mechanical	14.8	1808.5	7322.3	14.8	1810.1	4785.0
Lignosulfonate 1	8.000	Mechanical	14.2	1818.1	6108.8	14.2	1818.1	4467.8
Enzyme 1	0.019	Chemical	14.9	1754.0	4502.3	14.9	1758.8	999.7
Enzyme 1	0.050	Chemical	14.8	1750.8	4364.4	14.8	1754.0	986.0
Enzyme 1	0.100	Chemical	14.7	1747.6	4640.2	14.7	1734.8	1172.1
Enzyme 2	0.056	Chemical	15.4	1782.9	5391.7	15.4	1784.5	2151.2
Enzyme 2	0.100	Chemical	14.9	1774.8	4681.6	14.9	1766.8	1861.6
Enzyme 2	0.200	Chemical	15.5	1776.5	5026.3	15.5	1768.4	2813.1
Enzyme 3	0.021	Chemical	14.3	1773.2	4936.7	14.3	1776.5	1337.6
Enzyme 3	0.035	Chemical	14.8	1773.2	5115.9	14.8	1770.0	1592.7
Enzyme 3	0.106	Chemical	14.9	1779.7	5281.4	14.9	1754.0	1447.9
Enzyme 4	0.002	Chemical	14.7	1773.2	5184.9	14.7	1755.6	1199.7
Enzyme 4	0.020	Chemical	15.1	1757.2	4633.3	15.1	1750.8	1082.5
Enzyme 4	0.100	Chemical	14.7	1728.4	5088.4	14.7	1715.6	1144.5
Polymer 1	0.066	Mechanical	15.2	1768.4	5040.1	15.2	1746.0	999.7
Polymer 1	2.074	Mechanical	15.1	1774.8	5295.2	15.1	1766.8	1958.1
Polymer 1	5.000	Mechanical	14.9	1787.7	5977.8	14.9	1782.9	2778.6
Polymer 2	1.252	Mechanical	14.9	1755.6	4840.1	14.9	1755.6	1358.3

TABLE 3 (Continued). Unconfined Compression Test Results and Density Measurements for CL Test Series

Stabilizer Type	Application Rate By Dry Weight %	Primary Stabilization Mechanism	Dry Test			Wet Test		
			Water Content %	Dry Density[1] kg/m^3	Unconfined Compressive Strength, kPa	Water Content %	Dry Density[1] kg/m^3	Unconfined Compressive Strength, kPa
Nontraditional Stabilizer Specimens (Continued)								
Polymer 2	2.500	Mechanical	14.6	1733.2	3399.1	14.6	1725.2	1379.0
Polymer 2	5.000	Mechanical	15.2	1758.8	5115.9	15.2	1752.4	2254.6
Polymer 3	1.000	Mechanical	14.8	1771.6	4454.0	14.8	1768.4	1468.6
Polymer 3	2.500	Mechanical	16.7	1760.4	4909.1	16.7	1747.6	2578.7
Polymer 3	5.000	Mechanical	15.8	1739.6	4364.4	15.8	1734.8	1778.9
Polymer 4	0.104	Mechanical	14.7	1760.4	4488.5	14.7	1762.0	923.9
Polymer 4	2.500	Mechanical	16.7	1714.0	3178.5	16.7	1722.0	1372.1
Polymer 4	5.000	Mechanical	16.0	1657.9	1537.5	16.0	1654.7	0 [2]
Petroleum Emulsion 1	2.530	Mechanical	13.7	1818.1	4550.6	13.7	1818.1	2951.0
Petroleum Emulsion 1	5.000	Mechanical	13.8	1797.3	3454.3	13.8	1792.5	2171.9
Petroleum Emulsion 1	8.000	Mechanical	12.9	1781.3	2109.8	12.9	1787.7	1758.2
Tree Resin 1	7.300	Mechanical	13.2	1742.8	2502.8	13.2	1750.8	1482.4
Tree Resin 1	9.000	Mechanical	12.1	1688.3	1847.8	12.1	1706.0	751.5

[1] Dry density remained the same after the 28-day cure period although the moisture content changed due to evaporation.

[2] Specimen disintegrated when exposed to water. UCS could not be determined.

TABLE 4. Unconfined Compression Test Results and Density Measurements for CH Test Series

Stabilizer Type	Application Rate By Dry Weight %	Primary Stabilization Mechanism	Dry Test			Wet Test		
			Water Content %	Dry Density[1] kg/m^3	Unconfined Compressive Strength, kPa	Water Content %	Dry Density[1] kg/m^3	Unconfined Compressive Strength, kPa
Control and Traditional Stabilizer Specimens								
None	0.00	None	23.3	1595.4	4736.7	23.3	1593.8	1158.3
Hydrated Lime	3.00	Chemical	23.5	1492.9	1951.2	23.5	1489.7	0[2]
Hydrated Lime	5.00	Chemical	23.6	1491.3	1641.0	23.6	1496.1	0[2]
Hydrated Lime	7.00	Chemical	22.4	1464.1	1020.4	22.4	1467.3	0[2]
Nontraditional Stabilizer Specimens								
Acid 1	0.010	Chemical	22.7	1608.3	4509.2	22.7	1609.9	1151.4
Acid 1	0.050	Chemical	22.6	1621.1	5398.6	22.6	1597.0	827.4
Acid 1	0.100	Chemical	23.7	1598.6	4736.7	23.7	1592.2	861.9
Enzyme 1	0.019	Chemical	23.4	1603.5	4964.3	23.4	1595.4	951.5
Enzyme 1	0.050	Chemical	24.5	1595.4	6039.8	24.5	1597.0	1399.6
Enzyme 1	0.100	Chemical	23.1	1614.7	5557.2	23.1	1613.1	1323.8
Enzyme 2	0.056	Chemical	24.6	1597.0	6074.3	24.6	1593.8	1661.6
Enzyme 2	0.100	Chemical	23.9	1606.7	6274.3	23.9	1601.9	1758.2
Enzyme 3	0.021	Chemical	22.2	1629.1	5267.6	22.2	1624.3	868.7
Enzyme 3	0.050	Chemical	22.3	1597.0	4019.7	22.3	1609.9	1179.0
Enzyme 3	0.100	Chemical	21.9	1605.1	3426.7	21.9	1598.6	1110.1
Enzyme 4	0.010	Chemical	22.6	1608.3	4205.8	22.6	1600.2	1123.9
Enzyme 4	0.020	Chemical	22.5	1608.3	4281.7	22.5	1603.5	2027.1
Enzyme 4	0.100	Chemical	22.8	1613.1	4978.0	22.8	1600.2	1199.7
Polymer 1	0.066	Mechanical	22.8	1617.9	5260.7	22.8	1614.7	1379.0
Polymer 1	2.074	Mechanical	22.3	1582.6	4405.8	22.3	1576.2	1303.1
Polymer 1	5.000	Mechanical	23.5	1579.4	6674.2	23.5	1579.4	4019.7
Polymer 3	1.010	Mechanical	24.3	1557.0	3916.2	24.3	1561.8	1048.0
Polymer 3	2.500	Mechanical	24.2	1557.0	4316.1	24.1	1560.2	2668.3
Polymer 3	5.000	Mechanical	23.7	1525.0	3874.9	23.7	1529.8	1654.8

[1] Dry density remained the same after the 28-day cure period although the moisture content changed due to evaporation.

[2] Specimen disintegrated when exposed to water. UCS could not be determined.