PDHonline Course C315 (4 PDH)

Expansive Soil Stabilization

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7.5.7 Summary

Problematic soils can be treated using a variety of methods or a combination thereof. Improvement techniques that can be used to improve the strength and reduce the climatic variation of the foundation on pavement performance include

1. Improvement of subsurface drainage (see Section 7.2, and should always be considered).
2. Removal and replacement with better materials (*e.g.,* thick granular layers).
3. Mechanical stabilization using thick granular layers.
4. Mechanical stabilization of weak soils with geosynthetics (geotextiles and geogrids) in conjunction with granular layers.
5. Lightweight fill.
6. Stabilization of weak soils with admixtures (highly plastic or compressible soils).
7. Soil encapsulation.

Details for most of these stabilization methods will be reviewed in the next section.

7.6 SUBGRADE IMPROVEMENT AND STRENGTHENING

Proper treatment of problem soil conditions and the preparation of the foundation are extremely important to ensure a long-lasting pavement structure that does not require excessive maintenance. Some agencies have recognized certain materials simply do not perform well, and prefer to remove and replace such soils (*e.g.,* a state specification dictating that frost susceptible loess cannot be present in the frost penetration zone). However, in many cases, this is not the most economical or even desirable treatment (*e.g.,* excavation may create disturbance, plus additional problems of removal and disposal). Stabilization provides an alternate method to improve the structural support of the foundation for many of the subgrade conditions presented in the previous section. 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 stabilization techniques. Stabilization may also be used to improve soil workability, provide a weather resistant work platform, reduce swelling of expansive materials, and mitigate problems associated with frost heave. In this section, alternate stabilization methods will be reviewed, and guidance will be presented for the selection of the most appropriate method.

7.6.1 Objectives of Soil Stabilization

Soils that are 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 stiffness (in terms of resilient modulus) of some soils is highly dependent on moisture and stress state (see Section 5.4). 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 three reasons:

1. As a construction platform to dry very wet soils and facilitate compaction of the upper layers—for this case, the *stabilized* soil is usually not considered as a structural layer in the pavement design process.
2. To strengthen a weak soil and restrict the volume change potential of a highly plastic or compressible soil—for this case, the *modified* soil is usually given some structural value or credit in the pavement design process.
3. To reduce moisture susceptibility of fine grain soils.

A summary of the stabilization methods most commonly used in pavements, the types of soils for which they are most appropriate, and their intended effects on soil properties is presented in Table 7-13.

Mechanical stabilization using thick gravel layers or granular layers in conjunction with geotextiles or geogrids is an effective technique for improving roadway support over soft, wet subgrades. Thick granular layers provide a working platform, but do not provide strengthening of the subgrade. In fact, construction of thick granular layers in some cases results in disturbance of the subgrade due to required construction activities. Thick granular layers are also used to avoid or reduce frost problems by providing a protection to the underlying subgrade layers.

Table 7-13. Stabilization Methods for Pavements (after Rollings and Rollings, 1996).

Stabilization Method	Soil Type	Improvement	Remarks
Mechanical			
- More Gravel	Silts and Clays	None	Reduce dynamic stress level
- Blending	Moderately plastic	None	Too difficult to mix
	Other	Improve gradation Reduce plasticity Reduce breakage	
- Geosynthetics	Silts and Clays	Strength gain through minimum disturbance and consolidation	Fast, plus provides long-term separation
- Lightweight fill	Very weak silts, clays, peats	None Thermal barrier for frost protection	Fast, and reduces dynamic stress level
Admixture			
- Portland cement	Plastic		Less pronounced hydration of cement
	Coarse		Hydration of cement
- Lime	Plastic	Drying	Rapid
		Strength gain	Rapid
		Reduce plasticity	Rapid
		Coarsen texture	Rapid
		Long-term pozzolanic cementing	Slow
	Coarse with fines	Same as plastic	Dependent on quantity of plastic fines
	Nonplastic	None	No reactive material
- Lime-flyash	Same as lime	Same as lime	Covers broader range
- Lime-cement- flyash	Same as lime	Same as lime	Covers broader range
- Bituminous	Coarse	Strengthen/bind waterproof	Asphalt cement or liquid asphalt
	Some fines	Same as coarse	Liquid asphalt
	Fine	None	Can't mix
- Pozzolanic and slags	Silts and coarse	Acts as a filler	Dense and strong
		Cementing of grains	Slower than cement
- Chemicals	Plastic	Strength increase and volume stability	See vendor literature Difficult to mix
Water proofers			
- Asphalt	Plastic and collapsible	Reduce change in moisture	Long-term moisture migration problem
- Geomembranes	Plastic and collapsible	Reduce change in moisture	Long-term moisture migration problem

A common practice in several New England and Northwestern states is to use a meter (3.3 ft) or more of gravel beneath the pavement section. The gravel improves drainage of surface infiltration water and provides a weighting action that reduces and results in more uniform heave. Washington State recently reported the successful use of an 0.4 m (18 in.) layer of cap rock beneath the pavement section in severe frost regions (Ulmeyer et al., 2002).

Blending gravel and, more recently, recycled pavement material with poorer quality soils also can provide a working platform. The gravel acts as filler, creating a dryer condition and decreasing the influence of plasticity. However, if saturation conditions return, the gravel blend can take on the same poorer support characteristics of the subgrade.

Geotextiles and geogrids used in combination with quality aggregate minimize disturbance and allow construction equipment access to sites where the soils are normally too weak to support the initial construction work. They also allow compaction of initial lifts on sites where the use of ordinary compaction equipment is very difficult or even impossible. Geotextiles and geogrids reduce the extent of stress on the subgrade and prevent base aggregate from penetrating into the subgrade, thus reducing the thickness of aggregate required to stabilize the subgrade. Geotextiles also act as a separator to prevent subgrade fines from pumping or otherwise migrating up into the base. Geosynthetics have been found to allow for subgrade strength gain over time. However, the primary long-term benefit is preventing aggregate-subgrade mixing, thus maintaining the thickness of the base and subbase. In turn, rehabilitation of the pavement section should only require maintenance of surface pavement layers.

Stabilization with admixtures, such as lime, cement, and asphalt, have been mixed with subgrade soils used for controlling the swelling and frost heave of soils and improving the strength characteristics of unsuitable soils. For admixture stabilization or modification of cohesive soils, hydrated lime is the most widely used. Lime is applicable in clay soils (CH and CL type soils) and in granular soils containing clay binder (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 12. Lime stabilization is used in many areas of the U.S. to obtain a good construction platform in wet weather above highly plastic clays and other fine-grained soils. 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. Following is a brief description of the characteristics of stabilized soils followed by the treatment procedures. Additional guidance on soil stabilization with admixtures and stabilization with geosynthetics can be obtained from the following resources:

- "Lime Stabilization – Reactions, Properties, Design, and Construction," *State of the Art Report 5*, Transportation Research Board, Washington D.C., 1987.
- *Soil Stabilization for Pavements,* Joint Departments of the Army and Air Force, USA, TM 5-822-14/AFMAN 32-8010, 1994.
- *Geosynthetics Design and Construction Guidelines*, FHWA HI-95-038, 1998.
- *Standard Specifications for Geotextiles* - AASHTO M288, 1997.

7.6.2 Characteristics of Stabilized Soils

Although mechanical stabilization with thick granular layers or geosythetics and aggregate subbase provides the potential for strength improvement of the subgrade over time, this is generally not considered in the design of the pavement section, and no increase in structural support is attributed to the geosynthetic. However, the increase in gravel thickness (minus an allowance for rutting) can contribute to the support of the pavement. Alternatively, the aggregate thickness used in conjunction with the geosynthetic is designed to provide an equivalent subgrade modulus, which can be considered in the pavement design, discounting the additional aggregate thickness of the stabilization layer. Geosynthetics also allow more open graded aggregate, thus providing for the potential to drain the subbase into edgedrains and improving its support value.

The improvement of subgrade or unbound aggregate by application of a stabilizing agent is intended to cause the improvements outlined above (*i.e.,* construction platform, subgrade strengthening, and control of moisture). These improvements arise from several important mechanisms that must be considered and understood by the pavement designer. Admixtures used as 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 admixture type 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 chemical reaction between the soil and stabilizing agent (as in the case of lime or Portland cement). Additional improvement can arise from other chemical-physical reactions that affect the soil fabric (typically by flocculation) or the soil chemistry (typically by cation exchange). The down side of admixtures is that they require up front lab testing to confirm their performance and very good field control to obtain a uniform, long lasting product, as outlined later in this section. There are also issues of dust control and weather dependency, with some methods that should be carefully considered in the selection of these methods.

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, constructability, and the drainage characteristics of the geometric design and the underlying soil. When only a thin zone and/or short roadway length 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. Note that in this context, the use of the qualitative term "thin" is intentional, as the thickness of the zone can be described as thick or thin, based primarily on the project economics of the earthwork requirements and the depth of influence for the vehicle loads.

7.6.3 Thick Granular Layers

Many agencies have found that a thick granular layer is an important feature in pavement design and performance. Thick granular layers provide several benefits, including increased load-bearing capacity, frost protection, and improved drainage. While the composition of this layer takes many forms, the underlying strategy of each is to achieve desired pavement performance through improved foundation characteristics. The following sections describe the benefits of thick granular layers, typical characteristics, and considerations for the design and construction of granular embankments.

Objectives of Thick Granular Layers
Thick granular layers have been used in design for structural, drainage, and geometric reasons. Many times, a granular layer is used to provide uniformity and support as a construction platform. In areas with large quantities of readily accessible, good quality aggregates, a thick granular layer may be used as an alternative to soil stabilization. Whatever the reason, thick granular layers aim to improve the natural soil foundation. By doing this, many agencies are recognizing that the proper way to account for weak, poorly draining soils is through foundation improvement, as opposed to increasing the pavement layer thicknesses. The following is a list of objectives and benefits of thick granular layers:

- To increase the supporting capacity of weak, fine-grained subgrades.
- To provide a minimum bearing capacity for the design and construction of pavements.
- To provide uniform subgrade support over sections with highly variable soil conditions.

geotextile in combination with the grid meeting the following criteria. The important measures include the apparent opening size (AOS), the permeability (k), and permittivity (ψ) of the geotextile, and the 95% opening size, defined as the diameter of glass beads for which 95% will be retained on the geosynthetic. These values will be compared to a minimum standard or to the soil properties as follows

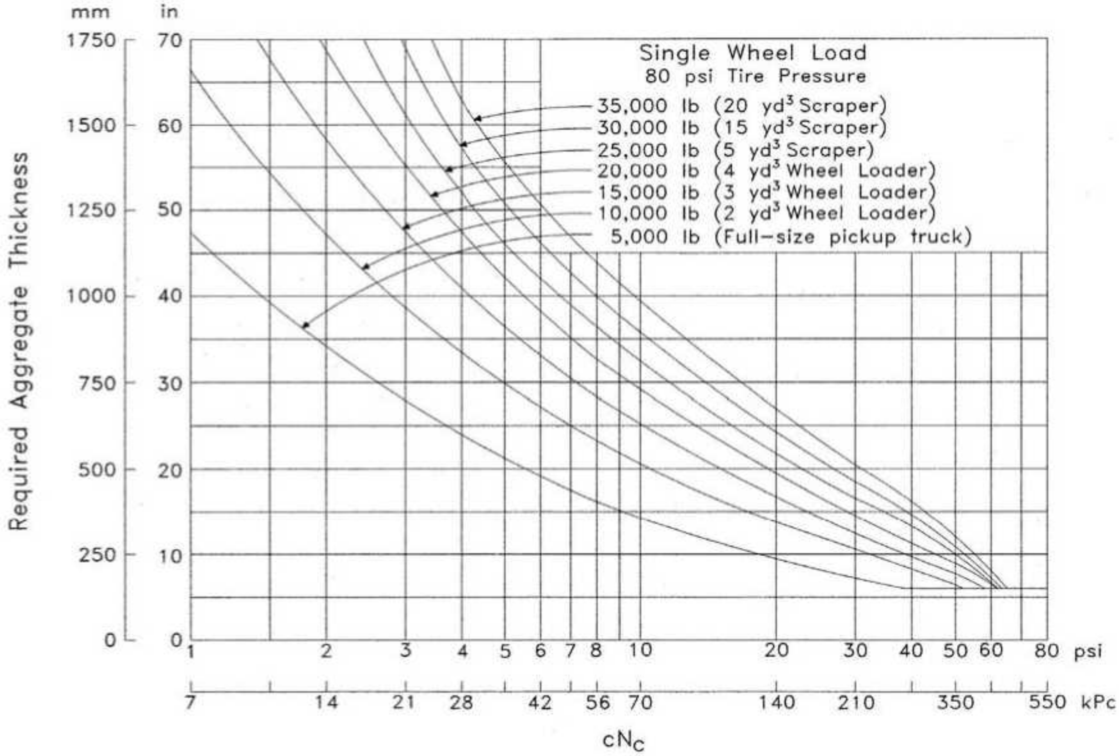
- $AOS \leq D_{85}$ (Wovens)
- $AOS \leq 1.8\ D_{85}$ (Nonwovens)
- $k_{geotextile} \geq k_{soil}$
- $\psi \geq 0.1\ sec^{-1}$

8. Determine geotextile survival criteria. The design is based on the assumption that the geosynthetic cannot function unless it survives the construction process. The AASHTO M288-99 standard categorizes the requirements for the geosynthetic based on the survival class. The requirements for the standard include the strength (grab, seam, tear, puncture, and burst), permittivity, apparent opening size, and resistance to UV degradation, based on the survival class. The survival class is determined from Table 7-5 (Section 7.2.12). For stabilization of soils, the default is Class 1, and for separation, the default is Class 2. These requirements may be reduced based on conditions and experience, as detailed in AASHTO M288. For geogrid survivability, see AASHTO PP46 and Berg et al. (2000).

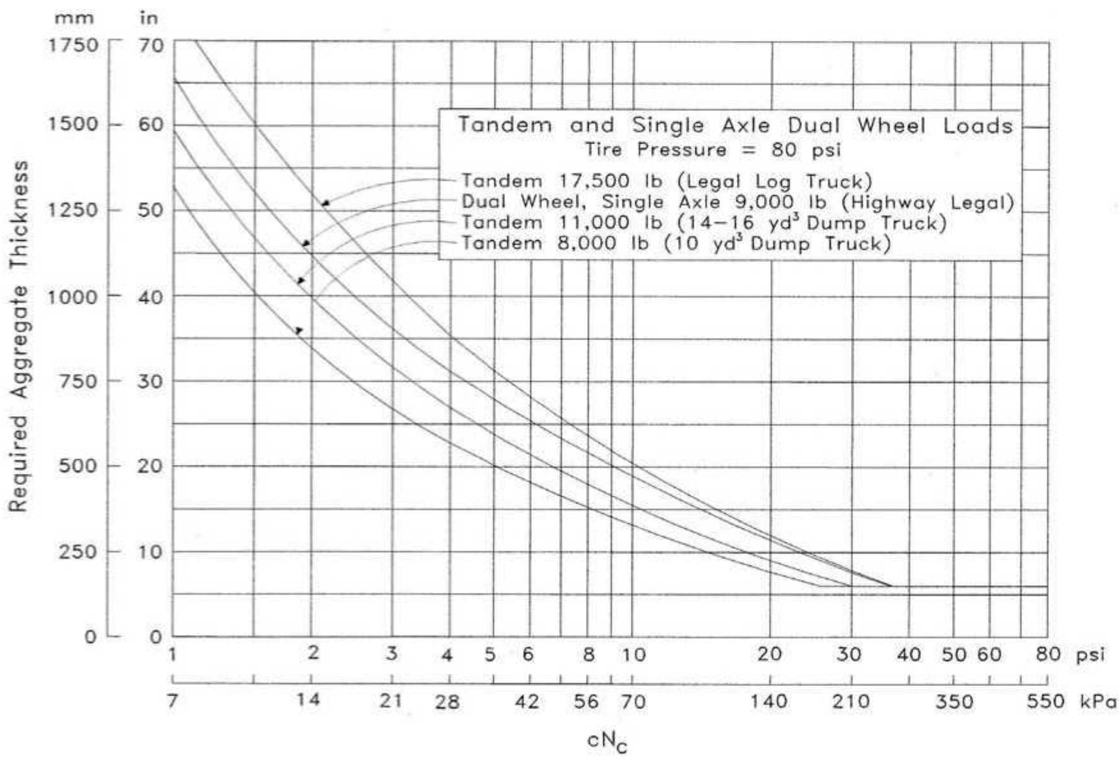
Field installation procedures introduce a number of special concerns; the AASHTO M288 standard includes a guide specification for geotextile construction. FHWA HI-905-038 (Holtz et al. 1998) recommends that this specification be modified to suit local conditions and contractors and provides example specifications. Concerns and criteria for field installation include, for example, the seam lap and sewing requirements, and construction sequencing and quality control.

7.6.5 Admixture Stabilization

As previously indicated in Section 7.6.1, there are a variety of admixtures that can be mixed with the subgrade to improve its performance. The various admixture types are shown in Table 7-15, along with initial guidance for evaluating the appropriate application of these methods. Following is a general overview of each method, followed by a generalized outline for determining the optimum admixture content requirements. Design details for each specific method are contained in Appendix F.



(a)



(b)

Figure 7-21. Thickness design curves with geosynthetics for a) single and b) dual wheel oads (after USFS, 1977, and FHWA NHI-95-038, 1998).

Table 7-16. Guide for selection of admixture stabilization method(s) (Austroads, 1998).

	MORE THAN 25% PASSING 75µm			LESS THAN 25% PASSING 75µm		
Plasticity Index	PI ≤ 10	10 < PI <20	PI ≥ 20	PI ≤ 6 PI x % passing 75µm ≤ 60	PI ≤ 10	PI > 10
Form of Stabilisation						
Cement and Cementitious Blends	Usually suitable	Doubtful	Usually not Suitable	Usually suitable	Usually suitable	Usually suitable
Lime	Doubtful	Usually suitable	Usually suitable	Usually not Suitable	Doubtful	Usually suitable
Bitumen	Doubtful	Doubtful	Usually not Suitable	Usually suitable	Usually suitable	Doubtful
Bitumen/ Cement Blends	Usually suitable	Doubtful	Usually not Suitable	Usually suitable	Usually suitable	Doubtful
Granular	Usually suitable	Usually not Suitable	Usually not Suitable	Usually suitable	Usually suitable	Doubtful
Miscellaneous Chemicals*	Usually not Suitable	Usually suitable	Usually suitable	Usually not Suitable	Doubtful	Usually suitable

Key: Usually suitable (solid black); Doubtful (hatched); Usually not Suitable (white)

* Should be taken as a broad guideline only. Refer to trade literature for further information.

Note: The above forms of stabilisation may be used in combination, e.g. lime stabilisation to dry out materials and reduce their plasticity, making them suitable for other methods of stabilisation.

Lime Treatment

Lime treatment or modification consists of the application of 1 – 3% hydrated lime to aid drying of the soil and permit compaction. As such, it is useful in the construction of a "working platform" to expedite construction. Lime modification may also be considered to condition a soil for follow-on 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.

Lime may also be used to treat expansive soils, as discussed in Section 7.3. Expansive soils as defined for pavement purposes are those that exhibit swell in excess of 3%. Expansion is characterized by heaving of a pavement or road when water is imbibed in the clay minerals. The plasticity characteristics of a soil often are a good indicator of the swell potential, as indicated in Table 7-17. If it has been determined that a soil has potential for excessive swell, lime treatment may be appropriate. Lime will reduce swell in an expansive soil to greater or lesser degrees, depending on the activity of the clay minerals present. The amount of lime to be added is the minimum amount that will reduce swell to acceptable limits. Procedures for conducting swell tests are indicated in the ASTM D 1883 CBR test and detailed in ASTM D 4546.

The depth to which lime should be incorporated into the soil is generally limited by the construction equipment used. However, 0.6 – 1 m (2 – 3 ft) generally is the maximum depth that can be treated directly without removal of the soil.

Lime Stabilization

Lime or pozzolonic stabilization of soils improves the strength characteristics and changes the chemical composition of some soils. The strength of fine-grained soils can be significantly improved with lime stabilization, while the strength of coarse-grained soils is usually moderately improved. Lime has been found most effective in improving workability and reducing swelling potential with highly plastic clay soils containing montmorillonite, illite, and kaolinite. Lime is also used to reduce the water content of wet soils during field compaction. In treating certain soils with lime, some soils are produced that are subject to fatigue cracking.

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 the soil that shows negligible to moderate frost heave 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. Adequate curing is also important if the strength characteristics of the soil are to be improved.

Table 7-17. Swell potential of soils (Joint Departments of the Army & Air Force, 1994).

Liquid Limit	Plasticity Index	Potential Swell
> 60	> 35	High
50 - 60	25 – 35	Marginal
< 50	< 25	Low

The most common varieties of lime for soil stabilization are hydrated lime [$Ca(OH)_2$], quicklime [CaO], and the dolomitic variations of these high-calcium limes [$Ca(OH)_2 \cdot MgO$ and $CaO \cdot MgO$]. While hydrated lime remains the most commonly used lime stabilization admixture in the U.S., use of the more caustic quicklime has grown steadily over the past two decades. Lime is usually produced by calcining[2] limestone or dolomite, although some lime—typically of more variable and poorer quality—is also produced as a byproduct of other chemical processes.

For lime stabilization of clay (or highly plastic) soils, the lime content should be from 3 – 8% of the dry weight of the soil, and the cured mass should have an unconfined compressive strength of at least 0.34 MPa (50 psi) within 28 days. 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. As discussed later in this section, pH can be used to determine the initial, near optimum lime content value. The pozzolanic strength gain in clay soils depends on the specific chemistry of the soil – *e.g.,* whether it can provide sufficient silica and alumina minerals to support the pozzolanic reactions. Plasticity is a rough indicator of reactivity. A plasticity index of about 10 is commonly taken as the lower limit for suitability of inorganic clays for lime stabilization. The lime-stabilized subgrade layer should be compacted to a minimum density of 95%, as defined by AASHTO T99.

Typical effects of lime stabilization on the engineering properties of a variety of natural soils are shown in Table 7-18 and Figure 7-22. These are the result of several chemical processes that occur after mixing the lime with the soil. Hydration of the lime absorbs water from the soil and causes an immediate drying effect. The addition of lime also introduces calcium (Ca^{+2}) and magnesium (Mg^{+2}) cations that exchange with the more active sodium (Na^{+}) and potassium (K^{+}) cations in the natural soil water chemistry; this cation exchange reduces the plasticity of the soil, which, in most cases, corresponds to a reduced swell and shrinkage potential, diminished susceptibility to strength loss with moisture, and improved workability. The changes in the soil-water chemistry also lead to agglomeration of particles and a coarsening of the soil gradation; plastic clay soils become more like silt or sand in texture after the addition of lime. These drying, plasticity reduction, and texture effects all occur very rapidly (usually with 1 hour after addition of lime), provided there is thorough mixing of the lime and the soil.

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[2] Calcining is the heating of limestone or dolomite to a high temperature below the melting or fusing point that decomposes the carbonates into oxides and hydroxides.

Table 7-18. Examples of the effects of lime stabilization on various soils (Rollings and Rollings, 1996).

Soil	Lime %	Atterberg Limits *LL*	Atterberg Limits *PL*	Atterberg Limits *PI*	Strength q_u[a]	Strength CBR
1. CH, residual clay[b]						
(a) Site 1, Dallas–Ft.	0	63	33	30	76	
Worth Airport,	2	62	48	14	123	
residuum from Eagle	3	60	47	13	202	
Ford shale, Britton member	4	56	46	10	323	
(b) Site 2, Dallas–	0	60	27	33	70	
Ft Worth Airport,	2	48	32	16	171	
residuum from Eagle Ford	3	45	32	13	177	
shale, Tarrant member	5	48	34	14	184	
(c) Site 3, Irving, Texas,	0	76	31	45	64	
residuum from Eagle Ford	2	61	45	16	116	
shale, Britton	3	56	45	11	193	
member	5	57	45	12	302	
2. CH, Bryce silty clay,[c]	0	53	24	29	81	
Illinois, B-horizon	3	48	27	21	201	
	5	NP	NP	NP	212	
3. CH, Appling sandy loam,[d]	0	71	33	38	92	
South Carolina, residuum	3				147	
from granite	6				171	
	8				206	
4. CH, St Ann red bauxite	0	58	25	33	119	
clay loam,[d] Jamaica,	3				127	
limestone residuum	5				334	
5. CL,[e] Pelucia Creek Dam,	0	29	18	11		
Mississippi	1	32	19	13		
	2	31	22	9		
	3	30	21	9		
6. CL, Illinoian till, Illinois,[c]	0	26	15	11	43	
glacial till	3	27	21	6	126	
	5	NP	NP	NP	126	
7. SC, sandy clay, San Lorenzo,	0	54	23	31		8
Honduras[f]	5	61	38	23		20
8. MH, Surinam red earth,[d]	0	60	32	28	72	
Surinam,	3				130	
residuum from acidic	5				136	
metamorphic rock						
9. OH, organic soil with 8.1%	0	63	27	36	4	
organics[g]	2			36	4	
	4			24	8	
	8			25	7	

[a]Unconfined compressive strength in psi at 28 days unless otherwise noted; different compaction efforts used by investigators.
[b]McCallister and Petry, 1990, accelerated curing.
[c]Thompson, 1966.
[d]Harty, 1971, 7-day cure.
[e]McElroy, 1989.
[f]Personal communication, Dr. Newel Brabston, Vicksburg, Mississippi.
[g]Arman and Munfakh, 1972, limits at 48 hours, q_u at 28 days, strength samples prepared with moisture content at the *LL*.

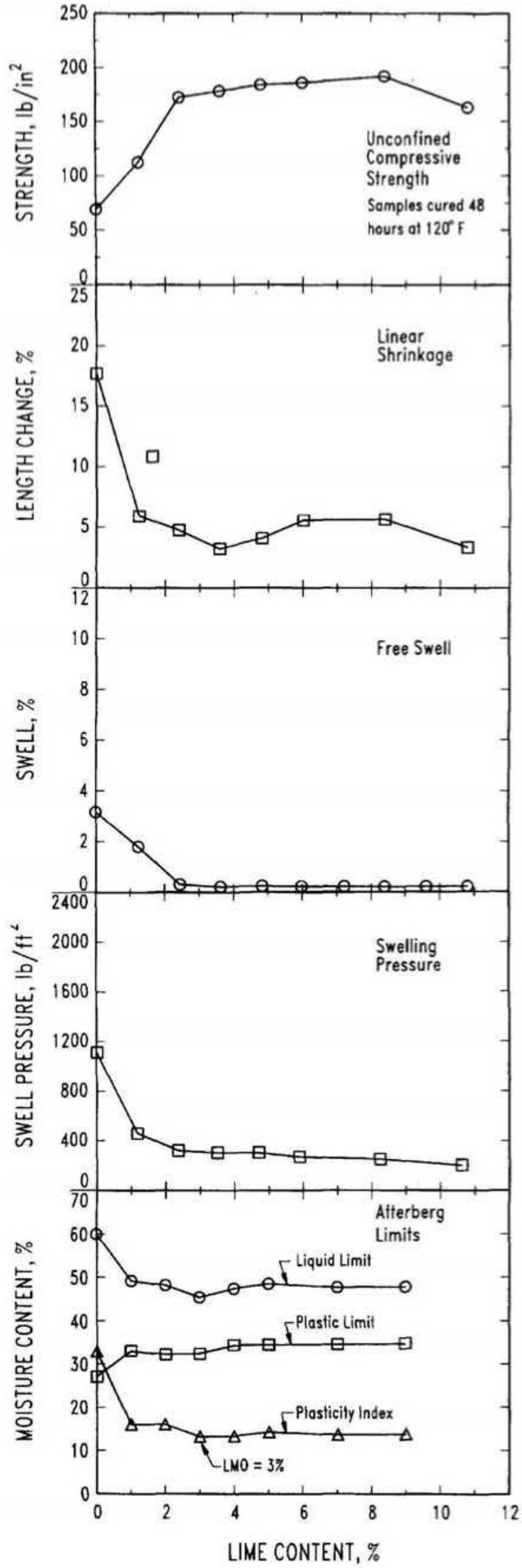

Figure 7-22. Effect of lime content on engineering properties of a CH clay (from Rollings and Rollings, 1996; from data reported by McCallister and Petry, 1990).

When soils are treated properly with lime, it has been observed that the lime-soil mixture may be subject to durability problems, the cyclic freezing and thawing of the soil. The durability of lime stabilization on swell potential and strength may be adversely affected by environmental influences:

- *Water:* Although most lime stabilized soils retain 70% to 85% of their long-term strength gains when exposed to water, there have been reported cases of poor strength retention for stabilized soils exposed to soaking. Therefore, testing of stabilized soils in the soaked condition is prudent.

- *Freeze/thaw cycles:* Freeze/thaw cycles can lead to strength deterioration, but subsequent healing often occurs where the strength loss caused by winter freeze/thaw reverses during the following warm season. The most common design approach is to specify a sufficiently high initial strength gain to retain sufficient residual strength after freeze/thaw damage.

- *Leaching:* Leaching of calcium can decrease the cation exchange in lime stabilized soil, which, in turn, can reverse the beneficial reduction in plasticity and swell potential. The potential for these effects is greater when low lime contents are used.

- *Carbonation:* If atmospheric carbon dioxide combines with lime to form calcium carbonate, the calcium silicate and calcium aluminate hydrate cements may become unstable and revert back to their original silica and alumina forms, reversing the long-term strength increase resulting from the pozzolanic reactions. Although this problem has been reported less in the United States than in other countries, its possibility should be recognized and its potential minimized by use of ample lime content, careful selection, placement, and compaction of the stabilized material to minimize carbon dioxide penetration, as well as prompt placement after lime mixing, and good curing.

- *Sulfate attack:* Sulfates present in the soil or groundwater can combine with the calcium from the lime or the alumina from the clay minerals to form ettringite, which has a volume that is more than 200% larger than that of its constituents. Massive irreversible swelling can therefore occur, and the damage it causes can be quite severe. It is difficult to predict the combinations of sulfate content, lime content, clay mineralogy and content, and environmental conditions that will trigger sulfate attack. Consequently, if there is a suspicion of possible sulfate attack, the lime stabilized soil should be tested in the laboratory to see whether it will swell when mixed and exposed to moisture.

Soils classified as CH, CL, MH, ML, SC, and GC with a plasticity index greater than 12 and with 10% passing the 0.425 mm (No. 40) sieve are potentially suitable for stabilization with lime. Lime-flyash 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-flyash stabilization are rather limited.

Hydrated lime, in powder form or mixed with water as a slurry, is used most often for stabilization.

Cement Stabilization

Portland cement is widely used 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 or cement-treated base, subbase, or subgrade.

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 0.425 mm (No. 40) sieve. However, highly plastic clays that have been pretreated with lime or flyash are sometimes suitable for subsequent treatment with Portland cement. For cement stabilization of granular and/or nonplastic soils, the cement content should be 3 – 10% of the dry weight of the soil, and the cured material should have an unconfined compressive strength of at least 1 MPa (150 psi) within 7 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 M 134.

Several different types of cement have been used successfully for stabilization of soils. Type I normal Portland cement and Type IA air-entraining cements were used extensively in the past, and produced about the same results. At the present time, Type II cement has largely replaced Type I cement as greater sulfate resistance is obtained, while the cost is often the same. High early strength cement (Type III) has been found to give a higher strength in some soils. Type III cement has a finer particle size and a different compound composition than do the other cement types. Chemical and physical property specifications for Portland cement can be found in ASTM C 150.

The presence of organic matter and/or sulfates may have a deleterious effect on soil cement. Tests are available for detection of these materials and should be conducted if their presence is suspected.

(1) *Organic matter.* A soil may be acid, neutral, or alkaline and still respond well to cement treatment. Although certain types of organic matter, such as undecomposed vegetation, may not influence stabilization adversely, organic compounds of lower molecular weight, such as nucleic acid and dextrose, act as hydration retarders and reduce strength. When such organics are present, they inhibit the normal hardening process. If the pH of a 10:1 mixture (by weight) of soil and cement 15 minutes after mixing is at least 12.0, it is probable that any organics present will not interfere with normal hardening.

(2) *Sulfates.* Although sulfate attack is known to have an adverse effect on the quality of hardened Portland cement concrete, less is known about the sulfate resistance of cement stabilized soils. The resistance to sulfate attack differs for cement-treated, coarse-grained and fine-grained soils, and is a function of sulfate concentrations. Sulfate-clay reactions can cause deterioration of fine-grained soil-cement. On the other hand, granular soil-cements do not appear susceptible to sulfate attack. In some cases, the presence of small amounts of sulfate in the soil at the time of mixing with the cement may even be beneficial. The use of sulfate-resistant cement may not improve the resistance of clay-bearing soils, but may be effective in granular soil-cements exposed to adjacent soils and/or groundwater containing high sulfate concentrations. The use of cement for fine-grained soils containing more than about 1% sulfate should be avoided.

Stabilization with Lime-Flyash (LF) and Lime-Cement-Flyash (LCF)

Stabilization of coarse-grained soils having little or no fines can often be accomplished by the use of LF or LCF combinations. Flyash, also termed coal ash, is a mineral residual from the combustion of pulverized coal. It contains silicon and aluminum compounds that, when mixed with lime and water, forms a hardened cementitious mass capable of obtaining high compressive strengths. Lime and flyash in combination can often be used successfully in stabilizing granular materials, since the flyash provides an agent with which the lime can react. Thus LF or LCF stabilization is often appropriate for base and subbase course materials.

Flyash is classified according to the type of coal from which the ash was derived. Class C flyash is derived from the burning of lignite or subbituminous coal and is often referred to as "high lime" ash because it contains a high percentage of lime. Class C flyash is self-reactive or cementitious in the presence of water, in addition to being pozzolanic. Class F flyash is derived from the burning of anthracite or bituminous coal and is sometimes referred to as "low lime" ash. It requires the addition of lime to form a pozzolanic reaction. To be acceptable quality, flyash used for stabilization must meet the requirements indicated in ASTM C 593.

Design with LF is somewhat different from stabilization with lime or cement. For a given combination of materials (aggregate, flyash, and lime), a number of factors can be varied in the mix design process, such as percentage of lime-flyash, the moisture content, and the ratio of lime to flyash. It is generally recognized that engineering characteristics such as strength and durability are directly related to the quality of the matrix material. The matrix material is that part consisting of flyash, lime, and minus No. 4 aggregate fines. Basically, higher strength and improved durability are achievable when the matrix material is able to "float" the coarse aggregate particles. In effect, the fine size particles overfill the void spaces between the coarse aggregate particles. For each coarse aggregate material, there is a quantity of matrix required to effectively fill the available void spaces and to "float" the coarse aggregate particles. The quantity of matrix required for maximum dry density of the total mixture is referred to as the optimum fines content. In LF mixtures, it is recommended that the quantity of matrix be approximately 2% above the optimum fines content. At the recommended fines content, the strength development is also influenced by the ratio of lime to flyash. Adjustment of the lime-flyash ratio will yield different values of strength and durability properties.

Asphalt Stabilization

Generally, asphalt-stabilized soils are used for base and 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-bitumen, which produces strength in cohesionless soils, such as clean sands, or acts as a binder or cementing agent, 2) soil-bitumen, which stabilizes the moisture content of cohesive fine-grained soils, and 3) sand-gravel bitumen, which provides cohesive strength and waterproofs pit-run gravelly soils with inherent frictional strength. The durability of bitumen-stabilized mixtures generally can be assessed by measurement of their water absorption characteristics. Treatment of soils containing fines in excess of 20% is not recommended.

Stabilization of soils and aggregates with asphalt differs greatly from cement and lime stabilization. The basic mechanism involved in asphalt stabilization of fine-grained soils is a waterproofing phenomenon. Soil particles or soil agglomerates are coated with asphalt that prevents or slows the penetration of water that could normally result in a decrease in soil strength. In addition, asphalt stabilization can improve durability characteristics by making the soil resistant to the detrimental effects of water, such as volume. In noncohesive materials, such as sands and gravel, crushed gravel, and crushed stone, two basic mechanisms are active: waterproofing and adhesion. The asphalt coating on the cohesionless materials provides a membrane that prevents or hinders the penetration of water and thereby reduces the tendency of the material to lose strength in the presence of water. The second mechanism has been identified as adhesion. The aggregate particles adhere to the asphalt and the asphalt acts as a binder or cement. The cementing effect thus increases shear strength by increasing cohesion. Criteria for design of bituminous-stabilized soils and aggregates are based almost entirely on stability and gradation requirements. Freeze-thaw and wet-dry durability tests are not applicable for asphalt-stabilized mixtures.

There are three basic types of bituminous-stabilized soils, including

(1) *Sand bitumen.* A mixture of sand and bitumen in which the sand particles are cemented together to provide a material of increased stability.
(2) *Gravel or crushed aggregate bitumen.* A mixture of bitumen and a well-graded gravel or crushed aggregate that, after compaction, provides a highly stable waterproof mass of subbase or base course quality.
(3) *Bitumen lime.* A mixture of soil, lime, and bitumen that, after compaction, may exhibit the characteristics of any of the bitumen-treated materials indicated above. Lime is used with materials that have a high PI, *i.e.,* above 10.

Bituminous stabilization is generally accomplished using asphalt cement, cutback asphalt, or asphalt emulsions. The type of bitumen to be used depends upon the type of soil to be stabilized, method of construction, and weather conditions. In frost areas, the use of tar as a binder should be avoided because of its high temperature susceptibility. Asphalts are affected to a lesser extent by temperature changes, but a grade of asphalt suitable to the prevailing climate should be selected. As a general rule, the most satisfactory results are obtained when the most viscous liquid asphalt that can be readily mixed into the soil is used. For higher quality mixes in which a central plant is used, viscosity-grade asphalt cements should be used. Much bituminous stabilization is performed in-place, with the bitumen being applied directly on the soil or soil aggregate system, and the mixing and compaction operations being conducted immediately thereafter. For this type of construction, liquid asphalts, *i.e.,* cutbacks and emulsions, are used. Emulsions are preferred over cutbacks because of energy constraints and pollution control efforts. The specific type and grade of bitumen will depend on the characteristics of the aggregate, the type of construction equipment, and the climatic conditions. Generally, the following types of bituminous materials will be used for the soil gradation indicated:

(1) Open-graded aggregate.
    a. Rapid- and medium-curing liquid asphalts RC-250, RC-800, and MC-3000.
    b. Medium-setting asphalt emulsion MS-2 and CMS-2.

(2) Well-graded aggregate with little or no material passing the 0.075 mm (No. 200) sieve.
   a. Rapid and medium-curing liquid asphalts RC-250, RC-800, MC-250, and MC-800.
   b. Slow-curing liquid asphalts SC-250 and SC-800.
   c. Medium-setting and slow-setting asphalt emulsions MS-2, CMS-2, SS-1, and CSS-1.

(3) Aggregate with a considerable percentage of fine aggregates and material passing the 0.075 mm (No. 200) sieve.
   a. Medium-curing liquid asphalt MC-250 and MC-800.
   b. Slow-curing liquid asphalts SC-250 and SC-800
   c. Slow-setting asphalt emulsions SS-1, SS-01h, CSS-1, and CSS-lh.

The simplest type of bituminous stabilization is the application of liquid asphalt to the surface of an unbound aggregate road. For this type of operation, the slow- and medium-curing liquid asphalts SC-70, SC-250, MC-70, and MC-250 are used.

The recommended soil gradations for subgrade materials and base or subbase course materials are shown in Tables 7-19 and 7-20, respectively.

Table 7-19. Recommended gradations for bituminous-stabilized subgrade materials (Joint Departments of the Army and Air Force, 1994).

Sieve Size	Percent Passing
75-mm (3-in.)	100
4.75-mm (#4)	50-100
600-µm (#30)	38-100
75-µm (#200)	2-30

Table 7-20. Recommended gradations for bituminous-stabilized base and subbase materials (Joint Departments of the Army and Air Force, 1994).

Sieve Size	37.5 mm (1 ½ in.) Maximum	25 mm (1-in.) Maximum	19 mm (¾-in.) Maximum	12.7 mm (½-in.) Maximum
37.5-mm (1½-in.)	100	-	-	-
25-mm (l-in.)	8 4 ± 9	100	-	-
19-mm (¾-in.)	76 ± 9	83 ± 9	100	-
M-in	66 ± 9	73 ± 9	82 ± 9	100
9.5-mm (3/8-in.)	59 ± 9	64 ± 9	72 ± 9	83 ± 9
0.475-mm (#4)	45 ± 9	48 ± 9	54 ± 9	62 ± 9
2.36-mm (#8)	35 ± 9	36 ± 9	41 ± 9	47 ± 9
1.18-mm (#16)	27 ± 9	28 ± 9	32 ± 9	36 ± 9
600-µm (#30)	20 ± 9	21 ± 9	24 ± 9	28 ± 9
300-µm (#50)	14 ± 7	16 ± 7	17 ± 7	20 ± 7
150-µm (#100)	9 ± 5	11 ± 5	12 ± 5	14 ± 5
75-µm (#200)	5 ± 2	5 ± 2	5 ± 2	5 ± 2

Stabilization with Lime-Cement and Lime-Bitumen

The advantage of using combination stabilizers is that one of the stabilizers in the combination compensates for the lack of effectiveness of the other in treating a particular aspect or characteristic of a given soil. For instance, in clay areas devoid of base material, lime has been used jointly with other stabilizers, notably Portland cement or asphalt, to provide acceptable base courses. Since Portland cement or asphalt cannot be mixed successfully with plastic clays, the lime is added first to reduce the plasticity of the clay. While such stabilization practice might be more costly than the conventional single stabilizer methods, it may still prove to be economical in areas where base aggregate costs are high. Two combination stabilizers are considered in this section: lime-cement and lime-asphalt.

a) *Lime-cement.* Lime can be used as an initial additive with Portland cement, or as the primary stabilizer. The main purpose of lime is to improve workability characteristics, mainly by reducing the plasticity of the soil. The design approach is to add enough lime to improve workability and to reduce the plasticity index to acceptable levels. The design lime content is the minimum that achieves desired results. The design cement content is determined following procedures for cement-stabilized soils presented in Appendix F.

b) *Lime-asphalt.* Lime can be used as an initial additive with asphalt, or as the primary stabilizer. The main purpose of lime is to improve workability characteristics and to act as an anti-stripping agent. In the latter capacity, the lime acts to neutralize acidic chemicals in the soil or aggregate that tend to interfere with bonding of the asphalt. Generally, about 1 – 2% percent lime is all that is needed for this objective. Since asphalt is the primary stabilizer, the procedures for asphalt-stabilized materials, as presented Appendix F, should be followed.

Admixture Design

Design of admixtures takes on a similar process regardless of the admixture type. The following steps are generally followed and are generic to lime, cement, L-FA and L-C-FA, or asphalt admixtures.

Step 1. Classify soil to be stabilized.
(% < 0.075 mm – No. 200 sieve, % < 0.425 mm – No. 40 Sieve, PI, etc.)

Step 2. Prepare trial mixes with varying % content.
Lime: Select lowest % with pH = 12.4 in 1 hour
Cement: Use table to estimate cement content requirements
Asphalt: Use equation & table in Appendix F to estimate the quantity of cutback asphalt

Step 3. Develop moisture-density relationship for initial design.

Step 4. Prepare triplicate samples and cure specimens at target density.
Use optimum water content and % initial admixture, +2% and +4%

Step 5. Determine index strength.
Lime and Cement: Determine unconfined compressive strength (ASTM D 5102)
Asphalt: Determine Marshall stability

Step 6. Determine resilient modulus for optimum percent admixture.
Perform test or estimate using correlations (See Chapter 5)

Step 7. Conduct freeze-thaw tests (Regional as required).
(For Cement, CFA, L-C-FA)

Step 8. Select % to achieve minimum design strength and F-T durability.

Step 9. Add 0.5 – 1% to compensate for non-uniform mixing.

Appendix F provides specific design requirements and design step details for each type of admixture reviewed in this section. Additional design and construction information can also be obtained from industry publications including

- *Soil-Cement Construction Handbook*, Portland Cement Association, Skokie, Il, 1995.
- *Lime-Treated Soil Construction Manual: Lime Stabilization & Lime Modification,* National Lime Associaiton, Arlington, Virginia, 2004.
- *Flexible Pavement Manual*, American Coal Ash Association, Washington, D.C., 1991.
- *A Basic Emulsion Manual*, Asphalt Institute, Manual Series #19.
- http://www.cement.org/index.asp
- http://www.lime.org/

7.6.6 Soil Encapsulation

Soil encapsulation is a foundation improvement technique that has been used to protect moisture sensitive soils from large variations in moisture content. 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. This technique has been used by a number of states (*e.g.,* Texas and Wyoming) on selected projects to improve the foundations of higher volume roadways. It is more commonly used as a technique in Europe and in foundation or subbase layers for low-volume roadways, where the import of higher quality paving materials is restricted from a cost standpoint. More than 100 projects have been identified around the world, usually reporting success in controlling expansive soils (Steinberg, 1998).

Fine-grained soils can provide adequate bearing strengths for use as structural layers in pavements and embankments, as long as the moisture content remains below the optimum moisture content. However, increases in moisture content above the optimum value can cause a significant reduction in the stiffness (*i.e.,* resilient modulus) and strength of fine-grained materials and soils. Increased moisture content in fine-grained soils below pavements occurs over time, especially in areas subject to frost penetration and freeze-thaw cycles. Thus, fine-grained soils cannot be used as a base or subbase layer unless the soils are protected from any increase in moisture.

The soil encapsulation concept, sometimes referred to as membrane encapsulated soil layer (MESL), is a method for maintaining the moisture content of the soil at the desired level by encapsulating the soil in waterproof membranes. The waterproof membranes prevent water from infiltrating the moisture sensitive material. The resilient modulus measured at or below optimum conditions remains relatively constant over the design life of the pavement.

The prepared subgrade is normally sprayed with an asphalt emulsion before the bottom membrane of polyethylene is placed. This asphalt emulsion provides added waterproofing protection in the event the membrane is punctured during construction operations, and acts as an adhesive for the membrane to be placed in windy conditions. The first layer of soil is placed in sufficient thickness such that the construction equipment will not displace the underlying material. The completed soil embankment is also sprayed with an asphalt emulsion before placement of the top membrane. To form a complete encapsulation, the bottom membrane is brought up the sides and wrapped around the top, for an excavated section, or the top membrane is draped over the sides, for an embankment situation. The top of the membrane is sprayed with the same asphalt emulsion and covered with a thin layer of clean sand to blot the asphalt and to provide added protection against puncture by the construction equipment used to place the upper paving layers.

The reliability of this method to maintain the resilient modulus and strength of the foundation soil over long periods of time is unknown. More importantly, roadway maintenance and the installation of utilities in areas over time limit the use of this technique. Thus, this improvement technique is not suggested unless there is no other option available.
If this technique is used, the pavement designer should be cautioned regarding the use of the environmental effects model (EICM) to predict changes in moisture over time. Special design computations will be needed to restrict the change in moisture content of the MESL over time. The resilient modulus used in design for the MESL should be held constant over the design life of the pavement. The designer should also remember that any utilities placed after pavement construction could make that assumption invalid.

7.6.7 Lightweight Fill

When constructing pavements on soft soils, there is always a concern for settlement. For deeper deposits where shallow surface stabilization may not be effective, thicker granular aggregate as discussed in Section 7.3, may be effective for control deformation under wheel load, but would increase the concern for settlement. An alternate to replacement with aggregate would be to use lightweight fill.