Introduction to Soil Stabilization in Pavements

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An Introduction to Soil Stabilization for Pavements

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AN INTRODUCTION TO

SOIL STABILIZATION FOR PAVEMENTS

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1. INTRODUCTION

1.1 PURPOSE. This section discusses criteria for improving the engineering properties of soils used for pavement base courses, subbase courses, and subgrades by the use of additives which are mixed into the soil to effect the desired improvement. These criteria are also applicable to roads and airfields having a stabilized surface layer.

1.2 SCOPE. This discussion covers the appropriate type or types of additive to be used with different soil types and procedures for determining a design treatment level for each type of additive.

1.3 DEFINITIONS

- *Soils.* Naturally occurring materials that are used for the construction of all except the surface layers of pavements (i.e., concrete and asphalt) and that are subject to classification tests (ASTM D 2487) to provide a general concept of their engineering characteristics.

- *Additives.* Manufactured commercial products that, when added to the soil in the proper quantities, improve some engineering characteristics of the soil such as strength, texture, workability, and plasticity. Additives addressed in this discussion are limited to portland cement, lime, flyash, and bitumen.

- *Stabilization.* Stabilization is the process of blending and mixing materials with a soil to improve certain properties of the soil. The process may include the blending of soils to achieve a desired gradation or the mixing of commercially available additives that may alter the gradation, texture or plasticity, or act as a binder for cementation of the soil.

- *Mechanical stabilization.* Mechanical stabilization is accomplished by mixing or blending soils of two or more gradations to obtain a material meeting the required specification. The soil blending may take place at the construction site, a central plant, or a borrow area. The blended material is then spread and compacted to required densities by conventional means.

- *Additive stabilization.* Additive stabilization is achieved by the addition of proper percentages of cement, lime, fly ash, bitumen, or combinations of these materials to the soil. The selection of type and determination of the percentage of additive to be used is dependent upon the soil classification and the degree of improvement in soil quality desired. Generally, smaller amounts of additives are required when it is simply desired to modify soil properties such as gradation, workability, and plasticity. When it is desired to improve the strength and durability significantly, larger quantities of additive are used. After the additive has been mixed with the soil, spreading and compaction are achieved by conventional means.

- *Modification.* Modification refers to the stabilization process that results in improvement in some property of the soil but does not by design result in a significant increase in soil strength and durability.

1.4 USES OF STABILIZATION. Pavement design is based on the premise that minimum specified structural quality will be achieved for each layer of material in the pavement system. Each layer must resist shearing, avoid excessive deflections that cause fatigue cracking within the layer or in overlying layers, and prevent excessive permanent deformation through densification. As the quality of a soil layer is increased, the ability of that layer to distribute the load over a greater area is generally increased so that a reduction in the required thickness of the soil and surface layers may be permitted.

- *Quality improvement.* The most common improvements achieved through stabilization include better soil gradation, reduction of plasticity index or swelling potential, and increases in durability and strength. In wet weather, stabilization may also be used to provide a working platform for construction operations. These types of soil quality improvement are referred to as soil modification.

- *Thickness reduction.* The strength and stiffness of a soil layer can be improved through the use of additives to permit a reduction in design thickness of the stabilized material compared with an unstabilized or unbound material. The design thickness strength, stability, and durability requirements of a base or subbase course can be reduced if further analysis indicates suitability.

2. SELECTION OF ADDITIVE

2.1 FACTORS TO BE CONSIDERED. In the selection of a stabilizer, the factors that must be considered are the type of soil to be stabilized, the purpose for which the stabilized layer will be used, the type of soil improvement desired, the required strength and durability of the stabilized layer, and the cost and environmental conditions.

2.1.1 SOIL TYPES AND ADDITIVES. There may be more than one candidate stabilizer applicable for one soil type, however, there are some general guidelines that make specific stabilizers more desirable based on soil granularity, plasticity, or texture. Portland cement for example is used with a variety of soil types; however, since it is imperative that the cement be mixed intimately with the fines fraction (< .074 mm), the more plastic materials should be avoided. Generally, well-graded granular materials that possess sufficient fines to produce a floating aggregate matrix (homogenous mixture) are best suited for portland cement stabilization. Lime will react with soils of medium to high plasticity to produce decreased plasticity, increased workability, reduced swell, and increased strength. Lime is used to stabilize a variety of materials including weak subgrade soils, transforming them into a “working table” or subbase; and with marginal granular base materials, i.e., clay-gravels, “dirty” gravels, to form a strong, high quality base course. Fly ash is a pozzolanic material, i.e. it reacts with lime and is therefore almost always used in combination with lime in soils that have little or no plastic fines. It has often been found desirable to use a small amount of portland cement with lime and fly ash for added strength. This combination of lime-cement-flyash (LCF) has been used successfully in base course stabilization. Asphalt or bituminous materials both are used for waterproofing and for strength gain. Generally, soils suitable for asphalt stabilization are the silty sandy and granular materials since it is desired to thoroughly coat all the soil particles.

2.1.2 SELECTION OF CANDIDATE ADDITIVES. The selection of candidate/stabilizers is made using Figure 1 and Table 1. The soil gradation triangle in Figure 1 is based upon the soil grain size characteristics and the triangle is divided into areas of soils with similar grain size and therefore pulverization characteristics. The selection process is continued with Table 1 which indicates for each area shown in Figure 1 candidate stabilizers and restrictions based on grain size and/or plasticity index (PI). Also provided in the second column of Table 1 is a listing of soil classification symbols applicable to the area determined from Figure 1. This is an added check to insure that the proper area was selected. Thus, information on grain size distribution and Atterberg limits must be known to initiate the selection process. Data required to enter Figure 1 are: percent material passing the No. 200 sieve and percent material passing the No. 4 sieve but retained on the No. 200 (i.e., total percent material between the No. 4 and the No. 200 sieves). The triangle is entered with these two values and the applicable area (1A, 2A, 3, etc.) is found at their intersection. The area determined from Figure 1 is then found in the first column of Table 1 and the soil classification is checked in the second column. Candidate stabilizers for each area are indicated in third column and restrictions for the use of each material are presented in the following columns. These restrictions are used to prevent use of stabilizing agents not applicable for the particular soil type under consideration. For example, assume a soil classified as a SC, with 93 percent passing the No. 4 and 25 percent passing the No. 200 with a liquid limit of 20 and plastic limit of 11. Thus 68 percent of the material is between the No. 4 and No. 200 and the plasticity index is 9. Entering Figure 2 with the values of 25 percent passing the No. 200 and 68 percent between the No. 4 and No. 200, the intersection of these values is found in area 1-C. Then going to the first column of Table 2-1, we find area 1-C and verify the soil classification, SC, in the second column. From the third column all four stabilizing materials are found to be potential candidates. The restrictions in the following columns are now examined. Bituminous stabilization is acceptable since the PI does not exceed 10 and the amount of material passing the No. 200 does not exceed 30 percent. However it should be noted that the soil only barely qualifies under these criteria and bituminous stabilization probably would not be the first choice. The restrictions under portland cement indicate that the PI must be less that in the equation indicated in footnote b of Table 1. Since the PI of 9 is less than that value, portland cement would be a candidate material. The restrictions under lime indicate that the PI not be less than 12, therefore lime is not a candidate material for stabilization. The restrictions under LCF stabilization indicate that the PI must not exceed 25, thus LCF is also a candidate stabilizing material. At this point, the designer must make the final selection based on other factors such as availability of material, economics, etc. Once the type of stabilizing agent to be used is determined, samples must be prepared and tested in the laboratory to develop a design mix meeting minimum engineering criteria for field stabilization.

2.2 USE OF STABILIZED SOILS IN FROST AREAS.

2.2.1 FROST CONSIDERATIONS. While bituminous, portland cement, lime, and LCF stabilization are the most common additives, other stabilizers may be used for pavement construction in areas of frost design.

2.2.2 LIMITATIONS. In frost areas, stabilized soil is only used in one of the upper elements of a pavement system if cost is justified by the reduced pavement thickness. Treatment with a lower degree of additive than that indicated for stabilization (i.e., soil modification) should be used in frost areas only with caution and after intensive tests, because weakly cemented material usually has less capacity to endure repeated freezing and thawing than has firmly cemented material. A possible exception is modification of a soil that will be encapsulated within an impervious envelope as part of a membrane-encapsulated-soil-layer pavement system. A soil that is unsuitable for encapsulation due to excessive moisture migration and thaw weakening may be made suitable for such use by moderate amounts of a stabilizing additive. Materials that are modified should also be tested to ascertain that the desired improvement is durable through repeated freeze-thaw cycles. The improvement should not be achieved at the expense of making the soil more susceptible to ice segregation.

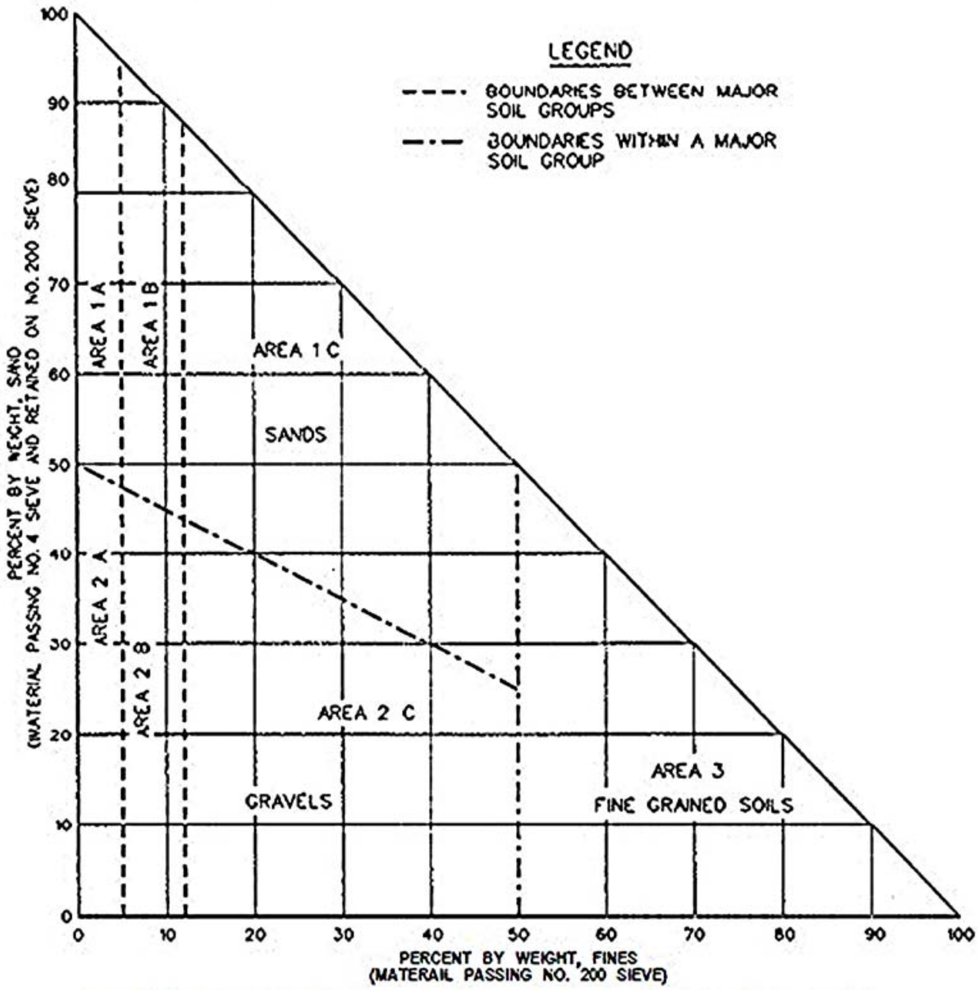


Figure 1

Gradation triangle for aid in selecting a commercial stabilizing agent

Area	Soil Class (a)	Type of stabilizing additive recommended	Restriction on LL and PI of soil	Restriction on percent passing No. 200 sieve (a)	Remarks
1A	SW or SP	(1) Bituminous (2) Portland cement (3) Lime-cement-fly ash	PI not to exceed 25		
1B	SW-SM or SP-SM or SW-SC or SP-SC	(1) Bituminous (2) Portland cement (3) Lime (4) Lime-cement-fly ash	PI not to exceed 10 PI not to exceed 30 PI not to exceed 12 PI not to exceed 25		
1C	SM or SC or SM-SC	(1) Bituminous (2) Portland cement (3) Lime (4) Lime-cement-fly ash	PI not to exceed 10 (b) PI not less than 12 PI not to exceed 25	Not to exceed 30% by weight	
2A	GW or GP	(1) Bituminous (2) Portland cement			Well-graded material only. Material should contain at least 45% by weight of material passing No. 4 sieve.
2B	GW-GM or GP-GM or GW-GC or GP-GC	(1) Bituminous (2) Portland cement (3) Lime (4) Lime-cement-fly ash	PI not to exceed 10 PI not to exceed 30 PI not less than 12 PI not to exceed 25		Well-graded material only. Material should contain at least 45% by weight of material passing No. 4 sieve.
2C	GM or GC or GM-GC	(1) Bituminous (2) Portland cement	PI not to exceed 10 (b)	Not to exceed 30% by weight	Well-graded material only. Material should contain at least 45% by weight of material passing No. 4 sieve.
3	CH or CL or MH or ML or OH or OL or ML-CL	(1) Portland cement (2) Lime	LL less than 40 and PI less than 20 PI not less than 12		Organic and strongly acid soils falling within this are are not susceptible to stabilization by ordinary means

(a) Soil classification corresponds to MIL-STD-619B. Restriction on liquid (LL) and plasticity index (PI) is in accordance with Method 103 in MIL-STD-621A
(b) PI $\leq$ 20 + (50 – percent passing No. 200 sieve)/4

Table 1

Guide for selecting a stabilizing additive

2.2.3 CONSTRUCTION CUTOFF DATES. Materials stabilized with cement, lime, or LCF should be constructed early enough during the construction season to allow the development of adequate strength before the first freezing cycle begins. The rate of strength gain is substantially lower at 50 degrees Fahrenheit than at 70 or 80 degrees Fahrenheit. Chemical reactions will not occur rapidly for lime-stabilized soils when the soil temperature is less than 60 degrees Fahrenheit and is not expected to increase for one month, or cement-stabilized soils when the soil temperature is less than 40 degrees Fahrenheit and is not expected to increase for one month. In frost areas, it is not always sufficient to protect the mixture from freezing during a 7-day curing period as required by the applicable guide specifications, and a construction cutoff date well in advance of the onset of freezing conditions (e.g. 30 days) may be essential.

2.3 THICKNESS REDUCTION FOR BASE AND SUBBASE COURSES. Stabilized base and subbase course materials must meet certain requirements of gradation, strength, and durability to qualify for reduced layer thickness design. Gradation requirements are presented in the sections covering design with each type of stabilizer. Unconfined compressive strength and durability requirements for bases and subbases treated with cement lime, LF, and LCF are indicated in Tables 2 and 3, respectively. All stabilized materials except those treated with bitumen must meet minimum durability criteria to be used in pavement structures. There are no durability criteria for bituminous stabilized materials since it is assumed that they will be sufficiently waterproofed if properly designed and constructed.

	Minimum Unconfined Compressive strength, psi[a]	
Stabilized Soil Layer	*Flexible pavement*	*Rigid pavement*
Base course	750	500
Subbase course, select material or subgrade	250	200

[a] Unconfined compressive strength determined at 7 days for cement stabilization and 28 days for lime, lime fly ash, or lime-cement-fly ash stabilization.

Table 2

Minimum unconfined compressive strength for cement, lime, lime-cement, and lime-cement-fly ash stabilized soils

Type of Soil Stabilized	Maximum Allowable Weight Loss After 12 Wet-Dry or Freeze-Thaw Cycles Percent of Initial Specimen Weight
Granular, PI < 10	11
Granular, PI > 210	8
Silt	8
Clays	6

Table 3
Durability requirements

3. DETERMINATION OF STABILIZER CONTENT

3.1 STABILIZATION WITH PORTLAND CEMENT. Portland cement can be used either to modify and improve the quality of the soil or to transform the soil into a cemented mass with increased strength and durability. The amount of cement used will depend upon whether the soil is to be modified or stabilized.

3.1.1 TYPES OF PORTLAND CEMENT. 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 gave 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.

3.1.2 SCREENING TESTS FOR ORGANIC MATTER AND SULFATES. 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.

3.1.2.1 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. A pH test to determine the presence of organic material should be performed. If the pH of a 10:1 mixture (by weight) of soil and cement is at least 12.0 after 15 minutes of mixing, it is probable that any organics present will not interfere with normal hardening.

3.1.2.2 Sulfates. Although a 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 a 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 ground water containing high sulfate concentrations. The use of cement for fine-grained soils containing more than about 1 percent sulfate should be avoided.

3.1.2.3 Water for hydration. Potable water is normally used for cement stabilization, although sea water has been found to be satisfactory.

3.1.2.4 Gradation requirements. Gradation requirements for cement stabilized base and subbase courses are indicated in Table 4 below.

Type Course	*Sieve Size*	*Percent Passing*
Base	1½ in.	100
	¾ in.	70-100
	No. 4	45-70
	No. 40	10-40
	No. 200	0-20
Subbase	1½ in.	100
	No. 4	45-100
	No. 40	10-50
	No. 200	0-20

Table 4
Gradation requirements for cement stabilized base and subbase courses

3.1.2.5 Cement content for modification of soils.

(1) *Improve plasticity.* The amount of cement required to improve the quality of the soil through modification is determined by the trial-and-error approach. If it is desired to reduce the PI of the soil, successive samples of soil-cement mixtures must be prepared at different treatment levels and the PI of each mixture determined. The Referee Test of ASTM D 423 and ASTM D 424 procedures will be used to determine the PI of the soil-cement mixture. The minimum cement content that yields the desired PI is selected, but since it was determined based upon the minus 40 fraction of the material, this value must be adjusted to find the design cement content based upon total sample weight expressed as:

$$A = 100BC \qquad \text{(eq 3-1)}$$

where

A = design cement content, percent total weight of soil

B = percent passing No. 40 sieve size, expressed as a decimal

C = percent cement required to obtain the desired PI of minus 40 material, expressed as a decimal

(2) *Improve gradation.* If the objective of modification is to improve the gradation of a granular soil through the addition of fines, then particle-size analysis (ASTM D 422) should be conducted on samples at various treatment levels to determine the minimum acceptable cement content.

(3) *Reduce swell potential.* Small amounts of portland cements may reduce swell potential of some swelling soils. However, portland cement generally is not as effective as lime and may be considered too expensive for this application. The determination of cement content to reduce the swell potential of fine-g-rained plastic soils can be accomplished by molding several samples at various cement contents and soaking the specimens along with untreated specimens for 4 days. The lowest cement content that eliminates the swell potential or reduces the swell characteristics to the minimum is the

design cement content. The cement content determined to accomplish soil modification should be checked to see whether it provides an unconfined compressive strength great enough to qualify for a reduced thickness design in accordance with criteria established for soil stabilization.

(4) *Frost areas.* Cement-modified soil may also be used in frost areas, but in addition to the procedures for mixture design described in items(1) and (2) above, cured specimens should be subjected to the 12 freeze-thaw cycles prescribed by ASTM D 560 (but omitting wire-brushing) or other applicable freeze-thaw procedures. This should be followed by determination of frost design soil classification by means of standard laboratory freezing tests. If cement-modified soil is used as subgrade, its frost-susceptibility, determined after freeze-thaw cycling, should be used as the basis of the pavement thickness design if the reduced subgrade design method is applied.

3.1.2.6 Cement content for stabilized soil. The following procedure is recommended for determining the design cement content for cement-stabilized soils.

(1) *Step 1.* Determine the classification and gradation of the untreated soil following procedures in ASTM D 422 and D 2487, respectively.

(2) *Step 2.* Using the soil classification select an estimated cement content for moisture-density tests from Table 5 below.

Soil *Classification*	*Initial Estimated Cement Content percent dry weight*
GW, SW	5
GP, GW-GC, GW-GM, SW-SC, SW-SM	6
GC, GM, GP-GC, GP-GM, GM-GC, SC, SM, SP-SC, SP-SM, SM-SC, SP	7
CL, ML, MH	9
CH	11

Table 5
Cement requirements for various soils

(3) *Step 3.* Using the estimated cement content, conduct moisture-density tests to determine the maximum dry density and optimum water content of the soil-cement mixture. The procedure contained in ASTM D 558 will be used to prepare the soil-cement mixture and to make the necessary calculations; however, the procedures outlined in ASTM D 1557 will be used to conduct the moisture density test.

(4) *Step 4.* Prepare triplicate samples of the soil-cement mixture for unconfined compression and durability tests at the cement content selected in step 2 and at cement contents 2 percent above and 2 percent below that determined in step 2.

The samples should be prepared at the density and water content to be expected in field construction. For example, if the design density is 95 percent of the laboratory maximum density, the samples should also be prepared at 95 percent. The samples should be prepared in accordance with ASTM D 1632 except that when more than 35 percent of the material is retained on the No. 4 sieve, a 4-inchdiameter mold should be used to prepare the specimens. Cure the specimens for 7 days in a humid room before testing. Test three specimens using the unconfined compression test in accordance with ASTM D 1633, and subject three specimens to durability tests, either wet-dry (ASTM D 559) or freeze-thaw (ASTM D 560) tests as appropriate. The frost susceptibility of the treated material should also be determined as indicated in appropriate pavement design manuals.

(5) *Step 5.* Compare the results of the unconfined compressive strength and durability tests with the requirements shown in Tables 2 and 3. The lowest cement content which meets the required unconfined compressive strength requirement and demonstrates the required durability is the design cement content. If the mixture should meet the durability requirements but not the strength requirements, the mixture is considered to be a modified soil. If the results of the specimens tested do not meet both the strength and durability requirements, then a higher cement content may be selected and steps 1 through 4 above repeated.

3.2 STABILIZATION WITH LIME. In general, all lime treated fine-grained soils exhibit decreased plasticity, improved workability and reduced volume change characteristics. However, not all soils exhibit improved strength characteristics. It should be emphasized that the properties of soil-lime mixtures are dependent on many variables. Soil type, lime type, lime percentage and curing conditions (time, temperature, moisture) are the most important.

3.2.1 TYPES OF LIME. Various forms of lime have been successfully used as soil stabilizing agents for many years. However, the most commonly used products are hydrated high-calcium lime, monohydrated dolomitic lime, calcitic quicklime, and dolomitic quicklime. Hydrated lime is used most often because it is much less caustic than quicklime; however, the use of quicklime for soil stabilization has increased in recent years mainly with slurry-type applications. The design lime contents determined from the criteria presented herein are for hydrated lime. If quicklime is used, the design lime contents determined herein for hydrated lime should be reduced by 25 percent. Specifications for quicklime and hydrated lime may be found in ASTM C 977.

3.2.2 GRADATION REQUIREMENTS. Gradation requirements for lime stabilized base and subbase courses are presented in Table 6 below.

Type Course	*Sieve Size*	*Percent Passing*
Base	1½ in.	100
	¾ in.	70-100
	No. 4	45-70
	No. 40	10-40
	No. 200	0-20
Subbase	1½ in.	100
	No. 4	45-100
	No. 40	10-50
	No. 200	0-20

Table 6
Gradation requirements for lime stabilized base
and subbase courses

3.2.3 LIME CONTENT FOR LIME-MODIFIED SOILS. The amount of lime required to improve the quality of a soil is determined through the same trial-and error process used for cement-modified soils.

3.2.3.1 Lime content for lime-stabilized soils. The following procedures are recommended for determining the lime content of lime stabilized soils.

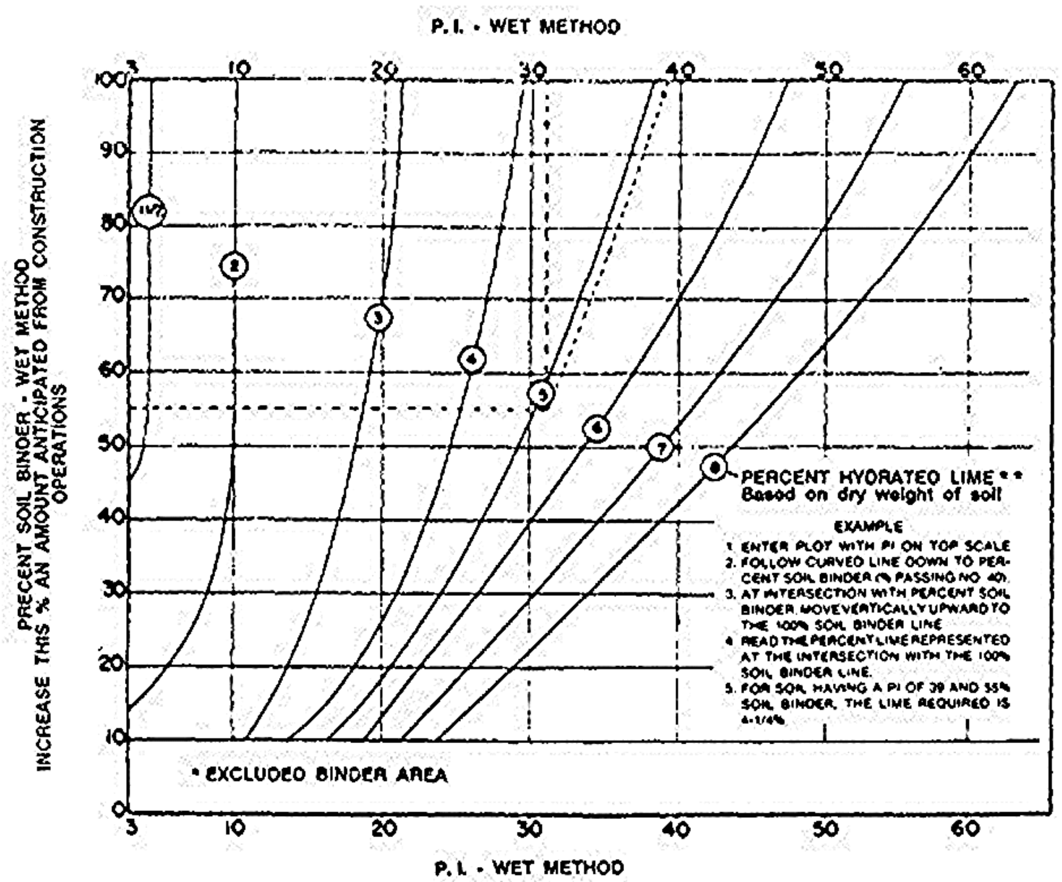
(1) *Step 1.* The preferred method for determining initial design lime content is the pH test. In this method several lime-soil slurries are prepared at different lime treatment levels such as 2, 4, 6, and 8 percent lime and the pH of each slurry is determined. The lowest lime content at which a pH of about 12.4 (the pH of free lime) is obtained is the initial design lime content. An alternate method of determining initial design lime content is by the use of Figure 2. Specific values required to use Figure 2 are the PI and the percent of material passing the No. 40 sieve.

(2) *Step 2.* Using the initial design lime content conduct moisture-density tests to determine the maximum dry density and optimum water content of the soil lime mixture. The procedures contained in ASTM D 3551 will be used to prepare the soil-lime mixture. The moisture density test will be conducted following procedures in ASTM D 1557.

(3) *Step 3.* Prepare triplicate samples of the soil lime mixture for unconfined compression and durability tests at the initial design lime content and at lime contents 2 and 4 percent above design if based on the preferred method, or 2 percent above and 2 percent below design if based on the alternate method. The mixture should be prepared as indicated in ASTM D 3551. If less than 35 percent of the soil is retained on the No. 4 sieve, the sample should be approximately 2 inches in diameter and 4 inches high. If more than 35 percent is retained on the No. 4 sieve, samples should be 4 inches in diameter and 8 inches high. The samples should be prepared at the density and water content expected in field construction. For example, if the design density is 95 percent of the laboratory maximum density, the sample should be prepared at 95 percent density. Specimens should be cured in a sealed container to prevent moisture loss and lime carbonation. Sealed metal cans, plastic bags, and so forth are satisfactory. The preferred method of curing is 73 degrees F for 28 days. Accelerated curing at 120

degrees F for 48 hours has also been found to give satisfactory results; however, check tests at 73 degrees for 28 days should also be conducted. Research has indicated that if accelerated curing temperatures are too high, the pozzolanic compounds formed during laboratory curing could differ substantially from those that would develop in the field.

(4) *Step 4.* Test three specimens using the unconfined compression test. If frost design is a consideration, test three specimens to 12 cycles of freeze-thaw durability tests (ASTM D 560) except wire brushing is omitted. The frost susceptibility of the treated material should be determined as indicated in appropriate design manuals.



* Exclude use of chart for materials with less than 10% - No. 40 and cohesionless materials (P. I. less than 3)

** Percent of relatively pure lime usually 90% or more of Ca and/or Mg hydroxides and 85% or more of which pass the No. 200 sieve. Percentages shown are for stabilizing subgrades and base courses where lasting effects are desired. Satisfactory temporary results are sometimes obtained by the use of as little as 1/2 of above percentages. Reference to cementing strength is implied when such termes as "Lasting Effects" and "Temporary Resulst" are used.

Figure 2
Chart for the initial determination of lime content

(5) *Step 5.* Compare the results of the unconfined compressive strength and durability tests with the requirements shown in Tables 2 and 3. The lowest lime content which meets the unconfined compressive strength requirement and demonstrates the required durability is the design lime content. The treated material also must meet frost susceptibility requirements as indicated in the appropriate pavement design manuals. If the mixture should meet the durability requirements but not the strength requirements, it is considered to be a modified soil. If results of the specimens tested do not meet both the strength and durability requirements, a higher lime content may be selected and steps 1 through 5 repeated.

3.3 STABILIZATION WITH LIME-FLY ASH (LF) AND LIME-CEMENT-FLY ASH (LCF). Stabilization of coarse-grained soils having little or no tines can often be accomplished by the use of LF or LCF combinations. Fly ash, 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 fly ash in combination can often be used successfully in stabilizing granular materials since the fly ash provides an agent, with which the lime can react. Thus LF or LCF stabilization is often appropriate for base and subbase course materials.

3.3.1 TYPES OF FLY ASH. Fly ash is classified according to the type of coal from which the ash was derived. Class C fly ash is derived from the burning of lignite or sub-bituminous coal and is often referred to as “high lime” ash because it contains a high percentage of lime. Class C fly ash is self-reactive or cementitious in the presence of water, in addition to being pozzolanic. Class F fly ash 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.

3.3.2 EVALUATION OF FLY-ASH. To be acceptable quality fly ash used for stabilization must meet the requirements indicated in ASTM C 593.

3.3.3 GRADATION REQUIREMENTS. Gradation requirements for LF and LCF stabilized base and subbase course are indicated in Table 7.

Type Course	*Sieve Size*	*Percent Passing*
Base	2 in.	100
	¾ in.	70-100
	3/8 in.	50-80
	No. 4	35-70
	No. 8	25-55
	No. 16	10-45
	No. 200	0-15
Subbase	1½ in.	100
	No. 4	45-100
	No. 40	10-50
	No. 200	0-15

Table 7
Gradation requirements for fly ash
stabilized base and subbase courses

3.3.4 SELECTION OF LIME-FLY ASH CONTENT FOR F AND LCF MIXTURES. Design with LF is somewhat different from stabilization with lime or cement. For a given combination of material (aggregate, fly ash, and lime), a number of factors can be varied in the mix design process such as percentage of lime-fly ash, the moisture content, and the ratio of lime to fly ash. 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 fly ash, 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. 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 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 percent above the optimum fines content. At the recommended fines content, the strength development is also influenced by the ration of lime to fly ash. Adjustment of the lime-fly ash ratio will yield different values of strength and durability properties.

(1) *Step 1.* The first step is to determine the optimum fines content that will give the maximum density. This is done by conducting a series of moisture-density tests using different percentages of fly ash and determining the mix level that yields maximum density. The initial fly ash content should be about 10 percent based on dry weight of the mix. It is recommended that material larger than ¾ in. be removed and the test conducted on the minus ¾ in. fraction. Tests are run at increasing increments of fly ash, e.g. 2 percent, up to a total of about 20 percent. Moisture density tests should be conducted following procedures indicated in ASTM D 1557. The design fly ash content is then selected at 2 percent above that yielding maximum density. An alternate method is to estimate optimum water content and conduct single point compaction tests at fly ash contents of 10-20 percent, make a plot of dry density versus fly ash content, and determine the fly ash content that yields maximum density. The design fly ash content is 2 percent above this value. A moisture density test is then conducted to determine the optimum water content and maximum dry density.

(2) *Step 2.* Determine the ratio of lime to fly ash that will yield highest strength and durability. Using the design fly ash content and the optimum water content determined in step 1, prepare triplicate specimens at three different lime-fly ash rations following procedures indicated in ASTM D 1557. Use LF ratios of 1:3, 1:4 and 1:5. If desired, about 1 percent of portland cement may be added at this time.

(3) *Step 3.* Test three specimens using the unconfined compression test. If frost design is a consideration, subject three specimens to 12 cycles of freeze-thaw durability tests (ASTM D 560) but omit wire brushing. The frost susceptibility of the treated material shall also be determined as indicated in appropriate design manual.

(4) Compare the results of the unconfined compressive strength and durability tests with the requirements shown in Tables 2 and 3. The lowest LF ratio content (i.e., ratio with

the lowest lime content which meets the required unconfined compressive strength requirement and demonstrates the required durability) is the design LF content. The treated material must also meet frost susceptibility requirements as indicated in the appropriate pavement design manuals. If the mixture should meet the durability requirements but not the strength requirements, it is considered to be a modified soil. If the results of the specimens tested do not meet both the strength and durability requirements, a different LF content may be selected or additional portland cement used and steps 2 through 4 repeated.

3.3.5 SELECTION OF CEMENT CONTENT FOR LCF MIXTURES. Portland cement may also be used in combination with LF for improved strength and durability. If it is desired to incorporate cement into the mixture, the same procedures indicated for LF design should be followed except that, beginning at step 2, the cement shall be included. Generally, about 1 to 2 percent cement is used. Cement may be used in place of or in addition to lime; however, the total tines content should be maintained. Strength and durability tests must be conducted on samples at various LCF ratios to determine the combination that gives best results.

3.4 STABILIZATION WITH BITUMEN. 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 which 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 non-cohesive 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 which prevents or hinders the penetration of water; thereby reducing 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, which in turn 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.

3.4.1 TYPES OF BITUMINOUS STABILIZED SOILS.

3.4.1.1 Sand bitumen. A mixture of sand and bitumen in which the sand particles are cemented together to provide a material of increased stability.

3.4.1.2 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.

3.4.1.3 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.

3.4.2 TYPES OF BITUMEN. 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 climatic conditions. Generally, the following types of bituminous materials will be used for the soil gradation indicated:

3.4.2.1 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.

3.4.2.2 Well-graded aggregate with little or no material passing the 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.

3.4.2.3 Aggregate with a considerable percentage of fine aggregate and material passing the 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.

3.4.3 SOIL GRADATION. The recommended soil gradations for subgrade materials and base or subbase course materials are shown in Tables 8 and 9, respectively.

Sieve Size	*Percent Passing*
3 in.	100
No. 4	50-100
No. 30	38-100
No. 200	2-30

Table 8
Recommended gradations for bituminous stabilized subgrade materials

Sieve Size	1½ in. Maximum	1-in. Maximum	¾-in. Maximum	½-in. Maximum
1½-in.	100	-	-	-
1-in.	84 ± 9	100	-	-
¾-in.	76 ± 9	83 ± 9	100	-
M-in.	66 ± 9	73 ± 9	82 ± 9	100
3/8-in.	59 ± 9	64 ± 9	72 ± 9	83 ± 9
No. 4	45 ± 9	48 ± 9	54 ± 9	62 ± 9
No. 8	35 ± 9	36 ± 9	41 ± 9	47 ± 9
No. 16	27 ± 9	28 ± 9	32 ± 9	36 ± 9
No. 30	20 ± 9	21 ± 9	24 ± 9	28 ± 9
No. 50	14 ± 7	16 ± 7	17 ± 7	20 ± 7
No. 100	9 ± 5	11 ± 5	12 ± 5	14 ± 5
No. 200	5 ± 2	5 ± 2	5 ± 2	5 ± 2

Table 9
Recommended gradations for bituminous-stabilized base and subbase materials

3.4.4 MIX DESIGN. For subgrade stabilization, the following equation may be used for estimating the preliminary quantity of cutback asphalt to be selected:

$$p = ((0.02(a) + 0.07(b) + 0.15(c) + 0.20(d))/(100 - S)) \times 100 \qquad \text{(eq 3-2)}$$

where,

p = percent cutback asphalt by weight of dry aggregate
a = percent of mineral aggregate retained on No. 50 sieve
b = percent of mineral aggregate passing No. 50 sieve and retained on No. 100 sieve
c = percent of mineral aggregate passing No. 100 and retained on No. 200 sieve
d = percent of mineral aggregate passing No. 200
S = percent solvent

The preliminary quantity of emulsified asphalt to be used in stabilizing subgrades can be determined from Table 10. The final design content of cutback or emulsified asphalt should be selected based upon the results of the Marshal Stability test procedure. The minimum Marshall Stability recommended for subgrades is 500 pounds. If a soil does not show increased stability when reasonable amounts of bituminous materials are added, the gradation of the soil should be modified or another type of bituminous material should be used. Poorly graded materials may be improved by the addition of suitable tines containing considerable material passing the No. 200 sieve. The amount of bitumen required for a given soil increases with an increase in percentage of the liner sizes.

Percent Passing No. 200 Sieve	Pounds of Emulsified Asphalt per 100 pound of Dry Aggregate at Percent Passing No. 10 Sieve					
	<50	60	70	80	90	100
0	6.0	6.3	6.5	6.7	7.0	7.2
2	6.3	6.5	6.7	7.0	7.2	7.5
4	6.5	6.7	7.0	7.2	7.5	7.7
6	6.7	7.0	7.2	7.5	7.7	7.9
8	7.0	7.2	7.5	7.7	7.9	8.2
10	7.2	7.5	7.7	7.9	8.2	8.4
12	7.5	7.7	7.9	8.2	8.4	8.6
14	7.2	7.5	7.7	7.9	8.2	8.4
16	7.0	7.2	7.5	7.7	7.9	8.2
18	6.7	7.0	7.2	7.5	7.7	7.9
20	6.5	6.7	7.0	7.2	7.5	7.6
22	6.3	6.5	6.7	7.0	7.2	7.5
24	6.0	6.3	6.5	6.7	7.0	7.2
25	6.2	6.4	6.6	6.9	7.1	7.3

Table 10
Emulsified asphalt requirements

3.5 STABILIZATION WITH LIME-CEMENT AND LIME-BITUMEN. The advantage in 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 characteristics 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 incorporated into the soil to make it friable; thereby, permitting the cement or asphalt to be adequately mixed. 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.

3.5.1 LIME-CEMENT. Lime can be used as an initial additive with portland cement or 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.

3.5.2 LIME-ASPHALT. Lime can be used as an initial additive with asphalt 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 which tend to interfere with bonding of the asphalt. Generally, about 1-2 percent lime is all that is needed for this objective.

3.6 LIME TREATMENT OF EXPANSIVE SOILS. Expansive soils as defined for pavement purposes are those that exhibit swell in excess of three percent. 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 11. 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 ASTM D 1883. The depth to which lime should be incorporated into the soil is generally limited by the construction equipment used. However, 2 to 3 feet generally is the maximum depth that can be treated directly without removal of the soil.

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

Table 11
Swell potential of soils