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RAPID STABILIZATION/POLYMERIZATION OF WET CLAY SOILS; LITERATURE REVIEW

Thomas L. Brandon, Jonathan J. Brown, W. Lee Daniels, Thomas L. DeFazio, George M. Filz, James K. Mitchell (23 February 2004)
Department of Civil and Environmental Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24060-0105

Jared Musselman and Clinton Forsha (15 January 2009)
Department of Crop and Soil Environmental Sciences
Virginia Polytechnic Institute and State University
Blacksburg, VA 24060-0105

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14. ABSTRACT
This report is written in response to a request from the Air Force Research Laboratory concerning research on rapid stabilization/polymerization of wet clay soils. The purpose of this report is to document the findings of a literature review (Phase I) carried out by the team assembled at Virginia Tech. The literature review covers approximately 200 papers, most of which deal with clay stabilization. This report contains the findings of this literature review, which are categorized by soil type, stabilization type, as well as other factors. This report also includes the recommendations of the Virginia Tech research team for a proposed research program for Phase II.

15. SUBJECT TERMS
Soil, Stabilization, Contingency, Airfield, C-17, C-130, Portland Cement, Lime, Geo-synthetic Fibers and Calcium Carbide, Clay, subbase, base, polymer, super plasticizer, accelerator, roadminer, quicklime and J.H. Becker Co.

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1 Introduction

This report is written in response to a request from the Air Force Research Laboratory concerning research on rapid stabilization/polymerization of wet clay soils. The purpose of this report is to document the findings of a literature review (Phase I) carried out by the team assembled at Virginia Tech. The literature review covers approximately 200 papers, most of which deal with clay stabilization. This report contains the findings of this literature review, which are categorized by soil type, stabilization type, as well as other factors. This report also includes the recommendations of the Virginia Tech research team for a proposed research program for Phase II.

2 Historical Perspective

Experiences in World War II demonstrated the need for stabilization or solidification of soils in the theatre of operation. The Army was particularly concerned with roads and airfields, and the Navy needed techniques for improving trafficability on beaches. Accordingly, research programs were initiated, starting in the late 1940s, with the objective of developing new materials that could be quickly and easily mixed with, or even better sprayed, on soft soils to create a treated material of sufficient strength to carry military vehicles. Projects were carried out both at military laboratories, e.g. Fort Belvoir, and university laboratories, e.g. M.I.T. and Princeton.

Research at M.I.T. during 1950-56 provides useful background for the program currently proposed by the U.S. Air Force to address much the same problems of rapid solidification of soft soil. The M.I.T. study, which was performed for the U.S. Army Engineer Research and Development Laboratory at Fort Belvoir, Virginia, was aimed at rapid solidification of soft, wet, plastic soils that in their initial state were far too weak to carry traffic.

It was recognized then that a successful search for suitable materials and methods would require a proper understanding of the compositional and physico-chemical properties of fine-grained soils. Accordingly, under the direction of Professor T.W. Lambe, procedures for identification of clay minerals and other soil minerals were implemented, correlations between composition and properties were developed, and the mysteries of clay-water-electrolyte systems were explored. Concurrently, chemists and chemical engineers were engaged to aid in the search for and development of new compounds that, when mixed with wet, plastic soils could undergo reactions to yield a solidified material.

From this research came the development of organic chemicals that could be mixed with the wet soil followed by polymerization reactions that would bind the soil particles together. Key in the process was the attachment of the polymer to the clay particles by ion exchange reactions. Calcium acrylate was identified as the most suitable polymeric compound for this purpose. Wet clays could be converted to a stiff, rubber-like mass within minutes after thorough mixing of the chemical with the soil.

Although initially appealing, in fact exciting, this approach suffered several disadvantag-es. Adequate mixing of additives, either as a powder or as a solution, with wet clay is very difficult, requiring special equipment, much energy, and time. Further, the treated material was water sensitive and underwent changes in strength and stiffness as a result of wetting and drying. Well into the research program it was realized, with the aid of analytical studies of the stress-deformation behavior of layered systems, that the strength and stiffness requirements for the vehicle loads were greater than could be achieved, given the very low strength and stiffness of the subgrade soil beneath the treated layer. Additionally, the material costs were high.

Given these limitations, attention began to focus on more conventional forms of admixture stabilization, including portland cement, lime, and asphalt, and these materials are the primary admixtures in use today. Polymeric materials, while not further pursued extensively as suitable for rapid pavement construction, have gone on to find application as chemical grouts for soils and jointed rocks. No new "magic juice" stabilizers that can achieve the original soil solidification goals have emerged in the nearly 50 years since. Nonetheless, advances in chemistry, polymer science, the understanding of chemical processes in soils, and improvements in construction equipment, as well as the availability of geosynthetics and new methods for soil reinforcement, suggest that a fresh look at the problem could yield rich rewards.

3 Previous Literature Reviews

During the course of this literature review it was recognized that past literature reviews have been executed by other researchers. The literature reviews deemed most applicable to our research goals are summarized in this section.

3.1 Materials Evaluated as Potential Soil Stabilizers, by Jessie C. Oldham, Royce, C. Eaves, and Dewey W. White, Jr. (1977)

A final report for the US Army Corps of Engineers' Waterways Experiment Station, this report documents the results of approximately 30 years worth of testing. The program was initiated by the military to explore the use of chemical soil stabilizers. The stabilizers tested include acids, asphalt, cement, lime, resins, salts, silicate, and other materials.

- Calcium acrylate was one of the stabilizers evaluated in this report, but similar to what is mentioned in Section 2 – Historical Perspective, while calcium acrylate gave great results initially, the performance dropped upon wetting in the field test.

- Quicklime, also called calcium oxide by Oldham et al., was found to give extremely favorable results after just a 24-hour cure time. Because of this favorable result, a field test was carried out, and according to Oldham et al., "field tests indicated this material could stabilize weak, wet soils very rapidly; however nonuniform strength resulted because proper mixing was very difficult to obtain." The authors concluded that quicklime was the best stabilizer for clay soils. In addition to the use of quicklime alone, magnesium sulfate was found to improve the ability of quicklime as a stabilizer in all instances of its use as an additive.

- Phosphorus pentoxide, another chemical evaluated by Oldham et al., was found to work extremely quickly, too quickly to allow for adequate mixing and compaction according to the authors. Another problem associated with phosphorus pentoxide was the neutralizing effect of trace amounts of calcium carbonate. Phosphorus pentoxide is also extremely toxic.

- Sodium hydroxide was analyzed as an additive to cement as a stabilizer. While sodium hydroxide was found to be beneficial to cement stabilization, it is a caustic, which means that it is a strong alkaline chemical, and extremely corrosive to many materials and human tissue.

- Lignin or lignosulfonate was mentioned as a potential soil stabilizer that was beneficial to some silts and clays. Since lignins are inexpensive, they could still be favorable over other stabilizers that may have better stabilizing properties.

- In addition to phosphorus pentoxide, phosphoric acid was mentioned to be effective, but extremely hazardous.

3.2 Stabilization of Landslides: Effects of Various Chemicals on the Laboratory Shear Strength of an Expansive Soil, Glenn Borchardt (1984)

Various chemicals were evaluated as stabilizers for a smectitic Diablo clay. These chemicals were categorized as chlorides, fluorides, hydroxides, organic chemicals, phosphates, sulfates, and other chemicals. Borchardt concluded that precipitating or cementing chemicals provide the best stabilization properties. Hydrofluoric acid was found to be the best chemical tested, increasing the shear strength threefold. Of the other chemicals examined, the following conclusions were made:

- Chlorides – Chlorides were found to initially decrease the shear strength before increasing it. In this study, each of the neutral chlorides examined decreased the liquid limit (LL), and the acidic chlorides polymerized. One important trend to note of the chlorides is that the shear strength decreases with increasing concentration in wet Diablo clay, while the shear strength increases after an initial decrease with concentration of chloride in dry smectitic Diablo clay.

- Fluorides – Borchardt stated that, "the soluble fluorides, HF and KF, produce rapid and substantial increases in shear strength at all moisture levels." Both hydrofluoric acid (HF) and potassium fluoride (KF) work to precipitate silica for HF, and Alluminum or iron for KF, which precipitate between the smectite layers within approximately 30 minutes.

- Hydroxides – Barium hydroxide ($Ba(OH)_2$), calcium hydroxide ($Ca(OH)_2$), also known as lime, and potassium hydroxide (KOH) were found to increase shear strength, and decrease expansive properties of Diablo clay. The lime exhibited the expected pozzolanic effects, creating cement to strengthen the smectitic clay. Sodium hydroxide (NaOH) increased the liquid limit, as well as the strength, but also increased the swelling of the smectitic Diablo clay.

- Organic Chemicals – The organic chemicals evaluated in this study were found to increase shear strength only in clays with a low moisture content. However, even at higher water contents, the organic chemicals were able to decrease the expansive nature of the Diablo clay.

- Phosphates – Like KF, the phosphates studied precipitate iron and aluminum which cement the soil and increase the shear strength.

- Sulfates – Only the ferrous sulfate produced significant increases in shear strength. The ferrous sulfate produces a ferrous hydroxide which in turn precipitates between the layers of the smectitic Diablo clay.

- Other Chemicals – Sodium metasilicate is the only chemical not categorized that produces an increase in both the liquid limit and the shear strength of the smectitic clay.

3.3 Non-Standard Stabilizers, Douglas E. Scholen (1992)

By examining 160 miles of stabilized roadway from over 60 separate projects, Scholen examined the effectiveness of 13 different stabilizers. Examined in his study were three pozzolans, four bioenzymes, two sulfonated oils, one ammonium chloride, a mineral pitch, two clay fillers, and an acrylic polymer. Scholen stated: "All of these stabilizers have performed well when applied to the appropriate soils or aggregates." What Scholen meant by this statement was that the only instances of failure of the roadways studied can be attributed to the misuse of the particular stabilizer.

- Pozzolans – When quicklime, or in some of the cases Class "C" flyash is exposed to water, the calcium cations of the quicklime exchange with the clay minerals to reduce the plasticity of the clay. The hydroxyl anion increases the pH, and when the pH increases above 12.4, the alumina and silica in the clay mineral are released which then react with the calcium to form cement. This pozzolanic reaction is very common in soil stabilization. As mentioned in the Historical Perspective (Section 2), while many stabilizers have been evaluated, it is often concluded that the pozzolanic reactions that are able to both reduce the plasticity as well as cement the clay particles, effectively stabilize the soil.

- Enzymes – An enzyme is defined as an organic catalyst. The catalytic nature of the enzymes are theorized to speed up the weathering processes in clays, essentially transforming the clay into shale in a matter of hours or days rather than millions of years. The four brand name enzymes evaluated for this study are Bio Cat®, EMC Squared®, Perma-Zyme®, and PSCS-320®.

- Sulfonated Oils – The two sulfonated oils examined for this study were Condor SS® (sulfonated naphthalene) and Roadbond EN-1® (sulfonated D-limonene). Condor SS® was able to penetrate several inches to feet from the point of application through the pore water by osmosis. For this reason, "intimate mixing of the soil with the stabilizer" was not required. One major drawback of the Condor

SS® was the slippery nature of the stabilized soil upon wetting, which Scholen noted could be remedied by addition of coarse material. The Condor SS® was found to be most effective in fat clays of kaolinite and illite containing small amounts of montmorillonite. Roadbond EN-1® was used as an aggregate stabilizer which is not applicable to this study on the stabilization of clay soils. The Roadbond EN-1® produces a weak sulfuric acid when diluted. The limonene works with the hydrogen cations to "attack the clay lattice." Roadbond EN-1® does not penetrate the soil as well as the Condor SS®, requiring mixing for adequate stabilization. After the Roadbond EN-1® is thoroughly mixed, and the soil is wetted and compacted to optimum conditions, minerals dissolve into solution followed by precipitation of those same minerals to cement the layer.

- Ammonium Chloride – The brand name for the ammonium chloride studied is Consolid 444®. While Consolid 444® is not able to permeate clay soils as well as the Condor SS®, Scholen states that the ammonium ion's "powerful force removes ionized water and draws the lattice together." The ammonium ion reduced capillarity in the soil requiring more thorough mixing of the soil since the ions cannot readily penetrate the large clods of clay.

- Mineral Pitch – Mineral pitch is similar to natural polymers. This is also known as a tree resin. Scholen states that mineral pitches behave similarly to asphalt, but pitches are able to achieve 5 times the strength of asphalt. Road Oyl®, the mineral pitch used in this study, is stated to be able to be used for surface treatments.

- Clay Fillers – The clay filler used for this study, bentonite, was used to stabilize aggregate. The clay filler is added to the aggregate to act as a binder. This is intended to reduce washboard of the surface.

- Acrylic Polymers – "Latex acrylic co-polymers are prepared in emulsion form with 40 to 60 percent solids; they are non-toxic and non-flammable. After curing they are not water soluble." The brand name acrylic polymer used for this study was Soil Seal®. While Soil Seal® was successfully implemented for a landslide repair by protecting the slope from erosion, an unsuccessful implementation occurred when utilized to stabilize the surface of a sand/limerock road. Scholen hypothesizes that this was unsuccessful due to the high fines content of the aggregate.

There are two important things to note for the purposes of our research objectives of stabilizing weak clay. While this report praises the use of enzymes as a soil stabilizer, other studies found in this literature review have not been able to support these claims. Also, it seems unfeasible to stabilize weak clay with unstable clay such as bentonite, especially when the high water content of the clay is of major concern.

3.4 Contingency Airfield Construction: Mechanical Stabilization Using Monofilament and Fibrillated Fibers, Randy C. Ahlrich, and Lee E. Tidwell (1994)

The study conducted by Ahlrich and Tidwell includes a brief literature review on the use of geosynthetics in pavement design. The literature review was followed up by a laboratory study of high-plasticity clay and beach sand. For our purposes, we focused on the study of the high-plasticity clay.

Two papers summarized in the literature review portion of the paper by Ahlrich and Tidwell are of relevance to our study. These two papers were encountered during our own literature review, and are summarized below:

- Stabilization of High Plasticity Clay and Silty Sand by Inclusion of Discrete Fibrillated Polypropylene Fibers for Use in Pavement Subgrades, W. P. Grogan, and W. G. Johnson (1993) – Polypropylene fibers 1-inch in length were used at rates between 0.0 and 0.5 percent by weight. The study was done using a full-scale test section of lime stabilization, fiber with lime stabilization and a control without any stabilization. It was found that the inclusion of fibers to the lime stabilized clay improved the strength and durability of the test section. Rutting and cracking was reduced, and the traffic to failure was increased. In addition to this study, fibers were also mixed into clay at a water content of 29 percent and an additive rate of 0.5 percent. A separate study, analyzing the effect of fiber length on mixing consistency concluded that the fibers were able to be mixed into CH material adequately, with a better distribution resulting from shorter length fibers.

- California Bearing Ratio Improvement of Remolded Soils by the Addition of Polypropylene Fiber Reinforcement, C. Scott Fletcher, and W. Kenneth Humphries (1991) – This paper studied the effects of fiber reinforcement on residual silt. Polypropylene fibers 1-in. in length were tested at additive rates of 0.5, 1.0, and 1.5 percent by weight. Fletcher and Humphries concluded that the addition of the fibers caused an increase in the maximum dry density with an associated decrease in optimum water content. What is of more importance to note is the increase in the California bearing ratio (CBR) values by 133 percent.

4 Literature Review Methodology

An initial search was carried out to find appropriate papers or reports. Once the search was carried out, the papers and books were obtained. A precursory review was carried out in which a one page summary was written for each source which included the title, a summary or the abstract, a brief description of the study, and the findings of the study. Each of the sources were then cataloged and categorized into a ProCite® database. An appendix was put together for this report using Microsoft® Access, with which a more thorough review of each source was carried out. A description of the implementation of Microsoft® Access database system is described in Section 4.3 – Use of Microsoft® Access Database.

4.1 Search Engines

The search engines utilized for this study are:

- Compendex® – (1970-present)
- Swedish Geotechnical Institute (SGI) – (1976-present)
- GeoFind – (1985-1995)
- *Geotechnique* – (1948-1999)
- Waterways Experiment Station (WES)
- Transportation Research Board (TRB)
- Federal Highway Administration (FHWA)
- National Technical Information Service (NTIS)

4.2 Use of ProCite®

ProCite® is the citation software used by our research team to catalog and categorize the sources utilized for this literature review. ProCite® allowed us to enter each source as we proceeded with the literature review with standardized input forms for information. Once the sources are entered they can be grouped according to keywords, or subjects similar to the ones utilized in this report (i.e. stabilizer type, soil type, etc.). One other powerful feature of ProCite® is the ability to automatically change the reference citation style.

4.3 Use of Microsoft® Access Database

A Microsoft® Access database was created to help us sort through the large volume of articles encountered from this literature review. This database contains summaries of the 138 papers found on stabilization of fine-grained soils for the purposes of this research project. Its contents include general information on each article, such as title, authors, year published, and the source from which it was found as well as some details of the research presented. The intent of these summaries is to provide a general overview of the papers, the overall objectives of the author's research, a description of the author's laboratory or field testing, and a brief summary of the author's findings. By use of this database, one can hopefully gain the important knowledge of a given research effort and decide to further investigate its usefulness for further testing and research.

Use of the Microsoft® Access database is fairly straightforward. Upon opening the database, the user will see the main switchboard form. It contains on-click buttons to navigate the user through the database. By selecting the desired option, a window will open taking the user to the next set of options. The user can either review the articles in the database on-screen or choose to review them from a report preview. The on-screen viewing can be done in edit-mode or in read-only mode. It is recommended that unless the user intends on making edits to the database information that he/she view in read-only mode. In edit-mode, once the user makes an edit (intended or not) and leaves the field, the changes are saved.

4.3.1 View Literature Review Papers (read-only or edit-mode)

This form presents each paper of this literature review as a separate record. The papers are organized alphabetically by first author and the paper numbers shown correspond to this organization. The top of this form provides general information regarding the article. By using the 'find' navigation button (represented with a picture of binoculars), the user can quickly search and navigate these fields. This is done by simply placing the cursor in the desired field and clicking on the binoculars. A search window will pop up with options to manage the search. Otherwise, the user can navigate through the records with the arrow buttons that will take the user from record to record in sequential order.

Below the general information on the papers, the form has three tabs that provide the summary information about the research. The tabs are: 1) Soil and Additive Info, 2) Application Rates and Soils Tested, and 3) Test Methods and Key Findings. By clicking on the tab the information can be seen for the given record.

4.3.2 Datasheet View of Papers in Database (by year published)

This form allows the user to view all the papers in the database in spreadsheet format. It is in chronological order from the latest research to the oldest.

4.3.3 Reports

The reports generated in this database were created for the intent of building the appendix of this white paper. They provide one-page summaries of each research paper in an organized fashion. In conjunction with the organization of this paper, the reports are given for each type of stabilizer. Each report is then ordered by the first author alphabetically.

4.3.4 Security of Database

There are no levels of security built into this database. The user is free to make any changes that he/she may desire. The format of existing reports and forms, or the addition of reports can be made easily by someone with a working knowledge of Microsoft® Access. It is highly recommended that the user save a copy of the database before any changes are attempted.

4.4 Summaries in Appendix

The Appendix to this report contains one-page summaries of the articles included in this literature review of stabilization of fine-grained soils. The papers were divided into three main categories based on their stabilization mechanism: 1) chemical reaction, 2) mechanical reinforcement, 3) a combination of chemical and mechanical.

The summaries provide the following information in these fields:
<u>Paper Title</u> – This is given title of the paper by the author.
<u>Author</u> – States the authors of the publication.
<u>Source</u> – Identifies the source in which the article was published.

Publication Date – This is the year the article was published.
Purpose of the research – This field identifies why the author was researching this stabilizer (e.g. subgrade stabilization, grouting, waterproofer, etc.)
Stabilizers Tested – Shows the different stabilizers that were tested as part of this research. Each stabilizer is separated by a comma, with combinations of stabilizers joined by an 'and'.
Soils Tested – This section summarizes the soils that were tested in laboratory or field testing as part of the research paper. The general description is given of the soils as described by the author as well as the Unified Soil Classification System (USCS) symbol if provided. Additionally, the primary and any secondary additives are identified as used on each soil with its form and dosage rate identified. Unless otherwise specified, these rates are by dry unit weight of the given soil.
Natural or Manufactured Soil? – This field identifies whether the soil was a natural soil or manufactured by combining soils or through the use of a commercially procured soil.
Clay Mineralogy – Provides the clay mineralogy if provided by the author.
Tests Performed – Lists the primary tests performed. This space allows three tests to be listed. An effort was made to identify any further testing in the next section (Test Methods) if more than three testing methods were performed.
Test Methods – Provides a short description of the sample preparation and testing method performed on the soil samples. This was not intended to be all inclusive or to great detail, but provide the reviewer with an idea of the extent of testing such that he/she can determine if the article is worth further investigation.
Key Findings – Summarizes the key findings as presented by the authors. An effort was made to quantify the findings in the case of strength gain, swell potential, etc., where possible. It was also our intent to keep these comments relevant to the intent of our research.
Comments – Contains any additional comments on the article that did not fall into the above fields.

5 Findings

Presented in the following sections are the general findings categorized by soil type, stabilization type, and any other factors that were encountered during our search.

5.1 Organization of Section

This section is broken into two major parts: Stabilization Type and Other Factors. Section 5.2 – Soil Type describes the different soil types encountered during the literature review with a description of how the papers were categorized according to soil type. Section 5.3 – Stabilization Type is broken up into three sections: Chemical Stabilization, Mechanical Reinforcement, and Combinations. Each of these sections are broken up into subsections based on different properties, except for Section 5.3.2 – Mechanical Stabilization which is just a general overview since mechanical stabilization as a stand-alone stabilizer is not typically utilized for clay soils. Section 5.4 – Other Factors is a section that takes into account some of the other parameters encountered such as water content, time effects, and mixing of stabilizers. Table 1 presents an overview of the distribution of the number of papers in each category.

Table 1 - Number of Papers Related to Clays
by Category, from Literature Review

Category	# of Sources
Stabilization Type	
Chemical	
- Heat	8
- Polymer/Resin	25
- Ionic/Charge	61
- Enzymes	4
- Lime/Cement	80
- Other	15
Mechanical Reinforcement	
- Wood/Natural	8
- Glass Fiber	1
- Polymer/Plastic Fibers	21
- Polymer Grids	1
Combinations	
- Lime/Cement with Reinforcement	11
- Lime/Cement with Other Chem. Stab.	15
Other Factors	
- Time	38
- Water Content	23
- Field Mixing	7

5.2 Stabilization Type

Two major forms of stabilization were encountered, chemical and mechanical stabilization. There were some instances of studies implementing a combination of mechanically reinforcing a chemically stabilized soil to improve properties such as strength, stiffness, or to accelerate the treatment of the soil.

5.2.1 Chemical Stabilization

Arora and Scott (1974) listed 18 different chemical mechanisms that may cause clay stabilization. Borchardt (1984) summarized Arora and Scott's mechanisms with the following list; the first six being the most important:

1. Exchange of cations
2. Exchange of anions
3. Adsorption
4. Fixation
5. Formation of new minerals
6. Cementation
7. Salt conversion
8. Modification of water films
9. Adsorption of water films

10. Enrichment of pore water with ions
11. Modification of capillary forces
12. Modification of the electrical surface tension of clay minerals
13. Modification of the electrical forces between particles
14. Modification of chemically bound water
15. Adsorption of chemically bound water
16. Neutralization of acids
17. Neutralization of bases
18. Proton exchange

Chemical stabilization is associated with modification of the actual chemical make-up of the soil matrix. Chemical stabilization can be carried out by applying heat to the soil, mixing polymers or resins with the soil, altering the charge or ionic makeup of the soil or pore water, addition of biological catalysts called enzymes, the addition of lime or cement to the soil, or other means. The papers were categorized according to these mechanisms which are summarized in the following sections.

5.2.1.1 Heat

The implementation of heat is most commonly used as a catalyst to accelerate the curing of treated soils. This phenomenon is evident in lime treatment when results of soils treated with quicklime are compared to soils treated with hydrated lime. Not only does the quicklime consume more water in the reaction process, but more heat is generated as well. This additional heat is most commonly attributed to the additional strength gain in soils treated with quicklime compared to those treated with hydrated lime, especially when time effects are analyzed. Two papers were found (Anday 1961 and Drake and Haliburton 1972) which investigated the effect of heat on the curing time of lime treated soils. Anday concluded that a laboratory curing of 18 hours at 140ºF, or two days at 120ºF could predict the same results as the same specimen cured in the field for 45 days in summer temperatures. Anday suggests the use of the 120ºF curing temperature over the 140ºF temperature accelerated curing since it is a lower temperature, a convenient curing time, and increased accuracy in prediction of the field strength from the more gradual slopes of the strength-time curves.

Heat has also been investigated as a standalone stabilizer for clays. This stabilization technique is derived from brick making. Joshi et al. (1994) found that clays will exhibit greater unconfined compressive strength (UCS) when dried above 110ºC. The samples exhibited an increase in strength associated with an increase in temperature but the samples disintegrate in water unless the temperature is taken above the dehydroxylation temperature which is between 500ºC and 700ºC. At temperatures above the dehydroxylation temperature, the increase in strength with increase in temperature is much steeper. While this may seem promising, it is believed to be impractical to achieve these temperatures within a clay soil in the field. However, Moritz and Gabrielson (2000) examined a field test in which two 1000 m^3 (10x10x10 m) structures were subjected to elevated temperatures on the order of 70 to 90ºC by the circulation of high temperature fluids through vertical ducts. The shear strengths decreased by approximately 30% initially, but then the shear strengths eventually increased by approximately 40%. While the study by Moritz and Gabrielson investigates the field implementation, the sizes of the two structures (1000 m^3 each) are still relatively small compared to the volumes required for airfield construction. The times required for the increase in shear strength are on the order of years, and not days as required by our scope.

5.2.1.2 Polymer/Resin

Polymer stabilizers tend to be characterized by commercial brand names. This makes it difficult to recognize similarities between different polymer stabilizers due to the fact that the chemical composition of each stabilizer is generally undisclosed by the individual suppliers. The brand names often become inconsistent due to the alteration of names based on different marketing strategies implemented by suppliers.

The most promising polymeric stabilizer found was a natural polymer known as lignin or lignosulfonate. Lignins are derived as a byproduct of the paper industry. These lignins act as a binder to glue the soil particles together reducing dust, and even stabilizing the entire soil matrix. Lignosulfonate dissolves in water due to its hydrophilic nature, while sulfate lignin is hydrophobic and does not dissolve in water. Lignins have been shown to improve soil engineering properties in the laboratory. Gow et al. (1960) demonstrated that the use of lignin liquor improved a soil aggregate mixture of pit-run gravel, silty clay loam, and glacial till with an unsoaked CBR value of 15.3 untreated to 71.0 immediately, and from 40.5 to 97.5 when cured for a week. The lignosulfonate of Toranil A® increased the uncured specimen to a CBR value of 64.0 and 97.0 when cured. The soaked specimens did not show as great of an improvement as the unsoaked specimens, but there was still an improvement with lignin liquor from a CBR value of 9.8 to 49.5 immediately, and in increase from 22.5 to 36.5 when cured for a week with lignin liquor. The Toranil A® demonstrated an increase to 52.0 immediately, and 46.0 after curing for a week. This strength loss with soaking is associated with the hydrophilic nature of the lignosulfonate.

A much wider array of synthetic polymers exists when compared to the number of natural polymers. Ajayi-Majebi et al. (1991) examined the implementation of an epoxy-resin polymer of bisphenol A/epichlorohydrin resin plus a polyamide hardener. While the largest unsoaked CBR value was obtained for the clay-silt mixture at a moisture content of 13%, the largest percentages of CBR value increase were found for the soils tested at a moisture content of 21%. For the soil with a clay-silt ratio of 0.4, the untreated CBR value at 90ºF was 0.7 which was increased to a CBR value of 87.1 when treated with 4% of the epoxy-resin stabilizer.

Bolander (1999) investigated the stabilization effects of lignosulfonate finding that the lignosulfonate would leach out of the material. The two synthetic polymers investigated, Soil Sement® and EnduraSeal®, resulted in a large improvement of tensile strength and would also retain a larger portion of the tensile strength compared to the lignosulfonate. Tingle et al. (2003) also investigated Soil Sement®, which resulted in a large improvement in wet UCS, but not dry strengths of both lean and fat clay. Tingle et al. also investigated Enviroseal 2001®, which has a name very similar to EnduraSeal®, but it is not clear whether these are the same stabilizer with the different names, the same stabilizer with minor modifications, or different stabilizers completely. The results of

Enviroseal 2001® are favorable, however. The Enviroseal 2001® polymer stabilizer exhibited increases in both dry and wet UCS for both low- and high-plasticity clays. It is of importance to note that Tingle et al. (2003) does not mention the brand names of the stabilizers, but the names were obtained through personal communication.

Bryn et al. (1984) compared the use of hydroxyl-aluminum (OH-Al) compound with unslaked lime, or quicklime for stabilizing sensitive clays. The hydroxyl-aluminum ($Al(OH)_{2.5}Cl_{0.5}$) used in this study belongs to a family called polymer aluminum hydroxides. For this study, the polymer is a chain of seven hexagonal rings with the chemical formula $[Al_{24}(OH)_{60}(H_2O)_{24}]^{18+}$. When the pH is raised, the rings condense to make a firm gel. The OH-Al also acts like a large cation in quick clays, making the clay plastic. Above certain concentrations, the mixture can become grainy and stiff. In the laboratory, the resulting shear strength from stabilizing with OH-Al is higher than that of the same soil stabilized with quicklime alone. The maximum unconfined compressive strength for OH-Al stabilization was 300 kPa compared to 150 kPa for the same soil stabilized with quicklime. Field tests were investigated to evaluate the mixing technique, as well as performance of 0.5-m diameter in situ stabilized clay columns. The field implementation of OH-Al in columns was only able to increase the shear strength to be equal to or less than quicklime. The reduction in strength of OH-Al, when compared to quicklime is attributed by Bryn et al. to incomplete mixing of the OH-Al into the soil. At the time of the study, OH-Al was only available in pharmaceutical quantities causing the cost of OH-Al compared to lime to be very high.

5.2.1.3 Ionic/Charge

Stabilization of soils by ionic or charge manipulation can be sorted into two major categories, electro-osmosis or chemicals such as salts or acids.

Electro-osmosis is a phenomenon described by Hausmann (1990) as a process in which an electrical potential is applied to the soil, which causes the positive ions to move through the soil to a negative electrode, essentially dragging the free water with them. Electro-osmosis is typically utilized to accelerate drainage through low permeability soils, but in some cases the electrodes are reversed to accelerate flow into the soil as a means of promoting a chemical stabilizer into the soil pores called “electrokinetic stabilization” (Senneset and Acar 1995). One application of this stabilization technique consists of the introduction of aluminum into the soil by electro-osmosis with the hypothesis that as the aluminum is introduced into the soil it will precipitate into the pore space, thus strengthening the soil. Gray (1970) and Ozkan et al. (1998) both tested this hypothesis. Gray’s study found a time dependent increase in shear strength exclusive of thixotropic effects as well as a decrease in liquid limit. The study by Ozkan et al. concentrated on kaolinite clays which resulted in an increase in undrained shear strength of 500% for aluminum sulfate/phosphoric acid treatment.

Salts are commonly used to alter the ionic makeup of the pore water. As a group, salts tend to flocculate clay soils, aiding in compaction by reducing the optimum water content, and increasing the maximum dry density. Salts are also commonly utilized to reduce freeze/thaw effects by reducing the freezing temperature of the pore water.

Similar to electrokinetic treatment with aluminum precipitates, it has been found that aluminum and iron salts are commonly utilized to precipitate the aluminum and iron into the pore spaces, increasing the strength of the soil in a manner similar to the one mentioned above. One common salt identified by this literature review was sodium chloride (NaCl) or table salt. Singh and Das (1998) studied the effects of NaCl on the UCS, CBR, and the indirect tensile strength test. Singh and Das concluded that, "CBR test values, unconfined compression strength, and indirect tensile strength are greatly improved with the inclusion of sodium chloride as a stabilizing agent."

Acids are another common chemical stabilizer that are categorized as an ionic stabilizer because the stabilization mechanism is due to the large concentration of hydrogen ions. While some acids have been found to effectively stabilize soils in the laboratory and the field, they are commonly avoided due to the danger of handling some of these highly acidic chemicals. Demirel et al. (1960) concluded that "Phosphoric acid treatment improves the strength and durability characteristics of compacted, moist cured, clayey soils." They also found that the amount of improvement depends on the application rate and clay mineralogy, with chlorite being the most reactive of the clay minerals when compared to montorillonite, illite, kaolinite, or vermiculite. Lyons and McEwan (1962) also concluded that based largely on 5-day cure times, "Phosphoric acid is an effective stabilizer for a broad range of clay containing soils." While phosphoric acid was found to produce an increase in soil strength, according to Demirel and Davidson (1962) the reaction takes longer than three days to bring about this improvement. Phosphoric acid was explored extensively in the 1960's, but was not explored as a soil stabilizer much afterwards, most likely due to handling and environmental concerns. Other than phosphoric acid, acids in general were found to be relatively ineffective.

5.2.1.4 Enzymes

As mentioned in the description of the paper by Scholen (1992), an enzyme is a biological catalyst. These enzymes are hypothesized to bond with large organic molecules which would then be attracted by the net negative charge of the clay surface. These large organic molecules would neutralize the negatively charged clay mineral, which would reduce the clay's affinity for water, improving the clay's stability. This effect results in a weathering of the clay minerals in a matter of hours or days compared to millions of years for this weathering to occur naturally.

Scholen (1992) is the only paper found that presents positive results for soil stabilization with enzymes. The test sections studied by Scholen consisted of aggregate stabilization by means of three commercial enzymes. The enzymes included a bacterial culture with an enzyme solution that multiplies rapidly when exposed to air, producing the organic molecules necessary to attach to the clay minerals. Scholen found that well-graded aggregates with high clay contents performed best, by "locking" the larger aggregate particles within the matrix. This produces a rigid surface, reducing raveling.

Rauch et al. (2003) found no significant improving effects of enzymes on the Atterberg limits, compacted density, shear strength, or swell potential. The hypothesized mechanisms of enzyme stabilization stated by Scholen (1992) did occur however. The dspacing of montmorillonite clay was fully expanded, meaning that application of the enzyme to an expansive clay would cause the clay minerals to expand to their fullest extent, reducing the potential for further expansion. The enzyme also caused the largest reduction in surface area of all the stabilizers studied, for each clay studied. The results presented in this report are reiterated by Thomas (2002), which is a thesis in conjunction with the same study as Rauch et al. (2003). For Thomas's thesis however, the enzymes were applied at rates ten times greater than the manufacturer's recommended dosage. Even at these large dosage rates, there was no significant improvement in the soil's engineering properties.

Tingle et al. (2003) conclude that while one of the four enzymes evaluated in their study produced small improvements in UCS for CL and CH, enzymes as a group had little to no effect on the strength of the soils compared to untreated samples.

5.2.1.5 Lime/Cement

Lime and cement stabilization is a topic that has been extensively researched and the number of publications dealing with lime and cement stabilization is vast. For the purposes of this project, the cache of studies covering lime and cement stabilization was limited to studies of short term properties of lime or cement stabilization, additives used with lime or cement stabilization, and/or studies examining lime or cement stabilization with high water content soils.

Lime stabilization can be described by three phases with the first phase being hydration of quicklime, which generates a considerable amount of heat, as well as hydrated, or slaked lime. Hausmann (1990) stated that "it could be said that a truckload of quicklime has 25% more lime available for the reaction with soil than slaked lime!" The heat produced in the hydration process of quicklime is extremely advantageous to the use of lime to treat wet clay soils. The second phase is flocculation, which results in an immediate reduction of plasticity. The calcium of the lime exchanges with the adsorbed cations of the clay mineral, causing the clay to flocculate, making the clay more workable and mixable. This flocculation phase becomes extremely beneficial when mixing fibers with clay soils which is explored in Section 5.3.3. The final phase of lime stabilization is the long-term cementation phase. This phase occurs when the pH of the pore water is increased to 12.4 releasing the silica from the clay mineral. The calcium then reacts with the released silica to produce cement which cures over time to strengthen the soil. The cementation process is highly dependent upon the amount of available silica which is why it has been found that lime stabilization is more effective for montmorillonite soils than for kaolinite soils (Lees et al. 1982). Additional heat will act as a catalyst, accelerating the pozzolanic reaction, thus reducing the curing time. Sulfates have been found to be detrimental to lime stabilization causing an increase in swell. It has been found that if a pretreatment of lime with soil with low sulfate content is carried out, the reaction between the sulfates and the lime can be neutralized, allowing a second treatment of lime to stabilize the soil without detrimental effects (Ferris et al. 1991).

Cement differs from lime stabilization in that the silica is inclusive of the cement. The fact that all of the constituents for cementation are present allows for less control of pH and silica content resulting in a more adaptive treatment.

5.2.2 Mechanical Reinforcement

It is also hypothesized that the engineering properties of clays can be improved by reinforcement. The issue of major concern for this mechanism is the field mixability of fibers into clays, especially highly plastic clays. Our group believes that while it will be difficult to mix fibers into highly plastic clay, the addition of lime to the clay, which will reduce the plasticity of the clay, will allow fibers to be effectively mixed into the soil.

Mechanical reinforcement materials are most commonly made from polymers and plastics, but can also be made from wood fibers, or glass fibers (i.e. fiberglass). Mechanical reinforcement as a stand-alone stabilizer is limited to coarse-grained materials due to their highly frictional nature. Clay soils can be stabilized with mechanical reinforcement in combination with lime or cement stabilization. For this reason the discussion in this report will be covered in Section 5.2.3.1 – Lime/Cement with Reinforcement.

5.2.3 Combinations

In an attempt to improve upon the stabilization effects of lime or cement, additives have been tested in combination with lime or cement. One of the most common combination techniques is the use of reinforcement with discrete, randomly distributed fibers to provide additional tensile strength to the soil. This technique is summarized in more detail in Section 5.2.3.1 – Lime/Cement with Reinforcement. The other combination summarized in this report is the use of chemical additives to enhance certain properties of lime or cement stabilization, which is summarized in Section 5.2.3.2 – Lime/Cement with Other Chemical Stabilizers. For this application, different chemical additives were applied to the lime or cement stabilized soil to address issues specific to the particular research objectives of the particular study.

5.2.3.1 Lime/Cement with Reinforcement

The hypothesis for the implementation of fibers with lime or cement is the fact that the fibers will provide an immediate strength gain until the lime or cement has had ample time to cure. Crockford et al. (1993) demonstrated that the inclusion of fibers to chemically stabilized soils increased the modulus and strength of the clay soils studied. One major point of contention for the implementation of fibers with clays is plasticity. Mixing of fibers into the clay matrix becomes increasingly difficult as the plasticity of the clay increases. The immediate reaction of lime with the clay minerals decreases the plasticity and theoretically will allow the fibers to be more easily mixed into the soil. It has been published by many that the decrease in plasticity from the cation exchange of the calcium with the clay minerals is adequate, and that fibers can be adequately mixed into a clay soil in the lab. There is still contention about whether this stabilization technique is applicable to field implementation, but both Freed (1990) and Grogan et al.

(1994) have demonstrated that fibers can be mixed adequately into high-plasticity fine-grained soil stabilized in combination with lime.

5.2.3.2 Lime/Cement with Other Chemical Stabilizers

Three additives were found to significantly improve the stabilization properties of lime stabilized soils. The most common additive to lime stabilization was the implementation of heat to the soil/lime mixture to accelerate the strength gain. Barium chloride was utilized by Ferris et al. (1991) as a pretreatment to improve the strength of soil to higher strengths than the use of lime alone. Sodium additives have been found to improve the stabilization characteristics of lime and cement stabilized soils. Ruff and Davidson (1961) and Hurley and Thornburn (1972) studied the effect of sodium silicate on lime and cement stabilization, which greatly improved the early strength. Moh (1962) studied the effects of various sodium additives on cement stabilized clays. Moh concluded that the addition of sodium compounds cause an increase in pH, reduction in calcium ion concentration, and an increase in the sodium-calcium ratio. These effects result in an increased rate of solubilization of soil silica, retardation of precipitation of calcium, and the formation of highly hydrated silicate gels, respectively. This produces an overall increase in the amount of the cementitious gel, with an associated improvement of distribution of cement throughout the soil. One other beneficial effect of sodium additives to stabilized soils is the increased resistance to sulfate attack. Lees et al. (1982) studied sodium chloride as an additive to lime stabilized kaolinite and montmorillonite. While there was no acceleration in strength gain, kaolinite soils exhibited a higher total strength gain than montmorillonite soils when sodium chloride was used as an additive to lime. Another study (Chandra 1987) was carried out using commercial stabilizers as additives to both lime and cement stabilization, but these commercial stabilizers were only identified by their commercial product names. While the paper does not mention the nature of the additive, it was found through additional research that Melment and Plastiment A40 are polymeric by nature. The nature of the additive Mowiton 370, however, is still unknown. Chandra concluded that, “some of the properties of clayey soils, such as low strength and high water adsorption, which do not encourage their uses as a building material can be improved, thereby making them more durable.”

5.3 Other Factors

In addition to categorizing the results of the literature review by soil type and stabilization technique, there were other factors addressed for this particular study. These include time effects, water content, and mixing.

5.3.1 Time

Time effects are the main driving force for this research project with the goal to achieve a soil stabilizer that will produce the appropriate stabilized soil properties within 72 hours of treatment.

The easiest way to address short term stabilization effects is to stabilize the soil with fibers. The theory behind the use of fibers is the fact that fibers will not need time to chemically react, and thus impart the stabilization properties to the soil immediately, by mechanical means. For clay soils, reinforcement needs to be implemented with lime stabilization to reduce the plasticity characteristics, which allows the fibers to be adequately mixed into the soil. The implementation of mechanical reinforcement with lime stabilization is described in the preceding Section 5.2.3.1 – Lime/Cement with Reinforcement.

The best way to chemically increase the rate of curing is to apply heat to catalyze the reaction. Anday (1961) tested lime stabilized soils at 140ºF and 120ºF in an attempt to mimic field curing conditions after 45 days of curing at summer temperatures. Anday concluded that curing at 140ºF would result in comparable strengths after 18 hours and two days at 120ºF. Drake and Haliburton (1972) conducted a similar study comparing lime stabilized samples and salt-treated lime stabilized samples cured at elevated temperatures of 120, 110, 105, and 100ºF to samples cured at 80ºF. Drake and Haliburton also found that the lime-soil mixtures cured at faster rates at elevated curing temperatures, with a 30 hour cure time necessary for a salt-treated sample cured at 105ºF to achieve the 28-day strength, and for treatment with just lime, the equivalent curing times were also decreased to times ranging from 30 to 72 hours, but the correlation was more complicated. Baykal et al. (1989) cured lime stabilized soil mixtures at both 73ºF and 122ºF. They found that similar elastic moduli and strength characteristics were found for curing a sample for one day at 122ºF when compared to curing a sample at 73ºC for 28 days. According to Baykal et al., the only major difference found between curing at the two different temperatures was that curing at higher temperatures causes higher strain to failure.

Katti et al. (1977) found that electrochemically treated Bombay marine clay achieved its maximum strength after 36 hours of treatment with the extent of the zone of hardening increasing beyond the cathode with time beyond 36 hours.

Lyons and McEwan (1962) discovered that phosphoric acid stabilization results in sufficient strength increase occurring after five days. However, Demeril and Davidson (1962) concluded that the reactions of phosphoric acid with clay minerals require more than three days to occur. While this is consistent with the results of the Lyons and McEwan study, the scope of this research is to find a stabilizer that will achieve required strengths in less than three days.

The study by Moh (1962) mentioned in Section 5.2.3.2 concludes, "Addition of sodium additive greatly intensifies the reaction between soil and cementing compound, and increases the abundance of reaction products." This should conceivably increase the rate of the reaction by increasing the availability of the reaction products, similar to the effect of grain size on reaction rate.

5.3.2 Water Content

Clay soils at (or near) optimum water content will most likely exhibit properties strong enough for airfield purposes, but will become weaker as the water content is increased beyond the optimum water content. Some stabilizers are simply used as a waterproofer which differs from our scope in that waterproofers are meant to protect the soil from future water exposure, rather than treating a soil that already exists at a high water content.

Alexander et al. (1972) studied the effect of different types of lime on the stabilization of clays at water contents higher than optimum. The five types of lime examined were a fine and coarse-grained hydrated lime, and granular, fine, and mill-run quicklime. Quicklime was found to be more effective due to what is called “the greater calcium hydroxide potential.” This means that on a per weight basis, quicklime has a greater potential for hydrating to calcium hydroxide compared to hydrated lime which is already in the calcium hydroxide state. Another reason for the increased effectiveness of quicklime compared to hydrated lime is the hydration process of the quicklime. The hydration process uses up excess free water in the soil matrix. Yet another property of the hydration reaction is the fact that it is an exothermic reaction which creates heat. The excess heat can become trapped in the soil, and even at low efficiencies, this heat can accelerate the curing process as well as drive off excess water.

5.3.3 Mixing

One factor that many studies ignore is the field applicability of the stabilization technique. The most important variable in field applicability of stabilizers is likely mixability. While there are other factors such as environmental concerns, cost, transportation, etc., many of these can be minimized or ignored due to the importance of finding an appropriate stabilizer to stabilize a weak clay soil in the theatre of operations within 72 hours of application.

The issue of field mixing of fibers into lime stabilized clay soils is examined in Section 5.2.3.1 – Lime/Cement with Reinforcement. Both Freed (1990) and Grogan et al. (1994) demonstrated that the immediate reaction of lime with clay minerals is enough to reduce the plasticity to a level low enough for adequate mixing of fibers into the clay-lime-soil matrix. Even though these two papers state that the fibers can be mixed into the soil, there is still contention about this subject.

5.4 Common Omissions

While our literature review is comprehensive and thorough, there are still many subjects for which little information was available. These omissions include:

- Clay mineralogy – While many papers dealt with clay soils, there was little literature found to address the effects of clay mineral type, or the mechanisms of stabilization by mineral type.

- Water content – Most of the studies found have tested soils at or near optimum water content. The studies with applicability to our scope, that address high water contents, are summarized in Section 5.3.2 – Water Content.

- Field implementation and practicality – Many of the studies encountered in this literature review deal with new and/or exotic stabilization techniques. Most of these techniques have been studied in the laboratory, but the field implementations become crucial when dealing with large scale projects.

- Modulus testing – The latest trend for soil testing for subgrades or unpaved roads is moving towards modulus testing, namely resilient modulus. The properties most commonly tested for are CBR or UCS, which may give a good initial view of how the stabilized soil may behave, but since subgrade soils rarely actually dramatically fail, these tests may not be entirely applicable. While correlations exist between CBR and resilient modulus, these correlations are not entirely accurate.

- Immediate strength gain – The last and probably most important factor with little information is the study of short term stabilization properties. Most studies investigate the effectiveness of a stabilizer after a 7- or 28-day cure time. The studies encountered that address time effects are summarized in Section 5.3.1 – Time.

6 Recommendations for Phase II

The overall goal of this research program (Phases I, II, and III) is to develop an integrated procedure for soil improvement that includes a system of recognition of soil type using a soil geographic data system, followed by selection of stabilizer type, and then followed by field implementation of stabilization. The following sections outline the Phase II research program developed to proceed toward this goal.

6.1 Identification of Soil Types in Theaters of Operation

One primary objective of Phase II will be the development of a GIS based approach for estimating soil type and associated mineralogy in various potential theaters of operation. The key analytical steps to the process will be to (1) obtain any existing soil mapping and classification data for the target study areas, (2) correlate the dominant soils found at each location with their parallel USDA-NRCS Soil Taxonomy class, and (3) estimate dominant clay mineral classes based upon their taxonomic classification and other interpretable data sets. For potential study/prediction areas where soil maps do not exist, our approach will be to choose an area of comparable geology/climate/topography to use as a proxy, and then use that area to estimate expected clay mineral suites.

The present system (USDA-NRCS) of soil taxonomy is based heavily on clay mineralogy at multiple levels of generalization or detail. At its most general and global level, the twelve *soil orders* which are mapped worldwide clearly differentiate soils that are likely to be dominated by smectites (Vertisols) from soils dominated by Fe/Al-oxides (Oxisols), from soils dominated by kaolinite (Ultisols), and from soils that are more likely to contain mixed or illitic mineralogy in their clay fractions (e.g. Alfisols and Mollisols). Soil taxonomy also uses detailed mineralogical criteria at the very detailed *soil family* level (5th hierarchical level), where it is one of the principal differentiating criteria. At this level, all soils are defined as to whether or not their dominant mineralogy is smectitic, oxidic, kaolinitic, illitic, mixed or silicic.

We currently have access via the USDA Soil Survey Division to worldwide soil maps available to the order and, in some instances, the suborder level. While it is doubtful that these maps could be used for site-specific interpretation of mineralogy due to their scale, they could definitely be used to sort broad regional risks and probabilities of clay types. Reasonably detailed maps are available of most regions of the world, however, which could be "taxonomically translated" over to our taxonomic classes. For example, a quick search of the web reveals that fairly detailed maps of Afghanistan exist compiled by the French, which could be digitized and taxonomically translated. This would take a certain amount of labor and soil classification expertise for the translation, but once accomplished, would not need to be "translated" again. For areas of the world without soil maps, we would utilize the best fit of a well-mapped and characterized landscape in the USA, Europe, or Australia (all three have detailed soils data bases) that is as similar as possible in geology, climate, topography and time of weathering (the four soil forming factors that govern soil mineralogy) to the target area, and then utilize detailed family level soil maps to predict the basic landforms vs. soils vs. mineralogy functions.

The GIS-Soil Information Systems lab integrates available soils data layers into GIS software (we use ESRI products, ArcGIS specifically) to analyze the distribution of soils across various landscapes. In this country, we use USDA-NRCS soils datasets including STATSGO (state soil maps with mapping scale 1:250,000) for broad planning and management use or NRCS SSURGO soils datasets which are mapped to 1:12,000 to 1:63,360 scale. While the SSURGO data is the most detailed soils layer NRCS publishes, it is not available in every county. Using ancillary datasets (hydro-geography, wetland datasets, geology, elevation models from which we can create slope and aspect models, aerial photography, and satellite imagery) greatly enhances the ability to determine the nature of soils at a particular location.

The result of this system is that we expect to be able to provide a good prediction of soil type in theaters of operation simply by providing site coordinates. The Phase II research will develop a functional beta version of this system that can be used for the potential theaters of operation identified by the US Air Force. Phase II does not include developing a final version of the system that is fully de-bugged and ready for transfer to the Air Force.

6.2 Laboratory Testing of Stabilization Methods

A second major focus of the Phase II research is to identify the stabilization methods that will provide the necessary strength and stiffness increase in the 72 hour time limit. Based on the literature review conducted during Phase I of this project, certain stabilization methods were identified that deserve further study. A main desire is not only to determine which improvement method achieves a high early strength and stiffness in different types of soft and wet clays, but to investigate the mechanisms responsible for the strength increase.

The list of factors that influence the performance of stabilized soil is extensive, and includes the following:

- Soil type and mineral content
- Soil moisture content (natural and as-compacted)
- Compacted dry density
- Compaction method
- Admixture type
- Admixture dose rate (amount)
- Curing conditions (time, temperature, humidity, and confining pressure)

It is not practical to test all combinations of soil types, admixtures, compaction, and curing conditions in the Phase II research. In order to keep the number of tests within a reasonable range, a judicious selection will be made considering the soil types, admixtures, etc., in cooperation with Air Force personnel involved with this project.

6.3 Soil Types

At lease four different soils will be tested in the Phase II research. First, a clay that classifies as a CL or CH according to the Unified Soil Classification System will be used as the base soil for the first series of screening tests. This soil will consist of the most common clay minerals (illite, kaolinite, and smectite) together with non-plastic silt in proportions representative of natural soils. The base soil will be manufactured in our laboratory from naturally occurring minerals to produce a well-defined soil of consistent properties. The base soil will allow an initial assessment of the performance of all the amendments at varying dose rates.

After completing the tests on the manufactured base soil, we will move on to natural soils that are representative of soils found in potential theaters of operation identified by the US Air Force. Soil type information provided by the US Air Force will be used to identify appropriate soil types. As our research progresses, the soil geographic data system described previously will be used to produce estimates of soil characteristics that can be compared with the information provided by the Air Force. However, in order to initiate the soil testing program at an early stage of the Phase II research, we will rely on the information provided by the Air Force and information available in the published literature to determine the soil types for testing. We will seek to identify three soil types that are (1) important to the Air Force from an operations standpoint and (2) different from each other so that general conclusions about amendment effectiveness on soil type can be drawn. Once the appropriate soil types are chosen, naturally occurring soil samples having similar mineralogical characteristics will be collected or blended in the laboratory from natural soils.

Phase III of the proposed research involves constructing a field test section near an existing USAF installation. If the site of the field test is identified during the Phase II testing, then the fifth soil tested will be the soil to be improved at the test site location. The test results collected on this soil will be important in designing the Phase III test section.

6.4 Amendment Types

Six chemical admixtures have been selected for the laboratory test program. These were selected based on the results of the Phase I literature review.

Quicklime – Quicklime will be used primarily as a control stabilizer for comparison to the other stabilizers. In addition to quicklime alone, the combination of quicklime and discrete fibers will be tested. The reinforcement mechanism provided by the fibers may allow an immediate strength gain, and the strength should keep increasing over time due to the pozzolanic reaction of the quicklime.

Portland Cement – Test specimens augmented with cement will also be tested to provide control test data.

Calcium Carbide – The concept of using calcium carbide is believed to be an original technology for soil stabilization. Calcium carbide reacts with water to produce quicklime, acetylene gas, and heat. The quicklime reacts with excess water in the soil to produce hydrated lime. It is hypothesized that the quicklime generated from the calcium carbide will work in the same manner as it does in conventional soil stabilization techniques, except for the assets of additional consumption of water and additional production of heat. The byproduct of acetylene gas may also be used to advantage in the stabilization process. Combustion of the acetylene would produce heat that could be implemented to accelerate the pozzolanic reactions, as well as evaporate more water. Another intriguing possible use of acetylene is as a source of hydrocarbon, which when combined with an appropriate radical, would produce in-situ polymerization within the soil. Thus, calcium carbide has the potential to (1) dry the soil, (2) reduce its plasticity, (3) induce pozzolanic reactions, and (4) create polymers within the soil. We are optimistic that the degree of improvement may be substantial.

Sodium Silicate (Waterglass) – Sodium silicate accelerates the strength gain of lime stabilized soil, and it will be investigated in the laboratory program.

Lignosulfonate (Sulfonated Lignin) – A natural polymer, lignosulfonate is derived from the production of wood pulp, and it will be tested. Lignosulfonate acts like a resin to bind the soil particles together.

Synthetic Polymer – A synthetic polymer, known by the trade name of ENVIROSEAL 2001®, will be tested. Based on the literature review, this polymer showed promise for soil stabilization, and it is currently being researched in a field test program in Colombia (Santoni (2003)).

Other Stabilizers – We will continue to search for other stabilizers that were not encountered during the literature review, and if found, these will become part of the test program as well. We will review the list of stabilizers with US Air Force personnel on a regular basis.

7 Summary

The Phase I literature review included 182 references (138 papers deal with clay stabilization), which are listed at the end of this proposal. We have entered the most relevant research findings from the references into a database. The complete list of references is included with this proposal. The references were categorized according to soil type and stabilizer type. Three stabilizer types or methods were cataloged: (1) chemical stabilization, (2) mechanical reinforcement, and (3) combinations of chemical stabilization and mechanical reinforcement. The chemical stabilizer category was used when a non-soil material was mixed with the soil resulting in a chemical reaction or when the soil was subjected to heating. The reinforcement category was used when the soil was treated with inclusion of randomly oriented fibers, such as wood and natural materials, shredded fabric, glass fibers, metal strips and wires, polymers or plastic, or polymer grids.

The chemical stabilizer category was further subdivided into *traditional admixtures* and *nontraditional admixtures*. Traditional admixtures are those that have been often used in civil engineering practice, including portland cement, lime, and fly ash. Nontraditional admixtures are those that have been used on a limited basis in practice, or those that have been used in research studies, including polymers, resins, enzymes, salts, etc. The following conclusions were drawn from the literature review:

- Heat – Heat can be applied to soil either thermally by the direct application of heat, or through an exothermic reaction within the soil. Heat acts as a catalyst to accelerate the curing of lime and cement (Drake and Haliburton (1972)). Heat alone will also stiffen a clay soil (Joshi et al. (1994), Moritz and Gabrielson (2000)).

- Polymer/Resin – Polymers are chemicals that have extremely high molecular weight. They are formed from hydrocarbons (monomers) bonded together by heating the initiator to form a radical with an unpaired electron that acts to link many molecules of the hydrocarbon with the unpaired electron transferring through the chain to the end, allowing a continuous chain to be formed.

  Polymeric soil stabilizers are often sold under commercial brand names of a proprietary nature instead of the chemical name for the polymer. This causes difficulty in identifying specific polymers that are beneficial as stabilizers. Some polymers exhibit the ability to improve soil, with significant increases in both as compacted (dry) strength and post-soaking (wet) strength.

  Tingle et al. (2003) found four polymer stabilizers (Dustac 100®, Enviroseal 2001®, Poly Pavement®, and Soil-Sement®) that increased the wet strength of a lean plasticity clay (CL), and two of those polymers (Dustac 100® and Enviroseal 2001®) increased the dry strength. The polymer that resulted in the greatest increase in both wet and dry strength was a lignosulfonate (Dustac 100®), which is a natural polymer derived from wood pulp. For tests conducted on a fat clay (CH), Enviroseal 2001® also provided an increase in the wet and dry strength. The lignosulfonate was not tested on the CH soil. Other references (Bolander (1999), Gow et al. (1960)) addressed the increase in strength associated with lignins, suggesting that lignins be studied further in the Phase II laboratory study.

Ajayi-Majebi et al. (1991) found that a combination of Bisphenol A with an Epichlorohydrin resin produced an increase in strength within three days of curing, with a significant strength gain occurring within three hours if heat was applied during curing.

- Ionic – The ions in salts have a tendency to flocculate clays, as well as aiding in compaction by increasing the maximum dry density and reducing the optimum water content. Some salts (e.g., calcium chloride) absorb water, while others tend to repel water. Ferris et al. (1991) used barium chloride as a pretreatment to lime stabilization, and this resulted in higher unconfined compression strengths than lime stabilization alone. While salts were found to have some benefit as a soil stabilizer, acids were found to be generally ineffective. The only acid to give positive results was phosphoric acid, which was found by many to improve both the strength and durability of compacted soils (Demirel et al. (1960), Gazali et al. (1991)). However, phosphoric acid does not seem to provide much increase in the short-term strength (Demirel and Davison (1962)).

- Lime/Cement – The addition of lime or cement to a soil has a proven record of increased strength and stiffness in many soils. The benefits of this method of stabilization can be accelerated by the addition of heat during the curing process. As indicated above, the addition of barium chloride can further increase the strength of a lime-treated soil. Also, the addition of sodium silicate has been found to increase the early strength of lime-stabilized clay (Hurley and Thornburn (1972)).

- Lime/Cement with Reinforcement – Lime or cement stabilization has been combined with reinforcement, with the intention of the reinforcement providing an immediate strength gain while the lime or cement results in a strength gain over time. This combination has been found to work in laboratory tests, but there are differences of opinion concerning applicability in the field owing to difficulty in mixing the reinforcing elements with a plastic clay (Tingle (2003)). However, it is possible that the decrease in plasticity resulting from the addition of lime may allow the fibers to be mixed efficiently into the soil, and this deserves further research.

- Most of the published research reviewed did not focus on short-term strength increases (i.e., elapsed time of days), but investigated strength increases that occurred over weeks and months.

Our project team envisions an integrated procedure for soil improvement including a system using a GIS-based soil information support system to recognize the relevant soil type, followed by selection of stabilizer type, and finally field implementation of stabilization. The Phase II research program will consists of the portion dedicated to the identification of appropriate soil types in the theatre of operation to be evaluated in the laboratory as well as testing those soils in the laboratory with the recommended amendment types. The appropriate soil types will be identified by developing a GIS based approach which will allow a soil to be identified with an associated soil mineralogy. Once the appropriate soil types have been identified and obtained, they will be treated with the recommended amendment types and tested for the engineering properties appropriate for use as an unsurfaced airfield in the theatre of operations within 72 hours of treatment.

The following amendment types are recommended for further research:

- Quicklime – Quicklime will be used primarily as a control stabilizer, but quicklime will also be combined with fibers to determine if the reinforcement mechanism is adequate for airfield applications within 72 hours of treatment.

- Portland Cement – Portland cement will be used as a control stabilizer.

- Calcium Carbide – Calcium carbide is believed to be an original soil stabilization technology. Since calcium carbide reacts with water to produce quicklime and acetylene gas, it is believed that calcium carbide as a standalone stabilizer will work. The acetylene gas byproduct can be combusted to supply additional heat to the soil, or it can be mixed with an appropriate catalyst to bring about polymerization which may further strengthen the soil.

- Sodium Silicate (Waterglass) – Sodium silicate will be evaluated as an additive to lime stabilization since it was found to accelerate the strength gain of lime stabilized soil.

- Lignosulfonate (Sulfonated Lignin) – A natural polymer, lignosulfonate will be evaluated since it is believed that it will act as a resin, binding the soil particles together.

- Synthetic Polymer – Enviroseal 2001® is recommended as a synthetic polymer for further evaluation in Phase II.

- Other Stabilizers – Continuing research will be carried out to determine if any as-yet undiscovered stabilizers exist.

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Appendix A – One Page Summaries from Microsoft® Access Database

Stabilizer Type: Chemical

Paper Title: Characteristics and Chemical Treatment of Expansive Clay in Al-Qatif, Saudi Arabia

Author: Abduljauwad, S.

Source: Engineering Geology

Publication Date: 1991

Purpose of Stabilizer: Control High Swell Potential

Stabilizers Tested: Lime, potassium phosphate, potassium chloride

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Al-Qatif Soil	CH	Commercial Lime	Powder	2, 5, 8%	N/A	N/A
Al-Qatif Soil	CH	Potassium Chloride	Power	2, 5, 8%	N/A	N/A
Al-Qatif Soil	CH	Potassium Phosphate	Power	2, 5, 8%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Montmorillonite (12-22%)

Tests Performed: Swell Potential by 1-D Consolidometer, X-Ray Diffraction

Test Methods: Undisturbed samples were taken from test pits. Proportions of the various minerals in soil samples were determined by X-ray diffraction. Consolidometer tests were conducted and swell pressure was measured. Effects of time, sample orientation, and water content were evaluated. Samples were treated with chemicals, compacted in the mold to a specific density, and the effects on swell pressure were measured.

Key Findings: Al-Qatif clays were found to have a high swell potential. Of the chemical treatments, lime reduced this potential the most effectively. With 2-8% lime, it reduced the swell pressure from nearly 4 to 2 kg/cm^2. This effect was almost immediate with 5% lime and the swell potential was further reduced to 1% after a year. Larger amounts of the other two were needed for approximately the same drop in swell pressure.

Comments: These types of soils are known to exist in the southern and eastern parts of Saudi Arabia.

Stabilizer Type: Reinforcement

Paper Title: Contingency Airfield Construction: Mechanical Stabilization Using Monofilament and Fibrillated Fibers

Author: Ahlrich R.C. and Tidwell L.E.

Source: US Army Corps of Engineers, Waterways Experiment Station

Publication Date: 1994

Purpose of Stabilizer: Stabilizer - Airfield Use

Stabilizers Tested: Monofilament and fibrillated fibers (Geofibers)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Beach Sand	SP	Fibrillated Fiber (0.5 in)	Fibers	0.5%	N/A	N/A
Beach Sand	SP	Monofilament (0.5-2.0 in)	Fibers	0.5, 1.0, 2.0%	N/A	N/A
High Plasticity Clay	CH	Monofilament (0.5-2.0 in)	Fibers	1.0%	N/A	N/A
High Plasticity Clay	CH	Fibrillated Fiber (0.5 in)	Fibers	0.5, 1.0, 2.0%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: California Bearing Ratio, Gyratory Testing Machine, Compaction Tests

Test Methods: Proctor compaction tests were performed to determine the optimum water content and CBR values were measured. Soils were then stabilized with fibers of various lengths and dosages by weight. CBR values were then taken for as molded (unsoaked) and soaked samples. Soils were also stabilized, compacted and gyratory shear strength properties of the samples were taken at 100-psi and 200-psi ram pressure and 100

Key Findings: Dry density decreased with addition of fibers. In lab studies, lower gyratory strengths were found for the stabilized clays when fibers were added. They exhibited higher strength at lower compactive efforts. Fibers also did not improve clay CBR values of high plasticity clay. In general for the sand samples, the gyratory shear strength increased with increasing fiber dosage, and the CBR decreased with the fibrillated fibers but increased with increased length of the fibers.

Comments: This paper includes a good literature review section on use of fibrillated fibers in clay soils stating improved performance by reducing rutting and cracking. Author claims that they can be adequately mixed in clay soils; smaller fibers of 1 in. and less can be distributed consistently. It was also noted that CBR tests may not effectively evaluate the effects of fiber stabilization.

Stabilizer Type: Chemical

Paper Title: Epoxy-Resin-Based Chemical Stabilization of a Fine, Poorly Graded Soil System

Author: Ajayi-Majebi, A., Grissom, W.A., Smith, L.S., and Jones, E.E.

Source: Transportation Research Record

Publication Date: 1991

Purpose of Stabilizer: Stabilizer - Low Duty Airport Subgrade

Stabilizers Tested: Two-part epoxy resin (bisphenol A/epichlorohydrin resin and water-insoluble polyamide)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Silt-clay systems	CL/ML	Two-part epoxy resin	Liquid	0.25, 1,4%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: California Bearing Ratio, Compaction Tests

Test Methods: Soil systems were developed based on clay to silt ratios of 0.4, 0.5 and 0.6. Testing was conducted at the soils' optimum water contents which ranged from 13-21 percent. The treated samples were mixed to uniform consistency and to an even texture. Specimens were then compacted in a standard CBR mold and cured for 3 days at temperatures of 40, 65 and 90ºF. Unsoaked CBR tests were then conducted and a limited number of soaked CBR tests were performed.

Key Findings: Within the limits of the laboratory test conditions, statistical regression models were developed to support the margin of increase of CBR caused by changes in curing temperature, percent additive, and moisture content. At the epoxy application of 4%, the largest unsoaked CBR value of 135 was obtained. Soaked CBR testing showed a CBR value to be ranging from 27 to 63 under 3 to 7 days of soaking (untreated samples had a wide range of CBR values, and no wet untreated CBR value is given).

Comments:

Stabilizer Type: Chemical

Paper Title: Chemical Stabilization of Sabkha Soils at High Moisture Contents

Author: Al-Amoudi, O.S.B.

Source: Engineering Geology

Publication Date: 1993

Purpose of Stabilizer: Stabilizer - Wet Expansive Soils

Stabilizers Tested: Cement

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Arid, saline (Sabka)	N/A	Lime	Powder	2.5, 5.0, 7.5, 10.0%	N/A	N/A
Arid, saline (Sabka)	N/A	Cement	Power	2.5, 5.0, 7.5, 10.0%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength, Compaction Tests

Test Methods: The Saudi Sabka soils were chemically treated with percentages of lime and cement at their natural water contents (16-22%) and cured for up to 90 days in plastic wrap.

Key Findings: Untreated undisturbed samples demonstrated unconfined compressive strengths of 15-22kPa. Results indicated that cement-stabilized soils gained high strength (300-2000 kPa) with time and proved to have a potential use in construction. Lime strength gain ranged from 200-1200 kPa with the sample percentages. At the high moisture contents, lime and cement stabilization effects were hampered, indicating if the water to additive rate was greater than 3 that significant long-term strength would be affected.

Comments: From graphs of the strength gains with time, early strength gain was significant after just 7-day cure time ranging from 100-800 kPa for cement for the given moisture contents. Lime was less effective showing a strength range of 20-120 kPa after 7-day cure.

Stabilizer Type: Chemical

Paper Title: Relative Stabilizing Effect of Various Limes on Clayey Soils

Author: Alexander, M.L., Smith R.E., and Sherman, G.B.

Source: Highway Research Board

Publication Date: 1972

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Lean Clay	CL-ML	Hydrated Lime	Powder	1-4%	N/A	N/A
Sandy Clay	CL	Hydrated Lime	Powder	1-4%	N/A	N/A
Lean Clay	CL	Quicklime	Powder	1-4%	N/A	N/A
Lean Clay	CL-ML	Quicklime	Powder	1-4%	N/A	N/A
Lean Clay	CL	Hydrated Lime	Powder	1-4%	N/A	N/A
Sandy Clay	CL	Quicklime	Powder	1-4%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength

Test Methods: All soils were tested slightly above their optimum water content (16-18%). Samples were cured loose for 24 hours, then compacted, sealed and cured at 110ºF for 7 days (thought to be equivalent of 3-months cure time in the field). The samples were then exposed to saturation for 21 days.

Key Findings: Quicklime proved more effective than hydrated lime in improving strength, due to more calcium hydroxide potential. For the lean clay, strength gain with quicklime ranged from approximately 90-220 psi with 1-4% additive. Above 2% additive, higher strengths were obtained with coarser quicklime products than fine-grained. Very fine lime doesn't appear to increase effectiveness of lime. A 24-hour loose curing period with quicklime is required to prevent expansion and pop-outs caused by hydration of the lime.

Comments:

Stabilizer Type: Chemical

Paper Title: Synergistic Effects of Sulfosuccinate/Polymer System for Clay Stabilization

Author: Alonso-DeBolt, M. and Jarrett, M.

Source: Drilling Technology

Publication Date: 1995

Purpose of Stabilizer: Stabilizer - On-Land Drilling Fluid Applications

Stabilizers Tested: Sulfosuccinate-based polymer surfactants

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Shale Rolling Test

Test Methods: Tests to imitate the shale rolling test, a commonly used test in the oil industry, were performed for shale stabilization testing.

Key Findings: The sulfosuccinate-based surfactant/polymer drilling fluid is a viable alternative to traditional salt/polymer drilling fluids. It provides improved shale stabilization by minimizing dispersion and swelling, without the environmental hazards of chlorides. The additives, being non-toxic with improved biodegradability, can be used to design a more effective well fluid system, having stable properties with greater ease of engineering maintenance of drilling water-sensitive shales.

Comments:

Stabilizer Type: Chemical

Paper Title: Accelerated Curing for Lime Stabilizer Soils

Author: Anday, M.C.

Source: Transportation Research Record

Publication Date: 1961

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Lime w/ Heat

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay Gravel	N/A	Lime	N/A	5%	Heat	140, 120º F
Micaceous Silty Soil	N/A	Lime	N/A	5%	Heat	140, 120º F

Natural or Manufactured Soil?

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength

Test Methods: Unconfined compression strength tests and a few CBR tests were compared to field curing at summer temperatures for 45 days.

Key Findings: Unconfined compressive strength of specimens field cured for approximately 45 days at summer temperatures could be predicted by an accelerated laboratory curing of either 18 hours at 140ºF, or two days at 120ºF. However, 120ºF is preferred for the following reasons: a) less condensation between the specimen and the protective coating during curing; b) a lower, therefore more realistic temperature; c) convenience of curing time; d) increased accuracy obtained with small slopes of the strength-time curves.

The soil's CBR values will increase many fold. However, these values are sometimes so high as to be unrealistic.

Comments: Not enough CBR test specimens were made for statistical evaluations.

Stabilizer Type: Reinforcement

Paper Title: Shear Strength of Kaolinite/Fiber Soil Mixtures

Author: Andersland, O.B. and Khattak, A.S.

Source: International Conference on Soil Reinforcement

Publication Date: 1979

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Pulp fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Kaolinite	N/A	Pulp fiber	Fibers	16,40%	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Kaolinite

Tests Performed: Triaxial Tests

Test Methods: Dry pulverized kaolinite samples were mixed with dry fiber. Water was added in amounts 'needed to form a slurry'. Fibrous samples were then formed by placement of the slurry into a split cylinder mold. Finally, they were trimmed to the desired size for consolidated undrained triaxial testing.

Key Findings: The addition of small amounts of fiber significantly increased the peak strength of kaolinite for undrained loading conditions. Large amounts of fiber changed the behavior from brittle to plastic with strength gain continuing to 20%+ axial strain. With 20% axial strain as failure, the friction angle increased from 20 to 31 degrees for fibrous samples.

Comments:

Stabilizer Type: Chemical

Paper Title: Hydraulic Cement Based Binders for Mass Stabilization of Organic Soils

Author: Andersson, R., Carlsson, T. and Leppanen, M.

Source: Soft Ground Technology Conference

Publication Date: 2000

Purpose of Stabilizer: Stabilizer - Soil Columns

Stabilizers Tested: Lime and cement, cement and blast furnace slag

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Peat/clay soils	N/A	Cement and blast furnace slag (50-50)	Powders	N/A	N/A	N/A
Peat/clay soils	N/A	Lime and cement (50-50)	Powders	N/A	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed:

Test Methods: Full scale testing and case histories were examined to depths of up to 8.5 meters on wet peat soils with in situ water contents from 50-128%. No mention of how the admixtures were mixed. Strengths were determined (no mention of the testing method was made).

Key Findings: The results of the field testing were positive on strength gain and cost effectiveness. The cement and blast furnace slag seemed to be more effective in terms of strength gains.

Comments:

Stabilizer Type: Reinforcement

Paper Title: Specimen Size Effects for Fiber-Reinforced Silty Clay in Unconfined Compression

Author: Ang, E.C. and Loehr, J.E.

Source: Geotechnical Testing Journal

Publication Date: 2003

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Fibrillated polypropylene fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Loessial Lean Clay	CL	Fibrillated Polypropylene Fibers	Fibers	0.2 & 0.4%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Clay fraction 22-25%, however essentially void of clay minerals

Tests Performed: Unconfined Compressive Strength, X-Ray Diffraction

Test Methods: Specimen size effects were tested as to their effects on measured strength gain on fiber reinforced silty clay specimens tested in unconfined compression. Soils were tested at sizes from 38 to 152 mm diameters and 12-20% moisture contents. Fibers were mechanically mixed into the wet soils to uniformity. Soils were then compacted to similar unit weights and tested immediately after compaction.

Key Findings: Specimen size effects were found to be most significant in measuring strength of specimens with moisture contents that were dry of optimum. Specimens greater than 70mm seemed to produce strengths representative of the true mass of fiber-reinforced soils. Compressive strengths were higher with increased fiber content, but decreased with increasing water content. With no fiber, compressive strength ranged from 270 kPa at 12% moisture content to 100 kPa at 18% moisture content. With 0.4% fiber, peak strength was increased to nearly 500 kPa at 12% moisture content and 350 kPa at 18% moisture content.

Comments:

Stabilizer Type: Chemical

Paper Title: Subgrade Stabilization Method Cuts Costs by Up to 80%

Author: Anonymous

Source: Better Roads

Publication Date: 1993

Purpose of Stabilizer: Stabilizer - Subgrades for Roadways

Stabilizers Tested: Sulfonate oil (Condor SS)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Expansive Clays	N/A	Condor SS	Liquid	1 gal to 300 gal of water	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: No Testing Conducted

Test Methods:

Key Findings:

Comments: This is a one-page magazine article that appeared in Better Roads. The author claims better orientation of clay particles, reduction of swell and permeability, and increasing strength gains from 20-68% depending on the soil. The anonymous author claims that sulfonate oil product breaks the electrochemical bonding of the clay with water. Preventing the electrochemical bond would allow free water to drain, thus reducing the amount of swell.

Stabilizer Type: Chemical

Paper Title: Lime Stabilization of Organic Soils

Author: Arman A. and Munfakh, G.A.

Source: Highway Research Record

Publication Date: 1972

Purpose of Stabilizer: Stabilizer - Organic Soils

Stabilizers Tested: Lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Silty Clay, natural organic and mineral content	N/A	Lime	Powder	4, 8, 12%	N/A	N/A
Silty Clay, nonorganic	N/A	Lime	Powder	2, 4, 8%	N/A	N/A
Silty Clay, predetermined organic content	N/A	Lime	Powder	4, 8, 12%	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength, Atterberg Limits, Compaction Tests

Test Methods: Samples were fabricated from natural soil deposits to control the organic content. They were oven dried and mixed at different water contents (near optimum and approximately at the soils' liquid limit) with lime additive. Samples were evaluated after 48-hour, 7-day, and 28-day cures.

Key Findings: Organic matter was not found to prevent pozzolanic reactions. However, with 20% organic content, it took 2% lime to bring the pH to 7 and satisfy the base-exchange-capacity of the organic matter. Others have found organics to have an adverse affect on these reactions. Plastic properties of organics were improved by lime treatment. Lime decreased the PI and increased the overall strength in all specimens as measured by unconfined compression tests. Short cure time (48-hour) strength ranged from 4 psi (no change) at low lime contents to a strength of 13 psi for 6% lime content.

Comments:

Stabilizer Type: Chemical

Paper Title: Chemical Stabilization of Landslides by Ion Exchange

Author: Arora H.S. and Scott J.B.

Source: California Geology

Publication Date: 1974

Purpose of Stabilizer: Landslide Case Studies of Chemical Stabilization

Stabilizers Tested: Ion exchange chemicals

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay	N/A	Ion Exchange Chemical (Used lab code names)	Liquid	1 gm/ 54 cc of water	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Kaolinite, montmorillonite, chlorite

Tests Performed: Triaxial Tests

Test Methods: No details were given on the triaxial test procedures of samples taken from bore holes.

Key Findings:

Comments: This paper provides a general overview of slopes stabilized with chemical additives. Active landslides were successfully halted by the addition of chemical additives and ion exchange. Notable results included 200% soil strength gains and reduction in the water table due to the chemical additives. Additives, however, are given code names in this paper and were not identified.

Stabilizer Type: Chemical

Paper Title: Standard Test Method for Field Determination of Water (Moisture) Content of Soil by the Calcium Carbide Gas Pressure Tester Method

Author: ASTM

Source: ASTM 4944-98

Publication Date: 1989

Purpose of Stabilizer: Field Determination of Water Content

Stabilizers Tested: Calcium carbide

Natural or Manufactured Soil? N/A

Clay Mineralogy: N/A

Tests Performed: No Testing Conducted

Test Methods: Calcium carbide is used as a reagent with soils to quickly measure the moisture content of soil samples. When added to the moist soil, the calcium carbide reacts with water to produce acetylene gas. The pressure of the acetylene gas is measured and compared to a value calibrated for the soil.

Key Findings:

Comments: Use of calcium carbide can provide a field determination of the water content of a soil once the pressure tester has been calibrated for the soil and reagent used.

Stabilizer Type: Chemical

Paper Title: Soil Stabilization with Burned Olive Waste

Author: Attom M.F. and Al-Sharif, Munjed M.

Source: Applied Clay Science

Publication Date: 1998

Purpose of Stabilizer: Stabilizer - Make Use of Waste Product

Stabilizers Tested: Burned olive waste

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
4 different clay soils	N/A	Burned Olive Waste	Other	2.5, 5.0, 7.5%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Kaolinite, illite, montmorillonite and chlorite clays

Tests Performed: Unconfined Compressive Strength, Swell Potential by 1-D Consolidometer, Compaction Tests

Test Methods: Samples were molded with a percentage of additive and were tested at their optimum moisture contents. Unconfined compressive strength tests and swell potential tests were conducted (cure times were not given).

Key Findings: Reduced plasticity and increased strength by 20-80% were reported with 2.5% burned olive waste added. Higher amounts of additive resulted in lower compressive strength but less swell potential.

Comments:

Stabilizer Type: Chemical

Paper Title: Organic Polymers' Effect on Soil Strength and Detachment by Single Raindrops

Author: Barry, P.V., Stott, D.E., Turco, R.F. and Bradford, J.M.

Source: Soil Science Society of America Journal

Publication Date: 1991

Purpose of Stabilizer: Stabilizer - Against Erodibility

Stabilizers Tested: Synthetic polymers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Raub silty loam	N/A	Starch graft polymer	Solid	0.04, 0.1, and 0.4%	N/A	N/A
Fincastle silty loam	N/A	Polyvinyl alcohol	Solid	0.04, 0.1, and 0.4%	N/A	N/A
Raub silty loam	N/A	Polyvinyl alcohol	Solid	0.04, 0.1, and 0.4%	N/A	N/A
Fincastle silty loam	N/A	Starch graft polymer	Solid	0.04, 0.1, and 0.4%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Laboratory Cone Penetration

Test Methods: Two soils were used in this test with differing organic matter contents. The purpose of the testing was to determine the effects of specific organics on erosional processes (this is more of a soil science paper in nature). Soils were treated with the varying amounts of the polymers. Then 25g of air-dried soil particles were placed in a Petri dish and subjected to 10 mL of 'raindrops' from a syringe. The treated soil was then allowed to air dry and placed on a stack of three sieves. Soil retention on each sieve was then measured after oscillating the sample. Shear strength was also measured of the samples with a laboratory cone penetration test.

Key Findings: The additives initially induced significant increases in soil shear strength ranging from 1.5 to 5.5 times greater than the untreated soil (appears to be after an aging process of several weeks) and the pattern of change was nearly identical for all treatments. There was less soil detachment of the stabilized soil when subjected to the raindrops. Further work was recommended to clarify the effects of organics and understand the soil stability properties.

Comments: This paper did not include any traditional geotechnical laboratory testing for comparison to other studies.

Stabilizer Type: Chemical

Paper Title: Treatment of Expansive Soils to Control Swelling

Author: Basma A.A. and Al-Sharif M.

Source: Geotechnical Engineering

Publication Date: 1994

Purpose of Stabilizer: Stabilizer - Control Swell

Stabilizers Tested: Salt, lime, cement

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay	CH	Lime	Powder	3, 6, 9%	N/A	N/A
Clay	CH	Cement	Powder	3, 6, 9%	N/A	N/A
Clay	CH	Salt (NaCl)	Powder	3, 6, 9%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Clay fraction is 80% smectite-illite, 20% kaolinite

Tests Performed: Swell Potential by 1-D Consolidometer, Compaction Tests

Test Methods: Swell properties of undisturbed and remolded samples were taken from boreholes for an Irbid soil (Northern Jordan). Soils were taken at various water contents (from 10-30%) and unit weights. Different portions of salt, lime and cement were used in an effort to reduce the swell potential of the soil.

Key Findings: Swelling properties were reduced drastically when increasing the initial compaction water content of the soils. Increase in water content additionally resulted in lower strengths. Reduction of swelling in the presence of salt was seen to an extent but remained constant after reaching a certain salt concentration. The addition of lime or cement in small percentages, 3-9%, decreased swell characteristics. Lime though was found to be the better overall stabilizing agent for swelling (reducing it by 50% at approximately 4% lime admixture).

Comments:

Stabilizer Type: Chemical

Paper Title: Accelerated Curing of Fly Ash-Lime Soil Mixtures

Author: Baykal G., Arman, A., and Ferrell, R.

Source: Transportation Research Record

Publication Date: 1989

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Flyash and lime, flyash, lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Bentonite	CH	Flyash	Powder	21%	N/A	N/A
Bentonite	CH	Lime	Powder	6%	N/A	N/A
Bentonite	CH	Flyash	Powder	20%	Lime	5%

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Bentonite

Tests Performed: Triaxial Tests, X-Ray Diffraction

Test Methods: Soil specimens were mixed with the chosen percent additives. Specimens were compacted into a Harvard miniature compaction device. Water contents of the specimens were pre-determined based a previous portion of this study. They ranged from 24-40%. After compaction, specimens were placed in air-tight bags and cured at 50ºC and 23ºC for up to 180 days. Moisture contents were determined before further testing. Compressive strength tests, with and without confining pressures, and X-ray diffraction tests were conducted after 1, 28, 90, and 180 days.

Key Findings: The same cementitious minerals formed at both curing temperatures, though possibly at a higher degree for the higher temperature. Curing at 50ºC for one day had comparable elastic moduli to the samples cured at 23ºC for 28 days and had a higher compressive strength. Curing at higher temperatures for shorter periods also resulted in higher failure strains.

Comments: Similar results can be obtained by increasing the curing temperature for short cure periods as can be measured for lower curing temperatures and longer curing times.

Stabilizer Type: Chemical

Paper Title: Nature of the Deformation and Failure of Silicate-Stabilized Loess

Author: Beketov A.K. and Seleznev A.F.

Source: Soil Mechanics and Foundation Engineering

Publication Date: 1971

Purpose of Stabilizer: Determine Nature of Deformation/Failure

Stabilizers Tested: Sodium silicate

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Loess	N/A	Sodium Silicate	Liquid	N/A	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Loess

Tests Performed: Creep Test, Relaxation Test

Test Methods: This paper looked at the failure mechanism of silicate-stabilized loess at water contents of 14 and 21% by conducting creep and relaxation experiments on undisturbed clay samples. Soils were subjected to a compressive strength of 11.4 kg/cm^2 and creep strains were observed for a period of 75 days. Relaxation tests were conducted at varying stresses and measured for 360 hours.

Key Findings: Based on experimental studies, the author conceived that the mechanisms for long-time deformation of stabilized loess is in the following manner: Stresses are shown to initially be absorbed by the stiff skeleton and gel component, then structural deformations occur over time in the form of micro-cracks in the structure and network to form larger cracks, which leads to failure.

Comments:

Stabilizer Type: Chemical

Paper Title: Frost Stabilization of Several Soils with Sodium-Tripolyphosphate and Sodiumpyrophosphate

Author: Beltz K. and Muller-Schiedmayer G.

Source: Highway Research Board Bulletin

Publication Date: 1961

Purpose of Stabilizer: Stabilizer - Against Frost

Stabilizers Tested: Polyphosphates

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Silty Sand	SM	Sodiumpyro-phosphate	Powder	0.3-1.0%	N/A	N/A
Loamy Soil	N/A	Sodiumpyro-phosphate	Powder	0.3-1.0%	N/A	N/A
Loamy Soil	N/A	Sodiumpyro-phosphate	Powder	0.3-1.0%	N/A	N/A
Sandy Soil	SW	Sodiumpyro-phosphate	Powder	0.3-1.0%	N/A	N/A
Silty Sand	SM	Sodiumpyro-phosphate	Powder	0.3-1.0%	N/A	N/A
Sandy Soil	SW	Sodiumpyro-phosphate	Powder	0.3-1.0%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Freezing Cabinet Test, Compaction Tests

Test Methods: Soils were tested at their natural water contents of 6 to 12%. Samples were mixed by hand, compacted in molds and placed in a freeze cabinet for a period of 4 days. Percentages of the additive were measured as a percentage of moist weight of the soils. Water intake during the freezing periods was measured. Additionally, Proctor compaction tests were conducted to determine the effect of admixtures on the soils' maximum dry density and optimum moisture contents.

Key Findings: It was found that the admixtures prevented frost heave in all three soils tested by at least 85% using economical quantities (approx. 0.5%) and reduced the water intake during freezing periods. Additionally, Proctor tests showed that with the addition of the additives the maximum dry density either remained unchanged or increased by less than 10%.

Comments:

Stabilizer Type: Chemical

Paper Title: Laboratory Testing of Non-Traditional Additives for Stabilization of Roads and Trail Surfaces

Author: Bolander P.

Source: Transportation Research Record

Publication Date: 1999

Purpose of Stabilizer: Stabilizer - Unpaved Roads and Trails

Stabilizers Tested: Chlorides, enzymes, lignin sulfonates, synthetic polymer emulsions, tall oil emulsions

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Dense-Graded Aggregate	N/A	Tall Oil Emulsions (EnduraSeal, Road Oyl)	N/A	1.0-3.0%	N/A	N/A
Dense-Graded Aggregate	N/A	Magnesium Chloride	N/A	5.8%	N/A	N/A
Dense-Graded Aggregate	N/A	Synthetic Polymer Emulsions (Marloc, Soil Sement)	N/A	0.5-6.0%	N/A	N/A
Dense-Graded Aggregate	N/A	Lignin Sulfonates	N/A	4.0%	N/A	N/A
Dense-Graded Aggregate	N/A	Enzymes (EMC-Squared)	N/A	0.25 l/m^3	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength, Indirect Tensile Tests Wet/Dry, Freeze/Thaw Cycles

Test Methods: Additives were added to samples at moisture contents from nearly 0% to 10%. Samples were compacted and cured from 7-28 days at various cure temperatures. Indirect tensile strengths were then measured. The paper provides a table of these various conditions. Some of the samples were also subjected to freeze-thaw cycles and wet-dry cycles.

Key Findings: Chlorides, clay additives, enzymes, and lignin sulfonate provide some tensile strength gain in warm dry climates. Synthetic polymer and tall oil emulsions provide significant strength once cured in warm dry climates. Their tensile strength slowly degraded when exposed to periodic wetting-drying and freeze-thaw. Cure temperature had a dramatic impact on the additives' effectiveness with increased effectiveness at higher temperatures and longer curing times.

Comments: Some field testing was done in conjunction with the laboratory tests. Performance in the field matched expectations as a result of the laboratory results.

Stabilizer Type: Chemical

Paper Title: Stabilization of Landslides - Effects of Various Chemicals on the Laboratory Shear Strength of an Expansive Soil

Author: Borchardt G.

Source: California Division of Mines and Geology

Publication Date: 1984

Purpose of Stabilizer: Stabilizer - Landslides

Stabilizers Tested: Various acids

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Expansive clay	CH	Other Chemicals	Liquid	5%	N/A	N/A
Expansive clay	CH	Various Sulfates	Liquid	2.5 to 5%	N/A	N/A
Expansive clay	CH	Various Phosphates	Liquid	5%	N/A	N/A
Expansive clay	CH	Various Fluorides	Liquid	5, 7, 10%	N/A	N/A
Expansive clay	CH	Various Hydroxides	Powder	5 to 10%	N/A	N/A
Expansive clay	CH	Various Organic Chemicals	Liquid	5%	N/A	N/A
Expansive clay	CH	Various Chlorides	Liquid	5%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Abundant montmorillonite, beidellite, and traces of mica

Tests Performed: X-Ray Diffraction, Torsional Vane Shear Test

Test Methods: This paper is an extensive report on various chemicals tested on an expansive soil. Samples were mixed with chemicals (5 g/60 ml of water) at high and low water contents, leached to simulate effects of rainfall, and cured for 150 days. Liquid and plastic limits were measured at various cure times to monitor its effects. Shear strengths were measured at varying moisture contents by using the torsion vane test. Curves of water content versus log of the shear strength were plotted.

Key Findings: Hydrofluoric acid was noted as producing relatively rapid and permanent increases in shear strength in a wide range of water contents. Other notable conclusions: 1) Sodium metasilicate produced large increases in the liquid limit and in the shear strength at all moisture contents. 2) Potassium iodide not effective with smectites. 3) Iron powder increased strength at all moisture contents. 4) Aluminum nitrate-treated soils displayed a tremendous increase in liquid limit and increased shear strength at high moisture levels. Most likely these results are produced through aluminum hydroxyl interlayer formation in smectites.

Comments: A decent literature review is provided on each chemical group tested.

Stabilizer Type: Chemical

Paper Title: Stabilization of Sensitive Clays (Quick Clays) Using $Al(OH)_{2.5}Cl_{0.5}$

Author: Bryhn, O.R., Loken, T., and Reed, M.G.

Source: Norwegian Geotechnical Institute

Publication Date: 1988

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Hydroxy-aluminum, hydroxy-aluminum and potassium chloride, hydroxy-aluminum and potassium sulfate, unslaked lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Norwegian Quick Clay	CH	Hydroxy-Aluminum	Powder	10-33 g/100 g pore water	N/A	N/A
Norwegian Quick Clay	CH	Hydroxy-Aluminum	Powder	15-50 g/100 g pore water	Potassium Chloride	5:4
Norwegian Quick Clay	CH	Hydroxy-Aluminum	Powder	12-44 g/100 g pore water	Potassium Sulfate	4:1
Norwegian Quick Clay	CH	Unslaked Lime	Powder	9-23 g/100 g pore water	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Natural illitic, chloritic, silty clay

Tests Performed: Unconfined Compressive Strength

Test Methods: This study was a follow-up of a previous study using hydroxy-aluminum. Three year-old insitu columns were tested and compared with earlier field and lab tests.

Key Findings: Lab samples showed a strength increase from 20 kPa to 500-600 kPa with OH-Al. Field tests showed largely inhomogeneous patterns of strength gain thoughout the soil columns. It was concluded for short-term strength gain that OH-Al gave the best strength gain and for long term OH-Al + K_2SO_4 gave the best results.

Comments:

Stabilizer Type: Chemical

Paper Title: Stabilization of Sensitive Clays with Hydroxy-Aluminium Compared with Unslaked Lime

Author: Bryhn, T. and Aas, G.

Source: Proceedings of the European Conf. On Soil Mechanics and Foundation Engineering

Publication Date: 1984

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Hydroxy-aluminum, hydroxy-aluminum and potassium chloride, hydroxy-aluminum and potassium sulfate, unslaked lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Norwegian Quick Clay	CH	Hydroxy-Aluminum	Powder	10-33 g/100 g pore water	N/A	N/A
Norwegian Quick Clay	CH	Hydroxy-Aluminum	Powder	15-50 g/100 g pore water	Potassium Chloride	5:4
Norwegian Quick Clay	CH	Hydroxy-Aluminum	Powder	12-44 g/100 g pore water	Potassium Sulfate	4:1
Norwegian Quick Clay	CH	Unslaked Lime	Powder	9-23 g/100 g pore water	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Fallcone Test, Unconfined Compressive Strength, Direct Shear Test

Test Methods: This paper looked at stabilization of clay columns of Norwegian quick clays at their natural moisture contents. Laboratory tests on undisturbed samples and field tests were performed, with 7-day lab cure times and 2-month field cure times.

Key Findings: Hydroxy-aluminum (OH-Al) was found effective compared to lime in all soils tested if used in sufficient quantities and mixed with additives to increase its stability effect. OH-Al, when brought to polymerization in clay, gave higher shear strengths than lime in the laboratory, but in the field they were the same or lower. Lime was less effective in clays with high moisture contents and in natural salt clays. Lime is very effective in silty clays. Lime + $CaSO_4$ usually shows better improvement than just lime. Field tests always showed lower strengths than lab tests. As a final note, OH-Al is costly compared to lime but showed promising lab results.

Comments:

Stabilizer Type: Reinforcement

Paper Title: Soil Fiber Reinforcement: Basic Understanding

Author: Bueno, B. and de Lima, D.

Source: Environmental Geotechnology Proceedings

Publication Date: 2003

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Plastic fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Cohesive soils	N/A	Plastic fibers (5-20 mm)	Fiber	70-280 m^2/ton	N/A	N/A
Clean sands	N/A	Various Sulfates	Fiber	70-280 m^2/ton	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Compaction Tests, Triaxial Tests, Swell Potential by 1-D Consolidometer

Test Methods: Short randomly distributed fibers were mixed with soils to determine their mechanical and hydraulic behavior. Eight different soils of different grain size distribution were used in this study. The paper analyzes the effects of fiber length, width, and thickness as parameters on the shear strength, compressibility and permeability of the soils. Soils were mixed simultaneously to their optimum moisture contents and fiber inclusion. They were compacted to standard Proctor effort and left standing for a 24-hour period. Unconfined compression tests were then performed.

Key Findings: Comparison of unconfined compression strength supports that more cohesive soils are less sensitive to variations in fiber length. Large variations of reinforced shear strength were found when compared to plain soil specimens. In general, cohesive soils showed a small decrease in friction angle and an increase in cohesion. Granular soils showed significant increases in both cohesion and friction angle. Inclusions of fibers in all cases improved the compressibility of the soil. Permeability was increased in cohesive soils and decreased in granular soils.

Comments:

Stabilizer Type: Reinforcement

Paper Title: Effect of Polypropylene Fibre and Lime Admixture on Engineering Properties of Clayey Soil

Author: Cai, Y., Shi, B., Ng, C.W.W. and Tang, C.

Source: Engineering Geology

Publication Date: 2006

Purpose of Stabilizer: reduce brittleness and increase strength of lime stabilized soil with fibers

Stabilizers Tested: Polypropylene fiber and lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Xiashu Soil	clay	Polypropylene fiber	Fibers	0.05, 0.15, 0.25%	Lime	2%, 5%, 8%

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined compression test, direct shear, swelling, shrinking

Test Methods: Twelve specimen groups were formed using a static compaction method. Samples tested include; one untreated sample, one reinforced with 0.25% fibers only, one stabilized with 8% lime only, and nine lime-fiber reinforced samples. All samples were wrapped in a thin plastic film, stored in a curing box, and tested at 7, 14, and 28 days. Samples were unwrapped and soaked in water for 24 hrs prior to unconfined compression testing. A strain rate of 2.4 mm/min was used during shear in the unconfined compression test. Direct shear tests were completed at a strain rate of 0.8 mm/min while applying a normal pressure of 50, 100, 200, and 300 kPa. Untreated and fiber reinforced only samples did not undergo the 24 hr emersion period prior to testing to prevent collapse.

Key Findings: Testing shows that all properties, (unconfined compressive strength, cohesion, and friction angle), increase with curing time for all samples. The addition of lime shows the presence of an optimum lime content. Increasing the lime fraction within a sample results in higher strengths until a maximum is reached, the strength then diminishes. The optimum strength gain was determined to be 5%. Addition of fibers lead to an increase in strength, shrinkage potential, and toughness while decreasing the swell potential. In conclusion, fiber-lime stabilized soil exhibited more unconfined compressive strength, cohesion, and friction angle gains than soils stabilized with lime only.

Comments: Xiashu soil is extensively distributed throughout Nanjing region of China

Stabilizer Type: Chemical

Paper Title: High Temperature Non-Aqueous Dispersion Polymerization of Aromatic Main Chain Liquid Crystal Polymers Using Organo-Clay Stabilization

Author: Carter N., MacDonald W.A., Pittman D., and Ryan T.G.

Source: Polymer

Publication Date: 1999

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Various polymers prepared by a high-temperature non-aqueous dispersion polymerization (NAD) route

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Organoclays (6 different specimens)	N/A	NAD	Liquid	5 wt% with respect to monomers	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Bentonite, vermiculite, hectorite

Tests Performed: Swell Potential by 1-D Consolidometer

Test Methods: Small-scale polymerizations were carried out to determine the effectiveness of the polymerization. Saturated manufactured clays were combined with the stabilizers in a liquid paraffin polymerization medium at temperatures ranging up to 320ºC for an hour duration.

Key Findings: The bentonite clays did not show effective stabilization. The vermiculite clays with their relatively high iron content reacted adversely with the stabilizer and there was some extraction of the metal from the clay by acetic acid. Therefore these samples were not further studied. Finally, bentonite and hectorite clay did show marked improvement in swell rate and stabilization. No quantitative values were given from the laboratory experiments though.

Comments: NAD prepared polymers showed some strength gain in certain clays utilizing high cure temperatures. The hydrophobic organo-clay is believed to provide a steric barrier to prevent flocculation.

Stabilizer Type: Chemical

Paper Title: Laboratory Studies on the Stabilization of Clays at High Moisture for Emergent Road Construction

Author: Chadda L.R.

Source: Roads and Road Construction

Publication Date: 1970

Purpose of Stabilizer: Stabilizer - Roadways

Stabilizers Tested: Lime, lime and reactive surkhi

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Alluvial Soil	N/A	Hydrated Lime	Powder	3, 5, 7, 10%	Reactive Surkhi	20, 30%
Alluvial Soil	N/A	Hydrated Lime	Powder	5, 7, 10, 15%	N/A	N/A
Black Cotton Soil	CH	Hydrated Lime	Powder	5, 7, 10, 15%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Montmorillonite and illite

Tests Performed: Unconfined Compressive Strength, California Bearing Ratio

Test Methods: Samples were first mixed with the different percentages of the additives. Standard CBR molds were then prepared and soaked for 7 days after setting for 24 hours. CBR values were determined. Moisture contents were approximately 50-60% for these tests. For the Black Cotton soil and alluvial clay, unconfined compressive strengths were taken on samples mixed at high water contents again. Strengths were read at 1, 2 and 4-week cure times.

Key Findings: Lime introduced at 7-15% produced strength gains with no compaction effort necessary. Alluvial samples near liquid limit showed high strength gain with 7-10% lime. Strengths increased with lime content, reactive surkhi, and cure time. CBR values went from 1.5 for untreated samples to as high as 33.3 with 15% lime for the Black Cotton Soil. Rapid formation of cementitious siliceous "gel" consisting of mostly calcium silicate hydrate caused initial rapid hardening of lime-clay mixtures. Irreversible shrinkage cracks caused some strength loss with the loss of moisture upon drying.

Comments:

Stabilizer Type: Chemical

Paper Title: Laboratory Studies on Lime-Clay Reaction and Its Importance in the Construction of Stabilized Soil Road Bases

Author: Chadda L.R., Dhawan P.K., and Mehta H.S.

Source: Indian Highways

Publication Date: 1975

Purpose of Stabilizer: Stabilizer - Roadways

Stabilizers Tested: Lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Silty Loam	N/A	Lime	Powder	3-5%	N/A	N/A
Lateritic Soil	N/A	Lime	Powder	3-5%	N/A	N/A
Alluvial Clay	N/A	Lime	Powder	3-5%	N/A	N/A
Black Cotton Soil	N/A	Lime	Powder	3-5%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: California Bearing Ratio

Test Methods: Laboratory investigations showed that the lime-clay reaction was fairly rapid in the presence of moisture and its equilibrium was reached within 1-2 hrs. Soils mixed at 2-3% above optimum water content with varying lag time between mixing and compacting were analyzed. The lag time was varied from 30 minutes to 48 hours. CBR tests were conducted after cure times of 1, 7, and 28 days.

Key Findings: Testing showed lag time beyond 4 hrs showed a slight reduction in strength. Lime-clay reactions are believed to occur quickly in mixing and no adverse effect on the development of strength was found by compacting quickly.

Comments:

Stabilizer Type: Chemical

Paper Title: Stabilization of Crushed Basaltic Rocks and Clay Mixtures using Cementitious Additives

Author: Chakrabarti, S. and Kodikara, J.

Source: Journal of Materials in Civil Engineering

Publication Date: 2005

Purpose of Stabilizer: Obtain suitable unconfined compressive strength

Stabilizers Tested: Alkali-activated slag (AAS), general blended cement (GB), general purpose Portland cement (GP) and hydrated lime (HL)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Crushed rock mixture	N/A	AAS	Powder	2, 3, 4, 6%	N/A	N/A
Crushed rock mixture	N/A	GB	Powder	2, 3, 4, 6%	N/A	N/A
Crushed rock mixture	N/A	GP	Powder	2, 3, 4, 6%	N/A	N/A
Crushed rock mixture	N/A	HL	Powder	2, 3, 4, 6%	N/A	N/A

Natural or Manufactured Soil? Blend of natural soil

Clay Mineralogy: N/A

Tests Performed: Unconfined compressive strength

Test Methods: The soil tested was a basaltic crushed rock with 0%, 6%, and 15% fine grained soils mixed in. Each soil mixture was then tested with 2%, 3%, 4%, and 6% by weight of each soil stabilizer at 1 day, 7 day, and 28 day curing times. Each sample was thoroughly mixed and left for 2 hours to promote moisture homogeneity. The samples were then compacted to a diameter of 105 mm and a height of 115.5 mm and cured in a wet room. Each sample was tested in an unconfined compression apparatus with a strain rate of 0.02 mm per second.

Key Findings: Unconfined compressive strength increased with the content of GP, GB and AAS at a rate that generally diminished with an increase in stabilizer material. The UCS was reduced with increasing fines content. If was concluded that using fly ash or slag could be more effective in stabilizing basaltic crushed rock materials than traditional GP cement.

Comments:

Stabilizer Type: Chemical

Paper Title: Stabilization of Clayey Soils with Lime, Cement and Chemical Additives Mixing

Author: Chandra S.

Source: Prediction and Performance in Geotechnical Engineering

Publication Date: 1987

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Lime and Mowiton 370, cement and Melment

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay-sand mixes	N/A	Lime	Powder	3%	Mowiton 370	10%
Clay-sand mixes	N/A	Cement	Powder	3%	Melment or Plastiment A40	1% or 0.5%

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength

Test Methods: Specimens were prepared by three parts sand and one part clay at a moisture content of 38% and thoroughly mixed with the additives. Specimens were then allowed to cure under water for 7 and 28 days. Strength tests were then conducted.

Key Findings: Strength gain was dependent on percent of additive used. With low cement contents, chemical additives were effective but decreased in effectiveness with higher cement contents. Lime had much more significant strength gains than cement with the clays. The addition of Mowiton M 370 with lime showed marked increases in strength after 28 days cure.

Comments: The paper also discusses water absorption of these mixtures at length.

Stabilizer Type: Chemical

Paper Title: Improvement of Dispersive Soils by Using Different Additives

Author: Chandra S. and James C.G.L.

Source: Indian Geotechnical Journal

Publication Date: 1984

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Lime, sodium chloride, flyash, gypsum, aluminum sulfate

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Samples from in Thailand	CL	Aluminum Sulfate	Powder	0.5, 1%	N/A	N/A
Samples from in Thailand	CL	Sodium Chloride	Powder	1-4%	N/A	N/A
Samples from in Thailand	CL	Gypsum	Powder	1%	Flyash	3, 6%
Samples from in Thailand	CL	Flyash	Powder	1-4%	N/A	N/A
Samples from in Thailand	CL	Gypsum	Powder	3,5,7,10%	N/A	N/A
Samples from in Thailand	CL	Lime	Powder	1-4%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength, X-Ray Diffraction

Test Methods: Approximately 250 samples were tested during this study. Samples were mixed with the additives at different rates and compacted at near optimum moisture contents (10-12%). Unsoaked compressive strength tests were conducted and recorded after cure times of 2, 7, 14, and 21 days.

Key Findings: A resulting table shows flyash providing a sizeable strength gain after only 2-day cure time, though I did not see mention of the untreated soil strength. Gypsum and flyash were found to be the most 'efficient stabizers'.

Comments: This paper provided unsoaked strengths for 2-21 days of cure time.

Stabilizer Type: Chemical

Paper Title: Resistance of Soil-Cement Exposed to Sulfates

Author: Cordon, W.A.

Source: Highway Research Board Bulletin

Publication Date: 1962

Purpose of Stabilizer: Study Soil-Cement Sulfate Interaction

Stabilizers Tested: Cement

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Fine-Grained	N/A	Cement (Types I, II, IV, V)	Powder	6, 10, 14%	N/A	N/A
Coarse-Grained	N/A	Cement (Types I, II, IV, V)	Powder	3, 6, 10%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Compaction Tests, Unconfined Compressive Strength, Wet/Dry, Freeze/Thaw Cycles

Test Methods: Laboratory samples were prepared then placed in the field. Soils were mixed with the cement additive and compacted at +/- 1 percent optimum moisture content. Samples were cured in the laboratory for a minimum of 28 days before being buried in the field at a depth of 1 foot along a bank of sulfate soil. Additional samples were made where sulfate salts were added directly during the mixing procedure. Compressive strengths were then measured on the samples for 7 days, 28 days, 3 months, and one year cure times.

Key Findings: Soil cement is subject to attack of sulfate salts much in the same manner as concrete but deteriorates even more rapidly. The more cement in the mix, the more resistant the soil was to the salts. Fine-grained cement soils deteriorate more rapidly with salts than coarse-grained. Small amounts of salt mixed with cement at the time of fabrication increases the strength. High concentrations of salt mixed with soil salt at fabrication can reduce strength and cause cracking.

Comments:

Stabilizer Type: Reinforcement

Paper Title: Strength and Life of Stabilized Pavement Layers Containing Fibrillated Polypropylene

Author: Crockford, W.W., Grogan W.P., and Chill, D.S.

Source: Transportation Research Record

Publication Date: 1993

Purpose of Stabilizer: Stabilizer - Subbase of Roadways

Stabilizers Tested: Cement and fibrillated polypropylene fibers, lime and fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay	CL-CH	Hydrated Lime	N/A	5%	Fibrillated Fibers	0-0.7%
Sand	SM	Cement	Powder	5%	Fibrillated Fibers	0-1.0%

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Triaxial Tests, Unconfined Compressive Strength, Compaction Tests

Test Methods: Samples were mixed at optimum water contents, first with the chemical stabilizers, then the fibers, and finally with a combination of the optimum amount of chemical stabilizer and varying fiber content. Stress-strain curves were plotted from triaxial tests with 5 psi confining pressure. Optimum cement of 5% for sand and 5% lime for clay was determined.

Key Findings: Clay with the combination of 5% lime and 0.3% fibers increased the strength from 80 to 300 psi. Fibers alone did not do better than traditional stabilizers, but enhanced these stabilizers when added in combination with them. Fibers under certain conditions may allow for a reduction in chemical stabilizer content or the thickness of the layer to be stabilized in subbase applications. Fibers increase the modulus, strength, and strain energy of the sand and clay materials.

Comments: Field test sections were built and tests were conducted on the straight runs. Approximately 5,000 passes were made with a loaded vehicle. The 12-inch thick sections of lime and fiber stabilized clay had not failed when traffic was suspended.

Stabilizer Type: Reinforcement

Paper Title: Stabilization of Weak Clay with Strong Sand and Geogrid at Sand-Clay Interface

Author: Das B.M., Khing K.H., and Shin E.C.

Source: Transportation Research Record

Publication Date: 1998

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Geogrid

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay	CL	Geogrid	Other	N/A	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Bearing Capacity Test, Cyclic Loading Test

Test Methods: Laboratory model tests were conducted on clay soils overlaid with a geogrid and granular soil. Tests were conducted to determine their load bearing capacity and settlement due to repeated cyclic load application.

Key Findings: The geogrid provided an increase in ultimate load-bearing capacity which was in good agreement with Meyerhoff and Hanna's theory, based on a plain strain assumption. The geogrid must be of sufficient size at the interface to provide an increase in capacity.

Comments: Article not conducive to stabilization in a contingency environment. It focuses on stabilization by reinforcement with a geogrid at a sand-clay interface.

Stabilizer Type: Chemical

Paper Title: The Mechanical Response of Soil-Lime Mixtures Reinforced with Short Synthetic Fiber

Author: de Lima, D.C., Bueno, B. and Thomasi, L.

Source: Environmental Geotechnology Proceedings

Publication Date: 2003

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Lime with synthetic fiber reinforcement

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Latyritic Red Soil	MH	Hydrated Lime	Liquid	4 & 8%	Synthetic Fibers	0.25 & 0.75%

Natural or Manufactured Soil? Natural

Clay Mineralogy: Predominantly Kaolinite

Tests Performed: Unconfined Compressive Strength, Indirect Tensile Tests, California Bearing Ratio

Test Methods: A commercial high-calcium hydrated lime containing 92 percent $Ca(OH)_2$, and short synthetic fiber strips 1.2 mm in width and 0.016 mm in thickness were used.

Fibers were tested at lengths of 5, 10, and 15 mm.

All specimens were tested at optimum moisture content and approximately maximum dry density according to AASHTO standard compaction effort.

Samples were cured for 3, 7, and 28 days.

Key Findings:

1. The unconfined compression and the tensile strength of soil-lime-fiber mixture increase with increases in the curing time and lime content.

2. The addition of fiber to the lime-soil mixtures is more effective on increasing the mixtures indirect tensile strength, as illustrated by the drops observed in the ratio sigma-c/sigma-t.

3. Data support the non-effectiveness of the fiber treatment on the stability of the soil-lime mixtures, as measured via the parameter CBR.

4. It is not feasible to conclude on the effect of fiber content and fiber length on the shear strength parameters of the soil-lime mixtures.

5. Data support the effectiveness of the fiber treatment on improving soil-lime mixtures ductility.

Comments:

Stabilizer Type: Chemical

Paper Title: Reactions of Phosphoric Acid with Clay Minerals

Author: Demirel T. and Davidson D.T.

Source: Highway Research Board Bulletin

Publication Date: 1962

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Phosphoric acid

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Volclay (Bentonite)	N/A	Phosphoric Acid	Liquid	40%	N/A	N/A
Vermiculite	N/A	Phosphoric Acid	Liquid	5, 10, 15, 40%	N/A	N/A
Prochlorite	N/A	Phosphoric Acid	Liquid	5, 10, 15, 40%	N/A	N/A
Florida Clay	N/A	Phosphoric Acid	Liquid	5, 10, 15, 40%	N/A	N/A
Grundite (Illite)	N/A	Phosphoric Acid	Liquid	5, 10, 15, 40%	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Kaolinite, montmorillonite, vermiculite, chlorite, illite

Tests Performed: X-Ray Diffraction

Test Methods: All soil samples were brought to their liquid limit. Then amounts of phosphoric acid were added by dry unit weight. Treated samples were analyzed with X-ray diffraction after periods of 1 and 2 weeks, and 1 and 4 months.

Key Findings: From the X-ray diffraction curves, diffraction peak heights were observed at certain intervals and divided by the original heights to determine the 'relative extent of reaction'. Rapid and extensive reactions were found with the chlorite and vermiculite clays. Montmorillonite gave a rapid but incomplete reaction, while kaolinite was rather slow and incomplete. These conclusions were in agreement with other researchers' findings with phosphoric acid as a stabilizer.

Comments: Paper focuses on relative extent of reactions with time via X-Ray diffraction. Seems to show that the reaction takes longer than 3 days, although it does seem to slow down with time.

Stabilizer Type: Chemical

Paper Title: Use of Phosphoric Acid in Soil Stabilization

Author: Demirel T., Benn C.H., and Davidson D.T.

Source: Highway Research Board Bulletin

Publication Date: 1960

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Phosphoric acid

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay (7 different clay samples)	CH	Phosphoric Acid	Liquid	0-10%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Mineralogy of clay given in table, mostly montmorillonite as predominant mineral

Tests Performed: X-Ray Diffraction, Unconfined Compressive Strength, Wet/Dry, Freeze/Thaw Cycles

Test Methods: Soils were machine mixed with water and phosphoric acid at their calculated optimum moisture contents for approximately one minute. Two-inch diameter specimens were compacted to a standard Proctor compactive effort. Samples were cured for 7, 14 and 28 days then immersed and unimmersed compressive strengths were conducted. Samples of plastic loess were also subjected to freeze-thaw cycles.

Key Findings: Unimmersed maximum strengths were reached with 2-10% phosphoric acid; no optimum was observed in the illitic-chloritic clays as strengths increased with increasing acid content. Immersed strengths reached a maximum with 4-14% additive. Highest strengths were found in the illitic-chloritic soils, where the chlorite seemed to be more reactive. Phosphoric acid treatment improved strength and durability characteristics of compacted moist clayey soils; the degree depended on the amount used and clay mineralogy. Chlorite seemed most interactive. Moist cured samples gave better immersed strengths than air cured. Combinations of phosphoric acid and soil had a cure time at which no additional strength gain was seen; depended on the mineralogy. More phosphoric acid provided more resistance to freeze-thaw. Phosphoric acid must neutralize calcium carbonate in soil before reacting with other soil constituents. By cost comparison with cement, only 3% phosphoric acid could be used economically in soil. Cementing compound with clay minerals appeared to be insoluble and irreversible.

Comments:

Stabilizer Type: Chemical

Paper Title: Soluble-Silicate Mud Additives Inhibit Unstable Clays

Author: Ding R., Qui Z., and Li J.

Source: Oil & Gas Journal

Publication Date: 1996

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Soluble-silicate (Potassium and sodium)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Bentonite used for slurry walls	CH	Soluble-silicates	Liquid	1-10 g per 100 g of clay	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Bentonite

Tests Performed: X-Ray Diffraction

Test Methods: Effects on bentonite were measured before and after a silicate was added. Properties observed were the isothermal adsorption, zeta potential (as determined by a micro-electrophoresis analyzer).

Key Findings: Particle sizes of bentonite are increased with silicate, possibly due to adsorption of silicate, preventing the clay from hydrating.

Comments: Article focus was analysis of the mechanisms of silicate muds used to stabilize boring holes and slurry walls for drilling in clay formations.

Stabilizer Type: Chemical

Paper Title: Accelerated Curing of Salt-Treated and Lime-Treated Cohesive Soils

Author: Drake J.A. and Haliburton T.A.

Source: Highway Research Record

Publication Date: 1972

Purpose of Stabilizer: Stabilizer - Acceleration Study

Stabilizers Tested: Lime, lime and sodium chloride

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Permian Red Clay (med plasticity clay)	N/A	Lime	Powder	4, 8%	NaCl	1%
Roger Mills gray clay (younger in age)	N/A	Lime	Powder	6, 11%	N/A	N/A
Permian Red Clay (med plasticity clay)	N/A	Lime	Powder	4, 8%	N/A	N/A
Roger Mills gray clay (younger in age)	N/A	Lime	Powder	6, 11%	NaCl	2%

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength, Compaction Tests

Test Methods: Soil samples were chosen based on previous research done by Marks and Haliburton where they determined the optimum amounts of additives for each soil. Samples were mixed at these optimum water contents (not mentioned in this article), as done by previous research procedures, and compacted in a modified Harvard miniature procedure. Samples were then cured at temperatures from 80 to 120ºF under moist conditions. Unconfined compression tests were taken at 12, 24, 36, 48, 60, and 72 hours. Tests were also conducted out to 28 days at room temperature

Key Findings: Heat was varied to speed up the processes to achieve the same strength as 28-day cure time strength. Approximately 5 to 7-day curing times at 105ºF produced the closest results to 28 -day strengths at room temperature. Small amounts of salt seemed to reduce the cure time of lime-stabilized samples to produce strength correlations after only 30 to 60 hours at the elevated cure temperature.

Comments:

Stabilizer Type: Chemical

Paper Title: Improved Characteristics in Sulfate Soils Treated with Barium Compounds Before Lime Stabilization

Author: Ferris G.A., Eades J.L., Graves R.E., and McClellan G.H.

Source: Transportation Research Record

Publication Date: 1991

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Lime (Calcium hydroxide), lime with barium compounds

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Texas soil	N/A	Lime	Powder	6%	N/A	N/A
California soil	N/A	Lime	Powder	6%	Barium Compound	3%
California soil	N/A	Lime	Powder	6%	N/A	N/A
Texas soil	N/A	Lime	Powder	6%	Barium Compound	3%

Natural or Manufactured Soil? Natural

Clay Mineralogy: Smectite, illite, kaolinite, gypsum, and quartz

Tests Performed: California Bearing Ratio, X-Ray Diffraction, Swell Potential by 1-D Consolidometer

Test Methods: The three soil types used in this testing were of high sulfate content and expansive in nature. Optimum water contents were determined for a modified Proctor compaction effort. Soils were mixed and compacted at optimum water content, soaked for 4, 14, 40, and 60 days, then swell and strength tests were performed at these intervals. A double lime treatment method was also conducted where the soils were treated with 3% lime, left uncompacted for a short time, and then treated with 3% more lime before compaction.

Key Findings: CBR values rose from 0.7 for untreated Texas soil to 5.1 with 6% lime after 14 days and 21.2 after 14 days with barium and lime treatment. California soil similarly went from 4.2 CBR untreated to 10.4 with only lime and 20.6 with lime and barium after 14 days. Barium compounds seemed to give higher strengths than just lime applications. It seemed to address the negative effects of lime on sulfates. Soils with low sulfate contents can be treated with double lime treatments. The first application will form gypsum and ettringite, while the second breaks up the crystals and sullies allowing more lime to form cementing agents.

Comments: Barium is expensive and untested as to its effects in the field. Recommendations in the paper included further investigation of double treatment of lime in high sulfate soils. CBR values for double treatment were only given after 60 days as 21.4 for Texas soils and 45.7 for California soils.

Stabilizer Type: Reinforcement

Paper Title: California Bearing Ratio Improvement of Remolded Soils by the Addition of Polypropylene Fiber Reinforcement

Author: Fletcher, C.S. and Humphries, W.K.

Source: Transportation Research Record

Publication Date: 1991

Purpose of Stabilizer: Stabilizer - Subgrade Soils

Stabilizers Tested: Polypropylene monofilament fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Micaceous sandy silt	MH	Fibrillated fiber (0.38 mm dia.)	Fiber	0.09-1.5%	N/A	N/A
Micaceous sandy silt	MH	Monofilament fiber (0.38 and 0.76 mm dia.)	Fiber	0.09-1.5%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: California Bearing Ratio, Compaction Tests

Test Methods: Three Standard Proctor compaction tests were performed on each of the soil-fiber mixtures. First soils were oven-dried and mixed with the fiber. Fiber length was 25 mm. Then water was added and the samples were mixed to uniform consistency and allowed to cure 24 hours prior to testing. The optimum water content was determined for the treated samples and CBR tests were conducted after a soaking period of 96 hours. The soaked CBR values and amount of swell were then measured.

Key Findings: The addition of polypropylene fibers significantly improved the CBR value of the soils tested. The improvement ranged from a 65% increase to a 133% increase for the 1.0%, 25-mm long, 0.76-mm diameter fiber dosage. Dosages greater than the optimal of 1% decreased in CBR, due to possible sliding on the fiber-to-fiber contact at higher dosages. The measurement of swell as indicators to predict CBR results of fiber-reinforced soils did not appear to be valid.

Comments: A significant literature review of fiber reinforcement on fine grained soils is included in this paper.

Stabilizer Type: Reinforcement

Paper Title: Innovative Method of Stabilizing Clay Utilizing on Centre Development Project

Author: Freed, W.W.

Source: Texas Contractor

Publication Date: 1990

Purpose of Stabilizer: Stabilizer - Subgrade

Stabilizers Tested: Cement and fibrillated polypropylene fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay soil (PI 35 to 45)	N/A	Cement	Powder	7%	Fibrillated Fibers	0.20 lbs/sq yd

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: No Testing Conducted

Test Methods: This paper describes the stabilization process of a clay subgrade soil for a development project covering 162,000 square feet. The cement was spread in powder form over the undisturbed soil, and then the soil was dragged with a chain link fence to evenly distribute the cement. Water was added to aid the chemical process while discing to 6 inch depth. Fibers were then spread uniformly with a tractor-towed spreader and mixed in with an average of 3-5 passes. The reinforced soil was then compacted with a sheep's-foot vibratory roller.

Key Findings: No actual strength gain data or intended strength gain was provided in this article. It only mentions that 'appreciable strength gain' was observed by the end of construction. The subgrade was able to support the ready-mix concrete trucks within days with resistance to rutting even when exposed to water.

Comments: Fibers were able to be mixed 'uniformly' with the clay at its optimum water content in the field despite windy and adverse conditions. The fibers were intended to provide immediate strength until the cement gained strength.

Stabilizer Type: Reinforcement

Paper Title: Soil Randomly Reinforced with Fibers

Author: Freitag D.R.

Source: Journal of Geotechnical Engineering

Publication Date: 1986

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Fibers (Nylon and polypropylene)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Lean sandy clay	CL	Polypropylene olefin concrete reinforcement fiber	Fibers	1% by volume	N/A	N/A
Lean sandy clay	CL	Polypropylene rope fiber	Fibers	1% by volume	N/A	N/A
Lean sandy clay	CL	Spun nylon string	Fibers	1% by volume	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Compaction Tests, Unconfined Compressive Strength

Test Methods: Dry soils were mixed with water to a wide range of moisture contents (17-24%) then mixed with the fibers. Individual specimens were then prepared in Harvard miniature compaction molds in five compacted layers. Unconfined compression tests were conducted immediately after compaction.

Key Findings: Randomly distributed fibers compacted in fine-grained soil can result in greater strength and toughness. Strength of reinforced soil compacted near and wet of optimum was greater than for plain soil at the same water content by up to 25%. Mixing was found to be difficult on the loose, moist soil.

Comments: For samples wet of optimum, unconfined compressive strength gains were about 25%. Mixing troubles seemed to be associated with the use of the nylon fibers as they tended to unravel.

Stabilizer Type: Chemical

Paper Title: Overconsolidated Behavior of Phosphoric Acid and Lime-Stabilized Kaolin Clay

Author: Ghazali F.M., Baghdadi Z.A., and Khan A.M.

Source: Transportation Research Record

Publication Date: 1991

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Phosphoric acid, lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Pure kaolin clay	N/A	Phosphoric acid	Liquid	4, 8, 12%	N/A	N/A
Pure kaolin clay	N/A	Lime (hydrated)	Powder	4, 8, 12%	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Kaolinite

Tests Performed: X-Ray Diffraction, Swell Potential by 1-D Consolidometer, Direct Shear Test

Test Methods: Dry soil was pulverized, added with lime, and then mixed with water to the liquid limits of the treated kaolin. Specimens were mixed wet before the addition of the phosphoric acid. Consolidation tests were conducted and shear strength tests were preformed at 0,7,14 and 28 days and at different levels of preconsolidation pressures.

Key Findings: Addition of lime or acid reduced the kaolin's Atterberg limits. Increases in shear strength were greater for lime than phosphoric acid with kaolin. The strength increases with the application of preconsolidation pressure both for lime and phosphoric acid stabilized kaolin clay mixes.

Comments:

Stabilizer Type: Reinforcement

Paper Title: Effect of Fibre Shapes and Coatings on Strength of Discrete Coir Fibre Reinforced Soil

Author: Girish, M.S., Jaya, C.K., and Joseph, M.

Source: Journal of the Institution of Engineers (India)

Publication Date: 2002

Purpose of Stabilizer: Stabilizer - Earth Structures

Stabilizers Tested: Coir natural fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Silty sand	SM	Coir fibers (0.1 to 0.5 dia.)	Fiber	0.1, 0.3, 0.5, 1.0%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Compaction Tests, Unconfined Compressive Strength

Test Methods: Coir fibers (with high lignin content), varying in diameter from 0.1 to 0.5 mm, were cut to 25 mm lengths and mixed with a dry, silty-sand. The mix was then compacted at different water contents, 17-25%, with standard Proctor compactive effort. In addition, some of the fiber was coated with cement. Unconfined compressive strength tests were then conducted on the treated, compacted samples.

Key Findings: There was a significant increase in strength of samples with cement coated fibers. Also, large diameter and curved fibers were found to contribute to greater reinforcement strengths. Without cement treatment, unconfined compressive strength gain was from 80 kPa to around 300 kPa at 20% water content. It is recommended that discrete coir fibers be segregated and surface treated with cement when used for soil improvement.

Comments:

Stabilizer Type: Chemical

Paper Title: Relative Effects of Chlorides, Lignosulfonates and Molasses on Properties of a Soil-Aggregate Mix

Author: Gow A.J., Davidson D.T., and Sheeler J.B.

Source: Highway Research Board Bulletin

Publication Date: 1960

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Calcium chloride pellets, sodium chloride, lignin sulphite liquors, and a Brix molasses

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Soil-aggregate mix (gravel, silty loam, till)	N/A	Brix molasses	Liquid	0.5, 1.0, 1.5, 2. 0%	N/A	N/A
Soil-aggregate mix (gravel, silty loam, till)	N/A	Calcium chloride	Pellets	0.5, 1.0, 1.5, 2. 0%	N/A	N/A
Soil-aggregate mix (gravel, silty loam, till)	N/A	Lignosulfonates	Liquid	0.5, 1.0, 1.5, 2. 0%	N/A	N/A
Soil-aggregate mix (gravel, silty loam, till)	N/A	Sodium Chloride	Pellets	0.5, 1.0, 1.5, 2. 0%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Illite, kaolinite, montmorillonite (predominant)

Tests Performed: California Bearing Ratio, Compaction Tests, Atterberg Limits

Test Methods: Samples were mixed for approximately 3 minutes, compacted to a depth of about 2" with a 5.5 lb rammer, and cured for 5 minutes. For the CBR tests, samples were prepared at their optimum moisture contents of 6%. Unsoaked and soaked tests were conducted (after 4 days immersion) after 4-day cure times.

Key Findings: Untreated soil had immediate CBR values of 15.3 unsoaked and 9.8 immersed. Strength was improved by any of the additives to a range of 24 to 52 for immersed CBR values. Immersed strengths with optimum amount of additives are approximately equal for all additives except molasses. Calcium chloride seemed to be the most effective of the additives for moisture retention and strength gain.

Comments:

Stabilizer Type: Chemical

Paper Title: Electrochemical Hardening of Clay Soils

Author: Gray D.H.

Source: Geotechnique

Publication Date: 1970

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Electrochemical with aluminum

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Bentonitic soil	CH	Hydrated aluminum chloride	Liquid	1%	Electric current	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Given in table as bentonitic soil; mainly quartz, montmorillonite and illite

Tests Performed: X-Ray Diffraction

Test Methods: Experimental soils were mixed thoroughly with distilled water and remolded before being packed into a specially designed electrolytic cell (10 x 10 x10 cm). Sample water contents were either between their Atterberg limits or near their liquid limit. Samples were then introduced with aluminum (1% solution of hydrated aluminum chloride anolyte) electrically through the use of a direct current power supply.

Key Findings: A time dependent increase in shear strength was noted with a tendency to be more effective in higher water content samples. These had a higher electrolytic transfer of the aluminum at the same or lower electrical energy input.

Comments:

Stabilizer Type: Reinforcement

Paper Title: Determination of Semi-Prepared Airfield Pavement Structural Requirements for Supporting C-17 Aircraft Operations

Author: Grogan W.P.

Source: Waterways Experiment Station - Technical Report

Publication Date: 1998

Purpose of Stabilizer: Stabilizer - Airfield Uses

Stabilizers Tested: Crushed limestone, fiber

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Sand	SM	Fiber	Fiber	0.8%	Road Oyl	1 gal /sq yd
Buckshot clay	CH	Crushed limestone	Other	15-24" depth	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: California Bearing Ratio

Test Methods: Full scale pavement section items were constructed and trafficked to failure with fully loaded C-17 aircraft main gear assembly (using six wheel partial configuration) in order to test the current CBR criteria for pavement items (CBR value of 9).

Key Findings: Three major conclusions were drawn from this study: (a) the current unsurfaced airfield criteria should be considered appropriate for use in designing/evaluating the expected performance of airfield operations for the C-17 aircraft, (b) the aggregate surface criteria should not be adjusted further, and (c) sand with fiber inclusions require further study before it can be considered for use in supporting C-17 aircraft.

Comments: The C-17 aircraft was designed to operate on a CBR-9 surface. Sand with fibers appeared to fail after 3 passes, the crushed limestone seemed to have held reasonably well after over 300 passes.

Stabilizer Type: Reinforcement

Paper Title: Stabilization of High Plasticity Clay and Silty Sand by Inclusion of Discrete Fibrillated Polypropylene Fibers (Fibergrids) for Use in Pavement Subgrades

Author: Grogan W.P. and Johnson W.G.

Source: Waterways Experiment Station - Technical Report

Publication Date: 1994

Purpose of Stabilizer: Stabilizer - Airfield Uses

Stabilizers Tested: Cement, cement and fibers, lime, lime and fibers, fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Heavy Clay	CH	Lime	Powder	5%	Fibrillated polypropylene fibers	0.1, 0.3%
Heavy Clay	CH	Lime	Powder	5%	N/A	N/A
Silty Sand	SM	Cement	Powder	5%	Fibrillated polypropylene fibers	0.5%
Silty Sand	SM	Cement	Powder	5%	N/A	N/A
Silty Sand	SM	Fibrillated polypropylene fibers	Fibers	0.5%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: California Bearing Ratio, Triaxial Tests

Test Methods: Field study quantities of admixtures were determined from laboratory testing with the clay and sand materials. Soils were mixed with the additives at their optimum moisture contents. A test track was built with various sections using the admixture materials. Field tests included CBR, DCP and other tests. Additionally, undisturbed samples were used for further laboratory testing.

Key Findings: Fibers benefited strength in both types of soils with the greatest benefit by inclusion with a chemical additive. With fiber, sand had a 60% increase in trafficking field tests while clay-lime-fiber had a 30% increase (measured in traffic to failure). Fibers seemed to slow the rutting process and enhance the post-peak load-carrying capacity. Even small amounts of fiber improved performance.

Comments: Author stated that the 1" long fibers were readily mixed with the soils investigated in this test.

Stabilizer Type: Chemical

Paper Title: Field Studies of Soil Stabilization with Phosphoric Acid

Author: Guinee, J.W.

Source: Highway Research Board Bulletin, #318

Publication Date: 1961

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Phosphoric acid

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Putnam silt loam	N/A	Phosphoric acid	Liquid	1-3%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength, Compaction Tests

Test Methods: Laboratory and field tests were conducted on the soils at their optimum moisture contents of 16-18%. A 6-inch depth 20' x 100' test section was built of Putnam silt loam with 2% acid inclusion as determined from the laboratory testing. Field spraying was accomplished with a distributor (8 trips with a 5-foot spray bar) and mixed with a tiller to the desired 6-inch depth. The pad was then compacted with a sheep's-foot roller.

Key Findings: The preliminary tests of the use of phosphoric acid as a stabilizing agent for heavy clay soils showed promise of obtaining an adequate stabilizing effect if basic soils or inclusions of lime are avoided. Unconfined compression tests of undisturbed samples from the field study gave strengths of 90-150 psi.

Comments: Author claims this is a promising stabilizing agent if lime soils are avoided.

Stabilizer Type: Reinforcement

Paper Title: Wood Fiber Fill to Reduce Airport Pavement Settlements

Author: Hardcastle, James H., and Howard, Terry R.

Source: Transportation Research Record, #1310

Publication Date: 1991

Purpose of Stabilizer: Stabilizer - Reduction of Settlements

Stabilizers Tested: Wood fiber fill

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Highly organic, silty, clayey soil	OH	Wood fiber	Fiber	Up to 11' depth	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Organic inclusions

Tests Performed: Triaxial Tests, Swell Potential by 1-D Consolidometer

Test Methods: Lightweight wood fiber fill was used over an unknown thickness of peaty, silty, clayey soil (which was highly organic) for an airport runway and apron operations. The original subbase of crushed rock settled more than 2 feet in a 10-year period. This material, along with up to 8 feet in depth of the subgrade was replaced with wood fiber.

Key Findings: The lightweight fill allowed higher elevation without an increase in effective stress. Though the settlements were higher than expected they fell within acceptable limits, and the objective of preventing a new cycle of subgrade consolidation settlement was achieved.

Comments:

Stabilizer Type: Chemical

Paper Title: Improvement of Dispersive Clay Erosion Resistance by Chemical Treatment

Author: Hayden, Myron L., and Haliburton, T. Allan

Source: Transportation Research Record, #593

Publication Date: 1976

Purpose of Stabilizer: Stabilizer and Erosion Resistance

Stabilizers Tested: Hydrated lime, sodium chloride, aluminum sulfate

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Four dispersive soils	CH	Sodium chloride	Powder	1, 2, 3%	N/A	N/A
Four dispersive soils	CH	Aluminum sulfate	Powder	1, 2, 3, 4%	N/A	N/A
Four dispersive soils	CH	Lime	Powder	0.5, 1.0, 1.5%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Physical Erosion Test, Compaction Tests

Test Methods: Four dispersive soils in Oklahoma and two known non-dispersive soils were used in this study. Soils were mixed with varying percentages of each of the additives at 2% above their optimum moisture content, cured for 24 hours, then compacted in a Harvard miniature mold. Erosion testing procedure was conducted on the samples 'after a relatively short period', as provided in reference papers. Erosion was a measurement of the initial dry weight - end dry weight / initial dry weight.

Key Findings: All three chemical stabilizers evaluated were successful treatments with lime being the most effective, aluminum sulfate, then sodium chloride. Lime reduced erosion with increasing additive from about 60% on average to less than 15% on average in the samples used.

Comments:

Stabilizer Type: Chemical

Paper Title: Anionic Polyacrylamide Polymers Effect on Rheological Behavior of Sodium-Montmorillonite Suspensions

Author: Heller, Hadar, and Keren, R.

Source: Soil Science Society of America Journal

Publication Date: 2002

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Polyacrylamide Polymer

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Sodium Montmorillonite	N/A	PAM90 Aldrich Chemical Company	Solution	N/A	N/A	N/A
Sodium Montmorillonite	N/A	A185 American Cyanamide Co.	Solution	N/A	N/A	N/A
Sodium Montmorillonite	N/A	A130 American Cyanamide Co.	Solution	N/A	N/A	N/A
Sodium Montmorillonite	N/A	A110 American Cyanamide Co.	Solution	N/A	N/A	N/A
Sodium Montmorillonite	N/A	P35 American Cyanamide Co.	Solution	N/A	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Sodium montmorillonite

Tests Performed: Rheological

Test Methods:

Key Findings:

1. "In free electrolyte clay, only the largest polymer (A185) could form a three-dimensional network, while the smallest polymer prevented edge-to-edge association."

2. "The greatest influence of the polymers was obtained in clay suspensions with electrolyte concentration of 10 mmol L^{-1} (at which the attractive forces between clay platelets are very weak, Heller and Keren,

Comments: The polymers prevented edge-to-edge association. The results suggest that high MW and high DH of negative PAM together with low electrolyte concentration in soil. Soil solution could be more effective in soil aggregate stabilization.

Stabilizer Type: Chemical

Paper Title: Basic Improvements in Phosphate Soil Stabilization

Author: Hemwall, John B., and Scott, Henry H.

Source: Highway Research Board Bulletin

Publication Date: 1962

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Rock phosphate or phosphoric acid and sulfuric acid or hydrochloric acid

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
13 soils with varying clay/silt/sand fractions	N/A	Rock phosphate	Powder	0.4-1.35%	Sulfuric or hydrochloric acid	30-120 Meg/100g soil

Natural or Manufactured Soil? Natural

Clay Mineralogy: Iron oxides

Tests Performed: Unconfined Compressive Strength

Test Methods: Various dry clay fractions were mixed with varying quantities of rock phosphate and acids then brought to its optimum water content. The samples were then statically compacted and allowed to cure. Soaked unconfined compression tests were then conducted.

Key Findings: Sulfuric acid with either rock phosphate or phosphoric acid resulted in improved treatments. Sulfuric acid is superior to hydrochloric acid in this use. Amounts of sulfuric acid are limited by the fact that excess acidity impaired the strength. Salts of iron and aluminum are beneficial to phosphoric acid treatment.

Comments:

Stabilizer Type: Chemical

Paper Title: Isolation and Investigation of a Lime-Montmorillonite Crystalline Reaction Product

Author: Hilt, G.H., and Davidson, D.T.

Source: Highway Research Board Bulletin

Publication Date: 1961

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Hydrated lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Bentonite	CH	Hydrated Lime	Powder	5-50%	N/A	N/A
Kaolinite	CH	Hydrated Lime	Powder	5-50%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Montonmorillonite, kaolinite, bentonite, illite

Tests Performed: X-Ray Diffraction

Test Methods: Research was undertaken to investigate various lime-soil-water systems, varying parameters one at a time. To determine the best relationships for crystal growth, of sufficient size to be observed under a microscope. Determination of properties were undertaken primarily by microscopic and x-ray methods.

Key Findings: When montmorillonite clay was tested at a water content of 105%, the optimum lime content was 20%. Only the clay size portion of the soil enters into reaction. The same crystalline reaction product develops in mixes of lime, water and bentonite, but only after a considerably longer curing time is it produced in considerable quantity. The chemical composition of the crystal could not be precisely determined.

Comments:

Stabilizer Type: Chemical

Paper Title: Performance of Pavement With Modified Asphalt Surface Layer on Cement Stabilized Subgrade With Short Curing Time

Author: Hirotsu, E., Yosida, N., Nisi, M., Sano, M., and Ohnishi, K.

Source: Conference of the Australian Road Research Board

Publication Date: 1998

Purpose of Stabilizer: Stabilizer - Subgrade Use

Stabilizers Tested: Cement

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Silty sand	SM	Cement	Powder	2.83%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Triaxial Tests, Elastic Modulus

Test Methods: A subgrade material (silty sand) was used with cement mixed at 2.83% of its dry unit weight at its optimum moisture content of 16.5%. Cure times of laboratory specimens were set at 6,12, 24 hours and 28 days. Triaxial tests were then conducted to predict the performance of a recently cement stabilized subgrade with an asphalt overlay.

Key Findings: The cement stabilization brought the CBR value to 30. It was found that with a short cure time the asphalt performance degraded rapidly in the first two years due to a sharp increase in the rut depths. However, the performance of the pavement after 7 day cure time was equal or better than that of a 28-day cure time.

Comments:

Stabilizer Type: Chemical

Paper Title: The Use of Lime-Treated British Clays in Pavement Construction. Part 2: The Effect of Mellowing on the Stabilization Process

Author: Holt, C.C., Freer-Hewish, R.J., and Ghataora, G.S.

Source: Proceedings of the Institution of Civil Engineers - Transportation

Publication Date: 2000

Purpose of Stabilizer: Stabilizer - Subbase of Roadways

Stabilizers Tested: Quicklime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
London Clay	N/A	Quicklime	Powder	N/A	N/A	N/A
Low Lias Clay	N/A	Quicklime	Powder	N/A	N/A	N/A
Mercia Mudstone	N/A	Quicklime	Powder	N/A	N/A	N/A
Oxford Clay	N/A	Quicklime	Powder	N/A	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Kaolinite, illite, chlortite-vermiculite, and montmorillonite

Tests Performed: Unconfined Compressive Strength, X-Ray Diffraction

Test Methods:

Key Findings: Unsoaked strength was improved. Soaking of specimens reduced the strengths by approximately a half. The optimum mellowing period was one half to one day, to allow the hydration of the lime. Mellowing times greater than one day were detrimental, although not significant in soaked samples. X-ray diffraction analysis confirmed consumption of lime in mellowed samples is greater than in unmellowed samples.

Comments:

Stabilizer Type: Chemical

Paper Title: Investigation of Several Additives for Controlling the Expansion of Pierre Shale

Author: Hoskins, E.R., Hammerquist, D.W., and Irby, D.

Source: Highway Research Record

Publication Date: 1972

Purpose of Stabilizer: Stabilizer - Swell potential

Stabilizers Tested: Gypsum, lignite, flyash, lime, slime tailings

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Pierre shale soils	N/A	Slimes	Liquid	5%	N/A	N/A
Pierre shale soils	N/A	Lignite	Powder	5%	N/A	N/A
Pierre shale soils	N/A	Lime	Powder	5%	N/A	N/A
Pierre shale soils	N/A	Inert Grit	Powder	5%	N/A	N/A
Pierre shale soils	N/A	Gypsum	Powder	5%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Swell Potential by 1-D Consolidometer

Test Methods: Laboratory tests on seven different admixtures (3-5% added) were tested to control the swell potential of a Pierre, South Dakota shale. Proctor tests were conducted on samples, then a small confining pressure was applied while the samples were saturated and tested for swell.

Key Findings: Results indicate the percentage of volume increase of the soil is best controlled by lime compared to the other additives. Swell potential was reduced by a third with all additives, but by about a factor of five with lime. The effects on strength and bearing capacity were not tested.

Comments:

Stabilizer Type: Chemical

Paper Title: Sodium Silicate Stabilization of Soils: A Review of the Literature

Author: Hurley, Claude H., and Thornburn, Thomas H.

Source: Highway Research Record

Publication Date: 1972

Purpose of Stabilizer: Stabilizer - Literature Review

Stabilizers Tested: Sodium silicate, sodium silicate and lime or cement

Natural or Manufactured Soil? N/A

Clay Mineralogy: N/A

Tests Performed: No Testing Conducted

Test Methods:

Key Findings: Sodium silicates used as additives appear to improve the strength and durability of soils stabilized with Portland cement, lime or lime-flyash. There is some evidence that sodium silicate can precipitate and increase strength and durability with Portland cement, lime or lime-flyash stabilized soils. Best results have been obtained with sands or relatively nonplastic fine-grained soils. Sodium silicates appear useful in increasing resistance to sulfate attack. It can also significantly reduce the amount of these additives in sands and produce the same strength gains.

Comments: The author notes that the early strength of lime-stabilized clay soil can be increased by small amounts of sodium silicates, and the resistance of the stabilized soil to cool temperature and freeze-thaw effects can be increased.

Stabilizer Type: Chemical

Paper Title: Mechanisms of Clay Stabilization with Inorganic Acids and Alkali

Author: Ingles, O.G.

Source: Australian Journal of Soil Research

Publication Date: 1970

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Barium hydroxide, calcium hydroxide, lithium hydroxide, sodium hydroxide, hydrofluoric acid, phosphoric acid

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Kaolinite	CL	Various hydroxides and acids	Powder	10%	N/A	N/A
Four dispersive soils	CH	Various hydroxides and acids	Powder	10%	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Kaolinite, montmorillonite

Tests Performed: Unconfined Compressive Strength, Swell Potential by 1-D Consolidometer, Indirect Tensile Tests

Test Methods: Stable hydroxides were ground to a fine powder and added with air-dried soil, while less stable hydroxides and acids were dissolved in water and added to the soil. The soils were thoroughly mixed and brought to moisture contents of 25% for the kaolin and 28% for the montmorillonite soil. Specimens were compacted to different levels, sealed and cured for up to 2 years. After curing, unconfined compression tests and indirect tensile tests were conducted. Dimensional changes were also recorded.

Key Findings: It was evident from the results that water-resistant enhanced strength both of kaolinite and montmorillonite is obtained only if a water-insoluble product appears as a result of degradation of the clay. Degradation of the clay to form water miscible products leads to a diminution of strength at a given level of compaction. Insoluble products were slow and caused initial losses in strength followed by later strength gains. Not all systems led to the same strength gains. Displacement of ions on the clay exchange complex is extremely rapid and important for immediate strength gains. However, sufficient strength was found to only occur by the degradation and reformation of the mineral components.

Comments: Paper gives a breakdown of each acid tried. Article also discusses some clay mineralogy and gives a range of pH for cationic and anionic stabilization of clay soils.

Stabilizer Type: Chemical

Paper Title: Experience with Chemical Stabilization of Soils in the Foundation Bed of Industrial and Residential Buildings in Volgodensk

Author: Isaev, B.N., and Kuzin, B. N.

Source: Soil Mechanics and Foundation Engineering

Publication Date: 1984

Purpose of Stabilizer: Stabilizer - Case Studies Review

Stabilizers Tested: Sodium silicate (gaseous and liquid form), sodium silicate and calcium chloride

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Loess-like clayey soil	N/A	Sodium silicate	Liquid	160 l/m^3	N/A	N/A
Loess-like clayey soil	N/A	Sodium silicate	Liquid	200-250 l/m^3	N/A	N/A
Loess-like clayey soil	N/A	Sodium silicate	Gaseous	200-270 l/m^3	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: No Testing Conducted

Test Methods: The results of 14 soil stabilization projects, including the properties of the soil prior to stabilization, the parameters of the hardening solutions, the flow rate of the reagents, the volumes of the soil, the cost of work, and building settlements after stabilization are given. Two methods were used for stabilization; chemical hardening and gaseous chemical hardening. The treated soils ranged in moisture contents from 10-28%.

Key Findings: Analysis of the effectiveness of the chemical stabilization of the soils indicates that it is possible to provide stabilization with sodium silicate solutions. Strengths presented after treatment ranged from 0.3 to 0.8 MPa. Settlements were reduced to about 25 mm or less for most cases (reduced by a factor of 10-12). The gaseous chemical hardening is recommended for more moist soils.

Comments: Case studies were of chemical hardening under existing buildings, new building construction, and tunneling operations.

Stabilizer Type: Chemical

Paper Title: Stabilization of Saturated Loess Soils by Gas Silication

Author: Isaev, B.N., Zelenski, V.Yu., Shuvalova, L.P., and Semenov, Yu. I.

Source: Soil Mechanics and Foundation Engineering

Publication Date: 1979

Purpose of Stabilizer: Stabilizer - Case Study

Stabilizers Tested: Gaseous sodium silicate

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Loess, clayey soils	N/A	Sodium silicate	Gaseous	170 l/m^3	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: No Testing Conducted

Test Methods: Case study involved strengthening of a saturated subgrade soil below an existing building for the purposes of expanding the number of stories of the building thus increasing the load on the subgrade soil. The soil was at a natural moisture content of 20-24%. Laboratory studies were carried out to determine the rate of application and percentages of the gaseous solution. These studies are only mentioned in the paper and no detail is provided.

Key Findings: This gaseous silication method seems to enable highly moistened and saturated loams under buildings and structures to be stabilized with sufficient reliability. Laboratory values of the stabilized soils indicate an increased compressive strength to 0.6-0.8 MPa while approximately 25% of the free water was replaced with carbon dioxide promoting an intensification of the stabilization process in wetter soils by means of the gaseous method.

Comments:

Stabilizer Type: Chemical

Paper Title: Effect of Heat Treatment on Strength of Clays

Author: Joshi, R.C., Achari, Gopal, Horsfield, D., and Nagaraj, T.S.

Source: Journal of Geotechnical Engineering

Publication Date: 1994

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Heat

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
A natural clay	N/A	Heat	Heat	300-700 ºC	N/A	N/A
Bentonite clay	CH	Heat	Heat	300-700 ºC	N/A	N/A
Kaolinite clay	CL	Heat	Heat	300-700 ºC	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Kaolinite and bentonite

Tests Performed: Unconfined Compressive Strength

Test Methods: Thermal treatments of clays are known to alter several material characteristics, such as strength, cohesion, internal friction angle and resistance to abrasion. Further, it causes a decrease in cation exchange and compressibility, and an increase in particle size. This paper analyzed the relationships between strength of the selected clays and heat treatment between 300 to 700ºC.

Key Findings: The strength of clays increases gradually with an increase in temperature from 110ºC up to dehydroxylation temperature, after which, the rate of increase in strength is significant. The order of increase in strength is much higher for bentonite than for kaolinite. The strength increase was not dependent on void ratio or particle-size distribution. And, although clays harden and develop strength when heated to temperatures below dehydroxylation, the hardened clays disintegrate on soaking in water, whereas samples heated above dehydroxylation attained a resistance to disintegration when soaked. The dehydroxylation temperature is well defined for pure clays but occur over a wider range for natural clays.

Comments:

Stabilizer Type: Reinforcement

Paper Title: Behavior of Cement-Stabilized Fiber-Reinforced Fly Ash-Soil Mixtures

Author: Kaniraj, S.R. and Havanagi, V.G.

Source: Journal of Geotechnical and Geoenvironmental Engineering

Publication Date: 2001

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Fiber and cement, fiber and flyash

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Proportions of silt, sand and flyash	N/A	Cement	Powder	3%	N/A	N/A
Proportions of silt, sand and flyash	N/A	Cement	Powder	3%	Polypropylene fibers	1%

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength, Direct Shear Test, Compaction Tests

Test Methods: The soil was dried and mixed with varying amounts of flyash (up to 75%). Standard compaction tests were performed on mixed samples with additives of cement and fibers. Direct shear, triaxial tests, and unconfined compression tests were preformed on the samples (did not see mention of the cure times).

Key Findings: Generally speaking, from the direct shear tests, the fiber inclusion improved the shear strength. The flyash-soil mixtures stabilized with cement exhibited brittle behavior, while the fiber inclusions resulted in a more ductile behavior. The fiber inclusions increase the failure deviator stress of the unstabilized flyash-soil specimens.

Comments:

Stabilizer Type: Chemical

Paper Title: Some Engineering Properties of Electrochemically Treated Bombay Marine Clay

Author: Katti, R.K., Thorat, S.S., and Patwardhan, S.H.

Source: International Symposium on Soft Clay

Publication Date: 1977

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Calcium chloride with an electrical current

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Bombay marine clay	CH	Calcium chloride	Powder	Continuous 3% solution	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength, Torsional Vane Shear Test

Test Methods: Samples of marine clay were air-dried, crushed and mixed with known quantities of water. They were then compacted in 6 cm lifts on the test tray. A 'pipe' of powder calcium chloride was created in the sample, and an electrical gradient was initiated. Electrical treatments of 12 to 48 hours were conducted for varying void ratios. After a 28-day cure period, unconfined compressive strength tests were performed.

Key Findings: Calcium chloride piles used in a cathode zone were found to be highly effective in increasing the zone of hardening. After 36 hours, change in pH was insignificant, and the strength increases during this time but further electrical treatment has no significant effect on the peak strength value. In all cases, there was an appreciable initial strength gain, particularly in higher void ratio samples. The maximum strength gain obtained was 11.7 kg/cm^2 (initial strength approx. 0.05 kg/cm^2) for a void ratio of 2.65. By comparison, a void ratio of 1.7 obtained an unconfined compressive strength of about 6.2 kg/cm^2.

Comments:

Stabilizer Type: Chemical

Paper Title: Mechanisms of Soil Stabilization with Liquid Ionic Stabilizer

Author: Katz, L.E., Rauch, A.F., Liljestrand, H.M., Harmon, J.S., Shaw, K.S., and Albers, H.

Source: Transportation Research Record

Publication Date: 2001

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Commercial ionic stabilizer (sulfonated limonene)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Sodium montmorillonite	CH	Ionic stabilizer	Liquid	1:500-6000 mg/mg of soil	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Sodium montmorillonite

Tests Performed: X-Ray Diffraction

Test Methods: Dried soils were mixed with the ionic stabilizer and water to bring the soil to its optimum moisture content of 24%. The samples were then cured for 7 days. After the 7 days, the samples were freeze-dried and analyzed with X-ray diffraction and SEM.

Key Findings: The expected mechanism of stabilization was observed, but there is no strength test data. The results indicate that the mechanism may involve removing cations from the lattice, leading to a breakdown of the clay mineral and expulsion of water from the double layer. There also seemed to be evidence of a change in the clay structure, including an apparent loss in expansive clay mineral content. However, the tests seemed inconclusive and it was concluded by the authors that SEM and X-ray diffraction alone are not viable tools for evaluating the use of ionic stabilizers that are dominated by minerals other than expanding clays.

Comments:

Stabilizer Type: Chemical

Paper Title: A Field Application for Lime Stabilization

Author: Kavak, A and Akyarh, A.

Source: Environmental Geology

Publication Date: 2007

Purpose of Stabilizer: Field application of lime stabilization

Stabilizers Tested: Lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay	CH	Lime	Powder	5%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Modified Proctor, CBR, Plate Load Test

Test Methods: Modified proctor, CBR, and Plate Load tests were performed. Procter tests were used to determine field compaction specifications from lab constructed samples. Lab and field samples underwent CBR testing while soaked CBR testing was only completed on field samples. Plate load testing was performed in the field with a maximum pressure of 1000 kPa.

Key Findings: Maximum settlement was reduced by application of lime. CBR values increased with lime stabilization over untreated soils by factors of 15-20. Swelling values from soaked CBR tests were below 1%.

Comments: CBR tests were found to require watering during long term tests, 28 days, to increase CBR values .

Stabilizer Type: Chemical

Paper Title: The Behavior of Lime-Stabilized Clays Subjected to Repeated Loading

Author: Kavak, Aydin, and Baykal, Gokhan

Source: 15th International Conference on Soil Mechanics and Geotechnical Engineering

Publication Date: 2001

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Bentonite	CH	Lime	Powder	8%	N/A	N/A
Kaolinite	CL	Lime	Powder	4%	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Kaolinite and bentonite

Tests Performed: Cyclic Loading Test, Unconfined Compressive Strength

Test Methods: The effect of repeated loading on the cementitious products of lime-stabilized soil is investigated in this paper. The optimum amount of lime was previously determined for each soil. Samples were prepared at their optimum moisture contents using a Harvard miniature compaction sample. Samples were then cured for 0, 7, and 28 days. Then repeated loading was applied from 1,000 to 1,000,000 cycles at a frequency of 6 Hz. Unconfined compression tests were then conducted.

Key Findings: A decrease in UCS at 28 days was observed after 1000 and 10,000 cycles. Most of the strength loss is recovered up to 1,000,000 load cycles due to the densification and strengthening of the soil. Bentonite at optimum water contents observed a strength gain from 100 kPa to 280 kPa after 7 days and 450 kPa after 28-day cure. Kaolinite went from 150 kPa to 400 kPa after 7 days to 990 kPa after 28-day cure.

Comments:

Stabilizer Type: Chemical

Paper Title: Evaluation of Phosphoric Acid for Stabilization of Fine-Grained Plastic Soils

Author: Kelley, J.A. and Kinter, E.B.

Source: Highway Research Record

Publication Date: 1962

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Phosphoric Acid

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Sassafras	CL	Phosphoric Acid	Liquid	1.5, 2.0, & 3.0 %	N/A	N/A
Hagerstown	CH	Phosphoric Acid	Liquid	1.5, 2.0, & 3.0 %	N/A	N/A
Pierre	CH	Phosphoric Acid	Liquid	1.5, 2.0, & 3.0 %	N/A	N/A
Keyport	CL	Phosphoric Acid	Liquid	1.5, 2.0, & 3.0 %	N/A	N/A
Jordan	ML	Phosphoric Acid	Liquid	1.5, 2.0, & 3.0 %	N/A	N/A
Penn	ML	Phosphoric Acid	Liquid	0.5, 1.0, 1.5, 2.0, & 3.0 %	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Illite, Chlorite, Montmorillonite, Kaolinite, and Vermiculite

Tests Performed: Unconfined Compressive Strength

Test Methods: Compacted samples were cured for 1 and 7 days.

Key Findings: Pronounced increases in unconfined compressive strength of soaked specimens were obtained for most of the soils when treated with acid alone, and slight additional increases resulted when the amine was also used.

Comments:

Stabilizer Type: Chemical

Paper Title: Stabilization of Clay with Inorganic By-Products

Author: Kukko, Heikki

Source: Journal of Materials in Civil Engineering

Publication Date: 2000

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Cement, blast furnace slag and desulfuration waste, blast furnace slag and cement, and lime + slag + cement

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay of high natural water contents	CH	70 % Slag + 30 % cement	Powder	20%	N/A	N/A
Clay of high natural water contents	CH	25% Cement + 60% slag + 15% lime	Powder	20%	N/A	N/A
Clay of high natural water contents	CH	70% Slag + 10-30% desulfuration waste + cement	Powder	20%	N/A	N/A
Clay of high natural water contents	CH	Cement	Powder	20%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Chlorite and illite

Tests Performed: Unconfined Compressive Strength

Test Methods: Strength tests were preformed on prepared samples at 99-100% water content. The testing ages of the samples were 7, 28, 91, and 180 days at temperatures of 8 to 60ºC. All samples were mixed with the combinations of the additives at 20% of the dry weight of the soil.

Key Findings: By-product binders are cheaper than cement based binders. The compressive strength of clays stabilized with by-product binders generally exceeds the strength in reference tests with cement. The strength of the stabilized soil was strongly dependent on the water-binder ratio. Compressive strengths were the highest for 70% slag + 30% cement mix, reaching nearly 4 MPa. Most combinations reached strengths between 1 and 3 MPa. Curing can be accelerated by increasing the temperature to 60ºC.

Comments:

Stabilizer Type: Chemical

Paper Title: Stabilization of Soils with Calcium Acrylate

Author: Lambe, T.W.

Source: Boston Society of Civil Engineers

Publication Date: 1951

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Calcium acrylate

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Sandy clay	N/A	Calcium acrylate	Powder	5, 7, 10%	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Kaolinite

Tests Performed: Compaction Tests, Indirect Tensile Tests

Test Methods: Tensile strengths were conducted on mixed samples at water contents from 30-65% with additive percentages from 5-10%. No details are provided on the testing methods and procedures.

Key Findings: Tensile strength of the soil-additive mixture decreases with increasing water content and decreasing additive. Author identifies treatment with calcium acrylate as a flexible membrane with some tensile strength, best used as a surface treatment for stabilized road surfaces, like road oyl. He also states that at the time of the study that no company mass produces this chemical.

Comments: Paper gives a short commentary of methods and additives investigated for soil stabilization.

Stabilizer Type: Chemical

Paper Title: Effect of the Clay Fraction on Some Mechanical Properties of Soil-Lime Mixtures

Author: Lees, G., Abdelkader, M.O., and Hamdani, S.K.

Source: The Highway Engineer

Publication Date: 1982

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Sand-clay mixtures (kaolinite 30%)	CL	Lime	Powder	2, 4, 8%	N/A	N/A
Sand-clay mixtures (montmorillonite 30%)	CH	Lime	Powder	2, 4, 8, 12%	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Kaolinite, and montmorillonite fractions (10, 30, & 50%)

Tests Performed: Unconfined Compressive Strength, Triaxial Tests, Compaction Tests

Test Methods: Commercial sands were blended and mixed with percentages of kaolinite and montmorillonite of 10, 30, and 50%. Samples were then mixed with 0-12% of lime which was considered the economically feasible range of use. Samples were compacted to standard Proctor at different moisture contents (based on the optimum moisture content after the admixture was added, more additive increased the optimum moisture content) and cured for 7 and 28 days. Triaxial and unconfined compressive tests were then conducted.

Key Findings: The strength gain in the montmorillonite soil is higher than that in the kaolinite. Strengths after 7 day-cure ranged from 0.1 to 1.0 MN/m^2 for montmorillonite, and 0.04-0.5 MN/m^2 for kaolinite, depending on the lime content. Optimum lime content appeared to be approximately 4% for kaolinite and 8% for montmorillonite; the higher the clay fraction though, the more lime was needed. Montmorillonitic soils showed much higher increase of cohesion than kaolinitic soils. Lime increased the elastic modulus of montmorillonite soils.

Comments:

Stabilizer Type: Chemical

Paper Title: Sodium Chloride as an Additive in Lime-Soil Stabilisation

Author: Lees, G., Abdelkader, M.O., and Hamdani, S.K.

Source: The Highway Engineer

Publication Date: 1982

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Lime, lime and sodium chloride

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Sand-clay mixtures (mont 30%)	CH	Lime	Powder	2, 4, 8%	Sodium chloride	1, 2, 3%
Sand-clay mixtures (kaolinite 30%)	CL	Lime	Powder	2, 4, 8%	N/A	N/A
Sand-clay mixtures (mont 30%)	CH	Lime	Powder	2, 4, 8%	N/A	N/A
Sand-clay mixtures (kaolinite 30%)	CL	Lime	Powder	2, 4, 8%	Sodium chloride	1, 2, 3%

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Kaolinite and montmorillonite fractions(10, 30, & 50%)

Tests Performed: Unconfined Compressive Strength, Compaction Tests

Test Methods: Commercial sands were blended and mixed with percentages of kaolinite and montmorillonite of 10, 30, and 50%. Samples were then mixed with 0-12% of lime which was considered the economically feasible range of use. Samples were compacted to standard Proctor at different moisture contents (based on the optimum moisture content after the admixture was added, more additive increased the optimum moisture content) and cured for 7 and 28 days. Triaxial and unconfined compressive tests were then conducted.

Key Findings: The addition of NaCl increased the maximum dry density, and slightly decreased optimum water content of the samples. NaCl did not accelerate the development of unconfined compressive strengths of lime-kaolinite mixtures, but did produce greater strength gains in the lime-montmorillonite mixtures. These strength gains were significant ranging from 100 - 300 % strength gain over lime treatment alone.

Comments: The addition of sodium chloride was useful for the highly plastic montmorillonite clay but showed no significant effect on the kaolinite sand-clay mixtures.

Stabilizer Type: Chemical

Paper Title: Laboratory and Field Evaluation of Cement Kiln Dust and Lime for Stabilizing Clayey Silt on Low-Volume Unpaved Roads

Author: Legere G. and Tremblay H.

Source: Transportation Research Record

Publication Date: 2003

Purpose of Stabilizer: Stabilizer - Low volume roads

Stabilizers Tested: Cement kiln dust, lime and cement kiln dust, lime and Portland cement

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clayey Silt	CL-ML	Lime	Powder	1.5-3%	Cement kiln dust	1.5-4.5%
Clayey Silt	CL-ML	Lime	Powder	3, 6%	N/A	N/A
Clayey Silt	CL-ML	Cement	Powder	3, 6%	N/A	N/A
Clayey Silt	CL-ML	Cement kiln dust	Powder	3, 6%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Illite and montmorillonite

Tests Performed: Unconfined Compressive Strength, California Bearing Ratio

Test Methods: Laboratory tests were conducted on the combinations of admixtures at different contents on a range of moisture contents (17-20%) of a clayey silt soil. Unconfined compression tests were performed. Field tests were then constructed with cement kiln dust (CKD) and with lime plus CKD. A gravel running surface was added as well. CBR and DCP tests were preformed after 1 day, 30 days and 300 days.

Key Findings: An admixture of 3% lime-3% CKD produced significant strength increases in the lab and field. The benefits of using CKD with lime at high moisture contents were evident. CKD did well on moisture contents lower than 18% alone. CBR values tripled in the long term. DCP tests were taken after one day and showed strength gains of approx. 60-100%. CBR values went from 3-10 untreated (varied with depth) to 8-15 after 1 day and then to 20+ after 300 days.

Comments: Paper demonstrates positive results with lime and lime/CKD mixtures. Laboratory and field tests were performed. Little rutting was evident after 30 days of treatment in the lime/CKD treated road base.

Stabilizer Type: Reinforcement

Paper Title: Experimental and Theoretical Study of Flexural Behavior of Polymer Fiber Reinforced, Cement-Treated Soils

Author: Liang, R.

Source: Proceedings from 1992 ASCE Specialty Conference

Publication Date: 1992

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Cement and polyester fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Silty soil	N/A	Cement	Powder	12%	Polyester fibers	0, 1, 3, 5%

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: 3-Point Beam Tests, Direct Shear Test, and Compaction Tests

Test Methods: All specimens were prepared using a small batch mechanical mixing method. The proportions of cement and water by weight of dry soil were 12 and 14% respectively. The sample preparations are not clearly defined but appear to be compacted in accordance with ASTM D558 at the optimum moisture content. Bond strength was determined from direct shear tests, while peak loads were analyzed using 3-point beam tests.

Key Findings: Fiber content affects the failure modes of 3-point beam specimens. Fiber content of 1% exhibits fiber bridging behavior. Bond strength between high flexure rigidity fiber and cement-treated soil matrix can be derived from a direct shear test using a simple limit equilibrium analysis. Only specimens with 1% fiber volume fraction satisfied the basic assumption of the cohesive crack model as proposed by Hillerborg (1976).

Comments:

Stabilizer Type: Chemical

Paper Title: Electrical Strengthening of Clays by Dielectrophoresis

Author: Lo, K.Y., Shang, J.Q., and Inculet, I.I.

Source: Canadian Geotechnical Journal

Publication Date: 1994

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Dielectrophoresis

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Leda clay	N/A	Dielectrophoresis (AC Current)	Current	N/A	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Triaxial Tests

Test Methods: The theory of dielectrophoresis in clay-water-electrolyte systems is developed in this paper. Dielectrophoresis is the motion of particles generated by a nonuniform electric field. In most clay-water-electrolyte systems, including natural clays, the dielectrophoretic forces are directed towards the lower field intensity, determined by the negative polarizability. In this experimental program, block samples of Leda clay were subjected to an AC voltage of 60 Hz and 15 kV for a period of 28 days.

Key Findings: Under three electrical-field configurations, the overall shear strengths increased up to 44% after 28 days, concurrent with significant reduction of sensitivity. The improvement of soil properties was also reflected as increases of preconsolidation pressure and shearing resistance in terms of effective stresses. The electrochemical reactions associated with electric current were minimized by insulation to the electrodes.

Comments: The properties of the Orleans clay were improved significantly after 28 days of dielectrophoretic treatment.

Stabilizer Type: Chemical

Paper Title: Stabilization Effects of Surplus Soft Clay with Cement and GBF Slag

Author: Lu, J., Modmoltin, C. and Onitsuka, K.

Source: Journal of Environmental Sciences

Publication Date: 2004

Purpose of Stabilizer: Stabilizer-increase strength of surplus soft clay- make use of waste product

Stabilizers Tested: Cement, granulated blast furnace slag

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Ariake Clay	CH	cement	powder	10, 15, 20, 40%	N/A	N/A
Ariake Clay	CH	Lime	powder	5, 10, 20%,	N/A	N/A
Ariake Clay	CH	cement	powder	10, 15%	GBF slag	10%, 15%, 25%

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed:

Test Methods: All samples were compacted to a diameter and height of 50x100 mm and cured for 7, 14, and 28 days in a wet room. Unconfined compression tests were then completed on each sample.

Key Findings: It was found that GBF slag can be successfully used to partially replace a portion of cement to stabilize the soft clays tested. In general, the amount of cement could be reduced by 5% or more when GBF slag was added in amounts of 10% to 20% depending on the amount of cement.

Comments: GBF slag alone did not produce high strengths, thus must be mixed with cement.

Stabilizer Type: Chemical

Paper Title: Phosphoric Acid in Soil Stabilization

Author: Lyons, J.W., and McEwan, G.J.

Source: Highway Research Board Bulletin

Publication Date: 1962

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Phosphoric acid

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Silty clay loam	N/A	Phosphoric acid	Liquid	0-10%	N/A	N/A
Cecil clay loam	N/A	Phosphoric acid	Liquid	0-10%	N/A	N/A
Keyport clay loam	N/A	Phosphoric acid	Liquid	0-10%	N/A	N/A
Clay loam	N/A	Phosphoric acid	Liquid	0-10%	N/A	N/A
Putnam silty clay loam	N/A	Phosphoric acid	Liquid	0-10%	N/A	N/A
Putnam clay	N/A	Phosphoric acid	Liquid	0-10%	N/A	N/A
Clay	N/A	Phosphoric acid	Liquid	0-10%	N/A	N/A
Clay loam	N/A	Phosphoric acid	Liquid	0-10%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength, Compaction Tests, Atterberg Limits

Test Methods: Atterberg limits were determined for the given soils tested. Air-dried soils were mixed with varying water and additive contents. They were then compacted and cured for a 5-day period in a humidity chamber. Unconfined compressive strength tests were then performed.

Key Findings: The immersed strengths reported after 5-day cure intervals are said to be sufficient for subgrade construction. The strength gain increased linearly with increasing phosphoric acid to approximately 110 psi at 2% additive. With the addition of more additive, additional strength gain was much slower, but doubled after 30-day cure time. Increased phosphoric acid reduced the optimum moisture contents of the soils and increased the maximum dry density.

Comments:

Stabilizer Type: Chemical

Paper Title: Compressive Strength and Permeability of Sand-Cement-Clay Composite and Application for Heavy Metals Stabilization

Author: Mahasneh, B. and Shawabkeh, R.

Source: Electronic Journal of Geotechnical Engineering

Publication Date: 2005

Purpose of Stabilizer: strength and permeability

Stabilizers Tested: cement

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Sand and clay	N/A	Cement	Powder	0, 25, 50, 75%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compression Test, Falling Head Permeability

Test Methods: Compressive test samples were compacted and cured for 1, 7, and 14 days. Unconfined compression tests were performed on the samples. Falling head permeability tests were performed per ASTM D 3434.

Key Findings: From the selected materials, a combination of 25% sand, 50% cement, and 25% clay was found to have the best performance regarding permeability and compressive strength.

Comments: This research was performed to optimize a mix formula to contain heavy metals.

Stabilizer Type: Reinforcement

Paper Title: Mechanical Properties of Kaolinite/Fiber Soil Composite

Author: Maher, M.H., and Ho, Y.C.

Source: Journal of Geotechnical Engineering

Publication Date: 1994

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Polypropylene fibers, glass fibers, and softwood pulp fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Kaolinite clay	CL	Polypropylene fibers (2.5-20 mm)	Fibers	1-5%	N/A	N/A
Kaolinite clay	CL	Glass fibers (6.4-25.4 mm)	Fibers	1-5%	N/A	N/A
Kaolinite clay	CL	Softwood pulp fibers (0.55-2.5 mm)	Fibers	1-5%	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Kaolinite

Tests Performed: Unconfined Compressive Strength, Compaction Tests

Test Methods: The soil used in this study was artificially prepared kaolin clay with an optimum water content of 25%. Kaolin clay-fiber samples were prepared by mixing the soils at water contents of 15-35% in a motorized rotary mixer. Fibers were mixed in randomly with a special oscillatory and helical action mixer.

Key Findings: Fibers increased the peak compressive strength and the ductility of kaolinite. The increase was more pronounced at lower water contents, reaching strengths of up to 400 kPa (from 200 kPa) with 5% polypropylene fibers. The strength gain significantly decreased at higher water contents. Fibers also significantly increased the splitting tensile strength.

Comments: No attempt was made to discuss the field mixability of the fibers or comparison with other more conventional stabilizers.

Stabilizer Type: Chemical

Paper Title: A Laboratory Study of the Effectiveness of Various Chemicals as Soil Stabilizing Agents

Author: Mainfort, R.C.

Source: US Department of Commerce, Civil Aeronautics Administration

Publication Date: 1945

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Sodium silicate, sodium silicate and sodium aluminate, raw tung oil, synthetic resin, and other various additives

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clayey silt	N/A	Sodium silicate and many other additives	Liquid/ powder	8%	N/A	N/A
Silty loam	N/A	Sodium silicate and many other additives	Liquid/ powder	8%	N/A	N/A
Sand	N/A	Sodium silicate and many other additives	Liquid/ powder	8%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength, Compaction Tests

Test Methods: Laboratory samples were evaluated with soaked and unsoaked unconfined compression tests. Additionally, tests were conducted to determine the resistance of the treated soil to the action of water. Test cylinders were prepared by adding various water contents and additives to the dry soil and thoroughly mixing and compacting the samples. The specimens were then either air-dried or oven-dried to a constant weight at a temperature of 140ºF (cure times appear to have been variable), then unconfined compression tests were conducted.

Key Findings: From the numerous laboratory results in this study, the following additives were identified as showing promise for further study: 1- Sodium silicate-sodium aluminate - sandy soils were best treated by the addition of sodium aluminate after the sodium silicate and soil are allowed drying time. 2- Raw tung oil - Showed good stabilizing properties with fine sandy loams. 3- Synthetic resin - Material formed by interaction of furfuryl alcohol and sulfuric acid gave promising results and was thought to be conducive to field application and construction.

Comments: Numerous other additives were tested in this report. The tests seemed to have been performed rapidly with little emphasis on controls, but more on preliminary results. The percentages of chemical in most cases are not even mentioned but considered to be approximately 8%.

Stabilizer Type: Chemical

Paper Title: Further Evaluation of Promising Chemical Additives for Accelerating Hardening of Soil-Lime-Fly Ash Mixtures

Author: Mateos, Manuel, and Davidson, Donald T.

Source: Highway Research Board Bulletin

Publication Date: 1961

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Lime-flyash soil mixtures with 12 different chemical additives (Sodiums, chlorides, and other acids)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Dune sand	N/A	Lime with flyash	Powder	6% lime 17.5% flyash	12 different chemical reagents	0.03-3.0%
Alluvial clay	N/A	Lime with flyash	Powder	6% lime 17.5% flyash	12 different chemical reagents	0.03-3.0%
Kansan Gumbotil	N/A	Lime with flyash	Powder	6% lime 17.5% flyash	12 different chemical reagents	0.03-3.0%
Friable loess	N/A	Lime with flyash	Powder	6% lime 17.5% flyash	12 different chemical reagents	0.03-3.0%

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength, Compaction Tests

Test Methods: Twelve chemicals were evaluated as additives to Ottawa sand and four natural soils in a soil-lime-flyash mixture. Samples were mixed in a Hobart mixer. Specimens were then compacted to optimum moisture contents of the natural soils and compacted using equivalent standard Proctor in 2-in diameter molds. Samples were cured for 7 and 28 days, and 3 or 4 months at 70ºF in a humid room. Strength testing was preformed with unconfined compressive tests.

Key Findings: The effect of chemical additives on these clayey soils stabilized with lime and flyash was very little and sometimes detrimental. This is based on ultimate strength, not necessarily time dependence. Sodium carbonate, hydroxide and chloride seemed to provide the best results, adding little to early strength gain, but substantially increased the 28-day strength.

Comments:

Stabilizer Type: Chemical

Paper Title: Soil Stabilization by Multivalent Cations

Author: Matsuo, S., and Kamon, M.

Source: 10th International Conference on Soil Mechanics and Foundation Engineering

Publication Date: 1981

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Poly-aluminum chloride (PAC) and iron powders

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Osaka-Nanko (very soft marine) clay	CH	Poly-aluminum chloride	Powder	0.002-0.02 mol/100g clay	Iron powders	0.002-0.02 mol/100g clay

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength, Compaction Tests, Swell Potential by 1-D Consolidometer

Test Methods: Soils were air-dried and powdered with additives. They were then brought to two water contents of 30% (near optimum MC) and 95% (near its liquid limit) for compaction properties under aerated and unaerated conditions. After periods of 1 day, 1 week, 1 month and 3 months, tests were performed to measure changes in engineering properties. Unconfined compression tests and one-dimensional consolidations were performed.

Key Findings: The PAC acted as the aggregating agent of the clay particles due to the cation exchange effect. The iron powders, which are oxidized in the soils, change to the trivalent cation and cement and bind inter-clay particles. Shearing strengths increased to over 1,000 kN/m^2 after one week of curing with the larger amounts of admixtures. The author states that because of the importance of the co-reaction of the PAC and the oxidizing iron powders, that this method is best applicable for shallow soil stabilization.

Comments:

Stabilizer Type: Chemical

Paper Title: A Laboratory Study of the Soil Stabilizing Effectiveness of a Complex Salt of Abietic Acid

Author: Mcalpin, George W., Mainfort, Robert C., and Winterkorn, Hans F.

Source: US Department of Commerce, Civil Aeronautics Administration

Publication Date: 1944

Purpose of Stabilizer: Stabilizer/Waterproofer

Stabilizers Tested: Salt of abeitic acid (Commercially known as Resin Stabilizer 321)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Loam sand	N/A	Resin Stabilizer 321	Powder	0.2, 0.5%	N/A	N/A
Clay	N/A	Resin Stabilizer 321	Powder	0.2, 0.5%	N/A	N/A
Silty clay	N/A	Resin Stabilizer 321	Powder	0.2, 0.5%	N/A	N/A
Sandy clay	N/A	Resin Stabilizer 321	Powder	0.2, 0.5%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: California Bearing Ratio, Unconfined Compressive Strength, Water Adsorption Tests

Test Methods: The chemical additive was added to dry soil and thoroughly dispersed before mixing with water to their optimum moisture contents. Samples were then compacted and oven-dried for 2 days then soaked for 4 days before conducting soaked CBR tests. This procedure was followed because it was found that the chemicals and stabilizing agents required a certain amount of curing or 'drying back' to be effective. For the unconfined tests, samples were compacted, allowed to dry back and soaked for 7 days before testing.

Key Findings: The treatment with Resin 321 greatly increased the CBR for the soils in this investigation. Increased percent resin produced increased CBR values. Expansion when exposed to water was decreased by more than 50% for all the soils but one. There seemed to be no noticeable increase in unconfined compressive strength in any of the samples.

Comments: The quantity necessary for stabilization seems to be very small. Resin 321 appears to mainly be a waterproofing agent and does not add to the natural cohesion of the soil.

Stabilizer Type: Chemical

Paper Title: Stabilization of Lateritic Soils with Phosphoric Acid

Author: Medina, J., and Guida, H.N.

Source: Geotechnical and Geological Engineering

Publication Date: 1995

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Phosphoric acid

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Sandy clay	MH	Phosphoric Acid	Liquid	2, 5%	N/A	N/A
Fine lateritic soil	CL	Phosphoric Acid	Liquid	2, 5%	N/A	N/A
Gravel (laterite) with fines	GC	Phosphoric Acid	Liquid	2, 5%	N/A	N/A
A medium grained basalt	ML	Portland Cement	Powder	1, 3, 5%	N/A	N/A
A medium grained basalt	ML	Phosphoric Acid	Liquid	1, 2, 3, 4, 5%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Kaolinite

Tests Performed: Unconfined Compressive Strength, Compaction Tests, Indirect Tensile Tests

Test Methods: For the fine grained soil types, the samples were molded in accordance with procedures specified by the American Portland Cement Association into 50mm diameter by 50mm high cylinders. Approximately 500 specimens were tested. Most of these were performed on the low plasticity silt. The variables of the test specimens were the percentage of acid used, the water content across a range of 10-33%, compaction energy, and curing time to 28 days. Strength tests and indirect Brazilian tensile tests were performed immediately after 1 day of soaking the specimens.

Key Findings: Test results have confirmed that there is potential for stabilizing tropical soils that have free iron and aluminum oxides with phosphoric acid. With 5% phosphoric acid, values of compressive strength as high as 4.0 MPa were obtained after 28-day cure time. After 7-day cure time, the unconfined compressive strengths of the ML ranged from 0.5 MPa with 1% acid to 2.5 MPa with 5% phosphoric acid over a range of water contents.

Comments: Additionally, X-ray diffraction and chemical analyses were performed to determine the mineralogical composition. This paper includes a literature review on phosphoric acid as well.

Stabilizer Type: Chemical

Paper Title: Phosphoric Acid Stabilization of Fine-Grained Soils: Improvements with Secondary Additives

Author: Michaels, Allan S., and Tausch, Frederick W. Jr.

Source: Highway Research Board Bulletin

Publication Date: 1960

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Phosphoric acid, phosphoric acid and chlorides, phosphoric acid and phosphates

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Vicksburg Buckshot clay	N/A	Phosphate Rock	Other	2%	Various admixtures	N/A
Massachusetts clayey silt	N/A	Phosphoric acid	Liquid	2, 5%	Various reagents	N/A
Vicksburg Buckshot clay	N/A	Phosphoric acid	Liquid	2%	Various reagents	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Illite and Montmorillonite

Tests Performed: Unconfined Compressive Strength

Test Methods: Soils were mixed and compacted in accordance with samples from a previous study into Harvard miniature molds. Samples were then cured for varying periods of time, soaked for 24 hours, then tested to failure in unconfined compression.

Key Findings: At 5% H3PO4, the accelerating effect of sodium fluosilicate is much more apparent. The fact that fluosilicate results in only 18% increase in 1-day strength with phosphate rock is undoubtedly due to the already high fluorine content of this material. Marginal soils can be successfully stabilized with phosphate rock-sulfuric acid mixtures, and orthophosphoric acid-P2O5 mixtures. With the use of a waterproofer reagent, phosphoric acid may be useful in stabilizing heavy clay soils.

Comments:

Stabilizer Type: Chemical

Paper Title: Polymer Grid Reinforced Pavement on Soft Clay Grounds

Author: Miura, N., Sakai, A., Taesiri, Y., Yamanouchi, T., and Yasuhara, K.

Source: Geotextiles and Geomembranes

Publication Date: 1990

Purpose of Stabilizer: Stabilizer - Roadway Surfaces

Stabilizers Tested: Cement

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Highly plastic clay	CH	Cement	Powder	5-15%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Swell Potential by 1-D Consolidometer

Test Methods:

Key Findings:

Comments: This paper deals with model and field tests for investigating the mechanism of reinforcement by a polymer grid in suppressing non-uniform settlement of pavements constructed on soft clay ground. A series of laboratory tests on reinforced and unreinforced model pavements in a soil tank indicates that the polymer grid is useful for suppressing non-uniform settlement of pavement under cyclic loading. Deformation analysis by FEM is carried out to make clear the reinforcement effect of a polymer grid in a model pavement. To investigate the performance of a polymer grid in practice, a test road of 300 m length with six sections of different kinds of pavement is constructed on soft clay ground. The function of a polymer grid is discussed by comparing the pavements made by conventional and reinforced methods.

Stabilizer Type: Chemical

Paper Title: Engineering Behavior of Cement Stabilized Clay at High Water Content

Author: Miura, N., Horpibulsuk, S., and Nagaraj, T.

Source: Soils and Foundations, Japanese Geotechnical Society

Publication Date: 2001

Purpose of Stabilizer: Stabilizer - Jet Grouting of Wet Clay Soils

Stabilizers Tested: Cement

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Highly plastic marine clays	CH	Cement	Powder	In ratios of the water content	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Triaxial Tests

Test Methods: This paper attempts to identify the critical factors that govern the engineering behavior of cement-stabilized clay. It proposes a new factor, clay-water/cement ratio, as the standard parameter for design investigation. Laboratory observations were made with deep soil mixing of soft ground in mind. Highly plastic clay samples were sieved and adjusted to high water contents above in situ to simulate water contents at jet grouting conditions. Specimens were mixed and cured. Oedometer tests were then carried

Key Findings: Cement-water/cement ratio is a prime parameter for analysis of strength and deformation behavior of induced cemented clay at high water contents. For the chosen soil, cementation bond strength increases as the clay-water/cement ratio decreases.

Comments: For the chosen soft clay, cementation bond strength increases as the clay-water/cement ratio decreases.

Stabilizer Type: Chemical

Paper Title: Improvement of Soil-Cement with Chemical Additives

Author: Moh Z.C, Lambe T.W, and Michaels A.S.

Source: Highway Research Board

Publication Date: 1962

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Cement, cement and various sodium (salts), cement and gypsum

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Sand	N/A	Cement	Powder	5-10%	Various salts	0.5-1.0%
Sand	N/A	Cement	Powder	5-10%	N/A	N/A
Iraq silty clay	N/A	Cement	Powder	5-10%	Various salts	0.5-1.0%
Iraq silty clay	N/A	Cement	Powder	5-10%	N/A	N/A
New Hamp. Silt	N/A	Cement	Powder	5-10%	Various salts	0.5-1.0%
Clays (Vick. Buckshot, TX, Iraq)	N/A	Cement	Powder	5-10%	N/A	N/A
New Hamp. Silt	N/A	Cement	Powder	5-10%	N/A	N/A
Clays (Vick. Buckshot, TX, Iraq)	N/A	Cement	Powder	5-10%	Various salts	0.5-1.0%

Stabilizer Type: Chemical

Natural or Manufactured Soil? Natural

Clay Mineralogy: Illite, Montmorillonite and Chlorite

Tests Performed: Unconfined Compressive Strength

Test Methods: For most tests, Portland cement Type I at 5% content was used. All soils were first air-dried, pulverized, and mixed with water to approximately its optimum water content and a secondary additive if used. Samples were then mixed with the cement and compacted in a Harvard miniature mold by static compaction. Specimens were then cured for varying periods of time, immersed for 24 hours, and tested for unconfined compressive strength. Additionally, samples were also tested as part of a sulfate attack study by saturating them in a saturated calcium sulfate solution.

Key Findings: Pre-treatment of heavy clays with small quantities of polyvalent metal salts and salts of organic cations improves their response to cement-additive stabilization by reducing the expansion of the montmorillonitic soils in water immersion. Sand-cement deteriorates in sulfate solution. Sodium additives considerably help resistance to the sulfates in all soil types. Sodium hydroxide in clay-cement can be materially improved by pretreating with secondary additives.

Comments:

Stabilizer Type: Chemical

Paper Title: Soil Stabilization with Cement and Sodium Additives

Author: Moh, Za-Chieh

Source: ASCE, Journal of Soil Mechanics Division

Publication Date: 1962

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Cement and sodium

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: No Testing Conducted

Test Methods:

Key Findings: The addition of sodium compounds cause an increase in pH, or increase in availability of hydroxyl ion concentration, a marked reduction in the calcium ion concentration, and a marked increase in the sodium-calcium ratio in solution. The results of these effects are an increased rate and solubilization of soil silica, retardation of precipitation of calcium silicate gel, and formation of highly hydrated silicate gels containing a substantial quantity of sodium.

Comments: This paper is a general discussion on the topic of sodium compound addition to soil-cement systems.

Stabilizer Type: Chemical

Paper Title: Effect of Sodium Chloride Treatment on the Engineering Properties of Compacted Earth Materials

Author: Moore J.C

Source: Degree Dissertation - U. of Illinois

Publication Date: 1973

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Sodium chloride

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Granular sandy soil	N/A	Sodium chloride	Powder	0.1-3.0%	N/A	N/A
Clayey soils	N/A	Sodium chloride	Powder	0.1-3.0%	N/A	N/A
Silty soil	N/A	Sodium chloride	Powder	0.1-3.0%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: X-Ray Diffraction, Unconfined Compressive Strength

Test Methods: This paper is part of a PhD dissertation on the effects of sodium chloride treatments on compacted soils. It mainly looked at soils compacted at their optimum water contents and the effects of adding sodium chloride. The optimum treatment was found to be 3% in most soils tested but varied in individual materials. Soaked unconfined compression tests were conducted after various curing times. Some specimens were allowed to dry to test its effect on the strength.

Key Findings: Sodium chloride treatment resulted in an increase in maximum dry density, and a decrease in optimum water content. Treated clays tended to shrink, except kaolinite which swells. Soils also tend to release silica and alumina with sodium chloride treatment. This suggests that it would be a good additive with a pozzolanic cementing agent. However, generally speaking, the sodium chloride treatments by themselves resulted in little benefit unless the soil is allowed to dry after compaction. Materials with abundant fines of clay or other weathered products did not respond well to sodium

Comments:

Stabilizer Type: Chemical

Paper Title: Temperature Effect on the Properties of Clay

Author: Moritz L. and Gabrielsson A

Source: Swedish Geotechnical Institute

Publication Date: 2000

Purpose of Stabilizer: Stabilizer - Property Effects of Temperature

Stabilizers Tested: Heat

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Soft homogenous clay	N/A	Heat treatment	Heat	Heated to 70-90ºC	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Torsional Vane Shear Test

Test Methods: This paper is based on a long term field test where a homogenous clay was exposed to varying temperatures for a period of 7.5 years while the clay properties were studied. While one clay type was cycled through temperatures of 35-70ºC, another was held at 70ºC for three years and then increased to 90ºC for 4.5 years.

Key Findings: From vane shear tests, it could be seen that the long term effects of the heat resulted in a stiffer soil with a shear strength gain of approximately 40% over the term of the study.

Comments: High temperatures in soft clay seemed to result in stiffer soil with time. However, there was an initial reduction in strength by 30% followed by a slow, long-term increase.

Stabilizer Type: Reinforcement

Paper Title: Strength and Deformation Characteristics of Fiber Reinforced Soils

Author: Nataraj, M.S., Addula, H.R., and McManis, K.L.

Source: Proceedings of the 3rd International Symposium

Publication Date: 2003

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Fibrillated fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Sand	N/A	Fibrillated fiber	Fiber	0.1,0.2,0.3,0.	N/A	N/A
Clay	N/A	Fibrillated fiber	Fiber	0.1, 0.2, 0.3, 0. 4%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Compaction Tests, Unconfined Compressive Strength, California Bearing Ratio

Test Methods: The effects of moisture contents and fiber content on the unconfined compression strength of sand and clay soils were studied. Soils were thoroughly mixed with the fibers and compacted in a Harvard miniature mold. Direct shear, unconfined compression, and CBR tests were conducted.

Key Findings: Tests show that fibers significantly increased the peak compressive strength of sand and clay. The increase in strength is a function of fiber content and moisture content. CBR values for sand and clay were also significantly improved with fiber reinforcement (from 8.4 to 12.6 in clay with 0.3% fiber). The study suggests that the optimum fiber content on a dry weight basis for both sand and clay is about 0.3%.

Comments:

Stabilizer Type: Chemical

Paper Title: Stability Properties of Uncured Lime-Treated Fine-Grained Soils

Author: Neubauer C.H. and Thompson M.R.

Source: Highway Research Record

Publication Date: 1972

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Hydrated lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Ava B	N/A	Hydrated lime	Powder	2,4,6%	N/A	N/A
Hurst B	N/A	Hydrated lime	Powder	2,4,6%	N/A	N/A
Vicksburg buckshot clay	N/A	Hydrated lime	Powder	2,4,6%	N/A	N/A
Roxana loess	N/A	Hydrated lime	Powder	2,4,6%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Montmorillonite, illite, and mixed layers both

Tests Performed: California Bearing Ratio, X-Ray Diffraction, Compaction Tests

Test Methods: The early strength and deformation properties of uncured lime-soil mixtures and untreated soils were investigated. Linear regression equations were developed based on results of cone penetrometer tests for shear strength, CBR, and modulus of deformation. The purpose of this study was to examine possible expedition of construction. A commercial high-calcium hydrated lime was used. Samples were evaluated at moisture contents above optimum with 0-6% lime treatment. Specimens were allowed to mellow for 1 hour prior to compaction into 4 in. molds of 2 in. diameter. Triaxial and compression tests were performed immediately after compaction.

Key Findings: The early strength and deformation properties of uncured lime-soil mixtures compacted wet of optimum were substantially improved relative to the untreated natural soils. Montmorillonitic clays increased in CBR from approximately 2 to 12 with 6% lime, while illitic clays increased from about 3-4 CBR to approximately 20. The loess soil showed little strength gain at any percentage of lime in the short-term testing. Overall though, the effects of the immediate lime-soil reactions greatly improved adverse in situ soil conditions for purposes of expedient construction.

Comments: Paper looks at short-term effects of lime treated soils with CBR results on 1 hour mellowed samples. It shows significant strength gain in the short-term.

Stabilizer Type: Chemical

Paper Title: Soil Stabilization with Large Organic Cations and Polyacids

Author: Nicholls R.L and Davidson D.T.

Source: Proceedings of the Iowa Academy of Science

Publication Date: 1957

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Polyacids and large organic cations

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Silty Loam	N/A	Arquad 2HT (Ammonium chloride)	Liquid	0.2-0.8%	N/A	N/A
Silty Loam	N/A	Arquad 2HT (Ammonium	Liquid	0.2-0.8%	Polyacids	0.2-0.6%

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength, Compaction Tests

Test Methods: The objectives of the experimental work were to evaluate the use of polyacids with large organic cations for soil stabilization. Additionally, the possibility of adding polyacids to the reaction to permit ionic bonding was tested. Soil specimens were prepared by adding Arquad 2HT in an aqueous solution to the soil to bring the soil to optimum moisture content at standard Proctor density. The polyacid was then added, mixed, and compacted. Specimens were air-cured for 7 days, soaked for 24 hours, and tested for unconfined compression.

Key Findings: The immersed strength and air-dry strength of a silty loam treated with a large organic cationic material was increased by the addition of polyacrylic acid; its effectiveness depended on its molecular weight. The hydroxide form of the large organic cation used with polyacrylic acid (Arquad 2HT) gives greater strength of treated soil than the chloride form.

Comments:

Stabilizer Type: Chemical

Paper Title: Stabilization of Clay Using Woodash

Author: Okagbue, C.

Source: Journal of Materials in Civil Engineering

Publication Date: 2007

Purpose of Stabilizer: stabilizer- make use of waste product

Stabilizers Tested: woodash

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay	N/A	woodash	powder	5, 10, 15, 20%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: CBR, Compressive strength, Atterberg limits, Compaction

Test Methods: Samples were mixed in a sample tray with a trowel and compacted in CBR molds. Compactive effort, moisture content, and cure time (7, 14, 21, and 28 days) were varied for samples that underwent CBR testing. All samples were cured in a water bath. CBR values were evaluated with time to observe strength development. Unconfined compression tests were completed on samples cured for 28 days.

Key Findings: The introduction of woodash reduced the plasticity, reduced maximum dry density, and increased the clay's strength. The highest strength was recorded with a 14 day cure time and 10% woodash, but was not sustained. After 14 more days, the strength increase was lost. It was determined that woodash was not a suitable soil stabilizer due to the strength loss.

Comments:

Stabilizer Type: Chemical

Paper Title: Factors Affecting Unconfined Compressive Strength of Salt-Lime-Treated Clay

Author: Ozier, J.M. and Moore R.K

Source: Transportation Research Record

Publication Date: 1977

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Lime, lime and salt, lime and heat

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Permian red clay (med plastic)	CL	Lime	Powder	2-6%	N/A	N/A
Houston clay (smectite)	CH	Lime	Powder	2-6%	Heat	4.4-43.3 ºC
Permian red clay (med plastic)	CL	Lime	Powder	2-6%	Salt	1-3%
Permian red clay (med plastic)	CL	Lime	Powder	2-6%	Heat	4.4-43.3 ºC
Houston clay(smectite)	CH	Lime	Powder	2-6%	N/A	N/A
Houston clay (smectite)	CH	Lime	Powder	2-6%	Salt	1-3%

Natural or Manufactured Soil? Natural

Clay Mineralogy: Smectite and kaolinite

Tests Performed: Unconfined Compressive Strength

Test Methods: Statistical procedures were used to analyze the effects of salt content, lime content, curing time, curing temperature, molding-water content, and soil type on the unconfined compressive strength of compacted specimens. Samples were mixed by hand until a uniform appearance was obtained at the desired water content ranging from 12.5 to 17.5 moisture content. Samples were then compacted with a Harvard miniature compaction mold. The specimens were then cured at the desired temperature for 10 to 30 days and unconfined compression tests were performed.

Key Findings: Unconfined compressive strength was increased by the following conditions: increased lime content, decreased salt content, increased curing temp, increased curing time, increased molding-water content. Lower water contents did not allow completion of the lime-salt reactions; soils were not tested at higher water contents. The low plasticity PRC clay had higher strengths overall than the Houston smectite clay.

Comments:

Stabilizer Type: Chemical

Paper Title: Chemical Stabilization of Kaolinite by Electrochemical Injection

Author: Ozkan, etal.

Source: Proceedings of the 1998 Geo-Congress

Publication Date: 1998

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Electrochemical injection of aluminum and phosphate ions

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Kaolinite clay	N/A	Aluminum and phosphate acids	Liquid solution	Continuous	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Kaolinite

Tests Performed: Torsional Vane Shear Test, Atterberg Limits

Test Methods: Cementation of kaolinite by the electrochemical injection of aluminum and phosphate ions was investigated. Electrodes were placed across a kaolinite bed of 35 cm length and a current was applied. At completion of the tests (exposure timeframe varied), changes in the kaolinite properties such as undrained shear strength (with vane shear tests), water content, and Atterberg limits were analyzed.

Key Findings: An average strength increase of 500-600% was observed, but with non-homogeneous strength distributions. Water content changes did not appear to significantly contribute to strength changes. Tests showed an average increase of 30% in Atterberg limits.

Comments:

Stabilizer Type: Chemical

Paper Title: Evaluation of Strength Properties of Several Soils Treated With Admixtures

Author: Paquette, R.J. and McGee, J.D.

Source: Highway Research Record Bulletin

Publication Date: 1960

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Portland cement, lime and flyash, phosphoric acid, asphalt cutback

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Five soils of varying gradation curves	N/A	Lime and flyash	Powder	25%	N/A	N/A
Five soils of varying gradation curves	N/A	Phosphoric acid	Liquid	1-2	N/A	N/A
Five soils of varying gradation curves	N/A	Portland cement	Powder	2-12%	N/A	N/A
Five soils of varying gradation curves	N/A	Asphalt cutback	Powder	3, 5, 7%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Compaction Tests, Unconfined Compressive Strength

Test Methods: Soil and admixtures were combined and mixed with a mechanical mixer for a 10-minute period. The soils were then brought to their optimum moisture contents and compacted to a standard Proctor maximum density. Specimens were placed in polyethylene freezer bags and cured for 7 and 28 days at room temperature.

Key Findings: Improvement of the strength varied with the soil and particular admixture. Portland cement was by far the most beneficial stabilizing agent producing a large strength gain in all soils. Phosphoric acid caused a nominal increase in all soils, but showed greatest benefit in the more clayey soil; the higher percentage, the higher the strength gain. Asphalt cutback gave mixed results or sometimes no results.

Comments:

Stabilizer Type: Chemical

Paper Title: Study of the Effectiveness of Cement Kiln Dusts (CKD) in Stabilizing Na-Montmorillonite Clay

Author: Peethamparan, S. and Olek, J.

Source: Journal of Materials in Civil Engineering

Publication Date: 2008

Purpose of Stabilizer: Stabilizer-increase strength

Stabilizers Tested: Cement Kiln Dust (CKD)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay	CH	4 types CKD	powder	8, 15, 25%	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Na-Montmorillonite

Tests Performed: Compressive strength, Atterberg limits, Compaction

Test Methods: The Atterberg limits of the treated clay with 15 and 25% CKD was determined using ASTM 4318. A Harvard miniature compaction apparatus was used to find the maximum dry density and optimum moisture content. Unconfined compression tests were performed on samples prepared at the maximum dry density and optimum moisture content with a strain rate of 1% per minute. UCS samples were compacted following the USBR-5510 standard. The effectiveness of the CKD's was determined by the improvement of Atterberg limits, pH, strength, and stiffness.

Key Findings: The addition of CKD's decreased both the LL and PL, the occurrence of pozzolanic reactions was reflected by changes in pH, and all CKD's were found to increase the soil's compressive strength.

Comments:

Stabilizer Type: Chemical

Paper Title: Stabilization of Expansive Clay Soils

Author: Petry, T.M. and Armstrong, J.C.

Source: Transportation Research Record

Publication Date: 1989

Purpose of Stabilizer: Stabilizer - Control Swell Potential

Stabilizers Tested: Lime, cement, flyash, calcium chloride

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: No Testing Conducted

Test Methods:

Key Findings:

Comments: This paper is a general review of the phenomena of stabilization by both mechanical and chemical methods. It gives a good general understanding of expansive clay stabilization by discussing the mechanisms of the stabilizers. Stabilizers are described that improve selected properties of Expansive soils. Examples of remedial treatments are discussed. Mechanical means mainly focus on compaction effort and control of water contents of the expansive soil. The chemical stabilization section includes discussion on the cation exchange process, effect of organics, and mixability of the admixtures. It briefly discusses a number of chemical agents used including lime, cement, flyash, calcium chloride, and others.

Stabilizer Type: Chemical

Paper Title: Laboratory and Field Experiences Using Soil Sta Chemical Soil Stabilizer

Author: Petry, T.M. and Brown R.W.

Source: Texas Civil Engineer

Publication Date: 1987

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Soil Sta (mixture of surfactant and a polyquarternaryamine)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
London clay	CH	Soil Sta	Liquid	Diluted	N/A	N/A
Weather soil mixed 3:1 with bentonite	CH	Soil Sta	Liquid	Diluted to 1:1; applied at 1/4 gallon per SF	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Bentonite is the only mineralogy mentioned

Tests Performed: Swell Potential by 1-D Consolidometer. Atterberg Limits, Compaction Tests

Test Methods: Samples were compacted into a CBR mold to 4-5% below their optimum water content at standard Proctor efforts to provide high swell potentials. Soil Sta was either added by injection or by surface application. Specimens were then soaked in either water or a 1:1 dilution of the agent for 96 hours. Swell tests were then run on the samples.

Key Findings: Improvements of Atterberg limits (20% reduction in plastic index) and linear shrinkage with Soil Sta was limited. It improved an active clay's reaction to soaking but not drying. The swell abatement was significant. It performed better in the field than lab. There did not seem to be any mention of strengths, as the study was geared more towards swelling and drying.

Comments:

Stabilizer Type: Chemical

Paper Title: Evaluation of Chemical Modifiers and Stabilizers for Chemically Active Soils - Clays

Author: Petry, T.M. and Das, B.

Source: Transportation Research Record

Publication Date: 2001

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Cation exchangeable salts

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Smectite, illite, montmorillonite

Tests Performed: No Testing Conducted

Test Methods:

Key Findings:

Comments: This paper is a discussion of expansive clay behavior, clay-water interactions, stabilization, and laboratory and field testing. It discusses the philosophy of evaluating chemical agents to stabilize clays and the minimum acceptable testing used to evaluate them. The authors note that from their experience that some chemical agents improve overall clay behavior, while some only provide improvements for one type of clay. Field testing for longevity of the chemical effects and their effectiveness in natural conditions is considered essential. No experimental data is provided and most of the discussion about chemical agents is very general.

Stabilizer Type: Chemical

Paper Title: Performance-Based Testing of Chemical Stabilizers

Author: Petry, TM.

Source: Transportation Research Record

Publication Date: 1997

Purpose of Stabilizer: Stabilizer - Control Swell Potential

Stabilizers Tested: Hydrated lime, cement, sodium chloride

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay soils	N/A	Hydrated lime	Powder	1-9%	N/A	N/A
Clay soils	N/A	Cement	Powder	9-15%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Swell Potential by 1-D Consolidometer, Unconfined Compressive Strength

Test Methods: Clay soils were prepared and tested in a number of ways to simulate field conditions, from leaching in the additives to thoroughly mixing them into the soil and compacting. Swell tests and compression tests were performed.

Key Findings: Performance expectations of chemical stabilizers derived from laboratory testing may not be realistic because of the lack of proper simulation to field conditions. Standard tests rely too heavily on small representations on the soil material to be stabilized.

Comments: This paper was on testing procedures of chemical stabilizers in general, focusing on resembling field conditions with laboratory testing. Its focus was more on controlling swell potential than analyzing strength gain from admixtures. It basically stated that reported strengths may not be accurate because lab conditions may not simulate field conditions. It recommends large specimens for testing due to the natural variabilities of soil-chemical properties. When feasible, the author recommends field tests to determine the performance of chemical stabilizers.

Stabilizer Type: Chemical

Paper Title: Development of Stabilizer Selection Tables for Low-Volume Roads

Author: Phillips M., Puppala A.J, Melton K.

Source: Transportation Research Record

Publication Date: 2003

Purpose of Stabilizer: Stabilizer - Soft Sulfate Soils

Stabilizers Tested: Lime, Portland cement, flyash, lime and fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Arlington TX soils	CH-	Cement	Powder	N/A	N/A	N/A
Arlington TX soils	CH-	Lime	Powder	N/A	N/A	N/A
Arlington TX soils	CH-	Flyash	Powder	N/A	N/A	N/A
Arlington TX soils	CL-ML	Cement	Powder	N/A	N/A	N/A
Arlington TX soils	CL-ML	Lime	Powder	N/A	N/A	N/A
Arlington TX soils	CL-ML	Flyash	Powder	N/A	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: No Testing Conducted

Test Methods: The purpose of this research was to develop matrix tables for soil stabilization of clay and silt soils in the Arlington, TX area. The matrix tables divide the soils into three sulfate group levels and three plasticity index levels. It provides recommendations for stabilization for soils within each of these classifications for use of lime, cement type I, cement type V (sulfate resistant), lime with fibers, flyash (not recommended for any case), blast furnace slag, and geosynthetics.

Key Findings: Soils were grouped into three sulfate level categories (paper was mainly looking at sulfate heave problems. If natural soils contain sulfates, lime or cement stabilization methods can lead to the formation of an expansive mineral called ettringite (sulfate-induced heave)). This paper developed a table for the stabilizers as suitable for a given combination of PI and sulfate content. Sulfate-resistant cement, lime, and lime and fibers provided effective stabilization of soft sulfate-rich clayey soils. Geosynthetics also provided effective stabilization but need further testing.

Comments: This study was limited to more traditional stabilizers because there was limited to no literature on other chemical stabilizers with Arlington soils.

Stabilizer Type: Chemical

Paper Title: Soil Stabilization Using Basic Oxygen Steel Slag Fines

Author: Poh, H.Y., Ghataora, G.S. and Ghazireh, N.

Source: Journal of Materials in Civil Engineering

Publication Date: 2006

Purpose of Stabilizer: stabilizer- make use of waste product

Stabilizers Tested: Basic oxygen steel slag fines

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
English China clay (EEC)	N/A	BOS slag	powder	10, 15, 20%	N/A	N/A
EEC	N/A	BOS slag	powder	10%	Quicklime	1.5, 2%
EEC	N/A	BOS slag	powder	10%	Na-metasilicate, pentahydrate	3%
EEC	N/A	Quicklime	powder	1.5, 5%	N/A	N/A
EEC	N/A	cement	powder	10%	N/A	N/A
EEC	N/A	ground granulated blastfurnace slag	powder	10%	quicklime	1.5%
Mercia Mudstone (MM)	N/A	BOS slag	powder	10, 15, 20%	N/A	N/A
MM	N/A	BOS slag	powder	10%	Quicklime	1.5, 2%
MM	N/A	BOS slag	powder	10%	Na-metasilicate, pentahydrate	3%
MM	N/A	Quicklime	powder	1.5, 5%	N/A	N/A
MM	N/A	cement	powder	10%	N/A	N/A
MM	N/A	ground granulated blastfurnace slag	powder	10%	quicklime	1.5%

Natural or Manufactured Soil? EEC-manufactured, MM-natural

Clay Mineralogy: EEC- kaolinite; MM- illite, montmorillonite, halloysite

Tests Performed: Unconfined Compressive Strength, One Dimensional Linear Expansion

Test Methods: Three samples of each mix design were made and cured for periods of 1, 7, 28, and 112 days. Unconfined compression tests were performed on all cured samples. Separate samples were created for the volume stability tests and allowed to cure for 21 days. For the volume stability test, samples were soaked in deionized water and allowed to soak for 7 days. During the 7 day soak in deionized water, samples were restricted laterally while vertical displacements were measured.

Key Findings: BOS slag fines increased strength and decreased swell potential of the two soils tested. However, high quantities of slag (15-20%) and long curing periods were needed to show significant improvement of the soils. The BOS slag was more effective when mixed with the coarser Mercia Mudstone than the finer English China clay.

Comments:

Stabilizer Type: Reinforcement

Paper Title: Effect of Random Inclusion of Sisal Fibre on Strength Behaviour of Soil

Author: Prabakar, J. and Sridhar, R.S.

Source: Construction and Building Materials

Publication Date: 2002

Purpose of Stabilizer: Stabilizer - Bearing Capacity

Stabilizers Tested: Sisal fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Low Plasticity Clay	CL	Sisal fibers (10-25 mm lengths)	Fiber	0.25-1.0%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Compaction Tests, Triaxial Tests, California Bearing Ratio

Test Methods: Fibers were mixed in the soil up to 1% inclusion. Beyond 1%, the mixing was felt to be very difficult as the fibers formed clumps. Water was added to the soils' optimum water content and the samples were mixed again. A light compaction method was adopted for testing purposes. Undrained triaxial compression tests were performed and CBR values were also

Key Findings: Soils reinforced with sisal fibre inclusion reduced the dry density of the soil due to the low specific gravity and unit weight of the sisal fibre. An increase in shear strength was obtained for fibre with length up to 20 mm. Beyond 0.75% fibre content, the shear strength reduces with increased fibre content. Friction angles increased from approximately 6 to 10 degrees. The cohesion increased to as high as 62 kPa from 18 kPa untreated.

Comments:

Stabilizer Type: Reinforcement

Paper Title: Fiber and Fly Ash Stabilization Methods to Treat Soft Expansive Soils

Author: Puppala A., Hoyos, L., Viyanant, C., and Musenda, C.

Source: Soft Ground Technology

Publication Date: 2001

Purpose of Stabilizer: Stabilizer - Soft Sulfate Soils

Stabilizers Tested: Flyash, polypropylene fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Arlington clay (silty clay)	N/A	Flyash	Powder	2,5,10,15,20%	N/A	N/A
Irving clay	CH	Polypropylene Fibers	Fibers	0.3,0.6,0.9%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A, sulfate content was determined in ppm

Tests Performed: Unconfined Compressive Strength, Compaction Tests, Swell Potential by 1-D Consolidometer

Test Methods: Soil specimens were prepared at the optimum moisture content (24-28%) and maximum dry unit weight conditions (mixing method is not provided). Samples were compacted at 95% standard Proctor. Flyash samples were allowed to cure for 7 days while no cure period was required with the fibers. Samples were then tested for unconfined compressive strength and swell potential.

Key Findings: Both methods increased strength and decreased shrinkage strains of raw expansive soils. Flyash also reduced plasticity and free swell characteristics. Strength gains after 7 days at 5% flyash were approx. 100% increase, increasing to 205% at 20% flyash. Fibers seem to have produced approx. a 30% strength gain in 7 days with 0.3% optimum fiber content.

Comments:

Stabilizer Type: Chemical

Paper Title: Ranking of Four Chemical and Mechanical Stabilization Methods to Treat Low-Volume Road Subgrades in Texas

Author: Puppala A., Wattanasanticharoen, E., and Hoyos, L.

Source: Transportation Research Record

Publication Date: 2003

Purpose of Stabilizer: Stabilizer - Soft Sulfate Soils

Stabilizers Tested: Flyash, Portand cement (Type V), blast furnace slag, lime and fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
4 Arlington TX clays (varying sulfate content)	CH	Lime	Powder	8%	Fiber	0.15,0.30
4 Arlington TX clays (varying sulfate	CH	Flyash	Powder	10,20%	N/A	N/A
4 Arlington TX clays (varying sulfate	CH	Blast furnace slag	Powder	10,20%	N/A	N/A
4 Arlington TX clays (varying sulfate	CH	Cement Type V	Powder	5,10%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A, sulfate content was determined in ppm

Tests Performed: Unconfined Compressive Strength, Atterberg Limits

Test Methods: Samples were thoroughly mixed with the applied admixture doses. All treated soils were then compacted to standard Proctor and cured at 100% humidity for periods of 3, 7, and 14 days. Unconfined compression and swell tests were then performed on the cured samples.

Key Findings: All stabilizers improved the soil properties to include strength, PI, and shrinkage potential. Flyash was the least effective stabilizer and gave only low to moderate strength improvements compared to the other stabilizers. Sulfate resistant cement provided the most effective treatment in soils by enhancing the unconfined compression strength and reduced swell and shrinkage. Lime/fiber method provided the next most effective treatment of present control soils. (similar strength gains to cement at same contents).

Comments:

Stabilizer Type: Chemical

Paper Title: Stabilization of Fine-Grained Soils with Cutback Asphalt and Secondary Additives

Author: Puzinauskas V.P. and Kallas B.F.

Source: Highway Research Board

Publication Date: 1962

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Cutback asphalt, cutback asphalt and various additives

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Loess	N/A	Cutback asphalt	Liquid	2.5-10.0%	N/A	N/A
Sandy clay	N/A	Cutback asphalt	Liquid	2.5-10.0%	Lime, cement, phosphoric acid, Na & Ca chloride	0.3-4.0%
Sandy clay	N/A	Cutback asphalt	Liquid	2.5-10.0%	N/A	N/A
Clayey silt	N/A	Cutback asphalt	Liquid	2.5-10.0%	Lime, cement, phosphoric acid, Na & Ca chloride	0.3-4.0%
Clayey silt	N/A	Cutback asphalt	Liquid	2.5-10.0%	N/A	N/A
Loess	N/A	Cutback asphalt	Liquid	2.5-10.0%	Lime, cement, phosphoric acid, Na & Ca chloride	0.3-4.0%

Natural or Manufactured Soil? Natural

Clay Mineralogy: Clayey silt - kaolinitic, sandy clay - illitic, and loess - montmorillonitic clay minerals

Tests Performed: Unconfined Compressive Strength, Compaction Tests

Test Methods: Asphalt cutback with a number of secondary additives was evaluated as a stabilizer on three soils. Specimens were thoroughly mixed with the secondary additives then mixed with the liquid asphalt. Four different compaction efforts were evaluated. After compaction, specimens were removed from the compaction molds and exposed to different curing conditions, with periods ranging from 1 to 4 days. Specimens were then immersed for 4 days to determine the effects of water on the properties of the compacted mixtures.

Key Findings: Asphalt alone at 5% resulted in diminished strength in all but the loess which remained unchanged. It did not appear promising compared to lime. With secondary additives, the samples were much stronger and proved a better waterproofer than asphalt alone. Asphalt-soil-additive systems seemed less sensitive to water contents at compaction producing a flatter compaction curve over a wider water content range.

Comments: Calcium carbide was used as a secondary additive, but no mention of its effects are identified except in a plot of its Marshall stability.

Stabilizer Type: Reinforcement

Paper Title: Probabilistic Analysis of Randomly Distributed Fiber-Reinforced Soil

Author: Ranjan, G., Vasan, R.M., and Charan, H.D.

Source: Journal of Geotechnical Engineering

Publication Date: 1996

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Synthetic and Natural

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Silty Sand	N/A	Bhabar	Fiber	1, 2, 3, & 4%	N/A	N/A
Medium Sand	N/A	Plastic	Fiber	1, 2, 3, & 4%	N/A	N/A
Fine Sand	N/A	Bhabar	Fiber	1, 2, 3, & 4%	N/A	N/A
Sandy Silt	N/A	Plastic	Fiber	1, 2, 3, & 4%	N/A	N/A
Sandy Silt	N/A	Coir	Fiber	1, 2, 3, & 4%	N/A	N/A
Fine Sand	N/A	Coir	Fiber	1, 2, 3, & 4%	N/A	N/A
Sandy Silt	N/A	Bhabar	Fiber	1, 2, 3, & 4%	N/A	N/A
Medium Sand	N/A	Coir	Fiber	1, 2, 3, & 4%	N/A	N/A
Medium Sand	N/A	Bhabar	Fiber	1, 2, 3, & 4%	N/A	N/A
Silty Sand	N/A	Coir	Fiber	1, 2, 3, & 4%	N/A	N/A
Fine Sand	N/A	Plastic	Fiber	1, 2, 3, & 4%	N/A	N/A
Sand	N/A	Plastic	Fiber	1, 2, 3, & 4%	N/A	N/A
Sand	N/A	Coir	Fiber	1, 2, 3, & 4%	N/A	N/A
Sand	N/A	Bhabar	Fiber	1, 2, 3, & 4%	N/A	N/A
Silty Sand	N/A	Plastic	Fiber	1, 2, 3, & 4%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Cohesionless

Tests Performed: Triaxial Tests

Test Methods: Fiber-reinforced soil samples were prepared at maximum dry density, as well as at 90% and 105% of maximum dry density, but all at optimum moisture content.

Consolidated undrained triaxial tests were conducted on partially saturated samples at confining stresses ranging from 50-400 kPa.

The results of the lab testing were then compared to the probabilistic analysis results.

Key Findings: ". . . randomly distributed discrete fiber-reinforced soil samples exhibit higher residual strength as compared to unreinforced soil"

"The strength envelopes for reinforced soil show the existence of critical confining stress, below which the fibers tend to slip."

"The amount of strength increase induced by reinforcement with short fibers depends on fiber content and aspect ratio, and soil grain size."

"Shear strength increases approximately linearly with increasing amounts of fibers up to 2% (approximately) by weight, beyond which the gain in strength is smaller."

Comments:

Stabilizer Type: Chemical

Paper Title: Compressibility Behaviour of Lime-Stabilized Clay

Author: Rao, S.M. and Shivananda, P.

Source: Geotechnical and Geological Engineering

Publication Date: 2005

Purpose of Stabilizer: stabilizer-reduce compressibility

Stabilizers Tested: Lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Black cotton soil	CH	Lime	powder	4, 7, 10%	N/A	N/A

Natural or Manufactured Soil? natural

Clay Mineralogy: N/A

Tests Performed: 1-dimensional consolidation test

Test Methods: Samples were saturated by allowing specimens to absorb water by the gradual application of a vacuum in a vacuum desiccator for a period of 8 hrs. They were then consolidated from an initial pressure of 6 kPa to a final pressure of 12,800 kPa with a consistent load increment ratio.

Key Findings: The samples experienced relatively low magnitudes of elastic strain (3-4%) in the pre yield stress region and large magnitudes of plastic strains (12-18%) in the post yield stress regions. In conclusion, while cumulative axial strains of the samples were influenced by the yield stress to applied stress ratio, axial strain per unit increase in pressure remains independent.

Comments:

Stabilizer Type: Chemical

Paper Title: Liquid Soil Stabilizers: Measured Effects on Engineering Properties of Clay

Author: Rauch A.F., Harmon, J.S., Katz, L.E., and Liljestrand, H.M.

Source: Transportation Research Board

Publication Date: 2002

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Ionic stabilizers, polymer stabilizers, enzymes

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Kaolinite, illitie, montmorillonite	N/A	Commercial enzyme stabilizer (not named)	Liquid	0.002%	N/A	N/A
Kaolinite, illitie, montmorillonite	N/A	Commercial polymer stabilizer (not named)	Liquid	0.1%	N/A	N/A
Kaolinite, illitie, montmorillonite	N/A	Commercial ionic stabilizer (not named)	Liquid	0.02%	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Kaolinite, illite, and sodium montmorillonite

Tests Performed: Compaction Tests, Swell Potential by 1-D Consolidometer, Triaxial Tests

Test Methods: The author classified stabilizers into three categories: ionic, polymeric, and enzymes. They then tested three unidentified commercial stabilizers in each of the categories with two natural CH clays and three manufactured clays. Samples were pulverized, mixed to just dry of the optimum water content, then the stabilizer solution was added, mixed, and allowed to stand for 1 hour. Samples were then compacted to modified Proctor compaction and cured for 7 days. Finally Atterberg limits, swell potential, and undrained shear strength were determined for all samples.

Key Findings: The testing of these stabilizers did not produce favorable results from these products. No marked changes were observed. While there were individual cases of some marked improvement, no trends or duplication could be obtained. Higher dosages than the manufacturers' recommendations were not tried.

Comments:

Stabilizer Type: Chemical

Paper Title: Subgrade Strengthening of Existing Airfield Runways

Author: Robnett, A.M

Source: Transportation Engineering Journal

Publication Date: 1973

Purpose of Stabilizer: Stabilizer - Existing Airfield Runways

Stabilizers Tested: Various salts, lime, aluminum and calcium with electro-osmosis

Natural or Manufactured Soil? Natural

Clay Mineralogy: Montmorillonite, illite, kaolinite

Tests Performed: California Bearing Ratio, Unconfined Compressive Strength, Torsional Vane Shear Test

Test Methods: No actual testing was performed in this research. The author theorizes on possible stabilization techniques to improve existing airfield subgrades. Stabilization methods considered were: (1) electrical, (2) grouting, (3) lime, and (4) a group of zonal treatment procedures. The author provides a table of types of chemicals used from his selected literature review.

Key Findings: This paper provides a table of potential techniques for soil stabilization based on procedure, admixture, and soil types, including clay mineralogy. The basic objective was to improve the soil to a CBR value of at least 20. He concluded that electrical methods were not capable of the required strength gain. Heat treatment was only reported successful with loess soils. Grouting with cement or lime appeared to be the best option, though this may not be economically practical. The paper concludes that strengthening of subgrade can beneficially affect the pavement structural response and the following should be further investigated for improvement of existing airfields: (1) drilled hole pressure injections of lime, (2) mixed-in-place, or (3) post-hole-pile (excavation and replacement with high quality material such as lime or cement).

Comments:

Stabilizer Type: Chemical

Paper Title: Lime and Sodium Silicate Stabilization of Montmorillonite Clay Soil

Author: Ruff C.G and Davidson, D.T.

Source: Highway Research Board

Publication Date: 1961

Purpose of Stabilizer: Stabilizer - Subgrade Uses

Stabilizers Tested: Lime and sodium silicate

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Kansan till (approx. equal sand, silt and clay)	N/A	Lime	Powder	6%	Sodium silicate	3.4-8.0%

Natural or Manufactured Soil? Natural

Clay Mineralogy: Montmorillonite

Tests Performed: Unconfined Compressive Strength, Wet/Dry, Freeze/Thaw Cycles, Compaction Tests

Test Methods: Samples were dry-mixed with powdered lime and sodium silicate for 2 minutes in a Hobart mixer, then brought to varying water contents to determine the optimum moisture contents with the additives. Five different powdered sodium silicates were tested, varying in molecular ratio of Na2 to SiO2. The mixtures were then aged for a period of time in a covered container (time not given). Samples were then compacted and cured in a moist room for 3, 7, and 28 days. Specimens were then soaked for 24 hours before unconfined compression tests and freeze-thaw testing (14 cycles of 24 hours) were completed.

Key Findings: Cured samples showed that as aging before compaction increased, the strength gain decreased. Silicate D (sodium sesquisilicate pentahydrate) and lime appeared least affected by elapsed time between mixing and compaction. The 28-day immersed strength was as high as 440 psi, 260 after 3-days with 4% Silicate D and lime (strength was about 50 psi without any additive).

Comments:

Stabilizer Type: Chemical

Paper Title: Chemical Stabilisation of Roading Aggregates - A Clay Mineralogical Approach

Author: Sameshima, T.

Source: Institution of Professional Engineers New Zealand

Publication Date: 1983

Purpose of Stabilizer: Stabilizer - Roadway Subbases

Stabilizers Tested: Lime, hydrochloric acid, potassium chloride

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
5 smectite dominant soils	N/A	Hydrated lime	Powder	N/A	N/A	N/A
5 smectite dominant soils	N/A	Hydrochloric acid	Liquid	N/A	N/A	N/A
5 smectite dominant soils	N/A	Potassium chloride	Liquid	N/A	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Smectite

Tests Performed: Atterberg Limits, X-Ray Diffraction

Test Methods: Five potassium-smectite clays were prepared by soaking the specimens in an HCl and KCl solution for 24 hours. The samples were then washed with water four times, centrifuged to remove excess water, and dried at room temperature. The Atterberg limits and plastic index were then determined.

Key Findings: HCl showed in some cases to actually increase the PI. Hydrated lime had problems in that it didn't fully react due to the carbonation of lime with expandable clay minerals. KCl at 5% seems promising as a stabilizer for an aggregate containing swelling clays based on its reduction of plastic

Comments:

Stabilizer Type: Reinforcement

Paper Title: Evaluation of the Performance of Polypropylene Fibers on Soil Stabilization

Author: Sangineni, S.M.

Source: Texas A&M University

Publication Date: 1992

Purpose of Stabilizer: Stabilizer - Subgrades of Flexible Pavements

Stabilizers Tested: Fibrillated polypropylene fibers, lime with fibers, lime, cement with fibers

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay	CL	Fibers	Fiber	0.3%		
Sand	SM	Cement	Powder	5%	Fibers	0.5%
Clay	CL	Lime	Powder	5%		
Clay	CL	Lime	Powder	5%	Fibers	0.3%

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Triaxial Tests, Compaction Tests

Test Methods: Soils were thoroughly mixed with the additives at varying water contents, wet and dry of optimum for the soils. Moisture-density tests and triaxial tests at low confining pressures of 5 psi were performed.

Key Findings: Paper found optimum percent additives: 5% lime with 0.3% fibers for clay, 5% cement with 0.5% fiber for sand. Fibers provided an initial increase in modulus and could withstand higher strains than stabilized soils without fibers. Failure of fiber composites occurred due to fiber pullout, showing that if the interfacial shear strength between the matrix and soil material is increased, it would be less likely to fail. This could be achieved with increased curing time. The inclusion of additives would effectively reduce the required thickness of the subbase and improve the performance of the pavement structure.

Comments:

Stabilizer Type: Chemical

Paper Title: Accelerated Strength Improvement of Silty Sand Using Nontraditional Additives

Author: Santoni, R.L., Tingle, J.S., and Nieves, M.

Source: Transportation Research Board

Publication Date: 2003

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: 1 lignosulfonate, 6 polymers, 1 silicate, and 1 tree resin, compared to Type 1 Portland Cement, and a cationic emulsified asphalt.

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Silty Sand	SM	Polymer 4	N/A	2.5%	N/A	N/A
Silty Sand	SM	Polymer 4	N/A	2.5%	Cement	1, 2, & 3%
Silty Sand	SM	Polymer 3	N/A	2.5%	Polymer 4	1, 2, & 3%
Silty Sand	SM	Lignosulfonate	N/A	3%	N/A	N/A
Silty Sand	SM	Polymer 5	N/A	3%	Cement	1%
Silty Sand	SM	Polymer 2	N/A	2.5%	N/A	N/A
Silty Sand	SM	Polymer 3	N/A	2.5%	Cement	1, 2, & 3%
Silty Sand	SM	Polymer 3	N/A	2.5%	N/A	N/A
Silty Sand	SM	Polymer 2	N/A	2.5%	Polymer 4	1, 2, & 3%
Silty Sand	SM	Polymer 2	N/A	2.5%	Cement	1, 2, & 3%
Silty Sand	SM	Polymer 1	N/A	2.5%	Polymer 4	1, 2, & 3%
Silty Sand	SM	Polymer 1	N/A	2.5%	Cement	1, 2, & 3%
Silty Sand	SM	Polymer 6	N/A	1, 2, & 3%	N/A	N/A
Silty Sand	SM	Lignosulfonate	N/A	3%	Polymer 4	1, 2, & 3%
Silty Sand	SM	Polymer 5	N/A	3%	Polymer 4	1%
Silty Sand	SM	Lignosulfonate	N/A	3%	Cement	1, 2, & 3%
Silty Sand	SM	Cement	N/A	1, 2, & 3%	N/A	N/A
Silty Sand	SM	Polymer 4	N/A	1, 2, & 3%	N/A	N/A
Silty Sand	SM	Emulsified Asphalt	N/A	5%	N/A	N/A
Silty Sand	SM	Emulsified Asphalt	N/A	5%	Cement	1, 2, & 3%
Silty Sand	SM	Emulsified Asphalt	N/A	5%	Polymer 4	1, 2, & 3%
Silty Sand	SM	Polymer 1	N/A	2.5%	N/A	N/A
Silty Sand	SM	Polymer 6	N/A	3%	Polymer 4	1%
Silty Sand	SM	Polymer 5	N/A	1, 2, & 3%	N/A	N/A
Silty Sand	SM	Silicate	N/A	0.1, 0.25, & 0.5%	N/A	N/A
Silty Sand	SM	Silicate	N/A	0.5%	Cement	1, 2, & 3%
Silty Sand	SM	Tree Resin	N/A	5%		
Silty Sand	SM	Tree Resin	N/A	5%	Cement	1, 2, & 3%
Silty Sand	SM	Tree Resin	N/A	5%	Polymer 4	1, 2, & 3%
Silty Sand	SM	Polymer 6	N/A	3%	Cement	1%

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength

Test Methods: Samples were compacted using a Pine® gyratory compaction machine at optimum moisture content of 5% including any water utilized to dilute the stabilizer when required. Samples were then cured at 72-deg F and 40% relative humidity for cure times of 1 and 7 days. This was considered an air-dried process which was utilized to represent field curing conditions. UCS tests were carried out on both dry and wet samples, with the wet samples being submerged on its side in 1-in of water for 15 minutes.

Key Findings: "Lignosulfonate with and without accelerators did not improve the SM soil load-carrying capacity. However, Lignosulfonate did provide significant waterproofing of the specimens"

"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."

"However, Polymer 5 and Silicate 1 without accelerators disintegrated once they were placed in water."

"For the two accelerators (i.e. Type 1 Portland cement and Polymer 4) used in this experiment, Type 1 Portland cement provided significant strength improvement for the SM soil 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."

"Significant savings can be realized by using these accelerators since traditional stabilization additives require up to 9 percent of cement or emulsified asphalt."

Comments:

Stabilizer Type: Chemical

Paper Title: Injection Stabilization of Expansive Clays Using a Hydrogen Ion Exchange Chemical

Author: Sarkar S.L., Herbert B.E., and Scharlin R.J.

Source: Advances in Unsaturated Geotechnics

Publication Date: 2000

Purpose of Stabilizer: Stabilizer - Subgrade for Flexible Pavments

Stabilizers Tested: Hydrogen ion exchange chemical (HIExC)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clayey Sand	Hydrogen ion exchange chemical	Liquid	Dilluted 300:1	N/A	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Smectite

Tests Performed: X-Ray Diffraction, Swell Potential by 1-D Consolidometer, Triaxial Tests

Test Methods: Injections of a diluted hydrogen ion exchange chemical (HIExC) solution were made through existing pavement using rods on 4-foot centers and at 5.5 gallons per minute. After two years, bulk samples were extracted for laboratory testing in this research. Samples were analyzed by x-ray diffraction, zeta potential, swell testing, and undrained triaxial tests. The in situ water contents of these soils were from 8-10.5%, at which they were tested. Samples were compared to untreated samples of the same soil.

Key Findings: The injections made the soils brittle and failed at lower strains. Treatment with HIExC reduces the shrink-swell potential by an average of 35% and produces a higher modulus. While the chemical treatment seemed to have improved the shrink-swell characteristics of the soil, there was no marked improvement on the strength characteristics.

Comments:

Stabilizer Type: Chemical

Paper Title: Forensic Evaluation of Three Failed Cement-Treated Base Pavements

Author: Scullion T. and Harris P.

Source: Transportation Research Record

Publication Date: 1998

Purpose of Stabilizer: Case Study of Cement-Treated Base Pavements

Stabilizers Tested: Lime, cement

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Subbases containing up to 15% clay	N/A	Lime	Powder	N/A	N/A	N/A
Subbases containing up to15% clay	N/A	Cement	Powder	N/A	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Kaolinite and smectite

Tests Performed: X-Ray Diffraction

Test Methods: This research studied three failed cement/lime-treated base pavements. Cores were taken of the failed sections. Hydrometer analysis were performed on the base material, and x-ray diffraction tests showed significant amounts of smectite and kaolinite in the roughly 15% clay fractions. Suction-dielectric tests also indicated that base layers were holding significant amounts of moisture.

Key Findings: The researchers found that there were problems in the material selection, quality control and pavement design of these projects. The aggregate in the base material, sandstone, was highly absorptive in nature. They also mostly found that stabilized bases had been constructed in layers which had cracked and debonded from one another. The layers were then trapping water which was destroying the cement matrix and weakening the treated bases.

Comments:

Stabilizer Type: Chemical

Paper Title: A Glimpse at Electrokinetic Soil Improvement

Author: Senneset K.

Source: Proceedings of Bengt B. Broms Symposium on Geotechnical

Publication Date: 1995

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Electrokinetic soil improvement

Natural or Manufactured Soil? N/A

Clay Mineralogy: Montmorillonite and illite

Tests Performed: No Testing Conducted

Test Methods:

Key Findings:

Comments: This paper provides an overview and discussion of electrokinetic soil studies and presents several cases where electroosmotic stabilization was demonstrated for short and long-term stabilization of Norwegian problematic clay soils. The method seems best suited for higher surface charge densities in clays, such as in monmorillonite and illite. This technique has also proved to be most applicable for soils contaminated by heavy metals. When these soil and site conditions exist, the use of electrokinetic remediation has proven to be both technically and economically feasible.

Stabilizer Type: Chemical

Paper Title: Utilization of a Very High Lime Fly Ash for Improvement of Izmir Clay

Author: Sezer, A., Inan, G., Yilmaz, H.R. and Ramyar, K.

Source: Building and Environment

Publication Date: 2006

Purpose of Stabilizer: Stabilizer- increase strength

Stabilizers Tested: Lime

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Izmir Clay	CH	High lime flyash	powder	0, 5, 10, 15, 20%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Standard Proctor Compaction, Unconfined Compression, Direct Shear

Test Methods: Test specimens were compacted at their respective optimum moisture contents to achieve maximum dry density. Compacted samples were used to determine the free swell values and strength parameters for each mixture. ASTM procedures were followed for unconfined compression (ASTM D2166) and direct shear (ASTM D3080) tests. The direct shear tests used a load application rate of 1 mm/min. Strength parameters were determined for samples that cured for periods of 1, 7, 28, and 90 days.

Key Findings: The addition of 0-15% high lime fly ash increases both unconfined compressive strength and cohesion. A negligible compressive strength increase occurs from 15-20% fly ash. The internal friction angle increases with the addition of fly ash and increases with time, regardless of fly ash content.

Comments:

Stabilizer Type: Chemical

Paper Title: A Study of Relative Efficiency of Various Soil Stabilization Additives on Clayey Soil

Author: Shah B.N. and Bhatt R.D,

Source: Indian Highways

Publication Date: 1980

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Lime, lime and flyash, lime and cement, cement

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Low plasticity clayey soil	CL	Lime	Powder	3, 12%	N/A	N/A
Low plasticity clayey soil	CL	Lime	Powder	3%	Cement	3%
Low plasticity clayey soil	CL	Lime	Powder	3, 5, 7, 9%	N/A	N/A
Low plasticity clayey soil	CL	Lime	Powder	3, 5%	Flyash	12,20%

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Atterberg Limits, California Bearing Ratio, Unconfined Compressive Strength

Test Methods: Soils were thoroughly mixed with the various percentages of additives at the optimum moisture content of 19%. Atterberg limits were determined on the mixed samples. The samples were then compacted, cured for 3 and 7 days, and tested for soaked and unsoaked unconfined compressive

Key Findings: CBR values increased for the stabilized soil with up to 7% lime content. Soil-flyash admixtures showed an appreciable increase in CBR over lime alone. As cement content was increased, the CBR value increased. To reach a CBR of 20, 7% lime or 3% lime and 3% cement was advisable. Smaller additions of up to 3% lime showed little strength gain.

Comments:

Stabilizer Type: Chemical

Paper Title: Sodium Chloride Stabilized Roads in Iowa

Author: Sheeler, J.B.

Source: Transportation Research Board

Publication Date: 1960

Purpose of Stabilizer: Stabilizer - Roadways

Stabilizers Tested: Sodium chloride

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Gravel and glacial clay	N/A	Sodium chloride	Powder	5-20% (tons/mile)	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: No Testing Conducted

Test Methods: Research is a summation of testimonies of county engineers who used sodium chloride in practice in Iowa. Most roads were constructed from materials mixed in the field either by blade or by a Seaman Pulvimixer. After uniform spreading, the salt is bladed in and compacted to 90 to 95 percent Proctor density.

Key Findings: Based on testimony of county engineers who used sodium chloride in practice, sodium chloride improves performance as dust control and smoothness of road. It also provides good resistance to freeze-thaw break-up. Sodium chloride roads are believed to have a lower permeability, moisture retention, lowered freezing point of water, gel formation, flocculation and increased cohesiveness of clay due to the sodium ions.

Comments:

Stabilizer Type: Chemical

Paper Title: A Probabilistic Estimate of the Design Strength of Chemically Stabilized Loess Clayey Soil

Author: Sheinin, V.I., Ulyakhin, O.V., and Grachev, Yu.A.

Source: Soil Mechanics & Foundation Engineering

Publication Date: 1989

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength

Test Methods:

Key Findings:

Comments: In this study the authors estimate the strength of chemically stabilized loess clay soil by means of probability distribution functions. As the results of computations performed in accordance with the analysis for several strengthened masses, the relationship between the dispersion of strength and the dispersion of the derivative of the correlation function and the area of the foundation are approximately the same in nature. In design practice, the author claims it is possible to use the curves presented in this paper to determine these values. It was not quite understood how conclusions were made when stabilization type was not taken into account.

Stabilizer Type: Chemical

Paper Title: Full-Depth Reclamation with Calcium Chloride

Author: Shepard, James M., Pickett, James, and Kienzle, Michael

Source: Transportation Research Record

Publication Date: 1991

Purpose of Stabilizer: Stabilizer - Low Volume Secondary Roads

Stabilizers Tested: Calcium chloride

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Reclamated asphalt with silty clay subgrade	N/A	Calcium chloride	Liquid	0.35 gal / sq yd treated	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Triaxial Tests

Test Methods: The reclamation process involved churning the top 8 inches of existing asphalt paved surface and blending of gravel into the pulverized material. With pulverization complete, calcium chloride was added, the mix was re-pulverized and placed for compaction. To achieve long-lasting results, a wear course was placed on the finished base.

Key Findings: Data presented in this research consistently indicate that road strength has been improved in the test sections using calcium chloride addition versus the control section with no additive. The resilient moduli from triaxial tests indicate an increase of 24 to 36 percent in the treated sections. Reduced freeze-thaw susceptibility is also indicated.

Comments: The calcium chloride works to absorb ambient moisture. The applications in this paper deal mainly with the granular material.

Stabilizer Type: Chemical

Paper Title: Reuse of Incinerator Fly Ash in Soft Soil Stabilization

Author: Show, K., Tay, J. and Goh, A.T.C

Source: Journal of Materials in Civil Engineering

Publication Date: 2003

Purpose of Stabilizer: stabilizer- reuse waste material

Stabilizers Tested: fly ash

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Marine clay	CH	Cement	powder	20, 20, 30, 30%	Fly Ash	20, 20%

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Atterberg Limits, Undrained Shear Strength, Consolidation, Permeability

Test Methods: Test specimens were mixed with a mechanical mixer, compacted into molds, and cured in a wet room. The samples cured for periods of 1, 7, 30, 60, 90 and 120 days. After curing, the samples were extracted from their molds and a suite of Atterberg limits, undrained shear, and consolidation tests were performed. Constant head permeability tests were used to determine permeability parameters for the samples.

Key Findings: All samples treated with the stabilizer had a decreased plasticity index that continued to decrease with time. Cement only mixes had slightly higher strengths than the cement/fly ash mix. The strength exhibited by the cement/fly ash mix was sufficiently large to suggest municipal solid waste fly ash could be used for partial replacement of cement in stabilizers.

Comments:

Stabilizer Type: Chemical

Paper Title: Soil Stabilization with Sodium Chloride

Author: Singh, Gurdev, and Das, Braja M.

Source: Transportation Research Record

Publication Date: 1999

Purpose of Stabilizer: Stabilizer - Roadway Base Uses

Stabilizers Tested: Sodium chloride

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Sand and gravel with clay	GC	Rock salt	Solid	1.0,1.5%	N/A	N/A
Soil/Agg. Mixture	MH	Rock salt	Solid	1.0,1.5%	N/A	N/A
Soil/Agg. Mixture	MH	Brine (Dissolved rock salt)	Liquid	1.0%	N/A	N/A
Soil/Agg. Mixture	MH	Rock salt	Solid	1.0,1.5%	Lime	2.0%
Soil/Agg. Mixture	SC	Rock salt	Solid	1.0,1.5%	N/A	N/A
Soil/Agg. Mixture	SC	Rock salt	Solid	1.0,1.5%	Lime	2.0%
Sand and gravel with clay	GC	Brine (Dissolved rock salt)	Liquid	1.0%	N/A	N/A
Sand and gravel with clay	GC	Rock salt	Solid	1.0,1.5%	Lime	2.0%
Soil/Agg. Mixture	SC	Brine (Dissolved rock salt)	Liquid	1.0%	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Montmorillonite, kaolinite, and illite

Tests Performed: Compaction Tests, Unconfined Compressive Strength, California Bearing Ratio

Test Methods: A commercial clay, River Aire soil, sand and gravel were used in this study to prepare three soil aggregate mixtures. X-ray diffraction was preformed on the clay portion of the mixtures and was found to be predominately montmorillonite. Specimens were thoroughly mixed with the different percentages of additives and 95% of the maximum dry unit weight with optimum moisture content. Specimens were cured under varying conditions and lengths. Atterberg limits, CBR tests, unconfined compression tests, and cyclic triaxial tests were then performed.

Key Findings: CBR test values, UCS, and indirect tensile strength were greatly improved with inclusion of sodium chloride as a stabilizing agent. The greatest increase in the maximum dry unit weight of compaction is found with salt content of about 1 percent.

Comments: Though this paper presents positive findings, its literature review presents poor laboratory results with sodium chloride.

Stabilizer Type: Chemical

Paper Title: Lignins as Stabilizing Agents for Northeastern Iowa Loess

Author: Sinha, S.P., Davidson, D.T., and Hoover, J.M.

Source: Proceedings of the Iowa Academy of Science

Publication Date: 1957

Purpose of Stabilizer: Stabilizer - Highway and Airfield Use

Stabilizers Tested: Lignins (Clarian extract, sulphite lignin, spent sulphite liquor)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Iowa loess (silty clay loam)	N/A	Lignins (different grades)	Liquid	1,3,6,9%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Compaction Tests, California Bearing Ratio

Test Methods: Soil samples were air-dried and pulverized. Either powder lignin was added and brought to the desired moisture content, or a liquid lignin water mixture was added to the desired moisture content. The effect of the amount and kind of admixture on the optimum moisture content was determined with the standard Proctor test. Molded samples were air cured for 7-days then tested for dry unconfined compressive strength.

Key Findings: Lignins used alone as admixtures did not show much promise for stabilization of fine grained loess and loess-derivative soils. Moist curing of lignin-treated soil specimens resulted in much lower strengths than air curing. All the lignin forms gave approximately the same results. The findings did suggest though that lignins should be much more effective for granular soils.

Comments:

Stabilizer Type: Reinforcement

Paper Title: Strength and Stiffness Response of Coir Fiber-Reinforced Tropical Soil

Author: Sivakumar Babu, G.L. and Vasudevan, A.K.

Source: Journal of Materials in Civil Engineering

Publication Date: 2008

Purpose of Stabilizer: reinforcement

Stabilizers Tested: Coir Fiber

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Tropical Soil	CL	Coir fibers	fiber	0, 0.5, 1, 1.5, 2, 2.5%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Undrained Triaxial Test

Test Methods: Test soils were compacted in standard proctor molds at their respective optimum moisture content to reach a maximum dry density. Once remolded, the samples were tested in an undrained triaxial test with confining pressures of 50 to 150 kPa. A strain rate of 1.58% per minute was used until sample failure or 20% strain. Test factors for the 59 test series included; confining pressure, fiber content, fiber length, and fiber diameter.

Key Findings: Deviator stress at failure for fiber reinforced samples was up to 3.5 times higher than unreinforced soil. Also, deviator stress at failure increased with increasing fiber length and diameter. Soil stiffness showed a notable increase due to fiber inclusion.

Comments:

Stabilizer Type: Chemical

Paper Title: Preliminary Findings and Future Programming of a Basic Research Project Involving Calcium Chloride with Pure Clays

Author: Slate, Floyd O.

Source: Highway Research Board Bulletin

Publication Date: 1960

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Calcium chloride

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Montmorillonite	CH	Calcium chloride	Powder	1-10%	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Montmorillonite

Tests Performed: Compaction Tests

Test Methods: Only standard Proctor tests were performed in this preliminary study. Percentages of the additive were dissolved in water and mixed with the commercial clay. They were then compacted at various moisture contents to develop the compaction properties of the clay-additive mixtures.

Key Findings: The effect of calcium chloride on maximum dry density shows an appreciable increase in density to the sodium montmorillonite caused by the chemical (4% calcium chloride increase density by 11%). Above 4% made no appreciable increases though.

Comments: This is really a plan of attack, not a study that has been carried out. There is no strength testing or data presented in this paper.

Stabilizer Type: Chemical

Paper Title: Chemical Soil Stabilization and the Environment

Author: Sokolovich, V.E.

Source: Soil Mechanics & Foundation Engineering

Publication Date: 1988

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Carbamide resins, silicate-injections, alkalization, cement

Natural or Manufactured Soil?

Clay Mineralogy: N/A

Tests Performed: No Testing Conducted

Test Methods:

Key Findings:

Comments: This paper is a discussion of the chemical stabilization methods prevalent in Russia and their effects on the environment. For clays, alkalization (by forcing a 40% caustic solution under pressure) can be harmful to the environment causing prolonged contamination; additionally, quick stabilization is not achieved with this method. The author states though that quick (immediate) stabilization of loess can be obtained under silication. From an environmental standpoint, cement is still considered the most favorable method of stabilization.

Stabilizer Type: Chemical

Paper Title: Chemical Soil Stabilization: A Laboratory Comparison of the Effectiveness of Three Liquid Products and Lime

Author: Thomas, John Albert

Source: Thesis, Univeristy of Texas at Austin

Publication Date: 2002

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Ionic (Sulfonated Limonene), Polymer (Sodium Silicate), and Enzyme (Polyethylene Glycol)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Fire Clay	CH	Ionic	Liquid	0.2%	N/A	N/A
Dark Gray Taylor Clay	CH	Ionic	Liquid	0.2%	N/A	N/A
Dark Gray Taylor Clay	CH	Polymer	Liquid	1.0%	N/A	N/A
Dark Gray Taylor Clay	CH	Enzyme	Liquid	0.02%	N/A	N/A
Tan & Gray Taylor Clay	CH	Enzyme	Liquid	0.02%	N/A	N/A
Tan & Gray Taylor Clay	CH	Polymer	Liquid	1.0%	N/A	N/A
Tan & Gray Taylor Clay	CH	Ionic	Liquid	0.2%	N/A	N/A
Fire Clay	CH	Polymer	Liquid	1.0%	N/A	N/A
Fire Clay	CH	Enzyme	Liquid	0.02%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Triaxial Tests, Atterberg Limits, Swell Potential by 1-D Consolidometer

Test Methods: Tests for 1-D free swell and UU TRX tests were compacted at optimum water content with standard Proctor effort. The samples were then allowed to cure for 7 days in a sealed plastic bag at 75-deg. F.

Key Findings: Significant improvements in engineering properties were not observed for three natural clay soils when treated with three selected liquid stabilizers at application rates 10 times the manufacturers' recommended application

Comments: The three liquid stabilizers produced only minor changes as compared with untreated soils. Overall, this report shows poor results, which concur with WES.

Stabilizer Type: Chemical

Paper Title: Changes in Soil Plasticity and Swell Caused by Electro-Osmosis

Author: Thomas, Tracy J., and Lentz, Rodney W.

Source: Symposium on Physico-Chemical Aspects on Soil, Rock, and Related Materials

Publication Date: 1990

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Electro-osmosis

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Mixture of sand, silt, and clay (30, 30, 40%)	N/A	Electric field	Current	16V across carbon electrodes	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Kaolinite and montmorillonite

Tests Performed: Atterberg Limits, Swell Potential by 1-D Consolidometer, Unconfined Compressive Strength

Test Methods: The manufactured soils were first mixed at a ratio of 30% fine sand, 30% silt, 30% kaolinite, and 10% montmorillonite. The soil was brought to a water content of 26% with a 100% degree of saturation with a fine mist sprayer. The soil was mixed with the water and allowed to cure for 24 hours. Specimens were then compacted in the testing apparatus and subjected to a voltage of 16V across the carbon electrodes in the tank. Measurements of voltage, current, and pH were taken at various times of the testing. Undisturbed samples were then taken. Swell potential and unconfined compressive strength tests were then performed.

Key Findings: Significant changes were noted in the shrinkage limit and swell characteristics of the moderately swelling soil. The ranges of volumes as a result of shrinkage and swell were significantly reduced. Strength gain was evident in the samples near the anodes. The strength increased from 0.31 to 0.52 kg/cm^2 for the first test series and from 0.38 to 1.08 kg/cm^2 at the test moisture contents of 26 and 27% respectively.

Comments: Electro-osmosis may be effective as a method of soil stabilization in some field applications, but cost of treatment is a major drawback at this time.

Stabilizer Type: Chemical

Paper Title: Stabilization of Soils with Inorganic Salts and Bases: A Review of the Literature

Author: Thornburn, Thomas H., and Mura, Romeo

Source: Highway Research Board Bulletin

Publication Date: 1969

Purpose of Stabilizer: Stabilizer - Literature Review

Stabilizers Tested: Sodium chloride, calcium carbide, sodium hydroxide, salts as additives to lime or cement

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: No Testing Conducted

Test Methods:

Key Findings:

Comments: This paper is a literature review on soil and aggregate stabilization with inorganic salts as published prior to 1965. Focus was given to the inorganic salts that have been researched enough to draw sufficiently meaningful solutions. In general, it is found that the addition of inorganic salts or bases permits lime-treated soil to cure at lower temperatures and limit freeze-thaw effects on the soil. Sodium additives considerably increase the resistance of cement-stabilized soil to sulfate attack. Optimum moisture contents are usually lowered by addition of salts. Leaching of the additive will occur unless a protective cover is applied. In addition to conclusions based on the authors' literature review, they provide a summary of each of the references cited (74 references).

Stabilizer Type: Chemical

Paper Title: Testing and Analysis of C-17 Live-Flight Operations on Semi-Prepared Airfields

Author: Tingle, J.S.

Source: Waterways Experiment Station - Technical Report

Publication Date: 1998

Purpose of Stabilizer: Stabilizer - Unpaved Airfield Use

Stabilizers Tested: Cement

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
High plasticity clays	CH	Compaction only	N/A	N/A	N/A	N/A
Slightly plastic silty sands	SM-SC	Compaction only	N/A	N/A	N/A	N/A
High plasticity clayey sand	SC	Cement	Powder	7%	N/A	N/A
Low-plasticity clays and silts	CL-ML	Compaction only	N/A	N/A	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: California Bearing Ratio

Test Methods: Live field tests of the C-17 aircraft were preformed at six test locations. The analysis of the field data was conducted to determine a relationship between the physical properties of the runway surfaces and the performance of these surfaces under live loading conditions. Additionally, the validity of existing unsurfaced airfield criteria for the C-17 was evaluated. Tests conducted included the measurement of moisture content, density, CBR and DCP measurements, and rut depths created during flight operations. All field tests were conducted at existing unpaved airfields with arid environments where the in situ moisture contents were well below optimum.

Key Findings: Field tests showed that failure was caused by the shearing action of the landing gear on the runway's unpaved surface. The estimated number of operations to failure could be reasonably predicted and a nomograph was developed based on the field testing and flight operations observed. FOD and dust potential was a major problem in the testing and caused significant damage to the aircraft, especially at the cement treated test site. Aircraft testing on wet conditions indicated severe limitations under such conditions.

Comments:

Stabilizer Type: Reinforcement

Paper Title: Behavior of Unsurfaced Airfields Supporting Operations of C-17 Aircraft

Author: Tingle, J.S. and Grogan, W.P.

Source: Journal of Transportation Engineering

Publication Date: 1999

Purpose of Stabilizer: Stabilizer - Airfield Uses

Stabilizers Tested: Compaction only

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clayey sand	SM-SC	Compaction only	N/A	N/A	N/A	N/A
Low plasticity clay	CL	Compaction only	N/A	N/A	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: California Bearing Ratio

Test Methods: Full scale field tests were performed on selected semiprepared test sites and the airfield behavior was documented under actual C-17 aircraft operations. CBR and DCP testing was performed prior to the analysis and rutting depths were measured after each operation. A nomograph and regression model is presented to be used to predict the behavior of unsurfaced airfields in semiarid environments under C-17 aircraft traffic.

Key Findings: Results were heavily influenced by the arid environment. The clayey soil would be expected to have a more plastic behavior in wetter climates. The airfields evaluated in this investigation achieved functional failure prematurely despite displaying sufficient structural strength in terms of CBR. Failure was due to abrasive shearing during landing and breaking operations.

Comments:

Stabilizer Type: Chemical

Paper Title: Stabilization of Clay Soils with Nontraditional Additives

Author: Tingle, Jeb S., and Santoni, Rosa L.

Source: Transportation Research Record

Publication Date: 2003

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Type 1 Cement, Hydrated Lime, Acid, Lignosulfonate, 4 Enzymes, 4 Polymers, Petroleum Emulsion, and Tree Resin

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Lean Clay	CL	Petroleum Emulsion	N/A	2.53, 5, & 8%	N/A	N/A
Lean Clay	CL	Hydrated Lime	N/A	3, 5, & 7	N/A	N/A
Lean Clay	CL	Acid 1	N/A	0.01, 0.05, & 0.1%	N/A	N/A
Lean Clay	CL	Lignosulfonate 1	N/A	3.37, 5, & 8%	N/A	N/A
Lean Clay	CL	Enzyme 1	N/A	0.019, 0.050, & 0.1%	N/A	N/A
Lean Clay	CL	Enzyme 2	N/A	0.056, 0.1, & 0.2%	N/A	N/A
Lean Clay	CL	Enzyme 3	N/A	0.021, 0.035, & 0.106%	N/A	N/A
Lean Clay	CL	Enzyme 4	N/A	0.002, 0.02, & 0.1%	N/A	N/A
Lean Clay	CL	Polymer 1	N/A	0.066, 2.074, & 5%	N/A	N/A
Lean Clay	CL	Polymer 2	N/A	1.252, 2.5, & 5%	N/A	N/A
Lean Clay	CL	Polymer 4	N/A	0.104, 2.5, & 5%	N/A	N/A
Lean Clay	CL	Tree Resin 1	N/A	7.3, & 9%	N/A	N/A
Fat Clay	CH	Hydrated Lime	N/A	3, 5, & 7%	N/A	N/A
Fat Clay	CH	Acid 1	N/A	0.01, 0.05, & 0.1%	N/A	N/A
Fat Clay	CH	Enzyme 1	N/A	0.019, 0.05, & 0.1%	N/A	N/A
Fat Clay	CH	Enzyme 2	N/A	0.056, & 0.1%	N/A	N/A
Fat Clay	CH	Enzyme 3	N/A	0.021, 0.05, & 0.1%	N/A	N/A
Fat Clay	CH	Enzyme 4	N/A	0.10, 0.20, & 0.1%	N/A	N/A
Fat Clay	CH	Polymer 1	N/A	0.066, 2.074, &	N/A	N/A

				5%		
Fat Clay	CH	Polymer 3	N/A	1.01, 2.5, & 5%	N/A	N/A
Lean Clay	CL	Polymer 3	N/A	1, 2.5, & 5%	N/A	N/A
Lean Clay	CL	Type 1 Cement	N/A	7 & 9%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength

Test Methods: Samples were compacted using a Pine® gyratory compaction machine at optimum moisture content of 5% including any water utilized to dilute the stabilizer when required.

Samples were then cured at 72-deg F and 40% relative humidity for 28 days. This was considered an air-dried process which was utilized to represent field curing conditions.

UCS tests were carried out on both dry and wet samples, with the wet samples being submerged on it's side in 1-in of water for 15 minutes.

Key Findings: The results of the tests indicated that some of nontraditional stabilizers significantly improved the UCS of the clay materials, while others had no significant effect on the UCS.

Lignosulfonate 1 and Polymer 1 increased both the dry and wet UCS.

Enzyme 2, Polymer 2, Polymer 3, and Petroleum Emulsion 1 demonstrated significant “wet” UCS improvement for the CL soil specimens. For the CH soil stabilized with nontraditional products (Figures 7 through 9), Acid 1, Enzyme 1, Enzyme 2, and Polymer 1 increased the dry UCS. The wet test results for the CH specimens show that Enzymes 1, 2, and 4 along with Polymers 1 and 3 significantly improved the wet UCS by at least 345 kPa.

Lignosulfonate 1, Enzyme 2, Polymer 3, Petroleum Emulsion 1, and Tree Resin 1 demonstrated effective resistance to moisture degradation for CL soil specimens.

Comments:

Stabilizer Type: Chemical

Paper Title: Mechanical Improvement and Vertical Yield Stress Prediction of Clayey Soils from Eastern Canada Treated with Lime or Cement

Author: Tremblay, Helene, Leroueil, Serge, and Locat, Jaques

Source: Canadian Geotechnical Journal

Publication Date: 2001

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Lime, cement

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Eastern Canadian clayey soils	CL	Lime	Powder	3-15%	N/A	N/A
Eastern Canadian clayey soils	CL	Cement	Powder	3-9%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Illite and chlorite

Tests Performed: Swell Potential by 1-D Consolidometer, Atterberg Limits

Test Methods: This research project was conducted to define the general mechanical behavior of high water content clayey soils from eastern Canada treated with lime or cement. General relationships between initial void ratio, additive content, and vertical yield stress for a given inorganic soil was analyzed. Samples were mixed at various moisture and additive contents. By conducting compression tests, the main objective was to develop a simple method to estimate the vertical yield stress of the soil treated with a given additive content and any initial void ratio.

Key Findings: A general compressibility model for eastern Canadian clayey soils treated with lime or cement was developed which defines relationships between the initial void ratio, additive content, and vertical yield stress. This model can be used to estimate the resistance to compression of stabilized soils for preliminary design (with caution since it is based only on laboratory testing and no field testing was conducted).

Comments: Results are compressibility results, no strength tests, or modulus tests.

Stabilizer Type: Chemical

Paper Title: Soil Stabilization Using Oil-Shale Solid Waste

Author: Turner, John P.

Source: Journal of Geotechnical Engineering

Publication Date: 1994

Purpose of Stabilizer: Stabilizer - Subgrade Use

Stabilizers Tested: Oil-shale solid waste

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Silty sand	N/A	Oil-shale waste (containing lime and pozzolans)	Solid	10-25%	N/A	N/A
Coarse-grained soil	N/A	Oil-shale waste (containing lime and pozzolans)	Solid	10-25%	N/A	N/A
Clay	CH	Oil-shale waste (containing lime and pozzolans)	Solid	10-25%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Triaxial Tests, Unconfined Compressive Strength, Wet/Dry, Freeze/Thaw Cycles

Test Methods: Laboratory testing was performed to evaluate the use of oil-shale solid wastes as a cost effective soil stabilizer. Testing consisted of unconfined compressive strengths, moisture-density relationships, wet-dry and freeze-thaw durability, and resilient modulus of compacted samples.

Key Findings: Oil shale solid waste (that contains lime and pozzolanic silica and alumina) will react in the presence of water and form calcium and magnesium carbonates, silicates, aluminates, and other hydrous cements. Large amounts increased compressive strengths by a factor of two. Treatment of CH resulted in little change in compressive strength (20%); lime during the combustion process had to be added to achieve higher strengths.

Comments: Seems to be just a low grade lime treatment made cost effective since it is a waste product.

Stabilizer Type: Chemical

Paper Title: Research on Polyelectrolyte Stabilized Clay Composites

Author: Usmani, A.M.

Source: Journal of Elastomers & Plastics

Publication Date: 1983

Purpose of Stabilizer: Stabilizer - Clay Bricks

Stabilizers Tested: Polyelectrolyte (high carboxylic acid resin) and wax

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Clay	N/A	Resin	Liquid	1-10%	Wax and lime	2 and 0.5%

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Unconfined Compressive Strength

Test Methods: Clays were mixed with sand, lime and water (unknown amount). Percentages of the polyelectrolyte were mixed in and pressed into a mold constructed to prepare roofing tiles. After the samples were pressed, they were allowed to dry in the sun. Inclusion of wax into the mix provided a waterproofer and is essential as the bricks loose their strength if wetted.

Key Findings: The amount of polyelectrolyte needed to bond clay is very low (1% produced a sun-dried strength of 4100 psi). Sun baking however is the largest requirement. Water resistance even with the wax was marginal. Could possibly be used to stabilize clays in arid climates.

Comments:

Stabilizer Type: Chemical

Paper Title: The Nature of Immediate Reaction of Lime in Treating Soils for Road Construction

Author: Verhasselt, Andre F.

Source: ASTM Special Technical Publication

Publication Date: 1990

Purpose of Stabilizer: Stabilizer - Study of Immediate Effects of Lime

Stabilizers Tested: Hydrated lime, strontium hydroxide, barium hydroxide, sodium hydroxide, calcium chloride, calcium sulphonate hemihydrate, aluminum sulphate

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
10 different silty soils	N/A	Barium hydroxide	Powder	5.4%	N/A	N/A
10 different silty soils	N/A	Calcium sulphate hemihydrate	Powder	2.5%	N/A	N/A
10 different silty soils	N/A	Calcium hydroxide	Powder	2.0%	N/A	N/A
10 different silty soils	N/A	Sodium hydroxide	Powder	0.7%	N/A	N/A
10 different silty soils	N/A	Strontium hydroxide	Powder	4.4%	N/A	N/A
10 different silty soils	N/A	Aluminum sulfate	Powder	6.0%	N/A	N/A
10 different silty soils	N/A	Hydrated lime	Powder	1.3%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Illite

Tests Performed: Unconfined Compressive Strength, Crumb Test

Test Methods: Treatment agents were introduced into the cohesive silty soils at an amount of cations equivalent to 1% quicklime. Samples were mixed and compacted to approximately 95% modified Proctor on the wet side of optimum. The remaining free CaO versus time was evaluated after 0-7 days in accordance with the method of a Belgian standard test procedure. Crumb tests were performed after a 3-day cure time and unconfined compressive strengths were conducted on uncured samples.

Key Findings: The rapid reaction which is responsible for the immediate effects of lime on a clayey soil is clearly different from the slow reaction which results in the gradual progression of the mechanical properties of the compacted soil-lime mixture. The most probable hypothesis is that of a linkage process between the clay minerals as the immediate reaction mechanism. This is through hydrogen and hydroxyl bonds of the clay minerals.

Comments: This paper studies the immediate reaction mechanism of lime with clayey soils.

Stabilizer Type: Chemical

Paper Title: Use of Modified Poly(Vinyl Alcohol) for Reinforcement of Clayey Soils

Author: Voronkevich, S.D., Zgadzai, L.K., and Kuleev, M.T.

Source: Soviet Plastics

Publication Date: 1973

Purpose of Stabilizer: Stabilizer - Slopes and Reduce Erosion

Stabilizers Tested: Poly-vinyl alcohol

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Loess	ML	Poly-vinyl Alcohol (PVAL)	Liquid	0.5-2.0%	N/A	N/A
Kaolinite clay	CL	Poly-vinyl Alcohol (PVAL)	Liquid	0.5-2.0%	N/A	N/A
Montmorillonite clay	CH	Poly-vinyl Alcohol (PVAL)	Liquid	0.5-2.0%	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Loess, kaolinite, and montmorillonite

Tests Performed:

Test Methods: Soils were pulverized, breaking their textures. Their sieve size gradations were determined. Then aqueous solutions of the PVAL were introduced to the soils, either together or successively with an interval of up to 4 days by impregnation or mixing. The specimens were then subjected to soaking. Finally the gradation of the polymer-treated soils was determined.

Key Findings: All of the soil aggregates formed by treatment with modified PVAL were characterized by their high water resistance. Polymerization was evident in the new gradation with less fines and considerable clumping. Additionally, they were resistant to long term soaking. No strength tests were taken, but the additive showed good bonding.

Comments:

Stabilizer Type: Chemical

Paper Title: Stabilization of Swelling clays by Mg(OH)2. Changes in Clay Properties After Addition of Mg-Hydroxide

Author: Xeidakis, G.S.

Source: Engineering Geology

Publication Date: 1996

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Magnesium-hydroxide

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Kaolinite	N/A	Magnesium-hydroxide	Liquid	12 meq/gm of clay	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Montmorillonite, kaolinite, bentonite, and illite

Tests Performed: X-Ray Diffraction, Swell Potential by 1-D Consolidometer

Test Methods: Dilute and well-dispersed clay suspensions (about 1% clay) with a pH between 10 and 12 were mixed with around 12 meq of MgCl2 per gram of clay by drop-wise titration of 1-2 N NaOH solution. Vigorous agitation of the suspensions was applied during titration. The supernatant liquid was then centrifuged and the treated clay was dried at 250 C. The various clays were examined with the Methylene Blue test, X-ray diffraction, and differential thermal analysis methods.

Key Findings: The interaction of magnesium-hydroxide into the clay layers and the stabilization of the swelling clay structure was beyond any doubt. Brucite layers were formed in between the clay layers providing stability as evident from the X-ray diffraction analysis, creating a chlorite-like structure. The mechanism for adsorption of the Mg(OH)2 was basically the same for all clays; it involved physical adsorption with some chemical bonding, cementation due to crystallization, and in the long term some pozzolanic reactions are also taking place. With swelling clays, these reactions were on the clay surfaces as well as internal surfaces.

Comments: It is noted that the method formulated in the laboratory would not be easily applicable in the field and more research is needed in this direction.

Stabilizer Type: Chemical

Paper Title: Stabilization of Montmorillonite Clay in Porous Media by Polyacrylamides

Author: Zaitoun, A., and Berton, N.

Source: SPE International Symposium on Formation Damage Control 1996

Publication Date: 1996

Purpose of Stabilizer: Stabilizer - For Sandpacks with 5% Montmorillonite

Stabilizers Tested: Nonionic polyacrylamides (PAM), cationic polyacrylamides (CPAM)

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Sandpack with 5% montmorillonite	SC	PAM	Liquid	N/A	N/A	N/A
Sandpack with 5% montmorillonite	SC	CPAM	Liquid	N/A	N/A	N/A

Natural or Manufactured Soil? Manufactured

Clay Mineralogy: Montmorillonite

Tests Performed: Permeability Tests

Test Methods: The critical salinity concentration (CSC) as described in a previous paper by the authors was used to compare the ability of nonionic polyacrylamides (PAM) to cationic polyacrylamides (CPAM) to stabilize montmorillonite clays in sand packs. The method consisted on injecting brine at decreasing salinity levels until clay release is detected by a continuous increase in pressure drop.

Key Findings: All polymers tested in this study were said to be very efficient clay stabilizers. As expected, because of the neutralization of negative clay surface charges, CPAM had a higher stabilizing power than PAM. However, CPAM also strongly reduced the permeability of the sandpack. Therefore, the low-molecular-weight PAM may be preferred because of its good stabilizing power with minimal loss of permeability.

Comments: Different application, trying to stabilize the clay in the pores of sand.

Stabilizer Type: Chemical

Paper Title: Experience with Chemical Stabilization of Saturated Loesslike Loams in the Foundation Beds of Existing Structures

Author: Zelenskii, V.Yu, and Isaev, B.N.

Source: Soil Mechanics and Foundation Engineering

Publication Date: 1975

Purpose of Stabilizer: Stabilizer - Foundations of Existing Structures

Stabilizers Tested: Gas-silicatization method with carbon dioxide treatment

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Loesslike loams	N/A	Sodium silicate	Gaseous	N/A	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: No Testing Conducted

Test Methods:

Key Findings:

Comments: This paper discusses current construction practice and stabilization methods for wet loess-like loams with low permeability. While methods of liquid chemical stabilization produce small areas of stabilization, the method of gas-silication with preliminary activation of the soil not only permits pumping the sodium silicate into the saturated loam without disturbing its structure, but also results in uniform distribution of the grout through the mass being stabilized and ensures a sufficiently high strength. Experimental field work with this method has proven effective to control settlement. Pumping of carbon dioxide after the gas results in increased strength and water resistance of the treated mass.

Stabilizer Type: Chemical

Paper Title: Concrete Sludge Powder for Soil Stabilization

Author: Zhang, J. and Fujiwara, T.

Source: Transportation Research Record

Publication Date: 2007

Purpose of Stabilizer: Stabilizer- makes use of waste product

Stabilizers Tested: Concrete Sludge powder

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
clay	N/A	Concrete sludge powder	Powder	0, 3, 5, 7, 9, 11, 15, 20%	N/A	N/A
clay	N/A	Lime	powder	5, 20%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: N/A

Tests Performed: Atterberg Limits, Cone Index, Freezing Heave, Compaction, CBR

Test Methods: Soil with a natural water content of 44% was used in the experiments. The additive was mixed into the soil by an automatic mixer. Atterberg limits, compaction, CBR, cone index tests, and freezing heave tests were performed on the samples.

Key Findings: The addition of concrete sludge powder decreased the soil's water content, plasticity index, and frozen heave. A concrete sludge powder content of 20% causes the soil classification to change from CH to ML.

Comments:

Stabilizer Type: Chemical

Paper Title: Influence of Chlorides and Hydroxides of Calcium and Sodium on Consistency Limits of a Fat Clay

Author: Zolkov, Elias

Source: Highway Research Board Bulletin

Publication Date: 1962

Purpose of Stabilizer: Stabilizer

Stabilizers Tested: Sodium chloride, calcium chloride, sodium hydroxide, calcium hydroxide

Soil Tested	USCS	Primary Additive	Additive Form	Primary Rate	Secondary Additive	Secondary Rate
Fat clay	N/A	Sodium chloride	Powder	0.5-15%	N/A	N/A
Fat clay	N/A	Calcium chloride	Powder	0.5-15%	N/A	N/A
Fat clay	N/A	Sodium hydroxide	Liquid	0.5-15%	N/A	N/A
Fat clay	N/A	Hydrated lime	Powder	0.5-10%	N/A	N/A

Natural or Manufactured Soil? Natural

Clay Mineralogy: Smectite and calcite

Tests Performed: Atterberg Limits

Test Methods: Soil was air dried and pulverized. Chemicals were added in a water solution bringing the soil to its liquid limit of 66% moisture content. Samples were then stored in sealed jars. Atterberg limits, shrinkage limit, and the pH value were taken immediately after mixing, after 1 month, 4 to 6 months, and 18 to 24 months.

Key Findings: There was no essential difference between the sodium and calcium chlorides and neither caused any significant alteration that remained for the duration of testing. Similar results were obtained for the hydroxides (NaOH and CaOH), except that the hydroxides caused relatively high increases in the liquid limit and plastic limit with increases in pH to approximately 12 as well.

Comments: The paper provided very limited data and no meaningful conclusions, as even admitted by the author, who was trying to rely heavily on the plasticity index to describe the soil.