Stabilization of Expansive Clay Soils

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Natural hazards cause billions of dollars of damage to transportation facilities each year—only flooding causes more damage than expansive soils. Nearly all types of transportation facilities have been affected by expansive soil behavior and, as a result, many have failed or are no longer serviceable. It is imperative that the damage caused by expansive soils be controlled, and proper application of soil stabilization methods can significantly reduce the damage that results from these problem soils. The purpose of this presentation is to discuss the phenomena associated with stabilizing these soils, their behavioral patterns that affect stabilization, and the initial and remedial stabilization methods that can be applied to them. The factors considered include conditions requiring and allowing stabilization, changes of properties with time, the effects of stress history and desiccation, the influence of climate, and the effects of physicochemical environments. Effects that can be improved by stabilization are pinpointed. Stabilization methods are described that improve selected properties of expansive soils by mechanical and chemical means. Well-established methods are discussed along with those that are very promising. Examples of remedial treatments are discussed. It is concluded that there is a need for analyses of all alternatives and for stabilization during construction rather than costly remedial projects. Research needs are outlined that can improve our understanding of the stabilization requirements of these problem soils.

It has been estimated that the damage to the infrastructure caused by natural hazards may account for direct costs of at least 1 percent of the gross national product. The damage caused by expansive soils is surpassed only by that resulting from flooding. Expansive soils are found in every state and cover approximately one-fifth of the land area; however, if soil stabilization is widely adopted, the billions of dollars of damage that occur each year can be significantly reduced. These efforts may reduce the new construction losses by 75 percent and overall losses by approximately one-third by the year 2000 (*1*).

Few transportation facilities are immune to problems associated with expansive soils. Roadways and runways have suffered from destructive differential movements caused by these soils. The nature of these soils has led to many slope failures, and retaining walls and bridge abutments have experienced extreme distortion and have been overturned by swell pressures associated with these soils. Track systems have been moved out of alignment, both vertically and horizontally, by the effects of expansive soils, and port facilities have been affected by both the power and the amount of volume change. Even pipelines have had their share of damage, as exhibited in changes in alignment and crushing. It is imperative, therefore, that the detrimental effects of these problem soils be controlled or limited.

The object of this paper is to look at the phenomena associated with stabilizing expansive soils, the problem behavioral patterns of these soils, the possible and most efficient stabilization methods, and remedial stabilization methods. It is important to realize that problem soils can be successfully and economically stabilized, especially when the costs of probable damage and remedial corrections are taken into account. Traditionally, only stabilization methods well-proven or accepted have been used. This has meant that, in some cases, more effective and economical methods were not considered because they were less well-known. One of the purposes of this presentation will be to discuss those methods now commonly used and to propose others, less well known but also effective, that may be used. It is not the intention of the authors to provide new and innovative methods, but to promote the consideration and use of all alternative methods.

PHENOMENA AFFECTING STABILIZATION

The phenomena associated with expansive clay soils that affect stabilization include (a) the specific clay mineralogies present, (b) the stress histories of the respective soil masses, (c) the desiccation histories of the subgrades, (d) the climates where these soils are found, (e) the property changes that occur in these soils with time, and (f) the physicochemical environments existing in the soil masses and around the clay particles. For some of these phenomena, soil stabilization can be used to improve the properties of the soil masses.

The effects of particular clay minerals are, for the most part, well-known and documented (*2*). The clay minerals present are not normally determined during the investigation procedures used, but certain clay minerals, including those from the smectite, illite, and (sometimes) chlorite families, are known to exhibit expansive characteristics. Of these, the members of the smectite family have proven to be the most active. It is not likely that stabilization can totally change the clay minerals present, but their effects can often be lessened.

Those phenomena that relate to particular stress histories and desiccation cannot be changed by stabilization. One must take these effects into consideration during analyses of methods that may work for particular situations. Generally, these methods are known to increase the expansive nature of the soil masses because of the residual stress release that occurs with time, diagenetic bond releases that result in long-term heave, strength loss with time, and the general fractured nature of the soil mass as a result of desiccation stresses (*3*).

The effects of climate on the behavior of expansive clay

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soils are known to be extremely important (*4*). In climates that provide natural moisture year round or a continuously dry environment, the associated long-term soil mass moisture changes are minimal. Semiarid climatic conditions lead to the most damaging behavior of expansive clays. This climate provides significant periods of both wetting and drying, which, in turn, will cause both swelling and shrinkage of active soils each year. Over a number of years or cycles, this causes the soil subgrade to become fissured, and many facilities tend to experience significant differential movements. The effects of all climatic situations on expansive soils must be considered during design analyses and may very well need to be overcome by stabilization methods in areas where seasonal moisture variations occur.

The phenomena associated with property changes that occur in expansive clay soils include (a) shear strength losses as the soils take on moisture and release negative pore pressures, (b) changes in volume change characteristics as in situ conditions change in subgrades between initial sampling and the construction phase, (c) alterations to soil properties as these materials are remolded during construction, (d) changes to soil mass macrostructures that occur during the cyclic processes caused by climatic conditions, and (e) changes that occur as the result of variations in stress during construction. Most of these property changes are well documented and can be considered during design analyses, and a number of these can be overcome or used as part of stabilization methods.

The physicochemical environment around and inside expansive clay particles has much to do with how these particles react to changes in load and moisture levels. Physical environmental factors include dry unit weight, soil mass particle microstructure, soil mass block or clod macrostructure, overburden pressures, load-induced pressures, soil mass porosity, soil mass block or clod porosity, moisture levels at the time of construction, and relative exposure of parts of the soil mass to drying or wetting. The environmental factors that are of a chemical nature have to do with the type and concentrations of cations both inside clay particles and in the water around these particles. Most of the effects of physical environmental factors are well known; however, the effects of chemical factors are still understood only in gross terms (*5*).

The combined effects of overburden, dry unit weight, and water content on the expected expansion of active clay soils are shown in Figures 1 and 2. Figure 1 shows the relationship of water content at the beginning of swell versus the relative amount of swell that occurs for differing overburden pressures. As the magnitude of overburden increases, the amount of swell for any water content decreases. In addition, it can be seen that there is some water content for each magnitude of overburden where the swell that occurs is minimal or nonexistent. Figure 2 is a three-dimensional plot of how the amount of swell is related to both dry unit weight and water content at construction. The general trends illustrated in Figure 2 form a surface, which explains behavioral patterns. The amount of swell occurring is directly related to the dry unit weight and inversely related to water content.

Soil particle orientation causes the most volume change to develop perpendicular to the flat surfaces of the particles. This would lead one to deduce that a parallel structure would cause the most volume change in the direction perpendicular to these particle surfaces and that much less would occur in the direction parallel to the particle edges. It is well documented that the vast majority of swell or volume change in these soils happens between the clay mineral layers, so that soil particle orientation has a significant effect on swelling (*2*).

The effects of soil structure are far more complex than described above, however. Actual soil subgrades are not only made up of discrete clay particles but also include packets of clay particles that lie together (like the pages of a book) and may be made less homogeneous by the presence of cracks, fissures, and slickensides. All these features make up the pattern of blocks, columns, and clods of soil particles called the macrostructure. The particular amount of volume change that occurs is therefore affected by the complex orientation of clay particles and the relative compressibility of the soil mass in each direction caused by macrostructure features. The relative porosity and permeability of the soil mass in each direction are also affected by its micro- and macrostructures, and the ease with which the clay will gain and lose moisture is directly related to these porosities and permeabilities.

Another physical factor that affects the behavior of expansive clay soil subgrades is their relative exposure to concentrated drying and wetting. These situations lead to the most damaging type of soil mass movements, because transportation facilities will endure significant differential shrink and swell. Those situations in which concentrated wetting occurs include improper drainage and cracks through the facilities that allow concentrated infiltration of moisture. Nonuniform exposure to rainfall and runoff will eventually cause nonuniform movements. Concentrated drying occurs where the soil mass is exposed differentially to climatic effects and to the roots of large bushes and trees. It has been established that tree roots have a drying effect that extends at least as far from the tree as it is tall and, in many cases, much farther (*6*).

Many of the physical environmental factors affecting the behavior of expansive clay soils can be modified and controlled by stabilization methods. These methods are usually of the mechanical type.

As important as the physical environment factors are to the behavior of expansive clay soils, the chemical environment around and inside clay particles affects their behavior much more profoundly. Differences in this environment can cause an expansive clay to have high volume change potential or to have none at all. Depending on the type and concentration of cations associated with the clay, these behavioral patterns exist. The capacity of a clay soil to associate with cations is determined by its cation exchange capacity (CEC), and the capacity of cations to have water associated with them is dependent on type.

The most active clays are those with sodium cations in their exchange complex, or cation exchange sites. The least active generally have bivalent cations, which have the least affinity for water. In addition, the types and concentrations of cations in the water around the clay particles will affect the ease with which water can move into and out of the clay. Cation concentrations in the exchange complex also affect the flocculation of clay particles, thereby affecting clay behavioral patterns. Finally, there are chemicals in the soil or that may be added to the soil that affect the way water is held by clay particles and in the pore water, thereby affecting the volume change behavior of the clay, which is directly dependent on

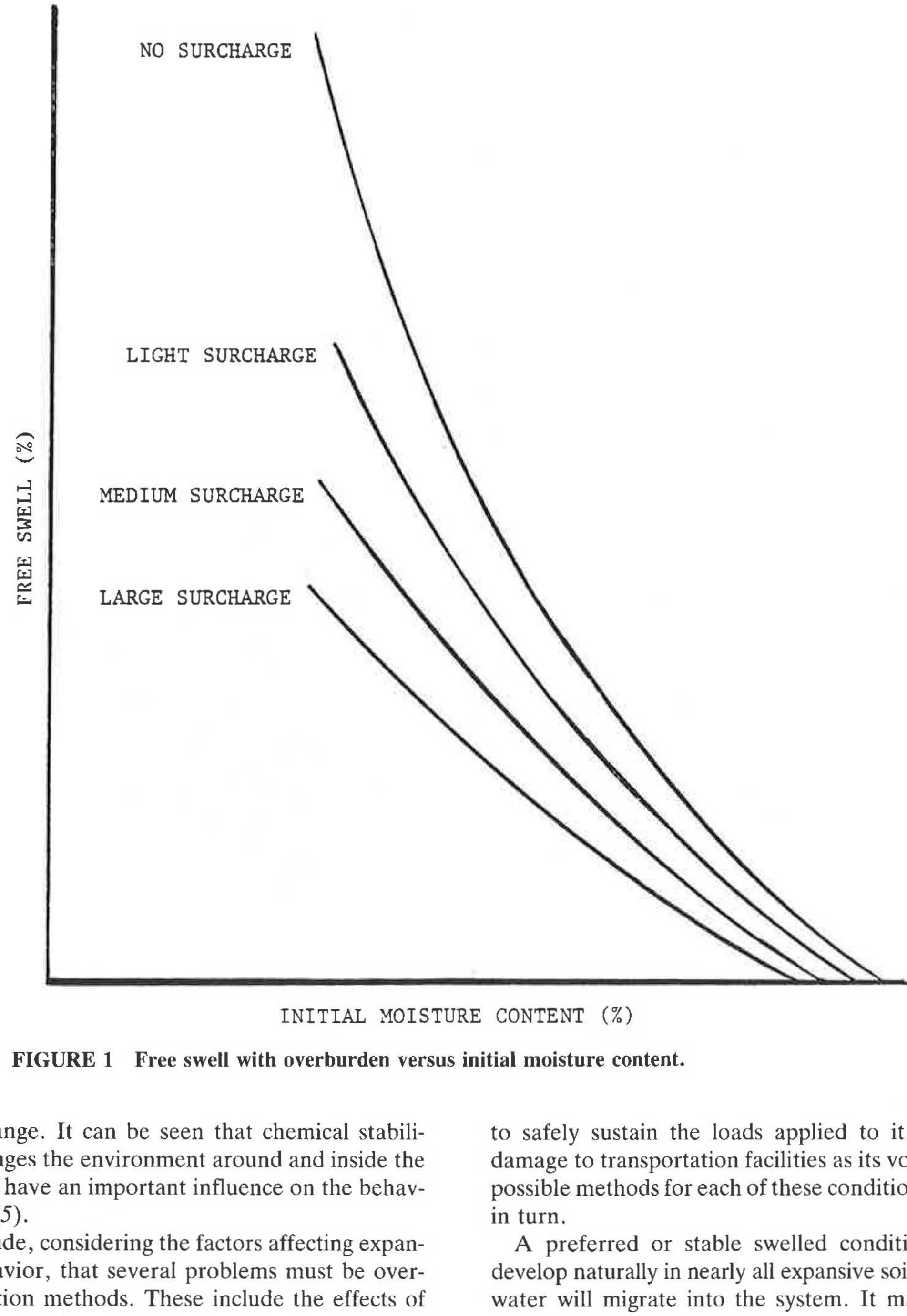

FIGURE 1 Free swell with overburden versus initial moisture content.

water content change. It can be seen that chemical stabilization, which changes the environment around and inside the clay complex, will have an important influence on the behavior of these soils (*5*).

One may conclude, considering the factors affecting expansive clay soil behavior, that several problems must be overcome by stabilization methods. These include the effects of heave, the cyclic and differential effects of shrink and swell, the changes of properties (such as shear strength) with time, and the prediction of behavior during design procedures. The rest of this presentation will deal with how all but the last of these may be dealt with by using stabilization methods.

MECHANICAL STABILIZATION METHODS

Mechanical stabilization includes all improvements to either soil or soil mass properties without the addition of stabilizing agents. The central idea of mechanical stabilization of expansive clay soils is production of a soil or soil mass that (a) will not or cannot change in volume, (b) has sufficient strength to safely sustain the loads applied to it, or (c) causes no damage to transportation facilities as its volume changes. The possible methods for each of these conditions will be discussed in turn.

A preferred or stable swelled condition will eventually develop naturally in nearly all expansive soil subgrades because water will migrate into the system. It makes sense then to provide this level of moisture during construction, and this may be done for natural or cut subgrades by prewetting them to the desired levels of moisture. This has been accomplished with some degree of success by ponding, but most successfully by injecting water that contains surfactants. Prewetting of expansive soil subgrades by transfer of ponded water to sufficient depths into the ground can take months to accomplish satisfactorily; however, injection of moisture into these subgrades may be successfully accomplished in only weeks. For the injections to work, the subgrade needs to be somewhat fractured. As many as four passes may be made during the injection process, and if these are spaced at, say, 4-day intervals, significant water content change will occur (*7*). Another advantage of the injection process is the depth to which the

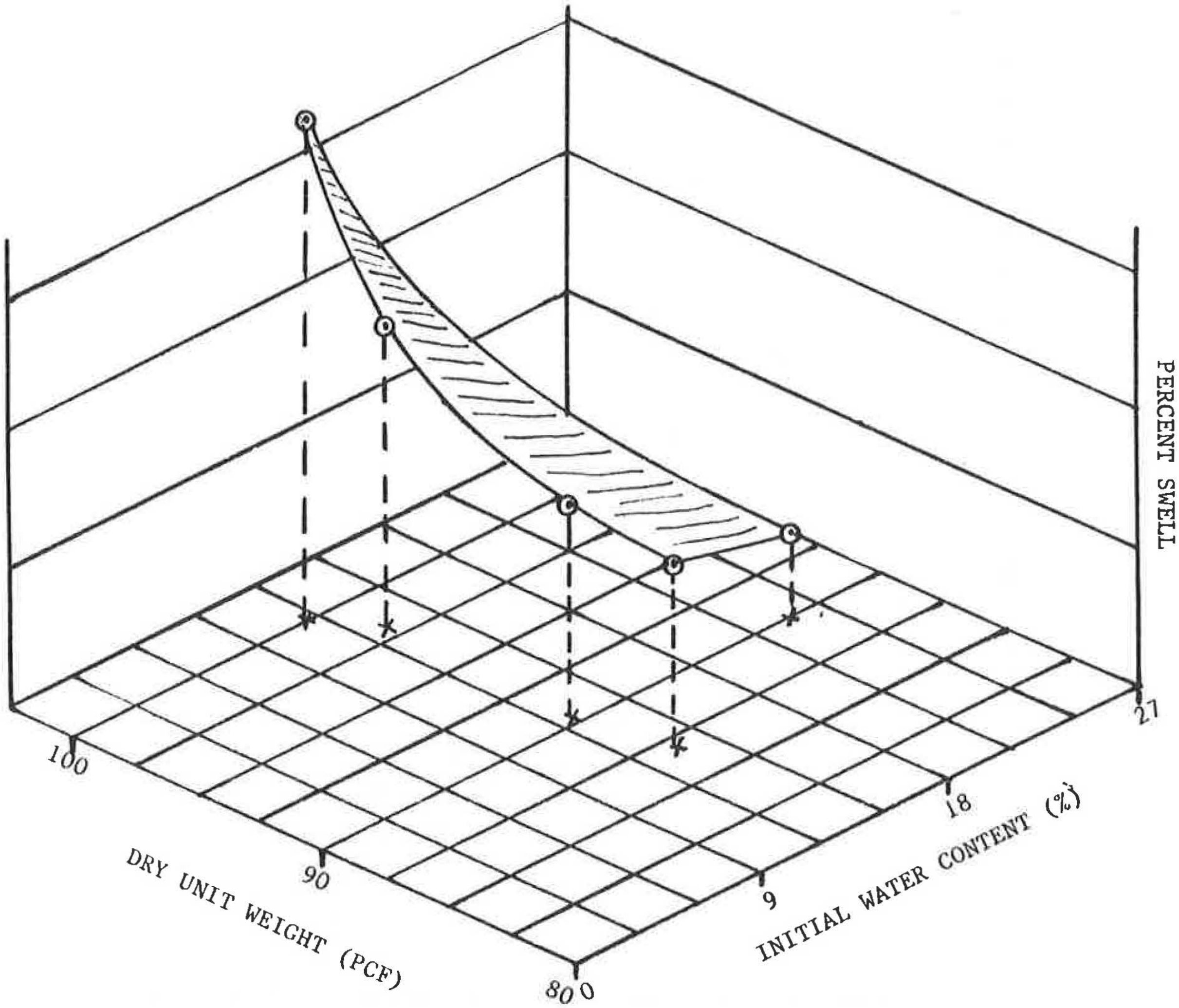

FIGURE 2 Percent swell versus dry unit weight and initial water content.

subgrade is preswelled, which may be from as little as 5 ft to as much as 10 ft, normally.

When one is constructing a fill of expansive soil, establishment of these preferred moisture levels is a matter of controlling compaction water content. Compaction moisture contents above the optimum will provide a subgrade that will have little swell potential in most cases, with the practical limit being 4 percent above optimum because of difficulties with compaction and equipment movement. One danger of high water contents during compaction is the buildup of excessive pore water pressure in high fills. Because of these factors, one may compact these high fills at lower water contents and provide time for them to achieve their preferred levels of moisture naturally before the facility is finished. Monitoring of soil suction and pore pressure levels would be advisable in these cases (*2*, *7*, *8*). Once a stable moisture level is achieved in subgrade soils, it is then necessary to ensure that it will not change significantly during the life of the facility.

Maintenance of nearly constant moisture levels in expansive soil masses includes deletion of those previously described conditions that result in concentrated wetting or drying. Special attention should be paid to proper drainage grading, placement of large bushes and trees, handling of facility water runoff, and draining of retaining wall backfill. One recently well-proven concept for retention of established stable levels of moisture is the vertical moisture movement barrier. These barriers are constructed using asphalt, recycled chips of rubber, well-densified lean concrete, lime slurry pressure injection (LSPI), and relatively thick sheets of polyvinyl chloride (PVC) or geomembranes. All of these, except the recycled rubber and LSPI barriers, have performed extremely well. The effects of LSPI will be discussed in the section on chemical stabilization. Figures 3 and 4 show this concept of moisture maintenance, which maintains moisture levels by encapsulating the soil mass and thus removing sources of change (*8–11*).

Other methods used to limit the movement of expansive soils have to do with imposed loads and the internal compressibility of the soil structure. Expansive clay soils are compacted at dry unit weights that are lower than normally acceptable for a particular application to lessen the effects of swelling. A common type of specification may call for at least 90 percent, but no more than 95 percent, of maximum dry unit weight established by the Standard Proctor test at water contents of at least optimum, but no more than about 4 percent above optimum. The reason for limiting the range of water

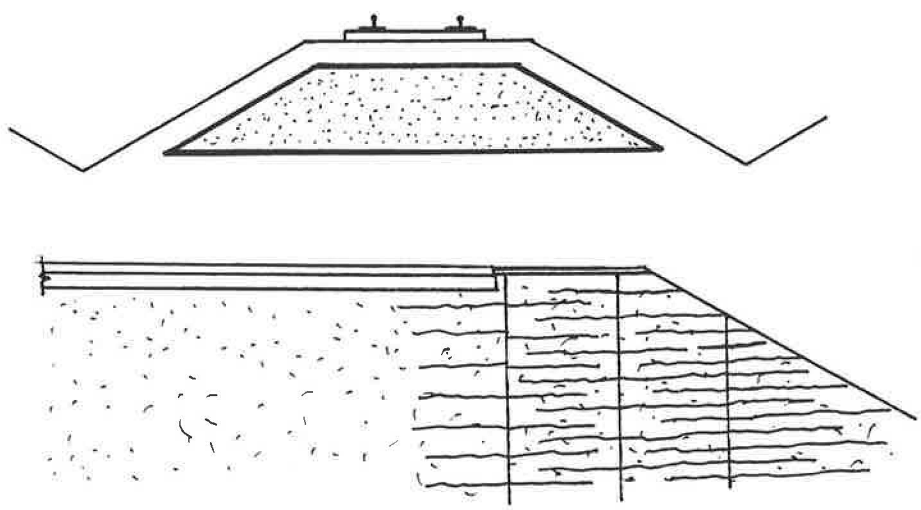

FIGURE 3 *(top)* **Encapsulation with asphalt membrane;** *(bottom)* **injected moisture movement barrier.**

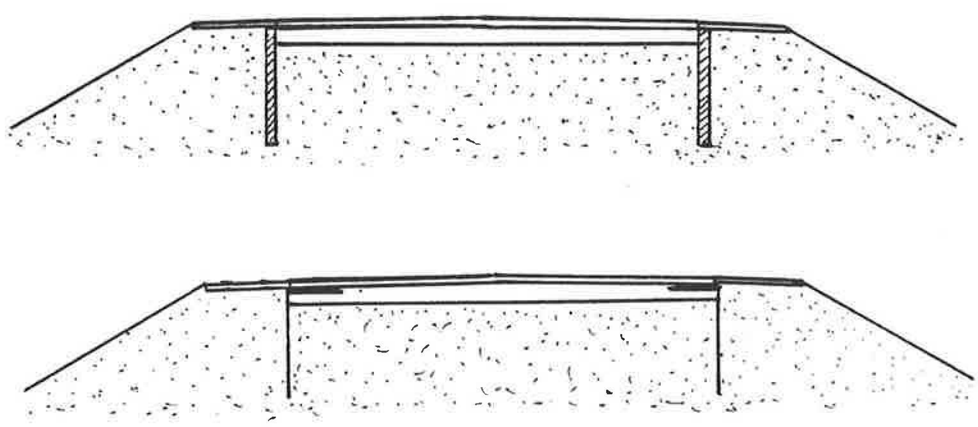

FIGURE 4 *(top)* **Lean concrete moisture movement barriers;** *(bottom)* **PVC moisture movement barriers.**

content is to provide adequate compacted dry unit weight, as shown in Figure 5.

In some applications, this percentage of maximum dry unit weight could be even lower than 90 percent, but few are willing to risk the possibility of low soil shear strength and increased compressibility. With appropriate testing, the impact on these properties of lowering percentages of compaction could be assessed. The reduction of compaction requirements, therefore, can reduce the effects of swelling. The other method of limiting swell is the use of soil mass contact pressures imposed by the facility that are as high as or higher than the soil's swelling pressure. In this way, theoretically, no swell can occur. It should be recognized that these measures do not prevent shrinkage from occurring, however. Both of these methods have been applied with good success in differing types of transportation facilities (*6*, *12*).

The first three types of stabilization for expansive clay subgrades and slopes might not be considered actual stabilization, but rather maintenance of stable conditions. It makes sense for soil subgrades to be stable in both water content and strength before facilities are placed on them. In this way, the changes in soil properties that may occur with increases of moisture level will be eliminated. Prevention of swelling will provide the shear strengths on which the original designs were made. The actual methods used to accomplish these conditions have been discussed above.

Strength for slopes and backslopes is often underdesigned in transportation facilities. The strength actually used is that determined as peak strength during direct shear and triaxial shear tests. In actuality, the shear strength at failure of the soils involved can be as low as the residual strength, and the residual strength is significantly lower than the peak strength. Several processes cause this phenomenon to occur: gradual stress release, loss of soil suction potential, and increase of moisture levels during cyclic shrinking and swelling caused by climate. Soil stabilization during these processes includes proper selection of testing conditions to establish the real strength to be expected for the field soil mass.

Another way of maintaining stable subgrades for transportation facilities is proper isolation of the subgrade from both construction and operating loadings. During construction, the use of self-propelled compaction equipment may lead to fracturing of subgrade soil layers, particularly when these layers are made of friable chemically stabilized soils. The fractures

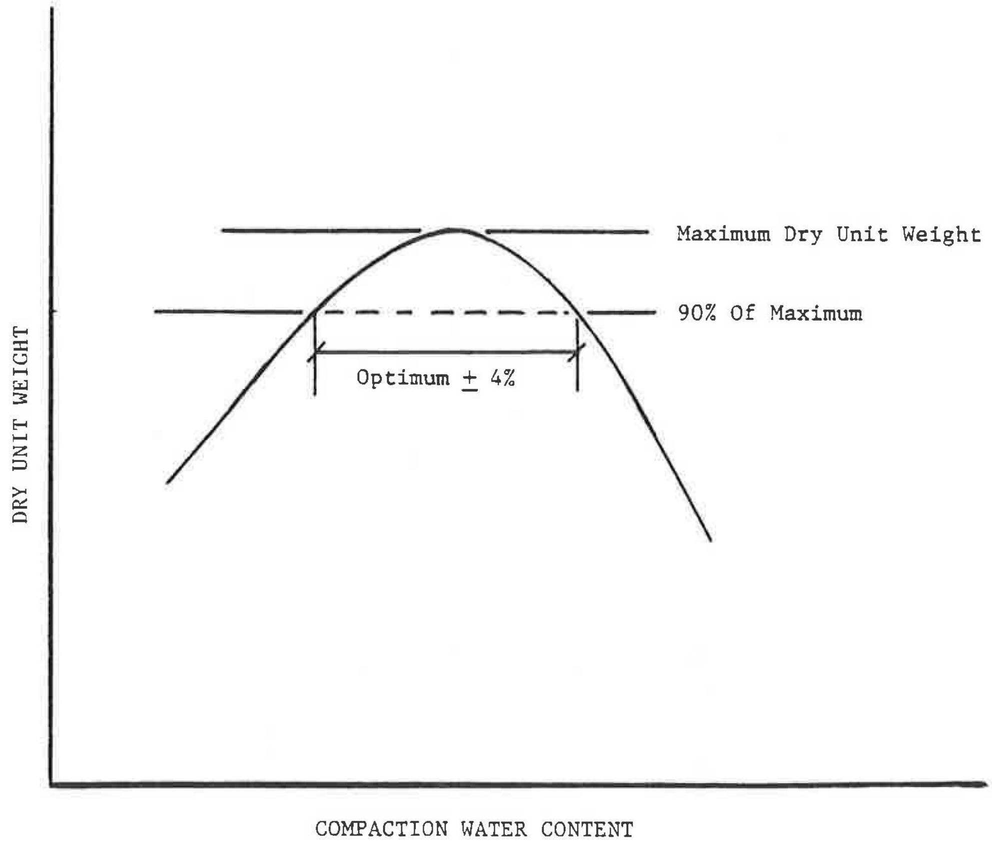

FIGURE 5 Example of compaction water content controls.

that result allow moisture to infiltrate both the stabilized layer and the nonstabilized soils below. This process eventually leads to swelling, which further fractures the stabilized subgrade, allowing large quantities of moisture to infiltrate, and so on (Figure 6).

The initial fracture can be prevented by proper operation of construction equipment to prevent continual direction reversals of self-propelled rollers at nearly the same place. Isolation of soil subgrades from excessive loadings caused by operational situations is well understood and should be based on adequate determination of real subgrade strengths and operational loads prior to design (*4*). When operational loadings exceed those used for design, fracturing of the subgrade and the facility will likely lead to swelling and softening, as described earlier.

These prevention measures are normal to the design process, because the damage that might result is most severe in expansive clay subgrades. The most obvious mechanical stabilization method to prevent damage in the design process is to bridge over the movements expected of the expansive soil mass. Such designs support the facility deep in the soil mass where volume change will not occur and separate the facility from the part of the soil mass that will change in volume. The design usually includes types of pier and beam structures, supported initially near the surface by degradable cartons and structurally designed to transmit the imposed loads to pier elements. Another method is used for the backfill behind retaining walls. The expansive soil mass surface behind the wall is cut back to at least 45 degrees from the horizontal, so that as it swells, it will not impose loads on the wall. The remaining backfill material is made of nonactive, free-draining material, and a system of weep holes and filter-protected drains is installed at the base of the wall in the backfill (Figure 7). The remaining method includes design of the facilities to take the expected movements without loss of service or significant damage. Of course, this method cannot be used when the alignment and grade of the facility are critical, but where movement can be figured and allowed, it is a workable concept. One example is retaining wall elements that will not suffer loss of function or cause failure under these circumstances.

CHEMICAL STABILIZATION METHODS

Chemical stabilization for expansive clay soil property improvement consists of changing the physicochemical environment around and inside clay particles, changing the nature of the water that moves into and out of the voids, and effecting behavioral changes in the soil mass as a whole. These methods include making the clay require less water to satisfy the charge imbalance, making it difficult for water to move into and out of the system, flocculating the clay to cause aggromulation, and, perhaps, cementing particles together to reduce volume change. If chemical stabilizing agents are mixed intimately with soil layers, it may be desirable to apply compaction aids to improve achievable dry unit weight after heavy flocculation of the clay. When such agents are injected into the soil, surfactants are added to the agent slurries to lower their surface tension characteristics. In addition, electroosmosis has been

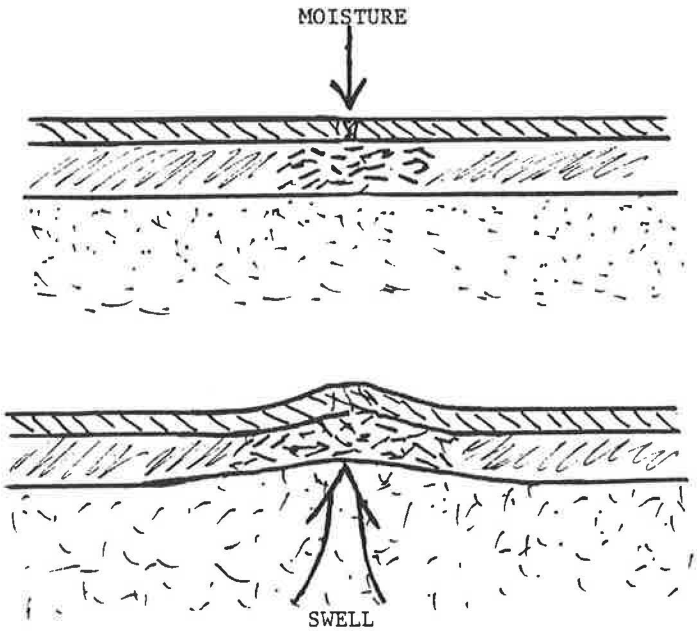

FIGURE 6 (*top*) **Construction fracturing;** (*bottom*) **subgrade swelling damage.**

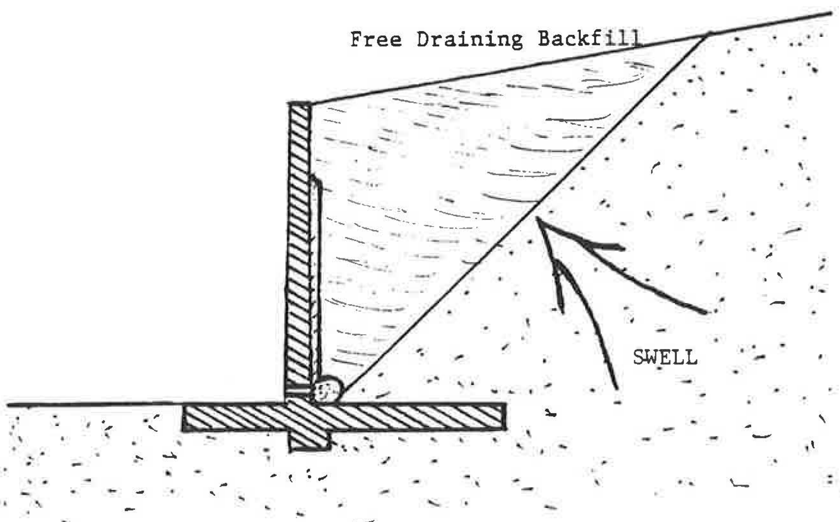

FIGURE 7 Retaining wall backfill treatment.

used to a limited extent with some success to supply cations to expansive clay soil subgrades. It would be most advantageous if the agents were effective as surface treatments, but few, if any, are (*4*).

Probably the most effective chemical stabilization of expansive clays occurs when the cations associated with the natural clay are exchanged for types that are bivalent or have low affinities for water. Many types of cations have been researched, but the most effective and readily available for use is calcium. Potassium has been proven somewhat useful at reducing the swell capacity of these clays and, in some cases, has been found to cause smectites to act and even look like illites in x-ray diffraction analyses. The exchange process is dependent on several factors, of which soil pH, cation concentrations, and temperature are most important. It is important to note that this process of cation exchange alone will not render these clays nonexpansive in behavior.

Another outcome of the cation exchange process is the accumulation of exchanged cations around the clay particles in the associated and free pore water. This ion crowding is believed to be a major contributing force to further reduce active clay behavior. The many cations in the water around the clay will significantly restrict the passage of water into and out of the clay particles. These two phenomena together cause the soil to behave, in some cases, nonexpansively.

The flocculation, or as some might call it, superflocculation, of the clay particles that occurs at the same time as cation exchange has a further stabilizing effect. The clay particles are somewhat more tightly held together by this phenomenon and therefore exhibit less active behavior. In addition, this process tends to assist in the waterproofing of the clay. Agents that have cementing properties would work in these clays, also.

One of the problems associated with flocculation is a lowering of the compactibility of these clays, resulting in significant losses in the dry unit weights achievable. To help overcome these losses, compaction aids, which are usually made of sodium compounds, are added in small quantities to the compaction water. It is believed that these aids reduce the flocculation enough to improve the compactibility of the soil to that in its natural condition.

Many inorganic and organic agents have been tested as stabilizers for expansive clay soil. Because of their proprietary nature, the chemical makeup and the mechanism by which they stabilize are unknown for most. Manufacturers and distributors of these compounds make claims of how they work around and within the clay, but few compounds have withstood independent testing and evaluation. In addition to the amount of cation exchange that occurs with their use, these compounds usually change the nature of the water surrounding the clay particles so that some or all of the volume change behavior of the soil is negated. More than one will effectively reduce the swelling tendencies of the soil but have little effect on its shrinkage behavior. It is therefore important that before any stabilizer is used, it be thoroughly tested by an independent laboratory, using the same testing sequences for all agents compared, and the economics of its use must be studied. One little-discussed effect that must be determined for all chemical stabilizers is the effect they have on the environment. Environmental impact studies should be part of the considerations for using the various agents, especially for those agents that are less well known.

The success of injecting stabilizing agents into the soil subgrade is dependent on the nature of the macrostructure of the soil. In order to provide agent to as much of the subgrade as possible, it is necessary that the subgrade be highly fissured. To ensure that these fissures are open enough to allow adequate penetration of the agent slurries, the subgrade must be relatively dry or elevated injection pressures must be used, or both. On the other hand, injection pressures that are too high may cause excessive hydraulic fracturing of the subgrade or may overcome the overburden pressure present and cause damage to the subgrade. One relatively new concept is short-term, relatively high-pressure pulses during the injection process. Some skepticism still exists about the use of injection stabilization for expansive clay soil subgrades, primarily because of those contractors who choose not to follow accepted procedures and inspections. This method of placing stabilizing agent slurries into the subgrade can be done effectively, however, so long as one realizes its limitations and the possible stabilizing effects of its use (*7*).

The stabilizing effects of surfactants, compaction aids, and the general chemical agents were discussed earlier, but the stabilizing effects of the most common agents require some additional explanation. The following discussion will include a brief synopsis of these stabilizing effects.

The effects of lime and lime slurries are well known; they depend on how and in what form the lime is applied. Mixing hydrated lime and hydrated lime slurries intimately in those expansive clay soils that react favorably with lime will cause cation exchange, ion crowding, flocculation, and if enough lime is present, pozzolanic cementation. In many cases, this will render the stabilized material nonexpansive, nonactive, and waterproof. Quicklime and quicklime slurries result in much the same property improvements and less agent is required for the same amount of stabilization. It is believed that the use of high-temperature quicklime slurries will result in better and quicker stabilization. This belief is based on the facts that chemical reactions work better at higher temperatures and that these slurries have finer gradations of lime and more highly calcium-charged supernatants. The injection of proper lime slurries into well-fractured and desiccated subgrades results in somewhat differing stabilization results, which include filling of the fissures with lime, preswelling of the soil mass between the lime-filled seams, some modifying of the clay between the lime seams, reducing moisture change in the soil mass, and modifying the surface layer where the slurries are mixed intimately with the soil. It is believed that either injection of water after lime slurries or injection of high-temperature quicklime slurries, or both, will result in all of the foregoing effects plus further modification of the clay between the lime seams (*7*). Because of these factors, lime is the most popular agent used to stabilize expansive clay soils.

Other agents that may provide calcium cations for stabilizing expansive clay soil include calcium chloride, portland cement, and calcareous fly ash. The reasons why calcium chloride has not been widely used are not clear. It is believed that the main one is economics, but perhaps it is also because little definitive research has been done to define or support its use. Calcium chloride is known to be more easily made into a calcium-charged supernatant than is lime. Another possible reason for its restricted use is that the resulting pH of the soil will not adequately promote cation exchange.

Portland cement has been used successfully to modify clay, but the mechanisms involved are not the same as those for lime. The small amounts of lime in the cement provide some cation exchange, but the similarity to lime ends there. The water-cement paste is known to coat the clay particles, thereby waterproofing them, and the cement binds particles together, causing what appears to be flocculation and agglomulation. Looking at the stabilized material, one would believe that both lime and cement accomplish the same modification using nearly the same amount of agent.

Calcareous fly ash is known to have two effects when mixed intimately with expansive clay soils. The available quicklime in the fly ash will produce significantly the same amount of change that lime alone would provide and pozzolanic cementation will occur similar to that caused by portland cement. In some cases, the addition of relatively low percentages of fly ash alone will have the same effects as nearly the same quantities of lime, but most often the addition of some lime with the fly ash will be necessary. Fly ash, which is considerably less expensive than either lime or portland cement, seems a natural alternative, but its use has not been that extensive, mostly because of the lack of experience with this agent and the relatively poor quality control. Until there are much faster methods to evaluate the quality of fly ash as it is delivered in the field, the use of this valuable resource will likely be severely limited.

REMEDIAL TREATMENTS

Remedial treatments are actually after-the-fact stabilizers of expansive clay soils and the facilities on which they are built. The processes used may be as simple as drainage corrections or as complex as rebuilding of the facility, and they are almost always more costly to institute than the stabilization that should have been done initially. It is interesting to note that the best methods of remedial stabilization are usually the simplest and most direct. One of the greatest detriments of remedial treatment is the interruption in use of the facility while the work is being performed.

Three procedures must be completed if the remedial treatment is to be a success. First, adequate information should be sought about the soil conditions, including sampling and testing. Second, a history of the project should be compiled to determine the processes that resulted in the need for remedial treatment. The information gathered during this phase will usually be very valuable when the methods of stabilization are determined. Third, the possible alternative ways to correct the problem should be determined. It is essential that the process chosen result in a final product that will require no further remedial treatment and will function adequately for the purpose for which it was designed (*6*).

An example that highlights how remedial treatments are accomplished is a slope that has been determined to be unstable or has failed. To lower the potential of failure, the angle of the slope may be decreased, and (if right-of-way is available) the slope can simply be flattened. The slope may also be terraced to lower the effective angle of the total slope. If the angle of the slope cannot be changed, the strength of the soil mass must be improved. This may be done by draining the slope in some cases, and by injecting agents that will improve the strength of the soil along potential failure planes. These methods are generally applicable to slopes that have not failed. Once the slope has failed, the material must be cleaned from the failure plane, and the slope must be rebuilt either at a flatter angle or with material that has an improved strength. The surface of all slopes must be protected from erosion, and this may require surface stabilization techniques.

Another frequent problem is the distortion and misalignment of pavement systems caused by differential movements of expansive clay soils. It is likely that this condition is the result of lack of stabilization of these materials and may be a problem that changes with the effects of the climate. The first step in the remedial process is to provide stability for the active foundation soils of the pavement. This may be done by (a) providing vertical moisture barriers to hold moisture in the soils and waiting for the moisture stability to return naturally, (b) applying moisture at the edge of the pavement and devising some means of maintaining the stable moisture levels achieved, or (c) injecting water or stabilizing agents (or both) into the soil. An integral part of the moisture stabilization process is sealing all cracks in the pavement system that would allow entrance or exit of moisture and correcting drainage conditions that may lead to concentrations of water at the subgrade level.

Once moisture stabilization is complete, realignment of the pavement can be accomplished. The most frequently used methods to realign pavements are grouting and mudjacking. If the differential movements are severe, replacement of the pavement may be necessary; and the process of stabilization begins with subgrade soil stabilization. Injection stabilization may well be used during this process, and as with all injection remedial processes, the spread of the injected slurry must be confined so that more damage outside the distressed area does not result.

The failure of retaining walls caused by the action of expansive clay soils can be remedied by using the same methods recommended for initial stabilization. Soils retained by walls may be repaired in similar ways to soils in slopes, and clay backfill should be cut back as indicated previously. Rebuilding or replacement of the wall, or both, may often be necessary when the damage is severe. With this in mind, it is easy to see why these remedial processes are much more expensive than constructing the facilities correctly in the first place.

CONCLUSIONS

It is almost always most advisable, from the standpoint of economics, to stabilize expansive clay soils during the construction of a transportation facility rather than leave the soils unstable, thereby risking the need for remedial treatment. Stabilization can be performed more economically and more completely initially than when repairs are needed to keep up with an unstable situation. Unstable expansive clay soils do not have to be accepted for use. Even at this time, much is known about stabilizing these problem soils, and the stabilization processes are economical alternatives to potential problems.

RESEARCH NEEDS

Further research is needed to provide answers to some of the questions raised in this paper and to continually investigate new agents and methods. This research is most useful when it includes full-scale applications and is best done by independent organizations that have no vested interest in the outcome. There is a definite need to investigate available waste products to determine their efficiency for stabilization. One such material, fly ash, is becoming more accepted for use, but there are still problems in determining the quality of the ash in the field. Research should be publicized so that decision makers can make maximum use of alternative methods of stabilization.

Two problems with the behavior of these problem soils need further attention: (a) the effects of cyclic shrink-swell on the behavior of the soil mass and (b) prediction of the vertical rise expected from the soil mass.

Last, with the potential for damage caused by expansive clay soils and the condition of the nation's infrastructure, more funds for research must be forthcoming in this area.

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