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In the paper by Epps, Dunlap, Gallaway, and Currin (pages 1-20), the references to Tables 3 through 15 in Figures 2, 3, 4, and 8 should all be reduced by 2; e.g., reference to "Table 5" should read "Table 3".

SOIL STABILIZATION: A MISSION ORIENTED APPROACH

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The widespread use of chemical additives for improving the physical properties of soils and soil-aggregate systems has emphasized the critical need for a classification and indexing system to simplify the selection of the most desirable chemical to be used for the existing environmental conditions and service demands. Such a system is described in this paper. The soil stabilization indexing system is subdivided into parts dealing separately with lime, portland cement, bituminous materials, and combinations of these materials. The different criteria for the use of each of these stabilizers are described in detail with extensive references to the literature. A series of flow charts have been developed that can be used in selecting the type and the amount of stabilizer for a given soil.

•THE U.S. Department of the Air Force demands and utilizes a broad array of airfield pavement types, ranging from very austere temporary runways in forward combat zones to well-engineered, heavy-duty runways designed for the most up-to-date aircraft. Because many of the existing pavements were built in the early 1930's, a continual program of maintenance and reconstruction is carried so that the airfields can accommodate modern aircraft. New construction is also mandatory, and this includes permanent facilities as well as limited-life pavement systems, many of which are constructed within very severe time constraints. Expedient construction must take full advantage of on-site construction materials because all additional materials and equipment must be airlifted in to ensure rapid response.

The attractive engineering and economic benefits of soil stabilization make it necessary that this construction alternative be considered. Yet, in many cases, the engineer has no past experience or specialized training in soil stabilization techniques. To alleviate this problem, an index system is required that will allow the engineer to select the appropriate type and amount of stabilizer. The use of the index system in the field should require determination of relatively simple properties of the soil. These soil properties, together with suitable use factors and environmental data, should be used as input to the index system.

AIR FORCE SOIL STABILIZATION INDEX SYSTEM

An overall systematic approach was used in developing the Air Force soil stabilization index system (SSIS). The development of this system, shown in Figure 1, is discussed in this section (1).

Type of Stabilization

Chemical stabilization is of primary concern in the SSIS. However, both chemical and mechanical stabilization must be considered and the alternatives evaluated.

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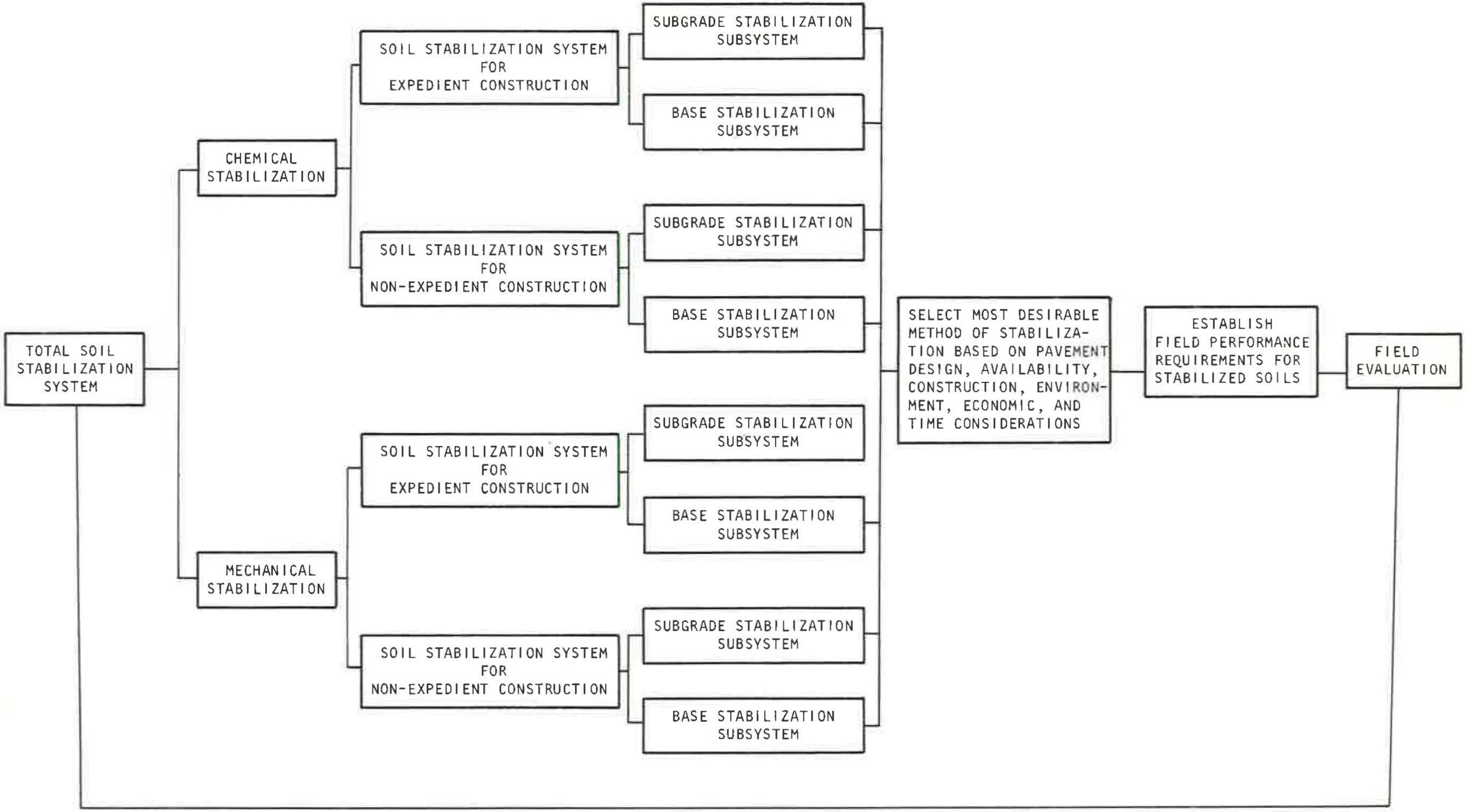


Figure 1. The Air Force soil stabilization index system.

Use Factors

The soil stabilization system should be capable of being utilized for (a) theater of operations use on both expedient and nonexpedient pavements and (b) zone of interior use on permanent pavements.

Expedient refers to short-lived, high-risk, rapidly constructed pavements, whereas nonexpedient and permanent pavements have a longer life and require an extended construction period. The major difference between nonexpedient and permanent pavements is that the latter would probably be constructed by civilian firms and the design lead time would allow more thorough and detailed investigation of stabilization alternatives. Permanent construction is identical to that used by state highway departments for primary roads, and the index system for nonexpedient construction supplies a "jumping-off" point for investigations in permanent construction.

Figure 1 shows another way in which use factors are entered in the index system by specifying different subsystems for subgrade and base course stabilization. Subbases are not considered directly, but they may fall either in the subgrade or base course subsystems depending on the material type and desired strength characteristics.

Environmental Factors

Environmental factors might influence the ultimate durability and suitability of the stabilized soil. They are based primarily on climatological effects. Both rainfall and temperature must be considered because either can significantly influence the type and amount of stabilizer used as well as the time of the year in which certain stabilizers can be used.

Construction Factors

Military engineers faced with hasty construction in the theater of operations usually are faced with limited equipment also. Knowledge of the type of equipment required for a certain stabilization task may prove to be a valuable planning tool not only in anticipating the type of equipment necessary to perform a stabilization task but also in eliminating the use of a particular stabilizer if adequate equipment and time are not available.

Field Performance Requirements for Stabilized Soils

The desired performance of the stabilized soils is established by the Air Force. In most cases, this is based on anticipated life of the structure and allowable time for construction. Examples of this information include the recent mobility concepts and various other operational requirements that have been developed by the Air Force.

Field Evaluation

The verification of the index system for soil stabilization must ultimately come from the user, i. e., the Air Force and its military partners. On pavement projects where stabilization has been used, adequate construction records and follow-up evaluations will be absolutely necessary to verify the adequacy of the stabilized sections. Continual evaluations of stabilized sections that are already in place will also aid in evaluating the ultimate performance of the index system.

Finally, it should be stressed that the SSIS is not a substitute for structural pavement design. In its present form, it will not indicate to an engineer whether a layer should be stabilized or whether there are structural advantages of stabilizing one layer instead of another. Rather, the role of the index system is this: If the engineer decides to use stabilization, then he should be able to use the index system to tell him what kind of stabilization to use and how much stabilizer he should use. Soils that are not amenable to stabilization can be so identified in the index system. If other circumstances, such as climatic conditions or lack of appropriate equipment, rule out the possibility of stabilization, the index system can also provide this information.

GENERAL REQUIREMENTS FOR SELECTING STABILIZERS

Several guides have been published that assist the engineer in the selection of a stabilizer for a particular soil (2, 3). These guides indicate that selection of the stabilizer is dependent on the location of the stabilized layer in the pavement as well as the soil type. Systems have been developed for both base course and subgrade stabilization (1), although only the base course stabilization system will be presented in this paper.

Both the Unified Soil Classification System and the AASHO Soil Classification System have been utilized to select soil stabilizers (4, 5). Because both grain size and Atterberg limits are necessary inputs to classify soils according to either system, these 2 parameters were used for the initial separation of the soils into specific categories. In particular, the percentage passing the No. 200 sieve and the plasticity index (PI) were selected.

Specific guidelines for stabilizer selection are also available from literature published by consumer, producer, user, and general interest groups. These guidelines are discussed here in detail for lime, cement, bituminous materials, and combinations of these stabilizers.

Criteria for Lime Stabilization

Lime will react with most medium, moderately fine, and fine-grained soils to decrease plasticity, increase workability, reduce swell, and increase strength (6). In general terms, the soils that are most reactive to lime include (7) clayey gravels, silty clays, and clays. All soils classified by AASHO as A-5, A-6, and A-7 and some soils classified as A-2-6 and A-2-7 are most readily susceptible to stabilization with lime. Soils classified according to the Unified System as CH, CL, MH, ML, CL-ML, SC, SM, GC, and GM should be considered as potentially capable of being stabilized with lime.

Robnett and Thompson (6), based on experience gained with Illinois soils, have indicated that lime may be an effective stabilizer with clay contents ($< 2\mu$) as low as 7 percent; and, furthermore, soils with a PI as low as 8 can be satisfactorily stabilized with lime in certain instances (8). Armed forces criteria (2) indicate that the PI should be greater than 12, while representatives of the National Lime Association (9) indicate that a PI greater than 10 would be a reasonable lower limit to utilize.

In view of these suggested criteria, it is believed that the PI of the soil should have a lower limit of 10 to ensure that a reasonable degree of certainty will exist for successful stabilization with lime.

Criteria for Cement Stabilization

The Portland Cement Association (10, 11) indicates that all types of soils can be stabilized with cement. However, well-graded granular materials that possess a floating aggregate matrix have given the best results (12).

Limits on PI have been established by the armed forces (2), depending on the soil type. The PI should be less than 30 for sandy and gravelly materials and less than 20 for the fine-grained soils. These limitations are necessary to ensure proper mixing of the stabilizer in the soil.

Information developed by the Federal Highway Administration (5) indicates that cement should be used as a stabilizer for materials with less than 35 percent passing the No. 200 sieve and with a PI less than 20. Thus, this implies that A-2 and A-3 soils can be best stabilized by cement, while A-5, A-6, and A-7 soils can be best stabilized by lime.

The authors have selected a maximum PI of 30 for those soils to be stabilized with cement.

Criteria for Bituminous Stabilization

The majority of soil-bituminous stabilization has been performed with asphalt cement, cutback asphalts, and emulsified asphalts. For this reason, only these types of bituminous stabilizers are considered.

Some of the earliest criteria for bituminous stabilization were developed by the HRB Committee on Soil-Bituminous Roads. These criteria were revised and published by Winterkorn (13). Other criteria have been presented by the American Road Builders Association (14), The Asphalt Institute (15, 16), Herrin (17), Chevron Asphalt Company (18), Douglas Oil Company (19), and the U.S. Department of the Navy (20). Although these criteria were developed for particular types of bituminous stabilizers (i.e., soil-bitumen made with cutback asphalt), they are given in a single table (Table 1) for comparison purposes.

Current trends indicate that stabilization with asphalt cements is gaining widespread application. Requirements for aggregate grading and mixture properties of mixes containing asphalt cement have recently been summarized by the HRB Committee on Bituminous Aggregate Bases (21). This survey of criteria together with data published by the armed forces (22) suggests that soils that are nearly nonplastic and contain less than 18 percent passing the No. 200 sieve are most suitable for hot-mix asphalt cement stabilization.

Based on these criteria, a limit of 20 percent passing the No. 200 sieve, a PI less than 6, and the product of PI and the minus No. 200 material less than 60 have been utilized for selecting soils suitable for stabilization by asphalt. Less stringent requirements have been used in conjunction with the other stabilization subsystems developed for the Air Force (1).

Criteria for Combination Stabilizers

Combination stabilization is here defined specifically as lime-cement, lime-asphalt, and lime-fly ash. Because lime-fly ash stabilization is not expected to be a common stabilization method used by the Air Force, it will not be incorporated into the index system. The purpose of using combination stabilizers (lime and then one or the other stabilizers) is to reduce plasticity and increase workability so that the soil may be effectively stabilized by the second agent or additive.

Robnett and Thompson (23) have reviewed the literature and have suggested that soils that may be treated by these combination stabilizers are those classified by AASHO as A-6 and A-7 and certain soils classified as A-4 and A-5.

Based on these findings, it has been suggested that these combination stabilizers be utilized with materials that have greater than 35 percent passing the No. 200 sieve and that quantities of lime be used sufficient in magnitude to ensure that the PI is less than the established criteria for either cement or asphalt stabilization as appropriate.

These criteria together with appropriate environmental and construction precautions as given in Table 2 have been used to establish the base course stabilization system shown in Figure 2.

This stabilization system separates soils into various groups so the engineer may select the stabilizer suitable for use within these particular groups. This system will not, however, indicate the amount of stabilizer that must be used for a particular soil. The following discussion will suggest criteria that will allow the development of appropriate subsystems for the determination of stabilizer quantities.

TABLE 1

CRITERIA DEVELOPED FOR BITUMINOUS STABILIZATION

Developer	Percent Passing No. 200 Sieve	Plasticity Index	Plasticity Index x Percent Passing No. 200 Sieve
Winterkorn	8 to 50	18	
American Road Builders Association	0 to 35	10	
Herrin	0 to 30	10	
The Asphalt Institute, Pacific Coast Division	3 to 15	6	60
Chevron Asphalt Company	0 to 25	Nonplastic	72
Douglas Oil Company	0 to 30	7	

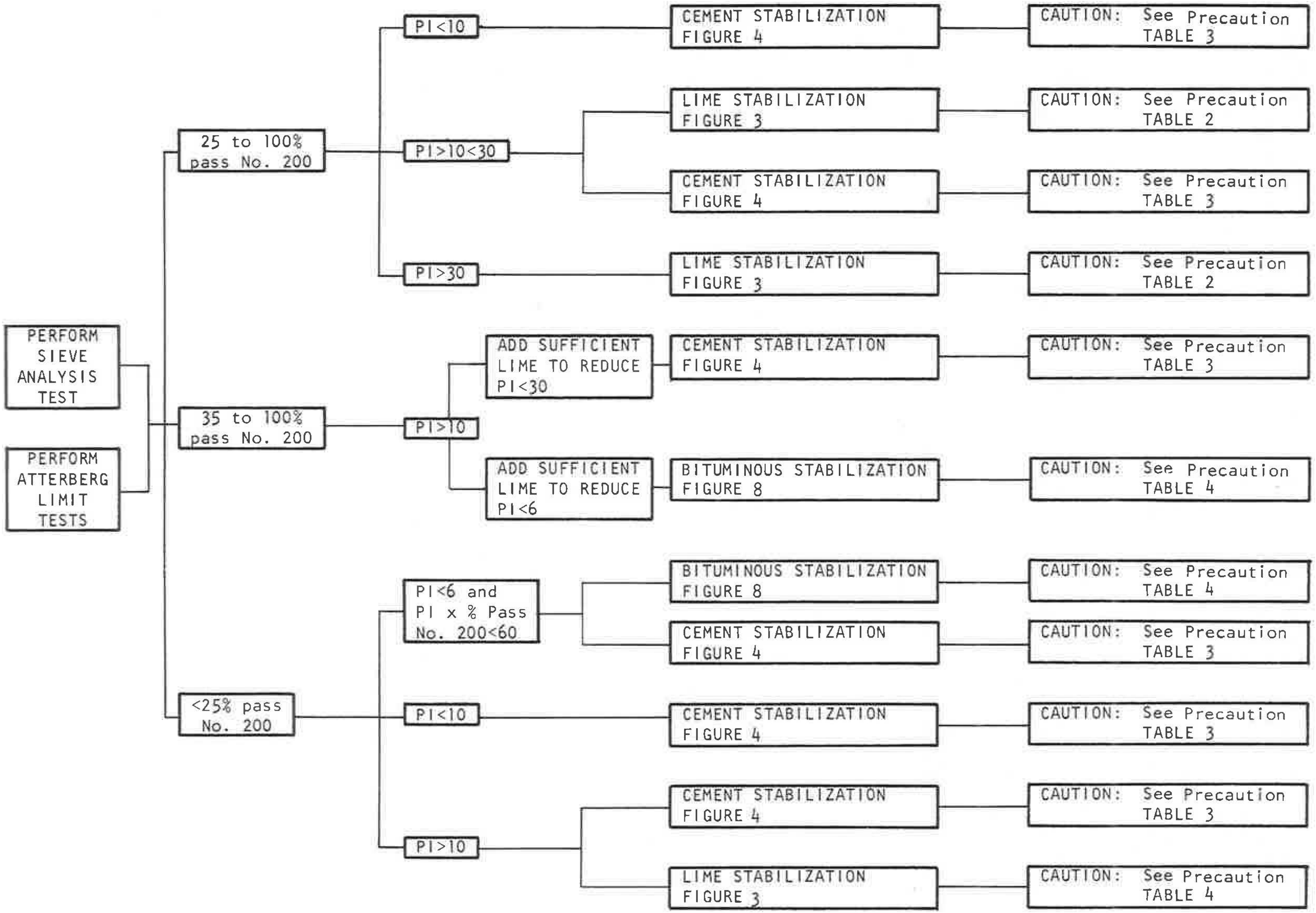


Figure 2. Selection of stabilizer for nonexpedient base construction.

TABLE 2

ENVIRONMENTAL AND CONSTRUCTION PRECAUTIONS

Stabilization	Environmental or Construction	Precaution
Lime	Environmental	If the soil temperature is less than 40 F and is not expected to increase for 1 month, chemical reactions will not occur rapidly and, thus, the strength gain of the lime-soil mixture will be minimal. Lime-soil mixtures should be scheduled for construction such that sufficient durability will be gained to resist any expected freeze-thaw cycles.
	Construction	Heavy vehicles should not be allowed on the lime-stabilized soil for 10 to 14 days after construction.
Cement	Environmental	If the soil temperature is less than 40 F and is not expected to increase for 1 month, chemical reactions will not occur rapidly and, thus, the strength gain of the cement-soil mixture will be minimal. Cement-soil mixtures should be scheduled for construction such that sufficient durability will be gained to resist the expected freeze-thaw cycles. Construction during periods of heavy rainfall should be avoided.
	Construction	Heavy vehicles should not be allowed on the cement-stabilized soil for 7 to 10 days after construction.
Bituminous	Environmental	When asphalt cements are used, construction should be allowed only when proper compaction is possible. If thin lifts are being placed, the air temperature should be 40 F and rising. Adequate compaction can be obtained at freezing temperatures. When cutbacks and emulsions are being used, the air temperature and soil temperature should be above freezing. Bituminous materials should completely coat the soil particles prior to compaction.
	Construction	Central batch plants, together with other specialized equipment, are necessary for bituminous stabilization with asphalt cements. Hot, dry weather is preferred for all types of bituminous stabilization.

DESIGN SUBSYSTEMS

Numerous research publications and technical guides are available to aid the engineer in the selection of criteria to determine the amount of stabilizer. A wide variety of test methods have been proposed; however, quantitative criteria are not always available. The criteria discussed here are for establishing the design subsystems aimed at determining appropriate stabilizer quantities for lime, cement, and bituminous stabilization.

Lime Stabilization

Selection of Appropriate Soils—The preceding section discussed the general requirements of the soil with respect to gradation and plasticity. However, there are other physicochemical features that must be considered in determining whether lime will react with a soil.

Thompson (24) has defined soils as being lime-reactive if they display significant strength increase (measured by unconfined compressive strength) when treated with lime. Soils that are not lime-reactive according to this definition are not necessarily unimproved by the addition of lime because lime may still decrease the plasticity, decrease the susceptibility to water, and enhance the overall engineering behavior of the soil. However, because improved load-bearing characteristics are desired in the stabilization index system, strength will be a major consideration here.

Factors that may prohibit soils from being lime-reactive include soil pH and the presence of organics and sulfates. Soils with a pH less than 7 may not be lime-reactive, although some soils with pH values as low as 5.7 have reportedly been effectively stabilized with lime (24). It has also been reported that soils with organic carbon contents exceeding about 1 percent are not satisfactorily lime-reactive (24). In addition, experience has shown that the presence of significant amounts of sulfates diminishes the effectiveness of lime.

It has been reported that A-horizon soils in Illinois do not satisfactorily react with lime (24), and similar reports have been made on other soils. This is probably the result of high organic contents in the upper horizon. Poorly drained soils often are the most reactive to lime, possibly because of the higher pH and the availability of lime-reactive constituents, such as unweathered soil minerals.

Selection of Type of Lime—Lime is generally used as an all-encompassing term to denote either slaked (hydrated) lime or quicklime. Both calcitic lime and dolomitic (high magnesium) lime are available in the United States. Although there is some disagreement as to whether the type of lime influences the strength of lime-soil mixtures (25), the selection of the lime type is usually predicated by availability of the stabilizer and safety requirements of the particular job.

Selection of Lime Quantity—There are fewer definitive criteria for evaluating the correct quantity of lime than for cement or bituminous materials.

Eades and Grim (26) have proposed a short-cut test where the appropriate lime content is that which will produce a minimum pH of 12.4 one hour after mixing. This test has not been validated for soils on a worldwide basis and should be used with caution.

Most authors have reported that a minimum of 3 percent lime is necessary to produce adequate reactions in the field (27). The Air Force (28) suggests that 2, 3, and 5 percent lime be used in coarse soils (those containing 50 percent or less passing the No. 200 sieve) while 3, 5, and 7 percent be tried for fine-grained soils (greater than 50 percent passing the No. 200 sieve). The National Lime Association recommends 3, 5, and 7 percent lime in trial mixtures (27). With the exception of the pH test described, the lime content must generally be determined by trial mixtures with the amount of lime being the minimum required to produce the desired reactions.

Methods of Evaluating Soil-Lime Mixtures—Several types of tests have been proposed for evaluating soil-lime mixtures. These include, but are not limited to, unconfined compressive strength, California bearing ratio, flexural fatigue strength, triaxial compressive strength, tests yielding elastic properties, cohesiometer values, and freeze-thaw and wet-dry tests. Most of these tests are not used routinely, and satisfactory criteria are not generally available. Some of the most reliable data are based on unconfined compressive strengths developed from research done by Thompson (29). Table 3 gives his results.

Durability, the ability of a material to retain stability and integrity over years of exposure to service and weathering, is perhaps the most difficult to determine. Of the many tests developed, only a modified freeze-thaw test shows substantial merit (30).

Figure 3, the lime stabilization subsystem, has been developed from these criteria.

TABLE 3

TENTATIVE LIME-SOIL MIXTURE COMPRESSIVE STRENGTH REQUIREMENTS

Anticipated Use	Residual Strength Requirement[b] (psi)	Strength Requirements for Various Anticipated Service Conditions[a]			
		8-Day Extended Soaking (psi)	Cyclic Freeze-Thaw[c] (psi)		
			3 Cycles	7 Cycles	10 Cycles
Modified subgrade	20	50	50	90 50[d]	120
Subbase					
Rigid pavement	20	50	50	90 50[d]	120
Flexible pavement					
10-in. cover[e]	30	60	60	100 60[d]	130
8-in. cover[e]	40	70	70	110 75[d]	140
5-in. cover[e]	60	90	90	130 100[d]	160
Base	100[f]	130	130	170 150[d]	200

[a] Strength required at termination of filed curing (following construction) to provide adequate residual strength.

[b] Minimum anticipated strength following first winter exposure.

[c] Number of freeze-thaw cycles expected in the lime-soil layer during the first winter of service.

[d] Freeze-thaw strength losses are based on 10 psi/cycle except for these 7-cycle values that are based on a previously established regression equation.

[e] Total pavement thickness overlying the subbase; requirements are based on Boussinesq stress distribution; rigid pavement requirements apply if cemented materials are used as base courses.

[f] Flexural strength should be considered in thickness design.

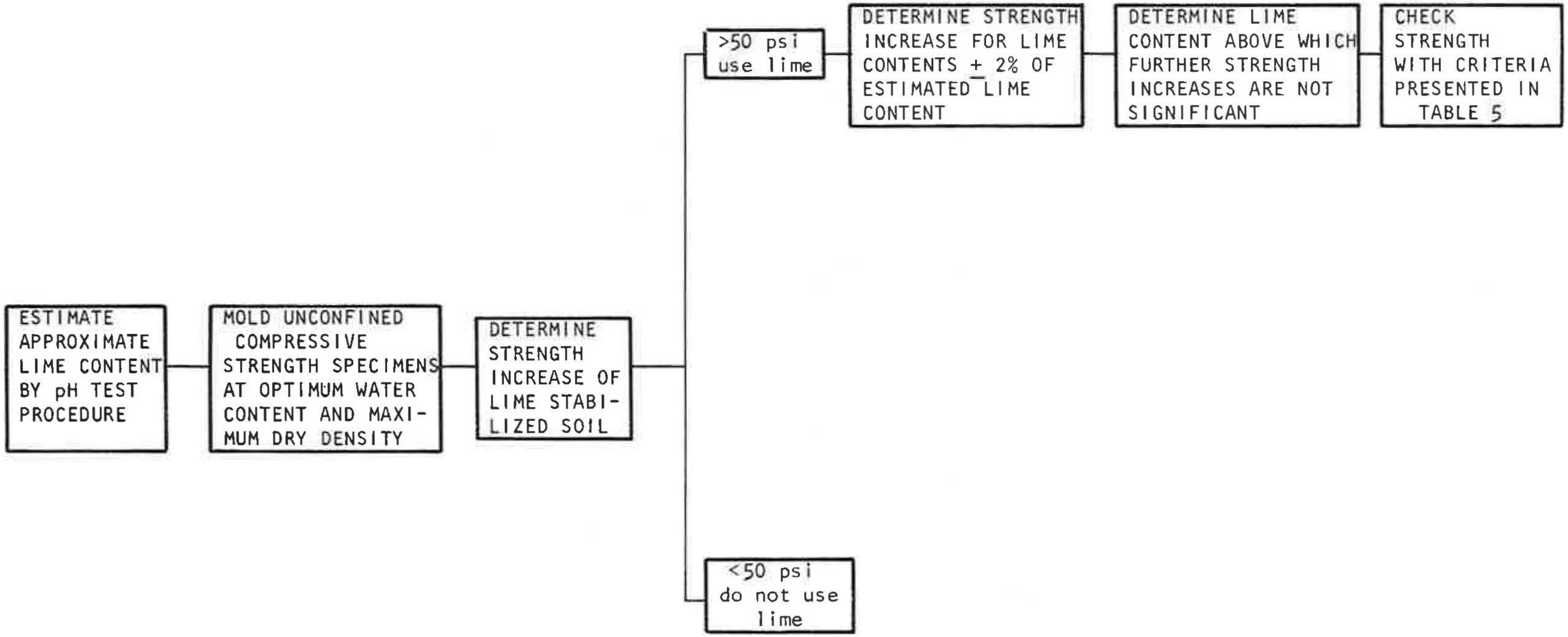


Figure 3. Subsystem for base course stabilization with lime.

Cement Stabilization

Information as to general requirements such as gradation and Atterberg limits have been discussed previously. Most research and construction with cement-soil mixtures has been performed on soils that have been classified according to the AASHO classification system. Experience has shown that this approach is satisfactory; but, it does not include important soil properties such as clay type, soil pH, organic content, and soil sulfate content that may influence the suitability of a soil for cement stabilization. These effects are discussed in this section.

Effects of pH, Organics, and Sulfates—The Road Research Laboratory has shown a general trend of strength increase with soils possessing high pH values. For pH values greater than 7, no ill effects on strength were noted (31). The Portland Cement Association has conducted pH tests on soils, but it has found no general correlation between pH and performance (32).

Two tests have been proposed to assess the effects of organics on soil-cement strength. The Portland Cement Association (33) has suggested the use of the calcium adsorption test to determine the presence of organics in sandy soils, but this test should not be used for clay soils. Additional research conducted by the Portland Cement Association (32, 33) has shown that the standard colorimetric tests will not identify the presence of organics satisfactorily.

A satisfactory method for determining the presence of active organic matter, according to MacLean and Sherwood (31), is the pH test conducted on a soil-cement paste 15 minutes after mixing. This test essentially indicates the reactivity of the soil with cement; however, the reactivity is not solely a function of the organic content (32, 34), but it is dependent on both the organic content and the type of organics (35).

Studies conducted by Sherwood (36) have indicated that sulfate contents in soils in excess of 0.5 to 1.0 percent reduce the strength of soil-cement mixtures. Similarly, sulfate concentrations in water in excess of 0.05 percent create strength loss. For these reasons the sulfate content of the soil should be ascertained.

Type of Cement—The influence of the type of cement on the properties of soil-cement mixtures has been examined by several investigators (36, 37, 38, 39). In general, Types I, II, III, and V produce only small differences in behavior for most soils. Thus, because of its general availability and economy, it is recommended that Type I cement be utilized.

Selection of the Cement Quantity—Research performed by the Portland Cement Association (10, 40, 41, 42) on more than 2,000 soils provides data for determining cement contents for various types of soils. Cement contents for subsurface soils are given in Table 4 (10). Requirements for soils in various horizons are also specified by the Portland Cement Association.

TABLE 4

CEMENT REQUIREMENTS FOR VARIOUS SOILS

AASHO Soil Classification	Unified Soil Classification[a]	Usual Range in Cement Requirement[b]		Estimated Cement Content Used in Moisture-Density Test (percent by weight)	Cement Content for Wet-Dry and Freeze-Thaw Tests (percent by weight)
		Percent by Volume	Percent by Weight		
A-1-a	GW, GP, GM, SW, SP, SM	5 to 7	3 to 5	5	3 to 5 to 7
A-1-b	GM, GP, SM, SP	7 to 9	5 to 8	6	4 to 6 to 8
A-2	GM, GC, SM, SC	7 to 10	5 to 9	7	5 to 7 to 9
A-3	SP	8 to 12	7 to 11	9	7 to 9 to 11
A-4	CL, ML	8 to 12	7 to 12	10	8 to 10 to 12
A-5	ML, MH, OH	8 to 12	8 to 13	10	8 to 10 to 12
A-6	CL, CH	10 to 14	9 to 15	12	10 to 12 to 14
A-7	OH, MH, CH	10 to 14	10 to 16	13	11 to 13 to 15

[a] Based on U.S Air Force recommendations (2).

[b] For most A-horizon soils, the cement content should be increased 4 percentage points if the soil is dark gray to gray and 6 percentage points if the soil is black.

Methods of Evaluating Soil-Cement Mixtures—Various types of tests have been used to evaluate the properties of soil-cement mixtures (43). These methods include unconfined compressive strength, flexural strength, modulus of elasticity, California bearing ratio, plate bearing value, fatigue, R-value, and freeze-thaw and wet-dry tests.

Many of these test methods have not been used extensively, and satisfactory criteria are not available. However, the Portland Cement Association recommends the use of freeze-thaw and wet-dry tests and has established criteria (Table 5) for these tests.

The design subsystem for cement based on these criteria is shown in Figure 4.

TABLE 5

PORTLAND CEMENT ASSOCIATION CRITERIA FOR SOIL-CEMENT MIXTURES USED IN BASE COURSES

AASHO Soil Classification	Unified Soil Classification[a]	Soil-Cement Weight Loss During 12 Cycles of Either Wet-Dry or Freeze-Thaw Test (percent)
A-1	GW, GP, GM, SW, SP, SM	≤14
A-2-4, A-2-5	GM, GC, SM, SC	
A-3	SP	
A-2-6, A-2-7	GM, GC, SM, SC	≤10
A-4	CL, ML	
A-5	ML, MH, OH	
A-6	CL, CH	≤7
A-7	OH, MH, CH	

[a] Based on correlation presented by U.S. Air Force (2).

Bituminous Stabilization

A bituminous binder in 1 of 3 forms is generally used; the forms include cutbacks, emulsions, or cements. An indication of the type of bitumen to use for certain types of soils has been suggested by The Asphalt Institute (15), Herrin (17), the U.S. Navy (20), the Air Force (28), and Chevron Asphalt Company (18). Selection of the proper bituminous stabilizer should depend on the grain-size distribution in addition to the function of the stabilized layer in the pavement system. Table 6, adapted from Herrin and prepared by using the soil gradings also suggested by Herrin (17), and Table 7 give data regarding bitumen stabilization.

Asphalt Cement—Criteria used for selection of the binder viscosity and the quantity of cement for base stabilization vary among state highway departments (21), and a suitable method based on highway experience is not available. The armed forces, however, base the selection of asphalt cement viscosity or grade on the pavement temperature index. Their recommendations have been altered and are used in the design subsystem (Table 8).

The quantity of asphalt can be estimated on a surface area and particle surface characteristic concept such as the California CKE method, or the quantity can be estimated from experience. Data given in Table 9 can be used to obtain a preliminary estimate of asphalt content, but these quantities are a guide only. Final selection should be based on a test performed on the asphalt-aggregate mixture.

A recent summary of state practices (21) indicates that both Hveem and Marshall tests are popular evaluation methods among state highway departments and that criteria

TABLE 6

SELECTION OF A SUITABLE TYPE OF BITUMEN FOR SOIL STABILIZATION PURPOSES

Mix	Sand-Bitumen	Soil-Bitumen	Crushed Stones and Sand-Gravel-Bitumen
Hot	Asphalt cements 60 to 70 hot climate 85 to 100 120 to 150 cold climate		Asphalt cements 45 to 50 hot climate 60 to 70 85 to 100 cold climate
Cold	Cutbacks See Figure 5	Cutbacks See Figure 5	Cutbacks See Figure 5
Emulsions	Emulsions See Table 11 See Figures 6 and 7 to determine whether cationic or anionic emulsion should be used	Emulsions See Table 11 See Figures 6 and 7 to determine whether cationic or anionic emulsion should be used	Emulsions See Table 11 See Figures 6 and 7 to determine whether cationic or anionic emulsion should be used

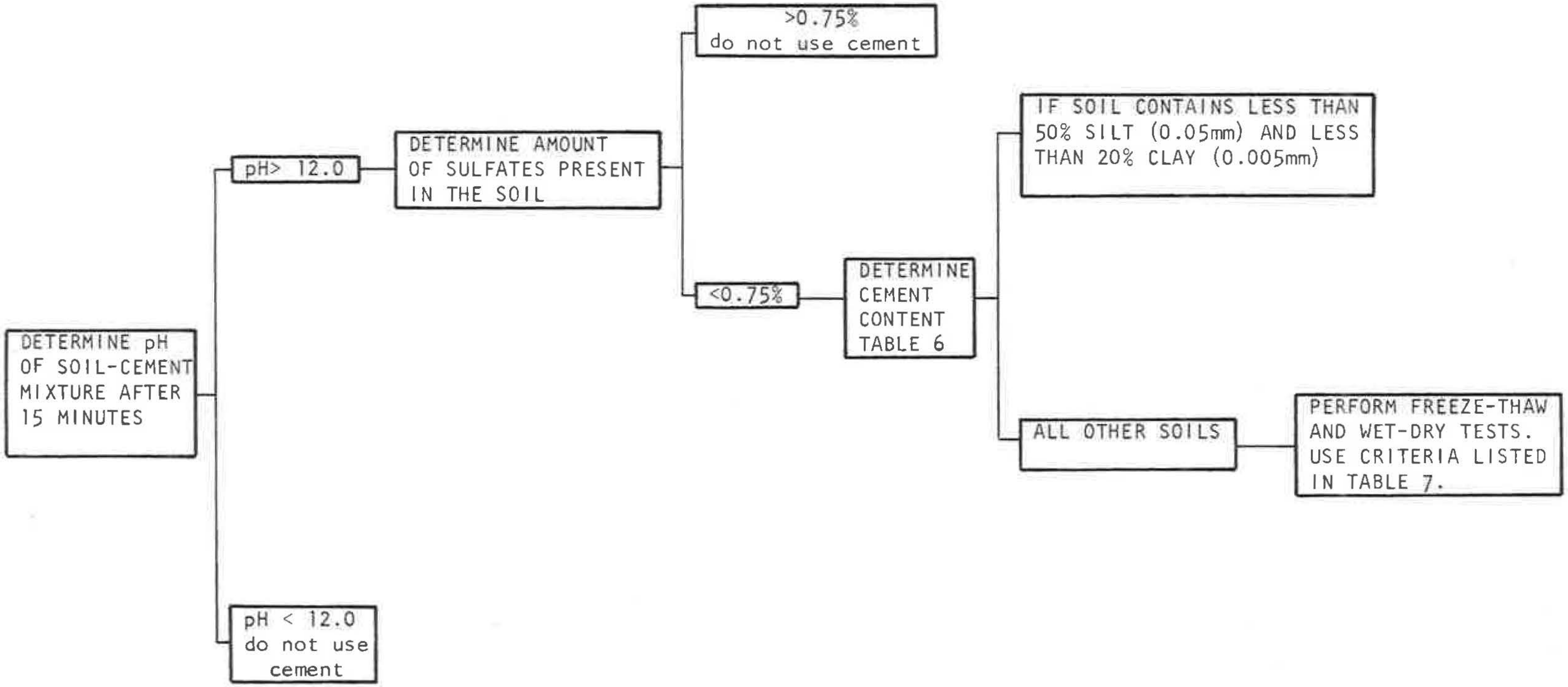


Figure 4. Subsystem for base course stabilization with cement.

TABLE 7

ENGINEERING PROPERTIES OF MATERIALS SUITABLE FOR BITUMINOUS STABILIZATION

Item	Sand-Bitumen	Soil-Bitumen		Sand-Gravel-Bitumen
Gradation (percent passing)				
1½-in. sieve				100
1-in. sieve	100			
¾-in. sieve				60 to 100
No. 4 sieve	50 to 100		50 to 100	35 to 100
No. 10 sieve	40 to 100			
No. 40 sieve			35 to 100	13 to 50
No. 100 sieve				8 to 35
No. 200 sieve	5 to 12	Good	3 to 20	
		Fair	0 to 3 and 20 to 30	0 to 12
		Poor	>30	
Liquid limit		Good	<20	
		Fair	20 to 30	
		Poor	30 to 40	
		Unusable	>40	
Plasticity index	<10	Good	<5	
		Fair	5 to 9	
		Poor	9 to 15	<10
		Unusable	>12 to 15	

Note: Includes slight modifications later made by Herrin (17).

vary from state to state. Marshall method criteria utilized by the armed forces (2) are given in Table 10 (2). The criteria listed for asphaltic-concrete binder course are indicated for use with coarse-graded, hot-mix base courses, while separate criteria are given for sand-asphalt. The Air Force has also indicated that the asphalt content determined by the Marshall method should be altered depending on the pavement temperature index. However, this criterion, which was developed for surface courses, does not appear to be warranted for base courses.

The Asphalt Institute (44) recommends Marshall, Hveem, and Hubbard-Field criteria for use in hot-mix base course design. Specifically, The Asphalt Institute recommends the same criteria that are utilized for surface courses, but with a test temperature of 100 F rather than 140 F. This recommendation applies to regions having climatic conditions similar to those prevailing throughout most of the United States and to bases that are 4 in. or more below the surface.

Zoeph (45) recommends Marshall criteria based on studies conducted in Germany, while McDowell and Smith (46) have recently presented a design procedure based on unconfined compressive strength and air void criteria.

Recently, attempts have been made to develop a more rational approach to pavement design. Among others, Monismith (47) has indicated that elastic and fatigue properties of asphalt-treated base courses should be considered in pavement design. These more rational methods should allow engineers to better assess the engineering behavior of these stabilized materials.

TABLE 8

DETERMINATION OF ASPHALT GRADE FOR BASE COURSE STABILIZATION

Pavement Temperature Index[a]	Asphalt Grade (penetration)
Negative	100 to 120
0 to 40	85 to 100
40 to 100	60 to 70
100 or more	40 to 50

[a] The sum, for a 1-year period, of the increments above 75 F of monthly averages of the daily maximum temperatures. Average daily maximum temperatures for the period of record should be used where 10 or more years of record are available. For records of less than 10-year duration, the record for the hottest year should be used. A negative index results when no monthly average exceeds 75 F. Negative indexes are evaluated merely by subtracting the largest monthly average from 75 F.

TABLE 9

SELECTION OF PRELIMINARY ASPHALT CEMENT CONTENT FOR BASE COURSE CONSTRUCTION

Aggregate Shape and Surface Texture	Asphalt by Weight of Dry Aggregate (percent)
Rounded and smooth	4
Angular and rough	6
Intermediate	5

TABLE 10

CRITERIA OF MARSHALL METHOD FOR DETERMINATION OF OPTIMUM BITUMEN CONTENT

Test Property	Type of Mix	Point on Curve		Criteria	
		For 100-psi Tires[a]	For 200-psi Tires[a]	For 100-psi Tires[a]	For 200-psi Tires[a]
Stability	Asphaltic-concrete surface course	Peak of curve	Peak of curve	500 lb or higher	1,800 lb or higher
	Asphaltic-concrete binder course	Peak of curve[b]	Peak of curve[b]	500 lb or higher	1,800 lb or higher
	Sand asphalt	Peak of curve		500 lb or higher	
Unit weight	Asphaltic-concrete surface course	Peak of curve	Peak of curve	Not used	Not used
	Asphaltic course binder course	Not used	Not used	Not used	Not used
	Sand asphalt	Peak of curve		Not used	Not used
Flow	Asphaltic-concrete surface course	Not used	Not used	20 or less	16 or less
	Asphaltic course binder course	Not used	Not used	20 or less	16 or less
	Sand asphalt	Not used	Not used	20 or less	16 or less
Percentage voids in total mix	Asphaltic-concrete surface course	4 (3)	4 (3)	3 to 5 (2 to 4)	3 to 5 (2 to 4)
	Asphaltic-concrete binder course	5 (4)	6 (5)	4 to 6 (3 to 5)	5 to 7 (4 to 6)
	Sand asphalt	6 (5)	— (-)	5 to 7 (4 to 6)	— (---)
Percentage voids filled with bitumen	Asphaltic-concrete surface course	80 (85)	75 (80)	75 to 85 (80 to 90)	70 to 80 (75 to 85)
	Asphaltic-concrete binder course	70 (75)	60 (65)[b]	65 to 75 (70 to 80)	70 to 80 (55 to 75)
	Sand asphalt	70 (75)	— (--)	65 to 75 (70 to 80)	— (--)

[a] Figures in parentheses are for use with bulk-impregnated specific gravity (water absorption greater than 2.5 percent).

[b] If the inclusion of asphalt contents of these points in the average causes the voids to fall outside the limits, then the optimum asphalt content should be adjusted so that the voids in the total mix are within the limits.

Criteria currently used by the armed forces for binder course utilizing Marshall mix design methods have been suggested for use.

Cutback Asphalts—The U.S. Navy (20) has suggested that the grade of cutback can be selected based on the percentage of the soil passing the No. 200 sieve and the ambient temperature of the soil (Fig. 5). The Air Force (28) and The Asphalt Institute (15) recommendations are rather general in nature.

Several methods are available to the engineer for selecting the quantity of cutback asphalts. The California CKE method could be utilized as could equations developed in Oklahoma (48) and by The Asphalt Institute (15) based on the surface-area concept. The equation recommended by The Asphalt Institute (15) is

$$p = 0.02(a) + 0.07(b) + 0.15(c) + 0.20(d) \qquad (1)$$

where

p = percentage of asphalt material by weight of dry aggregate;
a = percentage of mineral aggregate retained on No. 50 sieve;
b = percentage of mineral aggregate passing No. 50 and retained on No. 100 sieve;
c = percentage of mineral aggregate passing No. 100 and retained on No. 200 sieve; and
d = percentage of mineral aggregate passing No. 200 sieve.

Numerous laboratory tests have been used to determine asphalt contents for cutback and emulsified asphalts. These methods include Hubbard-Field, Hveem stability, Marshall stability, Florida bearing, Iowa bearing, extrusion, unconfined compression, triaxial compression, R-value, and elastic modulus. Mixing methods, curing conditions,

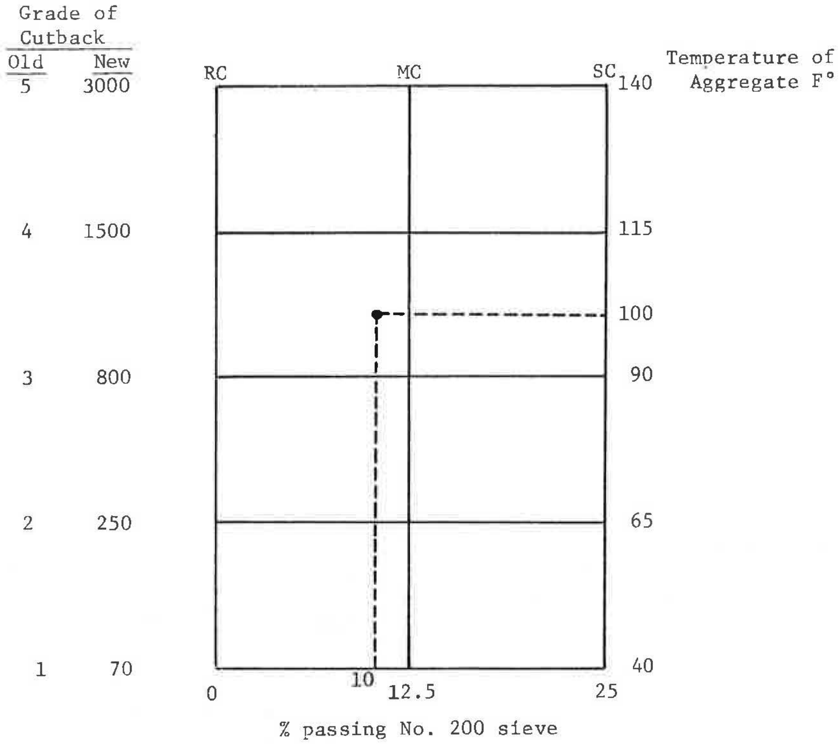
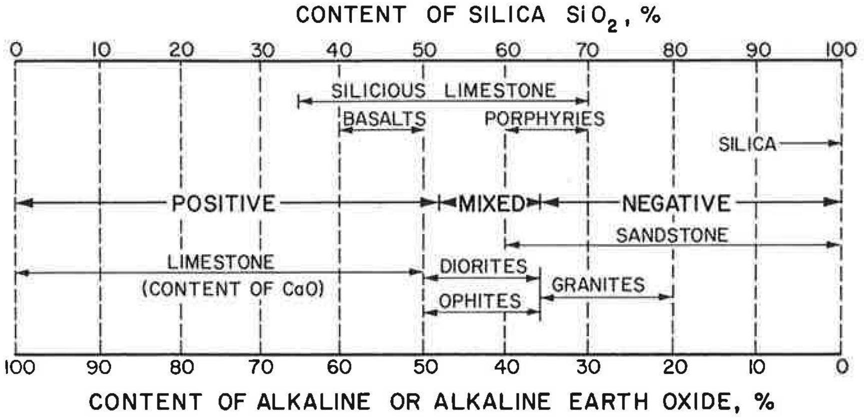


Figure 5. Selection of type of cutback asphalt for stabilization.

rate of loading, and temperature are important variables that must be carefully controlled when these tests are performed.

The Air Force is currently utilizing the extrusion test (28) for mixture design. The unconfined compression test is easy to perform, but sufficient experience to determine adequate criteria for its use is not available.



After Mertens and Wright (52)

Figure 6. Classification of aggregates.

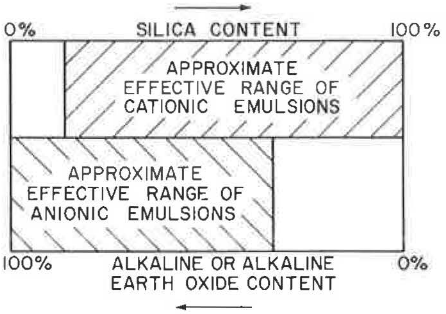
TABLE 11

SELECTION OF TYPE OF EMULSIFIED ASPHALT FOR STABILIZATION

Percent Passing No. 200 Sieve	Relative Water Content of Soil	
	Wet (5 percent or more)	Dry (0 to 5 percent)
0 to 5	SS-1h (or SS-Kh)	SM-K (or SS-1h)[a]
5 to 15	SS-1, SS-1h (or SS-K, SS-Kh)	SM-K (or SS-1h, SS-1)[a]
15 to 25	SS-1 (or SS-K)	SM-K

Note: Determine from Figures 6 and 7 whether an anionic or a cationic emulsion is to be used.

[a] Soil should be prewetted with water before using these types of emulsified asphalts.



After Mertens and Wright (52)

Figure 7. Approximate effective range of cationic and anionic emulsions on various types of aggregates.

It is important to note that not only are strength or stability criteria necessary for the determination of asphalt content but also a durability criterion is recommended by most agencies. Typical examples of durability tests are the immersion-compression test utilized by Winterkorn (13) and by Riley and Blumquist (49) and moisture vapor susceptibility that is utilized by Chevron Asphalt Company (18), The Asphalt Institute (50), and Finn et al. (51).

Emulsified Asphalts—The selection of the grade of emulsion can be conveniently determined from data given in Table 11, prepared by the U.S. Navy (20). Criteria are based on the percentage passing the No. 200 sieve and the relative water content. The selection of either a cationic or an anionic emulsion should be based on the type of aggregate that is used. Mertens and Wright (52) have developed a method by which aggregate can be classified (Fig. 6) to indicate its probable surface charge and the type of emulsion (anionic or cationic) selected to satisfy particular aggregate surface characteristics (Fig. 7).

A preliminary selection of the quantity of emulsion can be obtained from data given in Table 12 (20). Other methods based on surface area concepts have been used by The Asphalt Institute (15) and Bird (53). The final selection of the quantity should be based on laboratory testing of the asphalt-soil mixture. Because the armed forces are equipped to perform Marshall tests, and apparently a better testing method with proven field performance is not available, the Marshall method with criteria suggested by

TABLE 12

EMULSIFIED ASPHALT REQUIREMENT

Percent Passing No. 200 Sieve	Pounds of Emulsified Asphalt per 100 lb or Dry Aggregate When Percentage Passing No. 10 Sieve Is					
	50 or Less	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	7.7
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

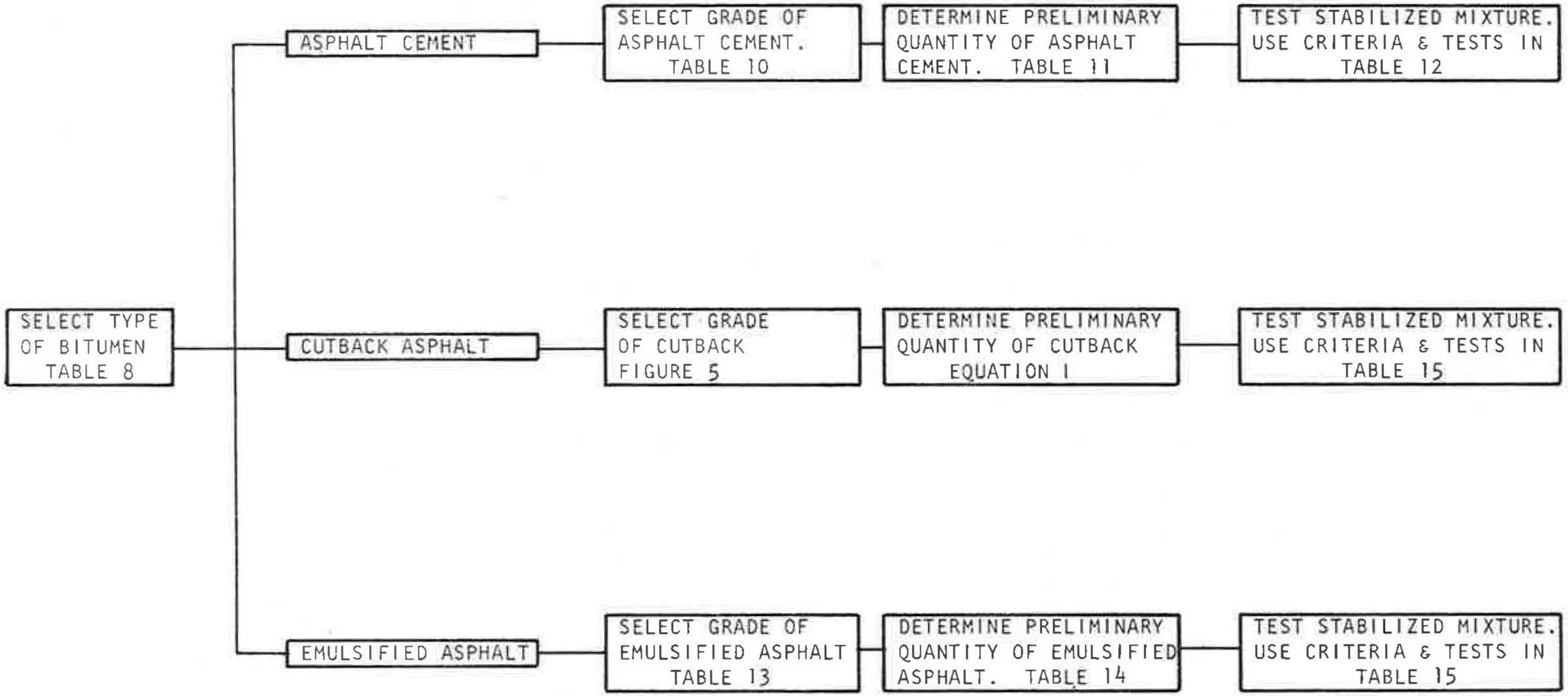


Figure 8. Subsystem for base course stabilization with bituminous materials.

Lefebvre (54) is suggested for use (Table 13). It should be recognized that this test is performed at 77 F.

The design subsystem for bituminous stabilization is shown in Figure 8.

TABLE 13

MARSHALL MIX DESIGN CRITERIA FOR CUTBACK AND EMULSIFIED ASPHALT MIXTURES

Marshall Test	Criteria for a Test Temperature of 77 F	
	Minimum	Maximum
Stability, lb	750	—
Flow, 0.01 in.	7	16
Air voids, percent	3	5

SUMMARY

A system utilizing currently available information has been developed to aid the engineer in the selection of a stabilizer or stabilizers for particular soil types. In addition, design subsystems have been developed to aid the engineer in the selection of the quantity of stabilizer for particular applications.

Many of the criteria utilized are based on observations and experience gained in constructing highway pavements. Because the Air Force is primarily concerned with airfield construction, validation or adjustment of these criteria may be necessary.

Equipment and environmental factors have not been included in the detail desired. In particular, field durability of the stabilized mixture is not well documented and, thus, suitable test methods are not always available to evaluate this important factor.

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