

Stabilization Mechanisms of Nontraditional Additives

Jeb S. Tingle, J. Kent Newman, Steve L. Larson, Charles A. Weiss, and John F. Rushing

Because of the high cost of quality construction materials, transportation engineers are often forced to seek alternative designs using substandard materials, commercial construction aids, alternative pavement materials, and innovative design practices. Nontraditional soil stabilization additives are being marketed as viable solutions for stabilizing marginal materials as a low-cost alternative to traditional construction materials. Nontraditional additives are diverse in their composition and the way they interact with soil. Unfortunately, little is known about their interaction with geotechnical materials and their fundamental stabilization mechanisms. The objective of this research was to advance current understanding of the chemical and physical bonding mechanisms associated with selected nontraditional stabilizers. The research consisted of conducting qualitative analyses of hypothesized stabilization mechanisms, examining historical literature for supporting documentation, and performing laboratory experiments to improve the understanding of how these nontraditional additives stabilize soils. Laboratory experiments included image analyses, physical characterization, and chemical analyses to determine the primary constituents of the mineral, soil, stabilizer, and stabilized soil composite. The focus of this effort was to provide insight into the proposed mechanisms by using the laboratory data to examine proposed mechanisms from the historical literature and to provide additional hypotheses for the interaction between nontraditional additives and different soil types.

Traditional pavement design and construction practices require high-quality materials to fulfill minimum construction standards. In many areas of the world, quality materials are unavailable, forcing engineers to seek alternative materials such as soil stabilization additives. Soil stabilizers can be divided into two broad categories: traditional stabilizers and nontraditional additives. Traditional stabilizers such as cement, lime, fly ash, and bituminous products have been intensely researched, and their fundamental stabilization mechanisms have been identified. Nontraditional soil stabilization additives consist of a variety of chemical agents that are diverse in their composition and in the way they interact with the soil. Unfortunately, relatively little is known about their interaction with geotechnical materials or their fundamental stabilization mechanisms.

The objective of this research was to advance the current understanding of the chemical and physical bonding mechanisms associated with selected nontraditional stabilizers. The research consisted of

conducting qualitative analyses of hypothetical stabilization mechanisms, reviewing historical literature for supporting data, and conducting laboratory experiments on selected stabilization products to verify proposed stabilization mechanisms. Laboratory experiments were conducted to determine the primary constituents of the mineral, soil, stabilizer, and stabilized soil composite. The results of the laboratory test program were used to evaluate hypothetical stabilization mechanisms, and pertinent conclusions were drawn about the potential of each material to stabilize soils. The focus of this effort was to evaluate the stabilization mechanisms of various nontraditional additives. Thus, this paper does not intend to provide a detailed summary of the laboratory test program but instead presents a discussion of the proposed stabilization mechanisms, using the laboratory data to examine possible stabilization mechanisms.

TYPES OF NONTRADITIONAL ADDITIVES

Because of the proprietary nature of the commercial stabilization additives, their exact chemical compositions are not disclosed. For the purpose of examining fundamental stabilization mechanisms, it is convenient to group these products into like categories based on their primary chemical components and proposed reinforcement properties. Most nontraditional additives can be grouped into seven categories: ionic, enzymes, lignosulfonates, salts, petroleum resins, polymers, and tree resins. Many of the products include secondary additives such as surfactants, catalysts, and ultraviolet inhibitors. There is typically a dominant or primary stabilization mechanism supported by secondary mechanisms because of the inclusion of complementary additives. The following paragraphs describe stabilization mechanisms proposed in historical literature, the hypothesized mechanisms of additives used in this experiment, and supporting laboratory test results.

BACKGROUND

Unlike traditional stabilizers, attempts to define the reinforcement mechanisms of nontraditional additives have been limited. Most laboratory and field experimentation with nontraditional additives have focused on performance evaluation instead of mechanism identification. Thus, there is relatively little literature concerning stabilization mechanisms of nontraditional additives.

Scholen (1, 2) described the reinforcement mechanisms for electrolytes and enzymes. Scholen hypothesized that electrolytes or ionic stabilizers alter the electrolyte concentration of the pore fluid, which results 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

U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, CEERD-GM-A, Vicksburg, MS 39180. Corresponding author: J. S. Tingle, Jeb.S.Tingle@erd.c.usace.army.mil.

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into a more stable configuration exuding excess double-layer water in the process. However, Scholen (*1*) noted 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. Scholen also 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.

Katz et al. (*3*) and Rauch et al. (*4, 5*) conducted a series of laboratory experiments designed to evaluate the mechanisms of an ionic, an enzyme, and a polymer stabilizer with five clay soils. The clay materials consisted of three relatively "pure" clay minerals (kaolinite, illite, and sodium montmorillonite) and two high-plasticity clays (CHs) with plasticity indices ranging from 37 to 48. Katz et al. (*3*) reported only minor changes in the d-spacing between molecular layers for a sodium montmorillonite stabilized with an ionic stabilizer and concluded that the application rates were much too low to accelerate the clay's "weathering" process effectively as proposed by Scholen (*1, 2*). However, Rauch et al. (*4*) 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, optimum moisture content, or swell potential. Rauch et al. (*5*) indicated only minimal changes in X-ray diffraction results, specific surface area, and alumina-silica ratios for very high additive quantities of 50% 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.

Laboratory testing conducted by T. Scullion (personal communication, Feb. 2002) 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 imaging, and energy dispersive spectrometer analyses.

Santoni et al. (*6, 7*), Tingle and Santoni (*8*), and Newman et al. (*9*) report a series of laboratory tests with nontraditional stabilizers evaluating the performance effects in terms of increased strength improvement in both granular and fine-grained subgrade materials. However, these experiments only categorized the proposed stabilization mechanisms as either a mechanical bonding or a chemical reaction mechanism. No details of the proposed physicochemical changes were provided.

In summary, attempts to define the fundamental reinforcement mechanisms of nontraditional stabilization additives have been limited. Laboratory experimentation has focused on evaluating the effects of stabilized materials on engineering properties with minimal understanding of the stabilization mechanisms.

HYPOTHESIZED STABILIZATION MECHANISMS

This section of the paper describes hypothesized reinforcement mechanisms for each category of nontraditional additive. Often, there are not clear delineations in the mechanisms between many commercial stabilizers, as they may rely on multiple pathways toward an end state. Chemical stabilizers such as ionic, lignosulfonate, salts, and enzyme stabilizers may rely on specific chemical reactions with soil particles; thus, the performance should be expected to be very soil specific. Physical stabilization of soil particles using

binding agents such as petroleum products, tree resins, and polymers should act on a wider variety of soils. Physicochemical mechanisms may occur with the lignosulfonates, salts, and polymers, depending on the chemical constituents present in some polymers. Often, many of these products contain surfactants to improve wetting of the soil particles, which alters the surface charge on the soil particle and affects the surface tension of the pore fluid. Surfactants may also participate in ion-exchange reactions.

Ionic Stabilizers

Ionic stabilizers such as acids and alkaline additives have gained considerable attention due to the small effective quantities used for stabilization reported by commercial vendors. Scholen (*1*) hypothesized that the electrolytes or ionic stabilizers alter the electrolyte concentration of the pore fluid, resulting in cation exchange and leading to flocculation of the clay minerals. Adsorption of ions by soil particles, ionic reactions with soil constituents, and ion exchange alter the molecular structure of the soil. These reactions reduce the surface charge of the soil particles, resulting in loss of double-layer water and allowing for close packing or even flocculation of the soil particles. This process is illustrated in Figure 1. This mechanism would be particularly important for smaller clay minerals such as montmorillonites where the double-layer water is significantly larger than the size of the montmorillonite particle sheets. The resulting clay material should demonstrate reduced plasticity, reduced swell potential, and reduced particle size. Unfortunately, the effects on the molecular structure due to changes in the electrolyte pore fluid from alkali to acidic or vice versa usually occur over long periods of time (*1*). Laboratory testing by Katz et al. (*3*) and Rauch et al. (*4, 5*) reported minor changes in the d-spacing between molecular layers of treated clay minerals and concluded that the vendor-recommended application rates were much too low. They also reported only minimal changes in X-ray diffraction results, specific surface area, and alumina/silica ratios for very high additive quantities of 50% by dry weight of clay. However, the minor changes observed did tend to support Scholen's hypothesized mechanisms for the ionic additives. Tingle and Santoni (*8*) reported minimal effects when attempting to stabilize clay soils with an acid after 28 days. Santoni et al. (*6, 7*) reported no effect in treating granular soils with ionic additives after 28 days.

The proposed mechanism for ionic stabilizers suggests that these additives are suitable only for fine-grained soils, silts, and clays, where the electrical charges of the particles and pore fluid significantly affect soil behavior. In addition, the ionic stabilizers should be more effective as the particle size decreases because of the increasing importance of the double-layer water in interparticle behavior. Because the process requires cation exchange, the cation exchange capacity may be an important variable for evaluating the suitability of ionic additives for specific soils. Additionally, because of the varying chemical composition, very specific reactions may occur with one soil-product combination and not another. Thus, only certain soils would be expected to respond well to ionic stabilizers. Granular soils would be unsuitable for stabilization with ionic additives that rely on the mechanism described here.

Enzyme Stabilizers

Enzymes are organic molecules that catalyze very specific chemical reactions if conditions are conducive to the reaction. They are typically used in low concentrations as they are not consumed by the reactions

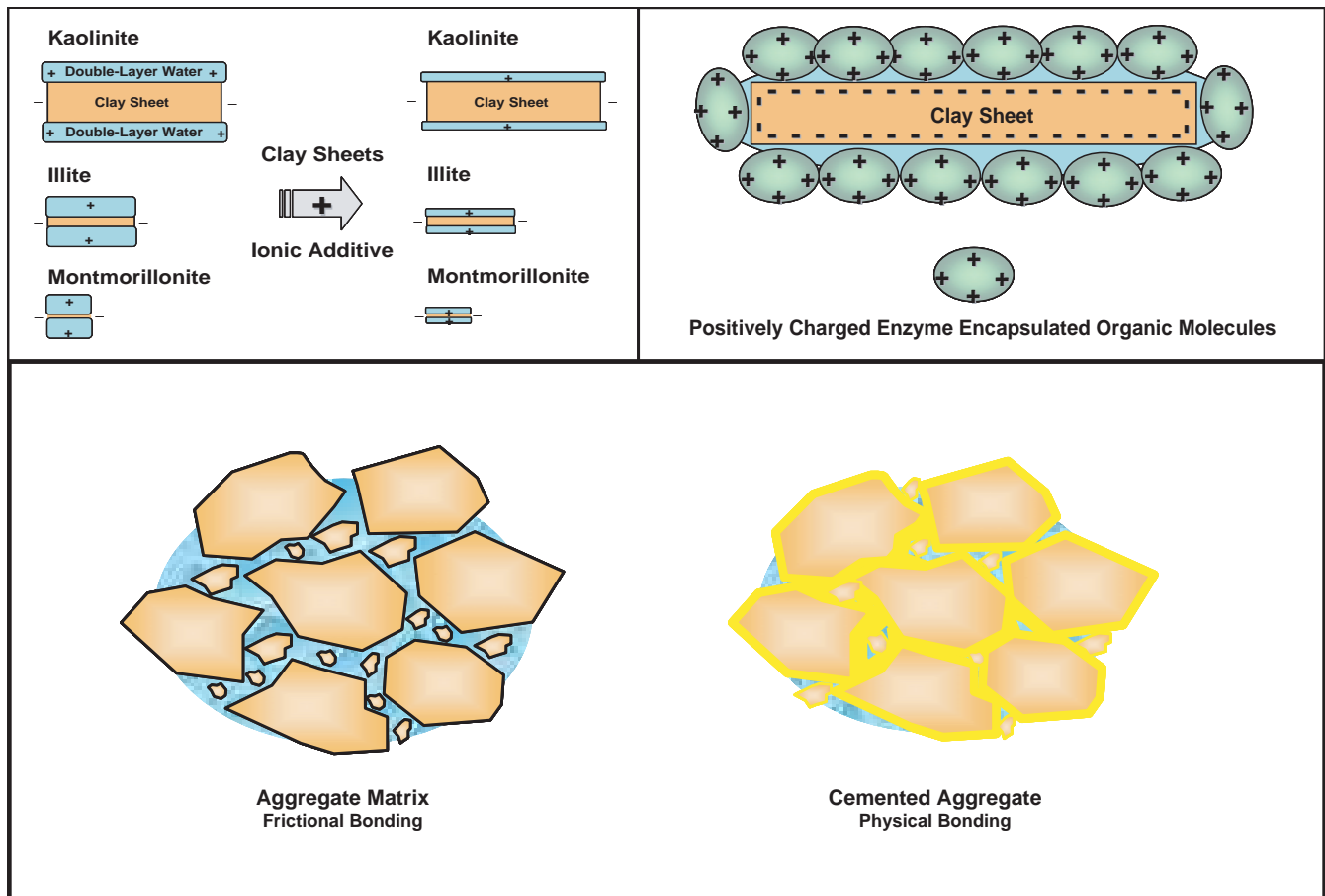


FIGURE 1 Proposed stabilization mechanisms.

they facilitate. For an enzyme to be active in a soil, it must have mobility to reach a reaction site. The pore fluid provides the means for mobility, the specific soil chemistry provides the reaction site, and time is needed for the enzyme to diffuse to the reaction site. In theory, an enzyme would stay active in a soil until there are no more reactions to catalyze—hence, the need for small dosages. Enzymes would be expected to be very soil specific. Scholen (1) proposed that the enzyme additives bond with large organic molecules that are attracted to the clay mineral's 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 as illustrated in Figure 1. Rauch et al. (5) reported minor changes in X-ray diffraction results, specific surface area, and alumina/silica ratios for very high enzyme quantities of 50% by dry weight of clay. As with the ionic additives, the minor changes in the properties of the clay minerals did tend to support Scholen's hypothesized mechanism. Tingle and Santoni (8) treated various soils with four different enzyme products, and the results showed only a minor improvement in wet unconfined compressive strength (UCS) of a low-plasticity clay (CL) and a CH soil for one of the enzymes. Santoni et al. (6, 7) reported no effect in treating granular soils with four enzyme additives after 28 days.

The proposed mechanism for enzyme stabilization resulting in a reduced affinity for moisture appears theoretically valid, but limited laboratory verification has occurred. Given that the proposed mechanism results in reduced affinity for water, shrink-swell tests

may be appropriate for evaluating the hypothesized mechanism. The proposed mechanism would indicate that enzymes are appropriate only for use with clay materials that have an affinity for water, particularly high-plasticity clays with some organic content. Materials such as silts and granular soils would not possess a significant affinity for water and would be unsuitable for stabilization with enzyme products. The proposed mechanism suggests that the use of enzymes will also be critically dependent on the environmental conditions and may take considerable time to occur.

Lignosulfonate Stabilizers

Lignosulfonate stabilization products including sodium, calcium, and ammonium lignosulfonates are derived from the lignin that binds cellulose fibers together. Because of the variations in the wood and plant source materials, the exact chemical composition of lignosulfonates varies. Lignosulfonates can coat individual soil particles with a thin adhesive-like film that binds the particles together (Figure 1). Lignosulfonates are primarily cementing agents with minor chemical effects depending on their composition. The cementing effect stabilizes the soil by physically bonding soil particles together. However, as these products are also ionic, they have a capacity for ion exchange and reactions with some soils. Most commercially available lignosulfonates are water soluble and susceptible to leaching under wet conditions.

Tingle and Santoni (8) treated a CL soil with a solution derived from a powdered lignosulfonate, and the lignosulfonate showed significant strength improvement under both dry and wet testing after 28 days of curing. Santoni et al. (6) treated a silty sand (SM) soil with two lignosulfonates, but only one demonstrated improved compressive strength. Santoni et al. (7) conducted laboratory unconfined compression tests on a silty sand treated with the same lignosulfonate, reporting a moderate increase in wet strength compared with untreated specimens after only 7 days of curing. These results support the proposed stabilization mechanism of physical bonding or cementation with natural polymers. Thus, the potential for improvement in strength and shrink–swell reduction is a function of the ability to coat the soil particles adequately and the strength of the binding agent. The ability to coat soil particles adequately would be expected to diminish with the increased specific surface area. This implies that the cementation mechanism of lignosulfonates would be more effective in granular soils and would diminish with decreasing particle sizes. A secondary mechanism of the particle coating was reduced moisture susceptibility, evidenced by the strength improvement during wet testing. However, the wet testing noted did not include total immersion or long-term effects, and the reduction in moisture susceptibility may be short-lived given the water solubility of most lignosulfonates. Lignosulfonates are occasionally used to deflocculate clays in suspensions because of their negative surface charge. This property could result in poor performance when clays are stabilized.

Salt Stabilizers

Salt stabilizers generally consist of calcium and magnesium chloride compounds (CaCl_2 and MgCl_2 , respectively). Salts are hygroscopic, attracting moisture from the surrounding environment and maintaining the soil in a moist condition. The introduction of divalent cations into the soil also creates the potential for cation exchange between the divalent cations in the salt and monovalent cations in the soil. Cation exchange may improve the soil by stabilizing the soil particle and reducing the double-layer water capacity. This decreases the spacing between particles and increases flocculation. Furthermore, recrystallization of salts in the pore spaces creates weak physical bonds between soil particles and increases the treated soil density. Salts can also result in increased pore water surface tension, producing an increase in apparent cohesion of the soil and improvement in strength. Thus, salt stabilizers use a variety of potential mechanisms for improving soils. Unfortunately, salts are very corrosive to metals and are susceptible to leaching because they are water soluble.

The proposed stabilization mechanisms of salt additives suggest that the materials may be suitable for both granular and fine-grained soils. In granular soils, the hygroscopic characteristics of salt stabilizers may be used to aid compaction and the recrystallization may form weak physical bonds between soil particles. Additional improvement in strength due to increased surface tension of pore water may also be provided. For fine-grained soils, particularly clays, the hygroscopic properties may improve the soil's cohesion by preventing the soil from drying. Cation exchange in clay soils can result in permanent stabilization effects. These mechanisms, with the exception of cation exchange, offer relatively moderate strength improvement benefits compared with other additives. Rushing et al. (10, 11) reported that admixtures of 2% by dry weight of a 38% solution of calcium chloride were effective in stabilizing a gravelly clayey sand (SC) in an arid environment and a gravelly silty sand in a temperate environment after 90 and 220 days, respectively.

Petroleum Resins

Two fundamentally different types of petroleum products are commonly used for soil stabilization: asphalt emulsions and synthetic isoalkane fluids. Typical asphalt emulsions consist of asphalt particles dispersed in water with an emulsifying agent, typically a surfactant that suspends the asphalt cement particles. When applied, the emulsion water adsorbs onto the soil particle surface and, coupled with evaporation, deposits the asphalt cement residue onto the soil particle surface. The emulsifying agent can also serve as a surfactant, reducing surface tension to permit improved penetration for topical applications and improved particle coating for admix procedures. Asphalt emulsions are typically cationic or anionic. Because most soils have a net negative surface charge, cationic emulsions are typically used for soil stabilization. Asphalt emulsions are also categorized according to the speed at which they coalesce or cure. Medium-setting emulsions are typically used with coarse aggregates and slow-setting emulsions are used with fine aggregates. Because the primary stabilization mechanism is physical bonding, strength improvement depends on the ability to coat the soil particles adequately and the physical properties of the binder. Thus, stabilization with asphalt emulsions is suitable for granular materials but not fine-grained soils because of their high specific surface area. Because the physical bond depends on the asphalt cement, a viscoelastic material, the physical bonds possess moderate strength. However, asphalt cement is not miscible in water and thus provides excellent waterproofing of the coated particles, reducing susceptibility to moisture.

Synthetic fluids consisting of isoalkanes are also available that do not dry or cure with time. These products typically serve as a compaction aid by dispersing the soil particles and by reducing interparticle friction, allowing for rearrangement of the particles with less compactive effort. These products are also not miscible with water, serving as a waterproofing agent that reduces the moisture susceptibility of stabilized soils. Because these products do not offer a chemical or significant physical bonding, minimal improvement in strength would be expected. Santoni et al. (7) evaluated two of these types of additives with a silty sand and reported no discernible improvement in strength.

Polymer Stabilizers

Polymer stabilizers are typically vinyl acetates or acrylic copolymers suspended in an emulsion by surfactants. The polymer stabilizer coats soil particles, and physical bonds are formed when the emulsion water evaporates, leaving a soil–polymer matrix. As with asphalt emulsions, the emulsifying agent can also serve as a surfactant, improving penetration for topical applications and particle coating for admix conditions. Because the primary stabilization mechanism is physical bonding, the improvement in strength depends on the ability to coat the soil particles adequately and on the physical properties of the polymer. Thus, stabilization with polymer emulsions is suitable for granular materials but is less effective in fine-grained soils because of reduced mixing efficiency resulting from their high specific surface area. The polymers typically used in soil stabilization have excellent tensile and flexural strength, producing physical bonds with excellent strength. As with asphalt cement, the polymers are resistant to water, providing excellent waterproofing of the coated particles and reducing susceptibility to moisture.

Rauch et al. (5) confirmed the proposed mechanism of particle coating and physical bonding through scanning electron microscope

images and surface area analyses. Santoni et al. (6) reported significant improvement in strength of the silty sand treated with three polymers after 28 days of curing. Santoni et al. (7) concluded that five of the six polymers in a follow-up test were effective in stabilizing a silty sand under both dry and wet testing after 7 days of curing. Their experiment also demonstrated a synergistic effect when the polymers were applied in concert with small percentages of Type I portland cement. The Type I portland cement used the excess emulsion water for hydration and provided early strength, whereas the residual polymer provided improved ductility. However, Tingle and Santoni (8) observed that only one of four polymer emulsions produced significant improvement in strength for a CL and a CH soil under both dry and wet test conditions after 7 days, but all the polymers showed improved strength compared with untreated specimens under wet test conditions after 28 days of curing. Newman et al. (9) used six polymer emulsions to treat a silty-sand soil. The polymer emulsions demonstrated significant improvement in strength after 7 days of curing and strengths similar to cement-stabilized specimens after 28 days. Furthermore, Newman et al. (9) quantified the improved ductility or toughness of the polymer-stabilized soils by comparing the areas under the stress-strain curves. Thus, significant laboratory experimentation supports the significant physical bonding mechanism proposed for polymer emulsions and identified reduced performance with fine-grained soils probably because of an inadequate ability to coat the soil particles.

Tree Resin Stabilizers

Lignosulfonates are typically produced through controlled manufacturing processes, but tree resins are relatively unprocessed by-products of the timber and paper industries. Emulsifying agents are added to prevent the premature coalescence of the resin. Tree resin emulsions are used to coat individual soil particles with a film that binds the particles together. Thus, like lignosulfonates, tree resins are principally cementing agents that physically bond soil particles together. Similar to polymer emulsions, tree resins are suitable for granular materials but are less effective in fine-grained soils because of reduced mixing efficiency. Intuitively, the tree resins should be water soluble, similar to lignosulfonates, but experience suggests that the natural resins are less miscible with water than processed lignosulfonates and thus less susceptible to leaching under wet conditions.

Santoni et al. (6, 7) treated a silty-sand soil with a tree resin and reported improved strength under wet test conditions after 28 and 7 days, respectively. However, the strength improvement was less than that of the polymer emulsions evaluated. Tingle and Santoni (8) treated a low-plasticity clay with one tree resin and reported no discernible differences from untreated specimens. Tingle et al. (12) tested two tree resin products as a surface treatment for a fiber-stabilized poorly graded sand (SP). Both tree resins provided improved strength compared with untreated materials. These laboratory and field test results support the physical bonding mechanism of tree resins, and experience suggests that these materials are by nature more variable than lignosulfonates but less susceptible to leaching.

LABORATORY EXPERIMENTS

A series of laboratory experiments were conducted in an attempt to verify the proposed reinforcement mechanisms for selected nontraditional soil stabilization additives. Tingle et al. (13) provide a detailed description of the test methods used and the characterization

of the individual additives. Additional research was conducted to characterize the behavior of soils stabilized with nontraditional additives using the same experimentation techniques. The objective of this paper is to discuss qualitatively the stabilization mechanisms of various nontraditional additives instead of providing a detailed accounting of these laboratory tests. Thus, the information presented in the following paragraphs is submitted as supporting documentation to the proposed mechanisms described in the previous section.

Characterization of Stabilization Mechanisms

Laboratory tests were conducted to characterize relatively pure soil minerals, natural soils, individual stabilization additives, and stabilized soils. Laboratory tests included particle size determination, X-ray diffraction, scanning electron microscope imaging, Atterberg limits, grain-size distribution, specific gravity, modified Proctor compaction tests, unconfined compression tests, Fourier transform infrared spectrometer (FTIR) analyses, comparative solubility, gas chromatography with mass spectroscopic detection (GC/MS), inductively coupled plasma with mass spectroscopic detection, and gel permeation chromatography (GPC). A complete description of the experiment devices and procedures is beyond the scope of this paper and may be found elsewhere (13). Four relatively pure soil minerals (kaolinite, sodium montmorillonite, calcium montmorillonite, and quartz sand) and four natural soils were used to evaluate the additive effects on different materials. The natural soils included crushed limestone aggregate (SP-SM), silty sand, low-plasticity clay, and high-plasticity clay. A range of nontraditional additives were evaluated including one ionic (acid), two enzymes, one lignosulfonate, one tree resin, and two polymers.

Summary of Laboratory Test Results

An acidic ionic stabilizer was evaluated by using the techniques described previously. Figure 2 (note that the scales of the two plots are very different) compares the GPC results for the kaolinite mineral and the kaolinite treated with the ionic additive. The results show a shift in retention time from a relatively high concentration (early peak) of large molecular weight particles to smaller molecular weight particles. These data tend to support the proposed mechanism that ionic additives rearrange the molecular structure—in this case, destabilizing the clay structure of kaolin. This is consistent with the unconfined compression tests on treated and untreated specimens after 7 days of curing that show a slight, but statistically discernible, decrease in strength (4% to 6%) for the treated kaolinite specimens. Although not observable from GPC tests, increases in strength (5% to 8%) for the treated low-plasticity clay and calcium montmorillonite clay specimens were recorded, possibly indicating a more stable clay structure.

The laboratory tests conducted to evaluate the effect of enzyme-treated materials failed to produce any significant differences. Unconfined compression tests on enzyme-treated low-plasticity clay showed a slight (4% to 6%) increase in strength compared with untreated specimens. However, like the ionic additive, the UCS decreased by 3% to 6% for the treated kaolinite minerals. These results failed to substantiate the hypothesized mechanism of enzyme-treated soils' reduced affinity for moisture.

The lignosulfonate produced large increases in concentrations of aluminum, silicon, calcium, phosphorous, vanadium, manganese, and strontium in the treated kaolinite mineral. The increase in available

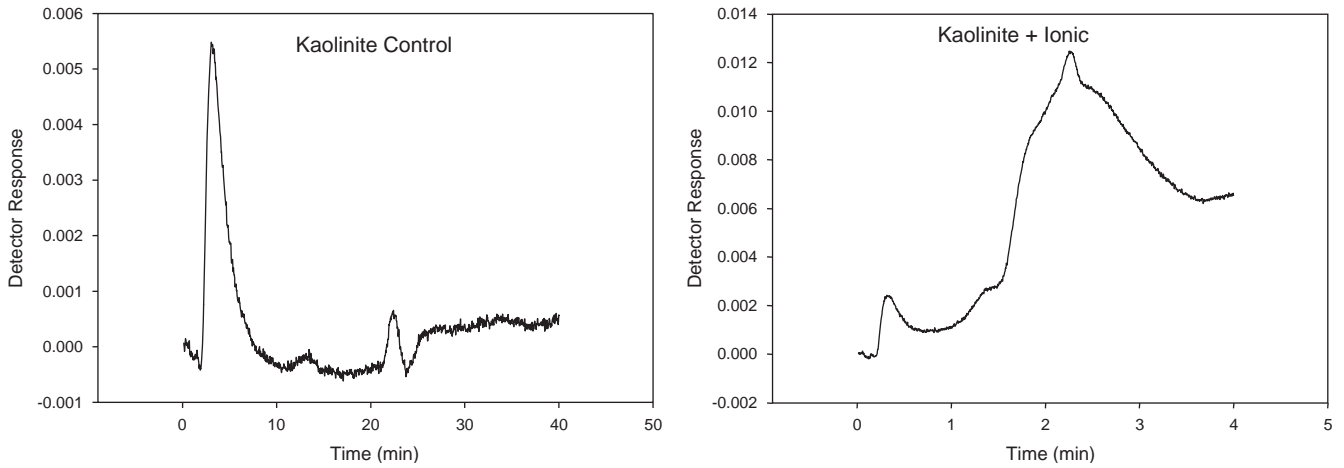


FIGURE 2 GPC results showing shift in molecular weight distribution of kaolinite treated with ionic additive.

exchangeable cations indicates the potential for cation exchange with the clay minerals. Unconfined compression tests conducted on kaolinite specimens treated with lignosulfonate showed a slight (7% to 8%) increase in compressive strength after 7 days of curing. These results provide limited support for the proposed mechanisms described previously.

Salts and petroleum emulsions were not evaluated in the laboratory experiment. These materials have been extensively evaluated in the literature, and strong support for their proposed mechanisms exists.

X-ray diffraction tests conducted on polymer-treated kaolinite samples produced negligible changes in the d-spacing between particles as indicated in Figure 3. Scanning electron microscope images of untreated and polymer-treated kaolinite shown in Figure 4 indicate some particle coating and increased aggregation. Figure 5 presents FTIR results for kaolin, a typical polyethylene vinyl acetate

copolymer and a blend of kaolin and polymer. The carbonyl absorbance of the vinyl acetate moiety exhibits a shift in the peak absorbance for the polymer-treated kaolinite, clearly indicating surface adhesion. These data strongly suggest that polar moieties present in the polymer play a significant role in adhesion to soil particles. Figure 6 presents light microscopy images of untreated sodium montmorillonite and polymer-treated sodium montmorillonite that were treated with fluorescent dye. The light microscopy image of the untreated sodium montmorillonite shows a lack of fluorescence resulting from a lack of affinity of the fluorescent dye for the soil minerals. In contrast, there is an intense fluorescence for individual soil particles, demonstrating an association of the polymer materials (hydrophobic compounds) with hydrophilic soil minerals. These laboratory test results support the proposed stabilization mechanism for polymer additives.

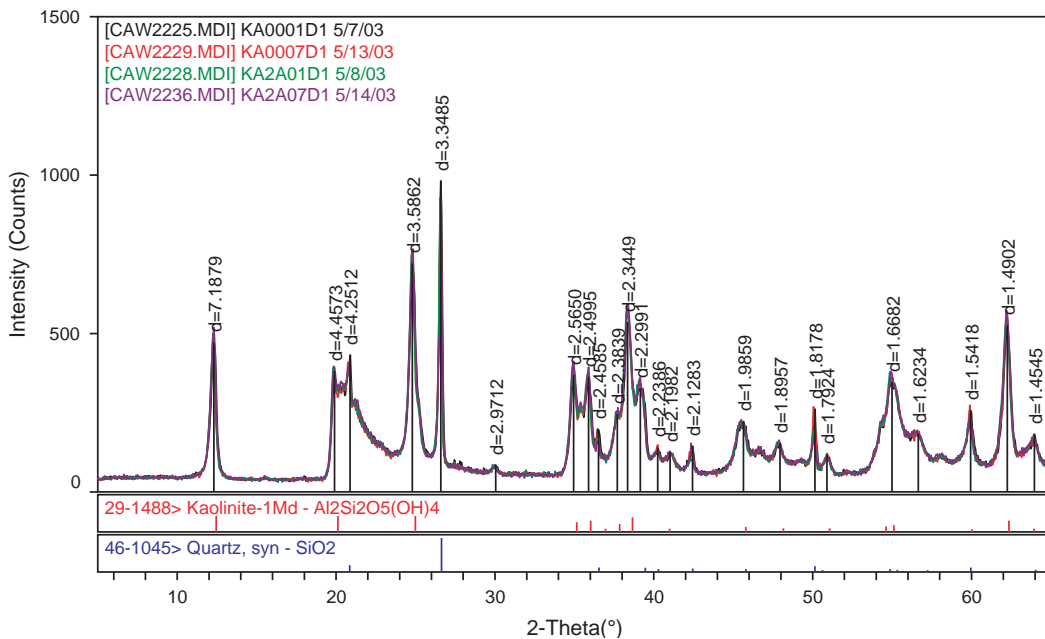


FIGURE 3 Negligible variation in d-spacing for polymer-treated kaolinite.

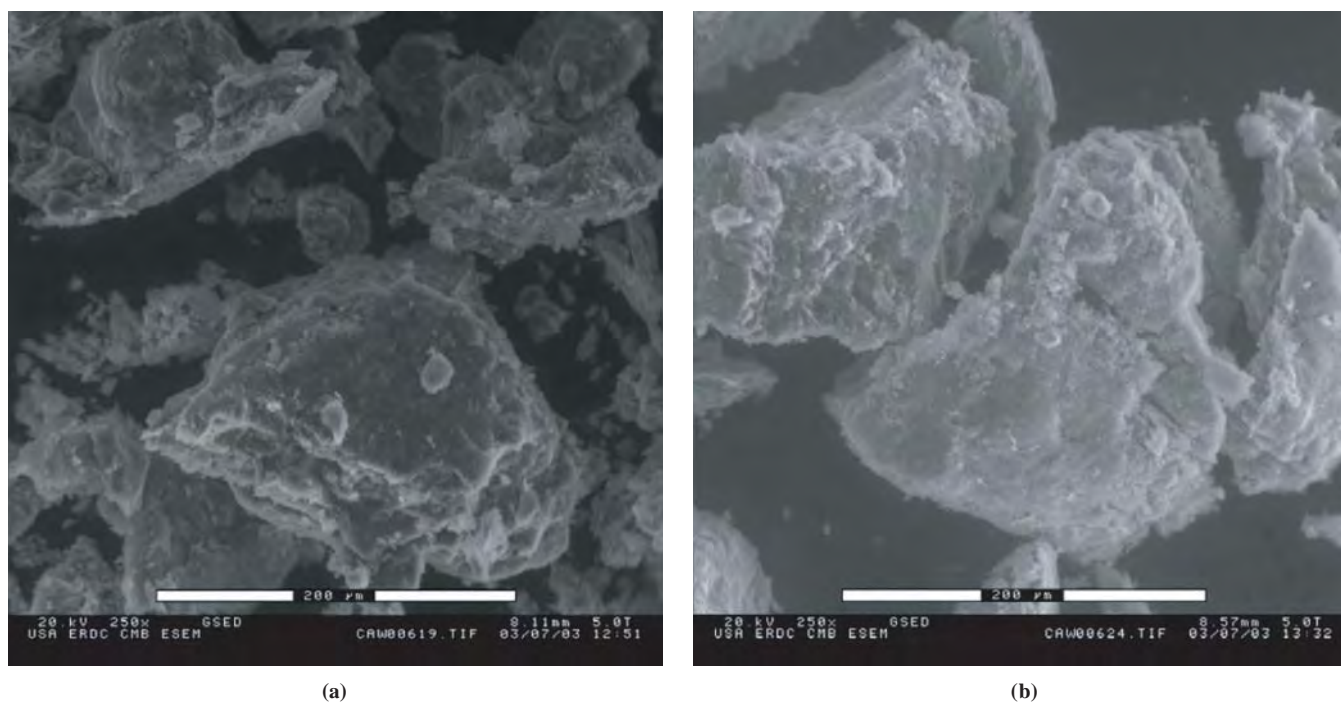


FIGURE 4 Scanning electron micrographs: (a) untreated kaolinite and (b) polymer-coated kaolinite.

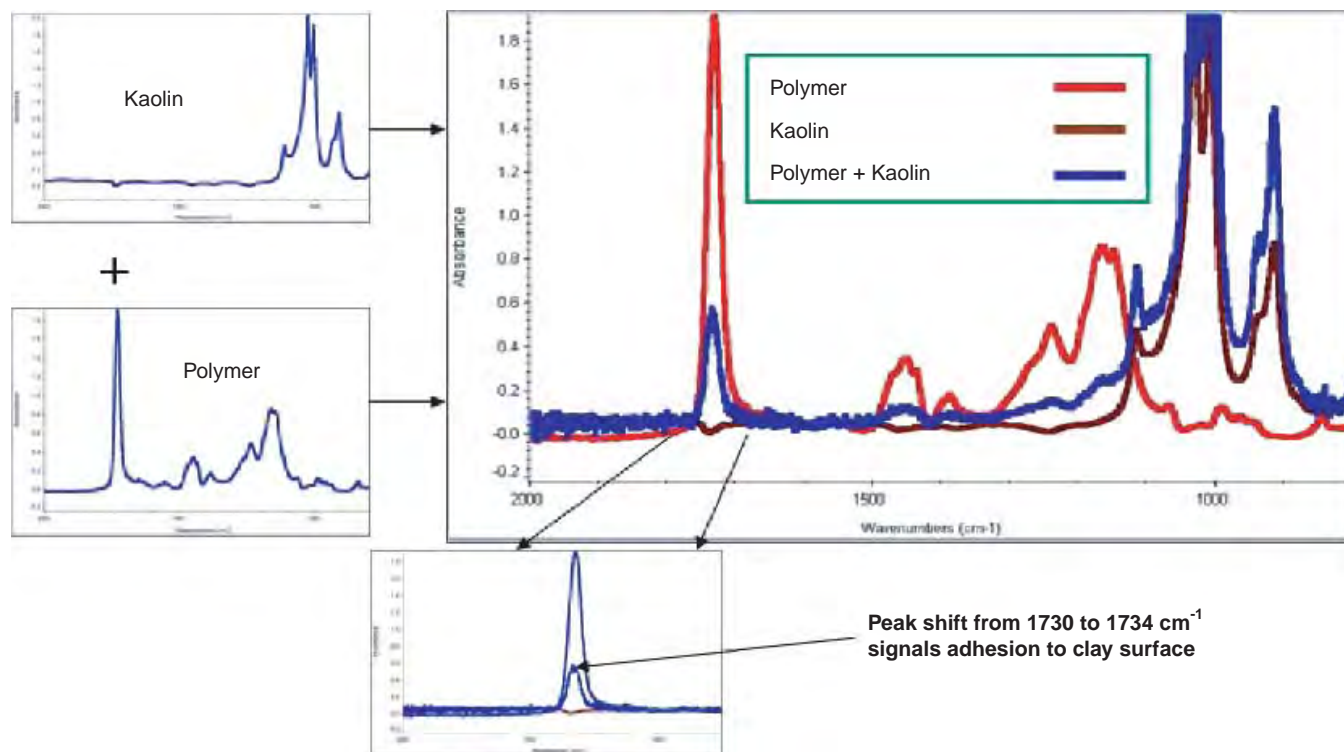


FIGURE 5 FTIR results showing peak shifts for polymer-treated kaolinite, indicating surface adhesion.

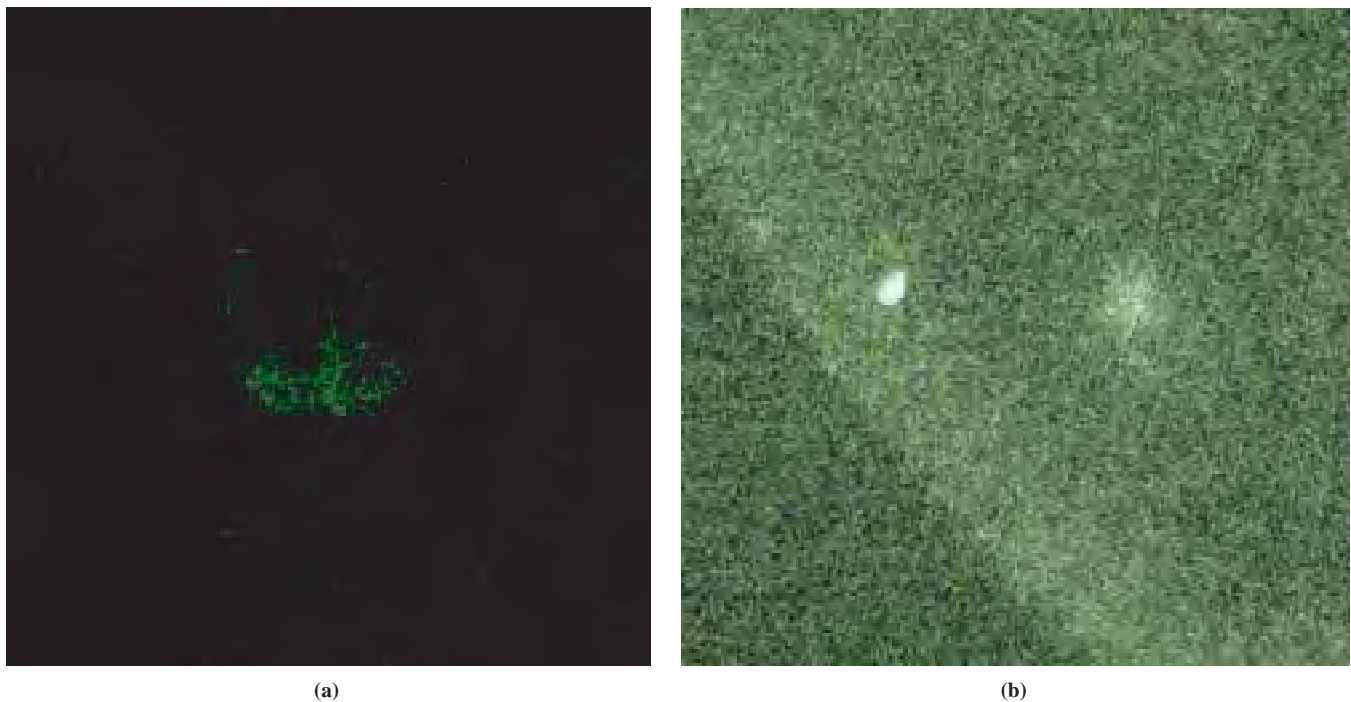


FIGURE 6 Light microscopy images of sodium montmorillonite exposed to a fluorescent dye: (a) untreated and (b) polymer treated.

Treating the kaolinite mineral with polymer emulsions actually decreased the unconfined compression strength of the treated materials by 3% to 9% after 7 days of curing. The UCS increased by 2% to 5% for the treated sodium montmorillonite specimens and by 3% to 6% for the treated calcium montmorillonite specimens. There was no discernible increase for CH and there was a 2% to 7% increase in UCS for the treated crushed limestone material. Thus, the 7-day cured specimens treated with polymer emulsions did not demonstrate large increases in UCS, which would fully validate the proposed physical bonding mechanisms. The small increases in strength tend to indicate improved physical bonding between particles. The effectiveness of the polymers in producing significant increases in strength may be partially because most of the minerals and soils are fine grained, where the increased specific surface area resulted in reduced mixing efficiency and inadequate particle coating. However, larger increases in strength would have been expected for the crushed limestone material.

Laboratory tests conducted on specimens treated with the tree resin produced a 3% to 4% increase in UCS for the crushed limestone material. There was a slight 1% to 2% decrease in UCS for the kaolinite mineral specimens treated with the tree resin. These limited data tend to support improved physical bonding, particularly for granular materials.

DISCUSSION OF RESULTS

Nontraditional soil stabilizers represent an emerging technology of increasing interest for improving the engineering properties of marginal construction materials. Soil stabilization technology continues to be of particular interest for low-volume road construction and rehabilitation where marginal materials are frequently used. Laboratory test results on nontraditionally stabilized soils and aggregates have reported mixed results based on engineering performance or

index tests. Possible reasons for the mixed performance results include a general lack of understanding of product applications, improper use of additives with specific soils, variable product supplies, inadequate application or mixing of the products and soils, and misinformation distributed by vendors. To understand the appropriate applications and limitations of nontraditional stabilizers, the fundamental stabilization mechanisms must be understood. This paper presents hypothesized stabilization mechanisms for categories of nontraditional additives based on historical literature and recent experiments. An attempt was made to link laboratory performance or index test results to the hypothesized mechanisms. The laboratory test results provide some support for the proposed mechanisms but fall short of complete verification. Additional laboratory tests were conducted to evaluate potential mechanisms using more fundamental chemical tests and imagery. These results provided additional insight into the hypothetical stabilization mechanisms but again fall short of complete verification. Table 1 presents a summary of the proposed primary stabilization mechanisms and an evaluation of the suitability of specific nontraditional stabilizer categories for specific soils and engineering applications. The discussion and results presented should enhance the understanding of nontraditional stabilizer mechanisms, leading to improved product implementation for specific engineering applications.

CONCLUSIONS

1. Ionic stabilizers such as acids and alkali materials alter the electrolyte concentration of the pore fluid, resulting in ion exchange, and may lead to flocculation of the clay minerals.
2. Enzymes catalyze very specific chemical reactions. As such, it is difficult to discern a general stabilization mechanism due to variations in the soil-specific reactions.

TABLE 1 Proposed Stabilization Mechanisms and Suitability for Stabilization Applications

Stabilization Additive	Proposed Primary Stabilization Mechanism	Suitability Assessment			
		Soil Compatibility	Strength Improvement	Volume Stability	Waterproofing
Ionic	Cationic exchange and flocculation	Fine-grained soils	Low–medium	Low–medium	Low–medium
Enzymes	Organic molecule encapsulation	Fine-grained soils	Low	Low–medium	Low
Lignosulfonates	Physical bonding/cementation	Granular soils	Medium	Low–medium	Low–medium
Salts	HygroscoPy/cation exchange and flocculation/crystallization and cementation	All	Low–medium	Low	Low
Petroleum resins	Physical bonding/cementation	Granular soils	Medium	Medium	High
Polymers	Physical bonding/cementation	Granular soils	Medium–high	Medium	Medium–high
Tree resins	Physical bonding/cementation	Granular soils	Medium–high	Medium	Medium–high

3. Lignosulfonates coat individual soil particles with a thin adhesive-like film that binds the particles together. They may also participate in ion exchange.

4. Salts attract moisture from the environment, maintaining the soil in a moist condition and increasing effective particle size by surface tension between soil particles. Salts also create the potential for cation exchange, which may improve the soil by reducing spacing between particles and increasing flocculation. Additionally, recrystallization of salts in the pore spaces creates weak physical bonds between soil particles and increases the density of the stabilized soil.

5. Asphalt emulsions stabilize soils by coating individual particles and physically bonding the particles together. Isoalkanes are petroleum-based products that serve as compaction aids, dispersing the soil particles and reducing interparticle friction for rearrangement of the particles with less compactive effort.

6. Polymer stabilizers coat soil particles and form strong physical bonds. Polar components present in the polymer may adsorb strongly onto soil particle surfaces, promoting adhesion. Depending on the specific polymer composition, ion exchange between the polymer and soil matrix may occur.

7. Tree resin emulsions are used to coat individual soil particles with a film that binds the particles together.

8. The proposed stabilization mechanisms presented are still largely unsubstantiated, but the limited data from literature and recent laboratory testing tend to support them. In general, clays and silts that have small particle sizes, large surface areas, and high water contents should be more amenable to stabilization by chemical means. Sandy and gravelly soils generally will respond well to physical stabilization.

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