
Foundation Improvement and Stabilization

A. General Information

Soft subgrade and moisture-sensitive soils such as expansive soils, frost-prone soils, and collapsing soils present a construction challenge as well as a pavement performance challenge. Proper treatment of problem soils and the preparation of the foundation are important to ensure a long-lasting pavement structure that does not require excessive maintenance. Such soils can be stabilized to form a construction pad or a long-term subsurface layer capable of carrying pavement applied loads. In all cases, the provision for a uniform soil relative to textural classification, moisture, and density in the upper portion of the subgrade cannot be over emphasized. This uniformity can be achieved through soil sub-cutting or other techniques. Five techniques can be used to improve the strength and reduce the climatic variation of the foundation on pavement performance: stabilization of weak or moisture-sensitive soils, thick granular layers, subsurface drainage systems, geosynthetics, and soil encapsulation. Thick granular layers are generally greater than 18 inches in thickness and require readily accessible, good quality aggregates. Therefore, thick granular layers are seldom used in Iowa and will not be discussed further in this section.

B. Stabilization

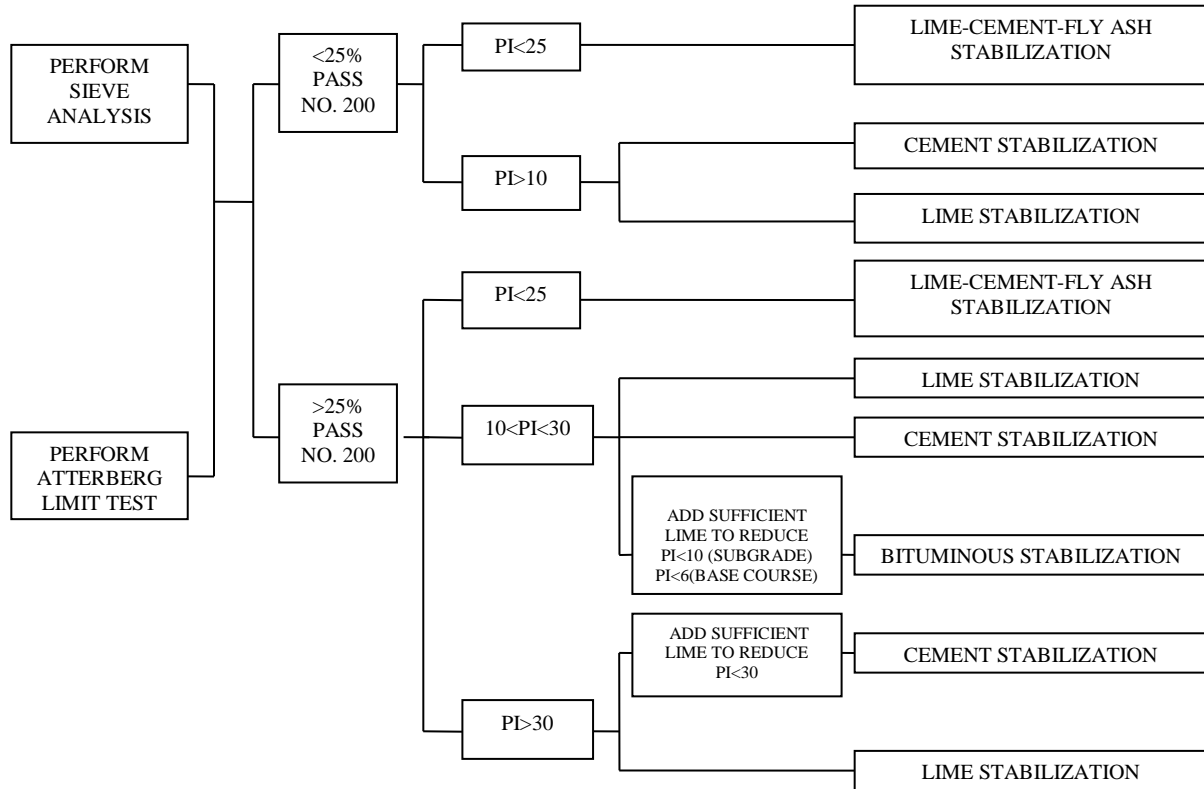
Soil that is highly susceptible to volume and strength changes can cause severe roughness and accelerate the deterioration of the pavement structure in the form of increased cracking and decreased ride quality when combined with truck traffic. Generally, the strength and stiffness of some soils are highly dependent on moisture and stress state. In some cases, the subgrade soil can be treated with various materials to improve the strength and stiffness characteristics of the soil. Stabilization of soils is usually performed for two reasons:

1. As a construction foundation to dry very wet soils and facilitate compaction of the upper layers. In this case, the stabilized soil is usually not considered as a structural layer in the pavement design process. This process is also sometimes referred to as soil modification.
2. To strengthen a weak soil and restrict the volume change potential of a highly plastic or compressible soil. In this case, the stabilized soil is usually given some structural value in the pavement design process.

Lime, fly ash, cement, and asphalt stabilization have been used for controlling the swelling and frost heave of soils and improving the strength characteristics of unsuitable soils. For stabilization or modification of cohesive soils, hydrated lime is most widely used. Lime modification is used in many areas of the U.S. to obtain a good construction foundation in wet weather above highly plastic clays and other fine-grained soils. Lime is applicable in clayey soils (i.e., CH and CL type soils) and in granular soils containing clay binder (i.e., GC and SC), while Portland cement is more commonly used in non-plastic soils. Lime reduces the Plasticity Index (PI) and renders a clay soil less sensitive to moisture changes. The use of lime should be considered whenever the PI of the soil is greater than 10. It is important to note that changing the physical properties of a soil through chemical stabilization can produce a soil that is susceptible to frost heave.

Some basic definitions of soil modification and stabilization using lime, cement, and asphalt are provided below. Additional guidance on how stabilization is achieved using lime, cement, and asphalt can be found in TRB 1987; PCA 1995; and AI MS19, respectively. A flow chart for the determination of chemical treatment options for soil stabilization based on the percent passing the No. 200 sieve and the plasticity index of the soil is shown in Figure 6H-1.01.

Figure 6H-1.01: Selection of Stabilizer



Source: U.S. Department of Transportation 1976

- a. **Lime Treatment:** Lime treatment or modification consists of the application of 1 to 3% hydrated lime to aid drying of the soil and permit compaction. As such, it is useful in the construction of a working foundation to expedite construction. Lime modification may also be considered to condition a soil for follow-up stabilization with cement or asphalt. Lime treatment of subgrade soils is intended to expedite construction, and no reduction in the required pavement thickness should be made.
- b. **Lime Stabilization:** Lime stabilization of soils improves the strength characteristics and changes the chemical composition of some soils. The strength of fine-grained soils can be improved significantly with lime stabilization, while the strength of coarse-grained soils is usually moderately improved. Lime has been found most effective with highly plastic clay soils containing montmorillonite (expansive clay mineral).

Lime stabilization has been found to be an effective method to reduce the volume change potential of many soils. However, lime treatment of soils can convert soil that shows negligible-to-moderate frost heave potential into a soil that is highly susceptible to frost heave, acquiring characteristics more typically associated with silts. It has been reported that this adverse effect has been caused by an insufficient curing period accompanied by an inadequate compaction effort. Adequate curing is also important if the strength

characteristics of the soil are to be improved.

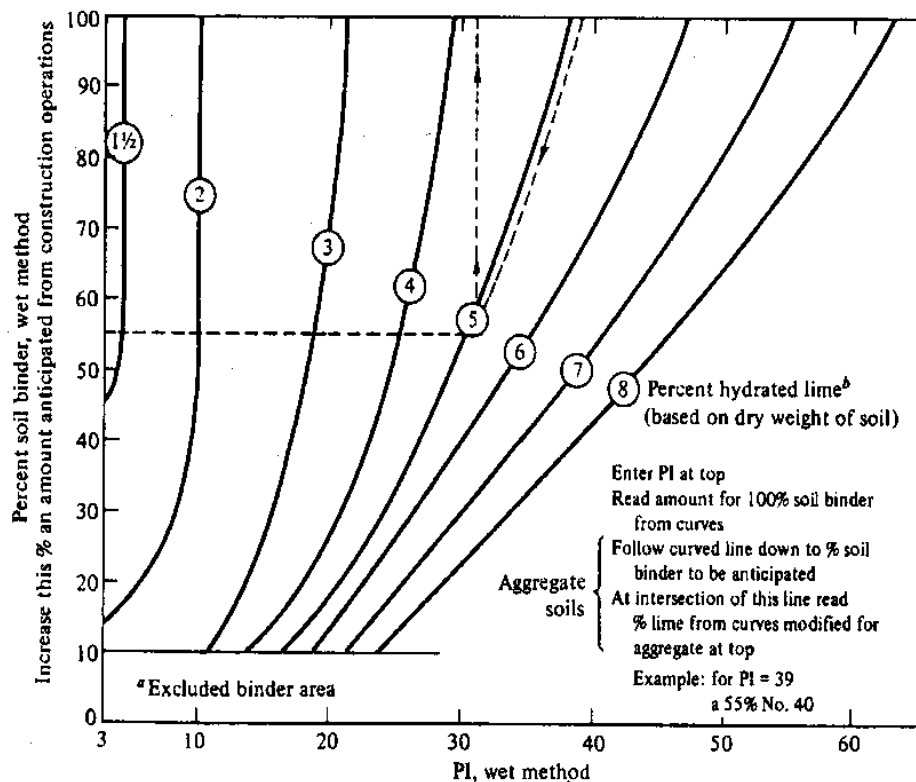
For successful lime stabilization of clay (or other highly plastic) soils, the lime content should be from 3 to 8% of the dry weight of the soil, and the cured mass should have an unconfined compressive strength increase of at least 50 psi after a 28 day curing period over the uncured material. The optimum lime content should be determined with the use of unconfined compressive strength and the Atterberg limits tests on laboratory lime-soil mixtures molded at varying percentages of lime. The lime-stabilized subgrade layer should be compacted to a minimum density of 95%, as defined by Standard Proctor density. The minimum strength requirement for this material is a function of pavement type and the importance of the layer within the pavement structure.

When soils are treated properly with lime, it has been observed that the lime-soil mixture may be subject to durability problems caused by the cyclic freezing and thawing of the soil.

Lime-fly ash stabilization is applicable to a broader range of soils because the cementing action of the material is less dependent on the fines contained within the soil. However, long-term durability studies of pavements with lime-fly ash stabilization are rather limited.

Soils classified as CH, CL, MH, ML, SM, SC, and GC with a plasticity index greater than 10 and with at least 25% passing the No. 200 sieve potentially are suitable for stabilization with lime. Hydrated lime, in powder form or mixed with water as slurry, is used most often for stabilization. Figure 2 can be used to estimate the design lime content for a subgrade. The quantities found from this chart should be used as a guideline, and laboratory testing mix design studies should be conducted for specific applications. Additional information can be obtained in the National Lime Association's Lime Stabilization Construction Manual (1972).

Figure 6H-1.02: Recommended Amounts of Lime for Stabilization of Subgrade and Bases



Source: National Lime Association 1972

- a. Cement Stabilization:** Portland cement is used widely for stabilizing low-plasticity clays, sandy soils, and granular soils to improve the engineering properties of strength and stiffness. Increasing the cement content increases the quality of the mixture. At low cement contents, the product is generally termed cement-modified soil. A cement-modified soil has improved properties of reduced plasticity or expansive characteristics and reduced frost susceptibility. At higher cement contents, the end product is termed soil-cement. Higher cement contents will unavoidably induce higher incidences of shrinkage cracking caused by moisture/temperature changes.

For soils to be stabilized with cement, proper mixing requires that the soil have a PI of less than 20 and a minimum of 45% passing the No. 40 sieve. However, highly plastic clays that have been pre-treated with lime or fly ash are sometimes suitable for subsequent treatment. For cement stabilization of granular and/or non-plastic soils, the cement content should be 3 to 10% of the dry weight of the soil, and the cured material should have an unconfined compressive strength of at least 150 psi within seven days. The Portland cement should meet the minimum requirements of AASHTO M 85. The cement-stabilized subgrade should be compacted to a minimum density of 95%, as defined by AASHTO T 134. Only fine-grained soils can be treated effectively with lime for marginal strength improvement.

- b. Asphalt Stabilization:** Generally, asphalt-stabilized soils are used for subbase construction. Use of asphalt as a stabilizing agent produces different effects, depending on the soil, and may be divided into three major groups:
- 1) Sand-asphalt, which produces strength in cohesionless soils, such as clean sands, or acts as a binder or cementing agent
 - 2) Soil-asphalt, which stabilizes the moisture content of cohesive fine-grained soils
 - 3) Sand-gravel asphalt, which provides cohesive strength and waterproofs pit-run gravelly soils with inherent frictional strength. The durability of asphalt-stabilized mixtures generally can be assessed by measurement of their water absorption characteristics.
- c. Fly Ash Stabilization:** Fly ash and similar materials can be used in the stabilization of clay soils either in place of lime or cement or in combination with lime and cement. Generally, the use of fly ash and similar materials reduces the shrink-swell properties of the soils. Additionally, the act of drying the soil facilitates soil compaction. These materials are used with clay-type soils that are above the optimum water content.

- 3. Characteristics of Stabilized Soils:** The improvement of subgrade or unbound aggregate by application of a stabilizing agent is intended to cause the improvements outlined above. These improvements arise from several important mechanisms that must be considered and understood by the pavement designer. Subgrade stabilizing agents may fill or partially fill the voids between the soil particles. This reduces the permeability of the soil by increasing the tortuosity of the pathways for water to migrate through the soil. Reduction of permeability may be relied upon to create a waterproof surface to protect underlying, water-sensitive soils from the intrusion of surface water. This mechanism must be accompanied by other aspects of the geometric design into a comprehensive system. The reduction of void spaces may also tend to change the volume change under shear from a contractive to a dilative condition. The stabilizing agent also acts by binding the particles of soil together, adding cohesive shear strength, and increasing the difficulty with which particles can move into a denser packing under load. Particle binding serves to reduce swelling by resisting the tendency of particles to move apart. The particles may be bound together by the action of the stabilizing agent itself (as in the case of asphalt cement), or may be cemented by byproducts of chemical reactions between the soil and stabilizing agent (as in the case of lime or portland cement).

The zone that may be selected for improvement depends upon a number of factors. Among these are the depth of soft soil, anticipated traffic loads, the importance of the transportation network, and the drainage characteristics of the geometric design and the underlying soil. When only a thin zone is subject to improvement, removal and replacement will usually be the preferred alternative by most agencies, unless a suitable replacement soil is not economically available. The zone can be described as thick or thin, based primarily on the economics of the earthwork requirements and the depth of influence for the vehicle loads.

- 4. Pavement Design Considerations for Stabilized Subgrades:** The application of the stabilizing agent will usually increase the strength properties of the soil. This increase will generally appear in the pavement design process as an increase in the modulus of the improved soil, reducing the pavement structural layer thicknesses. The cost of the stabilization process, therefore, can be offset by savings in the pavement structural layers. However, it is important that the actual increase used in the design process be matched in the constructed product, making construction quality control and quality assurance programs very important. When pavement design is performed using only a single parameter to describe the subgrade condition, the thickness of the stabilized zone is a critical component in determining the increased modulus to use in design.

The thickness of the improved subgrade zone is both a design and a construction consideration. From the design standpoint, it would obviously be advantageous to stabilize and improve the properties of a zone as thick as may be reasonably stabilized. From a constructability perspective, there are practical and economic implications related to the thickness of the stabilized zone. Stabilization requires that the agent be thoroughly distributed into the soil matrix, and that the soil matrix must be well pulverized to prevent unimproved clumps from remaining isolated within the mass. The construction equipment used to mix must be capable of achieving high levels of uniformity throughout the depth of desired improvement. If the zone to be improved is very thick, it may be necessary to process the stabilized soil in multiple lifts, which will usually require the stripping and stockpiling of upper lifts within the subgrade. Stabilization therefore rarely exceeds a few inches in depth in transportation applications, except for deep mixing applications that might be used in the vicinity of bridge foundations or abutments to provide improved foundation support.

C. Subsurface Drainage

Subsurface drainage systems are used for three basic reasons:

- To lower the groundwater level
- To intercept the lateral flow of subsurface water beneath the pavement structure
- To remove the water that infiltrates the pavement's surface

Deep subdrains (below frost line) are usually installed to handle groundwater problems. The design and placement of these subdrains should be handled as part of the geotechnical investigation of the site. Edgedrains placed in trenches under the shoulders at shallower depths are used to handle water infiltrating the pavement from above. The design and placement of these drainage systems is discussed in Section 6G-1 - Subsurface Drainage Systems.

D. Geosynthetics

Geosynthetics are a class of geomaterials that are used to improve soil conditions for a number of applications. They consist of manufactured polymeric materials used in contact with soil materials or pavements as an integral part of a man-made system (ASTM D 4439). The most common applications in general use are in pavement systems for both paved and unpaved roadways, for reinforcing embankments and foundation soils, for creating barriers to water flow in liners and cutoffs, and for improving drainage. The generic term “geosynthetic” is often used to cover a wide range of different materials, including geotextiles, geogrids, and geomembranes. Combinations of these materials in layered systems are usually called geocomposites.

1. Materials:

- a. **Geotextiles:** A geotextile, as defined by ASTM D 4439, is “a permeable geosynthetic comprised solely of textiles.” These materials are also known as engineering fabrics. Fabrics are usually created from polymers, most commonly polypropylene, but also potentially including polyester, polyethylene, or nylon (Koerner 1998). Geotextiles are usually classified by their manufacturing process as either woven or non-woven. Both kinds of geosynthetics use a polymer fiber as raw material. Depending on the application, the fibers may be used singly or spun into yarns by wrapping several fibers together, or created by a slit film process. Woven geosynthetics are manufactured by weaving fibers or yarns together in the same way as any form of textile, although generally only fairly simple weaving patterns are used. Non-woven geosynthetics are made by placing fibers in a bed, either in full-length or in short sections. The fibers are then bonded together, either by raising the temperature, applying an adhesive chemical, or by mechanical means (usually punching the bed of fabric with barbed needles, in essence, tangling them into a tight mat).
- b. **Geogrids:** Geogrids, as their name suggests, consist of a regular grid of plastic with large openings (called apertures) between the tensile elements. The function of the apertures is to allow the surrounding soil materials to interlock across the plane of the geogrid; hence, the selection of the size of the aperture is partially dependent on the gradation of the material into which it will be placed. The geogrid is manufactured using high-density polymers of higher stiffnesses than are common for geotextiles. These polymers are then punched in a regular pattern and drawn in one or two directions. Alternatively, a weaving process may be used in which the crossing fibers are left wide apart and the junctions between them are reinforced.
- c. **Geomembranes:** Geomembranes are used to retard or prevent fluid from penetrating the soil and as such consist of continuous sheets of low permeability materials. These materials are made by forming the polymer into a flat sheet, which may have a roughened surface created to aid in the performance of the membrane by increasing friction with the adjacent soil layer.

Several other kinds of geosynthetic materials may be made by slight variations of these general types. For example, geonets are similar in appearance to geogrids but are manufactured slightly differently so that the individual elements of the geonet are at acute angles to each other. These materials are usually used in drainage applications.

- d. **Geocomposites:** Geocomposite materials are often created by combining two or more of the specific types of products described previously to take advantage of multiple benefits. Further, geocomposites may be formed by combining geosynthetics with more traditional geomaterials, the most common example being the geosynthetic clay liner. A geosynthetic clay liner consists of a layer of bentonite sandwiched together with geomembrane or geotextile materials to create a very low permeability barrier.

- 2. Applications:** There are six widely recognized functions for geosynthetic applications as shown across the top of Table 6H-1.01. The typical classes of geosynthetic used for each function are also shown. Although the table indicates only primary functions, most geosynthetic applications call for the material to satisfy at least one secondary function as well (e.g., a separation layer under a pavement may also be required to reinforce the subgrade and influence drainage under the pavement).

Table 6H-1.02 provides a summary of the most commonly used geosynthetic functions for transportation applications. Comparison of Tables 6H-1.01 and 6H-1.02 reveals that the geotextile and geogrid materials are the most commonly used in transportation, although certainly others are sometimes used. This generality is more accurate when only the pavement itself (not including the adjoining fill or cut slopes, retaining walls, abutments, or drainage facilities) is considered. The most common usage for geosynthetics in the United States has historically been for unpaved roads but use in paved, permanent roads is increasing.

Each of these functional classes, while potentially related by the specific application being proposed, refers to an individual mechanism for the improvement of the soil subgrade. The separation function describes the maintenance of materials of different gradations as separate and distinct materials. In the specific case of the pavement application, separation relates to the maintenance of unbound granular base course materials as distinct from the subgrade (Koerner 1998; Christopher and Holtz 1991).

These materials may tend to become mixed in service due to pumping of the subgrade into the subbase, or due to localized bearing capacity failures leading to migration of aggregate particles into the subgrade (TRB 1987). This potential behavior has been confirmed in the field, as well as the ability of geosynthetic materials to resist it (Macdonald and Baltzer 1997; McKeen 1976). Once the unbound subbase is mixed with the subgrade, its strength and drainage properties may be detrimentally affected.

Table 6H-1.01: Functions of Geosynthetic Materials

Geosynthetic Materials	Function					
	<i>Filtration</i>	<i>Drainage</i>	<i>Separation</i>	<i>Reinforcement</i>	<i>Fluid Barrier</i>	<i>Protection</i>
Geotextile	x	x	x	x		x
Geogrid			x	x		
Geomembrane					x	
Geonet		x				
Geocomposites:						
Geosynthetic Clay Liner					x	
Thin Film Geotextile Composite					x	
Field Coated Geotextile					x	

Source: Laguros and Miller 1997.

Table 6H-1.02: Transportation Uses of Geosynthetic Materials

Function	Specific Use
Filtration	<ul style="list-style-type: none"> Beneath aggregate subbase for paved and unpaved roads and airfields or railroad ballast
Drainage	<ul style="list-style-type: none"> Drainage interceptor for horizontal flow Drain beneath other geosynthetic systems
Separation (of dissimilar materials)	<ul style="list-style-type: none"> Between subgrade and aggregate subbase in paved and unpaved roads and airfields Between subgrade and ballast for railroads Between old and new asphalt layers
Reinforcement (of weak materials)	<ul style="list-style-type: none"> Over soft soils for unpaved roads, paved roads, airfield, railroads, construction foundations

Source: Koerner 1998

- a. Reinforcement Function:** The reinforcement function is very similar to the reinforcement process in reinforced concrete elements. The geosynthetic is introduced to provide elements with tensile resistance into the unbound material, which on its own would exhibit very low tensile resistance. The specific improvements imparted to pavement designs include the potential for improved lateral restraint of the subbase and subgrade, modifications of bearing capacity failure surfaces, and tensile load transfer under the wheel load. The lateral restraint arises as the subbase material tends to move outward under load beneath the wheel. The geosynthetic tends to be pulled along as a result of friction or interlock with the aggregate particles, and resists that tendency through its own tensile strength. The particles are therefore held in place as well. Bearing capacity surfaces may be forced to remain above the geosynthetic, in the stronger base course. Finally, the tendency of the subbase to bend under the wheel loads introduces tensile stress at the subbase/subgrade interface, which may be taken by the geosynthetic. Careful consideration must be given to the mobilization behavior of the geosynthetic, which may require fairly large strains to provide the desired reinforcement.
- b. Filtration Function:** The filtration function is similar to the separation function, but in this case the reason for mixing or migration of particles is the seepage forces induced by water flowing through the unbound material. The function of the filter is to provide a means to allow water to flow through unbound material without excessive loss of soil due to seepage forces, and without clogging (Koerner 1998). Zonal filters may offer the same protection, but may be less convenient or practical to install. The drainage function is related to the filtration function, in that once again the desired behavior is the movement of water out of or through the unbound material with sufficient maintenance of the fine particles in place. The difference arises in the focus and intent; filtration applications tend to be predicated on the maintenance of the soil, while drainage applications tend to attach more importance to the quantity of flow to be maintained or the desired reduction in pore water pressure. Further, the drainage function may be carried out by designing for drainage along the plane of the geotextile itself, rather than through surrounding unbound material.

The specific function to be provided by the geosynthetic in transportation applications is a function of the soil conditions. Table 6H-1.03 indicates that the following functions most commonly arise as a function of the soil strength.

Table 6H-1.03: Function of the Geosynthetic vs. Subgrade Properties

S_u (kPa) ¹	CBR	Function
60-90	2-3	Filtration, some separation
30-60	1-2	Filtration, separation, some reinforcement
<30	Below 1	Filtration, separation, reinforcement

¹ S_u (kPa) = undrained shear strength (1 kPa = 20.89 psf)

Source: Holtz et al. 1998

The range of functions potentially served by the geosynthetic thus increases as the subgrade strength decreases. In all cases reported in Table 6H-1.03, the soil conditions are rather poor. Table 6H-1.04 indicates that geosynthetics are most appropriate under the conditions outlined.

Table 6H-1.04: Appropriate Conditions for Geosynthetic Use

Condition	Related Measures
Poor soils	USCS: SC, CL, CH, ML, MH, OH, or PT soils; or AASHTO: A-5, A-6, A-7, or A7-6 soils
Low strength	$S_u < 13$ kPa, CBR <3, or MR <4500 psi
High water table	Within zone of influence of surface soils
High sensitivity	High undisturbed strength compared to remolded strength

Source: Holtz et al. 1998

- Design Considerations:** Koerner describes three potential design approaches: design by cost, design by specification, and design by function, to design geosynthetics for engineering application. Additional information on these design approaches can be found in Koerner 1998.

E. Soil Encapsulation

Soil encapsulation is an embankment placement technique that has been used to protect moisture sensitive soils from large variations in moisture content. However, this technique is rarely used to improve the foundations of higher-volume roadways. It is more commonly used as a foundation or subbase layer for low-volume roadways, where the import of higher-quality embankment materials is restricted from a cost standpoint. The concept of soil encapsulation is to keep the fine-grained soils at or slightly below optimum moisture content, where the strength of these soils can support heavier trucks and traffic. See Section 6D-1 - Embankment Construction, for placement of unsuitable soils within embankment sections.

F. Moisture Conditioning

Table 6H-1.05 shows the relationship between optimum moisture content and density/strength of Iowa soils. For gaining maximum dry density and better compressive strength of soil, the water content should be kept at or around optimum moisture content. The SUDAS Specifications require a moisture content between optimum and 4% above optimum moisture for prepared subgrades.

According to ASTM D 698 Method A, a wide range of maximum densities and optimum moisture contents were determined. Table 6H-1.05 shows the typical relationships between optimum moisture contents and density/strength of some Iowa soils.

Table 6H-1.05: Typical Optimum Moisture Contents and Density/Strengths

Soil	Optimum Moisture Content (%)	Maximum Dry Unit Weight γ_d , (pcf)	Unconfined Compressive Strength at Optimum Moisture Content (psi)
Paleosol	17.0	106.7	48
Alluvium	19.8	102.6	44
Glacial Till	12.5	118.4	44
Le Grand Loess	17.2	106.1	44
Turin Loess	16.6	105.2	33

Source: White, et al. 2005

G. Granular Subbases

Granular subbases are used as a substitute for subgrade materials in regions having poor soils (i.e., high moisture content fine-grained soils) when the subgrade is not treated with another chemical or mechanical stabilizer. The granular subbase provides additional load bearing strength directly below the pavement, reduces the stress applied to the subgrade, provides drainage for the pavement system, and provides a uniform, stable construction platform. See Section 6F-1 - Pavement Subbase Design and Construction, for more information.

H. References

Asphalt Institute. *The Basic Emulsion Manual*. Third Edition. Lexington, KY: Manual Series No. 19. 2007.

Christopher, B.R., and R.D. Holtz. *Geotextiles for Subgrade Stabilization in Permanent Roads and Highways*. Atlanta, GA: Proceedings, Geosynthetics. 1991.

Holtz, R.D., B.R. Christopher, and R.R. Berg. *Geosynthetic Design and Construction Guideline*. Washington, DC: Participant Notebook, NHI Course No. 13213, Publication No. FHWA HI-95-038 (revised), Federal Highway Administration, Washington, D.C. 1998.

Koerner, R.M. *Designing with Geosynthetics*. Fourth Edition. Upper Saddle River, NJ: Prentice Hall. 1998.

Macdonald, R., and S. Baltzer. *Subgrade performance study part I: Materials, Construction and Instrumentation*. Denmark: Danish Road Institute. 1997.

McKeen, R.G. *Design and Construction of Airport Pavements on Expansive Soils*. Washington, DC: Report No. FAA-RD-76-66. 1976.

National Lime Association. *Lime Stabilization Construction Manual*. Fifth Edition. Washington, DC. 1972.

Portland Cement Association. *Soil-Cement Construction Handbook*. Skokie, IL. 1995.

Transportation Research Board. *Lime Stabilization – Reactions, Properties, Design, and Construction, State of the Art Report 5*. Washington, DC. 1987.

U.S. Department of Transportation. *Soil Stabilization in Pavement Structures, A Users Manual, Vol. 1*. 1976.

White, D., D. Harrington, and Z. Thomas. *Soil Stabilization of Non-uniform Subgrade Soils*. Iowa: Report No. TR-461, Iowa Department of Transportation. 2005.

Additional Resources:

Bergeson, K., C. Jahren, and D. White. *Embankment Quality Phase I*. Iowa: Report No. TR-401, Iowa Department of Transportation. 1998.

Christopher, B.R., and V.C. McGuffey. *Synthesis of Highway Practice 239: Pavement Subsurface Drainage Systems*. Washington, DC: National Cooperative Highway Research Program, Transportation Research Board, National Academy Press. 1997.

Laguros, J.G., and G.A. Miller. *Stabilization of Existing Subgrades to Improve Constructability During Interstate Pavement Reconstruction*. Washington, DC: NCHRP Synthesis 247, Transportation Research Board. 1997.

Newcomb, D.A., and B. Birgisson. *Measuring In Situ Mechanical Properties of Pavement Subgrade Soils*. Washington, DC: NCHRP Synthesis 278, Transportation Research Board. 1999.

Skok, E.L., E.N. Johnson, and M. Brown. *Special practices for design and construction of subgrades in poor, wet and/or saturated soil condition*. Minnesota: Report No. MN/RC-2003-36, Minnesota Department of Transportation. 2003.

Snethen, D.R., L.D. Johnson, and D.M. Patrick. *An Evaluation of Expedient Methodology for Identification of Potentially Expansive Soils*. Washington, DC: Report No. FHWA-RD-77-94. 1977.

U.S. Army Corps of Engineers. *Engineering and Design - Pavement Criteria for Seasonal Frost Conditions - Mobilization Construction*. Engineering Manual EM 1110-3-138. 1984.

White, D., K. Bergeson, and C. Jahren. *Embankment Quality: Phase II*. Iowa: Report No. TR-401, Iowa Department of Transportation. 2000.

White, D., K. Bergeson, and C. Jahren. *Embankment Quality: Phase III*. Report No. TR-401, Iowa Department of Transportation. 2002.