International Building Lime Symposium 2005
Orlando, Florida, March 9 -11, 2005

2005
INTERNATIONAL
BUILDING LIME
SYMPOSIUM

LIME APPLICATIONS FOR SITE AND INFRASTRUCTURE CONSTRUCTION*

Eric A. Berger[1]

Abstract

Lime soil-stabilization plays an important role in transportation and industrial/commercial development. Fine-grained clay soils that are generally regarded as unsuitable for structural use can be chemically transformed into strong, stable, non-expansive materials that make a structural contribution to infrastructures built on them. The chemical transformation is permanent and can result in significant cost savings over other engineering solutions. This paper examines the chemistry of the lime/soil reaction, proposes design and testing protocols, describes fundamental quality control procedures, and highlights cost benefits that may be achieved by choosing lime stabilization.

Keywords

Lime, soil, stabilization, construction

The views presented in this paper are solely those of the authors. The National Lime Association (NLA) and the Building Lime Group assume no liability or responsibility for any errors, omissions, or other limitations in this paper or for any products, services, or methods presented. This paper is intended for use by professional personnel competent to evaluate the significance and limitations of the information provided and who will accept full responsibility for the application of this information. NLA and the Building Lime Group do not intend to infringe on any patent or other intellectual property right or induce any other party to do so, and thus users of this document are responsible for determining whether any method, technique, or technology described herein is protected by patent or other legal restriction.

---

[1] Eric A. Berger, Project Manager, R&D, Chemical Lime Company, USA, eric.berger@chemicallime.com

1 Introduction

Although virtually all of the papers in this Symposium address the use of building lime in mortars, stuccos, and plasters, lime can also be used to treat wet or unstable soils to greatly facilitate construction activities. Fine-grained soils (clays and silts) are problematical for construction because they are subject to expansion and contraction resulting from changes in moisture and subject to substantial variability in bearing capacity. Lime, sometimes in combination with added pozzolans, can react chemically with clays to produce pozzolanic cements that are stable, non-expansive, and strong enough to contribute to the structural section being designed to support the intended infrastructure. Lime is also used to dry-up wet soils and to temporarily modify soils to create stable construction platforms. Following is a survey of the general chemistry of the lime/soil reaction; a protocol for designing lime stabilization projects; quality control/assurance elements that are critical for the construction of projects; and, an assessment of cost savings that can be achieved by using lime stabilization.

2 Lime for site construction

Lime's uses in road and site construction range from simple dry-up to complete stabilization of fine-grained soils. Because hydration of quicklime is highly exothermic, it can be advantageously used when any construction site is too wet for work to proceed. High-calcium quicklime will generate 490 Btu/lb during hydration (Boynton, 1980). In other words, each pound of pure quicklime that is added to a construction site can raise the temperature of 3.4 lbs of water from 70° F to boiling. Because of that simple reaction, the addition of only one to two percent of lime by weight of soil is extremely useful as a construction expedient. The addition of small percentages of lime to clay soils can also substantially improve the workability of those soils for construction of temporary haul roads or lay-down areas that will be abandoned when a project is completed.

Of substantially greater value, and the principle use of lime in roadway and site construction, is lime's ability to permanently stabilize fine-grained soils by transforming them into high-quality construction materials. The chemical reactions that produce the soil changes are applicable not only to roads and building pads, but also to site elements such as embankments and canal linings. The technology involved in lime soil-stabilization is mature and robust, supported by decades of laboratory research and thousands of field projects. Stabilization can be accomplished using several different methods. Most commonly, lime is spread across the site, either dry or in slurry form, and mixed in-place using large roto-mixers. Depending upon site constraints, it can also be pressure-injected or mixed off-site and transported to the foundation being constructed. Each of those techniques will be discussed later in the paper. Properly constructed lime-stabilized soils will perform for the life of the project, providing strength and stability in otherwise unstable ground.

3 Chemistry of lime soil-stabilization

Clay soils have been among the most difficult materials on which to build any type of infrastructure. They are characterized by an affinity for water that causes them to swell and shrink depending upon environmental conditions. When clay soils are dry and suitably compacted, they can have substantial bearing capacity, but as they become successively more saturated with water, that bearing strength reduces and can disappear altogether. The resulting soils movement contributes to damage that commonly totals billions of dollars each year in the United States.

Clay minerals are composed of several combinations of oxygen, silica, and alumina molecules that are configured in a variety of plate-like structures. They have very large surface areas, ranging from 3,000 ft^2/oz for kaolinite to 120,000 ft^2/oz for smectite clays. The particles carry a net negative surface charge that causes them to attract naturally-occurring cations in the soil and dipole molecules, such as water. When water molecules attach to the particle surfaces, the water acts as a lubricant and the layers of plates swell and tend to slide laterally with respect to each other. As a result, the soils become unstable, which often translates into distress to infrastructure built upon them.

In the presence of water, lime forms calcium (Ca^{++}) and hydroxyl (OH^{-}) ions that react chemically with clay soils. In a span of seconds to minutes, the powerful calcium ions migrate to the clay surface, replacing the existing cations and water molecules. The texture of the clay changes from a plastic, sticky substance to a more granular and friable material in a process that is called "flocculation and agglomeration". At the same time that the soil texture is changed, the structure of the clay particles is attacked by the high pH environment induced by saturation of the soil with calcium hydroxide ($Ca[OH]_2$). The elevated pH (ideally about 12.4) solubalizes the silica and alumina components of the clay and allows them to combine with calcium and water to form cementitious calcium-silicate-hydrates (CSH) and calcium-aluminate-hydrates (CAH)—see Figure 1. Formation of those pozzolanic cements, which occurs over a span of weeks and months, produces the strength and stability that characterize lime-stabilized soils. Table 1 summarizes the chemical stages of lime-stabilization of soils.

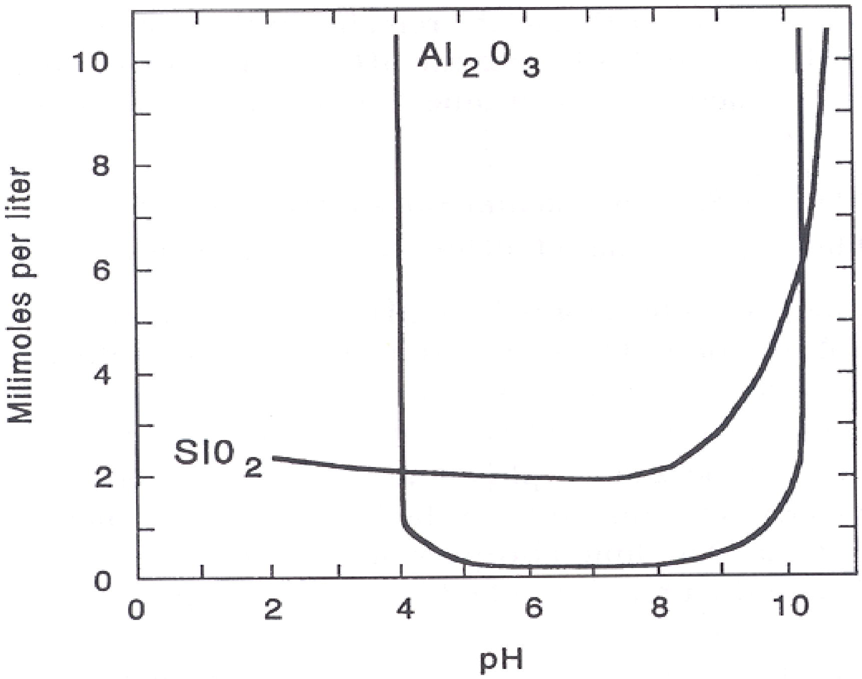

Figure 1- Solubility of Silica and Alumina by Change in pH

Table 1 The Chemical Stages of Lime Stabilization of Soils

#	Process	Reaction	Effects	Speed
1	Hydration of quicklime (calcium oxide) to calcium hydroxide.	$CaO + H_2O \rightarrow Ca(OH)_2$	Consumes water & releases heat. Drying action for muddy soils. Required to put lime in a form that reacts with pozzolans[2].	Fairly fast Sec–Min
2	Saturation of the waters with calcium hydroxide.	$Ca(OH)_2 \rightarrow Ca^{+2}_{aq} + OH^{-1}_{aq}$	pH increases. Calcium ion becomes mobile.	Fast Seconds
3	Saturation of ion exchange sites on clay particles with calcium ions. Increase concentration of ions both in pore water and double water layer.	Ca^{+2}_{aq} + Na-clay $\leftrightarrow$ Na^{+1}_{aq} + Ca-clay	1) Ca^{+2} occupies cation sites. 2) The ionic double layer thickness decreases. 3) Water bound to clays released from double layers. 4) Clays coagulate and flocculate. 5) The physical properties of clay minerals change.	Fast Seconds in aqueous and minutes in soil environment
4	Alkaline attack on silicate minerals.	$SiO_2 + H_2O + OH^{-1}_{aq} \leftrightarrow H_3SiO_4^{-1}{}_{aq}$	Strong function of pH. See chart 1 below. pH ≥ 10.5	Moderate Min–Hrs
5	Alkaline attack on aluminous minerals form aluminate ion.	Al^{+3}-mineral + $4OH^{-1}_{aq} \leftrightarrow Al(OH)_4^{-1}{}_{aq}$	Strong function of pH. See chart 2 below. pH ≥ 10.5	Moderate Min – Hrs
6	Polymerization of silica-complexes[3], for example:	$Si_3O_5(OH)_5^{-3}$, $Si_4O_6(OH)_6^{-2}$, etc.	Preparation for colloid and gel formation preparatory to new mineral precipitation.	Moderately fast Min–Hrs
7	Formation of hydrous calcium alumino-silicate colloids & gel as pH stabilizes or drops due to hydroxyl consumption, e.g.:	$H_3SiO_4^{-1}{}_{aq} + Al(OH)_4^{-1}{}_{aq} \leftrightarrow AlSiO_2(OH)_5^{-2} + H_2O$ $x\,Ca^{+2}_{aq} + AlSiO_2(OH)_5^{-2} \leftrightarrow (Ca_xAlSiO_2(OH)_5)^{-2+2x}$	Presumably pore filling CAH - CSH- like materials. Some strength development	Moderately slow Hrs – Days
8	Formation of hydrous calcium-aluminosilicate minerals, e.g.:	Chabazite, $CaAl_2Si_4O_{12}$•6H2O; Tobermorite, $Ca_5Si_6O_{16}(OH)_2$•$4(H_2O)$	Strength development – requires considerable silica, therefore needs maintenance of high pH.	Slow Days – Weeks – Mos–Yrs

---

[2] **Pozzolan** - "Finely divided siliceous or siliceous and aluminous material that reacts chemically with slaked lime (calcium hydroxide) at ordinary temperature and in the presence of moisture to form a strong slow-hardening cement", [*Italian pozzolana (1706)*], Webster's New Ninth Collegiate Dictionary, 1983, p. 923. Pozzolans include many clay minerals, fly ash, finely divided silica, volcanic ashes, and natural and synthetic siliceous glasses.

[3] Andrew R. Felmy, Herman Cho, David A. Dixon, James R. Rustad, Zheming Wang, and Gregory R. Choppin, 2000, The Aqueous Thermodynamics and Complexation Reactions of Anionic Silica Species to High Concentration: Effects on Neutralization of Leaked Tank Wastes and Migration of Radionuclides in the Subsurface, http://www.pnl.gov/emsp/fy2002/presentations/index.html

In general, the design of lime-stabilized layers adds only one test to those that are customarily performed in geotechnical assessment of any fine-grained soil:

- The plasticity of the soil is evaluated; the grain size distribution and clay fraction are quantified;
- The moisture/density relationship of the soil is determined; bearing strength is assessed; and,
- Often, expansivity is evaluated.

Based upon those tests, the engineering properties of the soil are identified and the structural attributes are incorporated into the design of the road, building, or other structure. Because fine-grained soils are highly problematic, the design often requires that they be excavated and replaced with better materials or mitigated using moisture conditioning or expensive foundations.

An assessment of the potential benefit of lime-stabilizing the soil adds a single test to those just described. The Eades-Grim test (ASTM D 6276 Standard Test Method for Using pH to Estimate the Soil-Lime Proportion Requirement for Soil Stabilization) measures the pH of the candidate soil as successively greater percentages of lime are added to soil samples. When the pH reaches approximately 12.4, the soil is saturated with the calcium and hydroxyl ions that should produce both textural transformation and permanent strength gain—see Figure 2. To confirm that premise, the lime-treated soil should be tested as described above to evaluate its improved properties.

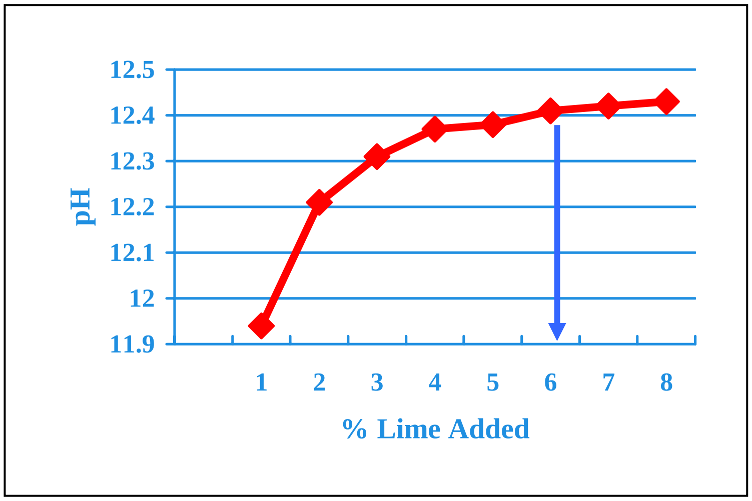

Figure 2 – Typical result from Eades-Grim pH test

3.1 Property changes of lime-stabilized soil

Because lime chemically changes the clay soils to which it is added, the properties of those soils will change as well. For instance, the transformed soil will have a lower unit weight than the native soil, as well as higher optimum moisture content—see Figure 3. Those changes need to be taken into account when developing the final moisture/density curves for the treated material.

To obtain test results that accurately characterize the lime-treated material, the soil should be blended with the optimum percentage of lime based upon the dry weight of the soil. The blended material should be allowed to “mellow” in an airtight container, at above optimum moisture content, for 24 hours. That mellowing time will allow the cation exchange to occur and the soil properties to begin to change. Samples for assessment of strength, expansivity, etc. can then be fabricated and cured for an appropriate length of time. The soil from which the samples are fabricated should also be up to 3 percent above optimum moisture content to provide sufficient water for formation of the pozzolanic cements. As was done during the mellowing period, the samples should be cured in airtight containers. During the curing period, the soil transformation will continue, its plasticity will diminish substantially, and its strength will slowly increase, producing a stable material with significant bearing capacity.

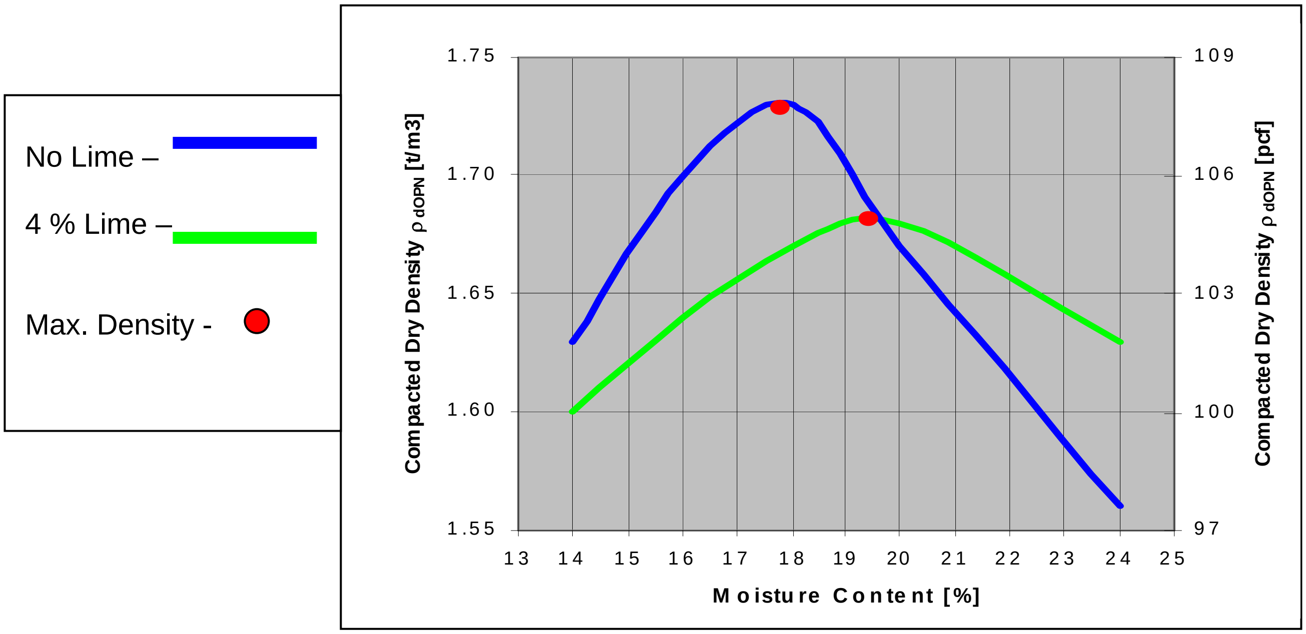

Figure 3 - Change in Unit Weight and Optimum Moisture Content

4 Construction of lime-stabilized subgrades

Lime can be introduced into the soil in a variety of ways, depending upon the size and objectives of the project. Most commonly, either dry quicklime fines (-1/4 inch) or slurry, manufactured from either quicklime or hydrated lime, is used. Dry hydrated lime is not commonly used in soil applications due to its small particle size and tendency to produce undesirable dust. Lime slurry can either be manufactured in central facilities or portable tanks at the job site. In either case, lime and water are combined in measured amounts to achieve the desired percentage of solids. Each of the products will produce quality projects as long as attention is paid to applying the equivalent percentage of calcium whether in oxide or hydroxide form.

The most common method used to mix lime into the soil is to spread the dry or slurried lime with a tanker truck and blend it into the soil using a “rotomixer”, which resembles a very large rototiller. Several passes with the mixer are generally necessary to pulverize the soil and to insure that the lime is distributed evenly throughout the project. Repeated watering of the soil is also necessary to provide sufficient moisture for the chemical reactions. For smaller projects, such as building pads, lime slurry is sometimes pressure-injected into the soil. A grid is laid out with sufficient spacing between holes so that the lime that is injected into adjacent holes will penetrate the soil and meet, fully covering the site. Pressure-injection is most appropriate in soils having moderate plasticity, since those soils fracture more easily than heavier clays. A third method of mixing lime with soil employs a stationary pugmill. This is the most expensive method, since the soil must be excavated, transported to the pugmill, blended with lime and water, and transported back to the project. However, use of a pugmill may be the best alternative for projects with significant access restrictions.

Once mixed into the soil, the lime must be allowed to mellow in order for the cation exchange to occur and the larger clods of clay to break down. For most soils, overnight mellowing is adequate, though several days of mellowing and repeated remixing may be required for some very heavy clays. During the mellowing period, the soil should be watered to insure that adequate moisture is available for the chemical changes to take place. After mellowing, the soil should appear sandy and friable.

Following the mellowing period, the soil is remixed to insure that the lime is thoroughly and evenly incorporated. At this point, the mixture should be at optimum moisture content or higher to allow maximum strength gain. After final mixing, the soil can be compacted, usually using a sheepsfoot type of roller followed by a smooth drum or pneumatic roller. The finished layer must then be moist-cured for a period of time generally ranging from two to seven days. When the stabilized layer is stiff enough to support construction traffic without significant deflection, it can be covered with whatever material it has been designed to support. Until that layer is placed over the lime-stabilized soil, it should be kept moist to minimize incidental cracking that might occur if it is allowed to dry out.

5 Quality control and assurance

Like any other construction process, the best designed lime-stabilization project must be correctly built if it is to perform according to plan. Several processes should be tracked and documented to assure that a quality project is constructed.

- Lime content – The lime content percent is based upon the dry unit weight of the soil being stabilized. The quantity of lime needed for a project can be calculated from the area being stabilized and the depth of the treatment. Lime delivery to the site can be assured by collecting certified weight slips from each of the delivery trucks. In the case of lime slurry deliveries, the quantity of lime can be calculated based upon the percent solids of each load of slurry.
- Lime spread rate – When dry quicklime is applied, the spread rate can be checked by placing a pan of known dimensions between the wheels of the spreader truck, collecting lime as the truck passes over the pan, and weighing the contents of the pan. By comparing that weight to the calculated theoretical spread rate, accurate application can be assured. With the known percent solids of slurry being produced and delivered to the site, an area can be calculated over which each tanker should distribute its load. Stakes can be used to mark that area to insure an accurate spread rate.
- Pulverization – In the initial mixing, the soil should be pulverized as thoroughly as possible, ideally to a point where the largest non-stone particle is no larger than two inches. That may not be possible in heavy clays, and additional mixing passes may be necessary during the mellowing period. After mellowing and remixing, most specifications require that 100 percent of the non-stone material must pass the one inch screen, and 60 percent must pass the number 4 sieve.
- Depth of lime treatment – Rough grading of a section to be lime-stabilized must be accurate to insure that the correct final depth is maintained throughout the project. The depth of treatment can be confirmed by digging a small hole to the design depth and spraying the sides and bottom with a pH-sensitive indicator such as phenolphthalein. The indicator should change color where the highly alkaline lime is present.
- Moisture content – For complete stabilization and optimum strength gain, moisture content of the stabilized layer should be maintained approximately three percent above optimum for the treated soil until final compaction. Final compaction should be performed at or above optimum moisture content for the same reason. During curing and until the stabilized layer is covered, it should be kept moist to promote strength gain and prevent incidental cracking.
- Density (proctor curve for treated soil) – The stabilized soil will be different from the native soil by possessing a lower unit weight and higher optimum moisture content. Those property changes must be taken into account if design density is to be achieved.

- Weather limitations – Chemical reactions in the stabilized layer slow dramatically during cold weather. Typically, stabilization is not performed when the air temperature is below 40° F. In freezing zones, stabilization should be completed in time to allow the layer to gain sufficient strength to resist the frost. If that is not possible, the stabilized layer should be protected until the weather warms.

6 Sulfate soils

In the Western United States and numerous other parts of the world, concentrations of water-soluble sulfate minerals are sometimes found in clay soils. When such soils are stabilized with lime (or any other chemical stabilizer that contains calcium, such as cement or fly ash), highly expansive minerals, called ettringite and thaumasite, sometimes form. If the sulfates are not known to be present and ettringite or thaumasite form unexpectedly, the stabilized layer and infrastructure built upon it can experience significant distress. If the sulfates are identified prior to construction, special techniques can be employed to mitigate their impact. If sulfates are suspected, additional testing is warranted to determine their concentration and evaluate the potential risk to the project. Improved identification and risk assessment techniques are currently under development and should be generally available in the near future.

7 Landscaping

The addition of lime to soil increases its pH and changes its properties to produce a strong, stable, and relatively impermeable structural section. When correctly designed and constructed, the finished layer should retain a pH greater than 10 for months, if not years. Consequently, lime-stabilized layers are not conducive to landscape plantings. When landscaping is desirable on a project, top soil can be placed on top of the stabilized layer, and shallow-rooted plants and grasses can be successfully grown. If such a strategy is planned, care should be taken to insure that the underlying stabilized layer drains laterally so that excessive water is not retained. For deeper-rooted plants and trees, oversized holes can be excavated in the stabilized layer and suitable soil can be imported for the plantings.

Once a correctly stabilized soil has begun to develop strength through the formation of pozzolanic cements, lime is unlikely to leach into surrounding areas. Research completed in Germany several years ago (Bollens, 2003) determined that calcium and hydroxyl ions migrated only a few inches into adjacent soils before being neutralized. Consequently, neither water quality nor features located near lime-stabilized roads, building pads, or parking lots should be adversely affected.

8 Cost savings

Mitigation of fine-grained clayey soils so that they can be used for structural purposes is often very costly. Traditionally, unsuitable soils were removed and replaced with aggregates or select fill materials prior to construction of additional infrastructure. Increasingly, however, that alternative has become less attractive due to high costs, restricted availability of quality replacement fill, and disposal costs of excavated clays.

Another alternative has been to moisture-condition the soil to control its expansive characteristics prior to building on it. Moisture-conditioning often reduces the bearing capacity of the soil, resulting in elaborate foundation systems or thicker structural sections on top of the clay. In addition, sophisticated drainage systems may need to be installed to assure that the moisture content of the clays remains constant over time.

Lime soil-stabilization can be an attractive alternative when clay soils are encountered. The existing soil will be utilized, saving excavation and disposal costs. Further savings are realized by eliminating costly imported aggregates or select fill. The stabilized section often develops strengths high enough that the structures built upon it can be reduced in thickness, resulting in further cost savings. In urban and suburban areas, truck traffic on surrounding roads during construction will be dramatically reduced, thereby mitigating the impact of projects on neighborhoods and damage to existing roads. Value engineering and analysis of numerous projects ranging from airports to highways to industrial facilities indicate that lime soil-stabilization can produce cost savings between 20 and 40 percent, compared to other alternatives.

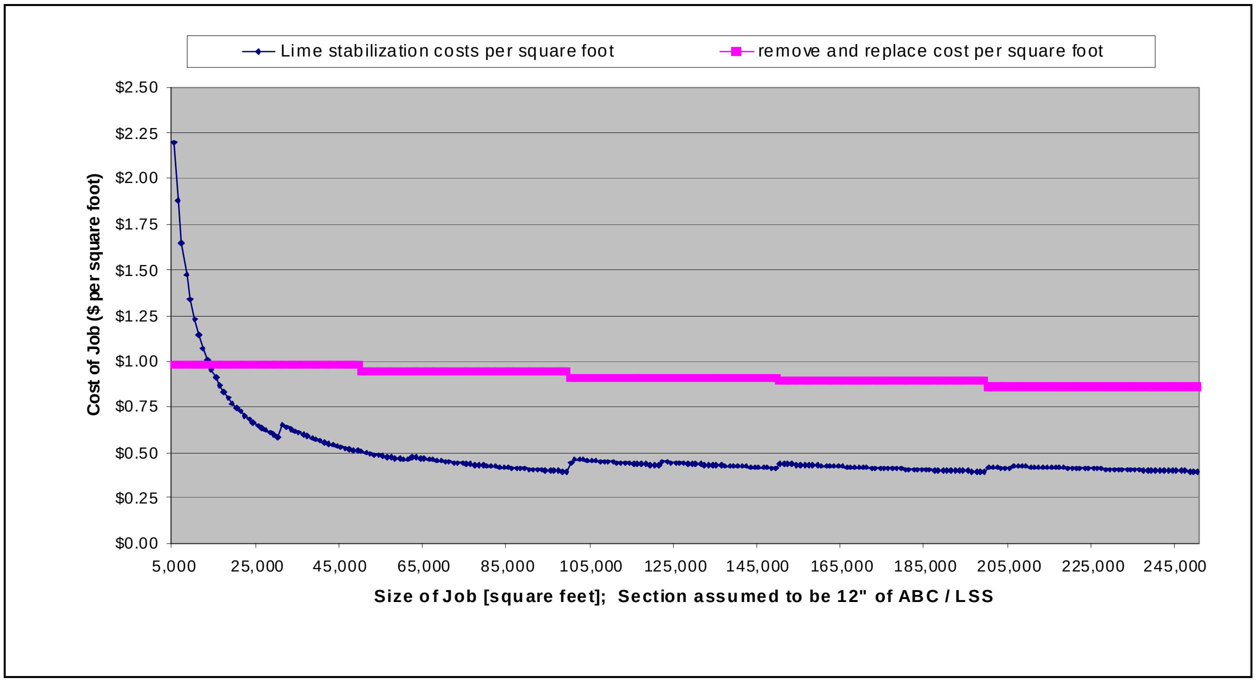

Figure 4 – Cost savings from lime stabilization vs. remove and replace, (Zaremba)

9 Conclusion

Decades of use have proven that lime soil-stabilization is an excellent solution to improve the engineering properties of otherwise unsuitable fine-grained soils. Lime can be used to dry or temporarily modify soils as a construction expedient, but its most important use is for fully- and permanently-stabilized subbase layers for transportation and industrial/commercial infrastructure. The design and testing of lime-stabilized layers is easily incorporated into geotechnical studies that are commonly performed as part of any site design. Both construction and quality control are straight forward, producing stable, strong, and non-expansive structural layers that will endure for the life of a project. The stabilization process has always been cost-effective and is becoming more so as replacement aggregates and structural fill materials increase in cost and decrease in availability. Since lime soil-stabilization utilizes on-site materials, disruption to adjacent properties and roads by construction activities is substantially decreased. Also, the use of on-site materials creates more sustainable construction, as rated by “green building” systems, such as LEED™. Lime soil-stabilization can play a critical role in the development of projects throughout the transportation and industrial/commercial communities.

References

Bollens, Quentin, 2003, Environmental Impact of Soil Treatment with Lime, Internal Technical Memo, Lhoist Group Research & Development

Boynton, Robert S., 1980, Chemistry and Technology of Lime and Limestone, John Wiley and Sons.

Little, Dallas N., 1995, Stabilization of Pavement Subgrades and Base Courses With Lime, National Lime Association.

Curtis, Starr, Berger, Eric, 2003, “Testing the Lime Content of Soils – Lime Mixtures”, Internal technical memo, Chemical Lime Company.

Curtis, Starr, 1999, “Recommended Practices for Landscape Plantings Associated With Lime-Stabilized Soils”, Internal technical memo, Chemical Lime Company.

Zaremba, 2002, Masters Degree Thesis, Redlands University, California