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Rapid Chemical Stabilization of Soft Clay Soils

Susan D. Rafalko, George M. Filz, Thomas L. Brandon, and James K. Mitchell

Since World War II, the military has sought methods for rapid stabilization of weak soils for support of its missions worldwide. Over the past 60 years, cement and lime have been the most effective stabilizers for road and airfield applications, although many nontraditional stabilizers also have been developed and used. The most effective stabilizer to increase the strength of two soft clay soils within 72 h for contingency airfields to support C-17 and C-130 aircraft traffic needed to be determined. The treatment of one clay with cement resulted in relatively high unconfined compressive strengths (UCS), whereas treating the same clay with quicklime and calcium carbide resulted in lower UCS. The treatment of another clay with higher plasticity resulted in similar UCS for cement, quicklime, and calcium carbide. Secondary stabilizers, including sodium silicate, superabsorbent polymers, a superplasticizer, and an accelerator, were ineffective in increasing the UCS of a soil treated with cement, quicklime, or calcium carbide.

Since World War II, the military has needed to stabilize weak soils to support its overseas operations, and as a result, initiated research programs on rapid soil stabilization both in the military and academia. The goal was to find a stabilizer that could be quickly and easily mixed into weak soil to create a pavement capable of supporting traffic from military vehicles. Over the past 60 years, progress has been made, but a magic juice has not yet been found that has the ability to convert a weak soil to a strong material with little effort and in a matter of hours. Cement and lime are still among the most effective stabilizers in use today, although many nontraditional stabilizers also have been developed and used.

The purpose of this research was to determine the effectiveness of various stabilizers to increase the strength of wet and soft clay soils within 72 h for contingency airfields. The Air Force Research Laboratory (AFRL) requested that the soils have an initial California bearing ratio (CBR) of 2, which represents a very poor subgrade condition. After treatment, the stabilized clay must sustain aircraft traffic from Globemaster C-17s and Hercules C-130s. Because of weight limitations on transport to remote airfield sites, the design must be based on strengthening the stabilized soil, using a lightweight prefabricated aluminum grid overlying the stabilized soil, or covering the stabilized soil with crushed aggregate, although the latter option depends on available resources near the airfield. If an alu-

minum grid or aggregate surface is used, the necessary degree of improvement of the soil will depend on the overlying material.

The study described here, which is part of a larger research project, used unconfined compression strength (UCS) tests to screen and compare the effectiveness of different stabilizers at a constant dosage rate of 5% by dry weight of soil. This dosage rate was selected because it is within the range typically used in the field. After the most effective stabilizers were determined, the clay was treated with various dosage rates in a follow-up study, in which UCS and CBR tests were performed, and the test results were correlated. This correlation permits UCS values to be used for pavement design by the CBR method for unsurfaced airfields. The larger research project, as well as the CBR method, are discussed and summarized elsewhere (1). An independent, but similar, research project is currently being performed by the U.S. Army Corps of Engineers at its Engineering Research and Development Center (ERDC). ERDC's research has focused on soil stabilization of silty sand and clay (2, 3) for unsurfaced airfields (4, 5) as part of the Joint Rapid Airfield Construction program (6).

This paper briefly reviews chemical stabilizers, and describes potentially promising new materials and methods. The results of UCS tests on stabilized soils are discussed and conclusions are drawn.

LITERATURE REVIEW

Portland Cement

The main compounds of portland cement are tricalcium silicates (C_3S), dicalcium silicates (C_2S), tricalcium aluminates (C_3A), and tetracalcium aluminoferrites (C_4AF) (where $C = Ca$, $S = SiO_2$, $A = Al_2O_3$, and $F = Fe_2O_3$). When cement is mixed with water and hydrates, the most important products from the chemical reaction include calcium silicate hydrate and calcium hydroxide (7). The calcium silicate hydrate stabilizes the soil by forming a hard structure around the soil particles. The calcium hydroxide stabilizes the soil through ion exchange, flocculation of the clay particles, and, over the long term, secondary cementing material formed by release of silicates from the clay and their combination with calcium from the calcium hydroxide. Calcium hydroxide generated from the hydration of the calcium silicates is believed to be more reactive than hydrated lime because the calcium hydroxide created from the calcium silicates is very fine and well dispersed throughout the soil (8).

These chemical reactions will occur more quickly if the cement particles are smaller, because smaller particles have increased surface area. Of the five standard types of portland cement specified by ASTM C150 (9), all except the Type III cement have a Blaine cement fineness of 370 to 380 m^2/kg , where the Type III cement, or high early strength cement, has a much higher Blaine cement fineness

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of 540 m²/kg. Because they have the same chemical composition, fineness is the only difference between Type III and Type I cement, which is the most commonly used cement for soil stabilization. The main disadvantage of Type III cement is its higher cost.

Microfine Cement

Microfine cement should hydrate more quickly and flow more easily than ordinary portland cement, based on its smaller particle size and larger surface area. Therefore, soil treated with microfine cement would be expected to have higher early strength than soil treated with ordinary portland cement. However, the microfine cement particles have a tendency to flocculate and in effect create larger particles with an overall smaller surface area (10). To counteract flocculation of microfine cement particles in the field, high-speed shear mixers can be used to separate individual cement particles (11), and then dispersants can be used to keep the cement particles separated.

Microfine cement typically contains large percentages of blast furnace slag or pumice (11), which increases the workability and set time of the cement (12). Because microfine cement is typically used for grouting applications, increases in workability and set time are usually beneficial, but these additives may not be desirable for high early strength.

Lime

Short- and long-term reactions occur in lime stabilization of clay soils (13). The short-term process involves ion exchange between calcium ions from lime and cations near the clay particle surface. This occurs only if the calcium ions have a higher charge or a greater concentration than the cations near the clay particle surface. Ion exchange can be quite beneficial, because it tends to transform the soil from a weak dispersed structure to a strong flocculated structure. The long-term pozzolanic reactions begin as an increase in hydroxyl ions from the lime causes an increase in the pH of the soil water, which then dissolves the silicate and aluminate sheets of the clay. As the silica and alumina are released, they combine with the calcium to form calcium silicate hydrates or calcium aluminate hydrates, which cement the clay particles together.

Unlike cement, where increases in dosage rate continue to strengthen the soil, lime has an optimal dosage rate for the maximum possible strength gain, which depends mainly on soil type and mineralogy. Only long-term pozzolanic reactions occur in lime stabilization of kaolinite, whereas short-term ion exchange must be completed before the long-term pozzolanic reactions occur in lime stabilization of montmorillonite (13). Therefore, higher dosages of lime are required to reach the optimal dosage for clays containing more montmorillonite than kaolinite. Although clays containing montmorillonite may require more lime to reach their optimal dose, they may be able to achieve higher strengths, because montmorillonite may be more receptive to pozzolanic reactions due to its high specific surface area, which allows greater access to silica or alumina. However, if the lime dosage is too high, the strength gain may not be as large because of a decrease in the dry density of the soil–lime mixture (14).

Calcium Carbide

Calcium carbide is used for the speedy moisture test [ASTM D4944 (15)] but apparently has not been used for soil stabilization. How-

ever, calcium carbide should stabilize soil in a manner similar to lime, and it could actually be more effective than lime.

When calcium carbide reacts with water in the soil, the end products are acetylene gas and hydrated lime, with production of quicklime during an intermediate step. More water is consumed in these chemical reactions than is consumed by quicklime hydration alone. In addition, more heat is generated by the calcium carbide reactions, which would evaporate more water than would be evaporated by quicklime hydration alone. Furthermore, if the acetylene gas were captured and combusted, even more water could be driven off. Alternatively, it may be possible to polymerize the acetylene gas in the clay, because acetylene gas consists of unsaturated monomers that can be polymerized under the right conditions. Such polymers could stiffen and strengthen the mixture.

Sodium Silicate

The addition of only sodium silicate to hydrated clay may actually negatively affect soil stabilization (16). Clay particles typically have a net negative charge on their face and a positive charge along their edges because of broken bonds. When sodium silicate is added to hydrated clay, the negative silicate ions from the sodium silicate are attracted and attach to clay particle edges, causing entire clay particles to become negatively charged. If the entire clay particles have a negative charge, they will repel one another and the clay structure will become dispersed and weak.

Although sodium silicate may weaken clay when added alone, it may strengthen clay if lime is added along with the sodium silicate (17). The lime can be used as a source of calcium ions, and, with the presence of both calcium ions and silicate ions, calcium silicate gel can form, hydrate, and harden, thereby cementing the clay particles together.

Superabsorbent Polymers

According to Joseph Rafalko (unpublished data), soil could possibly be stabilized with calcium and superabsorbent polymers, such as sodium or potassium polyacrylic acids. This combination of calcium and superabsorbent polymers could stabilize the soil by absorbing excess water, exchanging ions with the clay particles, and hardening a polymer network throughout the soil. When the polymers absorb water, a weak gel is formed, but calcium from other sources, such as quicklime or calcium carbide, could possibly crosslink the polymers of sodium or potassium polyacrylic acid together to form a harder material.

Little research exists on soil stabilization with calcium and sodium or potassium polyacrylic acids, but Lambe (18) studied a similar material, calcium acrylate, as a potential soil stabilizer. The calcium acrylate should theoretically exchange ions with the soil, as well as crosslink other polymers of calcium acrylate together. Tests showed that the addition of calcium acrylate did significantly increase the compressive strength. However, calcium acrylate-treated soil may lose strength over time, which may be a problem for a soil treated with calcium and sodium or potassium polyacrylic acid as well (19).

Dispersants, Superplasticizers, and Water Reducers

Dispersants, superplasticizers, and water reducers are all common cement admixtures that increase the workability and increase the

strength of a cement mixture at low water-to-cement ratios (20). More specifically, dispersants increase the workability by coating the cement particles with a negative charge so they will repel one another, which also prevents flocculation of microfine cement particles (11). If cement particles are prevented from flocculating, the overall surface area may not be reduced, and chemical reactions may not be slowed.

Accelerators

Accelerators are cement admixtures that decrease the set time and increase the rate of strength gain for a concrete mixture. The most common type of accelerator is calcium chloride, which can reduce the typical final set time from 6 to 3 h with a dosage rate of 1% of the cement weight and to 2 h with a dosage rate of 2% (12). Calcium chloride can slightly increase the workability of the cement and reduce the amount of water needed, similar to the effect of dispersants, superplasticizers, and water reducers but to a lesser degree (21). However, exposure of metals to this accelerator should be limited, because calcium chloride can corrode and weaken certain metals. Other nonchloride accelerators can be used when contact with metal is unavoidable, such as in reinforced concrete, but some of these accelerators are not as effective as calcium chloride.

MATERIALS AND METHODS

The following sections describe the test procedures used to characterize the soils, the test procedures used to determine the UCS of the soil–stabilizer mixtures, and the properties of the stabilizers, which were categorized as primary or secondary stabilizers. All of the primary stabilizers were applied at a dosage rate of 5% stabilizer by dry weight of soil. Secondary stabilizers were used in addition to the primary stabilizers. The most typical dosage rate for the secondary stabilizers was 1% by dry weight of soil, but this dosage rate ranged from 0.1% up to 3.33%.

Testing Program

Soil Characterization

The Air Force will encounter such a wide range of clays that a specific clay type cannot be determined in advance. Consequently, two clays, known as Staunton clay and Vicksburg Buckshot clay (VBC), were selected to represent part of that range. ASTM standard methods were used to determine the classification, Atterberg limits, particle size distribution, specific gravity, and organic content of both soils. Mineralogical analyses also were performed.

Initial Water Contents

To compare the effectiveness of stabilizers for the two soils, the water contents of both soils were adjusted to produce the same initial untreated strength, as represented by a CBR of 2, which was selected by the AFRL because it represents a poor subgrade condition. CBR values were determined for both soils according to ASTM D1883 (15) at various water contents using standard Proctor effort [ASTM D698 (15)]. Once a well-defined curve of CBR versus water content was established, the required water content for a CBR of 2 could be deter-

mined. Accordingly, the required initial water contents for the Staunton clay and the VBC were determined to be 33.5% and 44.2%, respectively. These water contents are much higher than the standard Proctor optimum water contents, which are 26.0% for the Staunton clay and 27.8% for the VBC.

Sample Preparation and Testing

For uniformity, the unprocessed soil was first air dried, broken down to particle sizes that could pass a #4 sieve, and then hydrated to the appropriate water content. The appropriate amount of stabilizer was added according to the desired percentage by dry weight of soil necessary for each batch. Kitchen stand mixers were used to mix the stabilizer into the clay for a total mixing time of 5 to 10 min. To ensure thorough mixing, the sides of the bowl were continuously scraped, and the mixer was stopped as often as needed to scrape off any material packed onto the bottom of the bowl.

On completion of mixing, the soil was compacted into four plastic tubes having an internal diameter of 2 in. (50 mm) and height of 4 in. (100 mm). To compact the samples, a machined aluminum stand was used to hold the mold in place, and a small drop hammer was used for compaction. Stand and hammer details can be found in Geiman (22). The soil was placed in five lifts to produce the same density as produced by ASTM D698 (15) at the same water content.

After compaction, both ends of the sample were leveled using a metal screed, capped with a plastic lid, and sealed using electrical tape. The samples for each batch were unsoaked and stored in a humid room for curing times of 1, 3, 7, and 28 days, after which the samples were removed and carefully extruded from the molds. UCS tests were run according to ASTM D2166 (15) at a strain rate of 1% per minute.

Two batches were prepared and tested to determine the 3-day UCS for each stabilizer or combination of stabilizers in the test regimen. The UCS test data were plotted against curing time for both batches, and the 3-day UCS was calculated from a trend line that best fit the data. This process mitigates the effect of scatter in the data.

Stabilizers

Portland Cement

Both Type I/II and Type III cement were used in the study. ASTM C150 (9) specifies that the composition of both Type I and Type III cement has a maximum of 55% to 56% C_3S , 19% C_2S , 10% C_3A , and 7% C_4AF , whereas the composition of Type II cement has a maximum of 51% C_3S , 24% C_2S , 6% C_3A , and 11% C_4AF . Type I/II cement must meet the compositional requirements of both Type I and Type II cements (12).

Microfine Cement

Four types of microfine cement were used in this study. Microfine 1 consists of 30% portland cement and 70% blast furnace slag, and it has a Blaine cement fineness of 900 m^2/kg . Microfine 2 consists of 45% Type V cement and 55% pumice, and it has a Blaine cement fineness of 1,710 m^2/kg . In addition, Microfine 2 contains 1.5% of a superplasticizer by dry weight of cement. Microfine 3 consists mainly of 15% to 40% portland cement, 15% to 40% silica, 15% to 40% iron oxide, and 5% to 10% limestone. Microfine 3 also contains

TABLE 1 Summary of Soil Index Properties

Soil Name	USCS Soil Type	Group Name	Atterberg Limits			Fines (<#200) (%)	Max. Dry Unit Weight ^a (pcf)	Opt. Moisture Content ^a (%)	Specific Gravity
			LL	PL	PI				
Staunton clay	CH	Fat clay	53	25	28	81	92.0	26.0	2.74
VBC	CH	Fat clay	84	35	49	> 95	89.8	27.8	2.79

^aStandard compactive effort (ASTM D698).

1 pcf = 0.1571 kN/m³.

USCS = Uniform Soil Classification System. LL = liquid limit, PL = plastic limit, PI = plasticity index.

less than 5% of gypsum, calcium oxide, amorphous silica, and magnesium oxide. Microfine 4 mainly consists of 30% to 60% silica, 15% to 40% portland cement, and 0% to 10% limestone. Microfine 4 also contains less than 5% of calcium oxide, gypsum, amorphous silica, magnesium oxide, and alumina cement.

Lime

Pelletized and pulverized quicklimes were chosen over hydrated lime, because quicklime consumes more water during the lime stabilization process. The pelletized quicklime contains more than 90% CaO and has particles less than 0.125 in. (3.2 mm) in size. The pulverized quicklime contains more than 90% CaO and has particles less than 0.0058 in. (0.15 mm) in size.

Calcium Carbide

The calcium carbide used in this study contains 75% to 85% calcium carbide and 10% to 20% calcium oxide.

Sodium Silicate

The sodium silicate used in this study consists of 74.4% SiO₂, 23.1% Na₂O, and 0% H₂O, and has particles less than 0.0083 in. (0.21 mm) in size.

Superabsorbent Polymers

Three types of superabsorbent polymers were used in this study. Polymer 1 is a sodium salt of cross-linked polyacrylic acid that gels in the presence of water and can absorb more than 200 times its weight in water. Polymer 1 is granular in form, with particle sizes ranging from 0.0039 to 0.033 in. (0.1 to 0.85 mm). Polymer 2 and Polymer 3 are both potassium salts of cross-linked polyacrylic acids/polyacrylamide copolymers in granular form that also gel in the presence of water. Polymer 2 can absorb more than 200 times its weight in water, and Polymer 3 can absorb more than 180 times its weight in water. The main difference between Polymer 2 and Polymer 3 is particle size, which ranges from 0.0079 to 0.039 in. (0.2 to 1 mm) for Polymer 2 and 0.039 to 0.12 in. (1 to 3 mm) for Polymer 3.

Superplasticizer

The superplasticizer used in this study is a sodium salt of an acrylic acid copolymer supplied as a powder with typical particle sizes of 0.003 in. (0.075 mm).

Accelerator

The accelerator used in this study is a calcium chloride accelerator in liquid form and a Type E admixture as defined by ASTM C 494 (9).

RESULTS

Soil Characterization

For the mineralogical analyses, the quantity of kaolinite in each clay fraction was first determined by thermogravimetric analysis (TGA) using Georgia kaolinite as a standard (Lucian Zelazny, unpublished data). The remaining percentages of crystalline minerals were then determined by X-ray diffraction using the TGA-determined kaolinite as an internal standard. Based on the mineralogical analyses, the clay fraction consists of 45% kaolinite, 20% montmorillonite, 10% mica, 10% vermiculite, 4% hydroxyl interlayered vermiculite, 1% gibbsite, and 10% quartz for the Staunton clay, and 10% kaolinite, 60% montmorillonite, 10% mica, 15% vermiculite, and 5% quartz for the VBC. The index properties of the two clays that were used in the study are shown in Table 1. Even though both the Staunton clay and VBC are classified as highly plastic clays, they have quite different compositions and properties.

UCS Tests

Staunton Clay

Primary Stabilizers Table 2 shows the 3-day UCS for both clays treated with 5% stabilizer by dry weight of soil. All treated samples developed significantly higher strengths than the untreated soil. For the Staunton clay, treatment with Type I/II cement and Type III cement produced the highest strengths. Even though the Staunton clay treated with pelletized quicklime and calcium carbide did not gain as much strength as the Staunton clay treated with Type I/II and Type III cement, these stabilizers still produced moderate strength gains.

Secondary Stabilizers Sodium silicate was the only secondary stabilizer tested on the Staunton clay, and Table 3 shows the results of the 3-day UCS for the Staunton clay treated with different ratios of sodium silicate to quicklime or calcium carbide by dry weight of soil. Although the overall amount of sodium silicate and quicklime or calcium carbide was held constant at 5% by dry weight of soil, the ratios of sodium silicate to quicklime or calcium carbide were varied. For both the quicklime and calcium carbide, the strength

TABLE 2 Three-Day UCS for Both Clays Treated with 5% Primary Stabilizer by Dry Weight of Soil

Primary Stabilizer	UCS	
	Staunton Clay (psi)	VBC (psi)
No stabilizer	16	7
Type I–II cement	284	95
Type III cement	266	112
Microfine 1	— ^a	64
Microfine 2	—	40
Microfine 3	—	31
Microfine 4	—	28
Pelletized quicklime	110	93
Pulverized quicklime	—	79
Calcium carbide	129	89

1 psi = 6.89 kPa.

^aTest not conducted.

increased as the amount of sodium silicate decreased. The results show that replacing quicklime or calcium carbide with sodium silicate reduces the strength. Even the untreated Staunton clay is stronger than the clay treated with only sodium silicate.

Vicksburg Buckshot Clay

Primary Stabilizers Table 2 shows that the VBC treated with 5% Type III cement by dry weight of soil had the best results, whereas the VBC treated with 5% Type I/II cement, pelletized quicklime, and calcium carbide by dry weight of soil had slightly lower and very similar strength gains. The next lower strength occurred for the

TABLE 3 Three-Day UCS for Staunton Clay Treated with 5% Stabilizers Consisting of Sodium Silicate and Calcium Carbide or Quicklime by Dry Weight of Soil

Ratio of Sodium Silicate to Calcium Carbide or Quicklime	UCS	
	Pelletized Quicklime (psi)	Calcium Carbide (psi)
No stabilizers	16	16
1:0	10	10
2:1	— ^a	48
1:1	60	77
1:2	97	110
0:1	110	129

^aTest not conducted.

VBC treated with 5% pulverized quicklime. The four microfine cements produced even lower strength gains.

Excluding the microfine cements that did not result in very significant strength gains, the pulverized quicklime produced stress–strain curves that were consistently more ductile than for the rest of the stabilizers. Figure 1 illustrates the difference in the stress–strain curves between the pulverized and pelletized quicklime.

Secondary Stabilizers Six different secondary stabilizers were tested with the VBC, including sodium silicate, three superabsorbent polymers, a superplasticizer, and an accelerator. Table 4 shows the 3-day UCS of the VBC treated with 5% primary stabilizer and the indicated percentage of secondary stabilizer by dry weight of soil. Addition of sodium silicate or the accelerator had little effect on the UCS, and addition of superabsorbent polymers or the superplasticizer decreased the UCS.

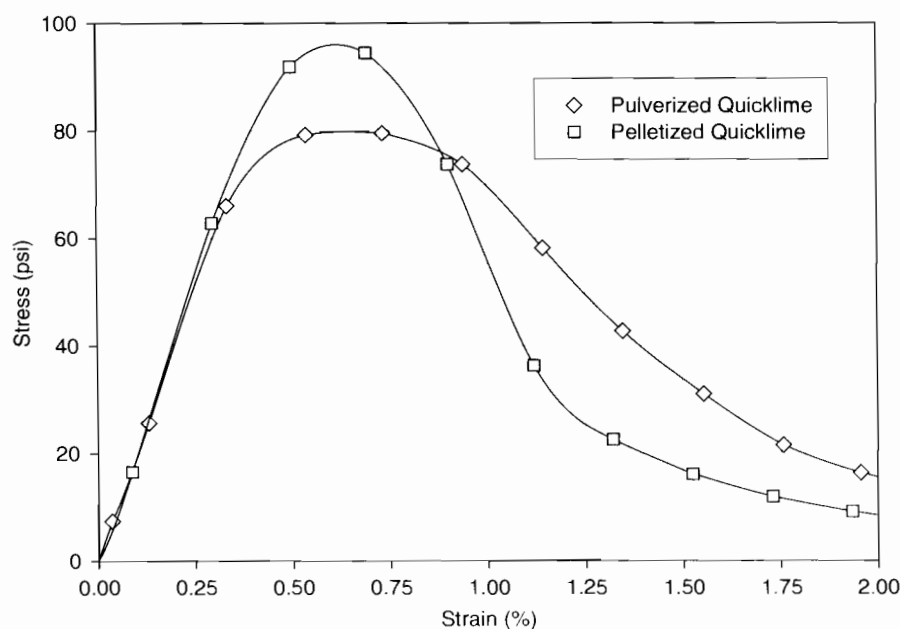
**FIGURE 1** Stress versus strain for VBC treated with 5% pulverized quicklime or 5% pelletized quicklime by dry weight of soil (1 psi = 6.89 kPa).

TABLE 4 Three-Day UCS for VBC Treated with 5% Primary Stabilizer and Indicated Percentage of Secondary Stabilizer by Dry Weight of Soil

Secondary Stabilizer	Secondary Stabilizer (%)	UCS					
		No Primary Stabilizer (psi)	Type III Cement (psi)	Microfine 1 (psi)	Pelletized Quicklime (psi)	Pulverized Quicklime (psi)	Calcium Carbide (psi)
No stabilizer	N/A	7	112	64	93	79	89
Sodium silicate	1	— ^a	—	—	88	77	88
Polymer 1	0.5	—	—	—	—	—	68
	1	—	—	—	—	—	51
Polymer 2	0.5	—	—	—	—	—	68
Polymer 3	0.5	—	—	—	—	—	63
Superplasticizer	0.1	—	—	60	—	—	—
	0.25	—	108	55	—	—	—
	1	—	83	46	70	—	78
Accelerator	0.1	—	113	—	—	—	—
	0.25	—	114	—	—	—	—
	0.5	—	110	—	—	—	—
	1	—	107	—	—	—	—

^aTests not conducted.

DISCUSSION OF RESULTS

Primary Stabilizers

Cement was consistently the most successful stabilizer for both the Staunton clay and the VBC. However, the strength of the cement-treated Staunton clay was much higher than the strength of the cement-treated VBC, even though both clays were treated with the same dosage rate of cement. The strength gain of cement-stabilized clays with high water contents is largely a function of the water-to-cement ratio (wc/c), where increases in wc/c decrease the strength (23). Because the untreated VBC requires a higher percentage of water to achieve a CBR value of 2 and both clays were treated with 5% cement by dry weight of soil, the VBC has a much higher wc/c of 8.8 compared with the Staunton clay, which has a wc/c of 6.7. This difference in wc/c may explain the higher strength of the treated Staunton clay. Soil type also may have an influence on the effectiveness of cement stabilization (7), but the wc/c appears to have a dominant effect, especially when the clay has a very high water content (23).

The strength results were quite similar for the Staunton clay treated with Type I/II and Type III cement, although the strength gain for the VBC treated with Type III cement was higher than with the Type I/II cement. Type III cement was likely more effective for the VBC, because in addition to the larger surface area of the Type III cement, the montmorillonite in the VBC also has a larger specific surface area that allows the calcium hydroxide created by the hydration of cement to have greater access to silica or alumina for pozzolanic reactions.

Compared with the Type I/II and Type III cements, the microfine cements were poor stabilizers for the VBC, which may have occurred for two reasons. First, the very fine particles of the microfine cements may have flocculated, creating larger particles with less surface area and an associated slower rate of strength gain. Second, some microfine cements contain large percentages of blast furnace slag or pumice, which may have slowed the reactions also.

The treatment of both clays with pelletized quicklime produced similar results. The effectiveness of the quicklime is influenced by both water content and soil type. Like cement, a higher water content lowers the strength gain from quicklime (22), so the resulting strength gain for the VBC may have been lower than for the Staunton clay because of the VBC's higher water content. Conversely, based solely on soil type, the VBC may have had a higher strength gain because the VBC contains more montmorillonite than the Staunton clay.

Based on the pulverized quicklime's smaller particle size and larger surface area, soil treated with pulverized quicklime would be expected to achieve higher peak strengths than pelletized quicklime, which was not the case for the soil tested here. Although the soil stabilized with pulverized quicklime had lower peak strengths, this soil had more ductility than the soil treated with the pelletized quicklime. If the pulverized quicklime particles were very well dispersed, the formation of chemical bonds from the flocculation of clay particles and pozzolanic reactions may have been uniformly distributed throughout the soil. By contrast, the chemical bonds within the soil treated with pelletized quicklime may have been concentrated near the surface of the quicklime granules, which may have formed a framework of highly treated soil around pockets of relatively untreated soil. Such a framework would likely be stronger yet more brittle than the more homogenous mixture thought to be produced by using pulverized quicklime. Alexander et al. (14) also found that coarser lime gave higher strengths, which they attributed to higher dry densities. The difference in strength gain was not caused by differences in dry density for the research reported here, because the clay treated with pelletized and pulverized quicklime had very similar dry densities.

Pelletized quicklime and calcium carbide gave similar results in each clay. Chemically, the calcium carbide should stabilize the soil in the same manner as quicklime, except the calcium carbide consumes more water and generates more heat. Although the calcium carbide does appear to have driven off more water than the quicklime, the difference does not appear to have had a great effect on the

resulting strength gain, perhaps because the water content is still well above optimum. Even though calcium carbide has stabilizing effects comparable to those of quicklime, quicklime may be preferable in field applications because calcium carbide costs more than quicklime, and the acetylene gas created during hydration of calcium carbide is highly flammable and dangerous. Conversely, additional research may be warranted to determine whether calcium carbide can be used safely, with the acetylene gas being polymerized in the soil or captured and used to heat the soil.

Secondary Stabilizers

For a secondary stabilizer to be considered effective, the secondary stabilizer must improve performance more than the primary stabilizer at a lower dosage rate. Even then, the effects from the secondary stabilizer must be sufficient to outweigh the added complexity.

Replacement of quicklime and calcium carbide with sodium silicate had a negative effect on strength gain for the Staunton clay, and the addition of 1% sodium silicate by dry weight of soil had little effect on the rate of strength gain for the VBC. Hurley and Thornburn (24, p. 50) noted that mixing sodium silicate "with almost any other inorganic material is likely to cause the formation of a silica gel," but "the properties of the gel, such as strength, durability, and permeability, may vary greatly depending on factors such as concentration of the solution, $\text{Na}_2\text{O}:\text{SiO}_2$ ratio, temperature, and the kind of salts, acids, and bases with which it reacts." In this research, the calcium silicate gel apparently was not very strong, as indicated by the soil strength after treatment. Also, because the calcium ions may have combined with silicates to form this weak calcium silicate gel, fewer calcium ions would have been available for ion exchange, which might have further decreased the strength of the treated soil. In addition, the larger dosages of sodium silicate may have created large concentrations of sodium ions, which may have weakened and dispersed the clay structure if ion exchange occurred between the high concentrations of sodium ions and any more positively charged cations on the clay particle surface. Finally, if a sufficient supply of calcium ions was not available, excess silicate ions may have attached to the edges of the clay particles and deflocculated the clay structure.

Compared with soil treated with calcium carbide only, the addition of superabsorbent polymers to calcium carbide treated soil appears to have had a negative effect on strength gain. For soil treated only with calcium carbide, the calcium ions from the calcium carbide are mainly used for ion exchange and pozzolanic reactions, but with the addition of the polymers, these calcium ions may have been used instead to crosslink the polymers together, and the resulting network of polymers may have also been quite weak. In addition, granules of the superabsorbent polymers were still visible after stabilization and may have acted as pockets of lubricant within the clay soil, especially after the polymers absorbed water.

The superplasticizer decreased the strength gain for soils treated with either microfine cement or Type III cement. Even though superplasticizers often are used with microfine cements to prevent fine cement particles from flocculating, this is usually for grouting applications where workability is of great concern and high early strength is not. If the superplasticizer was successful in preventing flocculation of cement particles, the negatively charged coating on the cement particles may have been detrimental to strength gain.

Another difficulty of secondary treatment with superplasticizers and accelerators is that a dosage rate of 5% cement by dry weight of soil is quite low compared with that for a typical concrete mixture, so

the appropriate amount of superplasticizer or accelerator is very small. The suggested dosage rate for a superplasticizer or accelerator is approximately 2% of cement weight, so only 0.1% superplasticizer or accelerator by dry weight of soil is needed for 5% cement treatment. With such a small dosage rate, the superplasticizer or accelerator may not come into contact with the cement particles enough to effectively coat or react with the majority of the particles. In addition, the superplasticizer and cement may not be thoroughly mixed together, because high-speed shear mixers are not used for soil treatment.

CONCLUSIONS

The traditional stabilizers—cement and lime—were most effective in increasing the UCS of the two clays tested in this study, whereas all of the secondary stabilizers failed to produce any significant increases in UCS. Other key findings are listed as follows:

1. Cement was consistently one of the most effective stabilizers, regardless of water content or soil type, although the water content appeared to have a strong influence on the strength gain.
2. Microfine cements were ineffective stabilizers. This may be due to flocculation of the fine cement particles and high percentages of blast furnace slag and pumice in the cement.
3. Quicklime had similar moderate strength gains in treating the Staunton clay and the VBC because the higher water content of the VBC may have decreased the strength gain, whereas the large percentage of montmorillonite in the VBC may have counteracted this decrease in strength.
4. Pelletized quicklime may have produced higher strengths and more brittle stress-strain response than the pulverized quicklime because the pelletized quicklime may have formed a stiff framework of highly treated soil compared with the more well dispersed pulverized quicklime.
5. Quicklime and calcium carbide had similar results, even though calcium carbide consumed more water than quicklime.
6. Sodium silicate was ineffective alone and as a secondary stabilizer. This may have been because of weak calcium silicate gel, fewer calcium ions available for ion exchange, or ions dissociated from the sodium silicate causing the clay structure to disperse.
7. The superabsorbent polymers reduced the effects of the calcium carbide because the polymers most likely did not harden and remained in granular form, which created pockets of weakness throughout the soil. In addition, if the polymers did react with the calcium carbide, the source of calcium originally used for ion exchange with the clay particles would have been reduced.
8. Superplasticizers may be beneficial for grouting applications to increase the workability of microfine cement by separating the cement particles, but superplasticizers decreased the rate of strength gain for the cement-stabilized soil in this study.
9. The superplasticizer and accelerator may have had little effect because the most effective dosage rate based on cement weight may have been too small considering that the percentage of cement used in the soil was much lower than the percentage typically used in concrete mixtures.

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REFERENCES

1. Rafalko, S. D. *Rapid Soil Stabilization of Soft Clay Soils for Contingency Airfields*. Virginia Polytechnic Institute and State University, Blacksburg, 2006.
2. Newman, J. K. *Rapid Soil Stabilization Technologies*. U.S. Army Engineer Research and Development Center, Vicksburg, Miss., 2005. www.mildust.net/uploads/NewmanSoilStabilizationAPOD32905-930.pdf. Accessed August 12, 2007.
3. Tingle, J. S., and R. L. Santoni. Stabilization of Clay Soils with Nontraditional Additives. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1819, Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 72–84.
4. Grogan, W. P., and J. S. Tingle. Evaluation of Unsurfaced Airfield Criteria for Operation of C-17 Aircraft. *Journal of Transportation Engineering*, Vol. 125, No. 1, 1999, pp. 67–74.
5. Tingle, J. S., and W. P. Grogan. Behavior of Unsurfaced Airfields Supporting Operations of C-17 Aircraft. *Journal of Transportation Engineering*, Vol. 125, No. 1, 1999, pp. 75–84.
6. Army/Air Force/Navy. Joint Rapid Airfield Construction. *JRAC Project Web Site*. <https://jrarc.erdcc.usace.army.mil/>. Accessed August 16, 2006.
7. Prusinski, J. R., and S. Bhattacharja. Effectiveness of Portland Cement and Lime in Stabilizing Clay Soils. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1652, TRB, National Research Council, Washington, D.C., 1999, pp. 215–227.
8. Herzog, A., and J. K. Mitchell. Reactions Accompanying Stabilization of Clay with Cement. In *Highway Research Record 36*, HRB, National Research Council, Washington, D.C., 1963, pp. 146–171.
9. Cement; Lime; Gypsum. *Annual Book of ASTM Standards*, Vol. 04.01, ASTM, West Conshohocken, Pa., 2004.
10. Krizek, R. J., and S. F. Pepper. Slurries in Geotechnical Engineering. *The Twelfth Spencer J. Buchanan Lecture*, Texas A&M University, College Station, 2004.
11. Gallagher, P. M. *Passive Site Remediation for Mitigation of Liquefaction Risk*. Virginia Polytechnic Institute and State University, Blacksburg, 2000.
12. Mamlouk, M. S., and J. P. Zaniewski. *Materials for Civil and Construction Engineers*. Addison Wesley Longman, Inc., Menlo Park, Calif., 1999.
13. Little, D. N. *Handbook for Stabilization of Pavement Subgrades and Base Courses with Lime*. Kendall/Hunt Publishing Company, Dubuque, Ia., 1995.
14. Alexander, M. L., R. E. Smith, and G. B. Sherman. Relative Stabilizing Effect of Various Limes on Clayey Soils. In *Highway Research Record 38*, HRB, National Research Council, Washington, D.C., 1972, pp. 27–36.
15. Soil and Rock; Construction. *Annual Book of ASTM Standards*, Vol. 04.08, ASTM, West Conshohocken, Pa., 2003.
16. Ding, R., Z. Qui, and J. Li. Soluble-Silicate Mud Additives Inhibit Unstable Clays. *Oil & Gas Journal*, Vol. 94, No. 14, 1996, pp. 66–68.
17. Ruff, C. G., and D. T. Davidson. Lime and Sodium Silicate Stabilization of Montmorillonite Clay Soil. In *Highway Research Record 304*, HRB, National Research Council, Washington, D.C., 1961, pp. 76–92.
18. Lambe, T. W. Stabilization of Soils with Calcium Acrylate. *Boston Society of Civil Engineers*, Vol. 38, No. 2, 1951, pp. 127–154.
19. Karol, R. H. *Chemical Grouting and Soil Stabilization*. Marcel Dekker, Inc., New York, 2003.
20. Naudts, A., E. Landry, S. Hooley, and W. Naudts. *Additives and Admixtures in Cement-Based Grouts*, ECO Grouting Specialists Ltd., Grand Valley, Ontario, Canada, 2000. www.ecogrout.com/AdditivesAdmixtures.pdf. Accessed July 6, 2006.
21. Materials Group, FHWA, U.S. Department of Transportation. *Accelerating*. June 14, 1999. www.fhwa.dot.gov/infrastructure/materialsgrp/acclerat.htm. Accessed July 9, 2006.
22. Geiman, C. M. *Stabilization of Soft Clay Subgrades in Virginia: Phase I Laboratory Study*. Virginia Polytechnic Institute and State University, Blacksburg, 2005.
23. Miura, N., S. Horpibulsuk, and T. S. Nagaraj. Engineering Behavior of Cement Stabilized Clay at High Water Content. *Soils and Foundations, Japanese Geotechnical Society*, Vol. 41, No. 5, 2001, pp. 33–45.
24. Hurley, C. H., and T. H. Thornburn. Sodium Silicate Stabilization of Soils: A Review of the Literature. In *Highway Research Record 381*, HRB, National Research Council, Washington, D.C., 1972, pp. 46–79.

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