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SYNOPSIS: This paper will present the results of a laboratory testing program and field implementation of the lime column stabilization technique to waste phosphatic clays. Results show increases in clay shear strength by 2 to 3 orders of magnitude and reduce the time of primary consolidation by 1 to 2 orders of magnitude.

1.0 INTRODUCTION AND PROJECT SUMMARY

1.1 Statement of Problem

There are presently more than 85,000 acres of phosphatic clay ponds and clay filled mine cuts in central Florida, with approximately 5,000 acres of additional ponds created each year by phosphate mining. Growth in central Florida counties have been constrained to expand along unmined corridors and around the waste clay ponds. The cities are being developed as if they were archipelagos in a sea of clay. The mining industry has viewed clay ponds as a long-term liability with extremely limited resource potential. The cost to route utilities, roadways, and other development around these areas has been burdensome.

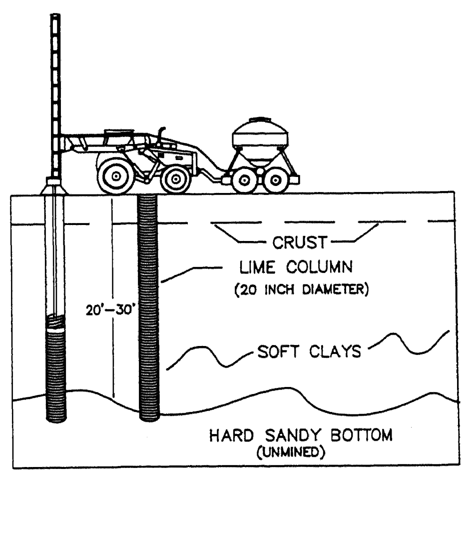
Techniques have been developed to drain, crust, and reclaim these areas, although as presently reclaimed, these areas remain generally only suitable for agriculture or for highly specialized use (such as wastewater effluent disposal areas). Construction of buildings or utilities by conventional methods is not possible, without extensive stabilization or excavation and replacement site work. This is because, just a few feet below the surface crust, the low strength clay remains very soft and compressible due to a high water content (low solids content). For this reason, a need has existed to develop economical and practical techniques to reclaim these areas to a level at which the land can be utilized for a broad range of purposes, including suburban housing or light commercial development.

If lime columns are used to reclaim these areas for construction purposes, support services such as transportation, water supply, and other utilities would be far more efficient, thereby lessening the impact of population growth in the central Florida area. Mined land could be re-used. Finally, the benefit to the local tax base could also be substantial, since lands treated by lime columns would have a much higher commercial value than at present.

1.2 The Lime Column Approach

The lime column method has been used in other countries of the world, primarily in the Scandinavia and Japan, to provide additional bearing capacity and reduced settlements for soft clays, and appears to be suitable for use with phosphatic waste clay. Lime columns are constructed in-situ by intimate mixing of clay and finely pulverized unhydrated lime, or "Quicklime" (CaO). A drilling apparatus is augered into the ground to the desired depth, reversed, and as the rod is slowly retracted, quicklime is injected into the clay by compressed air through a hollow rod in the auger. The auger blades turn to mix the lime with the wet clay as the rods are extracted, leaving behind a column of lime\clay mix which has reduced plasticity, increased permeability, and developed much higher strength characteristics through lowered water content by hydration and bonding by pozzolanic reactions (see Figure 1).

FIGURE 1. Graphical Representation of the Lime Column Installation Process



A two-phase research project was undertaken through the funding of the Florida Institute of Phosphate Research (FIPR) of Bartow, Florida with partial co-funding from the Civil Engineering Research Foundation (CERF) of Washington, D.C. The objectives of this project were to 1) investigate in a laboratory setting the engineering characteristics of phosphatic waste clay mixed with various amounts of lime, and 2) follow up with a field demonstration to evaluate the practical use of lime columns as a soil stabilization technique for structural foundations. Economic and physical constraints of lime columns were considered in choosing the initial condition of the clays prior to testing, as well as the overall testing scheme.

2.0 LABORATORY TESTING PROGRAM

Bulk samples of phosphatic clays used for the laboratory testing program were obtained from active or recently abandoned waste clay ponds at three mines in the Central Florida area. Clay pond selection was based on the results of a literature research effort to identify three sources of clays with low, medium, and high plasticity values, respectively. Plasticity indices (PI) for the clay samples selected ranged from 83 to 209.

Parameters which were laboratory tested were the plasticity, strength, permeability, compressibility, compaction, and pH. Laboratory controlled variables which affected the engineering properties were: 1) the initial strength of the untreated clay, set by the initial moisture content; 2) the percentage of lime admixture; and 3) the time of curing.

Samples were prepared for testing at several initial clay strengths to show the change in properties of clay admixtures over a wide range of initial conditions in the field. Based on available lime columns literature, a minimum initial strength of clay was selected at 42 psf. The moisture content for a clay with a strength of 42 psf corresponds roughly to the liquid limit of that clay, and varies from clay to clay. When the strength is below 42 psf, the clay has a high moisture content and too much lime has to be added to achieve the desired clay strengths. This, in turn, reduces the economical advantage of the process. Clays from each of the three sources were prepared at 42, 84, 167, and 250 psf initial strengths by air drying to the correct moisture content. Quicklime was then added to each sample at 0, 6, 10, 15 and 20 percent lime by dry weight of clay. The quantity of admixture was selected on the basis of the economical and practical constraints on installing lime columns. Each sample was mixed mechanically and cured in a controlled water bath. This process was to first simulate the in-situ mixing effort and then, secondly, to simulate the in-situ curing process under saturated conditions.

The laboratory program described above was comprehensive, involving over 1500 moisture content and strength readings, over 1200 pH tests, 67 Atterberg limit tests, 18 consolidation tests, and 26 permeability tests. In addition, x-ray diffraction, standard Proctor density and leach tests were done on selected samples.

3.0 RESULTS OF LABORATORY SAMPLE TESTING

The shear strength of phosphatic clay was found to be greatly increased when amended with various amounts of lime. The amount of strength gained depends on the initial strength of the clay, the amount of amendment, the amount of time the clay is allowed to cure, and the chemical properties of the clay itself.

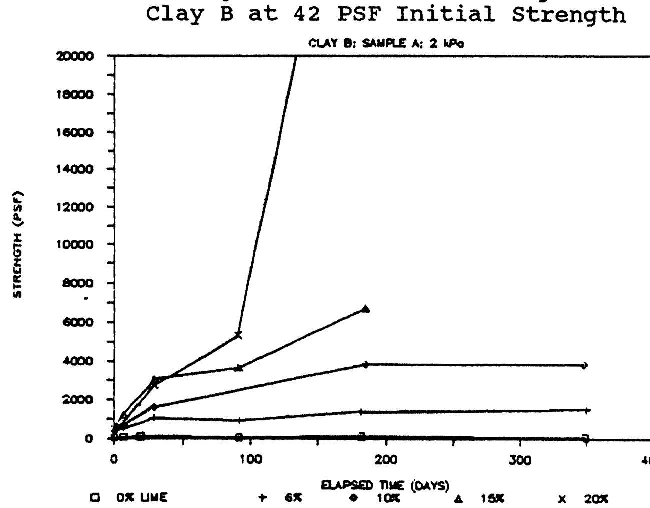
Adding lime to the clays had the immediate effects of reducing both the plasticity and the water content, and increasing the strength. Much of the immediate increase in strength is attributed to the drying out of the clays as hydration of the lime occurs. Table 1 presents a partial listing of the initial strengths achieved for each of the above controlled parameters with each of the three representative clays.

TABLE 1. Initial Strength Gains for 7-Day Curing of Clay Samples of 42 PSF Unamended Shear Strength

CLAY SAMPLE @ 42 PSF SHEAR STRENGTH (UNAMENDED)	7-DAY AMENDED STRENGTHS (PSF) BY % LIME ADDED			
	6%	10%	15%	20%
CLAY A	210	732	857	752
CLAY B	502	732	1270	836
CLAY C	171	288	500	961

Additionally, the strength increase is time dependent, which is thought to be caused by continued hydration and pozzolanic reaction. Figure 2 illustrates the time dependence of strength increase on sample mix B-2 (Clay B with 42 psf initial strength) for various lime contents. As lime content is increased, both the initial strength gain and the cured strengths increase. The benefits of increasing lime content appears to peak between 15 and 20 percent lime by dry weight of clay.The pattern of strength increase versus time for 6 and 10 percent lime indicates that the strength continues to increase only moderately after about 90 days.

FIGURE 2. Strength Gain versus Curing Time for Clay B at 42 PSF Initial Strength



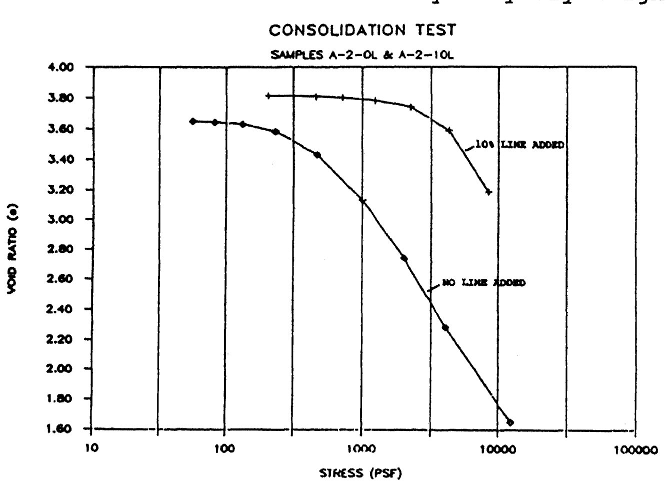
Initial moisture content of the clay is a key factor for the practical implementation of lime columns with phosphatic clay. In other parts of the world, experience has shown that a minimum strength of clay, corresponding primarily to the initial moisture content of the clays, exists below which the manufacture of lime columns is not economically practical.

Although a detailed economic analysis was beyond the scope of this study, preliminary research appears to support the above observations that initial moisture content is key to the economic practicality of lime column use. Samples of phosphatic clay mixed at about 42 psf had an initial moisture content of 130 to 210 percent (32 - 43 percent solids content). In order to reach the 4000 to 8000 psf shear strength range required for construction of 1- to 2-story buildings, 15 to 20 percent lime had to be added to the clay.

Compressibility of clay admixtures was significantly reduced over unamended clay. This is primarily due to cementing/bonding in the clay admixtures, which increases the strength and reduces the magnitude of deformations below the "apparent preconsolidation pressure" (the pressure at which the bonds begin to break down and deformation is increased). In practical terms, this means it takes more load or pressure on amended clay before "virgin" compression is induced. The result is a substantially reduced overall compression or volume change within the range of anticipated field pressure where lime columns might be used (1000-2000 psf).

Compressibility index values indicate that overall deformations of amended clays will be on the order of 1/10th to 1/70th of unamended clay. This means that a house that would have settled a foot without lime columns might only settle an inch if it is founded on lime columns. A comparison of a clay with no lime added to the same clay with 10 percent lime added is shown in Figure 3. Substantial reduction in overall deformations can be seen on the consolidation curve for clay with 10 percent lime. At a pressure of 1000 psf, the unamended clay has deformed almost twice as much as the amended clay.

FIGURE 3. Deformation Characteristics for Clay at 10 Percent Lime by Clay Dry Weight



Permeability of phosphatic clays increased from about one to two orders of magnitude when amended, depending on the type and amount of additive. Permeability of untreated clays averaged 1.8×10^{-4} ft/day (6.3×10^{-8} cm/sec). The average permeability of all treated clays was 1.5×10^{-3} ft/day (5.2×10^{-7} cm/sec), an increase of 8 times. Although the permeability of lime columns is still low compared to most soils), it will be higher than the clay which surrounds the column and therefore it will act as a vertical drain. In an area with lime columns installed, excess pore water pressures induced by the load of the structure will be dissipated through the columns instead of to the surface, and consolidation and settling will occur within months rather than tens of years.

4.0 Field Implementation

The objective of completing a field installation was to demonstrate the lime column method of stabilization as a viable means of stabilizing soft waste phosphatic clays. To accomplish this, several sites were evaluated with regard to size and depth of the clay deposit, accessibility to the site, and solids content profile of the clay. As a condition of funding of this project, site selection was limited to clay settling areas managed by a currently operating phosphate mining company.

Lime columns are installed in the Scandinavian countries using special equipment which has been designed to streamline and optimize the effort. This equipment is not available in the U.S. and would have to be shipped to the project site at great expense. Instead, BCI contracted with Hayward Baker, a specialty contractor experienced in the development and use of ground modification equipment. Hayward Baker, under BCI's supervision and specifications, was tasked to develop, through modification of existing equipment and fabrication of new equipment, the necessary system to install the lime columns using a rotary drill bit and air delivered lime system. For purposes of this project, a total production system was not required, but rather, a functional system which would allow for detailed monitoring and control of lime injection rates.

Having identified an appropriate site for field installation, specific field testing was completed to thoroughly document the initial conditions of the test area. Field measurements included a controlled survey of the exposed desiccated clay surface on a grid pattern to define the existing clay surface elevations, field vane shear testing to profile clay shear strength versus depth, and collection of undisturbed samples throughout the entire profile to determine solid content distribution versus depth. In addition, undisturbed samples were returned to the laboratory for determination of plasticity, permeability, and consolidation characteristics of the untreated clay. These field and laboratory results were used to estimate the total and differential settlement of the untreated reference test area and also to design the percentage of lime and column spacing to be used during lime column installation.

Based on the results of the laboratory testing program and the measured initial strength and moisture content profile of the unamended clay at the test site, it was determined that a lime content of 15 percent by dry weight would be best suited to the field installation efforts. Representative bulk samples of the test site clays were mixed in the laboratory with 15 percent quicklime and cured for 28 days, with periodic shear strength testing completed on these samples during that curing period. Results of this testing confirmed our previous laboratory data that a 15 percent lime rate would provide the necessary strength gains desired and would be appropriate for stabilization of the test site clays.

Following completion of the above test site field and laboratory testing, fill materials were placed over both test plots to a thickness of about 4 feet of sandy fill. This fill was to serve two purposes. First, the fill provides a trafficable working surface for the lime column equipment. Secondly, the fill subjects the clays to an imposed load simulating typical light commercial building loads.

The lime column equipment was mobilized to the site and a testing protocol was established to determine the overall equipment settings that would be used for lime column production. The three variables, or equipment settings, available in the mixing process are 1) the rate of auger withdrawal, 2) the rate of auger rotation, and 3) the lime flow rate to the auger. The rate of auger withdrawal and the rate of lime injection are linked in that setting of one variable controls the other to maintain the required percentage of lime mixed with clay on a dry weight basis. It was found during on-site testing of the prototype equipment that variations in mixing procedures resulted in significant variations in the resultant lime column that was developed. These variations were observed through visual inspection of the mixed lime/clay soils left in the column and vane shear testing with depth following a 24 hour curing period. It became very evident that the site specific conditions of the clay being amended must be put though a pre-production test column program, as a supplement to a detailed laboratory testing program, in order to determine the equipment operation settings most appropriate for achieving the desired lime column results.

Production lime column installation was completed without major incident. A total of 164 columns, averaging 28 feet deep, were installed over a 64 foot square test area. Initial testing of the completed production lime columns has yielded some very encouraging data. Vane shear strength testing of 16 different production columns has shown increases in shear strength between 5 and 10 times the initial unamended clay strengths after 7 curing days. Subsequent strength testing with time continues to show increases of the entire column profile.

5.0 Conclusions

In summary, the laboratory testing program and the field implementation of lime column technology to waste phosphatic clays in central Florida has yielded very promising preliminary results to show that lime columns can be of practical use as a soil stabilization technique. Field implementation has shown that lime column installation in these phosphatic clays can pattern the existing technology used in Scandinavia and Japan with minor modifications to adjust for the extreme plasticity, low initial strength, and high initial moisture content conditions characteristic of phosphatic waste clays.

Evaluation of the completed lime column installation is scheduled to continue through September of 1993. Monitoring of site settlement will be ongoing during this evaluation period, along with periodic measurements of excess pore pressures with depth, and additional shear strength and moisture content measurements with time. If the results of the field monitoring effort follow accordingly to the results achieved in the laboratory testing effort, the effectiveness of the lime column method should be confirmed as a method available to stabilize clay deposits for homes, roadways, light commercial buildings, underground utilities, and a host of other applications. Through the use of this method, potentially thousands of acres of soft clay lands can be made useable for development purposes.

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