PRESSURE-INJECTED LIME FOR TREATMENT OF SWELLING SOILS

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The pressure-injected lime technique for treating swelling soils is described and evaluated. Basic mechanisms of soil-lime reactions and pressure-injected lime are considered, and the effects of treatments with pressure-injected lime are discussed. Typical field experiences with pressure-injected lime are summarized, and the factors that appear to influence the effectiveness of the technique are identified. There are conflicting reports concerning the effectiveness of pressure-injected lime treatment of expansive soils. The condition most favoring the achievement of successful pressure-injected lime treatment of expansive soils is the presence of an extensive fissure and crack network into which the lime slurry can be successfully injected. The proposed treatment mechanisms (prewetting, development of soil-lime moisture barriers, and effective swell restraint with the formation of limited quantities of soil-lime reaction products) have validity. The relative significance of the prewetting and soil-lime pozzolanic reaction aspects of pressure-injected lime treatment has not been established. The various statements and reports in the literature and the information presented in the paper suggest that pressure-injected lime may not be effective under all circumstances but that in appropriate conditions it can be satisfactorily and economically used. It is indicated that appropriate guidelines and principles should be developed for evaluating (on a site-by-site basis) the potential effectiveness of pressure-injected lime treatment.

•EXPANSIVE clays in the design and construction of transportation facilities present a major problem. Many techniques (compaction control, prewetting, heating, and various additive stabilization procedures) have been used for controlling volume changes in expansive soils (1).

Pressure injection of lime-water slurry into the expansive soil deposit is a recently developed procedure that is attracting considerable attention. The purpose of this paper is to describe and evaluate the pressure-injected lime (PIL) technique based on information currently available.

BACKGROUND

Lime has been widely and successfully used as a stabilizing agent for fine-grained soils. When lime is added to a fine-grained soil and intimately mixed, several reactions are initiated. Cation exchange and agglomeration-flocculation reactions take place rapidly and produce immediate changes in soil plasticity, workability, and swell properties. Plasticity and swell are reduced, and workability is substantially improved because of the low plasticity and the friable nature of the mixture. A soil-lime pozzolanic reaction may commence depending on the characteristics of the soil being stabilized. The pozzolanic reaction results in the formation of various types of hydrated calcium silicate and calcium aluminate cementing agents or both. The cementing agents increase mixture strength and durability. Pozzolanic reactions are time dependent, and strength development is gradual but continuous for a long period of time (several years in some instances).

Extensive studies (2) have shown that practically all fine-grained soils react with lime (cation exchange, agglomeration-flocculation) to effect beneficial changes in workability, plasticity, and swell properties. The extent to which the lime-soil pozzolanic reaction proceeds is influenced primarily by natural soil properties (3). With some soils, the pozzolanic reaction is inhibited, and cementing agents are not extensively formed.

Thompson (3) has termed those soils that react with lime to produce substantial strength increase as reactive and those that display limited pozzolanic reactivity as nonreactive. Properties of compacted and cured soil-lime mixtures will be different for reactive and nonreactive soils.

For the nonreactive soils, plasticity, workability, and swell properties are altered, but strength increases are nominal. Reactive soils initially experience similar plasticity, workability, and swell changes and will attain substantial strength because of the pozzolanic reaction.

In the treatment of subgrade soils with high swell potential, the major objective of lime stabilization is swell control. If the soil and lime can be intimately mixed, it is highly probable that the soil swell potential can be drastically reduced. Holtz (4) summarized the beneficial effects of lime treatment relative to the control of volume change in expansive clay soils. Not all soils respond favorably to lime treatment as a control of swell potential. Plummer (5) reported that certain of the Red River, North Dakota, clays will expand around 10 percent even after lime treatment. Mitchell (1) indicated that lime was the most effective additive for stabilization.

Even though the efficacy of lime for swell control treatment has been conclusively demonstrated, the reality of field conditions has limited the use of conventional lime stabilization. Holtz (4) has suggested that for effective swell control the expansive soil should be stabilized to a depth of approximately 5 ft (1.5 m). The costs associated with using conventional soil-lime stabilization procedures for treating the subgrade of a typical roadway section to a 5-ft (1.5-m) depth are substantial and in many instances prohibitive.

Thus, other techniques such as drill-hole lime and pressure-injected lime have been devised in an attempt to lime stabilize clays in their in situ state.

DRILL-HOLE LIME

The drill-hole lime technique basically consists of introducing quicklime or hydrated lime into a soil mass by placing the lime in holes drilled in the soil mass. When placed in the holes, the lime (usually hydrated lime in a slurry form) migrates or diffuses into the soil system thereby initiating the soil-lime reactions. If sufficient migration or diffusion occurs, it is possible that the properties of a sizable quantity of the soil mass around the drill hole will be improved. However, lime migration or diffusion is a very slow process, and substantial time may be required before a substantial quantity of soil is affected.

In highway applications, small-diameter [6 to 12 in. (15 to 31 cm)] holes are advanced through the pavement into the subgrade soil by using a suitable apparatus such as a power post-hole digger equipped with a continuous flight auger. In highway applications, provision must be made to construct a hole in the pavement structure to gain access to the subgrade. Typically, the depths of the drill holes range from 30 to 50 in. (76 to 127 cm). The exact hole depth depends largely on the depth and nature of material to be treated. Typical hole spacings are about 4 to 5 ft (1.2 to 1.5 m) center-to-center.

After the hole has been made, it is partially filled with either quicklime or hydrated lime. In some cases, water is added to the lime to create a slurry, or a lime-water slurry is placed directly in the drill hole. However, dry lime (especially quicklime) is thought to act as a drying agent that absorbs soil moisture, thereby reducing the moisture content of the surrounding soil. The use of a lime-water slurry may, however, tend to increase the mobility of the lime since water acts as a medium for migration.

Backfilling the hole and patching the pavement are normally required. Both soil (from the drill hole) and aggregate have been used. The backfill should be tamped into the hole. The holes in the pavement may be patched with portland cement concrete or asphaltic concrete.

Several studies (6, 7, 8, 9) have considered the drill-hole procedure. Although in many instances the major stabilization objective was not swell control, the background information developed in the studies is still applicable.

In general, drill-hole lime treatment results have been erratic. Some report success, but others indicate that little or no improvement has been achieved. The various investigations have shown that the zone of influence in which soil-lime reactions have taken place is limited to the areas immediately adjacent to the drill hole.

It is apparent that the major factor limiting the effectiveness of the drill-hole lime procedure is the inability to achieve lime distribution throughout the soil mass.

PRESSURE-INJECTED LIME

In an attempt to achieve better lime distribution in the soil mass, the PIL procedure was developed. In this procedure, a lime-water slurry is pumped under pressure through hollow injection rods into the soil. Generally, the injection rods are pushed into the soil in about 12-in. (31-cm) intervals. At each depth, the lime slurry is injected to refusal. Refusal occurs when

1. Soil will not take additional slurry,
2. Slurry is running freely on the surface either around the injection pipe or out of previous injection holes, or
3. Injection has fractured or distorted the pavement surface.

Although there is substantial variability in the amount of slurry that can be injected, a normal take is about 10 gal/ft (124 liters/m) of injected depth. Obviously, the nature of the soil being treated will influence the quantity of slurry that can be injected.

The normal lime-water slurry composition is $2\frac{1}{2}$ to 3 lb of lime/gal (0.3 to 0.4 kg of lime/liter) of water with a wetting agent added in accordance with the manufacturer's recommendation. Based on extensive field experience, the above slurry composition has proved to be satisfactory.

Although injection pressures as high as several hundred pounds per inch^2 (pascals) can be developed with most lime slurry injection equipment, the majority of the work is injected in the pressure range of 50 to 200 psi (345 to 1380 kPa). In this pressure range, it is normally possible to disperse the maximum amount of slurry into the soil.

Spacings of 3 to 5 ft (0.9 to 1.5 m) on centers are common in pressure injection treatment for building foundation work. Spacings of 4 ft (1.2 m) were used in the deep-layer stabilization flexible pavement test sections at Altus Air Force Base, Oklahoma. Spacings of 5 ft (1.5 m) are also typical for PIL treatment of railroad subgrades. Various pressure injection contractors in the Dallas-Fort Worth, Texas, area indicated that the amount of lime slurry that could be injected per unit volume of soil was independent of injection probe spacing within the range of 3 to 6 ft (0.9 to 1.8 m).

Injection depths are variable, but current equipment is capable of injecting to depths of approximately 10 ft (3 m). Wright (10) has indicated that a treatment depth of 7 ft (2.1 m) is normally sufficient for foundation treatments. This depth compares reasonably well with the 5-ft (1.5-m) depth suggested by Holtz (4). The general guide is to inject to a depth sufficient to be below the zone of critical moisture change in the expansive soil deposit.

If the surface of the PIL-treated soil deposit is exposed, it is common practice to mix the free surface lime available into the soil to a depth of 6 to 8 in. (15 to 20 cm). The stabilized layer further contributes to the process of retarding moisture loss from the underlying soil. Teng, Mattox, and Clisby (11) have shown the effectiveness of a lime-treated Yazoo clay layer to act as an effective capillary barrier for preventing desiccation. Similar results have been found in a wide variety of soil-lime stabilization applications.

Field studies (12, 13) in which PIL-treated soils have been excavated show that the PIL slurry is forced along fracture zones, cracks, fissures, bedding planes, root lines, coarse-textured seams in varved clays, seams and fractures effected by the pressure slurry injection process, or other passages in the soil mass. The field observations and a recent laboratory investigation (14) have conclusively demonstrated that the lime-water slurry will not permeate an intact fine-grained soil mass.

Hillel (15) states,

> The hydraulic conductivity (of the soil mass) is obviously affected by structure as well as by texture, being greater if the soil is highly porous, fractured, or aggregated than if it is tightly compacted and dense. The conductivity depends not only on the total porosity, but also, and primarily, on the sizes of the conducting pores.

Lytton (16) in characterizing the geomorphological aspects of expansive clay indicated that in gilgai land forms the "soil is fractured to great depths." In the same paper, Lytton also discusses the crack pattern formation process in expansive soils. The fact that expansive soil deposits are typically cracked or fractured in the near surface depths that are of concern in swell control procedures is helpful when the problem of trying to pressure-inject lime-water slurry into the soil mass is considered.

It is apparent that the presence of openings in the soil mass is requisite for obtaining adequate slurry distribution. Wright (10) has described the final lime distribution pattern frequently obtained in swelling clays as "a network of horizontal, sheet lime seams, often interconnected with vertical or angular veins."

TREATMENT MECHANISMS

From the previously presented information, it is apparent that there are two major treatment mechanisms of concern relative to PIL. The first is the ability to permeate the soil mass with the stabilizing additive (in this case a lime-water slurry), and the second is the process whereby, following PIL treatment, the lime translocates and modifies the soil adjacent to the lime seams.

Lime Injection

When the basic theory of permeability is combined with Darcy's law of fluid flow in a soil mass, the total quantity of fluid that can be forced into a soil mass during a given interval of time can be approximated by equation 1:

$$Q = \frac{\rho g}{\eta} \left(\frac{p}{\ell}\right) K A t \tag{1}$$

where

- A = cross-sectional area over which pressure acts;
- η = viscosity of fluid;
- g = acceleration due to gravity;
- p = pressure head;
- K = Cd^2, intrinsic permeability of medium, where C is a shape factor and d is average pore size of mdeium;
- ℓ = length over which pressure head acts;
- Q = quantity of fluid flow;
- ρ = density of fluid; and
- t = time of pressure application.

Equation 1 indicates that the following major factors control the quantity of fluid that is injected: (a) fluid viscosity, (b) injection pressure and time, and (c) intrinsic permeability of the soil medium.

Since lime slurry is not an ideal fluid but rather a particulate suspension, the pore size distribution of the soil mass is an important consideration in the permeation process. Successful injection of the lime slurry into the soil mass would require that channels larger than the lime particles be present.

The inherent pore size of most fine-grained soils is quite small relative to the lime particle size. Thus, appreciable lime slurry movement through these pores is questionable.

Johnson (17) recommends that the groutability ratio, as calculated by using equation 2, be greater than 20 to 25 for successful cement grouting.

$$\text{Groutability ratio} = \frac{D_{(15)}\text{ soil}}{D_{(85)}\text{ grout}} \tag{2}$$

where

$D_{(15)}$ soil = particle size for which 15 percent of the soil fraction is finer, and
$D_{(85)}$ grout = particle size for which 85 percent of the cement grout is finer.

Many commercial hydrated lime specifications for soil stabilization purposes require a minimum of 85 percent passing the No. 200 sieve. Using 0.0029 in. (0.074 mm) as $D_{(85)}$ in Johnson's equation indicates the $D_{(15)}$ for the soil must be approximately 0.059 in. (1.5 mm) or larger to meet a groutability ratio criterion of 20. It is obvious that for fine-grained expansive soils the lime slurry cannot be effectively forced through the soil pore system.

Laboratory studies conducted at the University of Illinois (14) indicate that it is almost impossible to force a typical lime slurry (30 percent by weight) into fine-grained soils even when pressures of up to 1,000 psi (6.9 MPa) are applied for 20 min. Typical results from this limited study are shown in Figure 1. In general, slurry penetrations averaged less than ½ in. (12.7 mm) into the silty materials, and almost no penetration was achieved in the clayey materials.

Teng, Mattox, and Clisby (11) found in their water flooding studies of a remolded and compacted Yazoo clay embankment that little moisture penetration was achieved. The flooding of the undisturbed Yazoo clay in the cut sections was successful. These findings caused them to conclude, "The fissure system plays a very significant role in allowing water intrusion into the soil mass thus causing swell." The significance of the fissure system would be equally important for the PIL procedure. It is important to note that the fissure structure in the Yazoo clay study (11) was present in the in situ cut sections, but the fissure structure was destroyed in the embankment construction process.

It is apparent that to successfully pressure-inject lime slurry into a fine-grained soil natural channels and passages larger than the lime particles must be present in the soil mass. Such channels may be present as a result of (a) inherent pore structure of the soil mass; (b) cracks, fissures, seams, and root holes present in the soils; or (c) jetting or tearing of the soil effected by the pressure injection process.

Even though the permeability of the soil resulting from the inherent soil pore structure may be quite low, the mass permeability or conductivity may be substantially higher as a result of the presence of seams, fissures, cracks, varves, and so on. When this condition exists, the potential for successful lime slurry injection of a soil mass is greatly enhanced.

Diffusion-Migration of Lime

Based on the preceding discussion, it is apparent that

1. Intimate permeation of fine-grained soils through PIL is virtually impossible, and
2. Lime slurry can be pressure-injected into certain fine-grained soil masses if varves, seams, fissures, and cracks exist but the distribution of the slurry is stratified or of a network type.

However, the lime will tend to be translocated in the fine-grained soil mass as time progresses because of diffusion and migration phenomena.

Space limitations do not allow presentation and discussion of diffusion-migration theory. In general, however, factors such as differences in clay content, clay minerals, density, absorbed cations, and temperature have been found to affect the rate of diffusion (18, 19, 20, 21).

In an early study, Davidson, Demirel, and Handy (22) suggested that the diffusion of calcium cations in a soil-lime water system is an example of the diffusion phenomena. The processes accompanying lime diffusion may include (a) transfer of lime into the soil, (b) chemical reaction between the lime and the soil, (c) formation of nuclei and growth of the reaction product, and (d) further diffusion of the lime into the soil from the reaction product layer.

The following equation has been suggested for determining the rate of growth of a product layer from the lime source (22, 23):

$$\ell = k_d \sqrt{t} \tag{3}$$

where

ℓ = distance of lime migration for a time t in inches (millimeters),
k_d = diffusion constant in inches/day$^{1/2}$ [reported values range from 0.081 to 0.63 in./day$^{1/2}$ (2 to 16 mm/day$^{1/2}$) (22, 23)], and
t = elapsed time of diffusion in days.

Limited laboratory and field studies have been conducted to evaluate the rate and extent of lime migration. In a controlled laboratory study conducted by Fohs and Kinter (24), about 0.8 percent lime was found to migrate approximately 1½ to 2 in. (3.8 to 5 cm) after 180 days. They concluded that the migration process for effecting translocation of lime in a soil system is very slow and that only very small amounts of lime can be translocated. This makes this process impractical for effecting substantial soil mass strength increases (24). Robnett, Jamison, and Thompson (14) conducted a limited laboratory lime migration study. Typical results are shown in Figure 2. It is apparent that the amount of lime translocated by the migration process is small.

In a field study, Lundy, Jr., and Greenfield (13) found that after 1 year approximately ¾ to 1½ in. (19 to 38 mm) of lime migration had occurred away from the lime seams. A Louisiana Department of Highways study (12) found that about ½ to 1½ in. (13 to 38 mm) of lime migration occurred after 4 years.

It is evident that lime translocation by the diffusion-migration process is very slow. If equation 3 is used to estimate the required time for various distances of migration, the following values are found, if k_d is assumed to be 0.10 in./day$^{1/2}$ (2.5 mm/day$^{1/2}$) (1 in. = 25.4 mm):

Figure 1. Typical lime-water slurry pressure penetration data for Fayette C soil [AASHO A 4(8)].

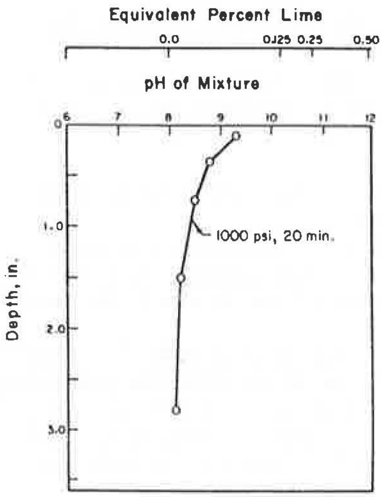
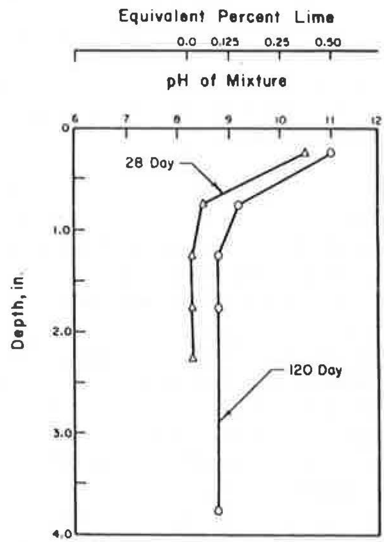


Figure 2. Typical lime migration data for Altus subgrade soil [AASHO A 6(13)].



ℓ (in.)	t (days)
1	100
6	3,600
12	14,600

Recent comprehensive studies by Stocker (25) have led to the development of an integrated theory of soil-lime stabilization reactions termed diffusion and diffuse cementation. Diffuse cementation theory as proposed by Stocker describes a process in which lime (from a PIL-deposited lime seam in the situation of interest) will diffuse into a natural soil lump. Based on his studies, Stocker stated,

> The diffused lime is shown to react with all the clay present, including that within unpulverized lumps, leading first to volume-stabilization (against wetting and drying) and increase in soaked strength, and later to remarkable increases in even unsoaked strength (for relatively high stabilizer contents). This cementation is diffuse. . . . It [diffuse cementation] is the dominant mechanism whereby included lumps of unpulverized soil are made impotent with respect to differential volume change and finally by which the lumps are increased in mechanical strength.

Stocker indicated that, in a lime-covered, soil-lump system in which diffuse cementation is occurring, the earliest physical property change effected is the "suppression of swell or wetting from the as-cured state." His studies further suggest that the development of limited cementing material is sufficient to prevent swelling but does not contribute to the development of substantial compressive or shear strength.

Stocker's diffuse cementation theory (25) suggests that in lime-reactive soils soil-pozzolanic reaction products may form in regions of low calcium concentration remote from the lime source. The applicability of the diffuse cementation theory depends on the soil being lime reactive (soil will react with lime to form calcium silicate and calcium aluminate hydrates).

EFFECTS OF PRESSURE-INJECTED LIME

As a consequence of PIL treatment, major changes are effected in the soil (assuming that there are sufficient soil passageways to facilitate lime slurry distribution in the soil mass). The soil moisture content is increased, and an initial network of lime seams is formed in the soil.

It is well established that initial water content has a significant influence on volume change in expansive soils. In general, the lower the initial water content is, the higher the swell will be. In some PIL jobs the moisture content of the treated soil is specified. Wright (10) indicates that a typical final moisture content requirement is 1 to 2 percent above the plastic limit. It is not uncommon to achieve several inches (millimeters) of swelling in the deposit following PIL, depending on the moisture content of the expansive soil before injection (10, 26). Mitchell and Raad (1) have considered the application of prewetting as a method of controlling volume change in expansive earth materials. Many engineers are prone to overlook this important aspect of PIL treatment, which is in reality a form of prewetting.

Following PIL treatment, soil-lime reactions may occur in the areas adjacent to the lime seam network. Lime diffusion-migration takes place as previously discussed. If the soil is reactive, soil-lime cementing products will form. The stabilized zones serve as moisture barriers. Stocker (25), as previously discussed, indicated that the formation of limited accumulations of soil-lime reaction products at or near the edges of the clay particles would effectively restrain moisture-related volume expansion. Even if only the boundaries of a soil mass have reacted with lime, Stocker (25) suggests that the nonswelling shell of modified soil may constrain the relatively unaffected core. Stocker's work with lime treatment of lumps of montmorillonitic soil even suggests that the swell characteristics of the soil had been substantially modified ahead of the penetrating diffusion-reaction front.

It is important to recall that, in a practical field application, the potential for soil swell is previously reduced by the PIL treatment prewetting effect so that the preservation of the in situ soil moisture content alone will ensure volume constancy. The restraint developed from the formation of reaction products is an added beneficial effect. It was noted by Stocker that higher soil moisture contents increase the rate of development of diffuse cementation. Thus the water content increase effected by PIL will enhance the diffusion cementation process.

The preceding discussion indicates that there are several potentially beneficial processes that can occur in a PIL-treated expansive soil deposit. Under the proper circumstances, PIL treatment should serve as an effective swell control procedure. At this time it is not possible to accurately define what conditions are required to ensure a high probability of success.

EVALUATION OF PRESSURE-INJECTED LIME

PIL has gained acceptance as a possible procedure for treating expansive soils in building foundation applications, but has not yet achieved the same degree of acceptance in transportation facility construction. PIL was not considered in any depth at the recent Denver conference, but some comments were made concerning lime treatment techniques.

1. Kelley and Kelly (27) referred to the successful use of PIL to treat the swelling soils under the Dallas-Fort Worth Regional Airport terminal buildings.
2. Krazynski (28) indicated that he did not think PIL treatments were very effective.
3. Teng, Mattox, and Clisby (11) thought that research and experience have shown that lime stabilization by pressure injection has not lessened the swell potential.
4. Blacklock (26), a PIL contractor, indicated that, based on results, PIL was definitely a solution to the swelling problem.
5. Gerhardt (29) reported on the successful use of drill-hole lime stabilization in a Colorado test section and concluded that potential swell can be reduced to almost

nothing for any depth.

6. Brakey (30) suggested that the drill-hole lime procedures were not effective in providing protection against expansion in the Mancos shale.

Ingles and Neil (31) have evaluated the effects of PIL treatment for typical Australian soil conditions. Their studies indicated that PIL treatment of expansive soils was an effective procedure, but only when the treatment was carried out at the time of maximum desiccation when the soil is fissured.

Robnett, Jamison, and Thompson in recent studies (32) of deep-layer stabilization procedures for pavement systems also considered the various aspects of PIL. Of the various procedures evaluated, the PIL procedure was determined to be one of the more promising methods.

Wright (10) cited the rapid growth of PIL building foundation treatment in Fort Worth, Texas, and indicated that the use of the procedure was spreading to other parts of Texas as well as Arkansas, Tennessee, Louisiana, and Oklahoma. It is apparent that PIL is an accepted expansive soils treatment procedure in some geographic areas.

The various statements and reports in the literature suggest that PIL may not be effective under all circumstances, but under appropriate conditions it can be satisfactorily and economically used. It appears that higher probabilities of success are achieved when the job conditions permit the satisfactory injection of lime slurry and the development of a comprehensive network of lime seams throughout the soil mass. The presence of an extensive fissure and crack system in the soil seems to be necessary.

If the lime slurry can be successfully injected throughout the fissures or cracks in the soil mass, the prewetting phase of the PIL treatment can then occur. The soil-lime pozzolanic reaction will also commence (reaction rate is influenced by time and temperature) if the soil is reactive. It is thus possible that in some PIL applications only the prewetting effect is achieved and that the soil-lime pozzolanic reaction does not occur. In such a case, the moisture barrier developed in the areas of the lime seams may not be as effective because any soil property change will be due to cation exchange and perhaps limited changes in soil structure but will not show the benefit of soil-lime reaction product formation. Whether or not the soil-lime pozzolanic reaction is essential for successful long-term PIL treatment has not been established. However, Stocker's theory (25) indicates that a lime-reactive soil is essential if effective diffuse cementation at points remote from the lime source is to be achieved. Fortunately, many expansive soils are lime reactive.

SUMMARY

There are conflicting reports concerning the effectiveness of PIL treatment of expansive soils. The proposed treatment mechanisms (prewetting, the development of soil-lime moisture barriers, and effective swell restraint with the formation of limited quantities of soil-lime reaction products) have validity. It therefore seems logical to conclude the PIL may be an effective swell control procedure under certain circumstances. The condition most favoring the achievement of successful PIL treatment of expansive soils is the presence of an extensive fissure and crack network into which the lime slurry can be successfully injected. The relative significance of the prewetting and soil-lime pozzolanic reaction aspects of PIL treatment has not been established. If soil-lime pozzolanic reactions are essential to achieving an effective application, perhaps that fact can be used to evaluate the potential success of an anticipated treatment and explain the apparent conflicting reports on PIL experience.

It is suggested that future research and development activities focus on the following areas:

1. The relative significance of prewetting and soil-lime pozzolanic reactions in PIL treatments,
2. Consideration of Stocker's diffusion cementation theory and its application to

PIL treatment, and

3. Development of appropriate guidelines and principles for evaluating (on a site-by-site basis) the potential effectiveness of PIL treatment.

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