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Accelerated Strength Improvement of Silty Sand Using Nontraditional Additives

Abstract

A laboratory experiment was conducted to evaluate the effect of two products designed to accelerate the strength improvement during the stabilization of a silty-sand (SM) material with nontraditional stabilizers. SM soil samples were mixed with various stabilization products and accelerators and compacted. Each sample was subjected to “wet” and dry testing following the designated cure period. Nine nontraditional stabilizers were evaluated in this experiment including lignosulfonates, polymers, silicates, and tree resins. Two accelerator products were evaluated including an acrylic polymer and Type I portland cement. Additional samples were stabilized with either an asphalt emulsion or cement to provide a comparison to traditional stabilizers under the same mixing, compaction, and curing conditions. The analysis of the data consisted of determining the average unconfined compressive strength (UCS) of three replicate samples of each mixture. The average UCS of the three replicates of each mixture was compared to the average strength results of the remaining mixtures, the traditional stabilization results, and a series of control samples that were not stabilized. The average UCS was determined at 1 and 7 days. The pH of each sample was also determined to evaluate the effect of the nontraditional stabilizer and accelerators on the stabilized soil pH. The results of the experiment indicate increased UCS of Silicate 1, Polymer 1, Polymer 2, and Polymer 3 stabilized samples when compared to both the control series and the traditional stabilization alternatives. Lignosulfonate 1, Polymer 4, Polymer 5, and Polymer 6, and Tree Resin 1 did not demonstrate significant increased strength compared to the control series for the conditions of this experiment. The USC following the 7-day cure period provided the maximum UCS of the samples evaluated in both dry and wet conditions. One accelerator, cement, in combination with a nontraditional stabilizer did show significant improvement in early strength gain when compared to the control series.

INTRODUCTION

The U.S. Army funded the work presented in this paper in an attempt to develop a rapid-curing stabilization mixture for constructing C-130 contingency airfields. Presently, light/medium military engineer units do not have the capability to either rapidly upgrade existing airfields or to construct contingency airfields to support the needs of rapid Army deployment. Current stabilization technology requires large amounts of cement, lime, or asphalt (5-10 % by weight) for contingency airfield construction. Cure times for these materials require up to 28 days. Military operations often cannot be delayed to permit sufficient curing of stabilized materials nor afford to allocate significant shipping volume for construction materials. To meet the Army's strategic responsiveness goals, cure times must be reduced to 1 to 7 days and stabilizer material weights must be reduced by up to 50%. The development of stabilization alternatives for accelerated curing is also beneficial for commercial constructions projects (i.e. state, federal agencies, and private industries projects). Delays in construction can be costly if adequate planning has not accounted for material cure times.

Nontraditional stabilization additives have become increasingly available for civil and military applications. These products can be divided into several categories (i.e. 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.

RESEARCH OBJECTIVES

The objective of this research was to evaluate the effect of two accelerators on the stabilization process of chemical stabilizers and to determine the potential engineering benefits of these products for stabilizing a silty-sand (SM) subgrade material. This research focused upon early increased UCS as the basis of performance characterization. The specific objectives included determining required accelerator types, accelerator quantities, the magnitude of UCS improvement, moisture susceptibility, pH changes, and optimum cure times. Furthermore, the relative strength improvement compared to traditional stabilization additives was also evaluated. The experiment was designed to develop stabilization alternatives for accelerated strength gain of a SM subgrade material.

The research scope included the execution of an extensive laboratory test matrix including variations in accelerator type, accelerator quantity, additive type, and cure times. Six samples of each mix design were molded using gyratory compaction. Unconfined compression (UC) tests were used to provide an index of performance for all test samples. A wet test procedure was developed to provide an indication of the moisture susceptibility of the stabilized samples. Three of the six samples for each mixture were tested under dry conditions, while the remaining three samples were subjected to UC tests following the wet test procedure. The researchers recognize that UC tests are not ideal for characterizing the fundamental material properties of a pavement material for the purposes of pavement design. Given the increased emphasis in mechanistic-empirical design procedures, resilient modulus tests would provide more valuable data for pavement applications. Unfortunately, resilient modulus tests are more

complicated and costly to perform than simple UC tests. The researchers chose to conduct these initial screening tests using unconfined compression test conditions in order to conduct a large number of tests during the initial screening process. Materials that demonstrate significant stabilization potential will be further evaluated using more rigorous test procedures. All stabilizers were mixed with a SM soil. 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 and accelerators for stabilizing a silty-sand material. This study is limited in terms of the number of accelerators evaluated, additives evaluated, the range of additive quantities used, the range of cure times, and the limitations of laboratory testing versus field testing.

LITERATURE REVIEW

A literature review was conducted to determine the state-of-the-art in soil stabilization. Numerous citations were identified that fully characterize the stabilization process and reinforcement mechanisms of traditional stabilization additives (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.

The variety of nontraditional stabilization additives has led to various attempts to categorize products according to their active components. Oldham et al. (4) 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 (5) categorized nontraditional stabilizers into 5 groups: electrolytes, enzymes, mineral pitches, clay fillers, and acrylic polymers. The proprietary nature of many of the products hinders the categorization process. The following paragraphs provide an overview of the available literature and pertinent conclusions. For organizational purposes, it was convenient to divide the stabilization into groups based upon their generically reported composition. The following stabilization groups were used: traditional additives, salts, acids, enzymes, ionic additives, polymers, lignins, silicates, and mineral pitches. The literature was also divided into two categories, stabilization of fine-grained soils and stabilization of granular soils.

Scholen (5, 6) attempted to describe the reinforcement mechanisms for stabilizing clay soils with ionic additives 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 (5) 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 but usually over long periods of time. Scholen (6) also hypothesized the mechanism by which enzymes could stabilize clay materials. 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.

Ajayi-Majebi et al. (7) 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 3 hours.

Katz et al. (8) and Rauch et al. (9) conducted a series of laboratory experiments designed to measure the engineering property effects and mechanisms of 3 liquid stabilizers on 5 clay soils. The 3 liquid stabilizers included an ionic stabilizer (electrolyte), an enzyme, and a polymer product. The clay materials consisted of 3 relatively "pure" clay minerals (kaolinite, illite, and sodium montmorillonite) and 2 high-plasticity clays. The liquid limits of the 2 natural clay soils ranged from 60 to 68, and the plasticity indices ranged from 37 to 48. Katz et al. (8) 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 (5, 6). A follow-on study was conducted by Rauch et al. (9) to measure changes in commonly reported engineering properties for the 3 stabilizers and 5 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 3 products evaluated, there was no consistent reduction in swell potential.

Many manufacturers contend that common laboratory testing procedures do not provide adequate indicators of field performance. Scholen (5) 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.

A literature review of research focused on the stabilization of granular materials with nontraditional additives produced fewer documented efforts than for fine-grained soils. This should be expected since fine-grained soils tend to be more problematic during geotechnical construction. Oldham et al. (4) concluded that polymer resins provided the greatest increase in UC strength for sand materials. A variety of polymer products were cited, but most products the products noted are no longer manufactured or have changed trade names.

Gopal et al. (10) performed comparative studies using urea-formaldehyde (UF) and its copolymers to stabilize dune sand. Specimens were prepared at different combinations of UF ratios, pH levels, and acid catalysts. All specimens were cured for 6 hours at 60°C. The results showed a maximum UC strength of 16 181 kPa. Lowering the pH of the additive mixture using phosphoric acid catalysts improved the relative strength increase of the specimens. The optimum UF ratio for their experiment was 1:2.25 urea to formaldehyde by weight. Gopal et al. recommended using 9 percent resin and 0.3 percent acid catalyst for stabilizing dune sands.

Vvedenskaya et al. (11) used copolymers to consolidate sands, silts, and clays. The copolymers used were guanidine acrylate (GA), methylene bisacrylamide (MBAM), and ethylene dimethacrylamide (EDMA). The additive formula consisted of a 24:1 ratio of vinyl monomer to diene. They reported increased strength due to increased hydrogen bonding, increased copolymer yield, and increased intermolecular bonding. The combination of GA and EDMA performed best in sands and loams followed by GA combined with MBAM. They reported an increase in UC strength of 2 452 - 2 942 kPa for a 5 percent additive mixture in sand. Vvedenskaya et al. reported that the formation of the polymer-soil structure during soil consolidation was completed in less than 10 days. They recommended that the additive quantity should range between 5 and 10 percent.

Santoni et al. (12) conducted a series of laboratory tests on the same silty-sand material used in this experiment. Santoni et al. conducted unconfined compression tests on silty-sand stabilized with acids, enzymes, polymers, ligninsulfonates, tree resins, and petroleum emulsions. The previous research included specimens air-dried for 28-days and did not include combinations of additives. The results of the previous study indicated excellent potential for polymers to stabilize the silty-sand material, while acid and enzyme materials failed to produce significant differences from the control specimens.

In summary, various researchers have divided nontraditional stabilization additives into broad categories dependent upon the stabilizer's primary active components. 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.

MATERIALS

The nontraditional additives consisted of 1 lignosulfonate, 6 polymers, 1 silicate, and 1 tree resin. These nontraditional additives were compared with two traditional additives. The traditional additives included: a Type I portland cement and a cationic emulsified asphalt. The accelerators included: a Type I portland cement and an acrylic polymer powder. Generic product names were used in this paper to prevent the specific endorsement of commercial products. The silty-sand (SM) material used in this experiment was blended from a combination of a typical "concrete" sand (SP), a loess silt (ML), and a uniform pea gravel (GP). It contained approximately 34 percent gravel sizes, 46 percent sand sizes, and 20 percent minus No. 200 U.S. standard sieve

size material. It was classified as silty-sand (SM) sand, American Society for Testing and Materials (ASTM) D 2487.

SAMPLE PREPARATION

The sample preparation was conducted as presented by Santoni et al. (12). Soil compaction curves were developed for 4-in.-diameter by 6-in.-high cylindrical samples of the SM material using a Pine® gyratory compaction machine. The test matrix required preparation of over 875 samples, and the gyratory compaction method provided a simple, reproducible, and reduced-effort method of preparing the samples 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 (12, 13). An angle of gyration of 1.25° (0.022 rad), a ram pressure of 126 psi, and 90 revolutions were selected to produce the same density as ASTM D 1557 moisture-density compaction for the SM material. The optimum water content for the raw SM material was 5 percent. The optimum water content for the SM material stabilized with the nontraditional stabilizers did not change significantly from that of the raw material and therefore 5 percent was used throughout. The maximum dry density of the SM soil was 141 lb/ft³.

Each sample was prepared following 6 steps: soil preparation, additive preparation, soil-additive mixing, molding, compaction, and curing. The soil was prepared by air drying the blended material to a moisture content of 2 - 3 percent, determining the free water requirements to obtain the desired moisture, and mixing the soil-water to obtain the desired moisture content. Since the material was an SM, a minimum time of only 1 hour was required 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 sample moisture content of 5 percent. 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.

The initial moisture content of the composite material was determined according to ASTM D 4643. An initial quantity of loose material was measured for each sample that would produce a 6-in.-high compacted sample. The material was molded using a 4-in.-diameter by 8-in.-high gyratory compaction mold. The material was placed in 5 layers, and each layer was hand-rodded 25 times with steel rod to reduce the loose height of the material. The top of the loose material was leveled using 10 blows of a rubber mallet on a 4-in-diameter steel plate. A 0.01-in-thick circular polypropylene membrane was placed on each end of the sample to prevent adherence to the top and bottom mold plates. Once molded, the samples were placed in the Pine® gyratory testing machine and compacted using the procedures described previously for the moisture-density curve development. The compacted samples were extruded from the gyratory mold using the hydraulic jack extrusion device. The height of the compacted sample was recorded, and the compacted sample was weighed to calculate the as-molded wet and dry densities. All six samples of each test series were compacted within 1 hour of mixing to achieve a minimum of 95 percent of ASTM D 1557 maximum density.

The compacted sample was then placed in a temperature-controlled room where it was allowed to cure at 72°F and 40 percent relative humidity for various cure times. The curing

process could be considered an air-dried process. It consisted of the evaporation of moisture from the samples over time and the hardening or cementation of the additive-soil matrix. This air-dried curing process was selected to represent field conditions during military construction operations and was also preferred by many of the suppliers of the nontraditional stabilizers over a moist-cure process.

TESTS AND RESULTS

Tests

Six samples of each mixture were prepared for each product, accelerator type and concentration, and cure times. Three of the 6 samples were subjected to UC tests once the designated curing period was complete. These three samples were tested according to the “dry” test procedure. The remaining 3 samples were tested according to the “wet” test procedure developed by Santoni et al. (12). This procedure was developed to evaluate the stabilized material’s moisture susceptibility. In this simplistic “wet” test procedure, the cured sample was placed on its side in 1-in of water for a period of 15 minutes. The sample was then removed from the water and allowed to drain for 5 minutes. The sample was then subjected to UC 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 samples. The height to diameter ratio of the samples 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. The UC strength can be adjusted for a height to diameter ratio of 2.0 by multiplying the values shown in Table 1 by 0.96 as described ASTM C42.

The UC tests were conducted using an Instron® 4208 testing system. The Instron® system consists of the test loading instrument and a computer for load-time recording of results. The test sample was positioned in the test instrument, and a seating load of 1 lb 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 sample at a constant rate of 0.10 in. per minute. Each sample was compressed until it reached a preset axial strain of 0.08 or until it collapsed.

The pH tests were useful in determining the solubility of soil minerals and the mobility of ions in the soil. Soil pH is an indication of the acidity or alkalinity of the soil and is measured on a scale of 0-14 with 7 being neutral. Soil pH is defined as the negative logarithm of the hydrogen ion concentration. As the amount of hydrogen ions in the soil increases, pH decreases thus becoming more acidic. From a pH 7 to 0 the soil is increasingly more acidic. From a pH 7 to 14, the soil is increasingly more alkaline or basic. The test was conducted as described ASTM D4972 using a potentiometer apparatus.

Results

Tables 1 and 2 show a tabulation of the average results of testing the 9 stabilization additives and the control samples. Table 1 divides the additives into the stabilizer categories described previously based upon the general composition of the additive. The results of the unconfined compression tests were used as an index of sample performance. The control sample was a SM sample prepared at the target moisture content without any stabilizer. For these experiments,

significant strength improvement was defined as a minimum increase in the compressive strength of the stabilized sample of 50 psi over the strength reported for the control samples.

Effect of Stabilizer Type

Polymer 1, Polymer 2, Polymer 3, and Silicate 1 demonstrated significant strength improvement especially when combined with cement. The addition of the powdered acrylic polymer “accelerator” to Polymer 1, Polymer 2, and Polymer 3 actually produced a decrease in UCS. However, the addition of polymer accelerator actually improved the UCS of Silicate 1. Lignosulfonate 1, Emulsified Asphalt, Tree Resin1, Polymer 5, and Polymer 6 failed to show significant strength improvement over the untreated soil samples. It should be noted that Polymers 5 and 6 were developed for dust control applications rather than stabilization. All products except Lignosulfonate 1, Polymer 5, and Polymer 6 exceeded the UCS of the untreated specimens for the 1-day cure period. For the 7-day cure period, all stabilizer types except Polymer 6 outperformed the untreated control samples. In many instances, the control sample with 3% Type I portland cement produced higher UCS than those samples stabilized with nontraditional additives. Polymer 3 produced the highest UCS when compared to its control, traditionally-stabilized specimens, and nontraditional stabilizers for both cure periods and both wet and dry tests. In general, the polymer category provided the most consistent strength improvement of the nontraditional additives, especially if Polymer 5 and Polymer 6 are considered as dust control products rather than stabilization additives.

Effect of Wet and Dry Test Conditions

All samples including traditional stabilizers, nontraditional stabilizers, and control samples were tested using wet and dry procedures to provide an index of the material’s moisture susceptibility. After 1 and 7 day curing periods, UCS tests were conducted on wet and dry specimens. The introduction of each specimen in 1 inch of water for 15 minutes provided an excellent indicator of the materials durability under wet conditions. The deterioration of the control specimens due to moisture exposure reduced UCS by 90 psi for the 1-day cured specimens and 300 psi for 7-day cured specimens. The Emulsified Asphalt provided excellent resistance to moisture deterioration and displayed minimal UCS loss when tested under the wet condition. In addition, all samples stabilized with Polymer 5 and Silicate 1 (without accelerator) began to disintegrate immediately upon being subjected to the 15-minute soaking period (Figures 1 and 2). Not only did the fragmentation of these specimens cause the reduction in UCS of each specimen but also altered the cross sectional area through the loss of fines in each sample indicating poor durability of these stabilizers. The results indicate that Polymer 1, Polymer 2, Polymer 3, and Polymer 4 performed well under both wet and dry conditions. The UC strength of Polymer 6 was low for wet and dry conditions but it demonstrated good potential for dust control since the loss of fines was hindered. Tree resin 1 and Lignosulfonate 1 did not represent any enhancement in UCS in combination with SM soil. However, due to the prevention of disintegration of each of these products during the wet trials, each product demonstrated potential for using these materials for waterproofing or dust control in the future.

Effect of Accelerator Type

The effect of accelerator type was evaluated by testing six control samples, two accelerator types, nine nontraditional stabilizer types, and two traditional stabilizer types (Table 1 and Figure 1). The cement and Polymer 4 were the accelerators used in this investigation to speed up the

strength improvement of the samples. They were selected based on the literature review and previous performance. The results of the tests indicated that the use of Type I portland cement as an accelerator significantly improved the UCS of the SM sand. The cement improved the UCS by more than 100 percent for both the dry and wet test conditions when compared with control samples. Samples stabilized with Polymer 1, Polymer 2, Polymer 3, Silicate 1, or Tree Resin 1 improved the UCS in both dry and wet conditions when combined with 1-3% Type I portland cement. Figure 3 illustrates typical test results identifying the effect of accelerator types on the control samples performance. A decrease in UCS with increasing of cement content was observed when SM soil were stabilized with Lignosulfonate 1 at 7 days under dry conditions. Similar UCS results were observed for 1- and 7-day cured specimens under wet conditions. SM soil stabilized with Polymer 4 did poorly when compared to the control sample at 1- and 7-day cure times in dry condition. Nevertheless, SM soil stabilized with Polymer 4 accelerator did excellent at 1- and 7-days in wet condition. The 7-day UCS of the samples stabilized with Polymer 1, Polymer 2, Polymer 3, and Tree Resin 1 and combined with Polymer 4 as an accelerator decreased with the increasing accelerator content. The UCS of samples stabilized with Lignosulfonate 1 and Polymer 4 accelerator was lower than the UCS of control SM samples at 1-day cure in both dry and wet conditions.

Effect of Accelerator Quantities

Three accelerator quantities (1 to 3 percent by dry weight of soil) were used to evaluate each stabilizer against the untreated sample and between each other (Table 1). These quantities were selected to see if an optimum quantity of accelerator existed or if UCS could be increased with increasing quantities. Accelerator quantities were limited to 3% so the total of amount of additives (i.e. stabilizer plus accelerator) remained 50% lower than traditional stabilizers (10-20%). Three percent of cement provided the highest UCS for the control sample and samples stabilized with Emulsified Asphalt, Polymers 1, 2, and 3, Silicate 1, and Tree Resin 1 in both dry and wet conditions. However, 1 percent of Polymer 4 provided the highest UCS for the SM soil stabilized with nontraditional additives. The stabilizer quantities for the Emulsified Asphalt, Lignosulfonate 1, Polymers 1-6, Silicate 1 and Tree Resin 1 were based on recommendations provided in previous study (12). For Polymer 5, Polymer 6, and Silicate 1, the UCS was higher at 1, 1, and 0.1 percent, respectively (Table 1). The 7-day UCS of Lignosulfonate 1 and Polymer 4 as an accelerator was maximized at Polymer 4 content of 2 percent in both dry and wet conditions.

Effect of Curing Time

The effect of curing time is presented in Table 1. For traditional stabilizers and nontraditional stabilizers, concentrations ranged between 0.1-5 percent depending on stabilizer type. Samples were cured for 1 day or 7 days, and all samples were tested under wet and dry conditions using two types of accelerators. The moisture content of each sample decreased with increasing curing time as shown in Table 1. For the control and Emulsified Asphalt samples, moisture content decreased over 70% from the 1-day to the 7-day cure period. Between these cure periods, UCS increased by almost 100 percent. The control specimen with 3 percent cement did not lose more than 30% of its initial moisture. Santoni et al. (12) showed that the traditional stabilizers developed approximately 60 percent of their 28-day strength within the first 7 days of curing.

The nontraditional stabilizers lost more than 50 percent of their moisture content with the exception of Lignosulfonate 1, which lost only 32 percent (Table 1). Nontraditional stabilizers gained more than doubled their UCS from 1 day to 7 days with the exception of Polymer 6. The nontraditional stabilizers combined with the accelerators gained their strength more rapidly than the traditional stabilizers with less additive quantities for both wet and dry condition (i.e. Lignosulfonate 1, Polymer 1, Polymer 2, Polymer 3, and Polymer 4). Silicate 1 surpassed traditional stabilizers UCS under the dry condition only. Neither Polymer 5 nor Polymer 6 exceeded the traditional stabilizers UCS in wet or dry conditions at 1 day and 7 days cure periods.

Effect of pH

The effect of potential hydrogen (pH) ion is presented in Table 2. Soils may be acidic, neutral, or alkaline. The nutrient availability, composition of the cation in the exchange complex, the solubility of cations and anions, the weathering of minerals, and microorganisms of the soil are affected by its pH. Soil pH (also known as soil reaction) can affect the stabilization of samples treated with cement and lime. Organic compounds of lower molecular weight, such as nucleic acid and dextrose, act as hydration retarders and reduce strength. When such organics are present, they inhibit the normal hardening process of cement. When cement is used, the pH of the sample should be at least 12.0 so the hydration process will not be affected. For samples stabilized with lime, the pH should be at least 12.4 to improve the soil strength.

For this investigation, the average pH for the control sample was 7.70 (or slightly alkaline). The SM samples stabilized with cement increased the pH up to 13.01. The pH of the sample increases with increasing cement content. Similar results were observed for samples stabilized with both nontraditional stabilizers and cement. Lignosulfonate 1 was the only exception since samples did not reach pH greater than 12. The average pH for samples stabilized with emulsified asphalt was 7.28. Based on the pH, the emulsified asphalt did not significantly alter the soil reaction since pHs between 6.6 to 7.3 are considered neutral. The pH of the samples stabilized with Lignosulfonate 1 was 6.51. The soil reaction of these samples is considered slightly acidic (i.e. pH between 6.1 to 6.5). Polymers 1, 2, 3, 4, 5, and 6 increased the sample pH by varying amounts ranging from moderately to very strongly alkaline (i.e. pH between 7.9 to 14) as shown in Table 2. When Polymer 4, the second accelerator, was combined with Polymers 2 and 3, the soil pH became moderately to strongly alkaline. The combination of Polymer 4 and Lignosulfonate 1 did not produce a soil reaction, and the sample pH remained neutral. Samples stabilized with Silicate 1 became very alkaline (pH > 9.1). The highest pH for Polymers 5 and 6 was reached when the percent of stabilizer was 2%. Samples stabilized with Tree Resin 1 became also slightly alkaline. Based on results, the alkaline mixtures performed better.

CONCLUSIONS AND RECOMMENDATION

Conclusions

The following conclusions are based only on the test conditions presented.

1. Lignosulfonate 1 with and without accelerators did not improve the SM soil load-carrying capacity. However, Lignosulfonate did provide significant waterproofing of the specimens.
2. The UCS of samples stabilized with nontraditional stabilizers increased more than doubled from 1 day curing to 7 days.

3. Polymers 2, 3, and 4 showed significant UC strength improvement relative to control samples and other nontraditional stabilized samples under at dry and wet conditions. Polymers 2, 3, and 4 provided up to 65% of UC strength increases under both wet and dry conditions when compared to control samples.
4. Cement at 3% and Emulsified Asphalt provided excellent resistance to moisture deterioration. However, Polymer 5 and Silicate 1 without accelerators disintegrated once they were placed in water.
5. For the two accelerators (i.e. Type I Portland cement and Polymer 4) used in this experiment, Type I Portland cement provided significant strength improvement for the SM soil for both wet and dry test conditions at 1 and 7 days. Polymer 4 showed improvement for both wet and dry test conditions at 7 days. However, the magnitude of this improvement was less than cement.
6. Three percent cement (accelerator 1) maximized the UCS of stabilized samples treated with accelerator. Of these samples treated with the Polymer 4 accelerator, one percent of Polymer 4 (accelerator 2) maximized the UCS of the stabilized samples.
7. Significant savings can be realized by using these accelerators since traditional stabilization additives require up to 9 percent of cement or emulsified asphalt.
8. Samples stabilized with cement became increasingly alkaline (i.e. their pH increased) increasing the cement content. Polymers 1, 2, 3, 4, 5, and 6 changed samples pH from neutral to very strongly alkaline (i.e. pH from 7.0 to 14). Soil pH became moderately to strongly alkaline when Polymer 4 was combined with Polymer 2 and 3. The combination of Polymer 4 and Lignosulfonate 1 did not produce a change in soil pH. Samples stabilized with Silicate 1 became very alkaline (pH > 9.1). Samples stabilized with Tree Resin 1 became slightly alkaline.

Recommendation

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

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REFERENCES

1. Transportation Research Board (TRB). *State of the Art Report 5: Lime Stabilization, Reactions, Properties, Design, and Construction*. Transportation Research Circular No. 180, Washington, D.C., 1987.
2. American Concrete Institute (ACI). *State-of-the-Art Report on Soil Cement*. ACI Materials Journal, Vol. 87 No. 4, ACI, Farmington Hills, MI, 1990, pp. 395-417.

3. American Coal Ash Association (ACAA). *Fly Ash Facts for Highway Engineers*. Report FHWA-SA-94-081, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., August 1995.
4. Oldham, J.C., R.C. Eaves, and D.W. White. *Materials Evaluated As Potential Soil Stabilizers*. Miscellaneous Paper S-77-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, September 1977.
5. Scholen, Douglas E. Nonstandard Stabilizers. Report FHWA-FLP-92-011, Federal Highway Administration (FHWA), Washington, D.C., July 1992, 113 pages.
6. Scholen, Douglas E. Stabilizer Mechanisms in Nonstandard Stabilizers. Proc., 6th International Conference on Low-Volume Roads, Vol. 2, Transportation Research Board, Washington, D.C., 1995, pp. 252-260.
7. Ajayi-Majebi, A., W.A. Grissom, L.S. Smith, and E.E. Jones. Epoxy-Resin-Based Chemical Stabilization of a Fine, Poorly Graded Soil System. In *Transportation Research Record 1295*, TRB, National Research Council, Washington, D.C., 1991.
8. Katz, L.E., A.F. Rauch, H.M. Liljestrand, J.S. Harmon, K.S. Shaw, and H. Albers. Mechanisms of Soil Stabilization with a Liquid Ionic Stabilizer. In *Transportation Research Record 1757*, TRB, National Research Council, Washington, D.C., 2001, pp. 50-57.
9. Rauch, A.F., J.S. Harmon, L.E. Katz, and H.M. Liljestrand. Liquid Soil Stabilizers: Measured Effects on Engineering Properties of Clay. Presented at the 81st Annual Transportation Research Board Conference, Awaiting publication in the *Transportation Research Record*, TRB, National Research Council, Washington, D.C., 2002.
10. Gopal, R., J. Singh, and G. Das. Chemical Stabilisation of Sand Comparative Studies On Urea-Formaldehyde Resins As Dune Sand Stabiliser and Effect Of Compaction On Strength (Part IV). In *Transactions of Indian Society of Desert Technology and University Centre of Desert Studies*, Vol. 8 No. 2, Indian Society of Desert Technology, Jodhpur, India, 1983, pp. 13-19.
11. Vvedenskaya, V.A., N.E. Ogneva, V.V. Korshak, L.I. Mekhant'eva, and Ts.A. Gogvadze. Translated by E.A. Inglis. Consolidation of Over-Moist Soils by Copolymers of Guanidine Acrylate and Methacryloguanidine-Urea Hydrochloride with Certain Alkylidene Bisacrylamides. In *Soviet Plastics*, Vol. 7, Rubber and Technical Press, London, England, 1971, pp. 55-58.
12. Santoni, R.L., Tingle, J.S., and Webster, S.L. *Stabilization of Silty-Sand with Nontraditional Additives*. TRB January 2002. TRB paper 02-3756.

13. Womack, L.M., J.F. Sirm, and S.L. Webster. *Gyratory Compaction of Soil*. Technical Report S-68-6, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, November 1969.

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TABLE 1 Average unconfined compression test results for SM soil

Stabilizer Type	Stabilizer Percentage	Accelerator Type	Accelerator Concentration	DRY			WET		
				Molded Water Content, % (1/7 Day)	At Testing Water Content % (1/7 Day)	Unconfined Compressive Strength, psi		Unconfined Compressive Strength, psi	
						1 Day	7 Day	1 Day	7 Day
Control Sample and Traditional Stabilizers									
Control	0	None	0	4.9/4.5	2.2/0.4	115	328	27	26
Control	0	Cement	1	5.4/5.6	2.9/1.6	241	309	177	130
Control	0	Cement	2	5.3/5.6	2.8/1.8	319	486	211	347
Control	0	Cement	3	6.2/6.2	3.6/2.1	329	589	255	469
Control	0	Polymer 4	1	4.8/5.4	2.8/1.6	83	301	85	302
Control	0	Polymer 4	2	4.9/4.8	3.3/1.8	76	290	78	244
Control	0	Polymer 4	3	5.1/4.9	3.8/2.3	100	272	91	228
Emulsified Asphalt	5	None	0	4.9/4.6	2.6/0.9	86	160	81	150
Emulsified Asphalt	5	Cement	1	5.0/5.2	3.1/2.2	147	229	117	167
Emulsified Asphalt	5	Cement	2	5.5/6.0	3.6/2.7	173	174	152	156
Emulsified Asphalt	5	Cement	3	5.9/5.8	3.9/2.8	148	263	142	213
Emulsified Asphalt	5	Polymer 4	1	4.8/4.6	3.2/1.5	46	120	42	120
Emulsified Asphalt	5	Polymer 4	2	4.7/4.9	3.6/2.4	38	88	30	85
Emulsified Asphalt	5	Polymer 4	3	5.1/4.5	4.1/3.2	34	104	29	100
Non-traditional Stabilizers									
Lignosulfate 1	3	None	0	5.0/5.0	4.3/2.9	57	256	24	161
Lignosulfate 1	3	Cement	1	5.3/5.5	4.3/3.1	131	364	97	189
Lignosulfate 1	3	Cement	2	5.6/5.9	4.6/3.5	135	331	97	180
Lignosulfate 1	3	Cement	3	5.9/5.9	4.7/3.5	114	297	80	164
Lignosulfate 1	3	Polymer 4	1	5.3/5.2	4.7/3.7	35	111	22	81
Lignosulfate 1	3	Polymer 4	2	5.1/5.2	4.5/3.7	27	162	20	104
Lignosulfate 1	3	Polymer 4	3	5.3/5.0	4.8/3.5	34	104	29	100
Polymer 1	2.5	None	0	5.7/5.7	2.7/0.9	95	273	62	170
Polymer 1	2.5	Cement	1	6.0/5.9	3.4/2.0	176	331	138	227
Polymer 1	2.5	Cement	2	6.1/6.4	3.5/2.5	213	434	199	283
Polymer 1	2.5	Cement	3	6.9/7.1	4.4/3.1	238	458	208	391
Polymer 1	2.5	Polymer 4	1	5.4/5.5	3.5/1.6	63	271	52	249
Polymer 1	2.5	Polymer 4	2	5.2/5.4	3.5/2.1	77	232	65	206
Polymer 1	2.5	Polymer 4	3	5.5/5.7	4.1/2.9	60	195	51	155
Polymer 2	2.5	None	0	5.5/5.4	2.7/1.1	125	396	93	267
Polymer 2	2.5	Cement	1	5.3/5.6	3.2/2.1	247	438	170	320
Polymer 2	2.5	Cement	2	6.2/6.0	4.1/2.4	260	504	234	416
Polymer 2	2.5	Cement	3	6.8/6.0	4.4/2.3	311	581	270	419
Polymer 2	2.5	Polymer 4	1	4.9/5.5	3.2/1.9	69	331	64	282
Polymer 2	2.5	Polymer 4	2	4.8/5.1	3.6/2.1	55	280	50	218
Polymer 2	2.5	Polymer 4	3	4.9/5.1	3.7/2.5	74	209	53	162

TABLE 1 Average unconfined compression test results for SM soil (Continued)

Stabilizer Type	Stabilizer Percentage	Accelerator Type	Accelerator Concentration	DRY			WET		
				Molded Water Content, % (1/7 Day)	At Testing Water Content, % (1/7 Day)	Unconfined Compressive Strength, psi		Unconfined Compressive Strength, psi	
						1 Day	7 Day	1 Day	7 Day
Non-traditional Stabilizers									
Polymer 3	2.5	None	0	5.2/6.3	2.6/1.2	252	543	179	374
Polymer 3	2.5	Cement	1	5.4/4.9	3.3/1.5	288	448	272	401
Polymer 3	2.5	Cement	2	5.9/5.7	3.7/2.3	330	570	358	525
Polymer 3	2.5	Cement	3	6.2/6.0	3.8/2.3	365	661	376	619
Polymer 3	2.5	Polymer 4	1	4.7/4.8	2.9/1.3	166	438	142	380
Polymer 3	2.5	Polymer 4	2	4.8/5.0	3.5/2.0	120	362	95	319
Polymer 3	2.5	Polymer 4	3	4.8/4.9	3.6/2.2	120	302	102	253
Polymer 4	2.5	None	0	5.9/4.1	4.4/1.2	89	261	71	226
Polymer 4	2.5	Cement	1	5.9/5.9	4.2/2.8	166	534	157	524
Polymer 4	2.5	Cement	2	6.2/6.5	4.3/3.5	151	658	144	639
Polymer 4	2.5	Cement	3	6.8/6.3	4.7/2.8	184	639	177	624
Polymer 5	1	None	0	5.5/5.2	2.7/1.1	86	161	42	86
Polymer 5	2	None	0	5.4/5.4	2.7/1.5	77	132	44	90
Polymer 5	3	None	0	5.3/5.7	2.5/1.8	50	103	24	53
Polymer 5	3	Cement	1	5.3/5.2	3.3/2.2	114	161	76	101
Polymer 5	3	Polymer 4	1	5.4/5.0	4.0/2.2	29	78	20	79
Polymer 6	1	None	0	5.1/5.0	2.8/1.3	38	65	25	48
Polymer 6	2	None	0	4.8/5.3	2.7/1.6	17	26	13	24
Polymer 6	3	None	0	4.7/4.8	3.3/1.8	9	13	7	12
Polymer 6	3	Cement	1	5.2/5.6	3.7/2.9	24	34	23	31
Polymer 6	3	Polymer 4	1	5.4/5.2	3.6/2.6	9	28	8	23
Silicate 1	0.1	None	0	5.0/5.0	2.2/0.7	161	365	57	99
Silicate 1	0.25	None	0	5.1/5.4	2.5/1.0	143	307	57	93
Silicate 1	0.5	None	0	6.1/5.5	3.2/0.9	150	257	49	57
Silicate 1	0.5	Cement	1	5.9/5.5	3.5/1.9	335	426	201	265
Silicate 1	0.5	Cement	2	6.2/6.4	4.0/2.8	432	605	360	433
Silicate 1	0.5	Cement	3	6.7/6.8	4.1/2.8	444	641	390	452
Tree Resin 1	5	None	0	4.9/4.6	2.8/1.1	25	140	27	116
Tree Resin 1	5	Cement	1	5.1/5.3	3.0/2.1	155	239	149	209
Tree Resin 1	5	Cement	2	6.2/5.9	4.0/2.5	144	278	156	260
Tree Resin 1	5	Cement	3	6.1/6.5	4.1/2.9	178	291	174	306
Tree Resin 1	5	Polymer 4	1	5.1/4.7	3.2/1.8	34	182	34	167
Tree Resin 1	5	Polymer 4	2	4.9/4.8	3.7/2.5	29	160	27	143
Tree Resin 1	5	Polymer 4	3	5.2/4.9	4.2/2.8	37	130	32	112

TABLE 2 Average pH test results for SM soil

Stabilizer	Percent Stabilizer	Accelerator											
		None	Cement			Polymer 4							
			1%	2%	3%	1%	2%	3%					
Control	None	7.7	12.66	13.01	13	9.48	9.16	9.69					
Emulsified Asphalt	5	7.28	12.7	12.87	12.95	7.78	7.91	8.88					
Lignosulfonate 1	3	6.51	11.42	11.49	11.95	6.89	6.92	7.23					
Polymer 1	2.5	8.45	12.78	12.99	13.02	8.61	8.65	9.04					
Polymer 2	2.5	10.49	12.77	12.89	12.88	8.39	8.77	9.37					
Polymer 3	2.5	8.96	12.85	12.94	12.99	9.24	9.19	9.31					
Polymer 4	2.5	9.94	12.77	12.85	12.84								
Polymer 5	1	8.75											
Polymer 5	2	8.9											
Polymer 5	3	8.3	12.71			7.71							
Polymer 6	1	7.82											
Polymer 6	2	7.89											
Polymer 6	3	7.66	12.57			8.03							
Silicate 1	0.1	9.9											
Silicate 1	0.25	9.86											
Silicate 1	0.5	10.23	12.75	12.97	12.97								
Tree Resin 1	5	7.71	12.77	13.17	12.95	7.19	7.39	7.45					

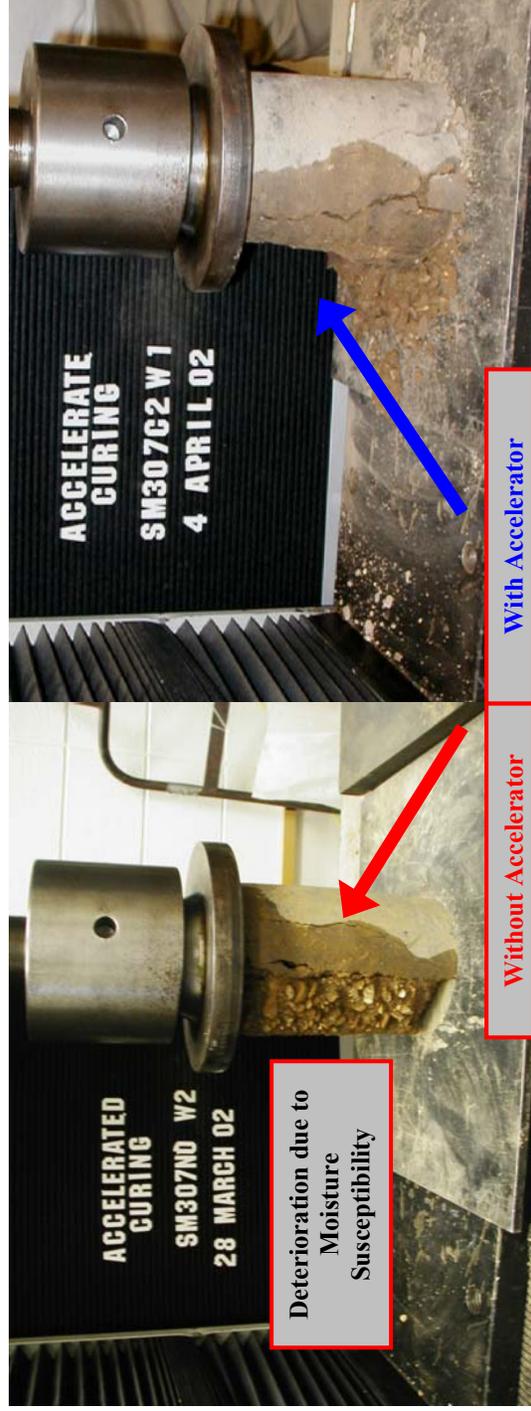


FIGURE 1 Moisture susceptibility of SM sample stabilized with 2.5 percent Silicate 1

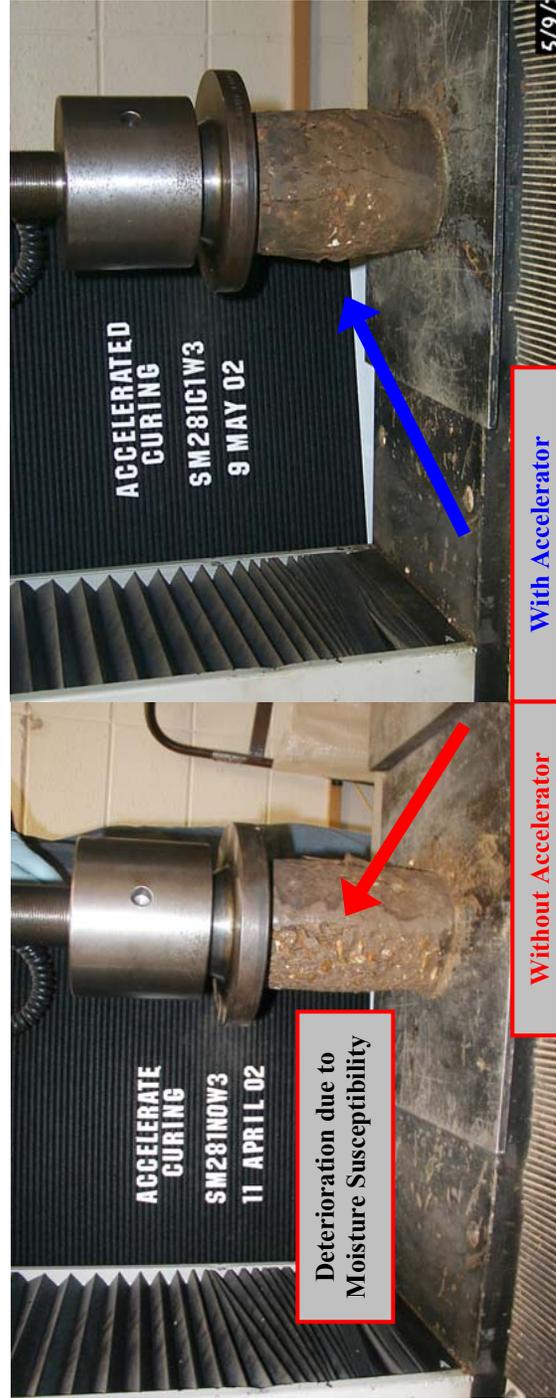


FIGURE 2 Moisture susceptibility of SM sample stabilized with 1 percent Polymer 6

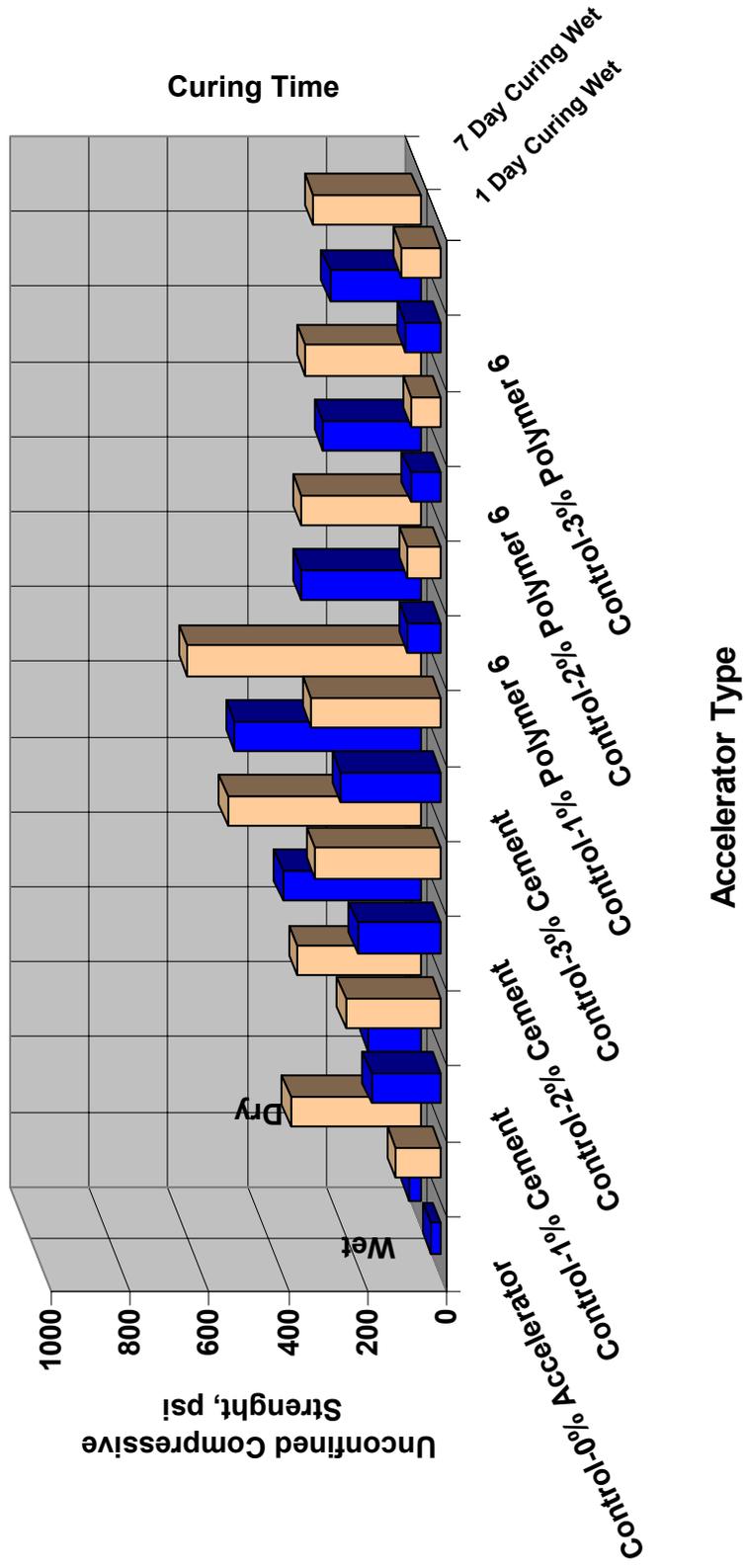


FIGURE 3 Typical test results for SM soils stabilized with Polymer and accelerators