Evaluation of Deep In-Situ Soil Stabilization by High-Pressure Lime-Slurry Injection


During the fall of 1965, a soft glacial clayey silt deposit was pressure­injected with a hydrated lime slurry to depths of 20 feet to determine the effects of the lime on the stabilization of the foundation beneath a 40-foot highway embankment in Pennsylvania. Field sampling programs, visual observations and laboratory testing programs were conducted up to one year after the lime slurry was injected. The laboratory testing data on treated and untreated lime samples are discussed in this paper.

High pressure lime-slurry injection was moderately successful in forcing a slurry uniformly into the soft clayey silt deposit. The physical characteristics of the treated soil generally appeared to remain unchanged after one year of in-situ curing, with the exception of the shear strengths which increased.

The results of the project reveal a definite usefulness for the high pressure lime-slurry method of in-situ stabilization in cohesive soils. Need for future investigation leading to successful, practical design applications is discussed.

HYDRATED lime, used to increase the shearing strength of plastic soils at or near the ground surface, has experienced a great deal of success in the past decade. Basically, this method of soil stabilization consists of mechanically mixing proper amounts of hydrated lime and soil and allowing this mixture to mellow before compaction. The ensuing reactions of the mixture reduce the plasticity and increase the shearing strength of lime-reactive soils. Since surface stabilization has obtained favorable results, it follows that some type of subsurface stabilization, 3 ft or more below the ground surface, may be possible. This paper presents the results of an experimental project of stabilizing the foundation for a proposed highway embankment by high-pressure lime-slurry injection to depths up to 20 ft.

In June 1965, the Swindell-Dressler Company, a Division of Pullman Incorporated, under contract with the Pennsylvania Department of Highways, initiated an experimental project involving subsurface lime stabilization of a deep, soft glacial lakebed using high-pressure injection of a hydrated lime slurry. The initiation of this project resulted from the proposed construction of a 40-ft highway embankment over the soft glacial lakebed deposit. A feasibility study involving construction of sand drains, lightweight embankments, embankment counterweights, a bridge, and/or the excavation of the foundation material resulted in the initiation of this project to determine whether deep in-situ lime stabilization could be used to increase the shearing strength of the foundation soils and, therefore, provide adequate support of the highway embankment.

SITE LOCATION

The area of the test site, located 2.5 miles northeast of Portersville on US 422 in the west-central section of Pennsylvania, is a finger of an old glacial lakebed

known as Lake Watts. The top 6 to 8 ft of the test site deposit is a stiff mottled gray-brown clay of post glacial origin. This material is underlain by about 60 ft of soft wet gray varved clayey silt deposited during the time of the glacial lake.

The gray-brown clay, hereafter referred to as the post-glacial deposit, generally classified as an A-7-6 soil having an average cohesion of about 1200 psf. The deeper soft clayey silt, referred to as the glacial deposit, classified as an A-4(8) soil, having an average cohesion of about 200 psf. Embankment stability analyses were conducted using the results of unconsolidated-undrained triaxial shear tests.

Figure 1 shows a cross section of this glacial lakebed area and the proposed embankment.

PURPOSE

The purposes of this experimental project were to determine whether or not the shearing strength would be increased in soils injected with a lime slurry to depths up to 20 ft; to pressure inject a lime slurry to depths up to 20 ft and obtain reliable horizontal and vertical injection patterns; to evaluate the horizontal penetration distance of the injected lime slurry; to evaluate the migration (vertical movement) of the lime slurry at various time periods following completion of the injection process; and to determine the effects of injected lime slurry on the physical properties of the soil.

This paper describes and evaluates the following:
1. Lime-slurry pressure-injection method of soil stabilization;
2. Results of the field soil sampling programs;
3. Results of the laboratory testing program; and
4. Effects of stabilization by the high-pressure lime-slurry injection method on subsurface soils.

CONSTRUCTION OF LIME-STABILIZED TEST MATS

The first phase of the field construction program was the completion of three 6-in. deep lime-stabilized test mats approximately 50 by 50 ft. These mats were constructed using routine surface lime-stabilization techniques. The top soil was removed prior to scarification of the post glacial soil and 5 percent of lime by weight was added, mixed with the soil and allowed to mellow for 3 days. The test areas were then properly compacted to 95 percent standard Proctor density with a sheepsfoot roller, and final rolling was performed using a D-6 dozer.

The three test mats, located in the areas chosen for the lime-slurry injection, were constructed to permit free movement of construction equipment during the lime-slurry injection process and to reduce the amount of lime slurry breaking through the ground surface during the injection process.

Although the project dealt with high-pressure lime injection, block samples were obtained from the test mats. Unconfined compression test results conducted on the samples obtained only 8 days after completion of the mats showed a 50 percent increase in shearing strength. This increase was not as large as expected because of the unusually cool October temperatures which occurred during the 8-day test period. Past research has shown that lime-soil reactions effectively occur at temperatures above 60°F.

LIME-SLURRY INJECTION PROCESS

The second phase of the project consisted of injecting a lime slurry into the soil to depths of 20 ft in a manner that would permit a complete study and analysis of the horizontal and vertical injection patterns as well as to obtain undisturbed samples for laboratory testing and evaluation.
The process of injecting a lime slurry into the subsurface to depths over several feet is a new and relatively untired technique. The concept of high-pressure injection used on this project differs from standard grouting techniques where the voids of a granular soil are filled with a chemical compound. In the lime-injection method, a slurry under high pressure is forced horizontally into the soil by rupturing the in-situ structure and is forced along existing cracks and fissures. After a sufficient period of time, the lime apparently migrates (moves vertically) through the soil and reacts with the soil, thereby increasing the soil's shearing strength (Fig. 2).

Completely automatic equipment was used to inject, at pressures of 300 and 600 psi, specified quantities of slurry at the desired levels. Eight to twelve gallons of slurry were injected every 6½ in. as the nozzle moved downward. The slurry used throughout the project was a mixture of 30 percent lime and 70 percent water by weight.

The slurry was injected at intervals beginning at 18 in. below the ground surface and continued to the desired depths. The injection nozzle was tapered to help prevent leakage up along the drill rod and to make a self-sealing hole as the rod was advanced into the soil (Fig. 2).

Although the injection bit was tapered, quantities of lime slurry broke through the mats around the injection rod and as far as 10 ft away from the injection hole. These breakthroughs were manually suppressed in areas away from the injection rod. However, the leakage was considerable and difficult to control at the injection rod. This loss, estimated at approximately 25 percent, usually occurred when the injection bit was in the deeper soft clayey silt. Since the soft glacial soil did not hold a tight seal against the injection nozzle, the slurry followed the path of least resistance and was lost by flowing back up along the outside of the injection rod. This loss of slurry indicated that the lime did not penetrate the softer soil to the extent that it did in the harder post-glacial material. This was later confirmed during the soil sampling programs.

SUBSURFACE EXPLORATION PROGRAM

After the completion of the lime-slurry injection, three subsurface exploration investigations were conducted. These investigations entailed the construction of trenches for visual observations (horizontal and vertical) of the injected lime and soil borings which included standard penetration testing to determine the horizontal and vertical locations of the injected lime and 2½-in. undisturbed thin-wall sampling for laboratory testing.

The first sampling phase, conducted one month after the lime-injection program, included a trench 3 ft wide and 8 ft deep located between two rows of injection holes and 4 soil borings located on one test site.

The second sampling phase, conducted three months after the lime-injection program, included 18 soil borings located on two test sites.

The third and final sampling phase, conducted one year after the lime-injection program, included a 3-ft wide by 8-ft deep trench located between two rows of injection holes and 33 soil borings located on two test sites.

The three soil sampling phases included a total of 57 soil borings, 492 linear feet of sampling, 240 standard penetration tests and 108 undisturbed thin-wall samples.

The subsurface exploration program determined the horizontal and vertical locations of the injected lime slurry, indicating the success of the injection process. Also, this exploration was conducted to obtain undisturbed samples for visual and laboratory analyses.

During the first soil sampling phase a trench was constructed parallel to two rows of injection holes with the face of the trench located about 5 ft from a line of injection holes. To help visually demonstrate the injected lime patterns, a
phenolphthalein solution (pH indicator) was sprayed on the face of the trench. The critical pH for the indicator is 8.3 but color changes occur around 7.0 to 7.3. Photographs 1 and 2, taken one month after the injection program, show the face of the trench sprayed with the indicator. The 8-ft deep trench shows the injection pattern in the post-glacial deposit only. Due to the walls collapsing, the trench could not be constructed deeper. The area of lime influence is about \( \frac{1}{4} \) to \( \frac{1}{2} \) in. above and below the horizontal lime seams.

To supplement the trench construction, 4 borings were drilled near injection holes to determine if the slurry had penetrated the soil in the glacial deposit from depths of 8 to 20 ft.

The second sampling phase consisted of 19 borings located on the various test sites. Lime seams (injected lime) were consistently encountered in the post-glacial material in all but 4 borings, but in the glacial deposit, lime seams were encountered in only 5 of the 19 borings.

The third and final sampling phase consisted of a trench located between two rows of injection holes in the same manner as during the first sampling program and 34 borings. The borings were located to insure that the thin-wall samples taken would contain lime seams suitable for laboratory analysis. This was accomplished by continuously sampling 8 pilot holes to locate the injected lime. Following this, 26 test borings were located about \( \frac{1}{2} \) ft from the pilot holes and samples were taken at the desired depths.

As previously done, a trench similar to the first was constructed and sprayed with a pH indicator. Photographs 3 and 4, taken one year after the injection program, show the face of this trench. Again, the trench was dug from 0 to 8 ft and shows only the injection pattern for the post-glacial deposit. The area of lime influence has increased to \( \frac{1}{4} \) to \( \frac{1}{2} \) in. above and below the horizontal seams. This is clearly indicated by comparing Photograph 2, taken one month after the lime injection and Photograph 4, taken one year after the lime injection.

The results of the sampling program clearly show that the lime slurry easily penetrated the post-glacial soil in consistent horizontal and vertical patterns up to 5 ft from the injection holes.

LABORATORY TESTING PROGRAM

The laboratory testing program was divided into testing of the lime-treated post-glacial soils and glacial soils, with control tests on untreated samples. Moisture contents, Atterberg limits and grain size analyses were performed in accordance with AASHO test procedures; permeability and unconsolidated-undrained triaxial shear tests were performed in accordance with ASTM test procedures. All tests were conducted on undisturbed soils taken from thin-wall samplers. The results of the testing program were developed graphically for comparison of the properties of the lime-treated and untreated soils for the glacial and post-glacial deposits. All samples were sprayed with the pH indicator before testing to determine the presence of lime in the samples and to help insure that each test was conducted on either a completely treated or untreated section of the soil sample.

Throughout the discussion of the laboratory test results, the following factors should be kept in mind:

1. The lime and soil were not mechanically mixed as is normally the case in laboratory research and surface stabilization; therefore, the reaction was retarded since the injected material must mix with the soil by vertical migration.
2. The reaction of the lime and soil are dependent on the amount of lime migration into the in-situ soil. Since these soils had permeabilities ranging from 0.1 to 12 in. per year, large migration of the slurry could not be expected for several years. From past research by R. L. Handy and L. K. Davidson, the rate of calcium migration expressed in the form \( d = k \sqrt{t} \) resulted in a \( k \) value of 0.081 in./day, where \( d \) is distance, \( t \) is time and \( k \) is a constant depending on soil factors. On this project the \( k \) values were 0.085 and 0.067 in./day after one month and one year, respectively. This is in reasonably close agreement with the past research on rates of calcium migration.

3. The ground temperature at which the reactions occurred was between 45 and 48 F, which is substantially below minimum temperature recommended for proper curing.

Post-Glacial Deposit

Moisture Contents—Figure 3 indicates that the moisture content prior to injection of the slurry and one year after the slurry injection remained unchanged. This was expected for the following reasons:

1. The lime was injected in slurry form (70 percent water), so initial absorption of moisture could not occur. This is contrary to surface stabilization where dry hydrated lime is used and the initial drying action is due to the adsorption and evaporation of water during mixing and manipulation.

2. The low permeabilities, ranging from 0.1 to 12 in./year, and a small driving head prevented significant movement of any freed pore water. Although the cation exchange (\( \text{Ca}^{++} \) replacing bonded water) releases the oriented pore water, the soil's low permeability resulted in the moisture content remaining unchanged.

Atterberg Limits—Figure 4 indicates that a slight reduction in the plasticity index occurred in the treated soils. This reduction, reported in previous laboratory research, is due to flocculation, agglomeration, cation exchange and pozzolanic reactions.

A marked reduction in the plasticity index has been achieved in field and laboratory testing where lime and soil are mechanically mixed and exposed to the air. However, on this project, migration of the lime is the only way that the soil and lime could intermix and react. After one year under field conditions, the reactions are not believed to be complete. Therefore, the reduction in plasticity index was nominal.

Particle Size—Grain size analyses for lime-treated and untreated soil, indicate that no change in the particle sizes has occurred. This can be attributed to the following:

1. As previously mentioned, only partial flocculation, agglomeration, cation exchange and pozzolanic reaction have occurred. These partial reactions may not
Failure sketches of the lime-treated samples are included in Figure 6 to illustrate the type of failures and the reason for the lack of strength increase. All treated samples contained lime seams and failed along these seams except for the two samples noted. Therefore, the triaxial tests were only indicative of the strength on the plane of the lime seam and not of the reacted soil. Visual observations indicate the magnitude of strength increases which have actually occurred.

**Glacial Deposit**

Moisture Contents—Figure 3 indicates, as it did for the post-glacial deposit, that the moisture content prior to injection of the slurry and one year after the slurry injection remained unchanged. This was expected for the reasons listed previously.

Atterberg Limits—Figure 7 indicates that the plasticity index has remained essentially unchanged. As previously mentioned, due to the incomplete reactions under the field conditions of the project, an appreciable change in the plastic properties was not expected.

Particle Size—Grain size analyses for lime-treated and untreated soil, indicate that no change in the particle sizes has occurred. As previously discussed, this is attributed to the incomplete reactions and the inability of these reactions to resist the destructive laboratory procedures used when preparing samples for testing.

Shear Strength—Figure 8 indicates that a more than twofold strength increase has occurred for the lime-treated samples.

Figure 9 also indicates that strength increases occurred and that the plastic soil showed brittle failure properties when treated with lime. Three of the treated samples showing strength increases exhibited plastic failure properties. To illustrate the reason for these failures, sketches of the samples after testing are included. The bottom of these three samples was untreated

be significant enough to appreciably alter the particle sizes.

2. What may be more significant is that these partial reactions may not be strong enough to resist the standard laboratory procedures conducted when preparing samples for testing. Specifically, the dispersant used in the test may reduce flocculation and agglomeration effects. This could easily destroy these weak lime-soil reactions and give results which show no change in particle size.

Shear Strength—Figure 5 indicates that no appreciable strength increase has occurred except for the two lime-treated samples noted. Figure 6 also indicates that strength increases did not occur and that the elastic properties of the lime-treated and untreated soil remained essentially the same.

**Figure 6. Deviator stress vs unit strain.**

**Figure 7. Plasticity index vs liquid limit.**
PHOTOGRAPH 1 - Face of trench one month after lime was injected. Red areas show horizontal penetration and vertical migration of injected lime slurry in post glacial deposit.

PHOTOGRAPH 2 - Face of trench one month after the lime was injected. Note, the vertical migration of the lime was about 1/2 inch above and below the lime seam.
PHOTOGRAPH 3 - Face of trench one year after lime was injected. Red areas show horizontal penetration and vertical migration of injected lime slurry in post glacial deposit. Note that the lime slurry seams are white prior to spraying with pH indicator.

PHOTOGRAPH 4 - Face of trench one year after lime was injected. Note, the vertical migration of the lime was about 3/4 to 1-1/2 inches above and below the lime seam.
The failure occurred in the lower portion of the samples and the treated portion (upper 90 percent) remained essentially unchanged in appearance.

**OBSERVATIONS**

Throughout the subsurface exploration program and laboratory testing program observations of the treated and untreated soils were noted. Although these observations do not represent numerical values, they do help to explain the increased shear strength characteristics of the treated soils which in many cases were difficult to measure by conventional field and laboratory testing procedures.

**Post-Glacial Soil**

During the construction of the two trenches in the lime-injected areas, a definite change in the soil strength was noticeable. These observations were made as the soil on the face of the trench was scraped off with a putty knife.

In the first trench, excavated one month after the slurry was injected, the soil near (1/2 in. above and below) the lime seams appeared to be somewhat stiffer. This apparent strength increase always occurred in areas where the pH indicator showed that the lime had migrated. However, this strength increase was not large enough at the time to make any definite conclusions concerning the lime-soil reactions.

During the inspection of the second trench, excavated one year after the slurry was injected, the soil near (1 1/2 in. above and below) the lime seams had the characteristics of a badly weathered clay shale. A putty knife could not penetrate these treated areas above and below the seams.

These same observations were noted in the laboratory when the undisturbed soils were removed from the thin-wall samplers. In many cases the samples recovered after 1 and 3-month periods could not be cut with either a laboratory spatula or a sample trimmer. Some of the samples, obtained one year after the slurry was injected, were trimmed for testing with a hacksaw blade, since the regular laboratory tools would not penetrate the treated areas. From these observations, it appears that a definite reaction and strength increase has occurred in those areas where the lime has migrated.

**Glacial Soil**

Although trenches could not be constructed in the deeper glacial deposit, several pertinent observations of field and laboratory samples were noted. In a number of split-spoon samples, a definite area of the sam-
ple held its original shape (that of the spoon) when the sampler was opened; in other areas soil in the spoon sample quickly lost its shape and flattened out. These more stable areas showed a pH reaction when the indicator was applied. This observation confirmed that the lime-soil reaction had strengthened the soil.

The majority of samples taken in the glacial deposit, which showed a pH reaction, did not have visible lime seams such as in the post-glacial deposit, indicating that migration in the glacial deposit was more extensive than in the post-glacial. Apparently this was due to the fact that the glacial material was originally coarser grained and thus more permeable.

CONCLUSIONS

1. Shear strength increases occurred in the in-situ soils treated by the lime slurry. The strength increases were observed one year after the lime slurry was injected and to depths up to 20 ft.

2. The magnitude of the strength increase in the soil one year after injection of the lime slurry was difficult to determine accurately by laboratory testing. Although the third sampling program was extensive, only a few samples recovered were completely reacted with the lime and did not contain a lime seam. Those samples which were completely reacted and did not contain lime seams showed an appreciable strength increase.

3. The moisture contents, plasticity indices and particle sizes of the lime-treated samples were not appreciably altered after one year of curing time, except for the plasticity index of the post-glacial soil.

4. A one-year waiting period between slurry injection and laboratory testing is not sufficient time for the complete occurrence of lime-soil reactions under the conditions on this project.

5. The field method of lime-slurry injection was successful in penetrating the post-glacial deposit, but only moderately successful in penetrating the glacial deposit.

6. The high-pressure lime-slurry method of soil stabilization can be used successfully to stabilize soft soils beneath proposed highway embankments provided that injection equipment and additives can be developed which will aid in the penetration and migration of the lime into the soil.

NEED FOR FURTHER INVESTIGATION

This project has demonstrated that high-pressure injection of a lime slurry into a clayey soil at depths up to 20 ft to increase the shearing strength of soils can be accomplished. To date, little research has been conducted on the effects of high-pressure soil stabilization on soft clayey soils and to our knowledge no one has tried to measure the undisturbed strengths of pressure-injected lime-treated soils. Further research into the strength increases of clayey soil, 20 ft and deeper below the ground surface, should be undertaken to better determine effects of high-pressure soil stabilization by lime injection.

The following suggestions are offered for future research:

1. The field injection equipment should be modified considerably to insure that the injected slurry is more effectively and accurately forced into the subsurface.

2. Actual test embankments should be constructed on treated and untreated test areas to study the effects of consolidation on the migration of the lime slurry and to observe the stability of the treated versus untreated areas.

3. More extensive sampling and testing programs providing longer curing periods between injection and testing are suggested to obtain more laboratory data documentation of strength increases.

4. Introduction of additives into the slurry to increase the speed of the reac-

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tion, increase of the migration, and increase the strength of the treated soils should be attempted and analyzed.

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REFERENCES