ESL-TR-86-19

SOIL STABILIZATION FOR ROADWAYS AND AIRFIELDS

D.N. LITTLE, M.R. THOMPSON, R.L. TERRELL,
J.A. EPPS, E.J. BARENBERG

DALLAS N. LITTLE & ASSOCIATES
2801 BRIAR GROVE
BRYAN TX 77801

JULY 1987

FINAL REPORT

JUNE 1981 - JULY 1982

AFESC

ENGINEERING & SERVICES LABORATORY
AIR FORCE ENGINEERING & SERVICES CENTER
TYNDALL AIR FORCE BASE, FLORIDA 32403

87

A183382

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT APPROVED FOR PUBLIC RELEASE DISTRIBUTION UNLIMITED
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S) ESL-TR-86-19
6a. NAME OF PERFORMING ORGANIZATION Dallas N. Little & Associates 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Air Force Engineering and Services Center RDCP
6c. ADDRESS (City, State, and ZIP Code) 2801 Briar Grove Bryan TX 77801	7b. ADDRESS (City, State, and ZIP Code) HQ AFESC/RDCP Tyndall AFB FL 32403-6001
8a. NAME OF FUNDING/SPONSORING ORGANIZATION AFESC 8b. OFFICE SYMBOL (If applicable) DEMP	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER Form 9 F5ESCG10690001
8c. ADDRESS (City, State, and ZIP Code) HQ AFESC/DEMP Tyndall AFB FL 32403-6001	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Soil Stabilization For Roadways and Airfields

12. PERSONAL AUTHOR(S)
Dallas N. Little, Marshal R. Thompson, Ronald L. Terrell, Jon A. Epps, Ernest J. Barenberg

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 6/17/81 TO 7/1/82	July 1987	340

16. SUPPLEMENTARY NOTATION
Availability of this report is specified on reverse of front cover

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Soil Stabilization, Lime Stabilization, Cement Stabilization, Asphalt Stabilization, Fly Ash
13	02		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report provides fundamental concepts of chemical soil stabilization so that a user might evaluate soil stabilization as a pavement construction alternative, determine the type and quantity of stabilizer required and direct the construction of stabilized pavement layers. The methods covered include stabilization of roadway and airfield systems with time, cement, asphalt, fly ash and combination stabilizers. Keywords: roads, roadways

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☒ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Charles E. Bailey	22b. TELEPHONE (Include Area Code) (904) 283-6318 22c. OFFICE SYMBOL HQ AFESC/RDCP

DD FORM 1473, 84 MAR
83 APR edition may be used until exhausted
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

(The reverse of this page is blank.)

PREFACE

This final report was prepared by Dr. Dallas Little, 2801 Briar Grove, Bryan, Texas 77801, under Contract F08637-81-C-0039 for the Engineering Research Division, Engineering and Services Laboratory, Headquarters Air Force Engineering and Services Center (AFESC), Tyndall Air Force Base, Florida 32403-6001.

This report summarizes the work performed from 17 June 1981 through 1 July 1982. It was originally intended for publication as an Air Force manual. This accounts for stylistic and format differences from our standard technical reports. It is being published as a technical report because of its usability to the worldwide scientific and engineering community. AFESC/RDCP project officers were James Murfee and Charles Bailey.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Services (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

Charles E. Bailey

CHARLES E. BAILEY
Project Officer

Robert R. Costigan

ROBERT R. COSTIGAN, Lt Col, USAF
Chief, Engineering Research Division

George E. Walrond

GEORGE E. WALROND, Maj, USAF
Chief, Pavement Technology Branch

Lawrence D. Hokanson

LAWRENCE D. HOKANSON, Lt Col, USAF
Director, Engineering and Services Laboratory

(The reverse of this page is blank)

TABLE OF CONTENTS

Section	Title	Page
I	INTRODUCTION	1
	A. Purpose	1
	B. Scope	1
	C. Using the Manual	2
	D. Advantages of Stabilization	11
	E. Pavement Improvement Considerations	11
	F. Types of Stabilization	12
	G. Definitions	13
II	STABILIZER SELECTION	16
	A. General	16
	B. Basic Criteria	16
	C. Selecting Best Stabilizer	18
III	LIME STABILIZATION	21
	A. General	21
	B. Soil-Lime Reactions	22
	C. Properties and Characteristics of Soil-Lime Mixtures	24
	D. Selection of Lime Content	38
	E. Additional Information	43
IV	CEMENT STABILIZATION	45
	A. Types and Properties of Cement	45
	B. Soil-Cement Reactions	45
	C. Soils Suitable for Cement Stabilization	46
	D. Typical Properties of Cement-Stabilized Soils	47
	E. Selection of Cement Content	57
	F. Additional Information	72
V	ASPHALT STABILIZATION	73
	A. General	73
	B. Related Material	73
	C. Types of Asphalts	74
	D. Mechanisms of Asphalt Stabilization	77
	E. Soils Suitable for Asphalt Stabilization	78
	F. Typical Properties of Asphalt Stabilized Soils	81

Section	Title	Page
	G. Selection of Asphalt Type and Asphalt Content	86
	H. Safety Precautions, Limitations of Use and Environmental Considerations.	106
VI	LIME FLY ASH AGGREGATE STABILIZATION.	108
	A. General	108
	B. Related Material.	108
	C. Constituents of Lime-Fly Ash-Aggregate Mixtures.	108
	D. Pozzolanic Reaction	111
	E. Engineering Properties of LFA Mixtures.	115
	F. Special Field Considerations.	119
	G. Mixture Design.	120
VII	COMBINATION STABILIZERS	127
	A. Introduction.	127
	B. Combination Stabilizer Reactions.	127
	C. Selection of Stabilizer	130
	D. Approximate Quantities.	130
	E. Detailed Testing.	132
	F. Criteria for Evaluation	135
	G. Climatic and/or Construction Limitations	136
VIII	THICKNESS DESIGN OF STABILIZED LAYERS	138
	A. Purpose	138
	B. Related Criteria.	138
	C. Airfield Thickness Design Using Stabilized Layers	139
	D. Roadway Thickness Design Using Stabilized Layers	148
IX	CONSTRUCTION TECHNIQUES	155
	A. Objectives.	155
	B. Related Material.	155
	C. Mixed-In-Place Operations	158
	D. Central Plant Mixing Operations	178
	E. Climatic Limitations.	185
X	QUALITY CONTROL	189
	A. Purpose	189
	B. Related Material.	189
	C. Scope	190
	D. Soil-Lime	190

Section	Title	Page
	E. Soil-Lime Fly Ash	192
	F. Soil Cement	192
	G. Soil-Asphalt	194
	H. Useful Tests	196
	I. Statistical Quality Control	197
	J. Factors to Consider in Statistical Quality Control	198
	K. Random Sampling Plans*	201
XI	GUIDE SPECIFICATIONS	208
	A. General	208
	B. Important Factors	208
XII	EXAMPLE PROBLEMS	210
	A. General	210
	B. Example 1	210
	C. Example 2	212
	D. Example 3	212
	E. Example 4	214
	F. Example 5	214
	G. Example 6	217
	H. Example 7	217
	REFERENCES	221
	A. Literature Cited	221
	B. ASTM Bibliography	225
	C. AASHTO Methods and Test Cited	227
	D. Military Standards Cited	227
	E. Air Force Manuals Cited	228
APPENDIX		
A	GUIDE SPECIFICATIONS	229
	SECTION I - Lime Treatment for Materials In-Place	229
	SECTION II - Typical Specifications for Lime Fly Ash--Aggregate Base/Subbase Courses[1]	236
	SECTION III - Typical Specification for Road-Mixed Asphalt for Base and Surface Courses[1]	247
	SECTION IV - Typical Specification for Travel Plant Mix Bitumuls Base Treatment[1]	254

Section	Title	Page
	SECTION V - Suggested Specification for Soil-Cement Base Course.	268
B	COST AND ECONOMIC ANALYSIS.	275
C	SPECIAL TESTS	301
	SECTION I - Compressive Strength of Molded Soil-Lime Cylinders	301
	SECTION II - Soil-Lime pH Test	304
	SECTION III - pH Test on Soil-Cement Mixtures.	306
	SECTION IV - Determination of Sulfate in Soils (Gravimetric Method). . . .	308
	SECTION V - Determination of Sulfate in Soils Turbidimetric Method. . . .	310
	SECTION VI - Emulsified Asphalt Mix Design - Illinois Method	314

LIST OF TABLES

Table	Title	Page
1	Climatic Limitations and Construction Safety Precautions (After Ref. 1)	20
2	Atterberg Limits for Natural and Lime-Treated Soils	25
3	CBR Values for Natural and Lime-Treated Soils	28
4	Compressive Strength Data for Natural and Lime-Treated Soils	32
5	Cured Strength Requirements for Soil-Lime Structural Layers	43
6	Summary of the Properties of Cement-Stabilized Soil (Modified from Ref. 1)	56
7	Cement Requirements for Various Soils (After Ref. 5)	58
8	Criteria for Soil-Cement as Indicated by Wet-Dry and Freeze-Thaw Durability Tests (After Ref. 5)	64
9	Asphalt Specifications	75
10	Engineering Properties of Materials Suitable for Bituminous Stabilization (After Herrin, Ref. 11)	79
11	Aggregate Gradations for Asphalt Concrete Pavements (After Ref. 1)	80
12	Design Methods and Criteria for Asphalt-Stabilized Base Courses (After Ref. 14)	83
13	Selection of a Suitable Type of Asphalt for Soil Stabilization Purposes (After Ref. 14)	90
14	Recommendations for Selection of Paving Asphalt	92
15	Selection of Emulsified Asphalt Type (After Ref. 10)	95
16	Selection of Asphalt Cement Content	97

Table		Page
17	Determination of Quantity of Cutback Asphalt (After Ref. 8)	97
18	Emulsified Asphalt Requirement (After Ref. 15)	98
19	Criteria for Determining Optimum Bitumen Content and Adequacy of Mix for Use with Aggregate Showing Water Absorption of Two and One-Half Percent or Less[1]	101
20	Minimum Percent Voids in Mineral Aggregate (VMA) for Bituminous Concrete Mixes - Navy Airfields	102
21	Suggested Criteria for Cutback Asphalt Mixes (After Ref. 8)	102
22	Marshall Design Criteria for Paving Mixtures Containing Cutback Asphalt (After Ref. 8)	103
23	Minimum Percent Voids in Mineral Aggregate (After Ref. 8)	104
24	Emulsified Asphalt-Aggregate Mixture Design Criteria (After Ref. 8)	105
25	Cessation Requirements (After Ref. 12)*	107
26	Approximate Elastic Parameter Values for Stabilized Pavement Materials (After Ref. 1)	141
27	Minimum Requirement for Stabilized Materials in Order to Apply Thickness Reduction Factors	143
28	Stabilized Layer Thickness Reduction Factors	144
29	Equipment Typically Associated with Mixed-In-Place Subgrade Stabilization Operations (After Ref. 1)	188
30	Areas Under the Normal Curve From K_α to ∞	202
31	Random Number for General Sampling Procedure	206

LIST OF FIGURES

Figure		Page
1	Use of Manual Flowchart - Stabilizer Selection.	3
2	Use of Manual Flowchart - Mixture Design.	4
3	Use of Manual Flowchart - Layer Thickness Design.	5
4	Use of Manual Flowchart - Construction Sequences	6
5	Use of Manual Flowchart - Quality Control and Specifications.	7
6	Use of Manual Flowchart - Inspection and Quality Control	8
7	Use of Manual Flowchart - Construction Techniques.	9
8	Use of Manual Flowchart - Economic Considerations.	10
9	Selection of Stabilizers.	19
10	Moisture-Density Relations for a Natural and Five Percent Lime-Treated CL Soil (AASHTO T-99 Compaction) (After Ref. 1)	27
11	CBR-Moisture Content Relations for Natural and Lime Treated (3%, 5%) CL Soil (AASHTO T-99 Compaction) (After Ref. 1)	29
12	Immediate Effects (No Curing) of Lime Treatment on Resilient Modulus	30
13	Compressive Stress-Strain Relations for Cured Soil-Lime Mixtures (Goose Lake Clay Plus Four Percent Lime; Curing Temperature of 73^{o}F, After Suddath and Thompson, Ref. 2)	34
14	Flexural Modulus - Flexural Strength Relationships for Cured Soil-Lime Mixture (Goose Lake Clay Plus Four Percent Lime, After Suddath and Thompson, Ref. 2)	36

Figure		Page
15	Flow Diagram for Soil-Lime Mixture Design.	44
16	Relation Between Cement Content and Unconfined Compressive Strength for Soil Cement Mixtures (After Ref. 1). (Equations give Strength in psi).	49
17	Failure Envelope for Cement-Treated Soils (After Raad, Monismith and Mitchell, Ref. 4)...........................	51
18	The Relation Between CBR and the Unconfined Compressive Strength of Soil Cement Mixtures (After Ref. 1)	52
19	Suggested Fatigue Failure Criteria for Cement Treated Soils (After Raad, Monismith and Mitchell, Ref. 4)..................	55
20	Subsystem for Nonexpedient Base Course Stabilization with Cement	59
21	Average Maximum Densities of the Minus No. 4 Fraction of Soil-Cement Mixtures (Reproduced with Permission of the Portland Cement Association, After Ref. 5). . .	66
22	Indicated Cement Contents of Soil-Cement Mixtures Not Containing Material Retained on the No. 4 Sieve (Reproduced with Permission of the Portland Cement Association, After Ref. 5).	67
23	Minimum 7-Day Compressive Strengths Required for Soil-Cement Not Containing Material Retained on the No. 4 Sieve (Reproduced with Permission of the Portland Cement Association, After Ref. 5). . .	67
24	Average Maximum Densities of Soil-Cement Mixtures Containing Material Retained on the No. 4 Sieve (Reproduced with Permission of the Portland Cement Asssociation, (After Ref. 5)	69
25	Indicated Cement Contents of Soil-Cement Mixtures Containing Material Retained on No. 4 Sieve (Reproduced with Permission of the Portland Cement Association, After Ref. 5)	70

Figure		Page

Figure		Page
26	Minimum 7-Day Compressive Strengths Required for Soil-Cement Mixtures Containing Material Retained on No. 4 Sieve (Reproduced with Permission of the Portland Cement Association, After Ref. 5).	71
27	Fatigue Criteria for Asphalt and Emulsion Mixes (After Santucci, Ref. 12).	84
28	Fatigue Criteria for Cement-Modified Asphalt Emulsion Mixes (After Santucci, Ref. 12).	85
29	Asphalt Concrete as a Function of Temperature and Time of Loading	86
30	Development of Resilient Modulus for a Cationic Medium Setting Emulsion Mixture at $68^{o}F$ (After Terrel and Wang, Ref. 13).	88
31	Subsystem for Expedient Base Course Stabilization with Bituminous Materials. Selection of Type, Grade and Quantity of Asphalt for Stabilization Purposes.	91
32	Selection of Type of Cutback for Stabilization (After Ref. 15)	93
33	Classification of Aggregates (After Mertens and Wright, Ref. 16).	94
34	Approximate Effect Range of Cationic and Anionic Emulsions on Various Types of Aggregates (After Mertens and Wright,Ref. 16).	94
35	Asphalt Paving Mix Design - Typical Mix	99
36	Relationship of Compressive Strength to Mixing Time for 72.1 Percent Slag, 24.0 Percent Fly Ash and 3.9 Percent Lime Mixture.	113
37	Degree Day Versus Compressive Strength Curves for Three Lime-Fly Ash-Aggregate Mixtures.	114

Figure		Page
38	Age Strength Relationships of Lime-Fly Ash-Aggregate Mixtures from Field Cores (After Ref. 1).	114
39	Relationship Between Maximum Stress Level and Logarithm of Number of Cycles to Fracture (Zero Minimum Stress Level) (After Ref. 1)	118
40	Effects of Relative Density on the Strength of an LFA Mixture.	121
41	Effect of Lime and Curing Conditions on the Compressive Strength of Lime-Fly Ash-Aggregate Mixtures.	123
42	Effect of Fly Ash Fineness on Compressive Strength.	124
43	Mixture Design Flow Diagram	125
44	Resilient Modulus Increases with Curing Time for Asphalt Emulsion Mixtures Containing Portland Cement Cured at 75°F (After Ref. 1).	129
45	Selection of Combination Stabilizers (After Ref. 1).	131
46	Relationship Between Vacuum Saturation Strength and 5-Cycle Freeze-Thaw Strength (All Data Adjusted to Equivalent L/D = 2. See ASTM C42) (After Ref. 1).	133
47	Effect of Subbase Thickness on Modulus of Subgrade Reaction (a) Nontreated and (b) Cement-Treated (After Ref. 19)...........	145
48	Changes in Pavement Stiffness Due to Base Course (After Ref. 19)...........	146
49	Equivalency Factors for Soils Stabilized with Cement, Lime or Cement and Lime Mixed with Fly Ash (Same as Figure 4, AFM 88-7, Chapter 3).	151
50	Soil Stabilization Construction Equipment	156
51	Hopper-Type Pugmill Travel Plant (After Ref. 7).	159

Figure		Page
52	Windrow-Type Pugmill Travel Plant (After Ref. 7).	159
53	Single Transverse Shaft Rotary Mixer (Flat Type)	160
54	Multiple Transverse Shaft Rotary Mixer (Flat Type)	160
55	Single Transverse Shaft Rotary Mixer.	161
56	Mixing with Motor Grader.	161
57	Scarification of Clay Subgrade with Disc Harrow (After Ref. 26)	163
58	Scarification with Motor Grader (After Ref. 26).	163
59	Bagged Lime Application	164
60	Spreading Bulk Lime from Pneumatic Tanker Truck Through Cyclone Spreader.	164
61	Mechanical Cement Spreaders (Must be Operated at Slow Speed to Provide Uniform Application).	165
62	Transit Mixing of Lime Slurry on City Street Project, Using Recirculating Pump at Rear. Pressure and Gravity Spray Bars Distribute Lime Evenly	167
63	Rotary Mixer Used for Simultaneous Mixing of Lime and Water in Clay Subgrade Soil (After Ref. 26)	167
64	Distributor Applying Asphalt (After Ref. 7)	168
65	Single Shaft Rotary Mixer with Asphalt Supply Tank (After Ref. 7).	168
66	Initial Compaction of Lime-Soil Mixture with Sheepsfoot Roller (After Ref. 7)	172
67	Pneumatic Tired Roller.	172
68	Steel-Wheel Tandem Roller (After Ref. 7).	173

Figure		Page

69 Flat Three-Wheel Roller Used for Final Compaction of Lime-Treated Base (After Ref. 26) 173

70 Sprinkling Lime-Treated Subgrade on Military Runway (After Ref. 7). 175

71 Membrane Curing with Asphalt. 175

72 Windrow Sizer (After Ref. 7). 177

73 Windrow-Type Mechanical Spreader Used to Place Cement on Top of Windrow of Soil (After Ref. 29) 179

74 Towed-Type Spreader (After Ref. 7). 182

75 Placing Lime-Fly Ash-Gravel Mixtures with Shoulder Base Spreader 182

76 Spreading Cold Mix with Conventional Mixer (After Ref. 7). 183

SECTION I

INTRODUCTION TO SOIL STABILIZATION

A. PURPOSE

This manual provides the fundamental concepts of chemical soil stabilization so that the user may:

1. Evaluate soil stabilization as a pavement construction alternative,

2. Determine the type and quantity of stabilizer required for a particular soil used as a subgrade, subbase or base layer,

3. Determine the required thickness of the stabilized layer in the pavement system,

4. Construct stabilized pavement layers or direct their construction, and

5. Inspect and control the quality of stabilized pavement layers.

B. SCOPE

This chapter is limited to the stabilization of soil and aggregate systems with additives or stabilizers in both airfield and roadway systems. Specifically, lime, cement, lime-fly ash, asphalt and combinations of these stabilizers will be discussed. Mechanical stabilization is treated only insofar as it applies to stabilization with the use of additives. The reader will be provided the information to:

1. Select the proper stabilizer,

2. Design a stabilized soil mix to provide strength and durability,

3. Design the thickness of the stabilized layer or layers as part of a structural pavement system,

4. Identify construction sequences and methods for soil stabilization operations,

5. Prepare specifications for soil stabilization operations and

6. Prepare quality control methods for soil stabilization operations.

C. USING THE MANUAL

The Purpose and Scope of this manual as discussed in paragraphs A and B span a wide range of objectives. The successful accomplishment of each individual objective is vital to the success of the end product - a functional stabilized soil or aggregate pavement layer. The readers of this manual are varied in background but, are bound by the objective of producing a successful product.

1. The Reader

The users of this manual may fall into any of the following categories:

a. Operations and Maintenance Engineering Officer,

b. Design Engineering Officer,

c. Construction Management Inspector,

d. Engineering Planner or Programmer,

e. Laboratory Engineering Technician or

f. Construction Specialist.

2. Reader's Objective

The specific objective of each reader will be to gather the information necessary to perform his task and to properly sequence this task. This paragraph is a guide to the reader. Figures 1 through 8 are flow diagrams which explain how the manual can be most effectively used to fulfill a specific reader objective. Of course, the reader's objective may combine two or more of the objectives described herein.

3. Intent of Manual

This manual provides a comprehensive treatment of soil stabilization. To include lime, cement, asphalt, fly ash and combination stabilizers. However, like all manuals, it cannot function as a comprehensive reference on supplementary topics such as thickness design, construction techniques, quality control, cost and economic analysis, etc.

The paragraphs explaining related material in the sections supplementary are referenced throughout the text and will aid the reader. Air Force and Department of Defense Manuals, Regulations and Standards are used where even possible.

Objective: Select Proper Stabilizer.

Typical Reader: Operations and Maintenance Engineering Officer, Design Engineering Officer, Laboratory Engineering Technician, Engineering Planner or Programmer.

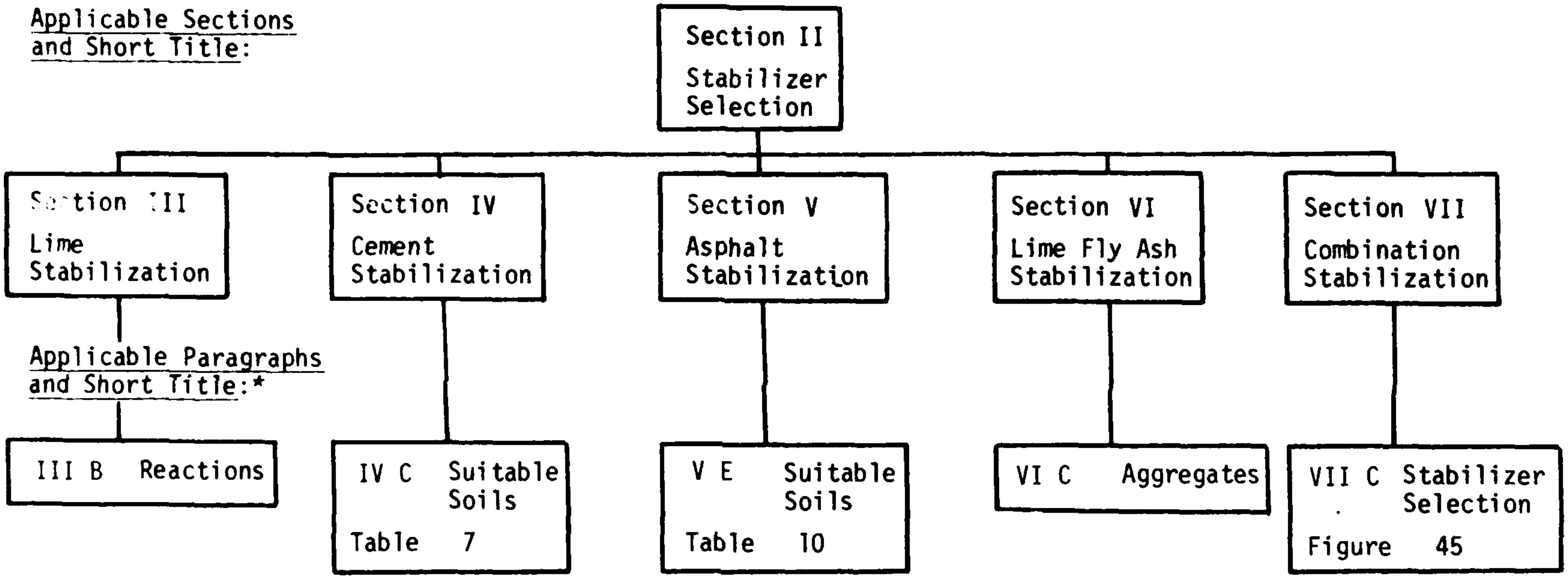


Figure 1. Use of Manual Flowchart - Stabilizer Selection.

*Although Section B alone may be adequate to select the proper stabilizer, a review of soil and/or aggregate requirements in the paragraphs outlined above is recommended.

Objective: Design a Stabilized Soil Mixture to Provide Strength and Durability.

Typical Reader: Laboratory Technician, Design Engineering Officer.

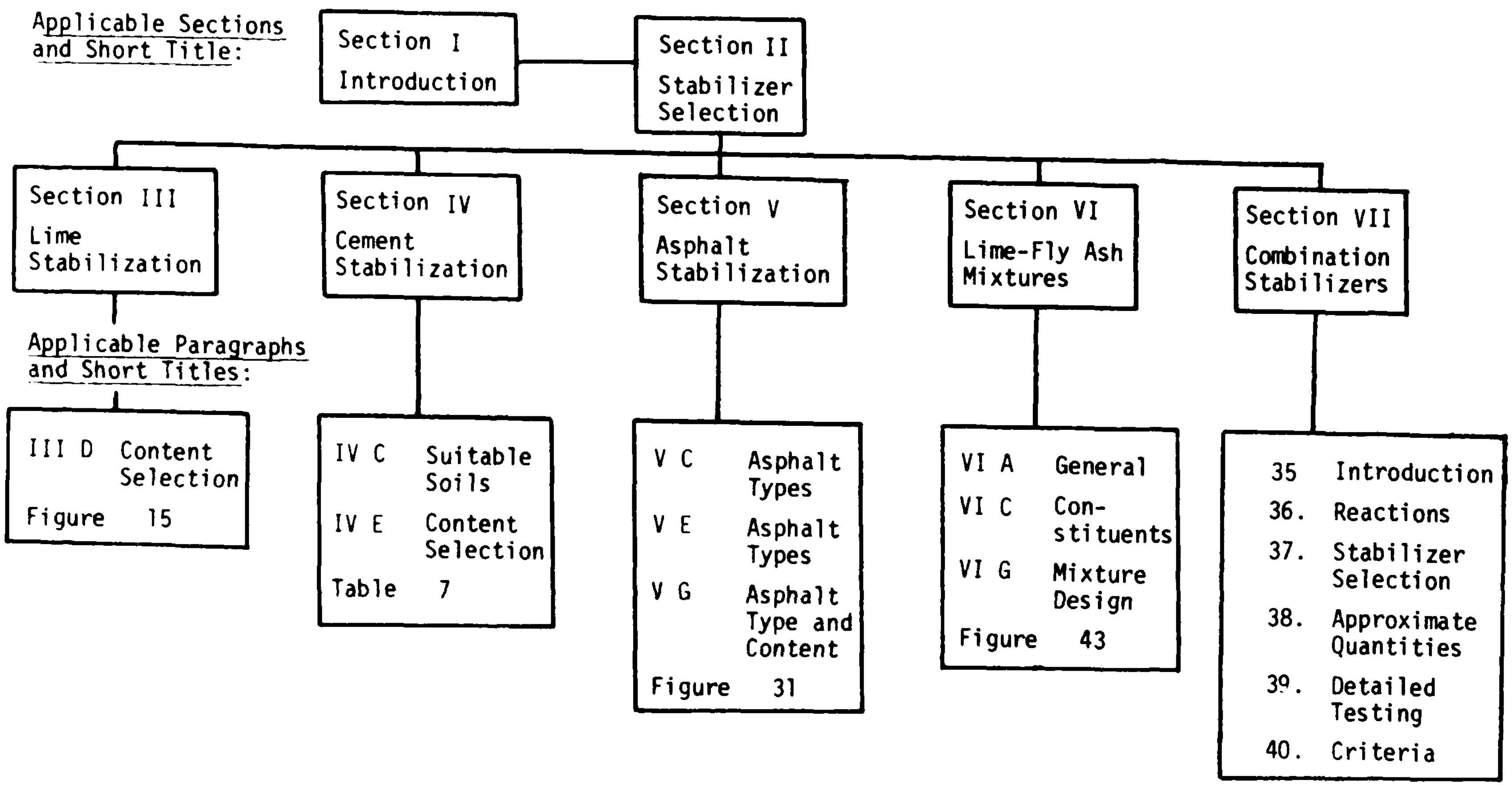


Figure 2. Use of *Manual Flowchart - Mixture Design*.

Objective: Design Thickness of Stabilized Layers as Part of Structural Pavement System.

Typical Reader: Design Engineering Officer

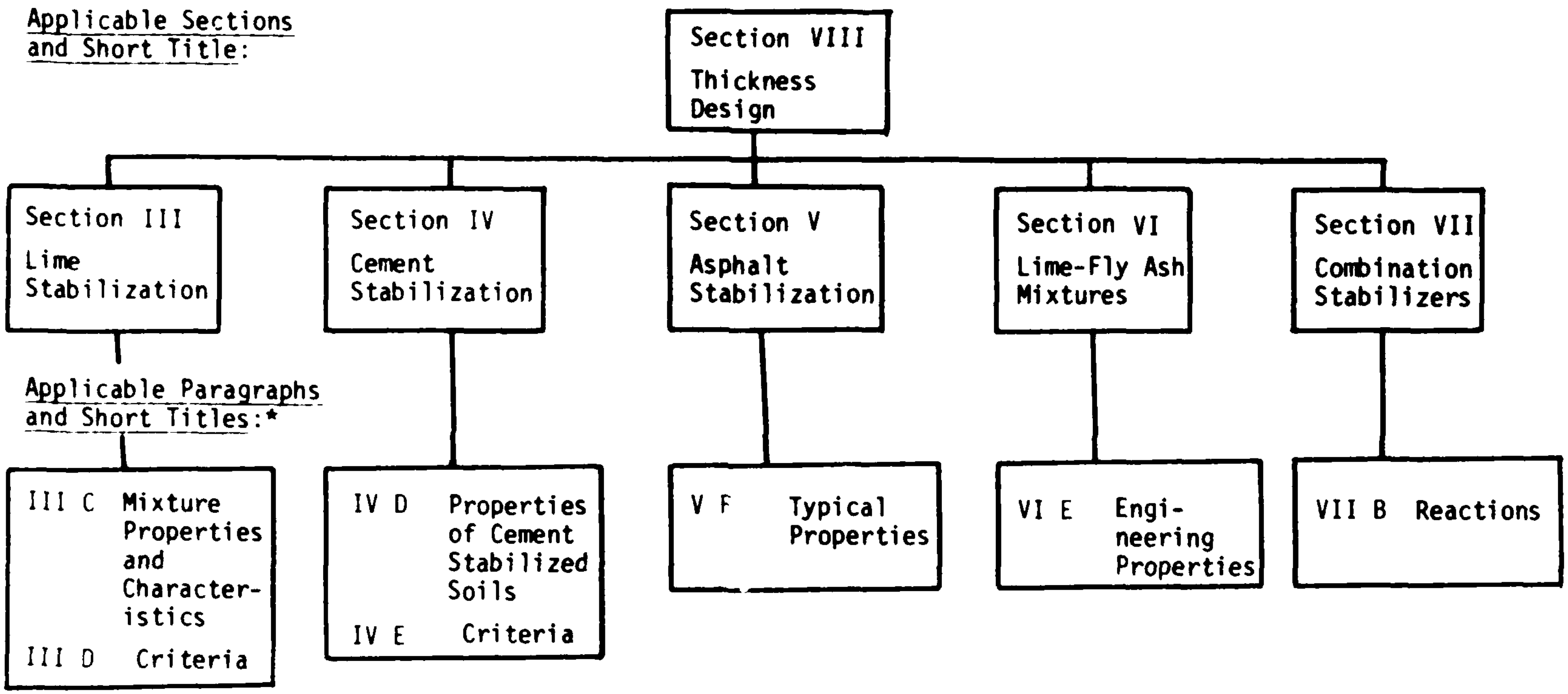


Figure 3. Use of Manual Flowchart - Layer Thickness Design.

*These applicable paragraphs explain material properties of stabilized materials which may be of use to pavement design engineers in predicting pavement performance and performing economic evaluations.

Objective: Identify Construction Sequences and Methods for Soil Stabilization Operations.

Typical Reader: Construction Management Inspector, Construction Specialist, Design Engineering Officer.

Applicable Sections and Short Title:

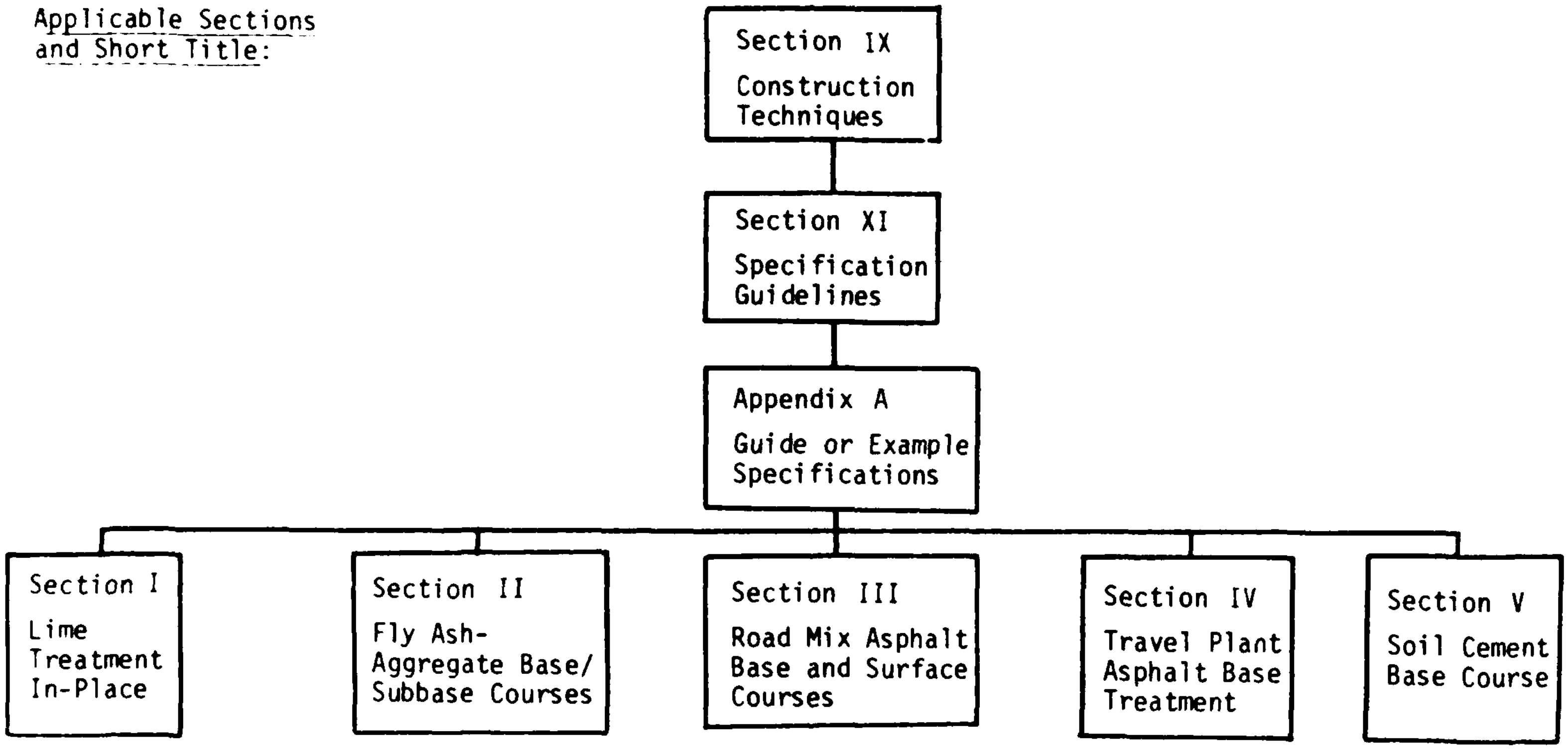


Figure 4. Use of Manual Flowchart - Construction Sequences.

Objective: Prepare Specifications or Quality Control Methods for Soil Stabilization Operations.

Typical Readers: Construction Management Inspector, Design Engineering Officer.

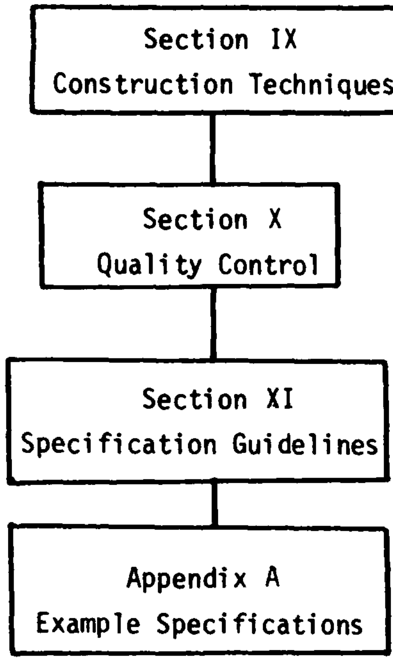


Figure 5. Use of Manual Flowchart - Quality Control and Specifications.

Objective: Inspect and Control the Quality of Stabilized Pavement Layers.

Typical Reader: Construction Management Inspector, Operations and Maintenance Engineering Officer.

Applicable Sections
and Short Title:

Applicable Paragraphs
and Short Title:

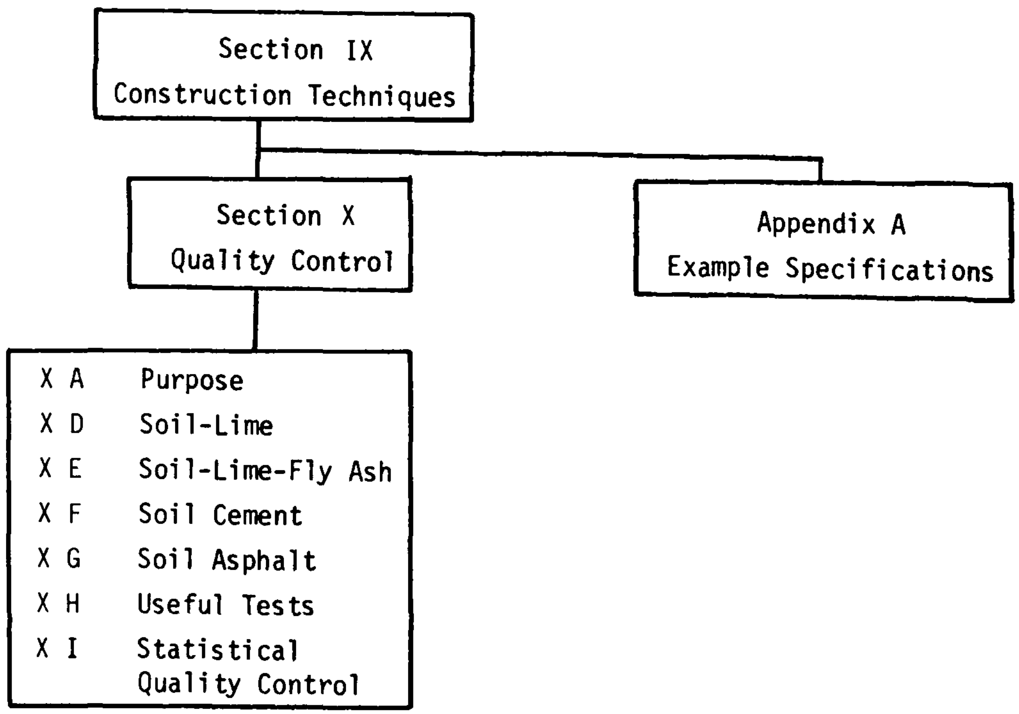


Figure 6. Use of Manual Flowchart - Inspection and Quality Control.

Objective: Construct Stabilized Pavement Layers.

Typical Reader: Construction Specialists (Superintendent).

Applicable Sections and Short Title:

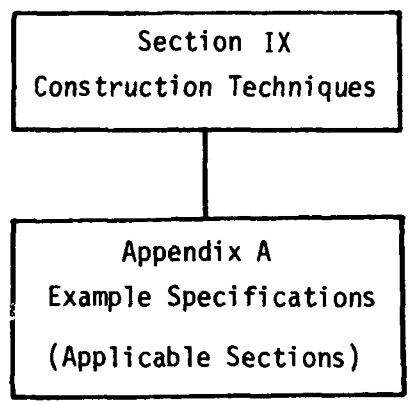


Figure 7. Use of Manual Flowchart - Construction Techniques.

Objective: Compare the Economy of Soil and/or Aggregate Stabilization with Other Structural Pavement Alternatives.

Typical Reader: Design Engineering Officer.

Applicable Sections and Short Title:

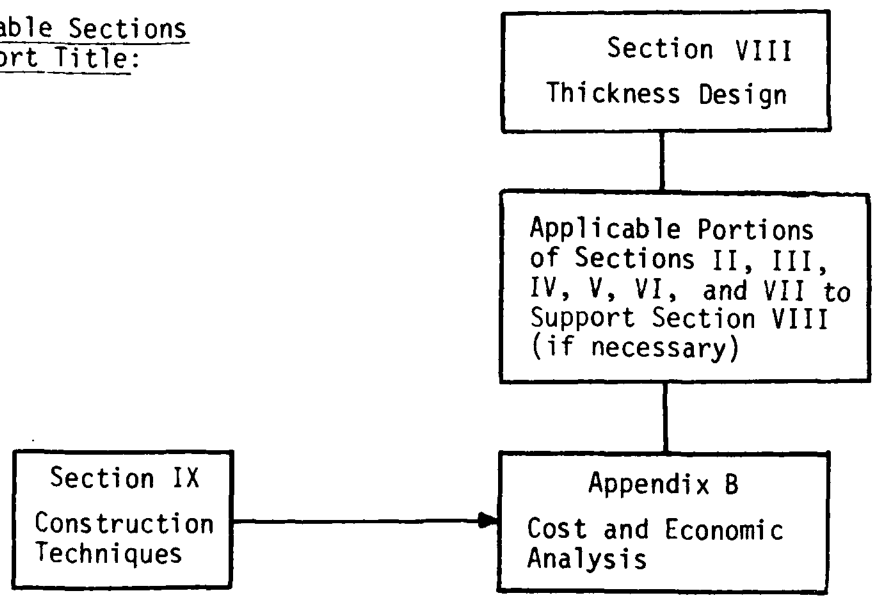


Figure 8. Use of Manual Flowchart - Economic Considerations.

D. ADVANTAGES OF STABILIZATION

Soil stabilization may be used to provide the following engineering advantages.

1. Functions as a working platform (construction expediency),
2. Reduces dusting,
3. Waterproofs the soil,
4. Upgrades marginal aggregates or soils,
5. Improves strength,
6. Improves durability,
7. Controls volume changes of soils,
8. Improves soil workability,
9. Dries wet soils,
10. Reduces pavement thickness requirements,
11. Conserves aggregates,
12. Reduces construction and haul costs,
13. Conserves energy and
14. Provides a temporary or permanent wearing surface.

E. PAVEMENT IMPROVEMENT CONSIDERATIONS

The decision criteria for use of stabilized soils in a pavement system should include consideration of the following (see Section VIII for pavement design considerations):

1. The pavement should limit subgrade stresses and deflections to preclude rutting and plastic deformation,

2. The structure should provide necessary support to the wearing course to limit transient deflections and retard fatigue cracking,

3. A working platform must often be provided to expedite construction. (An example of the function is the use of lime to provide a firm, dry surface for construction in areas of excessively wet natural subgrades. This technique proved successful in the Mekong Delta and at Dallas-Fort Worth Regional Airport.), and

4. An impermeable base course which would prevent moisture changes in the subgrade may be desirable. (However, if a high degree of saturation is attained in an unbound base or subbase course, it should be sufficiently permeable to prevent excess pore pressure buildup under repeated wheel loadings. This could lead to loss of stability.)

F. TYPES OF STABILIZATION:

1. Mechanical

The most common and normally least expensive method of stabilization is mechanical. Compaction is one type of mechanical stabilization which increases the soil or aggregate shear strength by moving the particles close together under load and/or vibration at favorable soil moisture contents. The advantages of mechanical stabilization are limited by the amount of particle interlocking that can be achieved. Generally, the soil strength is increased by increasing the angle of internal friction without affecting the cohesion.

2. Blending

The second type of mechanical stabilization involves blending of aggregates, binder or combinations of both with local material to improve engineering strength and durability properties. The addition of fine-grained binder will fill voids and increase shear strength. However, too much binder will decrease permeability. This can cause weakening or softening of the pavement layer involved due to a buildup in pore pressures when saturated and lead to loss of fines through pumping. This results in strength loss and pavement deterioration.

3. Additive

This is the altering of soil properties by using chemical additives which can change the surface molecular properties of the soil grain and in some cases cement the grains together. In this chapter, additive stabilization refers to stabilization with lime, cement, lime-fly ash, asphalt and any combination of these stabilizers. In the cases of lime, cement and lime-fly ash, an actual chemical reaction may occur between the binder and the soil in the presence of water resulting in increased shear strength by a cementing action. Asphalt, on the other hand, coats the individual grains, protecting them from the environment, and binds them together, increasing stength through added cohesion. Determination of the percentages of additives depends on the soil classification and degree of improvement desired. Generally, smaller amounts of additives are required when it is simply desired to alter soil gradation, plasticity, workability, etc., than when it is desired to improve the strength and durability sufficiently to permit pavement thickness reduction.

G. DEFINITIONS

1. General Definitions

a. Soil (Earth). Sediments or other unconsolidated accumulations of solid particles produced by the physical and chemical disintegration of rocks, and which may or may not contain organic matter (ASTM D-18).

b. Soil Stabilization. Chemical or mechanical treatment designed to increase or maintain the stability of a mass of soil or otherwise to improve its engineering properties (ASTM D-136).

c. Chemical Stabilization. The altering of soil properties by use of certain chemical additives which, when mixed into a soil, often change the surface molecular properties of the soil grains and sometimes cement the grains together resulting in strength increases.

d. Mechanical Stabilization. The alteration of soil properties by changing the gradation of the soil by the addition or removal of particles or by densifying or compacting the soil.

e. Aggregate. A granular material of mineral composition such as sand, gravel, shell, slag, or crushed stone, used with a cementing medium to form mortars or cement, or alone, as in base courses, railroad ballasts, etc.

f. AASHTO. An abbreviation used to designate the American Association of State Highway and Transportation Officials. The name of the group was recently changed to the American Association of State Highway Officials (AASHO), and the current abbreviation is also used.

g. ASTM. An abbreviation used to designate the American Society for Testing and Materials.

2. Definitions Associated with Lime Stabilization:

a. Lime. All classes of quicklime and hydrated lime, both calcitic (high calcium) and dolomitic (ASTM C-593).

b. Lime-Modified Soils. Mixtures of lime and soil that are either not fully cured or where the soil is not lime-reactive. The soil is modified in that a plasticity reduction and agglomeration of particles results.

c. Lime Soil Mixtures. Mixtures of lime and soil in the presence of moisture where the soil-lime system results in a cementitious reaction. The result is strength gain with time.

d. Lime Reactive Soil. Fine-grained soils that possess the potential for a cementitious reaction with lime.

3. Definitions Associated with Lime-Fly Ash Stabilization:

a. LFA. An abbreviation used to designate a mixture of lime-fly ash-aggregates.

b. LCFA. An abbreviation used to designate a mixture of lime- and cement-fly ash aggregates.

c. LFS. An abbreviation used to designate a mixture of lime-fly ash and soil.

4. Definitions Associated with Portland Cement Stabilization:

a. Portland Cement. A hydraulic cement produced by pulverizing clinker consisting essentially of hydraulic calcium silicates, and usually containing one or more of the forms of calcium sulfate as an interground addition (ASTM C-150). Portland cement will be referred to as cement in this manual.

b. Cement-Stabilized Soil. A mixture of soil and measured amounts of portland cement and water which is thoroughly mixed, compacted to a high density and protected against moisture loss during a specific curing period.

c. Soil-Cement. A hardened material formed by curing a mechanically compacted intimate mixture of pulverized soil, portland cement and water. Soil-cement contains sufficient cement to pass specified durability tests.

d. Cement-Modified Soil. An unhardened or semi-hardened intimate mixture of pulverized soil, portland cement and water. Significantly smaller cement contents are used in cement-modified soil than in soil-cement.

e. Plastic Soil-Cement. A hardened material formed by curing an intimate mixture of pulverized soil, portland cement and enough water to produce a mortarlike consistency at the time of mixing and placing. Plastic soil-cement can be used for highway ditch linings.

5. Definitions Associated with Asphalt Stabilization:

a. Bitumen. A class of black or dark-colored (solid, semi-solid, or viscous) cementitious substances, natural or manufactured, composed principally of high molecular weight hydrocarbons, of which asphalts, tars, pitches and asphaltites are typical.

b. Asphalt. A dark brown to black cementitious material in which the predominating constituents are bitumens which occur in nature or are obtained in petroleum processing.

c. Asphalt Cement. A fluxed or unfluxed asphalt specially prepared as to quality and consistency for direct use in the manufacture of bituminous pavements, and having a penetration at 77°F (25°C) of between 5 and 300, under a load of 100 g applied for 5 seconds.

d. Cut-Back Asphalt. Petroleum residues which have been blended with distillates such as naptha, gasoline, kerosene or other oils to control the mixing viscosity.

e. Anionic Emulsion. A type of emulsion such that a particular emulsifying agent establishes a predominance of negative charges on the discontinuous phase.

f. Cationic Emulsion. A type of emulsion such that a particular emulsifying agent establishes a predominance of positive charges on the discontinuous phase.

g. Liquid Bituminous Materials. Materials which utilize either distillates (cutbacks) or emulsifying systems (emulsions) to provide suitable flow properties at ambient temperatures to base asphalt cements for mixing and construction with aggregate systems.

SECTION II

STABILIZER SELECTION

A. GENERAL

Ideally, field tests should be performed to determine the type and characteristics of the subgrade soils as well as available borrow materials. Laboratory tests should be done to determine engineering properties of both the mechanically and chemically stabilized soils and borrow materials. The final decision of stabilizer would then be based on first costs and long term maintenance economics. Except for very large projects this desired approach is cost and/or time prohibitive. Simplified guidelines are necessary to direct the engineer to those stabilization techniques which appear most suitable for a particular situation. This section presents basic guidelines to establish the optimum chemical stabilizer.

B. BASIC CRITERIA

1. Lime Stabilization

Experience has shown that lime will react with medium, moderately fine, and fine grained soils to produce decreased plasticity, increased workability, reduced swell, and increased strength. Generally speaking, those soils classified by the Unified System (MIL-STD-619B) as CH, CL, MH, SC, SM, GC, SW-SC, SP-SC, SM-SC, GW-GC, CP-GC, or GM-GC should be considered as potentially capable of being stabilized with lime.

Lime may be an effective stabilizer with clay contents as low as seven percent and a PI as low as ten for certain soil types.

2. Cement Stabilization

The Portland Cement Association indicates that all types of soils can be stabilized with cement. However, well-graded granular materials that possess sufficient fines to produce a floating aggregate matrix have given the best results. The grading requirements to produce a floating matrix are: a minimum of 55 percent passing the Number 4 sieve, a minimum of 35 percent passing the Number 10 sieve and a minimum of 25 percent passing the Number 10 but retained on the Number 200 sieve.

The P.I. should be less than 30 for sandy materials while the P.I. should be less than 20 and the Liquid Limit less than 40 for fine grained soils. This limitations is necessary to ensure proper mixing of the stabilizer. For gravel type materials a minimum of 45 percent by weight passing the Number 4 sieve is desirable. In addition, the P.I. of the soil should not exceed the number indicated from the following equation:

$$PI = 20 + \frac{50 - \text{Fines Content (Percent)}}{4}$$

3. Fly Ash Stabilization

In stabilizations, fly ashes act as pozzolans and/or fillers to reduce air voids in naturally occurring or blended aggregate systems. Since the particle size of the fly ash is normally larger than the voids in fine grained soils, the filler role is not appropriate for use in fine grained soils. The fly ash is used only as a pozzolan. Most clays (but not all) are pozzolanic and do not require additional pozzolans. Thus, silts are generally considered the most suitable fine-grained soil type for treatment with lime-fly ash or cement-fly ash mixtures.

Aggregates which have been successfully used in lime-fly ash mixtures include a wide range of types and gradations, including sands, gravels, crushed stones and several types of slag. Lime-fly ash aggregate mixtures are often more economical to use than lime-fly ash fine-grained soil mixtures.

Some fly ashes that are high in calcium oxide can be used with fine-grained soils to form acceptable stabilized materials. These fly ashes are normally obtained from power plants utilizing Western United States coals.

4. Asphalt Stabilization

To insure suitable mixture strength and durability properties for asphalt-soil systems the maximum passing the Number 200 sieve should be 25 percent, plasticity index less than six, sand equivalent greater than 30 and the product of the plasticity index and percent passing Number 200 sieve less than 72. Generally, soils classified by the Unified System (MIL-STD-619B) as SW, SP, SW-SM, SP-SM, SW-SC, SP-SC, SM, SC, SM-SC, GW, GP, GW-GM, GP-GM, GW-GC, GP-GC, GC and GM-GC are suitable provided certain plasticity and grading requirements are met (see Section VI).

5. Combination Stabilizers

Combination stabilizers discussed in this section include lime-cement and lime-asphalt. Soil classified as ML, CL, MH and CH, according to the Unified System, can often be economically treated.

The main purpose of combination stabilization is to reduce plasticity and increase workability so the soil can be intimately mixed and effectively stabilized. Lime is the pretreatment stabilizer followed by cement or asphalt.

It is an advantage to add lime in some asphalt stabilization jobs to prevent stripping of asphalt from the aggregate in the presence of water.

Portland cement and lime have been used in emulsion stabilization to help control emulsion break and reduce curing time.

C. SELECTING BEST STABILIZER

Figure 9 presents a stabilizer selection system based on soil plasticity (Atterberg Limits) and the percent passing the Number 200 sieve (grain size). Once the stabilizer is selected, detailed tests should be performed as discussed in those chapters associated with the individual stabilizers.

More than one stabilizer may be suitable for stabilization based on Figure 9. The best stabilizer is always listed at the top. Once a stabilizer type has been selected for a particular soil, the engineer should consider climatic limitations that may restrict the use of the stabilizer. Also safety should be understood by the engineer prior to stabilizer selection. General climatic limitations and construction safety precautions are given in Table 1.

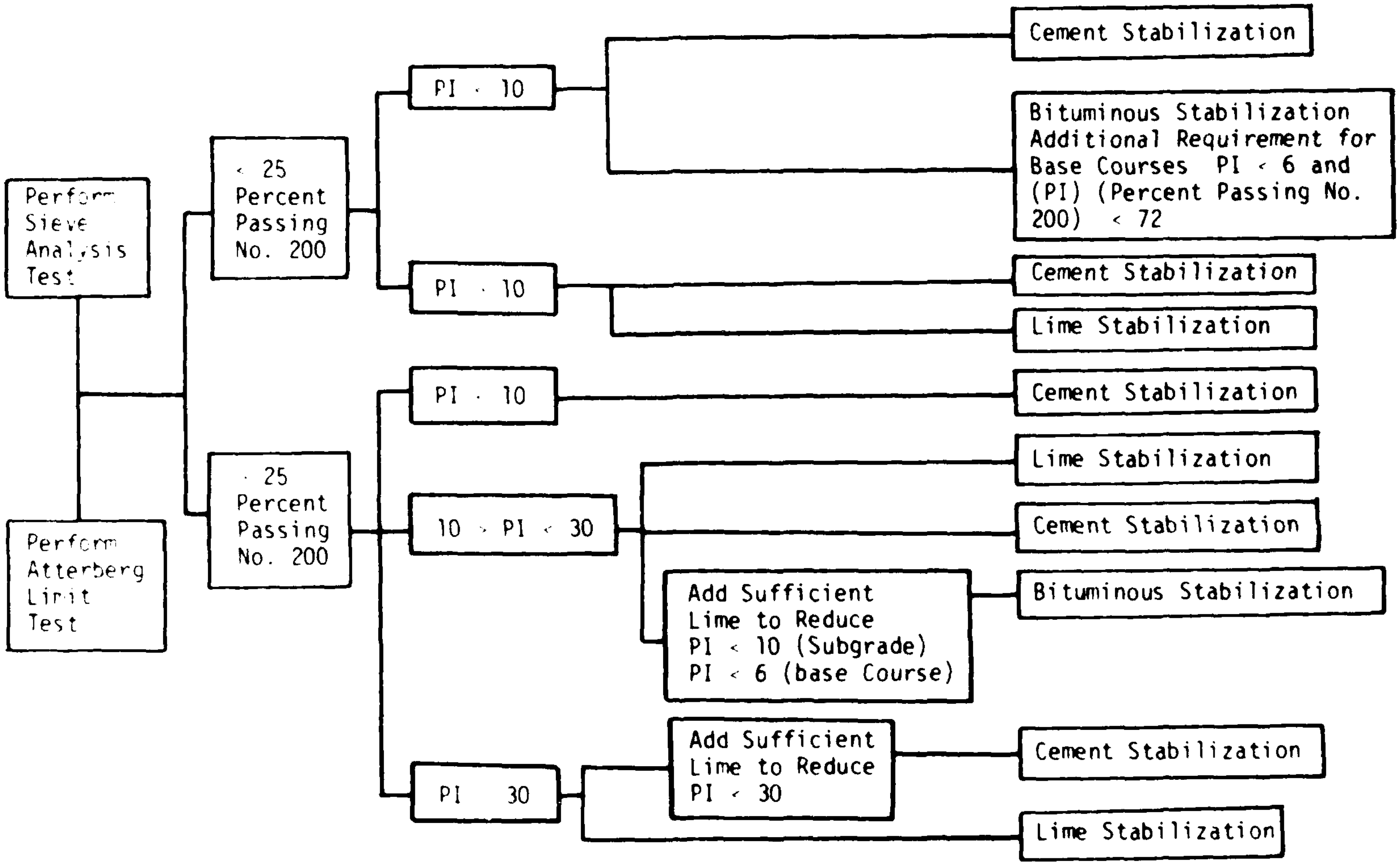


Figure 9. Selection of Stabilizers.

TABLE 1. CLIMATIC LIMITATIONS AND CONSTRUCTION SAFETY PRECAUTIONS.

Type of Stabilizer	Climatic Limitations	Construction Safety Precautions
Lime and Lime-Fly Ash	Do not use with frozen soils Air temperature should be 40°F and rising Complete stabilized base construction one month before first hard freeze Two weeks of warm to hot weather are desirable prior to fall and winter temperatures	Quicklime should not come in contact with moist skin Hydrated lime [$Ca(OH)_2$] should not come in contact with moist skin for prolonged periods of time Safety glasses and proper protective clothing should be worn at all times
Cement and Cement-Fly Ash	Do not use with frozen soils Air temperature should be 40°F and rising Complete stabilized layer one week before first hard freeze	Cement should not come in contact with moist skin for prolonged periods of time Safety glasses and proper protective clothing should be worn at all times
Asphalt	Air temperature should be above 32°F when using emulsions Air temperatures should be 40°F and rising when placing thin lifts (1-inch) of hot mixed asphalt concrete Hot, dry weather is preferred for all types of asphalt stabilization	Some cutbacks have flash and fire points below 100°F Hot mixed asphalt concrete temperatures may be as high as 350°F

SECTION III

LIME STABILIZATION

A. GENERAL

The term, "lime," refers to oxides and hydroxides of calcium and magnesium. There are various types of commercial lime. Calcitic quicklime (CaO) and dolomitic quicklime (CaO + MgO) are produced by calcining calcite or dolomite, respectively. The controlled addition of water to quicklime can produce three types of hydrated lime: (1) high-calcium, $Ca(OH)_2$; (2) monohydrated dolimitic, $Ca(OH)_2$ + MgO; and (3) dihydrated dolomitic, $Ca(OH)_2$ + $Mg(OH)_2$.

Various forms of lime have been successfully used as soil-stabilizing agents for many years, including products with varying degrees of purity. However, the most commonly used products are hydrated high-calcium produce lime $Ca(OH)_2$, monohydrated dolomitic lime $Ca(OH) \cdot MgO$, calcitic quicklime CaO, and dolomitic quicklime $CaO \cdot MgO$. The use of quicklime for soil stabilization in the United States has increased in recent years. In Europe, quicklime is the major type used.

By-product lime also provides a source that may be suitable for use in stabilization. This type of lime is usually available from various manufacturing processes. Two types of by-product limes commonly available are: (1) those that collect from the draft of the calcining process in lime production operations (flue dust), and (2) the by-product of acetylene gas production from calcium carbide. By-product lime may be a very economical source of lime; however, these limes may be nonuniform in quality.

Although many by-product limes may be similar to virgin limes in terms of chemical composition, other important properties may be considerably different. For example, commerical hydrates are generally more finely divided and have higher specific surfaces than carbide limes.

Most types of lime (exclusive of dihydrated dolomitic, $Ca(OH)_2 \cdot Mg(OH)_2$) are acceptable for stabilization purposes, if a quality soil-lime mixture meeting strength, durability, and economic criteria can be obtained. Laboratory testing may be used to indicate the effectiveness of a lime. Properties of the soil being stabilized may have a much greater influence on the soil-lime reaction than lime type or source.

In most instances, considerations of local availability and cost are more significant than lime type in selecting a product source. Significant hauling distances may be involved if lime stabilization is to be used in certain areas. Bulk lime is normally used. "Bagged" lime is considerably more expensive.

Lime specifications have been prepared by many groups and agencies. Chemical and physical (primarily particle size) properties are normally the major factors considered in a lime specification.

AASHTO M-216 is an example of a specification specifically directed to the use of lime for soil stabilization. Many state and agency specifications incorporate ASTM C-207 (Type N) or a modified version of ASTM C-207 in their own specifications. Note that ASTM C-207 is entitled, "Hydrated Lime for Masonry Purposes." ASTM has not developed a lime specification for soil stabilization. In foreign countries, local specifications should be evaluated to determine if they are appropriate for soil stabilization. For more detailed information of specifications, see Section XI and Appendix A.

"Special Provision" type specifications are required if by-product lime is used since such limes seldom meet commercial lime specification requirements.

Appropriate quality control testing should be conducted during the course of a project to ensure the quality and uniformity of the lime being incorporated into the construction. Producer certification of the lime is used in some cases in lieu of "on the job" lime testing. For more detailed information on quality control, see Section X.

B. SOIL-LIME REACTIONS

1. General

The addition of lime to a fine-grained soil initiates several reactions. Cation exchange and flocculation-agglomeration reactions take place rapidly and produce immediate changes in soil plasticity, workability and the immediate uncured strength and load-deformation properties. Depending on the characteristics of the soil being stabilized, a soil-lime pozzolanic reaction may occur. The pozzolanic reation results in the formation of various cementing agents which increase mixture strength and durability. Pozzolanic reactions are time-dependent; therefore, strength development is gradual but continuous for long periods of time amounting to several years in some instances. Temperature also affects the pozzolanic reaction. Temperatures less than 55 to 50^{o}F retard the reaction and higher temperatures accelerate the reaction.

Lime carbonation (lime reacts with carbon dioxide to form a carbonate; $CaO + CO_2 \rightarrow CaCO_3$) is an undesirable reaction which may also occur in soil-lime mixtures. Construction should be carried out in such a fashion that lime carbonation is minimized.

Prevention of long exposure of the lime prior to mixing with the soil, "rubber-tired" rolling of the mixture surface prior to leaving the mixture to mellow and the avoidance of long, intensive mixing and processing times are major items to consider.

2. Cation Exchange and Flocculation-Agglomeration

Practically all fine-grained soils display cation exchange and flocculation-agglomeration reactions when treated with lime. The reactions occur quite rapidly when soil and lime are intimately mixed.

The addition of lime to a soil in sufficient quantity supplies an excess of Ca^{++} ions to the soil. Cation exchange occurs, with Ca^{++} replacing other cations from the exchange complex of the soil.

Flocculation and agglomeration reactions produce an apparent change in texture with the clay particles "clumping" together into larger sized "aggregates". A "clayey" soil is changed and has a "silty" texture because of the flocculation and agglomeration reactions.

3. Soil-Lime Pozzolanic Reaction

The reactions between lime, water and various sources of soil silica and alumina to form cementing type materials are soil-lime pozzolanic reactions. When a significant quantity of lime is added to a soil, the pH of the soil-lime mixture is elevated to approximately 12.4, the pH of saturated lime water. This is a substantial pH increase, compared to the pH of natural soils. The solubilities of soil silica and alumina are greatly increased at elevated pH levels.

Studies have shown that soil-lime reaction products are forms of hydrated calcium silicates and hydrated calcium aluminates. A wide variety of hydrate forms can be obtained, depending on reaction conditions, curing time and temperature. The cementing products are similar to those produced by the hydration of portland cement.

The extent to which the soil-lime pozzolanic reactions proceeds is influenced primarily by natural soil properties. With some soils, the pozzolanic reaction is inhibited, and cementing agents are not extensively formed. Those soils that react with lime to produce substantial strength increase (greater than 50 psi following 28 day curing at $73^{o}F$) are "reactive" and those that display limited pozzolanic reactivity (less than 50 psi strength increase) are "nonreactive."

The major soil properties and characteristics which influence the lime-reactivity of a soil, i.e., ability of the soil to react with lime to produce cementitious materials, are soil pH, organic carbon content, natural drainage, presence of excessive quantities of exchangeable sodium, clay mineralogy, degree of weathering, presence of carbonates, extractable iron, silica-sesquioxide ratio and silica-alumina ratio. It is emphasized that the main factors controlling the development of pozzolanic cementing materials in a lime treated soil are the inherent properties and characteristics of the soil. If a soil is "nonreactive," extensive pozzolanic strength development will not be achieved regardless of lime type, lime percentage or curing conditions of time and temperature.

Soil-lime reactions are complex and not completely understood at this time. However, sufficient basic understanding and successful field experience are available to provide the basis of an adequate technology for successfully utilizing soil-lime stabilization under a wide variety of conditions.

C. PROPERTIES AND CHARACTERISTICS OF SOIL-LIME MIXTURES

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, stress-strain and fatigue 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.

Generally only lime-reactive soils (those that display a significant compressive strength increase) are used as structural paving layers. Cured lime-treated reactive soils are appropriately termed "cemented materials." Thus, the engineering properties of strength, stress-strain behavior and durability are of major interest. These properties will be considered in detail.

Lime treatment also has an immediate effect on pertinent soil properties. Immediate effects are achieved without curing and are of particular interest during the construction stage.

1. Uncured Mixtures

a. Plasticity. Substantial reduction in plasticity (reduced PI, increased shrinkage limit) is affected by lime treatment, and the soil sometimes becomes nonplastic. Generally, high initial PI and clay content soils require greater quantities of lime for achieving the nonplastic condition, if it can be achieved at all. The first increments of lime-added are most effective in reducing plasticity. The silty and friable texture of the treated soil causes a marked increase in workability. The improved level of workability expedites subsequent manipulation and placement of the treated soil. Typical effects are illustrated by the data in Table 2.

TABLE 2. ATTERBERG LIMITS FOR NATURAL AND LIME-TREATED SOILS.

Soil	Unified Classification	Natural Soil		3% Lime		5% Lime	
		LL	PI	LL	PI	LL	PI
Bryce B	CH	53	29	48	21	NP	
Clay Till	CL	49	27	51	12	59	11
Cowden B	CH	54	33	47	7	NP	
Drummer B	CH	54	31	44	10	NP	
Fayette C	CL	32	10	NP			
Hosmer B_2	CL	41	17	NP			
Piasa B	CH	55	36	48	11	NP	
Illinoian Till	CL	26	11	27	6	NP	

LL - Liquid Limit

NP - Nonplastic

PI - Plasticity Index

b. Moisture-Density Relations. For a given compactive effort, soil-lime mixtures have a lower maximum dry density and a higher optimum moisture content than the untreated soil. Maximum dry density reductions of 3-5 pcf and optimum water content increases of 2-4 percent are common. Figure 10 illustrates the effect of lime on the compaction characteristics of a CL soil (AASHTO T-99 compaction).

If a mixture is allowed to cure and gain strength prior to compaction, further reductions in maximum dry density and optimum moisture content increases may be noted. It is important that the appropriate moisture-density relation be used for field control purposes.

c. Swell Potential. Soil swell potential and swelling pressures are normally significantly reduced by lime treatment. CBR swell values (96 hour soak period) of lime treated soils vary, but it is common to decrease swell to less than 0.1 percent. Lime is an effective stabilization additive for swell control as indicated by the data in Table 3.

d. Strength and Deformation Properties. Lime treatment of fine-grained cohesive soils produces immediate improvements in the strength and deformation properties of "uncured" soil-lime mixtures. These immediate benefits can be characterized in terms of shear strength, CBR, cone index, static compressive modulus of elasticity and resilient modulus.

Typical moisture content - CBR relations for an uncured soil-lime mixture and the natural soil are shown in Figure 11. The compactive effort was AASHTO T-99.

The immediate effects of lime treatment are to improve the resilient behavior (repeated loading modulus of elasticity) of fine-grained cohesive soils. Figure 12 illustrates the improvements obtained for a ML soil.

The immediate strengthening effects of lime treatment are substantial. For "reactive" soils, as curing progresses and the soil-lime pozzolanic reaction proceeds the soil-lime mixture will develop much higher levels of strength and stiffness characteristics typical of "cemented materials."

2. Cured Mixtures

a. Strength and Deformation Properties. The strength and deformation properties of lime-treated soils are dependent on many variables. Soil type, lime type, lime percentage, compacted density and curing conditions (time-temperature) are the most important. The properties of a lime-treated soil are therefore, not "static values" but will vary in response to changes in the variables listed above.

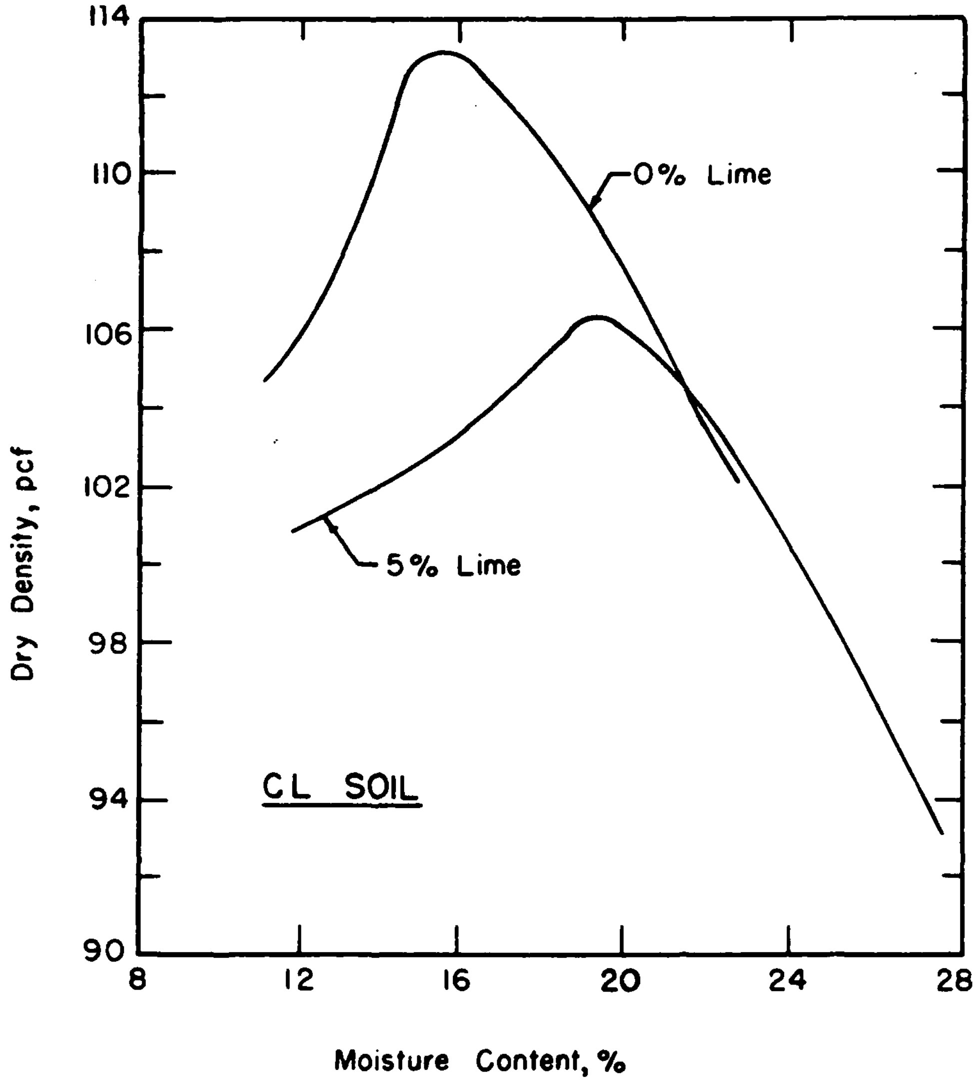


Figure 10. Moisture-Density Relations for a Natural and Five Percent Lime-Treated CL Soil (AASHTO T-99 Compaction)(After Ref. 1).

TABLE 3. CBR VALUES FOR NATURAL AND LIME-TREATED SOILS.

Soil	Unified Classification	Natural Soil		% Lime	Soil-Lime Mixtures			
					No Curing[1)]		48 Hours Curing @ 120°F	
		CBR, %	Swell, %		CBR, %	Swell, %	CBR, %	Swell, %
Reactive Soils								
Accretion Gley 2	CL	2.6	2.1	5	15.1	0.1	351.0	0.0
Accretion Gley 3	CL	3.1	1.4	5	88.1	0.0	370.0	0.1
Bryce B	CH	1.4	5.6	3	20.3	0.2	197.0	0.0
Champaign Co. Till	CL-ML	6.8	0.2	3	10.4	0.5	85.0	0.1
Cisne B	CH	2.1	0.1	5	14.5	0.1	150.0	0.1
Cowden B	CH	7.2	1.4	3	--	--	98.5	0.0
Cowden B	CH	4.0	2.9	5	13.9	0.1	116.0	0.1
Cowden C	CL	4.5	0.8	3	27.4	0.0	243.0	0.0
Darwin B	CH	1.1	8.8	5	7.7	1.9	13.6	0.1
East St. Louis Clay	CH	1.3	7.4	5	5.6	2.0	17.3	0.1
Fayette C	CL	1.3	0.0	5	32.4	0.0	295.0	0.1
Illinoian B	CL	1.5	1.8	3	29.0	0.0	274.0	0.0
Illinoian Till	CL	11.8	0.3	3	24.2	0.1	193.0	0.0
Illinoian Till	CL	5.9	0.3	3	18.0	0.9	213.0	0.1
Sable B	CH	1.8	4.2	3	15.9	0.2	127.0	0.0
Non-Reactive Soils								
Fayette B	CL	4.3	1.1	3	10.5	0.0	39.0	0.0
Miami B	CL	2.9	0.8	3	12.7	0.0	14.5	0.0
Tama B	CH	2.6	2.0	3	4.5	0.2	9.9	0.1

1) Specimens were placed in 96 hour soak immediately after compaction.

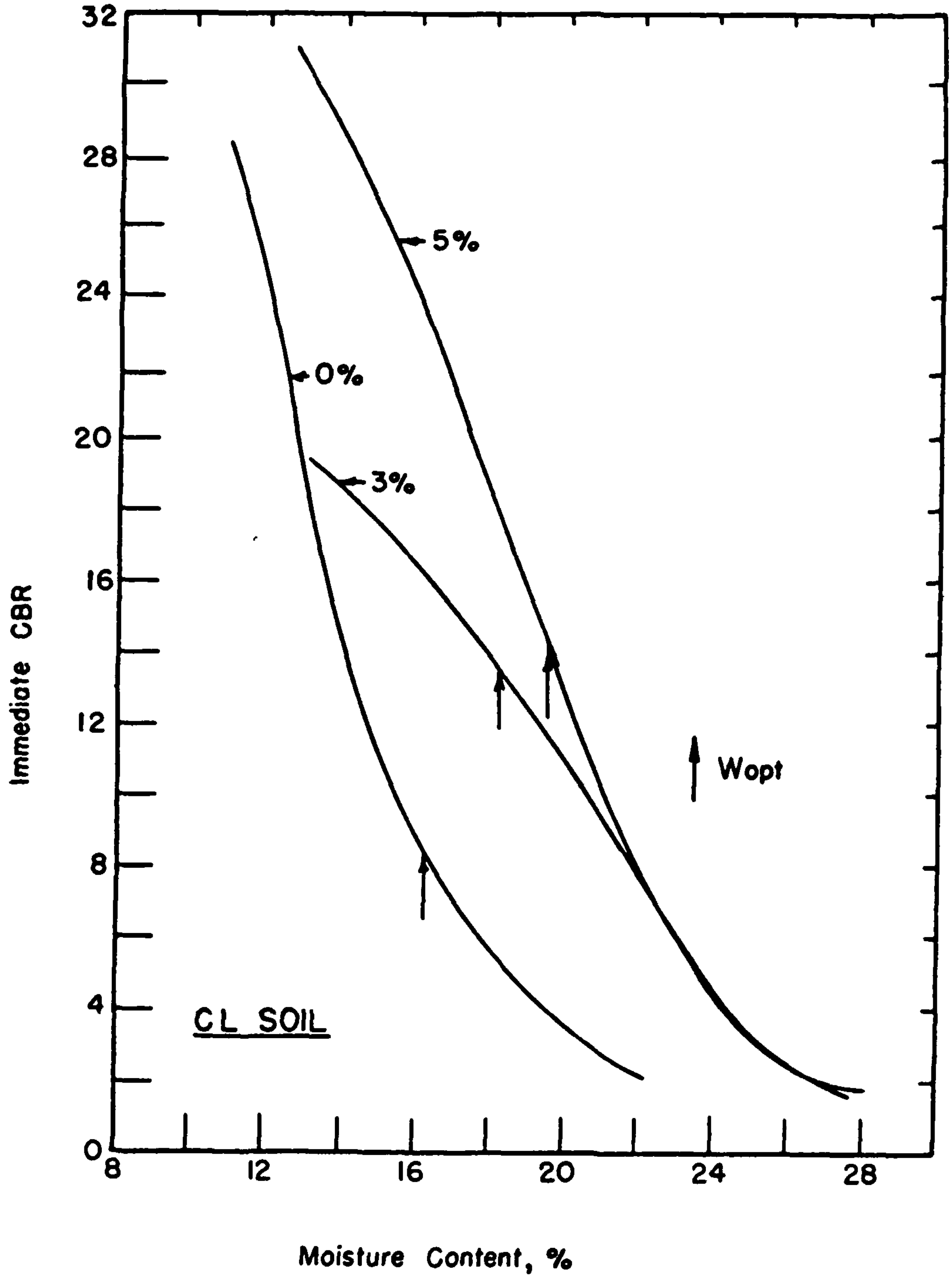


Figure 11. CBR-Moisture Content Relations for Natural and Lime-Treated (3%, 5%) CL Soil (AASHTO T-99 Compaction)(After Ref. 1).

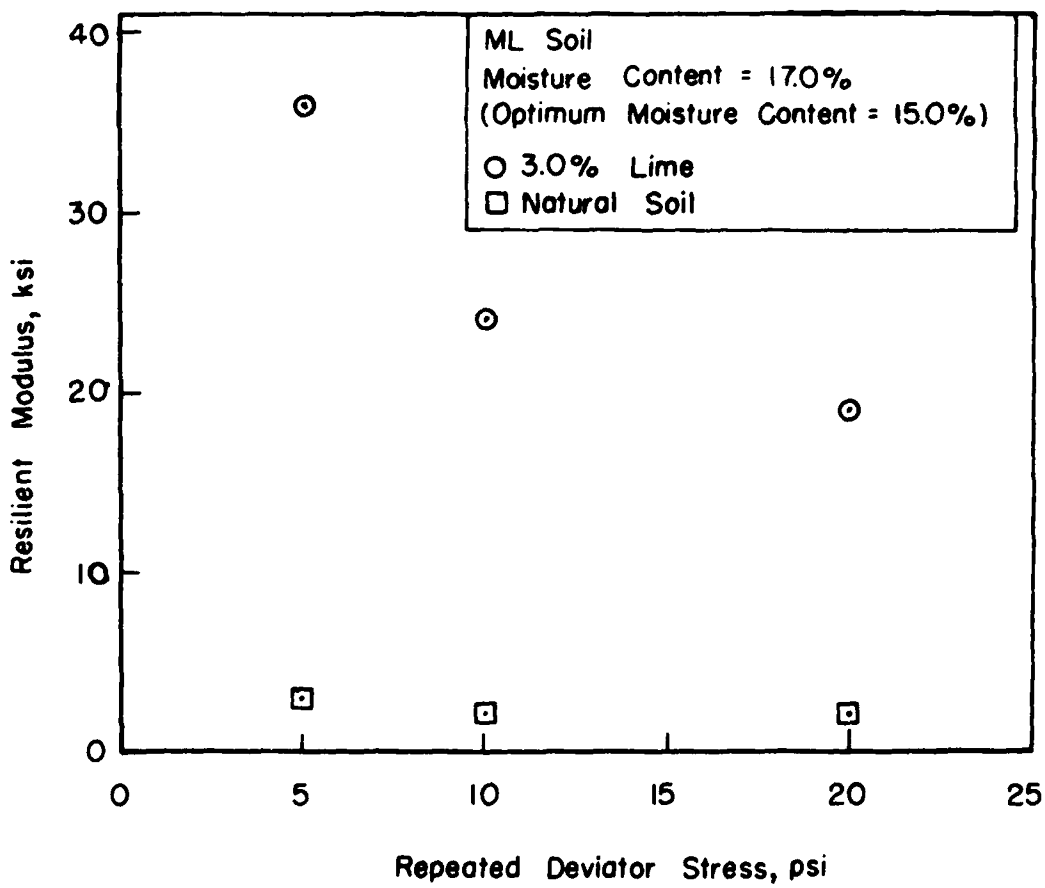


Figure 12. Immediate Effects (No Curing) of Lime Treatment on Resilient Modulus.

b. Strength Properties.

(1) Unconfined Compression. The unconfined compression test is a simple and effective test for evaluating the properties of stabilized soils.

Soil-lime mixtures strength varies substantially as indicated by the typical data in Table 4. Strength increases (cured mixture strength minus strength of natural soils; 28-day curing at 73°F) greater than 100 psi are achieved with many soils. Extended curing (either in the laboratory or under field conditions) may produce strength increases of several hundred psi. Field data indicate that with some soil-lime mixtures strength continues to increase with time up to in excess of 10 years.

The differences between the compressive strengths of the natural and lime-treated soil is an indication of the degree to which the soil-lime-pozzolanic reaction has proceeded. Substantial strength increase indicates that the soil is reactive with lime and can probably be stabilized to produce a structural layer quality material.

(2) Shear Strength. Some cured soil-lime mixtures (stabilized reactive soils) are cemented type materials. The major effect of lime on the shear strength of a reactive fine-grained soil is to produce a substantial increase in cohesion with some minor increase in friction angle (ϕ). The cohesion increase is of the greatest significance.

Substantial shear strength can be developed in cured lime-soil mixtures. Shear strength related failures have not been noted and/or reported to any extent for field service conditions.

Typical angles of shearing resistance (ϕ) are approximately 25° - 35°. The cohesion of the mixtures is substantially increased compared to the natural soils. Cohesion increases with increased mixture compressive strength. A rough estimate of cohesion is approximately 30 percent of the unconfined compressive strength.

(3) California Bearing Ratio (CBR). CBR testing procedures have been extensively used to evaluate the strength of lime stabilized soils. Many agencies have arbitrarily adopted this technique because of their familiarity with the test. CBR is not appropriate for characterizing the strength of soil-lime mixtures under all conditions.

CBR values for many cured soil-lime mixtures (see data in Table 3) are quite large and definitely indicate the extensive development of pozzolanic cementing agents. For mixtures with CBR values of 100 or more, the test results have little practical significance. If extensive pozzolanic cementing

TABLE 4. COMPRESSIVE STRENGTH DATA FOR NATURAL AND LIME-TREATED SOILS.

Soil	Unified Classification	Compressive Strength, psi			
		Natural Soil	% Lime		
			3	5	7
Bryce A	MH	57	43	58	53
Bryce B	CH	81	201	212	193
Cisne B	CH	93	107	190	189
Drummer A	ML	53	29	49	32
Drummer B	CH	68	186	152	146
Fayette A	ML	38	37	46	49
Fayette B	CL	70	109	114	113
Fayette C	CL	40	137	185	125
Accretion-Gley	CL	58	263	247	283
Huey B	CL	102	223	216	233
Huey D	CL	89	222	179	197
Illinoian Till	CL	51	150	186	143
Loam Till	MH	105	172	184	174
Davidson B_{22}	MH	113	198	268	324
Greenville B_{22}	CL	83	455	517	551
Norfolk B_{21}	SC	67	347	421	332
Clalitos B_{21}	MH	107	114	133	132
Nipe B_{22}	ML	67	87	220	311
Cecil B_{21}	CH	71	168	163	224
St. Ann Bauxite	CH	119	104	292	495

Note: Curing conditions of 28 days at 73°F.

action has not developed due to either lack of curing time or nonreactivity of the treated soil, CBR may serve as a general strength indicator.

(4) Tensile Strength. Tensile strength properties of soil-lime mixtures are important in pavement design.

Two test procedures, split-tensile and flexural, have been used for evaluating soil-lime mixture tensile strength. Split-tensile strengths display large variations, depending on the soil-lime mixture and curing conditions. The ratio of split-tensile strength to unconfined compressive strength of the mixtures is approximately 0.13.

The most common method used for evaluating the tensile strength of highway materials is the flexural test (beam strength). A realistic estimate of flexural strength (modulus of rupture) is 25 percent of the unconfined compressive strength of the cured soil-lime mixture.

(5) Fatigue Strength. For typical pavement loading conditions flexural strength, not the shear strength, of reactive soil-lime mixtures will probably be the limiting factor in applications as subbase and base course structural layers. Flexural fatigue is therefore an important consideration in the evaluation of lime-soil mixtures.

Cured coil-lime mixture flexural fatigue response curves are comparable to those normally obtained for similar materials (with regard to the nature of the cementitious products) such as lime-fly ash-aggregate mixtures soil-cement and concrete. The fatigue strengths (at 5 million stress repetitions) of soil-lime mixtures vary for different mixtures but are approximately 50 - 55 percent of the ultimate mixture flexural strength.

Soil-lime mixtures continue to gain strength with time and the ultimate strength of the mixture is a function of curing period and temperature. The magnitudes of the flexural stress repetitions applied to the mixture are relatively constant throughout its service life. Therefore, as the ultimate strength of the material increases due to curing, the stress level (as a percent of ultimate flexural strength) will decrease and the fatigue life of the mixture will increase.

c. Deformation Properties. Stress-strain properties are essential for analyzing the behavior of a pavement structure containing a soil-lime mixture structural layer. The marked effect of lime on the compressive stress-strain properties of fine-grained soils is shown in Figure 13. The failure stress is increased and the ultimate strain is decreased for soil-lime mixtures relative to the natural soil. Soil-lime mixtures tested in compression are strain sensitive and the ultimate strain (for

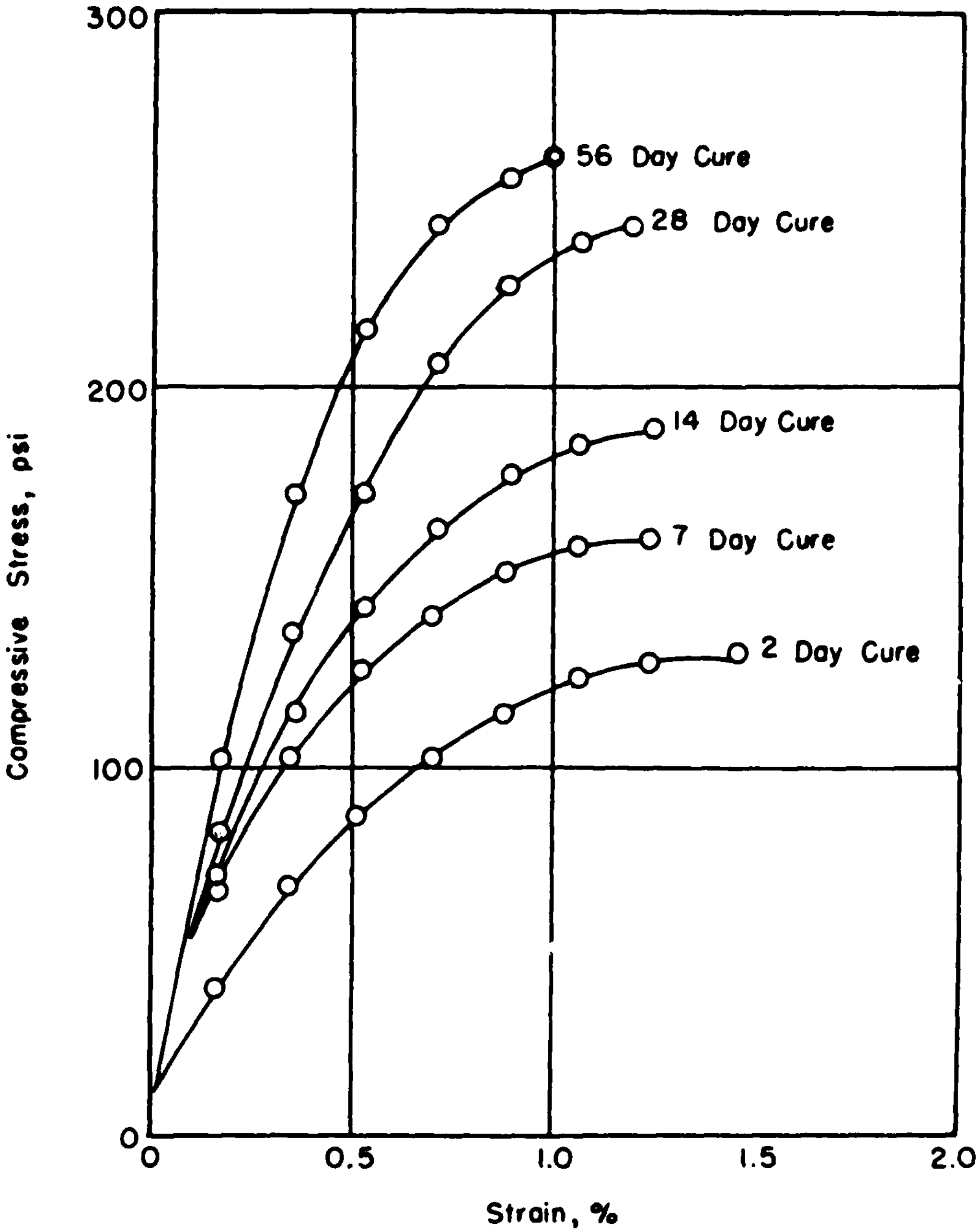


Figure 13. Compressive Stress-Strain Relations for Cured Soil-Lime Mixtures. (Goose Lake Clay Plus Four Percent Lime; Curing Temperature of 73°F, After Suddath and Thompson, Ref. 2).

maximum compressive stress) is approximately one percnet, regardless of the soil type or curing period. The compressive modulus of elasticity can be estimated from the unconfined compressive strength of the soil-lime mixture according to the following relation:

$$E(ksi) = 10 + 0.124 \text{ Unconfined Compressive Strength (psi)}$$

Repeated or dynamic compressive loading data for soil-lime mixtures are limited. Resilient modulus data are typically much higher than static moduli of elasticity values. Some data indicate the resilient values are approximately 2 to 3 times larger.

(1) Flexural Moduli. For lime-soil pavement structural layers possessing high shear strength, the flexural stresses in the lime-soil mixture may be the controlling design factor. Flexural moduli of elasticity have been evaluated for typical cured lime-soil mixtures. Figure 14 is a plot for flexural modulus versus flexural strength. Increased curing results in increased flexural strength accompanied by increased flexural moduli.

(2) Poisson's Ratio. Only limited data are available for cured soil-lime mixtures. Reported values at low stress levels (less than 50 percent of the ultimate compressive strength) are generally in the range of 0.1 to 0.2. At higher stress levels, Poisson's ratio may be closer to the 0.2 to 0.3 range. A value of 0.15 to 0.20 is frequently used.

Since the properties of a reactive soil-lime mixture change with further curing (due to the development of additional cementing products), it is not justified in some cases to conduct elaborate tests to precisely evaluate mixture properties that will soon change due to field curing effects. It is frequently acceptable to use unconfined compressive strength or other simple tests for evaluating the "quality" of the mixtures and estimating other pertient mixture properties using previously developed correlations.

3. Shrinkage

Shrinkage associated with the loss of moisture from the stabilized soil is of importance relative to the problem of "shrinkage cracking" of the materials and reflective cracking through overlying paving layers. Lime treatment decreases shrinkage potential. Field moisture content data for lime-treated soils suggest that the moisture content changes in the stabilized material are not large and the in situ water content stabilizes at approximately optimum.

Calculations based on laboratory shrinkage data, as well as field service data from many areas, indicate that, for typical

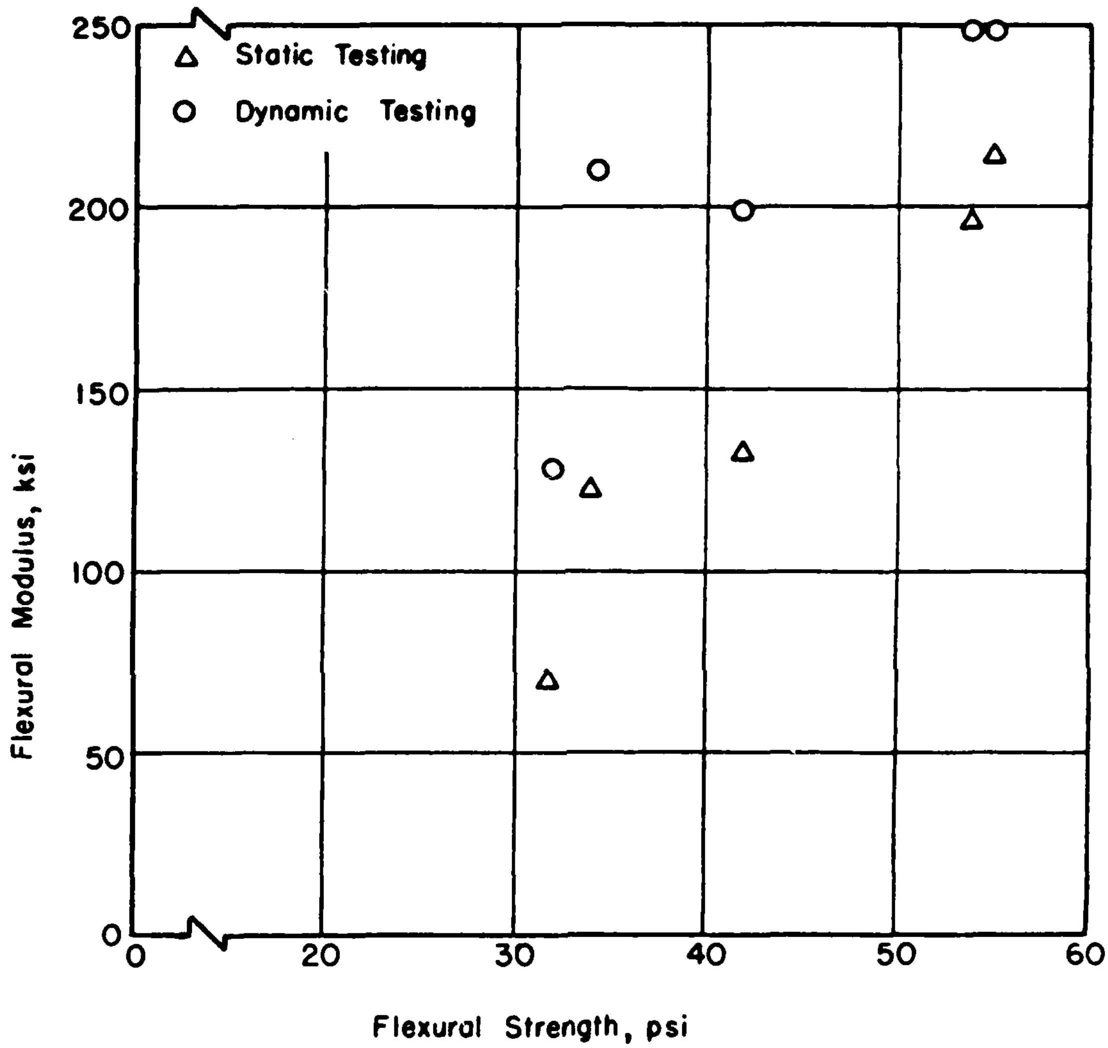


Figure 14. Flexural Modulus - Flexural Strength Relationships for Cured Soil-Lime Mixture. (Goose Lake Clay Plus Four Percent Lime, After Suddath and Thompson, Ref. 2).

field service conditions shrinkage of cured soil-lime mixtures will not be extensive. Thus, reflective cracking through the surface course will not occur frequently.

4. Durability

Durability characteristics are important in the evaluation of a paving material. This is particularly true when the effects of environment (temperature and moisture) are more pronounced due to the reduced thickness of base and subbase layers and the use of only thin surface courses or even only surface treatments.

a. Moisture Effects. Prolonged exposure of soil-lime mixtures to water produces only slightly detrimental effects, and the ratio of soaked to unsoaked compressive strength of the mixtures is quite high, on the order of .7 to .85. The mixtures seldom achieve 100 percent saturation and in most cases the maximum degree of saturation is in the range of 90 to 95 percent.

b. Freeze-Thaw Effects. Pavement systems may experience two general types of freeze-thaw action. Cyclic freeze-thaw occurs in the material when freezing occurs as the advancing frost line moves by and then thawing subsequently occurs. Heaving conditions develop when a quasi-equilibrium frost-line condition is established in the stabilized material layer. The static frost line situation provides favorable conditions for moisture migration and subsequent ice lens formation and heaving, if the material is frost-susceptible. Depending on the nature of the prevailing climate in an area, either cyclic freeze-thaw or heaving action or both may occur.

c. Cyclic Freeze-Thaw. In zones where freezing temperatures occur, freeze-thaw damage may be incurred by the soil-lime mixtures. The damage is generally characterized by volume increase and strength reduction.

Initial unconfined compressive strength (0 - freeze-thaw cycles) of the cured mixture is a good indicator of freeze-thaw resistance. Freeze-thaw durability studies of several different types of "cementious stabilized materials" (soil-lime, soil-cement, lime-fly ash) have confirmed that initial compressive strength of the cured stabilized mixture can be used to predict the cyclic freeze-thaw resistance of stabilized soils. Factors influencing strength development (curing time, density, additive, content, etc.) influence cyclic freeze-thaw resistance in the same fashion.

The cured soil-lime mixture must be sufficiently strong prior to the initiation of cyclic freeze-thaw action to withstand the freeze-thaw strength loss. Freeze-thaw durability considerations must, therefore, be considered in establishing mixture compressive strength requirements.

Some soil-lime mixtures display autogenous healing properties. If the stabilized soil has the ability to regain strength or "heal" with time, the distress produced during winter freeze-thaw cycles will not be cumulative, since autogenous healing during favorable curing conditions would restore the stability of the material.

d. Frost-Heaving Action. If "cemented systems" achieve a certain critical mixture strength level, the tensile strength of the stabilized material is sufficient to withstand the heaving pressures generated, thus limiting the heave potential to tolerable values. Cured compressive strengths greater than 200 psi generally display adequate "heave resistance."

e. Sulfate Effects. Laboratory and field data indicate that lime-treated soils containing significant sulfates may experience accelerated strength loss if the material is subjected to excessive moisture or cyclic freeze-thaw. Lime treatment of high sulfate content soils should be carefully considered.

f. Summary. Durable soil-lime mixtures can be obtained when reactive soils are stabilized with quality lime. Although some strength reduction and volume change may occur due to moisture and cyclic freeze-thaw, the "residual strength" of the stabilized materials is adequate to meet field service requirements. Durability considerations must be taken into account in establishing the mix composition and selecting engineering properties for use in pavement design.

D. SELECTION OF LIME CONTENT

The major objective of the mixture design process is to establish an appropriate lime content for construction. The primary variable that can be altered is lime percentage, since the inherent properties and characteristics of the soil are fixed. The general principle of soil-lime mixture design is that the mixture should provide satisfactory performance when constructed in a desired position in the pavement structure. A wide range of soil-lime mixtures of varying quality can be successfully used to accomplish differing lime treatment objectives. Design lime contents generally are based on an analysis of the effect of various lime percentages on selected engineering properties of the soil-lime mixture. For structural layer applications cured strength is the most appropriate property to consider. Immediate strength/stiffness improvements, changes in compaction and workability characteristics or swell potential reduction are frequently important in lime modification applications.

Mixture design criteria are needed to establish the quantity of lime required to produce an acceptable quality mixture. For base and subbase structural applications, soil-lime mixtures with acceptable cured strengths may not be produced, regardless of the lime percentage used to treat certain soils.

1. Treatment Level

Most fine-grained soils can be effectively stabilized with 3 to 10 percent (dry weight of soil basis) lime. Under normal field construction conditions, approximately two percent lime is the minimum quantity that can be effectively distributed and mixed with a fine-grained soil.

2. Laboratory Mixture Design

The basic components of the mixture design procedure are:

a. Method for preparing the soil-lime mixture,

b. Procedures for compacting and curing specimens,

c. Testing procedures for evaluating a selected property or properties of the soil-lime mixture and

d. Appropriate criteria for establishing the design lime content.

3. Mixture Preparation

Lime content is specified as a percentage of the dry weight of soil. Soil-lime mixtures are prepared by dry mixing the proper amounts of soil and lime and blending the required amount of water into the mixture. ASTM D-3551 should be followed. The mixture should be allowed to mellow approximately 1 hour prior to specimen preparation. Mixtures are normally prepared at or near optimum moisture content as determined by ASTM D-698 or D-1557, MIL-STD-621A, Method 100. Other moisture contents may also be used. In some situations a moisture content may be selected to represent an in situ field condition.

4. Density Control

The density of the compacted specimens must be carefully controlled. The strength of a cured soil-lime mixture is greatly influenced by density and small density variations make it difficult to accurately evaluate the effect of other variables such as lime percentages and curing conditions. Thus, the compactive effort should always be specified. MIL-STD-621A, Method 100 or ASTM D-698 compaction or the equivalent density is recommended for normal mixture design purposes. Other compactive efforts may be used to simulate anticipated field conditions.

5. Curing Conditions

Time, temperature and moisture must be controlled. For stabilization applications where "immediate" strength is an important factor, specimens can be tested immediately after compaction. Ambient temperature or accelerated (high temperature) curing are used for applications where field curing can be achieved prior to use of the stabilizer layer.

Laboratory curing conditions should be correlated with field conditions. Because the first winter's exposure is most critical. For freeze-thaw zones it is important to approximate the "field strength" of the mixture before the beginning of the winter.

Normal curing conditions are 72°F for 28 days. Accelerated curing conditions are 120°F for 48 hours.

Specimens should be cured in a "sealed container" to prevent moisture loss and lime carbonation. Sealed metal cans, plastic bags, etc., are satisfactory.

Disparities in curing conditions make it difficult to compare the results obtained from different testing methods. Mixture quality criteria developed for a particular test procedure should not be arbitrarily adopted for analyzing test results obtained from a different test method.

6. Testing Procedures

Moisture-density relations, plasticity characteristics, swell potential, uncured strength and cured strength are significant soil-lime mixture properties. Recommended testing procedures are presented below.

a. Moisture-Density Relations. Utilize MIL-STD-621A, Method 100 or ASTM D-698. In many instances lime stabilization is used under conditions (wet soils, poor "support," etc.) where it may be very difficult to achieve a high percentage of specified density, but adequate soil-lime mixture properties are obtained at lower densities.

b. Atterberg Limits Procedure. Use MIL-STD-621A, Method 103 or ASTM D-423 and ASTM D-424 to determine the plasticity characteristics of the soil-lime mixture. The mixture should not be cured prior to determining the PI since the field objective is related to obtaining immediate improvement and substantial pozzolanic strength development is not expected.

c. Swell Potential. Use MIL-STD-621A, Method 101 or ASTM D-3668 to evaluate swell potential.

d. CBR Test. The CBR test is appropriate for the following conditions:

(1) "Immediate" (uncured) strength is a major factor. (In this situation the soil-lime mixture is not highly

cemented.)

(2) The soil-lime mixture does not gain significant cured strength due to limited soil-lime-pozzolanic cementing reactions, and the mixture is considered a "modified" soil.

Conduct the CBR test in accordance with MIL-STD-621A, Method 101 or ASTM D-3668. The specimens may be either soaked or unsoaked depending on the stabilization objective. Unsoaked conditions are appropriate for "immediate strength" evaluation purposes.

For expedient testing procedures, CBR penetration tests (as per ASTM D-3668) can be conducted on "Proctor Sized" (4 inch diameter by 4.6 inch) specimens prepared in the process of determining the moisture-density relation of a soil-lime mixture. The data provide comprehensive moisture-density "immediate CBR" information for the soil-lime mixture. Typical results are shown in Figure 11.

e. Unconfined Compression Test. Unconfined compression test procedures should be used to evaluate soil-lime mixtures which develop significant cured strength. A strength gain of 50 psi [cured (28 days @ 72°F or equivalent) soil-lime mixture strength minus strength of natural soil] indicates that the soil-lime pozzolanic cementing reaction is proceeding.

Compressive strength testing should be in accordance with the procedure presented in Appendix C, Section A. Two-inch diameter by 4.0-inch specimens are recommended. Since the length to diameter ratios (l/d ratios) vary amoung test methods, compressive strength values should be corrected to an l/d ratio of 2 for comparison and specification purposes.

7. Mixture Design Criteria

a. Structural Layer Applications. Mixture design criteria are used to evaluate the adequacy of a given soil-lime mixture. Criteria vary depending on the stabilization objectives and anticipated field service conditions, i.e., environmental factors, wheel loading considerations, design life, etc. Mixture design criteria may, thus, range over a broad scale and are based on careful considerations of the specific conditions associated with the stabilization project. For soil-lime mixtures used in structural layer applications, minimum strength requirements are specified. Design lime content is normally that percentage which produces maximum strength for given curing conditions.

Strength criteria are specified in terms of compressive strength. Minimum strength requirements are higher for base materials than for subbase materials since stress and durability conditions differ for various depths in the pavement structure.

Cured compressive strength criteria for various structural layer applications are presented in Table 5.

b. Subgrade Modification. Lime modification is used to expedite construction (improve workability, facilitate drying, form "working platform") or to modify the in-situ subgrade or embankment soil properties (increase CBR, decrease swell potential, decrease plasticity).

For construction expedient and subgrade modification purposes, design lime content can be based on an evaluation of the effect of lime content on the "uncured" CBR strength and swell values and/or the PI (an indirect indication of "swell potential" and "work-ability").

An "uncured" CBR of 12 to 15 is adequate for many construction expediting applications where the stabilized layer is to serve as a "working platform". Lower CBR values (but not less than approximately 8) may be satisfactory in some situations.

For PI reduction and workability improvement applications, design lime content is the lime percentage beyond which further increases in lime content does not effect significant changes in PI. In some instances lower lime contents may produce acceptable PI reduction and satisfactory workability. Generally the first increments of lime ($\leq$ 3 percent) produce very substantial decreases in PI with increased percentage (> 3 percent) being less beneficial. Many soil-lime mixtures are nonplastic with 3 percent lime while others retain PI at increased treatment levels.

8. Proposed Mixture Design Process

Different procedures are used for structural layer applications and subgrade modification.

a. Structural Layer. A flow diagram of the proposed process is shown in Figure 15.

b. Subgrade Modification. Depending on the stabilization objective(s) (immediate strength improvement, PI reduction/workability improvements, swell reduction) either CBR tests and/or Atterberg Limit tests are appropriate. Soil-lime mixtures should be prepared at various lime percentages (2 percent increments are generally used) and tested. Select a design lime content, using the criteria presented in paragraph D.7.a.

TABLE 5. CURED STRENGTH REQUIREMENTS FOR SOIL-LIME STRUCTURAL LAYERS.

	No Freeze-Thaw Activity	Freeze-Thaw* Zone
Subbase	100 psi	150 psi
Base	150 psi	200 psi

*Use these criteria if F-T cycles will occur in the structural layer. It is possible to be in a mild F-T area and not experience F-T cycles in the subbase or base layer.

UNCONFINED COMPRESSIVE STRENGTH (Note 1)

a) Natural Soil

b) Soil + Lime; Curing: 48 hours at 120°F

DETERMINE STRENGTH INCREASE

< 50 psi
NONREACTIVE SOIL

(Mixture not suitable for structural layer application)

> 50 psi
REACTIVE SOIL

(Mixture suitable for structural layer application)

Unconfined Compressive Strength Testing (Variable Lime %, Note 2)

ANALYZE STRENGTH TEST RESULTS

DETERMINE DESIGN LIME %

Lime % above which further increases do not produce significant additional strength

CHECK STRENGTH OF DESIGN MIXTURE WITH CRITERIA-TABLE -5

DESIGNATE FIELD LIME %

Add 1/2 to 1% to design lime % to account for construction losses uneven distribution, etc.

Notes

1. All specimens compacted at optimum water content to maximum dry density (MIL-STD-621A, Method 100 or ASTM D-698). Lime treatment level for b may be 5% or as determined by the "pH procedure" presented in Appendix C, Section II.

2. Specimens compacted at optimum moisture content to maximum dry density. Use the "pH procedure" (Appendix C, Section II) to estimate the optimum lime content. Specimens should be prepared at optimum, optimum +2, and optimum -2 lime percentages. Additional and/or different lime percentages may be required for some soils. Four specimens should be prepared for each treatment lime percentage. Recommended curing conditions are 48 hours @ 120°F or 28 days @ 72°F.

Figure 15. Flow Diagram for Soil-Lime Mixture Design.

SECTION IV

CEMENT STABILIZATION

A. TYPES AND PROPERTIES OF CEMENT

Portland cement is an energy rich anhydrous tricalcium silicate (C_3S)* with excess lime. Unhydrated cements contain a range of particle sizes, with an average particle diameter of the order of 10 μm (10×10^{-6}m). Although the surface area of portland cement powder is only about 0.3 m^2/gm, the cement gel after hydration has a surface area of about 300 m^2/gm. This large surface area is responsible for the cementing action of cement pastes by adhesion forces to adjacent surfaces. Calcium silicate hydrate (CSH)*, termed tobermorite, is the predominant cementing compound in hydrated portland cement.

Several different cement types have been used successfully for cement stabilization of soils. Normal portland cement (Type I) and air-entraining cement (Type IA) were used extensively and gave about the same results. Type II cement has now largely replaced the Type I cements because of its greater sulfate resistance which is achieved by limiting the tricalcium aluminate (C_3A)* content to 8 percent. 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 than do the other cement types. Maximum contents of K_2O and Na_2O may be specified in any cement type to limit alkali-aggregate reactions if necessary. Chemical physical property specifications for portland cement can be found in ASTM C-150.

B. SOIL-CEMENT REACTIONS

Cement stabilization resembles lime stabilization in many ways, except with cement, pozzolanic material is present in the cement initially and need not be derived from the soil itself. In predominantly coarse-grained soils the cement paste bonds soil particles together by surface adhesion forces between the cement gel and particle surfaces. In fine-grained soils the clay phase may also contribute to the stabilization through solution in the high pH environment and reaction with the free lime from the cement to form additional calcium silicate hydrate (CSH). A basic difference is that the cement stabilization reaction with coarser soil occurs more quickly than does lime-soil reaction. However, both cement and lime reactions continue with time.

The crystallization structure formed by the set cement is mainly extraneous to the soil particles. This structure can be

---

*C = CaO, S = SiO_2, H = H_2O, A = Al_2O_3.

disrupted by subsequent swelling of soil particle groups if an insufficient cement content is used. Disruption of the cement structure can also be caused by certain salt solutions; e.g., sulfates, although some of these salts, if present initially, may have a beneficial effect.

C. SOILS SUITABLE FOR CEMENT STABILIZATION

A wide range of soil types may be stabilized using portland cement. The greatest effectiveness and economy in highway and airfield construction in comparison to other stabilizers, is with sands, sandy and silty soils and clayey soils of low to medium plasticity. If the plasticity index exceeds about 30 percent, cement becomes difficult to mix with the soil. If cement stabilization is to be used for highly plastic soils, then lime may be added to reduce the plasticity index prior to addition of cement. (See Section III B1).

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 12.1, it is probable that organics, if present, will not interfere with normal hardening (See Appendix C, Section C).

2. Sulfate Attack

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 sulfate of a soil should be considered in the selection of cement as a stabilizer. The use of cement for fine-grained soils containing more than about 1 percent sulfate should be avoided.

3. Water for Hydration

Potable water is normally used for cement stabilization, although sea water has been found to be satisfactory in several cases.

D. TYPICAL PROPERTIES OF CEMENT-STABILIZED SOILS

1. General

For many applications soil-cements and cement-treated soils can be divided into groups: granular and fine-grained. Granular soil-cements are made using the coarser-grained cohesionless soil types, i.e., A-1, A-2 and A-3 soils according to the AASHTO classification system and the (G-) and (S-) soils according to the Unified Soil Classification System, MIL-STD-619B. Fine-grained soil-cements are made using cohesive soils, i.e., AASHTO class A-4, A-5, A-6 and A-7 soils, corresponding to the (C-) and (M-) soils in the Unified System.

The properties of cement-treated soils are strongly dependent on density, water content and confining pressure. The development of generalized property relationships is further complicated by the fact that cement content, curing time and conditions, and the deleterious effects of past loadings and weathering are also important. Unconfined compressive strength is used successfully to indicate the suitability of particular soil cement for structural or modification applications.

In general, for a given cement content, the higher the density the higher the strength of cohesionless soil and cement mixtures. Both water content at compaction and compaction method may be important in cohesive soil and cement mixtures.

2. Compaction Characteristics

Cement addition to a soil generally causes some change in both the optimum water content and maximum dry density for a given compactive effort. Often direction of this change is not predictable. The flocculating action of the cement tends to give an increase in optimum water content and a decrease in maximum density; whereas, the high specific gravity of the unhydrated cement (3.1) relative to the soil tends to produce a higher density. The gradation of the unhydrated portland cement relative to that of the soil may also be important because it influences the packing of particles.

A delay between mixing and compaction leads to a decrease in both density and strength for a fixed compactive effort. If, however, the compactive effort is increased so that the original density is obtained, and provided no significant amount of cement hydration occurs during the delay period, then no strength loss is observed.

3. Strength

The strengths of soil and cement mixtures may range from less than a few tens to more than 2,000 psi, depending on such factors as type of loading, cement content and curing conditions. In general, the highest strengths are associated with mixtures prepared from cohesionless soils. The less plastic the soil, the smaller the deformation required to cause failure.

4. Compressive Strength

The unconfined compressive strength is probably the most widely used measure of the effectiveness of cement treatment. It may be as low as 200 psi for fine-grained soil cements (cement requirement as low as 3 percent by weight) to well over 2,000 psi for coarse grained soils with higher cement contents (about 15 percent by weight). A linear relationship has been used to approximate compressive strength of a given soil based on percent cement used. See Figure 16.

The relationship between strength and curing time for a given soil and cement mixture can be given by:

$$(UC)_d = (UC)_{d_0} + K \log (d/d_0)$$

where $(UC)_d$ = unconfined compressive strength at an age of d days, in psi

$(UC)_{d_0}$ = unconfined compressive strength at an age of d_0 days, in psi

K = 70 C for granular soils and 10 C for fine-grained soils and

C = cement content, in percent by weight.

The 28-day strength was found to be 1.4 to 1.7 times the 7-day strength by different researchers. A value of 1.5 times the 7-day strength would seem a reasonable value for estimating purposes.

5. Tensile Strength

Flexural beam tests, direct tension tests, and the split tension tests have all been used to evaluate the tensile strength. The results of several studies have indicated that the flexural strength is about one-fifth to one-third of the unconfined compressive strength. In low-strength mixtures, the flexural strength is a greater proportion of the compressive strength (up to one-third) than in high-strength mixtures (down to less than one-fifth). A good approximation for the flexural strength f is:

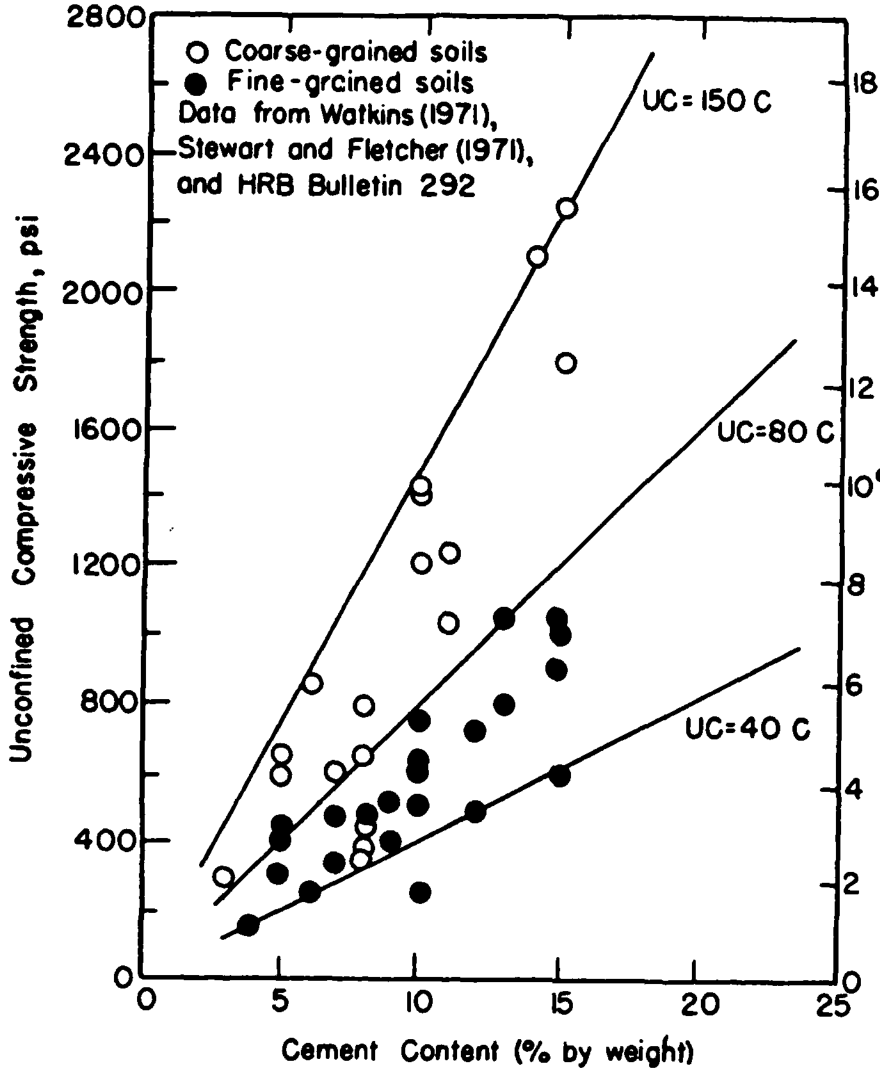


Figure 16. Relation Between Cement Content and Unconfined Compressive Strength for Soil and Cement Mixtures (After Ref. 1). (Equations give strength in psi).

$$f = 0.51\ (UC)^{0.88}$$

where UC is the unconfined compressive strength.

Griffith crack theory has been found useful for characterizing the strength of cement-treated soils under various combinations of major (σ_1) and minor (σ_3) principal stresses. Normalized strength data (failure stresses divided by the unconfined compressive strength) for several soils are summarized in Figure 17. With this figure and a knowledge of the unconfined compressive strength, principal stress combinations causing failure can be estimated directly. These data may prove valuable to the pavement engineer as a tool for predicting fracture potential for specialized or expedient design situations.

6. California Bearing Ratio (CBR)

The relationship between unconfined compressive strength and CBR for some granular and fine-grained soil and cement mixtures is shown in Figure 18. The difference between the relationships for fine-grained and granular-treated soils probably results from the uncertainty associated with the application of the CBR test to coarse-grained soils. The meaning of CBR values greater than 100 percent in relation to pavement design and performance is not clear. Accordingly, the high values of CBR in Figure 18 can be interpreted as a strength index only.

7. Deformation Characteristics and Moduli

In general, the stress-deformation behavior of cement-stabilized soils is nonlinear and stress-dependent. However, for many soils and treatment levels, and within limited loading ranges, the material may be assumed as linearly elastic under repeated loadings. Deformation moduli may range from about 10,000 psi to several million psi, depending on soil type, treatment level, curing time, water content and test conditions. Cement-treated fine-grained soils have modulus values near the lower end of the range, whereas granular soil-cements exhibit the higher values. Different relationships between modulus and strength apply to different soil types.

The modulus under repeated loading conditions depends on soil type, cement content, compaction and curing conditions, and test type. Still the unconfined compressive strength, which depends on the same variables, is a useful correlating parameter. Beyond some number of load repetitions, in the range of a few hundred to 10,000, the resilient modulus in compression M_{RC} can be expressed by:

$$M_{RC} = K_c\ (\sigma_1 - \sigma_3)^{-k_1}\ (\sigma_3)^{k_2}\ (UC)^n$$

where UC = unconfined compressive strength, in psi,

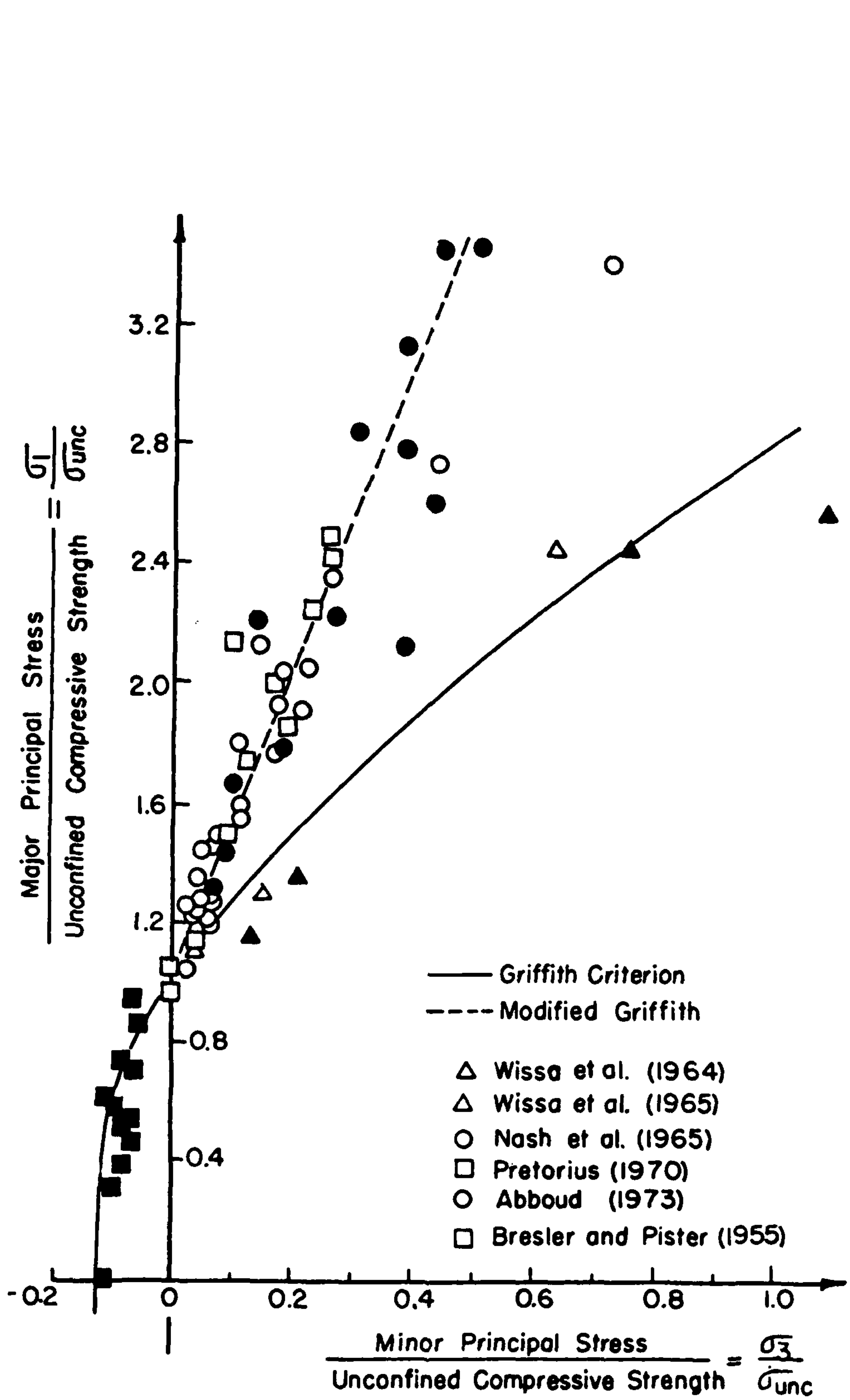


Figure 17. Failure Envelope for Cement-Treated Soils. (After Raad, Monismith and Mitchell, Ref. 4).

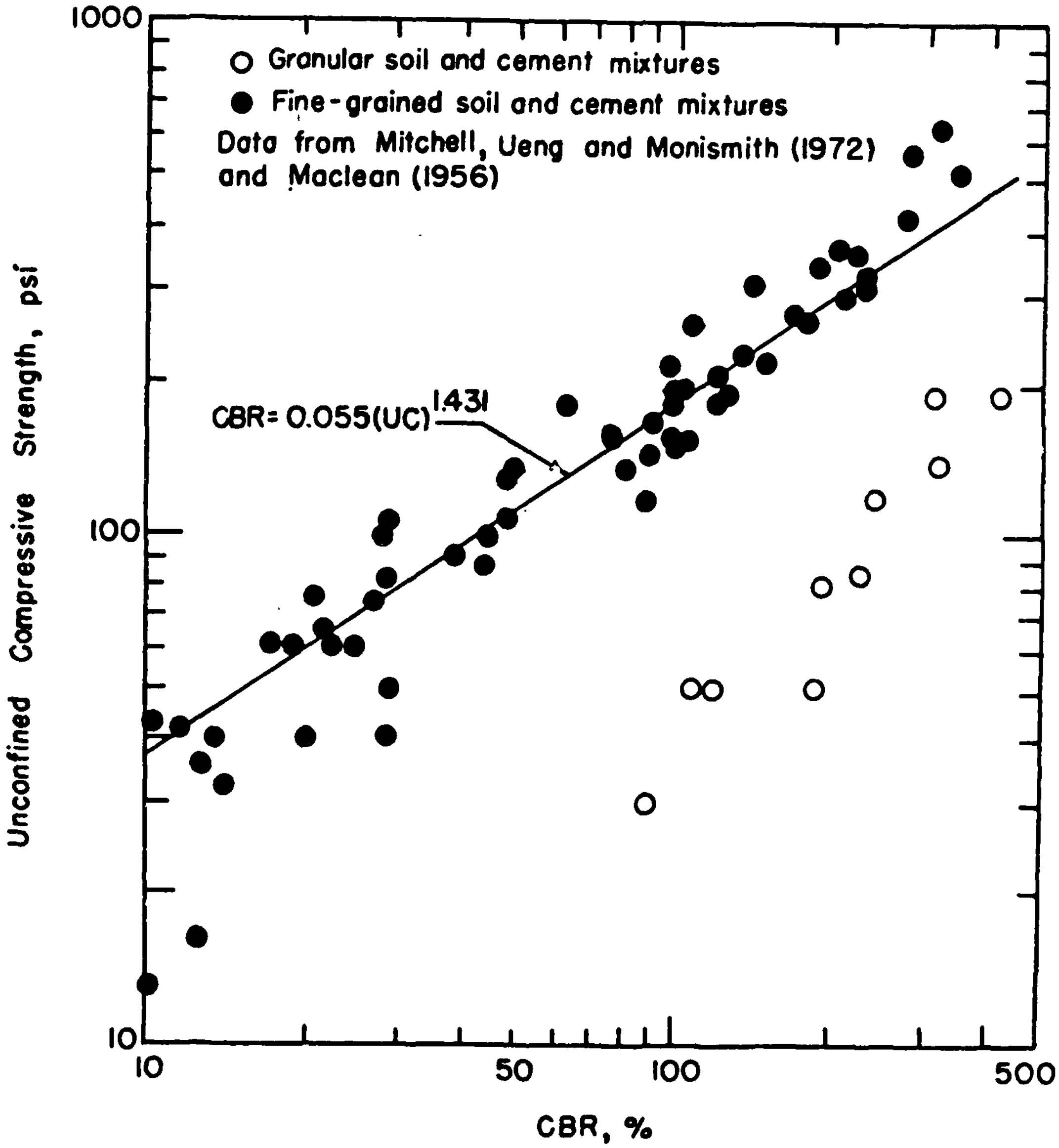


Figure 18. The Relation Between CBR and the Unconfined Compressive Strength of Soil and Cement Mixtures, (After Ref. 1).

$(\sigma_1 - \sigma_3)$ = deviator stress, in psi,

σ_3 = confining pressure, in psi,

K_c = material constant,

k_1 = 0.2 to 0.6,

k_2 = 0.25 to 0.7,

$n = 1.0 + 0.18\ C$ and

C = cement content in percent by weight.

Determination of k_1, k_2 and K_c requires separate measurements of M_{RC} under at least two values of σ_3 and two values of $(\sigma_1 - \sigma_3)$.

If it is assumed that confining pressure has no effect on resilient modulus in flexure, M_{RF}, then, from the results of beam tests:

$$M_{RF} = K_F (10)^m \cdot UC$$

where K_F = material constant,

UC = unconfined compressive strength, in psi,

$m = 0.04(10)^{-.186C}$ and

C = cement content in percent by weight.

At working stress levels for pavement bases and treated subgrades, Poisson's ratio is in the range of 0.1 to 0.2 for treated granular soils. Treated fine-grained soils exhibit somewhat higher values, with a typical range of 0.15 to 0.35.

8. Fatigue Behavior

Cement-treated soils are susceptible to fatigue failure after repeated application of stresses greater than some limiting value. Fatigue in flexure is of greatest interest because of its relevance to pavement cracking. Listed below are some general observations concerning the fatigue behavior of cement-treated soils.

a. Fatigue life is shorter under repeated direct tensile stresses than in compression.

b. Flexural fatigue is unlikely for repeated stress levels less than 50 percent of the flexural strength.

c. The flexural fatigue of soil-cement can be related to radius of curvature according to:

$$R_{c/R} = aN^{-b}$$

where R_c = critical radius of curvature, i.e., the radius of curvature causing failure under static loading,

R = radius of curvature leading to failure under N load applications,

$a = \dfrac{h^{3/2}}{2.1h-1}$,

h = slab thickness, inches

b = 0.025 for granular soil-cements and 0.050 for fine-grained soil cements and

N = number of load applications.

d. Repeated tensile stresses cause a progressive decrease in tensile strength froms its initial value T_i. When the strength drops to F, cracking failure is initiated. A relationship between F_{max}/T_i and the number of stress repetitions of N_f to cause failure that fits available fatigue data well is shown in Figure 19. The two curves shown pertain to different times after treatment.

9. Shrinkage

Cement-treated soils exhibit shrinkage on curing and drying in an amount that depends on cement content, soil type, water content, degree of compaction and curing conditions. Some amount of shrinkage cracking should be considered inevitable in soil-cement pavement slabs. Field observations indicate the cracks to be from 1/8 to 1/4 inch wide at spacings of 10 to 20 feet. The smaller crack spacings are usually associated with the higher clay content soils. Because of the likelihood of shrinkage cracks in soil-cement road bases, it is important to consider edge loading conditions in thickness design and to provide surface sealing so that water is prevented from entering the subgrade and consequent to loss of support.

Table 6 provides a general summary of the properties of cement-stabilized soils. The numerical values indicated are typical for usual conditions. Final design values in any case should be based, whenever possible, on carefully conducted tests in which the anticipated field conditions are simulated as closely as possible.

These summarized values are presented as a guide and can be used by the pavement engineer in analyzing pavement systems containing stabilized layers by layered elastic modeling.

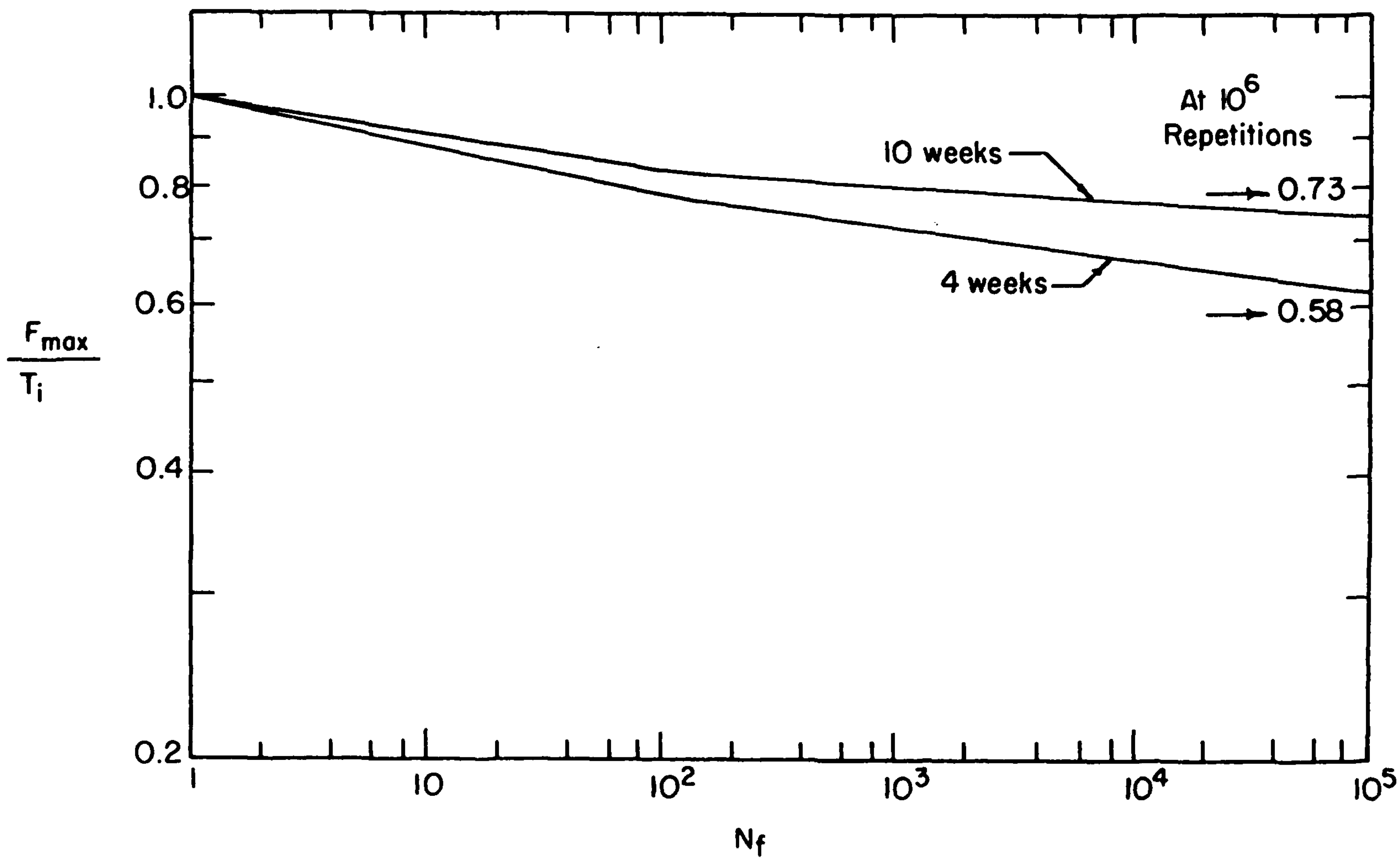


Figure 19. Suggested Fatigue Failure Criteria for Cement-Treated Soils. (After Raad, Monismith and Mitchell, Reference 4).

TABLE 6. SUMMARY OF THE PROPERTIES OF CEMENT-STABILIZED SOIL (MODIFIED FROM REF. 1).

(UC = Unconfined Compressive Strength; C = Cement Content, Percent by Weight)

Property	Granular Soils	Fine-Grained Soils	Notes
Unconfined Compressive Strength	UC = (90 to 150) C $(UC)_d = (UC)_d + K \log (d/d_o0)$ K = 70 C (psi)	UC = (40 to 80) C K = 10 C (psi)	UC in psi d = age (days) $(d > d_o)$ $(UC)_{d_o}$ = UC strength at age of d_o days
Cohesion	To a few hundred psi C = 7.0 + 0.225 (UC) psi	To a few hundred psi	Depends on C, d
Friction Angle	45-45°	30-40°	May decrease at high confining pressure
Flexural and Tensile Strength	Tensile Strength = $(\frac{1}{5}$ to $\frac{1}{3})$ Compressive Strength		Need 1-3 percent cement to develop
Strength under Combined Stress States	$(\sigma_1-\sigma_3)^2 = UC(\sigma_1+\sigma_3)$ for $\sigma_3/UC < 0.1$ $\sigma_1 = UC + 5\sigma_c$ for $\sigma_3/UC < 0.1$ (compression positives)		Relationships developed using Griffith crack theory
CBR	$CBR = 0.55\ (UC)^{1.431}$		UC in psi
Modulus-Compression	$1 \times 10^6 - 5 \times 10^6$ psi $E_t = [1 - \frac{0.75(1-\sin\phi)(\sigma_1-\sigma_3)}{2\ C \cos\phi + 2\sigma_3 \sin\phi}]^2 E_i$ $E_i = Kp_a (\frac{\sigma_3}{p_a})^n$	$10^5 - 10^6$ psi	Depends on stress level E_i = initial tangent modulus E_t = tangent modulus σ_3 = confining pressure p_a = atmospheric pressure n = 0.1 - 0.5 K = 1000 - 10,000
Modulus - Tension Flexure	Same order magnitude as in compression		$E_c > E_t$ (usually
Resilient Modulus - Compression	$M_{RC} = K_c(\sigma_1-\sigma_3)^{-k_1}(\sigma_3)^{k_2}(UC)^n$		k_1 = 0.2 to 0.6 k_2 = 0.25 to 0.7 n = 1.0 + 0.18 C
Resilient Modulus - Flexure	$M_{RF} = K_f(10)^m \cdot UC$		$m = 0.04(10)^{-.186C}$ Effect of confining pressure not known
Fatigue Behavior	No fatigue for $F/T_i < 0.50$ T_i = initial tensile strength $F = \frac{(\sigma_1-\sigma_3)^2}{8(\sigma_1+\sigma_3)}$ for $\sigma_1+3\sigma_3 > 0$ $F = -\sigma_3 \quad \sigma_1 + 3\sigma_3 < 0$		
Poisson's Ratio	0.1 - 0.2	0.15 - 0.35	
Shrinkage	A few tenths of 1 percent	Up to 1 percent	Shrinkage cracks generally inevitable
Thermal Properties (a) Conductivity	k = 0.6	k = 0.3	BTU - ft/hr . ft^2 . °F
(b) Heat Capacity	C = 0.82		BTU/lb . °F
(c) Thermal Expansion	$\epsilon = 5 \times 10^{-6}$ $\epsilon = 9 \times 10^{-6}$		°F^{-1} °C^{-1}

E. SELECTION OF CEMENT CONTENT

1. Approximate Quantities

Table 7 lists the usual cement requirements for soil-cement for various soil types classified according to the AASHTO and Unified systems. An approximate cement content may be selected from this table. The cement content ranges indicated are for soil-cement, a hardened material that will pass rather severe durability tests. For many applications, e.g., treated subgrades, subbases, low volume roads, and mild exposure conditions, satisfactory stabilization may be achieved with lower cement contents.

2. Detailed Testing

For major projects, and when soil-cement meeting specified durability conditions is required, a more detailed testing program is needed. The flow diagram in Figure 20 may be used as a basis for determination of the cement content. The pH determination is used to establish whether sufficient deleterious organic matter is present to inhibit cement hydration (see Appendix C, Section C). The sulfate determination will establish the possibility of adverse sulfate reactions (see Appendix C, Section IV).

a. Description. There are three standard tests: moisture-density, wet-dry and freeze-thaw; a short-cut test for sandy soils and a rapid test procedure used for soil-cement stabilization. The moisture-density test determines the proper (optimum) moisture content and maximum density for molding laboratory specimens. In the field, this test is used to determine the quantity of water to be added and the density to which the mixture should be compacted. The wet-dry test indicates whether the hardened soil-cement will stay hard or soften from exposure to moisture variations. The freeze-thaw test not only shows how soil-cement reacts to weather, but also whether the cement has hardened the soil or not. Short-cut test procedures for sandy soils do not involve a series of new tests, but rather use previous test information to reduce the testing required. The rapid test procedure is adequate for emergency construction and for small projects where more complete testing is impractical.

b. Selection of Cement Contents. Specimens prepared with very high cement contents will all pass the tests. On the other hand, inadequate cement contents will cause all specimens to fail the test.

(1) The principal requirement of a hardened soil-cement mixture is to withstand exposure to the elements. Although strength is also required, most soil-cement mixtures which possess adequate resistance to the elements also possess

TABLE 7. CEMENT REQUIREMENTS FOR VARIOUS SOILS (AFTER REF. 5).

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

*Based on correlation presented by Air Force.

**For most A horizon soils the cement should be increased four percentage points, if the soil is dark grey to grey, and six percentage points if the soil is black.

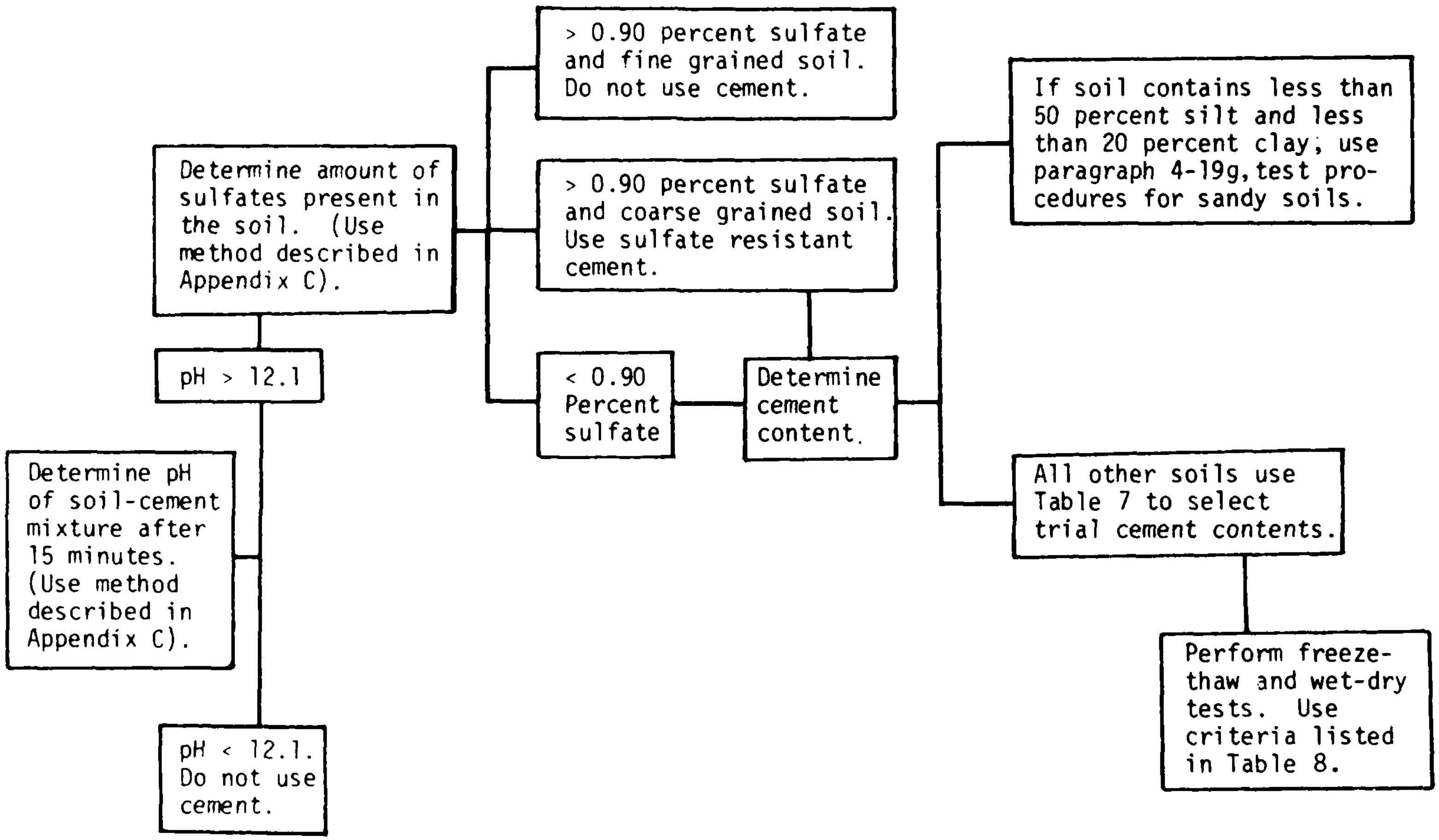


Figure 20. Subsystem for Nonexpedient Base Course Stabilization With Cement.

adequate strength. The reverse is not always true. For example, a compacted, clay loam soil (without added cement) can withstand relatively heavy loads. When mixed with cement and compacted, the same soil will have a stability equal to that of the raw soil (before the cement hardens). Under the effects of moisture, the original soil (without cement) will lose stability even though compacted. The soil with cement, upon hardening, will show an increase in stability.

(2) Economy is another important factor. Experience shows that approximately 85 percent of the soils considered for soil-cement stabilization can be adequately stabilized by adding 14 percent or less of cement. However, more than 50 percent require only 10 percent or less of cement. Selecting the optimum amount can result in a sizeable saving of cement.

(3) As a general rule, the cement requirement increases as the silt and clay content increases, and a gravelly or sandy soil will require less cement. There is one exception. A poorly graded, one-size-particle sand with no silt and clay will require more cement than a sandy soil with some silt and clay. Well graded mixtures; containing gravel, coarse and fine sands and with or without small amounts of silt or clay; require five percent or less of cement by weight. The poorly graded, one-particle-size sand requires about 9 percent by weight. The other sandy soils require only 7 percent. Nonplastic or moderately plastic silty soils require 10 percent and plastic clays 13 percent or more.

(4) Table 7 indicates the usual cement contents for moisture-density, strength, wet-dry and freeze-thaw durability testing. Where classification appears in more than one category, plasticity and organic content are considerations. The cement contents are used as preliminary estimates which are verified or modified as the test data become available.

c. Preparation for Testing. Two methods of testing will be described. The first is used with soils containing material that is retained on the Number 4 sieve (up to a maximum of 45 percent) and the second for soils not containing material that is retained on the Number 4 sieve. The maximum size particle used in the test specimen is 3/4 inch. If larger particles are present in the sample, they are replaced with an equivalent weight of material from the portion that passes the 3/4-inch sieve and is retained on the Number 4 sieve. About 75 to 100 pounds of soil are prepared for testing. When necessary, the sample is dried until it is friable under a trowel. This may be accomplished by air-drying or oven-drying at a temperature of 140°F. The soil is then separated on the 3-inch, 3/4-inch and Number 4 sieves. All clusters should be broken up into individual particles. The soil passing the Number 4 sieve should be well mixed and stored in a covered container throughout the duration of the test. The material larger than the 3-inch sieve is not included in the calculations of grain-size distribution, but its quantity is noted and the material discarded. The material retained on the 3/4-inch and Number 4 sieves is weighed and the weights recorded. They will be used in the computations. The material retained on the 3/4-inch sieve is replaced with the material retained on the Number 4 sieve.

3. Moisture-Density Relationship

Before starting this test, it is necessary to select the cement contents to be used in the freeze-thaw and wet-dry tests. The cement contents are usually selected in 2 percent increments to encompass the values given in Table 7. For example, Table 7 lists 7 to 11 percent for the SP sand. The cement content increments would be 7, 9 and 11 percent. In the CL-CH group (9 to 15 percent), the selected increments would be 10, 12 and 14 percent. Since maximum density varies only slightly with variations in the cement content, only the median value is used in preparing specimens for the moisture-density test. The procedures for determining the optimum moisture content (OMC) are similar to those described in MIL-STD-621A, Method 100, or ASTM D-558 with the following exceptions. Compaction is performed on five layers of approximately equal thickness to result in a total compacted depth of 5 inches. Each layer is compacted by 25 uniformly spaced blows of a 10-pound tamper (2-inch diameter face) dropped from a height of 18 inches. The computations and OMC determinations then follow the procedures described in MIL-STD-621A, Method 100 or ASTM D-558.

4. Wet-Dry and Freeze-Thaw Tests

After determining the maximum density and OMC, specimens must be molded for the wet-dry and freeze-thaw tests. These specimens are prepared, using the computed OMC and the cement contents described above for the different soil classifications. The cement contents are selected in 2 percent increments either side of the median value. Two specimens are molded for each of the three cement contents; one for the wet-dry test and one for the freeze-thaw test. The same procedure is used to mold the specimens as was used for the OMC determination. Special care must be used to scarify the surfaces between layers to assure a good bond. When the second layer is being placed, a 750-gram sample should be taken for a moisture determination. The molded specimens are placed in a moisture cabinet in an atmosphere of high humidity for 7 days to permit cement hydration before testing.

a. <u>Wet-Dry Test</u>. This test is to be performed in accordance with ASTM D-559.

b. <u>Freeze-Thaw Test</u>. This test is to be performed in accordance with ASTM D-560.

5. Compressive Strength Test

Compressive strength is a supplementary consideration to the resistance to weather. Five specimens are molded, for each of the three cement contents using the optimum moisture and the molding procedure of the moisture-density test. If a 4-inch diameter, 4.5-inch high specimen is to be molded (a 2.0-inch diameter, 4.0-inch high specimen is also acceptable), only the samples with material retained on the Number 4 sieve (up to 45 percent maximum) are used. Compressive strength tests are conducted after 2, 7, 14, 21, and 28 days (tests at 14 and 21 days are optional). Four hours prior to the test, one specimen at each cement content is withdrawn from the moisture cabinet and immersed in tap water at room temperature (approximately 70°F). Each specimen is tested in the compression machine until failure and the total load required for failure is recorded. The compressive strength in pounds per square inch is computed by dividing the total load by the average area of the top and bottom of the specimen. See ASTM D-1632 and D-1633 for fabrication and testing.

6. Calculations and Criteria

The results of the wet-dry and freeze-thaw cycles are indicated as soil-cement losses. These losses are computed by using the original dry weights and final corrected dry weights.

a. Water-of-Hydration Correction. The final oven-dry weight of the specimen includes some water used for cement hydration that cannot be driven off at 230°F. The average amount of this water retained in the specimen is based on the type of soil; gravels 1 1/2 percent $\pm$, sands 2 1/2 percent $\pm$, silts 3 percent $\pm$, and clays 3 1/2 percent $\pm$. This correction is computed by the following formula:

Corrected oven-dry weight =

$$\frac{\text{measured oven-dry weight of specimen}}{\text{percent water retained} + 100} \times 100$$

Example: Sample composed mostly of sand weighs 3.77 pounds at the end of the test. Water-of-hydration is 2.5 percent.

Corrected oven-dry weight =

$$\frac{3.77}{2.5 + 100} \times 100 = \frac{3.77}{1.025} = 3.68 \text{ lb.}$$

b. Soil-Cement Loss. The soil-cement loss can now be calculated, as a percentage of the original dry weight, or:

Soil-cement loss =

$$\frac{\text{(Original oven-dry weight)} - \text{(Corrected oven-dry weight)}}{\text{Original oven-dry weight}} \times 100$$

Example: The sample in the example above weighed 3.99 pounds originally.

$$\text{Soil-cement loss} = \frac{3.99 - 3.68}{3.99} \times 100 = 7.8 \text{ percent}$$

This value would be reported to the nearest whole number or as 8 percent.

c. Durability Criteria. Criteria for satisfactory performance of soil-cement in the durability tests are listed in Table 8. Cement contents sufficient to prevent weight losses greater than the values indicated after 12 cycles of wetting-drying-brushing or freezing-thawing-brushing are adequate to produce a durable soil-cement. Soil-cement mixes designed in this way can generally be expected to perform satisfactorily as roadway base courses. An exception to this is the case of cement-treated uniform sands. Recent experience shows that with low-cost, low-volume roads, excessive shrinkage cracks develop if the full cement requirement is used. An unsightly pavement develops as a result, and slippage of thin (1 to 1 1/2 inches) asphaltic concrete surfacing may occur. Although some shrinkage cracking is inevitable, as noted earlier, it can be minimized in uniform sands if the cement and water contents are held to a minimum while still obtaining a desired compressive strength, usually about 300 psi.

d. Strength Criteria. The strength of soil cement specimens tested in compression at various ages should increase with age and with increases in cement, in the ranges of cement contents producing results meeting the requirements above. A sample that has an unconfined compression strength of approximately 300 psi after curing 7 days and shows increasing strength with age can be considered adequately stabilized.

e. Cement Weight-to-Volume Conversion. The required cement content by weight must be converted to the equivalent cement content by volume for control during construction, since this is the easier quantity to use in the field. The following formula illustrates the calculation:

$$\text{Volume of cement (percent)} = \frac{D-(D/C)}{94} \times 100$$

where D = oven-dry density of soil-cement (lb/cu ft),

$$C = \frac{100 + \text{percent cement (by weight)}}{100} \text{ and}$$

94 = weight of 1 cu ft of cement.

TABLE 8. CRITERIA FOR SOIL-CEMENT AS INDICATED BY WET-DRY AND FREEZE-THAW DURABILITY TESTS (AFTER REF. 5).

AASHTO Soil Group	Unified Soil Group	Maximum Allowable Weight Loss - Percent
A-1-a	GW, GP, GM, SW, SP, SM	14
A-1-b	GM, GP, SM, SP	14
A-2	GM, GC, SM, SC	14*
A-3	SP	14
A-4	CL, ML	10
A-5	ML, MH, CH	10
A-6	CL, CH	7
A-7	OH, MH, CH	7

*10 percent is maximum allowable weight loss for A-2-6 and A-2-7 soils.

Additional Criteria:

1. Maximum volume changes during durability test should be less than 2 percent of the initial volume.

2. Maximum water content during the test should be less than the quantity required to saturate the sample at the time of molding.

3. Compressive strength should increase with age of specimen.

7. Modified-Mix Design for Sandy Soils

Sandy soils are generally the most readily and economically stabilized because they require the least amount of cement for adequate hardening and because they contain a minimum amount of material which prevents intimate mixing of soil and cement. The following short-cut testing procedures for sandy soils will not always indicate the minimum cement contents required but the results will be close enough to be on the safe side and economical.

Two procedures are used; one for soils not containing material retained on the Number 4 sieve, and the other for soils containing material retained on the Number 4 sieve. The procedures can be used only with soils containing less than 50 percent of material smaller than 0.005 mm (clay). Dark gray to black sandy soils obviously containing appreciable organic impurities, together with miscellaneous granular materials such as cinders, caliche, chat, chert, marl, red dog, scoria, shale, and slag should be tested using the full procedures and not tested by the modified methods for sandy soils. When coarse grained or sandy soils (generally of groups GW, GP, GM, SW or SM) are encountered, they may be classified for testing purposes using either the first or the second procedure. There is one other exception. Granular soils with materials retained on the Number 4 sieve whose bulk specific gravity is less than 2.45 cannot be tested.

a. The procedure consists of the following sequence:

(1) Determine the soil gradation.

(2) Determine the bulk specific gravity of the material retained on the Number 4 sieve, ASTM C-127.

(3) Perform the moisture-density test for an estimated soil-cement mixture.

(4) Locate the indicated cement requirements from the charts.

(5) Perform compressive-strength tests to verify the cement requirement.

b. The step-by-step method for soils with no material retained on the Number 4 sieve is as follows:

(1) Determine the maximum density and OMC for a mixture of soil and cement. Figure 21 will give an estimated maximum density. This value and the percentage of material smaller than 0.05 mm are used with Figure 22 to determine an estimated cement content.

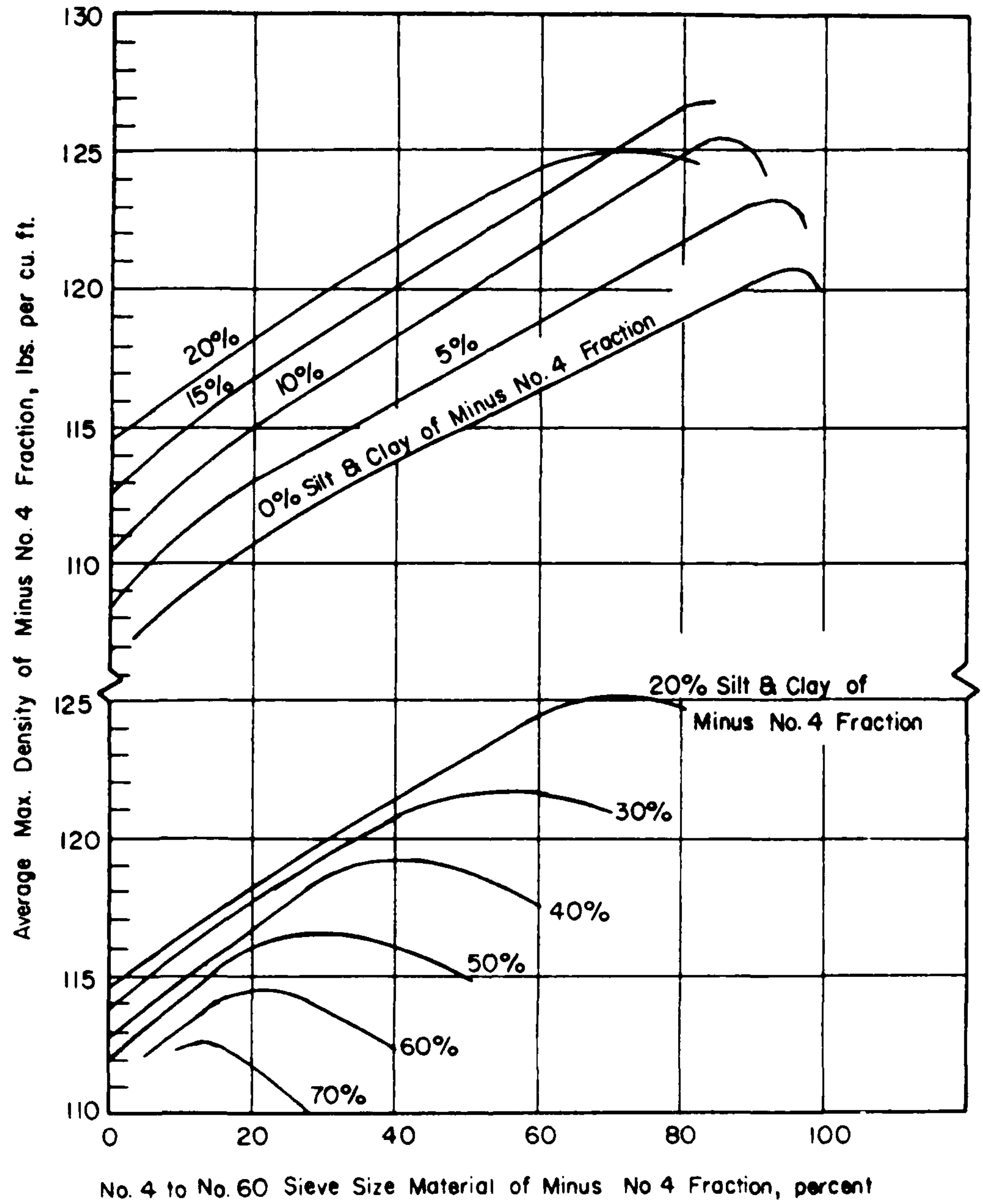


Figure 21. Average Maximum Densities of the Minus No. 4 Fraction of Soil-Cement Mixtures. (Reproduced with Permission of the Portland Cement Association, After Ref. 5).

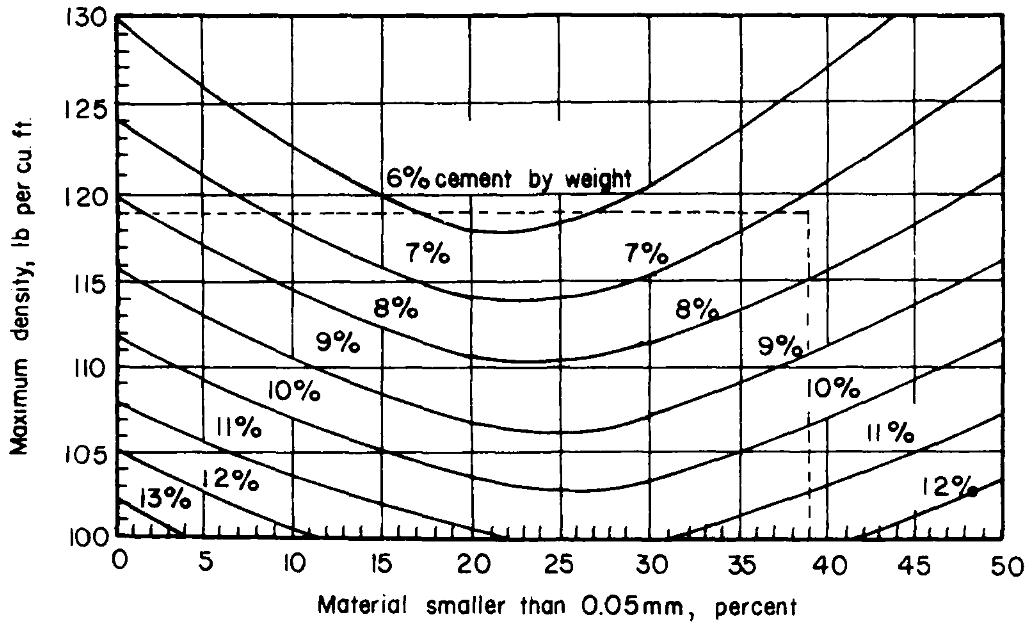


Figure 22. Indicated Cement Contents of Soil-Cement Mixtures Not Containing Material Retained on the No. 4 Sieve. (Reproduced with Permission of the Portland Cement Association.)

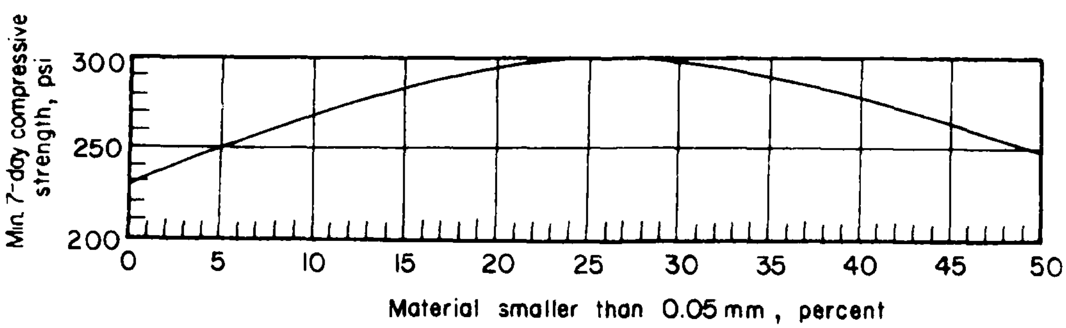


Figure 23. Minimum 7-Day Compressive Strengths Required for Soil-Cement Not Containing Material Retained on the No. 4 Sieve. (Reproduced with Permission of the Portland Cement Association.)

(2) Use the maximum value [(a) above] and Figure 22 to determine an indicated cement requirement.

(3) Mold three compressive-strength specimens at maximum density and OMC.

(4) Moist-cure the specimens for 7 days and test for strength.

(5) Plot the value of the averaged compressive strength in Figure 23. If this plot is below the curve, the cement factor is probably too low and needs adjusting. Two new test specimens are prepared; one at the cement content as computed in (b) above, and the second with a two percent higher cement content. The full freeze-thaw test is performed on these two specimens.

c. The method of testing of soils containing material retained on the Number 4 sieve is as follows:

(1) Determine the maximum density and optimum moisture content for a mixture of soil and cement. Use Figure 24 for an estimated maximum density, and Figure 25 with this density, percentage of material retained on the Number 4 sieve and percentage smaller than 0.05 mm to determine cement content. The 45 percent maximum retained on Number 4 sieve (discussed in Section IV E) still applies. Also, any material larger than 3/4-inch must be replaced with an equivalent weight of the material passing the 3/4-inch sieve and retained on the Number 4 sieve.

(2) Using the maximum density from (a) above and Figure 25, determine the indicated cement requirement.

(3) Mold test specimens at maximum density and OMC.

(4) After 7 days moist-curing, test for compressive strength and average.

(5) Using Figure 26, determine the allowable compressive strength for the soil-cement mixture. Connect points on the right-and-left hand scales of the nomograph and read the minimum required compressive strength from the inclined center scale. If the tested strength is equal to or greater than the allowable, the cement content is adequate. If the strength is too low, the cement factor is also too low, and a full test should be performed.

G. Approximate and Rapid Tests

a. <u>Squeeze Test</u>. A sample mixture of soil, cement and water may be tested for optimum moisture content by squeezing in the hands. When squeezed firmly, the sample at optimum moisture content will form a cast that will cling together and

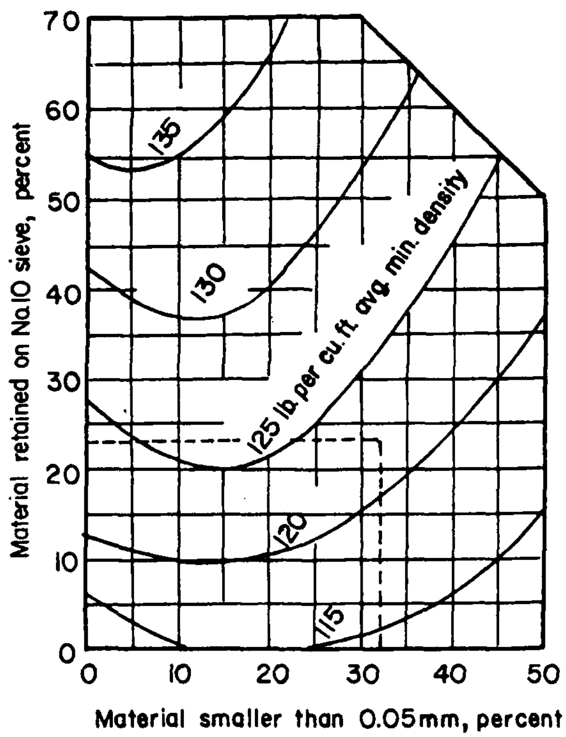


Figure 24. Average Maximum Densities of Soil-Cement Mixtures Containing Material Retained on the No. 4 Sieve. (Reproduced with Permission of the Portland Cement Association, After Ref. 5).

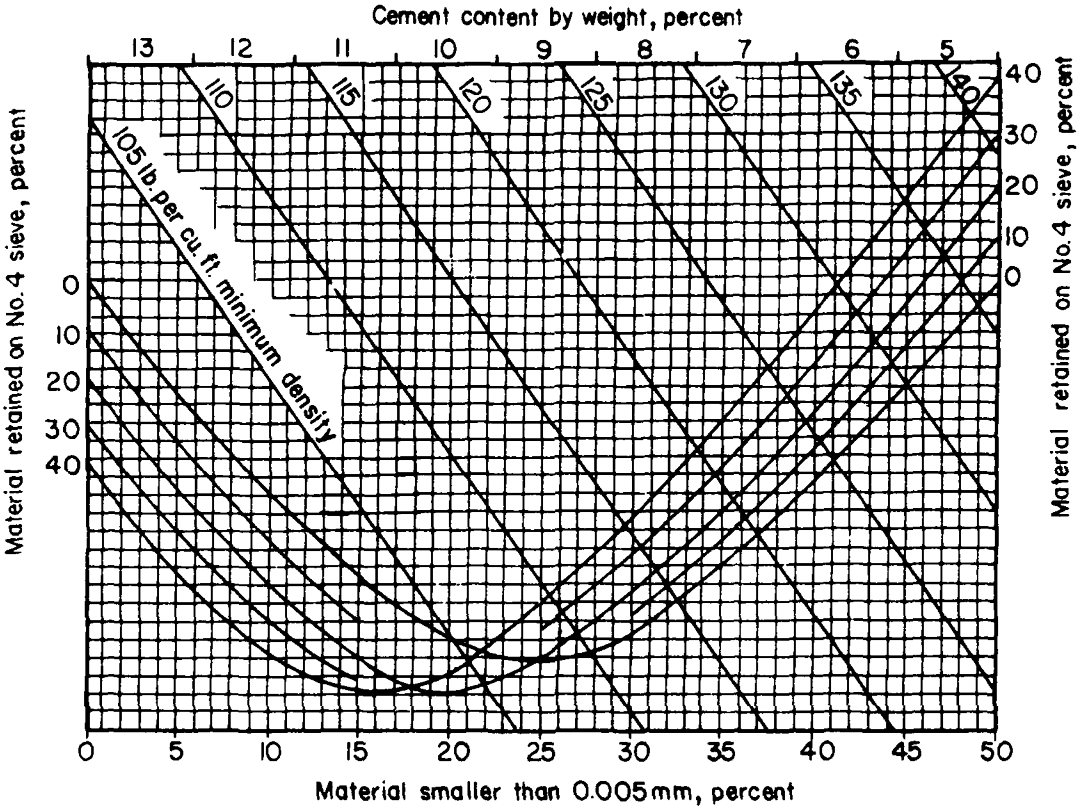


Figure 25. Indicated Cement Contents of Soil-Cement Mixtures Containing Material Retained on No. 4 Sieve. (Reproduced with Permission of the Portland Cement Association.)

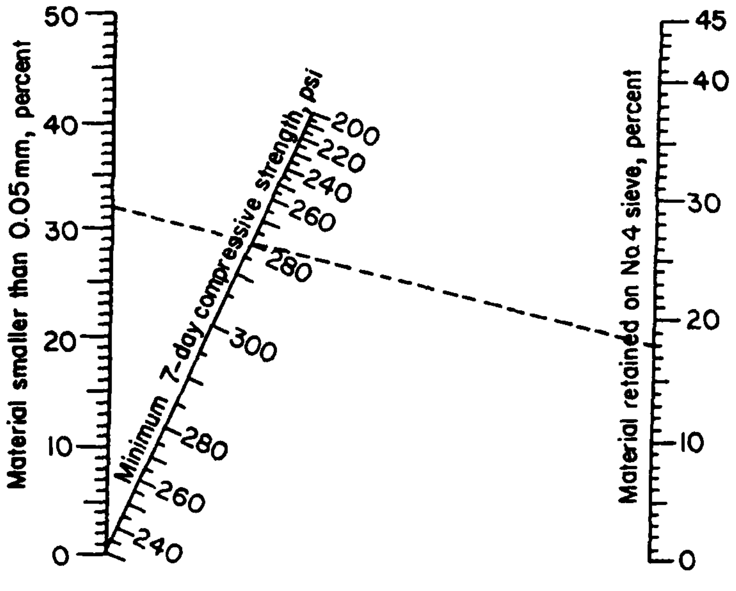


Figure 26. Minimum 7-Day Compressive Strengths Required for Soil-Cement Mixtures Containing Material Retained on No. 4 Sieve. (Reproduced with Permission of the Portland Cement Association, After Ref. 5).

moisten the hands but water cannot be squeezed out of the mixture.

b. "Pick" and "Click" Tests. Specimens covering a wide range of cement contents (for example: 10 percent, 14 percent, and 18 percent) are, molded at optimum moisture and maximum density. After at least 1 or 2 days of hardening while kept moist, and after a 3-hour soaking period, the specimens are inspected by "picking" - done with a pointed instrument such as a dull ice pick or bayonet - and by sharply "clicking" each specimen against a hard object such as concrete or another sound specimen, to determine their relative hardness when set. If the specimen cannot be penetrated more than 1/8 to 1/4 inch by "picking" and if it produces a clear or solid tone upon "clicking," and adequate cement factor is indicated. When a dull thud or "punky" sound is obtained, there is inadequate cement even though the specimen may resist picking. The age of the specimens is defintely a factor, and a specimen which may not test properly at first try may harden properly a few days later. Some satisfactory specimens require 7 days or longer to produce adequate hardening. The test results will indicate the proper content. If the results show that some intermediate content may be satisfactory, new test specimens (at the suggested content) should be prepared and tested. Too much cement is not harmful (although more expensive), but too little will not produce a satisfactory stabilization.

F. ADDITIONAL INFORMATION

Additional information concerning the design of cement stabilized soils can be obtained from the Soil Cement Laboratory Handbook (5).

SECTION V

ASPHALT STABILIZATION

A. GENERAL

Asphalt-bound materials provide a resilient, water-proof, load-distributing material that can be used for subbase, base or surface courses. The flexibility of asphalt-stabilized materials permits the pavement to undergo long-term movements, such as those caused by consolidation or active subgrade soils, without excessive cracking. However, asphalt-bound materials are unsatisfactory (if not properly protected) for use in areas where fuel spillage is expected and where heat and blast effects from jet aircraft are severe.

The major reasons for using asphalt stabilization are to:

1. Waterproof fine-grained soils,

2. Meet construction expediency,

3. Upgrade marginal materials,

4. Reduce pavement layer thickness to conserve materials, reduce costs and conserve energy,

5. Provide temporary and permanent wearing surfaces, and

6. Reduce dusting.

B. RELATED MATERIAL

1. Air Force Manual 88-6, Chapter 9, Bituminous Pavements Standard Practice, for design and construction operations.

2. Air Force Manual 88-6, Chapter 2, Section 7, Flexible Pavement Design for Airfields, for general design considerations associated with surface courses made with asphalt binders.

3. Air Force Manual 89-3, Materials Testing, for material testing techniques.

4. The Asphalt Institute (MISC-74-2) Mix Design Methods for Liquid Asphalt Mixtures, for mix design methods for liquid asphalt mixtures (6).

5. The Asphalt Institute (MS-14) Asphalt Cold Mix Manual, for construction procedures and specifications on cold-mix operations with asphalt (7).

6. The Asphalt Institute (MS-2) Mix Design Methods for Asphalt Concrete, for design methods associated with hot-mix operations (8).

7. Federal Highway Administration (FHWA-1P-79-1), Volume 1, A Basic Asphalt Emulsion Manual, for understanding, using and designing mixtures containing asphalt emulsions (9).

8. Federal Highway Administration (FHWA-1P-80-2) Soil Stabilization in Pavement Structures - A User's Manual, for additional detail on mixture design, pavement design and construction considerations (1).

9. Chevron, USA, Bituminous Mix Manual, for mix design and guide specifications for emulsion stabilization (10).

C. TYPES OF ASPHALTS

Asphalts are one of the two major groups of bituminous materials used in pavement construction. Tars are the other major group. Tars are more susceptible to temperature changes, more toxic and difficult to handle. However, tars are more resistant to jet fuel spillage and are less likely to strip from aggregates in the presence of water. This manual considers only the use of asphalt for stabilization purposes. Tars are rarely used for pavements except as binders for surface courses in areas where fuel spillage can be expected.

Asphalts are found in natural deposits; however, the vast majority are refined from petroleum. Asphalt cement is the basic refined material and is the hard, high-molecular weight, fraction of crude oil. Asphalt cement at ambient temperatures is a semi-solid. Liquid asphalt products are most often derived from asphalt cement by blending petroleum distillates to form cutbacks or by emulsifying with water to form emulsified asphalts.

1. Asphalt Cements

Asphalt cements are graded on the basis of consistency or viscosity. Three different techniques are used to grade asphalts on this basis: penetration at 77^{o}F of original asphalt, viscosity at 140^{o}F of original asphalt and viscosity at 140^{o}F of laboratory-aged asphalt. Specifications have been developed by AASHTO, ASTM and a West Coast User Producer group (Table 9). Typical penetration grades are 40-50, 60-70, 85-100, 120-150 and 200-300. Typical viscosity grades are AC-5, AC-10, AC-20 and AC-40.

Asphalt cements must be heated to obtain a mixing and spraying consistency. Asphalt cements are normally used in central plants with heated aggregates; however, soft asphalt cements have been mixed in-place and some hard asphalts have been used in foaming operations in-place. The curing or setting time

TABLE 9. ASPHALT SPECIFICATIONS.

Material		Specification AASHTO	ASTM
Asphalt Cement	Penetration basis	M20	D946
	Viscosity basis	M226	D3381
Cutback	Rapid curing	M81	D2028
	Medium curing	M82	D2027
	Slow curing	M141	D2026
Emulsion	Anionic	M140	D977
	Cationic	M208	D2397

of mixtures using asphalt cements occurs as the heat required for mixing, laydown and compaction dissipates. Thus, strength and other properties are developed within a few hours after construction is complete.

2. Cutback Asphalts

Cutbacks are combinations of asphalt cement and a petroleum diluent blended to provide viscosities suitable for mixing and spraying at relatively low temperatures. Cutbacks are graded based upon curing time and consistency. Curing time is varied by the solvent used in cutting back the asphalt cement, while the viscosity (consistency) is controlled by the amount of solvent. Rapid-cure cutbacks (RC) use a naphtha or gasoline type solvent, medium-cure cutbacks (MC) use kerosene-type solvents and slow-cure cutbacks (SC) use low-volatility oils or oils that are made during the refining process.

Grade designations for viscosity graded RC, MC or SC materials are typically as shown below:

RC-70, RC-250, RC-800, RC-3000

MC-30, MC-70, MC-250, MC-800, MC-3000 and

SC-70, SC-250, SC-800, SC-3000.

The lower limit of the viscosity range for the grade of cutback is given in the material designation. The upper viscosity limit is twice that of the lower limit. For example, an RC-70 is a Rapid Curing cutback with a viscosity at 140^{o}F between 70 and 140 centi-stokes.

It is usually desirable to heat cutbacks to aid distribution and mixing. Partial curing is usually necessary after mixing and before compaction. Most cutbacks are used for in-place operations.

3. Emulsified Asphalts

Emulsified asphalts are mixtures of asphalt cement, water and an emulsifying agent. Anionic emulsions are manufactured with anionic (negatively charged) emulsifying chemicals. Cationic emulsions are manufactured with cationic (positively charged) emulsifying chemicals. The type and amount of emulsifying agent will determine to a large degree the setting characteristics of the asphalt emulsion. Rapid-setting (RS), medium-setting (MS) and slow-setting (SS) anionic and cationic emulsions are manufactured. Some medium-setting emulsions may contain small amounts of petroleum solvents (up to 12 percent) to aid mixing and provide stockpiling capability to mixtures made with the emulsion. Characteristics of the asphalt cement used in manufacturing the emulsion and viscosity of the asphalt emulsion are used to define the grade. For example, a major difference between the CRS-1 and CRS-2 (cationic rapid-setting emulsions) is the viscosity of the emulsion, while the major difference between CMS-2 and CMS-2h (cationic medium-setting emulsions) is the penetration of the base asphalt content. It should be noted that a wide number of asphalt suppliers use company terminology to describe emulsions.

A review of the above descriptions of asphalt products indicates that a large number of asphalts are available for soil stabilization purposes. ASTM specified 49 different asphalts. Selections of the type of asphalt for a given stabilization use is discussed later. In general asphalt cements are used in hot central plant operations, while medium and slow curing cutbacks and medium and slow setting emulsions can be used for in-place stabilization operations.

D. MECHANISMS OF ASPHALT STABILIZATION

The mechanisms involved in the stabilization of soils and aggregates with asphalt differ greatly from those involved in 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, resulting in a membrane that prevents or slows the penetration of water. Under normal conditions water infiltration would result in a decrease of shear strength, compressive strength, tensile strength, flexural strength and elastic modulus. In addition, asphalt stabilization can improve durability characteristics. Since the soil particles or aggregates are coated with water-repelling asphalt film, the soil is resistant to the detrimental effects of water such as volume change due to alternating wet-dry and freeze-thaw cycles.

In noncohesive materials, such as sands and gravel, crushed gravel, and crushed stone, two basic mechanisms are active: water-proofing and adhesion. The asphalt coating on the cohesionless materials provides a membrane which prevents or hinders the penetration of water and thereby reduces the tendency of the material to lose strength, elastic modulus, etc., 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 increases shear strength by increasing cohesion. The effect of the asphalt on the angle of internal friction is minimal. Other property improvements resulting from the asphalt cement include an increase in tensile strength, compressive strength, flexural strength and elastic modulus.

In addition to the benefits cited above for asphalt stabilization, the stabilized layer may prevent surface water from penetrating into the subgrade, resulting in a strength loss of the subgrade materials. In surface course applications, the asphalt binder has the capability of eliminating or reducing the occurrence of raveling, rutting, washboarding, loss of fines, etc., under traffic.

E. SOILS SUITABLE FOR ASPHALT STABILIZATION

A number of criteria have been suggested for establishing the suitability of soils for asphalt stabilization. Suggested criteria are given below for both fine- and coarse-grained soils.

1. Fine-Grained Soils

Fine-grained soils may be stabilized with asphalt, depending upon the plasticity characteristics of the soil and the amount of material passing the Number 200 sieve. Because of the extremely high surface area of the finer soil particles, a large percent of asphalt would be required to coat all of the soil surfaces. Since this is virtually impossible, agglomerations of particles are coated with economical percentages of asphalt. The gradation of fine-grained soils suitable for asphalt stabilization are shown in Table 10. As noted in this table, the amount of material passing the Number 200 sieve should be less than 25 percent. In addition, the plastic index should be less than 10 to assure that adequate mixing is possible. If proper mixing is not obtained, the plastic fines may swell upon contact with water, resulting in a substantial loss of strength.

2. Coarse-Grained Soils

Cohesionless soils (plasticity index less than 6) suitable for asphalt stabilization are shown in Table 10 and identified as sand-bitumen and sand-gravel-bitumen. In addition, cohesionless soils identified as suitable for hot mix asphalt concrete by AASHTO, ASTM, and states, counties and cities are in general acceptable. Examples of acceptable gradations can be found in ASTM D-3515 or in Table 11. Asphalt stabilized materials made with well or dense-graded aggregate have higher strength, etc., than the more one-sized sand-asphalt mixture.

a. Suitability of Rock Types. Alkaline rocks (i.e., limestone, dolomite) provide better adhesion with asphaltic films in the presence of water than acid or silicious rocks (i.e., granite, quartzite). Where acid rocks are used, addition of an antistripping agent or hydrated lime may be required.

Currently, the most commonly specified tests to insure aggregates quality are resistance to abrasion (ASTM C-131) and soundness (ASTM C-88). Commonly specified values for abrasion are 40 (maximum) for surface courses and 50 (maximum) for

TABLE 10. ENGINEERING PROPERTIES OF MATERIALS SUITABLE FOR BITUMINOUS STABILIZATION (AFTER HERRIN, Ref. 11).

Percent Passing Sieve	Sand-Bitumen	Soil-Bitumen	Sand-Gravel Bitumen
1 - 1 1/2"			100
1"	100		
3/4"			60-100
No. 4	50-100	50-100	35-100
No. 10	40-100		
No. 40		35-100	13-50
No. 100			8-35
No. 200	5-12	Good - 3-20	
		Fair - 0-3 & 20-30	
		Poor - >30	
Liquid Limit		Good - <20	
		Fair - 20-30	
		Poor - 30-40	
		Unusable - >40	
Plasticity Index	10	Good - <5	
		Fair - 5-9	10
		Poor - 9-15	
		Unusable - >12-15	

TABLE 11. AGGREGATE GRADATIONS FOR ASPHALT CONCRETE PAVEMENTS (AFTER REF. 1).

Sieve Size	Percent Passing, by Weight											
	1-1/2-in. Maximum[1]		1-in. Maximum		3/4-in. Maximum		1/2-in. Maximum		3/8-in. Maximum		No. 4 Maximum	
	Low Pressure[2]	High Pressure[3]	Low Pressure	High Pressure	Low Pressure	High Pressure	Low Pressure	High Pressure	Low Pressure	High Pressure	Low Pressure	High Pressure
	Wearing Course											
1-1/2 inch	100	-	-	-	-	-	-	-	-	-	-	-
1 inch	87 ± 8	-	100	100	-	-	-	-	-	-	-	-
3/4 inch	79 ± 9	-	90 ± 7	90 ± 6	100	100	-	-	-	-	-	-
1/2 inch	70 ± 9	-	81 ± 9	81 ± 7	89 ± 9	89 ± 7	100	100	-	-	-	-
3/8 inch	63 ± 9	-	75 ± 9	75 ± 7	82 ± 9	82 ± 7	86 ± 9	86 ± 7	100	-	-	-
No 4	51 ± 9	-	60 ± 9	60 ± 7	66 ± 9	66 ± 7	66 ± 9	66 ± 7	85 ± 10	-	100 ±	-
No 8	42 ± 9	-	47 ± 9	47 ± 7	53 ± 9	53 ± 7	53 ± 9	53 ± 7	72 ± 10	-	86 ± 12	-
No 16	34 ± 9	-	37 ± 9	37 ± 7	41 ± 9	41 ± 7	41 ± 9	41 ± 7	56 ± 12	-	72 ± 16	-
No 30	24 ± 9	-	27 ± 9	27 ± 7	31 ± 9	31 ± 7	31 ± 9	31 ± 7	42 ± 10	-	57 ± 17	-
No 50	19 ± 8	-	19 ± 8	19 ± 6	21 ± 8	21 ± 6	21 ± 8	21 ± 6	29 ± 9	-	43 ± 17	-
No 100	12 ± 6	-	12 ± 6	13 ± 5	13 ± 6	13 ± 5	13 ± 6	13 ± 5	18 ± 7	-	28 ± 12	-
No 200	4 ± 3	-	4 ± 3	4.5 ± 1.5	4 ± 3	4.5 ± 1.5	4 ± 3	4.5 ± 1.5	8 ± 3	-	9 ± 5	-
	Binder or Intermediate Course											
1-1/2 inch	100	-	-	-	-	-	-	-	-	-	-	-
1 inch	84 ± 9	-	100	100	-	-	-	-	-	-	-	-
3/4 inch	76 ± 9	-	83 ± 9	90 ± 6	100	100	-	-	-	-	-	-
1/2 inch	66 ± 9	-	73 ± 9	81 ± 7	82 ± 9	89 ± 7	100	100	-	-	-	-
3/8 inch	59 ± 9	-	64 ± 9	75 ± 7	72 ± 9	82 ± 7	83 ± 7	86 ± 7	-	-	-	-
No 4	45 ± 9	-	48 ± 9	60 ± 7	54 ± 9	66 ± 7	62 ± 9	66 ± 7	-	-	-	-
No 8	35 ± 9	-	37 ± 9	47 ± 7	41 ± 9	53 ± 7	47 ± 9	53 ± 7	-	-	-	-
No 16	27 ± 9	-	28 ± 9	37 ± 7	32 ± 9	41 ± 7	36 ± 9	41 ± 7	-	-	-	-
No 30	20 ± 9	-	21 ± 9	27 ± 7	24 ± 9	31 ± 7	28 ± 9	31 ± 7	-	-	-	-
No 50	14 ± 7	-	16 ± 7	19 ± 6	17 ± 7	21 ± 6	20 ± 7	21 ± 6	-	-	-	-
No 100	9 ± 5	-	11 ± 5	13 ± 5	12 ± 5	13 ± 5	14 ± 5	13 ± 5	-	-	-	-
No 200	5 ± 2	-	5 ± 2	4.5 ± 1.5	5 ± 2	4.5 ± 1.5	5 ± 2	4.5 ± 1.5	-	-	-	-

[1] 1-1/2-inch maximum surface course gradation will be used only for thick-lift pavements (3-inch or more).

[2] The low-pressure gradation for pavements subjected to aircraft with tire pressures less than 100 psi.

[3] The high-pressure gradation for pavement to be subjected to aircraft with tire pressures of 100 psi or greater

base courses. Soundness values are often not specified for base course aggregates.

b. Crushed Aggregate. The coarse and fine aggregates used for airfield pavement surface should be crushed materials, in order to assure high stability and performance. Bituminous base courses, however, many include natural materials in the fine fraction.

c. Maximum Size. In general, the maximum size of aggregate for the wearing course should not exceed 3/4 inch; in no case should the aggregate size exceed one-half the thickness of the compacted wearing course or two-thirds the thickness of any binder, intermediate course or base or subbase course.

d. Mineral Filler. The type and quantity of mineral filler used affects the stability of the mix. For surface course mixes, mineral filler should be limestone dust, portland cement, or other inert similar materials. For bituminous bases natural filler is frequently adequate.

F. TYPICAL PROPERTIES OF ASPHALT-STABILIZED SOILS

The following mixture properties should be defined to satisfy the needs of a particular engineering application: (1) stability, (2) durability, (3) fatigue behavior, (4) tensile behavior, (5) stiffness, (6) flexibility and (7) workability. Few tests have been developed to indicate the flexibility and workability of bituminous stabilized materials. Elongation and certain tensile tests are attempts to measure flexibility, while gradation limits and compaction tests have been used to control workability.

Stability, durability, fatigue behavior, tensile properties and stiffness of asphalt mixtures have been defined by a number of investigators, and typical properties are available. However, prior to a delineation of these properties, it must be realized that unlike most other stabilized materials these properties are highly dependent upon the temperatures at which the test is conducted and the rate of loading or rate of elongation used by the test method. Other important variables which control asphalt-stabilized mixture properties include: (1) type of asphalt, (2) type and gradation of the aggregate, (3) density of the compacted mixture and (4) curing and/or aging conditions.

1. Stability

Specifications and criteria for bituminous-st[illegible] soils and aggregates are almost exclusively based [illegible] durability and gradation requirements. Some agencies [illegible] durability requirements and thus stability [illegible] laboratory test parameter used for mixture design.

The most widely used stability tests are the Hveem, Marshall and unconfined compression test. Typical criteria and hence typical values for Hveem, Marshall and unconfined compressive strength are shown in Table 12. Methods of sample preparation, test temperatures and curing conditions prior to testing vary. Most of the criteria presently used were originally developed for surface courses and adapted to base course design.

2. Durability

Durability tests which have been used for control of bituminous-stabilized mixtures include the California moisture vapor susceptibility test, the immersion compression test, the swell test and vacuum saturation tests. These water-susceptibility tests are usually perfomed on Hveem and Marshall stability samples or unconfined compression test samples, and acceptance criteria are based on a percent retained strength (70 percent) or a minimum stability after soaking.

Freeze-thaw and wet-dry durability-type tests for asphalt-stabilized mixtures are nearly nonexistent. The water saturation test coupled with freezing and thawing developed by Lottman is an exception (9).

3. Fatigue Behavior

The flexural fatigue behavior of asphalt concrete mixtures is influenced by asphalt type, aggregate gradation, aggregate type, air voids, etc. Typically fatigue data are expressed in terms of the number of repetitions to failure of a certain strain or stress level used to cause failure. Santucci (10), has presented some typical data for asphalt and emulsified asphalt mixes (see Figures 27 and 28).

4. Tensile Properties

The most popular form of tensile test at present appears to be the indirect tension or splitting tensile test. This test has been used widely to define tensile properties both prior to and after water susceptibility tests. Tensile strength is largely dependent upon voids, curing, rate of loading and temperature. Typical values obtained under conditions simulating highway loadings are on the order of 100 to 800 psi.

5. Stiffness

Stiffness of an asphalt-stabilized mixture is generally defined as the ratio of the applied stress to the observed strain for a test performed at a particular temperature and rate of loading. It is basically an "elastic" modulus at rapid rates of loading. Figure 29 indicates the wide range of this property as a function of temperature and time for an asphalt-stabilized

TABLE 12. DESIGN METHODS AND CRITERIA FOR ASPHALT-STABILIZED BASE COURSES (AFTER REF. 14).

A. Hveem Method

State	Stability	Percent Air Voids	Percent Voids Filled With Asphalt	Cohesiometer
California	35 minimum	4-6	80-85	300 minimum
Colorado	30-45	3-5	75	
Hawaii	35 minimum	4-10		
Nevada	30-37	3-5		
Oklahoma	35 minimum	8 maximum		
Oregon	30 minimum	10 maximum		150 minimum
Texas	30 minimum			
Washington	20 minimum			50 minimum

B. Marshall Method

State	Stability, Lbs.	Flow, 0.01 Inch	Percent Air Voids	Percent Voids Filled With Asphalt
District of Columbia	750 minimum	8-16	3-8	65-75
Georgia	1800 minimum	8-16	3-6	65-75
Kansas	800-3000	5-15	1-5	70-85
Kentucky	1100-1500	12-15	4-6	
Mississippi	1600	16 maximum	5-7	50-70
New Jersey	1100-1500	6-18	3-7	
N. Carolina	800	7-14	3-8	
N. Dakota	400 minimum	8-18	3-5	
Pennsylvania	700 minimum	6-16		60-85
Rhode Island	750 minimum		3-8	
S. Carolina	1200-3000	6-12		
S. Dakota		8-18	3-5	
Wyoming	1000 minimum			

C. Unconfined Compressive Strength

State	Load, psi	Percent Air Voids	Percent Voids Filled With Asphalt
Colorado	200-400	3-5	80-85
Oregon	150 minimum		

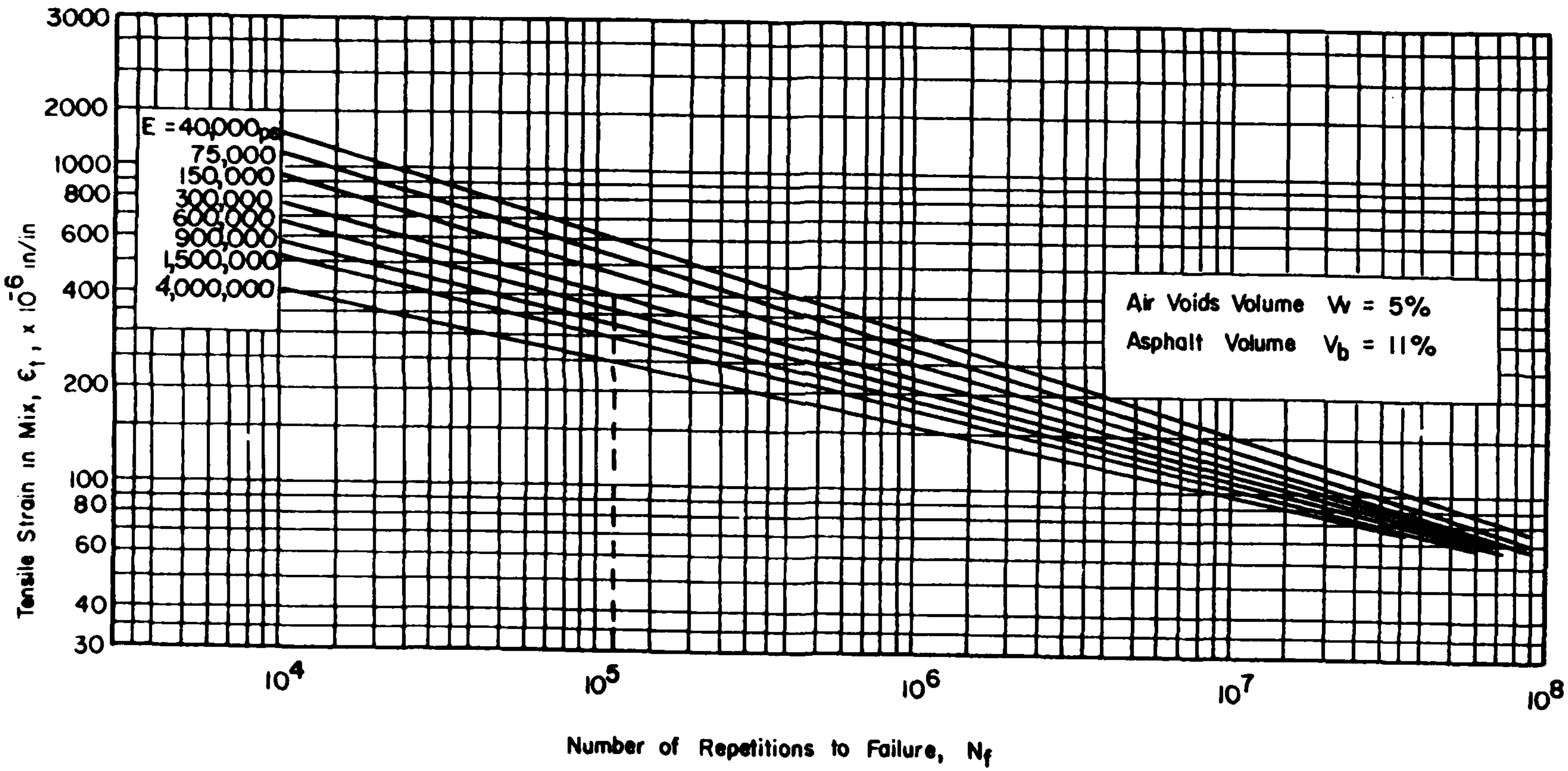


Figure 27. Fatigue Criteria for Asphalt and Emulsion Mixes. (After Santucci, Ref. 12).

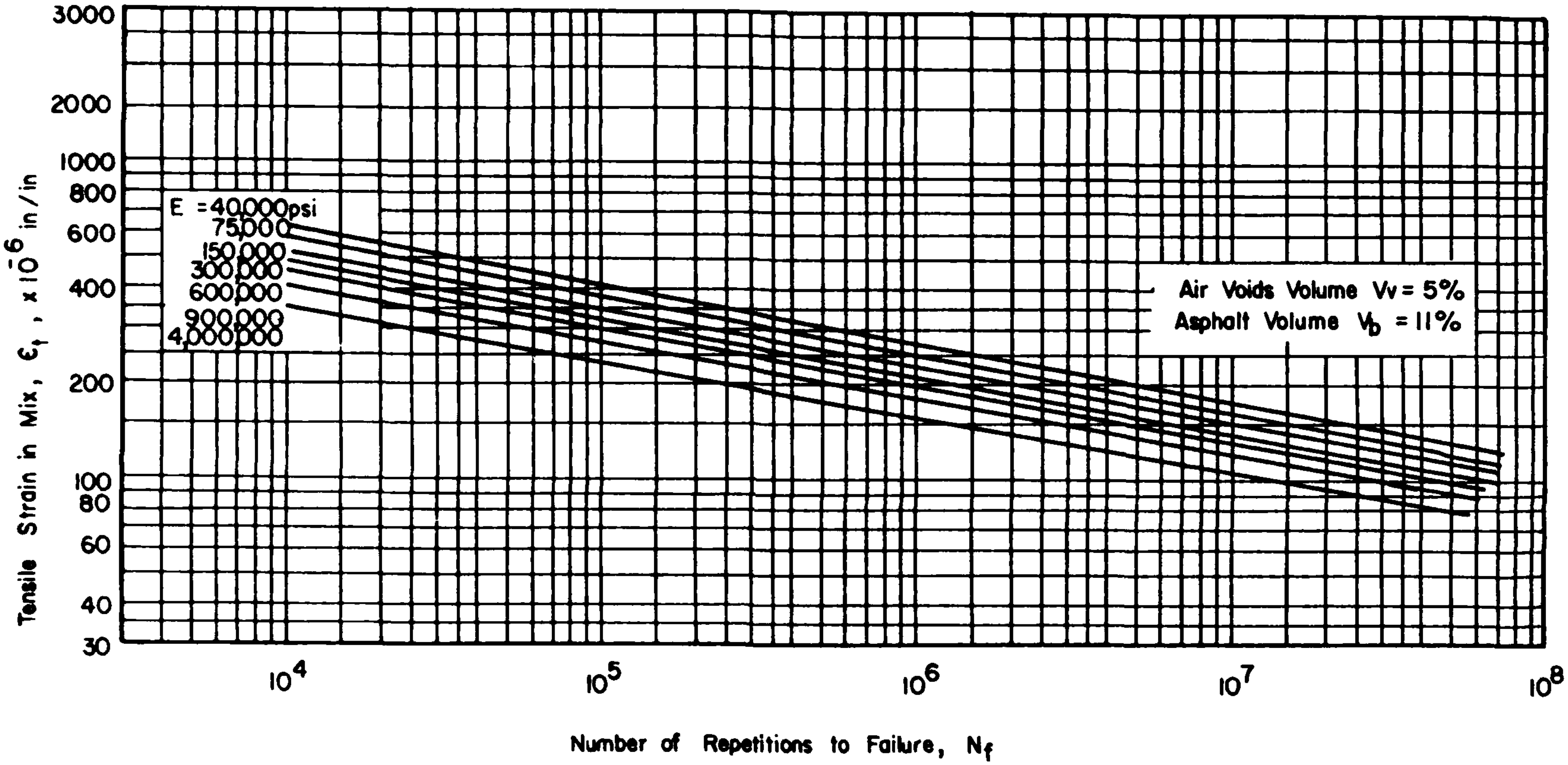


Figure 28. Fatigue Criteria for Cement-Modified Asphalt Emulsion Mixes. (After Santucci, Ref. 12.)

aggregate. Values typical of highway loading conditions are on the order of 200,000 to 800,000 psi.

Resilient modulus values for soils and aggregates stabilized with liquid asphalts (cutbacks and emulsions) are not only dependent upon the temperature of the test and the rate of loading but also upon the confining pressure and the curing time. Figure 30 indicates that at short curing times the behavior of the emulsion mixture is essentially that of an unstabilized material, i.e., dependent upon confining pressure and a relatively low value. As emulsion mixtures cure and the volatiles (water) are evaporated, the mixture increases in resilient modulus and becomes less dependent upon confining pressure. The strength of a mixture stabilized with liquid asphalt, will approach that of a mixture which is stabilized with the base asphalt cement used to produce the cutback or emulsions.

Presently-used mixture design procedures are based primarily on the use of stability and durability tests. Fatigue behavior, tensile properties and stiffness parameters are used for pavement structural design purposes but are not commonly used for establishing binder contents.

G. SELECTION OF ASPHALT TYPE AND ASPHALT CONTENT

Selection of the type and amount of asphalt for a particular use is influenced by several considerations. Some of the major factors are discussed below together with guidelines for selection of the type of asphalt, approximate quantities of asphalt and detailed test methods for selecting asphalt contents.

1. Type of Asphalt

The major factors influencing the selection of the type of asphalt are discussed below:

a. Method of Construction. The basic types of construction include central plant (both hot and cold operations) and mixed-in-place or on-grade construction. Asphalt cements are in general limited to hot central plant mixing operations; however, soft asphalt cements have been used for mixed-in-place operations. Some warm central plant operations have used emulsions.

b. Construction Equipment. Central plants are typically batch or continuous in operation. The drum-mixer continuous plants are the most popular plants presently marketed. The continuous plants using pugmills for mixing are often used for cold mixing operations. In-place equipment has various degrees of mixing capability. The desired setting characteristic of the emulsion to be selected may often be controlled by the type of equipment selected for the job. Examples of suitable types of construction equipment can be found in Section IX of this manual.

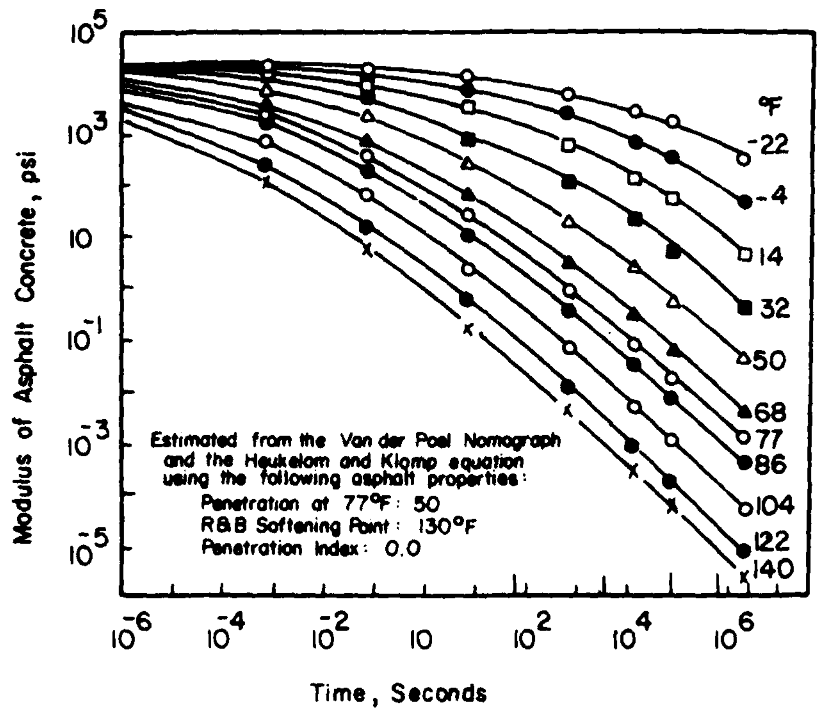
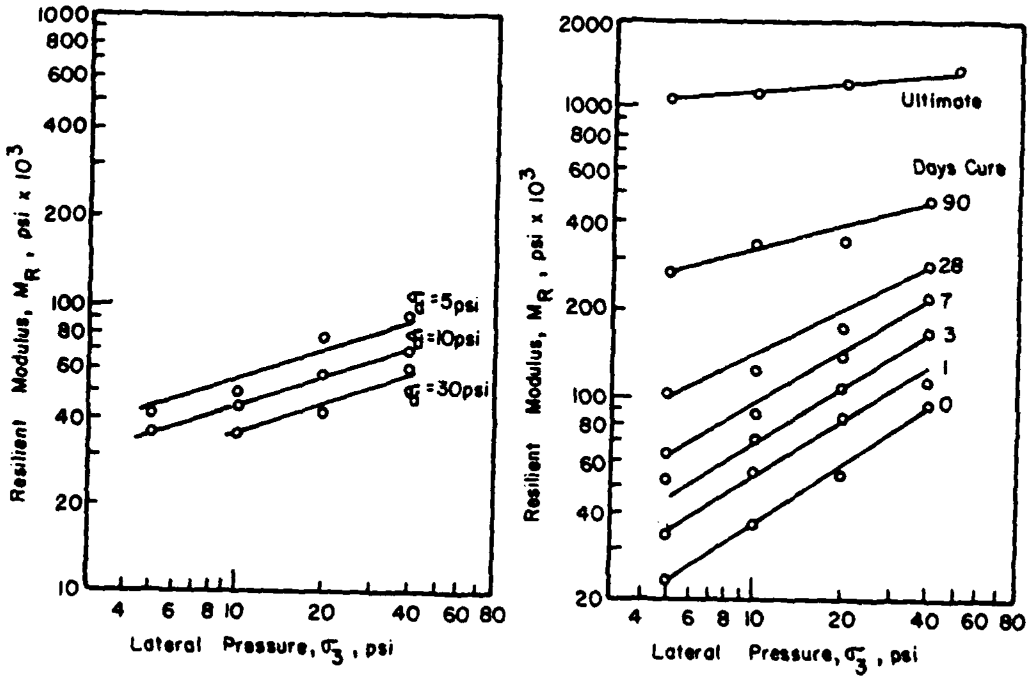


Figure 29. Asphalt Concrete as a Function of Temperature and Time of Loading.



A. No Curing After Compaction.

B. At Increased Ages.

Figure 30. Development of Resilient Modulus for a Cationic Medium Setting Emulsion Mixtures at 68°F. (After Terrel and Wang, Ref. 13.)

c. Pavement Layer. Asphalt-stabilized materials used as surface courses, base courses or subbases may require different types and quantities of asphalts. Asphalt cements are popular binders for surface courses while emulsions and mixed-in-place operations are used extensively for subbase and base course construction.

d. Loading and Environmental Conditions. The type of loading (static or dynamic), magnitude of loading (including gross loads and wheel loads) and climatic conditions (including temperature and moisture both before and after construction) should input to the selection of the type and grade of asphalt.

e. Aggregates. The gradation, surface texture, absorption and soundness of the aggregate will to some extent control the selection of the asphalt grade.

f. General. The method of construction and the equipment available will determine in general the type of asphalt (asphalt cement, cutback or emulsion). The grade selected, including its viscosity and setting or curing characteristics, will be influenced by the gradation and the amount of fine particles in the aggregate, the climatic conditions during and after construction, the type of mixing equipment, and, to a degree, the magnitude of loads expected on the pavement. In general, asphalt cements will normally be used with hot central plant operations, and emulsions will be used with mixed-in-place operations and some cold or warm central plant operations. The use of cutbacks is discouraged due to problems with air quality, safety and the alternate use of cutter stocks for more important purposes. Local restrictions on use of cutbacks should be checked.

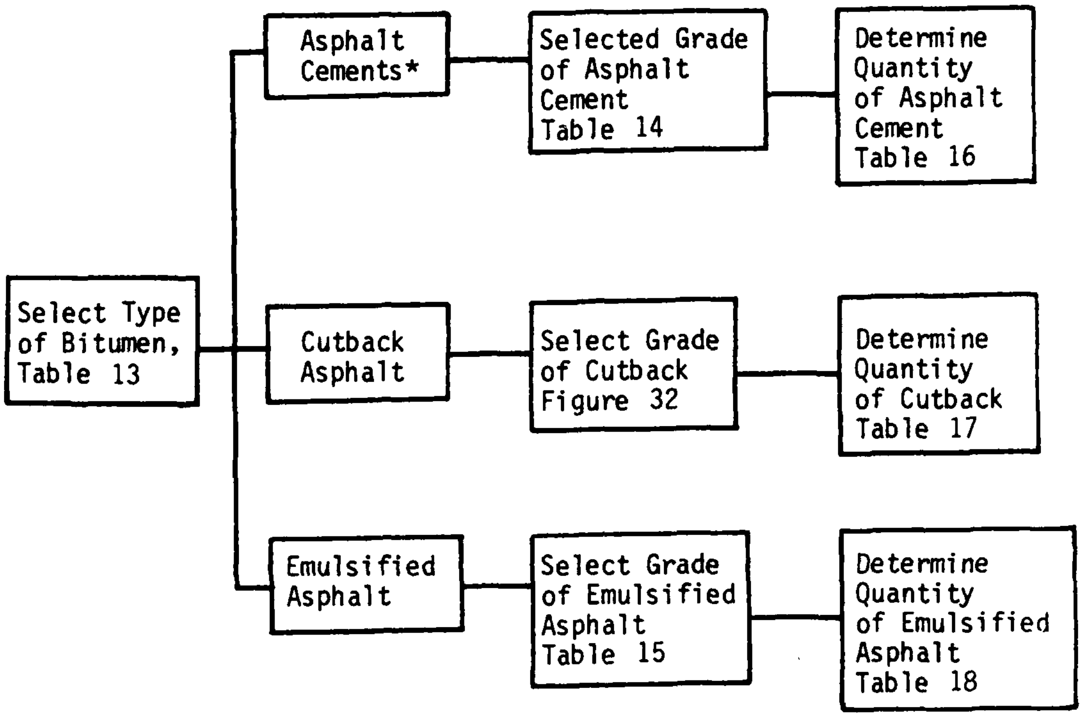
Table 13 and Figure 31 are a general guide to selecting a suitable type of asphalt, asphalt cement, cutback and emulsion for stabilization purposes. Table 14 is a recommended guide for selecting the type of paving asphalt.

The type of cutback asphalt can be selected from Figure 32. The primary factors that are considered in this selection are the percent passing the Number 200 sieve and temperature of the aggregate.

The primary factors to be considered for the selection of the type of emulsion are the type of aggregate, gradation of the aggregate, moisture content of the aggregate, moisture resistance required based on local environmental conditions and the type of construction equipment used. Figures 33 and 34 can be used to select either a cationic or anionic emulsion based on the aggregate characteristics. Table 15 can be used for emulsified grade selection.

TABLE 13. SELECTION OF A SUITABLE TYPE OF ASPHALT FOR SOIL STABILIZATION PURPOSES.

Sand Bitumen	Soil Bitumen	Crushed Stones and Sand-Gravel Bitumen
Hot Mix: Tables 14, 19		Hot Mix: Tables 14, 16, 19
Cold Mix: Cutbacks See Table 17 and Figure 32	Cold Mix: Cutbacks See Table 17 and Figure 32	Cold Mix: Cutbacks See Table 17 and Figure 32
Emulsions See Table 15 See Figures 33 and 34 to determine if a cationic or anionic emulsion should be used	Emulsions See Table 15 See Figures 33 and 34 to determine if a cationic or anionic emulsion should be used	Emulsions See Table 15 See Figures 33 and 34 to determine if a cationic or anionic emulsion should be used



*Hard asphalt cements are preferred in hot climates.

Figure 31. Subsystem for Expedient Base Course Stabilization with Bituminous Materials. Selection of Type, Grade and Quantity of Asphalt for Stabilization Purposes.

TABLE 14. RECOMMENDATIONS FOR SELECTION OF PAVING ASPHALT (AFTER REF. 14).

Thickness of Asphalt Concrete, in.[5]	Climate	AASHTO M-20	AASHTO M-226	West Coast[4]
	Cold[1]	200 - 300	AC-5	AR-1000
≤ 3	Moderate[2]	85 - 100	AC-10	AR-4000
	Hot[3]	85 - 100	AC-10	AR-4000
	Cold	120 - 150	AC-5	AR-2000
4 - 6	Moderate	85 - 100	AC-10	AR-4000
	Hot	60 - 70	AC-20	AR-8000
	Cold	120 - 150	AC-5	AR-2000
> 7	Moderate	60 - 70	AC-10	AR-8000
	Hot	40 - 50	AC-20	AR-16,000

[1]Normal minimum daily temperature* of 10°F or less; for extremely low temperatures special studies are recommended.

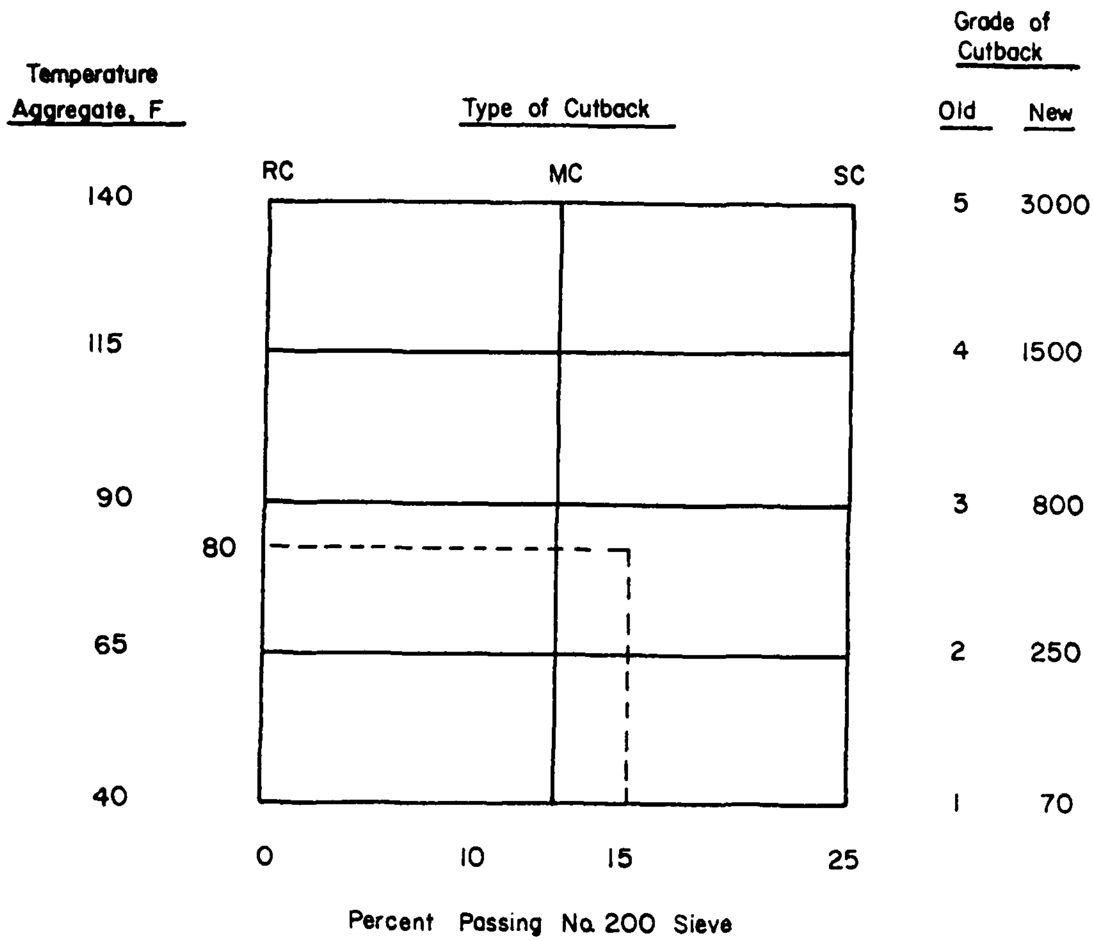
[2]Normal maximum daily temperature* of 90°F or less.

[3]Normal maximum daily temperature* greater than 90°F.

[4]Uniform Pacific Coast Specifications for AR-graded Paving Asphalts.

[5]Total thickness of asphalt concrete; surface plus base.

*As per U. S. Weather Bureau climatological reports.



Example: For aggregate temperature of 100°F and 10 percent passing No. 200 sieve, use MC 800 cutback.

Figure 32. Selection of Type of Cutback for Stabilization (After Ref. 15).

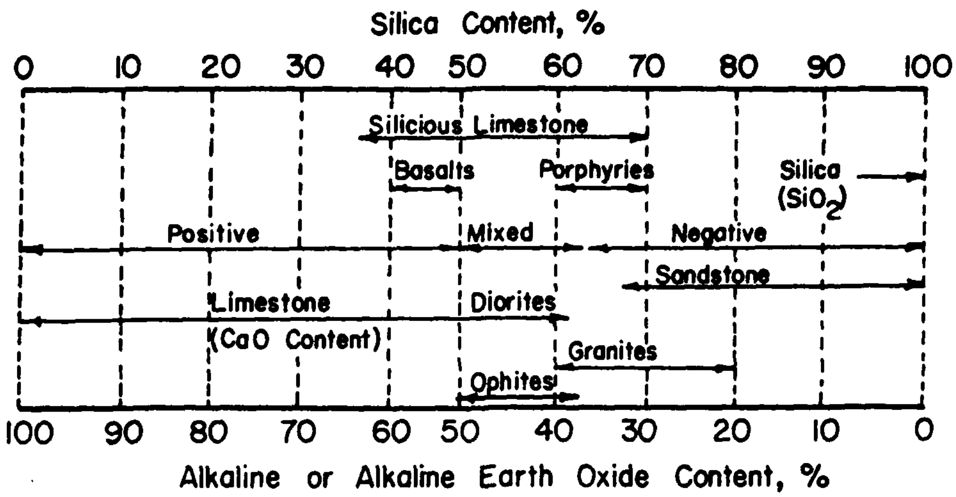


Figure 33. Classification of Aggregates.
(After Mertens and Wright, Ref. 16.)

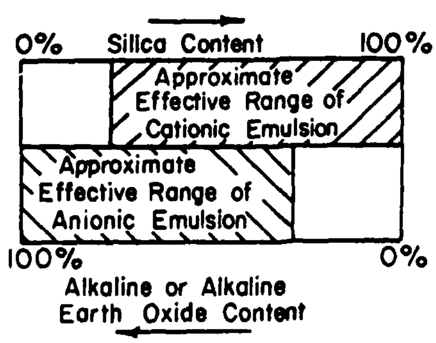


Figure 34. Approximate Effect Range of Cationic and Anionic Emulsions on Various Types of Aggregates.
(After Mertens and Wright, Ref. 16.)

2. Approximate Asphalt Quantities

The approximate quantity of asphalt can be selected (Tables 16 to 18). Gradation of the aggregate and shape and surface texture of the aggregate are the primary factors which control the selection of the asphalt quantity.

a. Asphalt Cement. Provided aggregate gradations are dense, the surface texture and shape of the aggregate largely control asphalt content. Table 16, which is based on this concept, has been developed for asphalt cements.

b. Cutback Asphalt. Table 17 can be used to select a preliminary quantity of cutback. The selected quantity is based on aggregate gradation.

c. Emulsified Asphalt. Table 18 can be used to select a preliminary quantity of emulsion. The selected quantity is based on aggregate gradations.

3. Detailed Testing to Establish Asphalt Quantities.

a. Asphalt Cement and Dense-Graded Aggregates. Marshall mixture design methods for asphalt cement in combination with dense graded aggregates, such as those shown in Table 11, can be found in AFM 88-6, Chapter 9, Bituminous Pavements Standard Practice. Laboratory compaction requirements are summarized as follows:

Types of Traffic	Design Compaction Requirements
Tire pressure 100 psi and over	75 blows Marshall method
Tire pressure less than 100 psi	50 blows Marshall method

Optimum asphalt content and adequacy of the mixture is obtained by plotting test data as shown in Figure 35. Table 19 describes the criteria for establishing the adequacy of the mixture. The conventional Marshall method determines the optimum asphalt content by averaging the following values:

(1) Bitumen content at peak of stability curve,

(2) Bitumen content at peak of unit weight curve (for wearing course only),

(3) Bitumen content at the appropriate point on air voids curve and

(4) Bitumen content at the appropriate point on voids filled with bitumen curve.

Use Table 19 to evaluate the adequacy of stability, flow, air voids and voids filled with asphalt.

TABLE 15. SELECTION OF EMULSIFIED ASPHALT TYPE (AFTER REF. 10).

Grade Designation	Preferred Usage		
ASTM	Aggregate	Rain Resistance	Construction Method
SS-1	Damp to wet dense-graded aggregates, high sand content gravels, poorly or well-graded sands.	Dependent on dehydration and absorption.	Central Mix or Travel Plant
CSS-1 CSS-1h CMS-2	Dry or damp low sand content gravels, well graded or silty sands.	Resistant to early rain-fall.	Travel Plent or In-Place Mixing
MS-1 MS-2 MS-2h	Dry or damp processed open-graded aggregates.	Resistant to early rain-fall.	Central Mix or Travel Plant
CMS-2 CMS-2h			

Note: Figures 4-33 and 4-34 can be used as a basis for selecting anionic or cationic emulsions. The geologic type of aggregate is located in Figure 4-33 and the approximate silica or alkaline earth oxide content determined. These contents are used to enter Figure 4-34 to select the type of emulsion.

TABLE 16. SELECTION OF ASPHALT CEMENT CONTENT.

Aggregate Shape and Surface Texture	Percent Asphalt by Weight of Dry Aggregate*
Rounded and Smooth	4
Angular and Rough	6
Intermediate	5

*Approximate quantities which may be adjusted in field based on observation of mix and engineering judgement.

TABLE 17. DETERMINATION OF QUANTITY OF CUTBACK ASPHALT (AFTER REF. 8).

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

Symbol	Definition
p	Percent of residual asphalt by weight of dry aggregate*
a	Percent of mineral aggregate retained on No. 50 sieve
b	Percent of mineral aggregate passing No. 50 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 sieve

*Percent cutback can be obtained by using the following equation:

$$\text{Percent cutback} = \frac{\text{percent residual asphalt (p)}}{(100 - \text{percent solvent})} \times 100$$

TABLE 18. EMULSIFIED ASPHALT REQUIREMENT (AFTER REF. 15).

Percent Passing No. 200	Lbs. of Emulsified Asphalt per 100 lbs. of Dry Aggregate When Percent Passing No. 10 Sieve is:					
	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	7.5	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	7.4

Example: 7.9 percent emulsified asphalt (by dry weight of aggregate) is required for an aggregate with 82 percent passing the No. 10 sieve and 15 percent passing the No. 200 sieve.

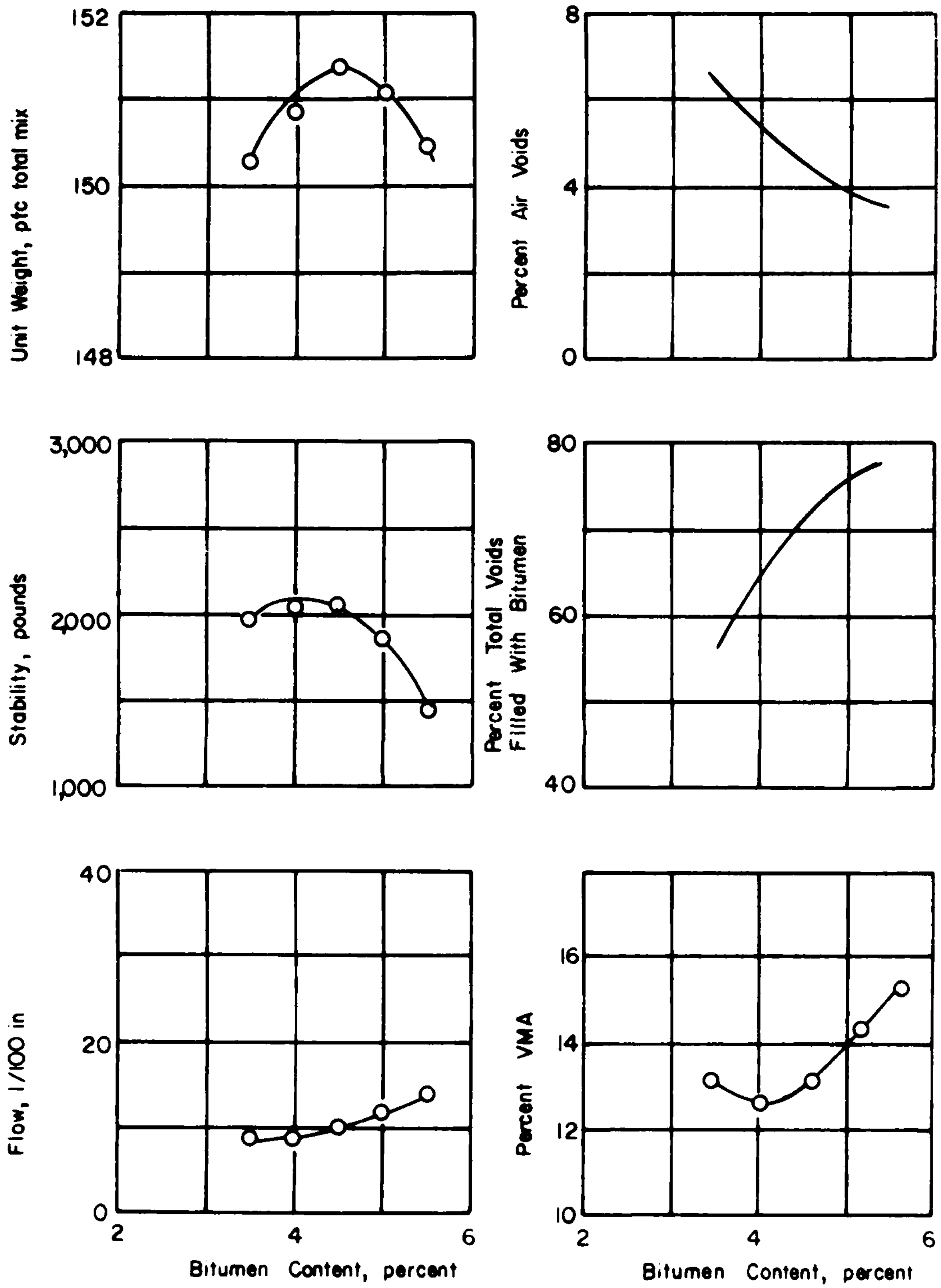


Figure 35. Asphalt Paving Mix Design - Typical Mix.

Table 20 summarizes minimum percent voids in the mineral aggregate (VMA). The Navy uses this requirement for airfield design. VMA represents the volume of void space between the aggregate particles of a compacted paving mixture that includes air voids and effective asphalt content, expressed as a percentage of the total volume of the specimen.

The above criteria have been developed for surface course mixes. Similar criteria are often used for base courses. However, The Asphalt Institute (4) has suggested that hot-mix asphalt bases which do not meet the above criteria when tested at 140°F should be satisfactory if they meet the criteria when tested at 100°F and are placed four inches or more below the surface. This recommendation applies only to regions having climatic conditions similar to those prevailing thoughout most of the United States.

b. Asphalt Cements and Sand Aggregates. Hot-mixed asphalt cement-stabilized sands have been used as base and subbase courses for airfields and highway pavements. Criteria for acceptance of these types of mixes has not been standardized. A suggested criterion is to use stability and flow values as stated above but allowing air voids contents to range from 3 to 12 percent and percent voids filled with asphalt allowed below 70 percent.

c. Cutbacks. Marshall mixture design procedures for use with cutbacks have been standardized by The Asphalt Institute. Details of the mixture fabrication, curing and testing procedures can be found in Reference 2. Design criteria are shown in Tables 21, 22 and 23. The critical elements of this suggested procedure are control of the mixing temperature, volatile content at compaction, method of curing prior to testing, test temperature and a water susceptibility test. The test temperature is 77°F and not the 140°F normally associated with Marshall testing of asphalt cement-stabilized materials.

d. Emulsions. Marshall mixture design procedures for use with emulsions have been developed by the University of Illinois (13), Purdue University (14) and ARMAC (15). Unfortunately, the developed methods have not been standardized by ASTM or AASHTO and are not based on correlations with field performance. Details of the Illinois and Purdue methods can be found in Appendix C, Section F and in Reference 13. Acceptance criteria based on the Illinois procedure are shown in Table 24. The critical elements of the suggested procedure are the moisture content during mixing and compaction, method of curing prior to testing, test temperature and water-susceptibility testing. It should be noted the test temperature is 77°F and not the 140°F normally associated with Marshall testing.

TABLE 19. CRITERIA FOR DETERMINING OPTIMUM BITUMEN CONTENT AND ADEQUACY OF MIX FOR USE WITH AGGREGATE SHOWING WATER ABSORPTION OF TWO AND ONE-HALF PERCENT OR LESS.[1]

Test Property	Wearing Course		Intermediate and Base Course	
	Point on Curve for Optimum Bitumen Content	Adequacy of Mix Criteria	Point on Curve for Optimum Bitumen Content	Adequacy of Mix Criteria
Marshall Stability blows[2]	peak of curve	1,800 or higher	peak of curve	1,800 or higher[3]
Unit weight	peak of curve	not used	not used	not used
Flow	not used	16 or less	not used	16 or less
Percent air voids	4	3-5	6	5-7[4]
Percent voids filled with bitumen	75	79-80	60	50-70
Percent voids mineral aggregate (VMA)[5]				

[1]See TM5-822/AFM 88-6, Chapter 9, for procedure with aggregate showing water absorption greater than 2-1/2 percent.

[2]For Army Airfields with tire pressures less than 100 psi. See TM5-822-8.

[3]For Navy base courses use stability of 1,500 or higher.

[4]With VMA procedure on Navy Airfields use 3-8 percent air voids.

[5]See Table 4-21 for minimum void requirements for Navy Airfields.

TABLE 20. MINIMUM PERCENT VOIDS IN MINERAL AGGREGATE (VMA) FOR BITUMINOUS CONCRETE MIXES - NAVY AIRFIELDS.

Nominal Maximum Aggregate Size (inches)	Minimum Voids in Mineral Aggregate (percent)
3/8	16
1/2	15
3/4	14
1.0	13

TABLE 21. SUGGESTED CRITERIA FOR CUTBACK ASPHALT MIXES (AFTER REF. 8).

Test	Requirement
Stabilometer Value	30 min.
Moisture Vapor Susceptibility (Stabilometer Value)	20 min.
Swell	0.030 in. max.

TABLE 22. MARSHALL DESIGN CRITERIA FOR PAVING MIXTURES CONTAINING CUTBACK ASPHALT (AFTER REF. 8).

Test Property	Minimum	Maximum
Degree of Curing		
Percent solvent evaporated		
Maintenance Mixtures	25	
Paving Mixtures	50	
Number of Hammer Blows		
Hand Compactor	75	
Percent Air Voids in Compacted Mix	3	5
Percent Voids in Mineral Aggregate (VMA)	(See Table 4-23)	
Stability [lb. at 77°F]		
Maintenance Mixtures	500	
Paving Mixtures	750	
Flow [units of 0.01 in.]	8	16
Percent Stability Retention		
After 4 days in water at 77°F	75	

TABLE 23. MINIMUM PERCENT VOIDS IN MINERAL AGGREGATE (AFTER REF. 8).

U.S. Standard Sieve No.	Nominal Maximum Particle Size, in.	Minimum Percent VMA
No. 16	0.0469	23.5
No. 8	0.093	21
No. 4	0.187	18
3/8 in.	0.375	16
1/2 in.	0.500	15
3/4 in.	0.750	14
1 in.	1.0	13
1-1/2 in.	1.5	12
2 in.	2.0	11.5
2-1/2 in.	2.5	11

Example: The minimum allowable voids in the mineral aggregate (VMA) for a 3/4 inch maximum size aggregate gradation is 14 percent.

TABLE 24. EMULSIFIED ASPHALT-AGGREGATE MIXTURE DESIGN CRITERIA.

Test Property	Minimum	Maximum
Stability, lb. at 72°F		
Paving Mixtures	500	
Percent Total Voids		
Compacted Mix (granular mixes, no requirement for sand)	2	8
Percent Stability Loss		
After 4 days soak at 72°F	-	50
Percent Absorbed Moisture		
After 4 days soak at 72°F	-	4
Aggregate Coating (percent)	50	-

H. SAFETY PRECAUTIONS, LIMITATIONS OF USE AND ENVIRONMENTAL CONSIDERATIONS

The engineer must be aware of certain precautions and limitations associated with the use of asphalts. These are briefly summarized below.

1. Safety Precautions

Most asphalts used for stabilization purposes must be heated in order that a low viscosity is obtained for handling, mixing and/or compaction purposes. Since elevated temperatures are required it is suggested that workmen wear protective clothing and are cautious. Asphalt cements are often heated above 300°F and will cause severe burns.

The flash and fire points of cutbacks are sometimes below the working temperature of these products. Workmen should not allow open flames or sparks near cutbacks or asphalt cement at elevated temperatures.

2. Climate Limitations

Hot, dry weather is preferred for all types of asphalt stabilizations. Stabilization with asphalts should not be used during periods of rainfall.

For good mixing asphalt emulsions and cutbacks should be used on mixed-in-place operations when aggregate temperatures are elevated (above 60°F). However, these materials can be used at temperatures as low as 32°F. Emulsions will break if frozen. Thus, heated storage tanks will be needed in cold climates. The engineer is directed to Reference 5 for additional handling precautions associated with emulsions.

Air temperatures should be a minimum of 40°F and rising when placing thin lifts (1-inch) of hot mixed asphalt stabilized materials. Adequate compaction can be obtained at freezing temperatures if thick lifts are used with hot-mixed, hot-laid asphalt-stabilized operations. Table 25 lists cessation requirements for hot-mix mats.

TABLE 25. CESSATION REQUIREMENTS (AFTER REF. 17)*.

Base Temperature	Recommended Minimum Laydown Temperature					
	1/2"**	3/4"	1"	1-1/2"	2"	3" and Greater
20-32	-	-	-	-	-	285[1]
32-40	-	-	-	305	295	280
40-50	-	-	310	300	285	275
50-60	-	310	300	295	280	270
60-70	310	300	290	285	275	265
70-80	300	290	285	280	270	265
80-90	290	280	275	270	265	260
90	280	275	270	265	260	255
Rolling time, min.	4	6	8	12	15	15

[1]Increase by 15°F when placement is on base or subbase containing frozen moisture.

*Laydown temperatures below which asphalt paving operation should be ceased.

**Mat thickness.

SECTION VI

LIME-FLY ASH-AGGREGATE STABILIZATION

A. GENERAL

Modern lime-fly ash-aggregate (LFA) mixtures are blends of mineral aggregate, lime fly ash and water combined in proper proportions so that, when compacted, they produce a dense mass. When compacted to a high relative density, and with favorable curing conditions, these mixtures will gradually harden to produce high quality paving materials with many unique and desirable properties. Cores with strengths greater than 3,000 psi in compression have been obtained from a number of sites, but strengths ranging from 500 to 1,000 psi after approximately a year in service are more typical.

LFA mixtures when used as paving materials are normally employed as the main load-carrying components of flexible pavements or as the subbase for portland cement concrete (PCC) pavements. These mixtures are placed in layers commonly referred to as base or subbase courses since a wearing surface must be applied to protect the material from the abrasive effects of traffic, from weathering and from water infiltration. LFA mixtures have been used under both concrete and asphalt surfaces with excellent results.

Not all LFA mixtures result in materials of the same quality. However, with proper mix design and construction controls, LFA materials can be expected to give excellent performance.

B. RELATED MATERIAL

The following document is considered valuable as a supplement to this manual.

Federal Highway Administration, "Fly Ash a Highway Construction Material," 76-16, Implementation Package (18).

C. CONSTITUENTS OF LIME-FLY ASH-AGGREGATE MIXTURES

1. Lime

The term lime as used in this section includes the various chemical and physical forms of CaO as explained in Section III.

2. Pozzolans

Pozzolan is defined by the American Society for Testing and Materials (ASTM) as:

"A siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value, but will, when in a finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties."

The most common pozzolan in use today is fly ash, a by-product from the burning of powdered coal. Fly ash is recovered from power plant flue gasses by mechanical and/or electrostatic precipitation and stored. When stored in the open, it must be conditioned by the addition of moisture to prevent dusting.

There are considerable variation in the quality and reactivity of fly ashes from different sources. In general, fly ashes from the bituminous coals from the Appalachian region behave as true pozzolans, with little or no cementing property except when a source of CaOH is added, such as with a hydrated lime. Fly ashes produced from burning coal from the mid-continent coals have some natural setting properties because of the CaO naturally available in the ash. Fly ashes produced from the subbituminous and lignite coals from the northern and western plains states have a high natural CaO content and are highly reactive even without the addition of lime. Steps may have to be taken to retard this initial reactivity.

ASTM classifies fly ashes as either type "C" or type "F" (ASTM Designation C-618). The basic difference in these two types is the percent CaO in the fly ash. Procedures for evaluating the suitability of a fly ash for use in lime-fly ash-aggregate mixes is given in ASTM Designation C-593.

Those fly ashes with natural reactivity will set up in the stockpile when conditioned with water to prevent dusting. These fly ashes must be crushed to a suitable fineness prior to use in a LFA mix. A typical gradation for fly ash after conditioning and recrushing is as follows:

Typical Gradation of Crushed Fly Ash

Sieve Designation	Percent Passing
#4	99
#10	75

To achieve a reactivity of a crushed fly ash it is necessary to have a significant percent passing the Number 200 sieve. However, it is virtually impossible to control the fineness under field conditions on the finer sieves. Experience has shown that if the fly ash has at least 75 percent passing the Number 10 sieve, it will normally contain sufficient quantities of the finer fraction to provide suitable reaction. If reactivity of a fly ash is marginal, it can be enhanced by increasing the finer fraction.

As indicated earlier, the coal source is a major factor in the reactivity of fly ash. Other factors will also affect the reactivity of fly ashes produced from the same coal source. These include the type and design of burners, the efficiency of the burning, and the method of collection of the fly ash. Efficiency of burning can be evaluated by the loss on ignition (LOI) test (ASTM C-114), but there are no effective tests to evaluate the other factors at this time. Therefore, the best procedure is to carefully evaluate the reactivity of the particular fly ash intended for use in a LFA mix using procedures outlined in ASTM Designation C-593. Uniformity of the fly ash from a given source should be monitored on a continuing basis. It is especially critical to monitor the burning efficiency by the LOI test.

Natural pozzolans, such as volcanic ash, calcined shale, pumicite and diatomaceous earth, may also be used where available. Not all fly ashes and pozzolans have the same chemical properties. To determine if a pozzolan is of satisfactory quality, it should be tested for pozzolanic reactivity in accordance with ASTM Designation C-593.

3. Aggregates

Aggregates which have been successfully used in LFA mixtures cover a wide range of types and gradations, including sand, gravel, crushed stone and several types of slag. Aggregates should be of such gradation that, when mixed with lime, fly ash and water, the resulting mixture is mechanically stable under compaction equipment and capable of being compacted in the field to high density. Further, the aggregate should be free from deleterious organic or chemical substances which may interfere with the desired chemical reaction between the lime, fly ash and water, and should consist of hard, durable particles, free from soft or disintegrated pieces.

A listing of aggregates used successfully in LFA mixes includes crushed stones, gravels, coarse sands, fine sands, air-cooled blast furnace slag and wet bottom boiler slag from utility plants.

Fine-grained mixtures have generally produced materials of greater durability than coarser grained mixtures. However, mixtures with coarser gradations are generally more mechanically stable and may possess higher strengths at an early age. With time, the mixtures with the fine-grained aggregates may ultimately develop higher strengths than those with coarser-grained aggregates. Furthermore, coarse-grained aggregates must be well graded and contain a large portion of the fine fraction to produce a suitable matrix. Also, silt and clay particles may be detrimental to the quality of an LFA mix.

4. Proportions

The relative proportions of each constituent used in a specific LFA mix will vary over a fairly wide range. Effective mixtures have been prepared with lime contents as low as two percent and as high as eight percent, while fly ash contents vary from a low of eight percent to a high of 36 percent. Typical proportions are 2-1/2 to 4 percent lime and 10 to 15 percent fly ash. Mix design procedures have been developed to determine the appropriate proportions for a specific mixture and use. The importance of proper mix design is indicated in the subsequent sections.

D. POZZOLANIC REACTION

Reactions occurring in compacted LFA mixtures are very complex and have not been fully defined. The complexity of these reactions is enhanced by the heterogeneous composition, both physically and chemically, of both the fly ash and aggregate used.

Several types of chemical reactions take place when lime is mixed with reactive fly ash and aggregates in the presence of water. Probably the most important reaction, with respect to paving applications, is the reaction which produces a cementitious gel, binding the mineral aggregate particles together. Apparently the critical reaction is the reaction of the calcium in the lime with certain aluminous and silceous minerals present in the fly ash, to produce a gel which is a compound of calcium or calcium aluminate.

Pozzolanic reactions, required for the development of cementitious compounds, will not take place unless sufficient moisture is present in the mixture. These desirable reactions are also retarded by low temperatures and almost completely stop at temperatures below about 40^{o}F. High organic carbon content in the mixture also tends to inhibit the reaction processes. This is one reason why the fly ashes are tested for carbon content using the loss on ignition tests.

As indicated in paragraph C.2, chemical reactivities of fly ashes obtained from different sources vary. Some sources produce a relatively nonreactive fly ash, while others produce highly reactive fly ashes. Since good reactivity is necessary to produce high quality LFA mixtures, it is important to test a fly ash for its chemical reactivity prior to use. If a nonreactive fly ash is used, cementing reaction will either be very slow or will not occur, and the mixture will not harden sufficiently to yield a satisfactory paving material.

Pozzolanic reactions which occur in LFA mixtures are influenced by many factors, including materials, proportions, processing, curing time, density and moisture content. All variables shown are important to the ultimate characteristics of an LFA mixture.

1. Effect of Blending

For a LFA mixture to develop its maximum possible strength, the ingredients must be thoroughly blended. The importance of thorough blending is shown in Figure 36. The data shown were obtained from a laboratory study using one type of laboratory mixer and for one set of mixture proportions. The intensity or degree of mixing obtained with heavy construction machinery is substantially greater than with the laboratory equipment, so the time scale in Figure 36 is relative rather than absolute. The effectiveness of some types of plant mixers will permit substantially shorter mixing times. In all cases, the materials should be thoroughly mixed and the time required to achieve uniform blending will be dependent upon the type and efficiency of the available mixing equipment and mixture proportions.

2. Effect of Curing Conditions

Curing conditions have a profound influence on the properties of LFA mixtures. Both curing time and temperature greatly affect the strength and durability of "hardened" mixtures. The literature clearly shows that as curing time and temperature are increased, the strength of the mixture also increases.

One method for taking into account the combined effects of temperature and time is to combine the two variables into a single variable called a degree-day. Figure 37 shows degree-day curves developed from three LFA mixtures from widely different sources. The degree-day strength relationships shown by these curves were developed using a base temperature of 40°F. That is, the degree-days were determined by subtracting 40 degrees from the curing temperature and multiplying the difference by the number of curing days.

Although the 40°F base was used for calculating the degree-days, the chemical reactions do not necessarily stop at 40°F. Data are available to indicate a continuing reaction occurring at temperatures even below freezing, especially with highly reactive fly ashes. As the temperature is reduced below approximately 40°F, however, the reactive process is highly retarded and relatively long curing times are required to produce significant changes in the properties of LFA mixtures.

While the low curing temperatures will retard the reaction process of LFA mixtures, neither reduced temperatures

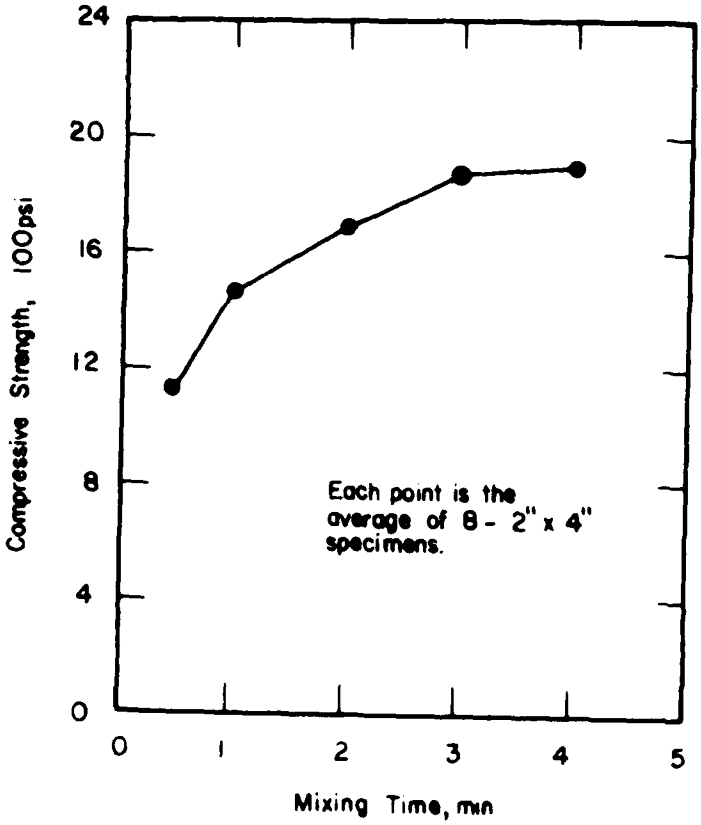


Figure 36. Relationship of Compressive Strength to Mixing Time for 72.1 Percent Slag, 24.0 Percent Fly Ash, and 3.9 Percent Lime Mixture.

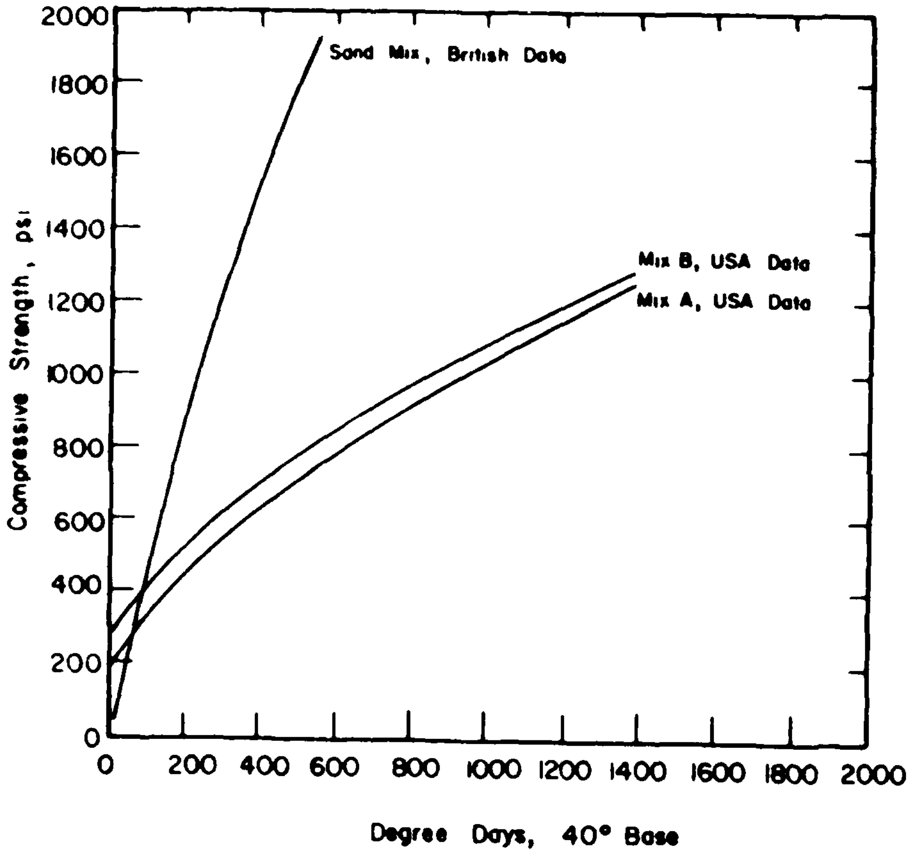


Figure 37. Degree Day Versus Compressive Strength Curves for Three Lime-Fly Ash-Aggregate Mixtures.

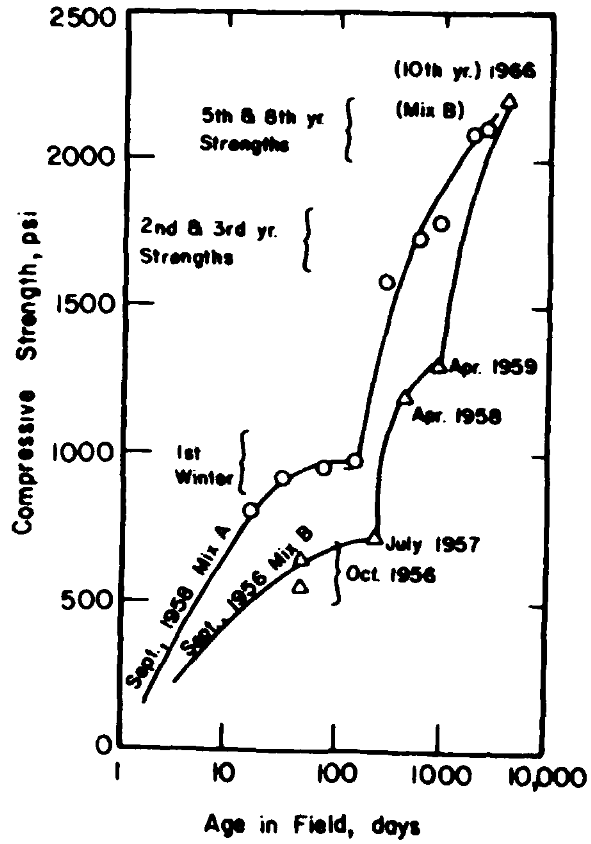


Figure 38. Age Strength Relationships of Lime-Fly Ash-Aggregate Mixtures From Field Cores (After Ref. 1).

nor actual freezing of the mixture have an apparent permanent detrimental effect on the chemical properties of the constituents. Figure 38 shows the cumulative development in the strength of cores taken from in-service pavements in the Chicago, Illinois, and Philadelphia, Pennsylvania, areas. Although the in-service pavements were subjected to a significant number of freeze-thaw cycles during the winter months, the continuing chemical reactions are indicated by the increase in strength which occurred with rising temperature during the subsequent spring and summer months.

Under acceptable curing conditions, chemical reactions in LFA mixtures will continue as long as sufficient lime and fly ash are available to react. Cores taken systematically from pavements over a 10-year period indicate a continuing development in the strength of the mixtures. This continuing reaction process can manifest itself in a phenomenon called autogenous healing, which is one of the unique properties of LFA mixtures. There are a number of recorded cases where distressed areas caused by improper loading of LFA pavements during early life have actually healed over with time.

3. Effect of Admixtures

In an effort to accelerate development of strength and improve the short-term durability characteristics of LFA mixtures, and thereby permit extension of the construction period to later in the fall, admixtures have been added to accelerate or compliment the lime-fly ash reaction. Most of the work in this area has been with chemicals in liquid suspension or in a powdered form.

Portland cement is an effective admixture for use in LFA mixtures. The early strength development associated with hydration of portland cement compliments the slower strength development associated with lime-fly reactions.

Certain other admixtures also give beneficial results. However, the use of many admixtures may not be feasible due to handling problems and prohibitive costs. Admixture costs of approximately $0.05 per pound when used in quantities of as little as 0.5 percent may increase the cost of the resulting mixture by as much as 24 percent. Therefore, the total cost of the LFA mixture must be given careful consideration when considering the addition of admixtures.

E. ENGINEERING PROPERTIES OF LFA MIXTURES

1. Compressive Strength

The quality of hardened LFA mixtures is usually evaluated by the unconfined compressive test. It is generally assumed that the higher the compressive strength, the better the quality of the LFA mixture.

Compressive strength of LFA mixtures is influenced by all of the factors discussed previously. Properly designed mixtures compacted to high relative density and properly cured may ultimately develop compressive strengths well in excess of 3,000 psi. Materials cured for seven days at 100°F will normally develop compressive strengths in the range of 500 to 1,200 psi. These same materials will likely develop compressive strengths of 1,500 psi or greater after one or two years in service.

LFA mixtures with compressive strengths in excess of 450 psi after seven days at 100°F are currently considered satisfactory for use as base and subbase materials. Each mix design of an LFA material must be checked for potential strength development, and the thickness design of the pavement system coordinated with expected strength characteristics of the material.

2. Flexural Strength

The flexural strength of a lime-fly ash-aggregate mixture can be estimated from its compressive strength. The flexural strength of a mixture usually ranges from 1/8 to 1/10 of the confined compressive strength as determined from ASTM C-593.

3. Durability

Properly designed LFA mixtures can be blended to meet the durability criteria of all highway departments for use as high-quality base materials. Several methods for evaluating the durability of LFA mixtures have been developed. The most commonly applied procedures include determination of the weight loss or loss of strength of laboratory prepared specimens after prescribed numbers of cyclic wetting and drying of cyclic freezing and thawing. Properly designed LFA mixtures, after reasonable curing times (7 days at 100°F) exhibit weight losses of less than one percent after 12 cycles of freezing and thawing and exhibit little or no reduction in strength under the same conditions. Conversely, improperly designed mixtures may disintegrate completely (100 percent weight loss) under the same test conditions.

4. Stiffness Modulus

The stiffness of an LFA mixture is usually expressed in terms of its modulus of elasticity (E). Typical E values for LFA mixtures range form 0.5×10^6 to 2.5×10^6 psi. Specific values will depend on whether a tangent modulus or secant modulus is used. The expected range of E values for a specific LFA mixture is a function of several factors, in particular, aggregate characteristics (particle hardness and gradation), degree of compaction and extent of curing.

5. Autogenous Healing

A unique characteristic of LFA mixtures is their inherent ability to heal or re-cement across cracks by a self-generating mechanism. This phenomenon is referred to as autogenous healing. The degree to which autogenous healing will occur depends on:

a. The age at which the mixture cracks,

b. The degree of contact of the fractured surfaces,

c. The curing conditions,

d. The availability of reaction products (lime and fly ash) and

e. Moisture conditions.

Because of the autogenous healing property, LFA mixtures are less susceptible to deterioration under repeated loading and are more resistant to attacks by the elements than other materials which do not possess this property.

6. Fatigue

Lime-fly ash-aggregate mixtures, like all paving materials, will fail under repeated loading at stress levels considerably less than those required to cause failure of the material when loaded to failure in a single load application. Pavements are subjected to repeated loads of varying quantities, magnitudes and frequencies. The concept of failure by repeated loading must be included in the pavement design process. The results of a repeated load study conducted on a lime-fly ash-aggregate mixture used in the University of Illinois Test Track are shown in Figure 39.

Because of autogenous healing characteristics, LFA mixtures are less susceptible to failure by fatigue than most other paving materials. Unless fatigue failure occurs during the first few days of loading, it will not normally be a factor in the performance of these pavements. This is due to the healing process which provides a greater curing effect than the damage being caused by the repeated loads.

7. Poisson's Ratio

The value for Poisson's ratio remains relatively constant at about 0.08 at stress levels below approximately 60 percent of ultimate and then increases at an increasing rate with the stress level to a value of about 0.3 at the failure stress level.

For most calculations, Poisson's ratio for LFA mixtures can be taken as 0.10 without appreciable error.

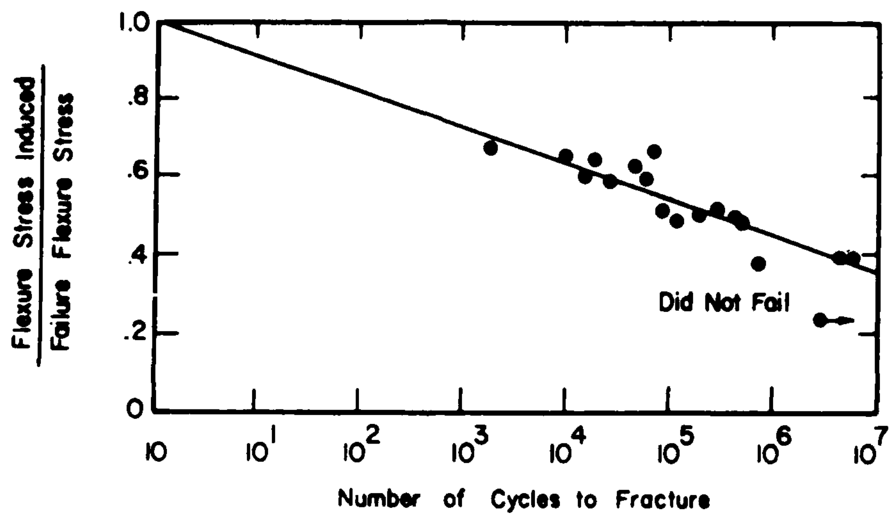


Figure 39. Relationship Between Maximum Stress Level and Logarithm of Number of Cycles to Fracture (Zero Minimum Stress Level) (After Ref. 1).

8. Coefficient of Thermal Expansion

Hardened LFA materials, like all stabilized paving materials, are subject to dimensional changes with changing temperatures. The magnitude of volumetric change is indicated by the coefficient of thermal expansion of the material and has the dimensions of inches per inch per degree Fahrenheit.

The coefficient of thermal expansion of LFA mixtures is influenced primarily by the aggregates and the moisture content of the material. Typical values for the coefficient are about the same as for concrete at the same moisture content (approximately 6×10^{-6} inches per inch per degree Fahrenheit).

F. SPECIAL FIELD CONSIDERATIONS

The reader is referred to Section IX for general construction considerations. However, since fly ash is used in combination with lime, a few special considerations are discussed in the following paragraphs.

Among the advantages of LFA mixtures for use in pavement construction are the ease of construction and the fact that no special construction equipment is needed. The major requirements during construction for the effective use of LFA materials are that they be well mixed, spread uniformly to the proper thickness and compacted to a high relative density. These operations can all be accomplished with construction equipment normally found on a pavement construction site. While the accepted construction procedures are fairly simple, it is emphasized that poor construction procedures will result in poor quality in the final product with a concomitant poor reliability in performance.

Successful central plants for the production of LFA mixtures require the following main components:

1. An aggregate source and hopper with a feed control,

2. A hopper and feed belt with controls for the fly ash,

3. A lime storage unit with feed hoppers and feed controls,

4. Water storage tanks will feed control and

5. A pugmill for blending the materials.

There have also been excellent jobs placed in which the ingredients were spread on a prepared roadbed and mixed in-place. Experience with the mixed in-place type of blending, however, shows that the overall quality of the final mixture is not as high as when the materials are proportioned and blended in a central plant.

Spreader boxes have been successfully used to spread the delivered LFA materials. An alternate procedure which has proven successful is to dump the prepared mixture from the truck into windrows and spread with a motor patrol. Particular care must be taken with this method of operation to prevent segregation of the aggregate particles by sizes. A third method of spreading the mixture which provides a high degree of thickness control is to place the mixture with equipment which controls the level of the spread mix by a string-line or similar screen elevation control. With all methods, care must be taken to produce a layer of uniform thickness and to prevent segregation of material during dumping and spreading.

Steel-wheeled, pneumatic-tired and vibratory rollers have all been used successfully to compact LFA mixtures. Vibratory pan type compactors are also effective for this operation. Since the material is basically granular in nature with little or no cohesion, pneumatic and vibratory rollers and the vibratory pans are usually most effective in producing the desired high relative densities. Steel-wheeled rollers are normally used only for producing a true and smooth final surface after initial compaction with the other types of compactors.

One of the advantages of LFA mixtures over some stabilized materials is that they can be effectively compacted at any time after mixing up to 24 hours or more. Compaction 4 to 8 hours after mixing is quite common, and there have been cases in which compaction was completed more than 48 hours after the material had been mixed and placed. The length of time that can elapse between mixing and final compaction is a function of climatic conditions. Generally, delays of 24 hours or more are to be discouraged.

Obtaining a high degree of relative density is an absolute necessity for obtaining a quality control. Figure 40 shows the effects of density on the strength of cured and hardened LFA mixtures. These data clearly show the criticalness of obtaining a high relative density in the LFA material. Relative density has a similar effect on the durability of LFA mixtures; that is, for a given curing condition, the durability of LFA mixtures decreases dramatically with decreasing density.

In general, traffic can be permitted on a compacted LFA mixture immediately after placement. To reduce the abrasive effects of traffic, it is recommended that a surface course be placed over LFA material as soon as possible. The surface course will also prevent evaporation of moisture from the mixture.

G. MIXTURE DESIGN

1. General

The relative proportions of lime, fly ash, aggregates and

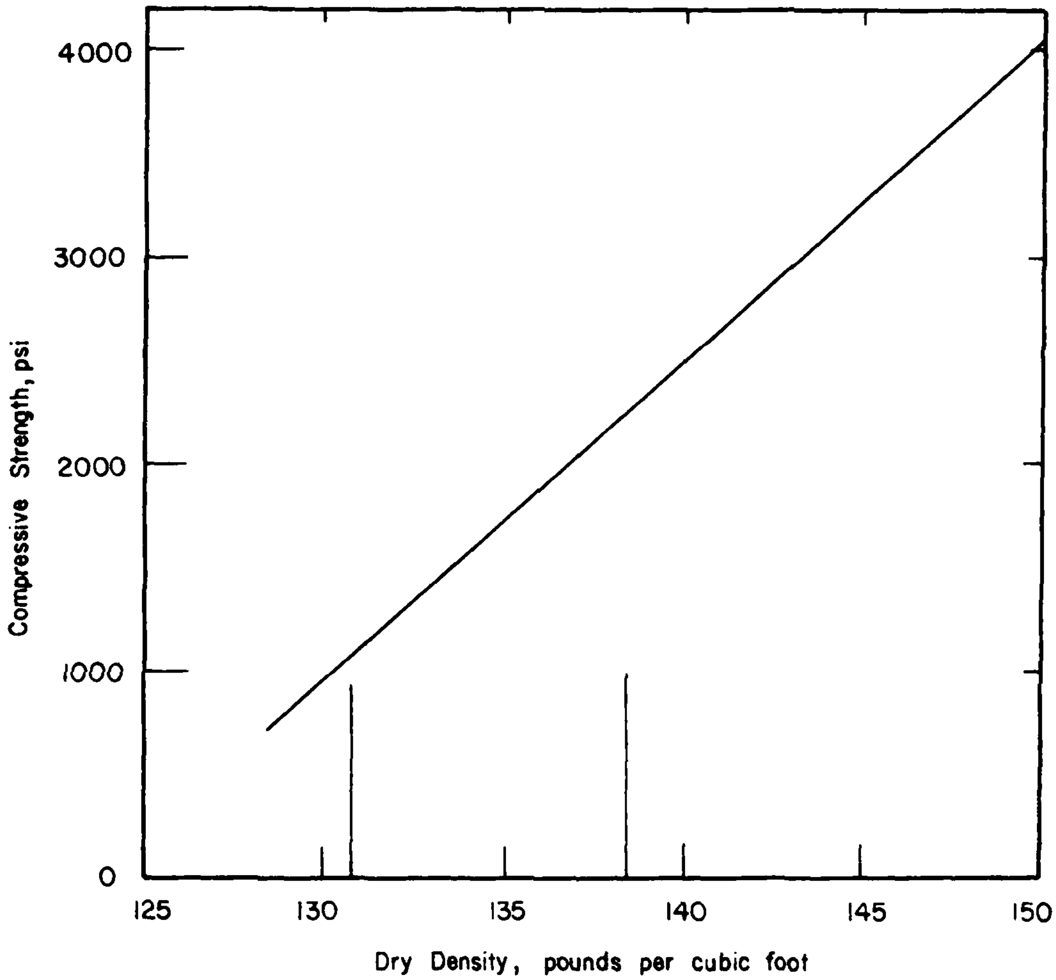


Figure 40. Effects of Relative Density on the Strength of an LFA Mixture.

water used in LFA mixtures vary with aggregate gradation, surface characteristics of the aggregate, fly ash reactivity, and with type of lime used. Normally, the minimum fly ash content is determined by the amount needed to achieve maximum density in the compacted mixture (i.e., fill the voids in the aggregate). Lime content is established, by trial batch procedures, to provide desired strength and durability characteristics for the final mix. Typical curves depicting the relationship between strength and lime content for an LFA mixture with a given aggregate and fly ash and a range of curing conditions are shown in Figure 41. For the particular aggregate and fly ash shown in Figure 41, the optimum lime content to provide maximum strength, after prolonged curing at 70°, would be approximately nine percent. With less extensive curing conditions, the apparent optimum lime content may be significantly lower.

The optimum fly ash content is a function of the fly ash and aggregate gradations.

Fly ash fineness has a significant influence on mixture strength. At least 85 percent of the fly ash should be finer than the Number 4 sieve if reasonable strengths are to be expected. The loss in strength with coarser fly ash can be attributed to a loss in fly ash reactivity due to a reduced surface area in the fly ash, and to a loss in density of the mixture. Attainment of high relative density in the final mix is essential for good durability and strength.

2. Fly Ash Content

To determine the optimum fly ash content for a specific aggregate gradation, the aggregate should be compacted at varying fly ash contents. In general, changes in fly ash content of about two to five percent by weight are used for this purpose. When the ratio of fly ash and aggregate produces a maximum density, this is the optimum fly ash content. Normally an increase in fly ash content of about two or three percent over the optimum amount is used to compensate for variations in mix uniformity (see Figure 42).

3. Lime Content

After the optimum fly ash content has been determined, the amount of lime needed to produce the desired strength and durability is determined by trial mixes. Specimens are prepared with the trial mixes and tested in accordance with the procedures given in ASTM Designation C-593. Figure 43 summarizes the mix design procedure.

4. Mixture Quality

The quality of LFA mixtures is closely related to the composition of the mixture. Both the lime and fly ash contents

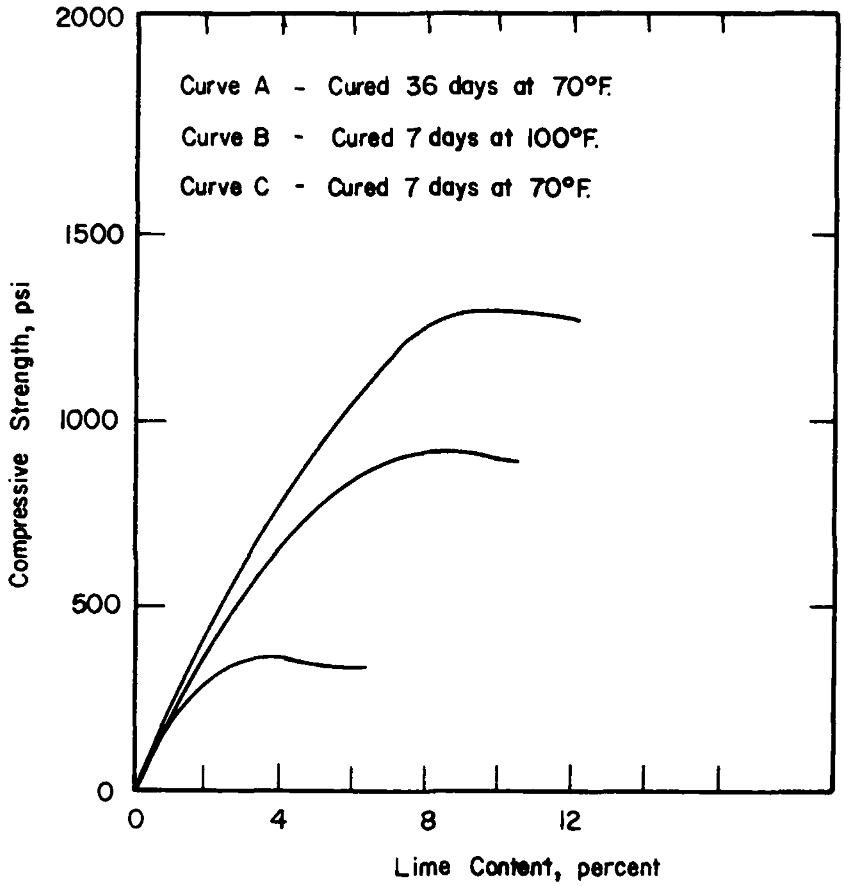


Figure 41. Effect of Lime and Curing Conditions on the Compressive Strength of Lime-Fly Ash-Aggregate Mixtures.

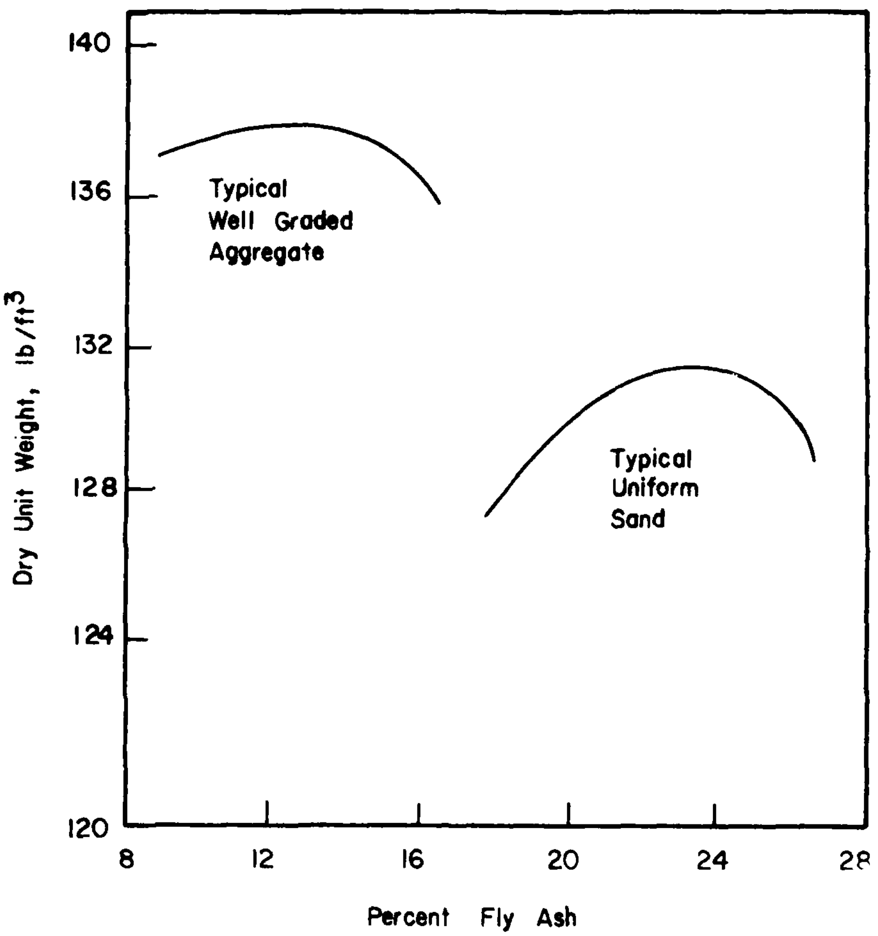
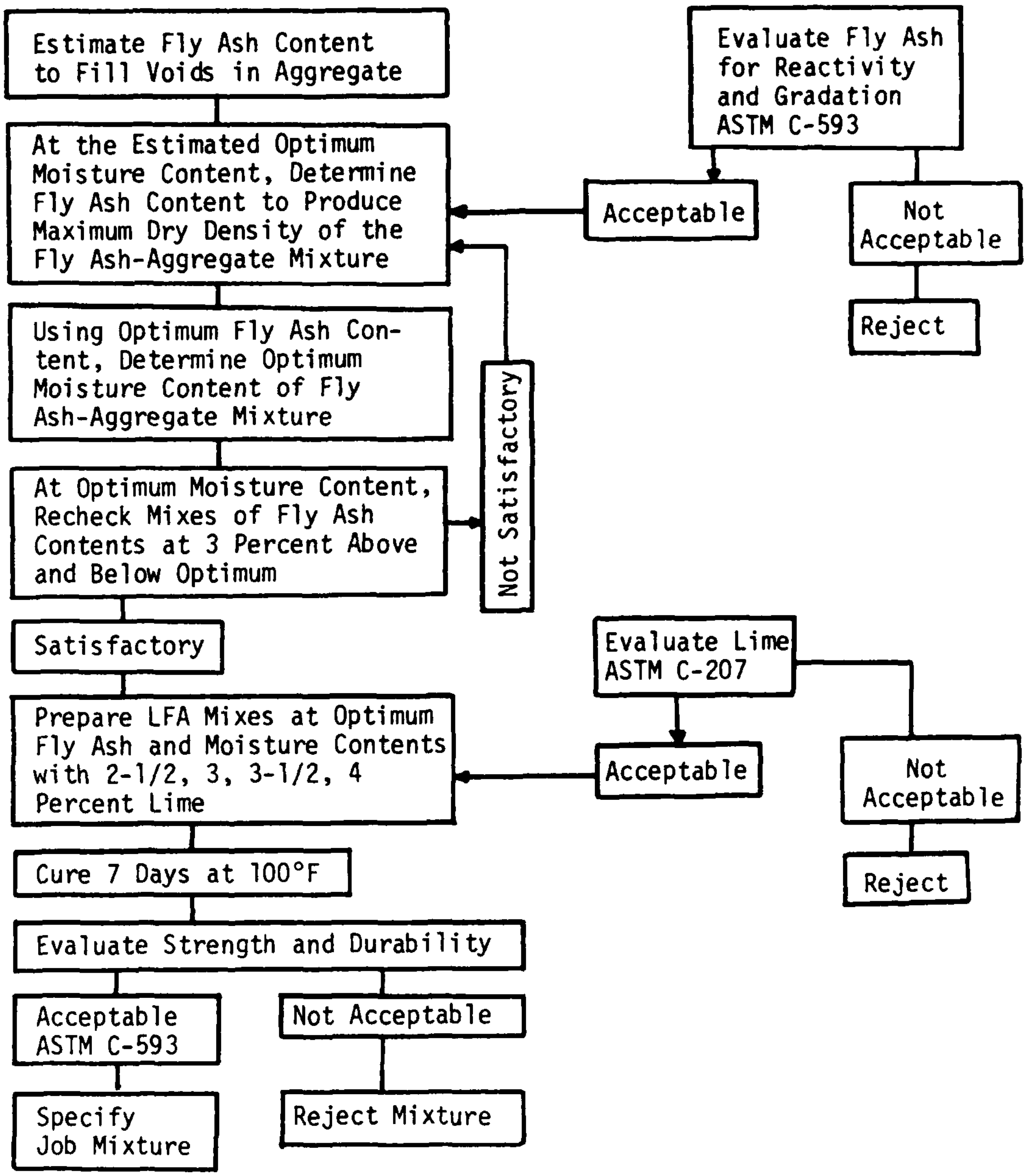


Figure 42. Effect of Fly Ash Fineness on Compressive Strength.



Note: Strength and durability specimens are to be prepared in triplicate (ASTM C-593).

Figure 43. Mixture Design Flow Diagram.

will influence the properties of the final mix. The quantity of fly ash required is influenced by the gradation of the aggregate and the fly ash, while the lime content is based on strength and durability criteria of the cured mix.

ASTM C-593 provides two criteria for judging the acceptability of the trial mix:

a. A minimum unconfined compressive strength following vacuum saturation of 400 psi and

b. A maximum of 14 percent weight loss following 12 cycles of freeze-thaw.

Either criterion may be used to evaluate the mixture acceptability.

SECTION VII

COMBINATION STABILIZERS

A. INTRODUCTION

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 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 incorporated into the soil to make it friable, thereby permitting the cement or asphalt to be adequatly 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. Four combination stabilizers are considered in this manual. There are:

a. Lime-cement,

b. Lime-asphalt,

c. Lime-emulsified asphalt and

d. Cement-emulsified asphalt.

B. COMBINATION STABILIZER REACTIONS

1. Lime-Cement Combinations

Combinations of lime and cement often are acceptable expedient stabilizers. Lime can be added to the soil to improve the mixing characteristics of the soil as well as reduce its plasticity. Cement can then be mixed with the soil to provide rapid strength gain.

a. Lime Reactions. Details of lime reactions have been covered in Section III. In general, lime reacts readily with most plastic soils containing clay, either the fine-grained clays or clay-gravel types. Such soils range in Plasticity Index (PI) from 10 to 50+ percent. Lime also reacts with some silts but normally will not react with sandy soils.

b. Cement Reactions. Details of cement reactions are discussed in Section IV. While cement cannot be used alone for heavy clays or highly plastic soils, lime can be first used to initiate cation exchange and flocculation-agglomeration reactions and to produce immediate changes by reducing the plasticity and improving the workability of these soils. Addition of cement then promotes rapid strength development of the mixture. This is especially advantageous when rapid strength gain is required under cooler weather conditions.

2. Lime-Asphalt Combinations

All asphalt paving materials currently being produced may be mixed with some type of sand, soil, or aggregate and soil mixture. The more viscous asphalt materials may require mixing in a plant, while more fluid materials may be mixed with soil-aggregate materials. The effect of moisture may have a significant influence on performance. The presence of moisture decreases the stiffness or modulus of asphalt mixtures and this influence is more marked with increased temperature. To solve this problem, combinations of lime and asphalt have often been effective. The lime addition may prevent stripping at the asphalt-aggregate interface as well as increase the stability of the mixture.

One percent lime slurry pretreatment of the soil or aggregate has been quite effective, not only in raising the modulus value, but in increasing water resistance. The gain in strength and water resistance of the lime-asphalt stabilized material can be far greater than simply the sum of the two binding actions of lime and asphalt, taken separately. A further observation is that lime improves the workability of some soil-aggregate materials through the pozzolanic action discussed in Section III.

3. Lime or Cement-Emulsified Asphalt Combinations

Curing is the key factor in the use of emulsified asphalt. The curing or setting of the emulsion-treated material requires loss of water from the mixture. When emulsion-treated base is placed, the curing proceeds rapidly only until the surfacing is laid. Afterwards, the rate of curing levels off, causing delay of strength development.

Hydrated lime or portland cement has been used to promote curing of the emulsified asphalt-treated materials. The rate of development of strength in emulsified asphalt mixtures on curing is greatly accelerated by cement. Figure 30 shows that when an emulsified asphalt mixture is uncured, it behaves essentially like an untreated granular material (i.e., resilient modulus is stress dependent). After increasing amounts of curing, the material becomes less stress dependent and more like asphalt concrete. Figure 44 illustrates how small amounts of portland cement can increase the early modulus gain for emulsified asphalt mixtures. Emulsion mixtures that might not cure to usable strength in a reasonable length of time (say, because of cool, damp weather) can be improved through the use of cement or lime.

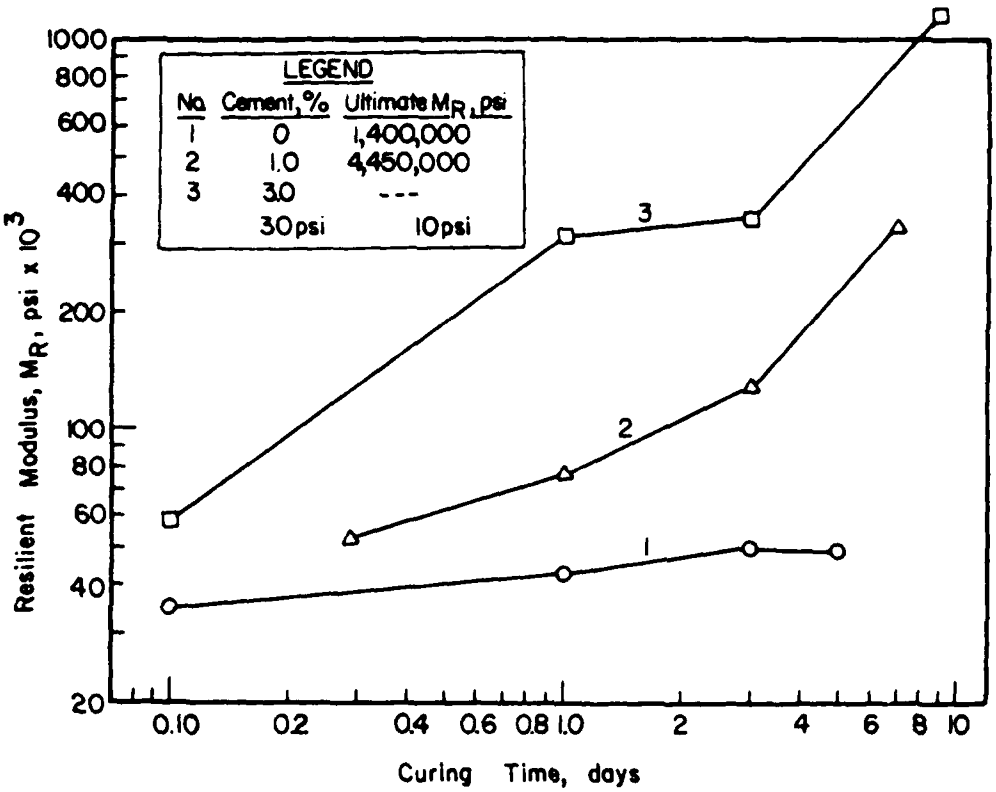


Figure 44. Resilient Modulus Increases with Curing Time for Asphalt Emulsion Mixtures Containing Portland Cement Cured at 75°F (After Ref. 1).

Moisture resistance of emulsified asphalt mixtures pretreated with lime or cement slurries is also improved.

C. SELECTION OF STABILIZER

The selection of the proper combination stabilizer to be used will depend on the soil type and on various tests to identify the materials. See Section II.

The stabilizer selection procedure can then be based on the percent passing the Number 200 sieve and the plasticity index. With the results of the tests, a combination stabilizer can be selected through the process suggested in Figure 45. In general, combination stabilizers are best used for soils that have more than 25 percent passing the Number 200 sieve and for plasticity index more than 10.

The various amounts of each individual stabilizer can be determined by the methods outlined in previous chapters of this manual. The general purpose of combination stabilizers is to first pretreat the soil to alter its properties prior to applying the dominant stabilizer. Normally the quantity of the first stabilizer applied will be less than the second. Approximate quantities of combinations are discussed later.

D. APPROXIMATE QUANTITIES

1. Lime-Cement

Since cement cannot be mixed successfully with plastic clays, one to three percent of lime can be first incorporated into the soil before about 3 to 10 percent cement is added. The amount of lime and cement added depends on the type of soil. For the same type of soil condition, more hydrated lime is required than quicklime in the lime-cement mixture.

2. Lime-Asphalt

Pretreatment of aggregates with at least one percent of lime in a slurry form is best used with emulsified asphalt. Pulverized lime works best with cutback or asphalt cement. In general, 1 to 3 percent of lime can be used with 4 to 7 percent asphalt in the mix for soil stabilization purposes.

3. Lime-Emulsified Asphalt

The addition of a small amount of lime to emulsified asphalt mixes at the time the asphalt emulsion is added to a base or subbase has a profound effect on the rate of strength development as well as the ultimate strength level attained. About 1 to 3 percent lime can be combined with 4 to 8 percent emulsified asphalt in the mix.

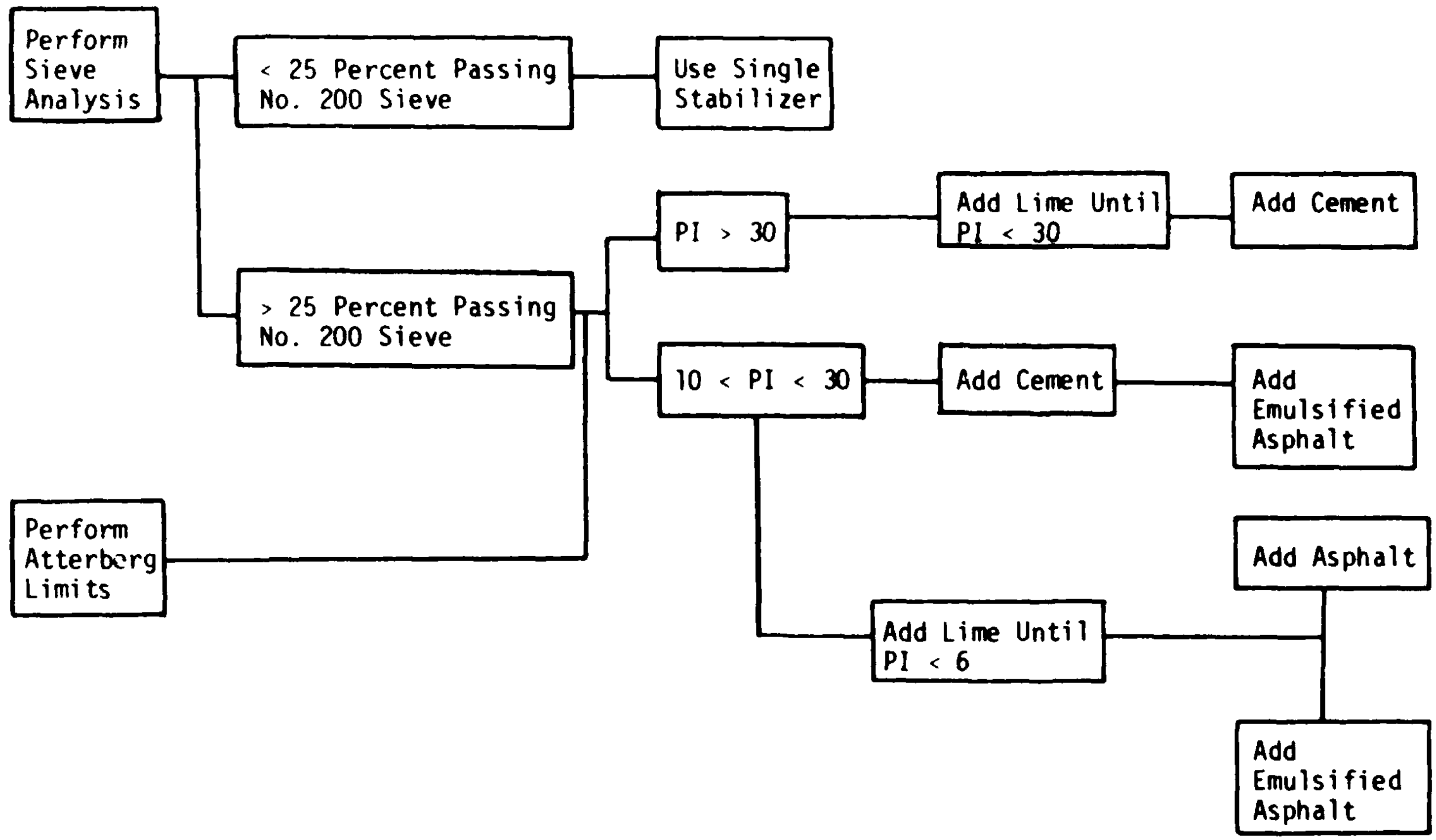


Figure 45. Selection of Combination Stabilizers (After Ref. 1).

4. Cement-Emulsified Asphalt

The addition of small amounts of cement (approximately 1 to 2 percent) by weight to emulsion-treated mixes assists in the development of early stiffness, as compared to the same mix without cement. Care must be taken not to incorporate too much cement; a ratio of cement to emulsion of the order of one to five (based on residual asphalt) appears appropriate to ensure adequate early stiffness without excessive embrittlement.

E. DETAILED TESTING

The quantity of stabilizer to be used is generally determined by means of laboratory durability or strength tests. Cyclic freeze-thaw or wet and dry actions are the major durability factors that must be considered for some combination stabilizer mixtures. The extent of cyclic freeze-thaw action depends on the location of material in the pavement structure, geographical location, climatic variability and pavement-strength characteristics. The laboratory tests necessary for determining strength and/or durability for the combination stabilizers are described in the following paragraphs.

1. Lime-Cement

The unconfined compression test is the most popular procedure for evaluating the strength of lime-cement soils. Specimens are molded in accordance with MIL-STD-621A, Method 100, and tested in accordance with ASTM C-593 using various amounts of admixture and at optimum water content and maximum density. The specimens are then cured in a moist room for a period of seven days before testing in unconfined compression or in a triaxial device.

Direct comparison of the strength data developed from specimens of different sizes is difficult. When it is impossible to use the standard sized samples, the use of a correlation factor based on length-to-diameter ratio as specified in ASTM C-42 should be considered in making such comparisons.

Cyclic freeze-thaw resistance of the lime-cement soil mixture can be determined in several ways. Cyclic freeze-thaw and brushing tests (ASTM C-593) can be used for evaluating durability. ASTM C-593 criteria require less than 14 percent weight loss following 12 freeze-thaw cycles of the stabilized material, but these criteria could be modified as desired.

A vacuum saturation test (ASTM C-593) has been found to correlate well with freeze-thaw damage when the unconfined compression test has been used to evaluate strength loss. The stabilized material is mixed and cured for seven days at 100°F in accordance with ASTM C-593 prior to vacuum saturation in accordance with ASTM C-593. Figure 46 shows the relationship

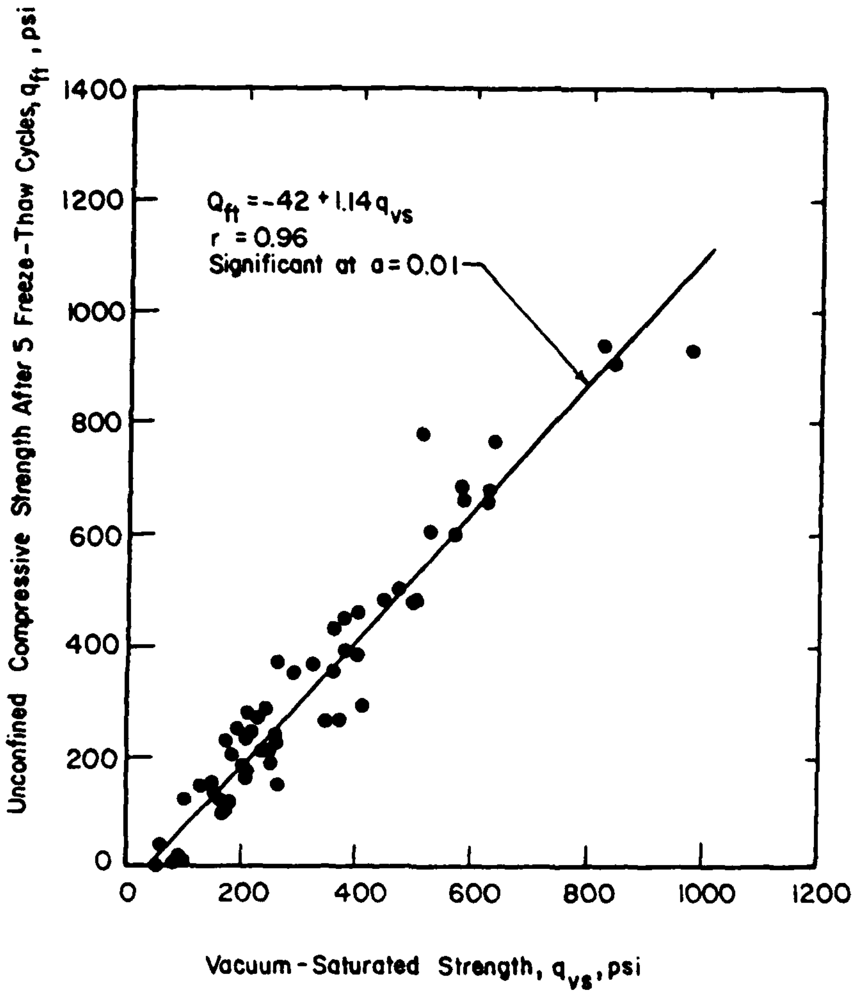


Figure 46. Relationship Between Vacuum Saturation Strength and 5-Cycle Freeze-Thaw Strength (All Data Adjusted to Equivalent L/D = 2. See ASTM C42) (After Ref. 1).

between vacuum saturation strength and 5-cycle freeze-thaw strength. This figure can be used to determine the durability of lime-cement stabilized soils.

2. Lime-Asphalt

The techniques for evaluating lime-asphalt stabilized materials depend upon soil type. For fine-grained materials, absorption tests may be made on the specimens at the desired moisture and density. After the specimens are cured at $100^{\circ}F$ for a period of at least 7 days, the specimen can be placed aupon felt pads or porous stones with the water level maintained at the bottom of the specimen. The purpose of the curing period is to make certain that all of the volatile materials in the asphalt are removed and that the lime has reacted completely with the mixture. The specimens are then weighed before and after saturation and the amount of absorbed water determined. No specific guidelines can be provided at this time, but comparison of absorption of lime-asphalt and asphalt-only specimens will indicate the relative effectiveness of the lime pretreatment. In other words, judgement is largely qualitative.

The lime-asphalt-gravel or lime-asphalt-gravel-sand mixtures, conventional CBR tests and triaxial tests may be used. Tests can be performed on the unstabilized material and then on the mixture; decisions relative to use of the appropriate mixture can be made based on several test results.

Durability tests for lime-asphalt stabilized materials are as outlined for lime-cement stabilized materials.

3. Lime or Cement-Emulsified Asphalt

The strength of lime-emulsified asphalt or cement-emulsified asphalt mixes can be determined by resilient modulus, M_R, testing.

The Resilient Modulus, M_R, is a dynamic test response defined as the ratio of the repeated axial deviator stress, σ_d, to the recovered axial strain, ε_a;

$$M_R = \frac{\sigma_d}{\varepsilon_a} .$$

The test can be conducted in a triaxial device equipped for repetitive loading conditions. Specimen size is normally four inches in diameter by eight inches high. The strain used to calculate the modulus is the recoverable portion of the deformation response (ASTM Test Method D-3497). As an alternative, a simplified resilient modulus test can be performed on Marshall sized specimens (2.5 x 4.0 inches). This diametral resilient modulus test is explained in References 7 and 10.

The resilient modulus, M_R, tests should be performed on fully-cured, water-soaked specimens to determine if the stabilized mixture can meet minimum bearing strength requirements when saturated with water. The tests should be performed at 77°F and 100°F to determine the effects of temperature on strength (see Reference 7 for more details).

F. CRITERIA FOR EVALUATION

1. Lime-Cement

The criteria established in ASTM C-593 should be used to evaluate lime-cement combination stabilized soil or aggregate mixtures. Either the unconfined compressive strength following vacuum saturation or cyclic freeze-thaw brushing weight loss can be used to determine suitability. The criteria are:

a. A minimum unconfined compressive strength of 400 psi following vacuum saturation as prescribed by ASTM C-593.

b. A maximum of 14 percent weight loss following 12 cycles of freeze-thaw as prescribed by ASTM C-593.

2. Lime-Asphalt

As no criteria have been established, it is best to follow the testing procedures discussed in paragraph E.2. Comparison specimens should be fabricated (lime-asphalt and asphalt only). Various percentages of lime should be tried (generally 1 to 3 percent) with the optimum percent of asphalt. The optimum mix is selected based on judgement and comparison.

The optimum percentage of asphalt should be determined by the procedure explained in detail in Section V. The companion specimens should be fabricated and cured as specified in the applicable paragraphs of Section V.

3. Lime or Cement-Emulsified Asphalt

The purpose of using lime or cement with emulsified asphalt is to promote curing. Thus criteria should be related to curing or strength development. No criteria exist. However, a comparative evaluation procedure is suggested, based on the dynamic modulus test (ASTM D-3497) or the diametral resilient modulus test.

Companion lime or cement-emulsified asphalt and asphalt only specimens should be fabricated, cured (paragraphs E.3) and tested in accordance with paragraph E.3. A decision is made based on this comparison. A higher dynamic modulus indicates greater stiffness and a greater degree of curing.

The optimum emulsified asphalt content should be determined before adding cement or lime. Use the detailed procedures explained in Section V. All specimens, those containing emulsified asphalt only and those containing both lime or cement and emulsified asphalt, must be fabricated at the optimum percentage of emulsified asphalt.

Fabrication and curing of specimens should be in accordance with Section V and Appendix C, Section VI.

G. CLIMATIC AND/OR CONSTRUCTION LIMITATIONS

1. General

Lime-stabilized soils are relatively slow-setting and require some warm weather to harden properly. Cement hydration also ceases when temperatures are near or below freezing. Lime-cement stabilization therefore should not be carred out in cold weather. As a general rule, lime-cement stabilization should not be attempted when the soil temperature is below 40°F, and there is not much prospect of the weather improving in the next day or two. During cold weather conditions, lime-cement stabilized soils should be protected by a suitable covering of hay, straw, or other protective material to prevent freezing for a period of seven days after placement and until they have hardened.

2. Traffic

If heavy vehicles are allowed on the lime-cement stabilized soil prior to 7- to 10-day curing period, damage to the structural layer may occur. However, light vehicles may be beneficial. All lime-cement stabilized bases require a wearing surface of at least a bituminous seal coat. An unprotected lime-cement stabilized base might have poor resistance to the abrasive action of continued traffic. Heavy vehicles should not be allowed on lime-emulsified asphalt or cement-emulsified asphalt stabilized soils prior to 7 to 10 days curing period in order to avoid damage to the structural layer.

3. Hot-Dry Weather

Hot dry weather is preferred for all types of lime-asphalt stabilization. If thin lifts of lime-hot asphalt stabilized material are being placed, the air temperature should be 40°F and rising, and compaction should be immediately after laydown. Adequate compaction can be obtained at freezing temperatures if thick lifts are used with hot mixed, hot laid asphalt stabilization operations.

4. Binder Effects

From a strength standpoint too much lime or cement in a stabilized mixture is not a problem. However, excessive asphalt in the mix will cause reduction in soil strength. Excess asphalt will be evident on the top, sides and bottom of the laboratory compacted soil samples.

5. Rain

Lime-emulsified asphalt or cement-emulsified asphalt applications should not be attempted during periods of rain or if the probability of rain exists. Unbroken emulsions subjected to rain can be further diluted and completely lost by runoff. A longer breaking or cure time should be anticipated during periods of high humidity. Stabilized material and air temperatures preferably should be above 60°F. During hot, dry weather conditions, it is advantageous to moisten the soil prior to application of emulsion.

SECTION VIII

THICKNESS DESIGN OF STABILIZED LAYERS

A. PURPOSE

This section explains the role and function of stabilized layers in the pavement structure. It also is a guide to thickness design of the stabilized layers. Thickness design of the individual stabilized layers as well as that of the entire pavement structure will be based on existing Air Force pavement design procedures.

B. RELATED CRITERIA

Additional criteria related to the design of Air Force pavements are provided in the following publications:

Subject	Source
Aircraft Loadings	AFM 88-6, Chapter 1
Airfield Geometric Design	AFM 96-2, AFM 86-8
Airfield Pavement Drainage	AFM 88-5, Chapter 1
Airfield Pavement Evaluation	AFM 88-23, Chapters 2, 3 and 4, AFR 95-3
Bituminous Materials	AFM 88-6, Chapter 9
Concrete Materials	AFM 88-6, Chapter 8
Materials Testing	AFM 89-3
Flexible Pavement Design (Airfields)	AFM 88-6, Chapter 2
Flexible Pavement Design (Roads)	AFM 88-7, Chapter 3
Frost Design	AFM 88-6, Chapter 4
Rigid Pavement Design (Airfields)	AFM 88-6, Chapter 3
Rigid Pavement Design (Roads)	AFM 88-7, Chapter 1
Test Methods for Subgrades, Subbases and Bases	MIL-STD-621A

Subject	Source
Unified Soil Classification	MIL-STD-619B

C. AIRFIELD THICKNESS DESIGN USING STABILIZED LAYERS

1. Role of Stabilized Layer

a. Flexible Pavement Structure. The fundamental purpose of a base course or subbase course in a flexible pavement is to provide a stress-distributing medium which will spread the load applied to the surface so that shear and consolidation deformation will not take place in the subgrade. To insure a satisfactory design, the thickness of the base plus subbase should be sufficient to prevent overstressing the subgrade.

Specifications for subbase and base courses for use in flexible pavements are presented in AFM 88-6, Chapter 2.

Materials stabilized with lime, cement, asphalt or a combination of stabilizers may prove superior to conventional aggregates and base courses or subbases because these materials generally have higher stiffnesses, greater cohesion and more load distributing capabilities. This may result in a thinner total pavement thickness.

Stabilized materials are suitable for use as a base course or subbase course in flexible pavement systems when mixture design and construction procedures are accomplished in accordance with the applicable sections of this manual.

b. Rigid Pavement Structure. Base courses may be required for one of the following reasons:

(1) To provide a uniform bearing surface for the pavement slab,

(2) To replace soft, highly compressible or expansive soil,

(3) To protect the subgrade from detrimental weakening in areas subjected to frost action or to provide uniform movement in subgrade areas subjected to detrimental frost-heaving.

(4) To produce a suitable surface for operating construction equipment during unfavorable weather and

(5) To improve the design subgrade value.

Stabilized layers may be highly effective in accomplishing the previous objectives. In many cases the *in situ* soil may be adequately stabilized to provide a suitable base without bringing in high-quality borrow material to be used as a base course.

Specifications for nonstabilized aggregate for rigid pavement systems are presented in AFM 88-6, Chapter 3.

Stabilized materials are suitable for use as bases under rigid pavements when mixture design and construction procedures are accomplished according to the applicable sections of this manual.

2. Material Properties of Stabilized Layers

The material properties of stabilized soils and stabilized aggregate systems using lime, cement, asphalt and lime-fly ash are discussed in the appropriate sections of this report. Generally the addition of any of these stabilizers to the appropriate soil or aggregate system enhances the load-distributing characteristics of the material when used as a pavement layer.

Although the standard Air Force procedures are to be used for thickness design (AFM 88-6, Chapters 2 and 3), it will be valuable to the pavement engineer to know approximate values of elastic modulus and Poisson's ratio for properly designed stabilized materials. These values are important for two reasons: (1) Elastic moduli correlations are often used to estimate other strength parameters and corrections to design parameters such as modulus of subgrade reaction, and (2) The engineer may wish to use layered elastic modeling to evaluate the effectiveness of his pavement designs. Layered elastic analysis and design procedures are discussed briefly in paragraph D4C.

Table 26 is provided as a guide to typical elastic properties of well designed and constructed stabilized materials.

3. Traffic Considerations

The wide variety of tire pressures, wheel loads, gear configurations and traffic wander characteristics for aircraft makes airfield pavement structural design very complex. Satisfactory aircraft equivalency factors based on the damage done per pass do not exist where stabilized layers are involved.

Air Force pavements are, therefore, designed for Light Load, Short Field Load, Medium Load or Heavy Load pavements and Types A, B, C or D traffic areas and overruns in accordance with AFM 88-6, Chapter 1, General Provisions for Airfield Design.

4. Thickness Design

a. Flexible Pavements

TABLE 26. APPROXIMATE ELASTIC PARAMETER VALUES FOR STABILIZED PAVEMENT MATERIALS.

Material	Modulus of Elasticity, psi	Poisson's Ratio	
Asphalt Treated Base	100,000 - 600,000	Low stiffness:	0.45
		High stiffness:	0.35
Cement Treated	Uncracked: Up to 2,000,000		0.20
	Cracked: Down to values for untreated granular base material		0.30
Lime-Fly Ash	1,500,000 - 2,500,000	Low stress level:	0.08
		High stress level:	0.30
Lime Treated Base	Uncracked: Up to 500,000		0.15
Soil Lime* Mixtures for Compressive Strength Range, psi			
100-200	25,000 - 100,000		0.15
200-400	100,000 - 300,000		0.15
> 400	300,000+		0.15

*For mixtures with strengths in excess of 400 psi, use the following relation for modulus:

$$E_{flexure} = 1.15S - 140$$

where E = flexural modulus, ksi

S = compressive strength, psi

(1) General Considerations. Thickness design for flexible airfield pavements is explained in AFM 88-6, Chapter 2.

This manual provides the necessary background information to design thicknesses of subbase, base and surface layers.

A thickness reduction concept is used for stabilized layers in AFM 88-6, Chapter 2. Stabilized base course and subbase course materials meeting the strength and durability requirements outlined in Table 27 can be assigned the thickness reduction factors expressed in Table 28 (a reproduction of Table 8-5 of AFM 88-6).

(2) Special Considerations. When portland cement is used to stabilize base course materials, the treatment level must be one that will minimize shrinkage cracking that will inevitably reflect through the bituminous concrete surface course. AFM 88-6, Chapter 2, limits to four percent the amount of portland cement that can be used (by weight) to stabilize a soil directly below a bituminous surface. In addition, it is imperative to provide adequate drainage for unbound granular layers which may be used between an asphalt concrete surface and a stabilized subbase course. This is to prevent excessive moisture entrapment in the layer resulting in strength reductions.

b. Rigid Pavements

Thickness design for rigid airfield pavements is explained in AFM 88-6, Chapter 3. The support offered by a stabilized subgrade or subbase to the concrete slab is measured by the plate bearing test (k-value). AFM 88-6, Chapter 3, establishes that in no case will k exceed 500 pounds per cubic inch.

The increase in k-value due to the presence of a cement stabilized subbase can be approximated by using Figure 47 and 48. Although data are scarce, it has been suggested that k-values for asphalt and lime treated subbases are similar to those of cement treated bases. Hence, Figures 47 and 48 can be used for estimating. A k-value should always be determined *in situ*.

5. Design Examples

a. Example 1

(1) Design a flexible heavy load pavement to accommodate a 480-kip gross load twin gear assembly aircraft in a Type B traffic area for 15,000 passes. Design CBR of the lean clay subgrade is 13, the natural in-place density of the clay is 87 percent extending to 10 feet.

(2) The design procedure outlined in Table 8-2 of AFM 88-6, Chapter 2, yields the following thickness requirements:

TABLE 27. MINIMUM REQUIREMENT FOR STABILIZED MATERIALS IN ORDER TO APPLY THICKNESS REDUCTION FACTORS.

Stabilized Layer Used as	Stabilizer	Test	Minimum Allowable Test Value
Base Course	Asphalt	Marshall Stability	1,800 or higher
		Flow	16 or less
		Percent Air Voids	5 - 7
		Percent Voids Filled With Bitumen	50 - 70
	Cement	Unconfined Compressive Strength	750[1] psi
		Weight Loss After 12 Freeze-Thaw or Wet-Dry Cycles	14 percent
Subbase Course	Cement	Unconfined Compressive Strength	250[1] psi
		Weight Loss After 12 Freeze-Thaw or Wet-Dry Cycles	14 percent
	Lime and Lime-Fly Ash	Unconfined Compressive Strength	150[2] psi

[1] Determined at 7 days for cement stabilization.

[2] Determined at 28 days for lime stabilization.

TABLE 28. STABILIZED LAYER THICKNESS REDUCTION FACTORS.

Material	Equivalency Factors	
	Base	Subbase
Unbound Crushed Stone	1.00	2.00
Unbound Aggregate	-[1]	1.00
Asphalt-Stabilized		
All-Bituminous Concrete	1.15	2.30
GW, GP, GM, GC	1.00	2.00
SW, SP, SM, SC	-[1]	1.50
Cement-Stabilized		
GW, GP, SW, SP	1.15[2]	2.30
GC, GM	1.00[2]	2.00
ML, MH, CL, CH	-[1]	1.70
SC, SM	-[1]	1.50
Lime-Stabilized		
ML, MH, CL, CH	-[1]	1.00
SC, SM, GC, GM	-[1]	1.10
Lime, Cement, Fly Ash Stabilized		
ML, MH, CL, CH	-[1]	1.30
SC, SM, GC, GM	-[1]	1.40

[1]Not used as base course.

[2]Cement limited to 4 percent by weight (or less).

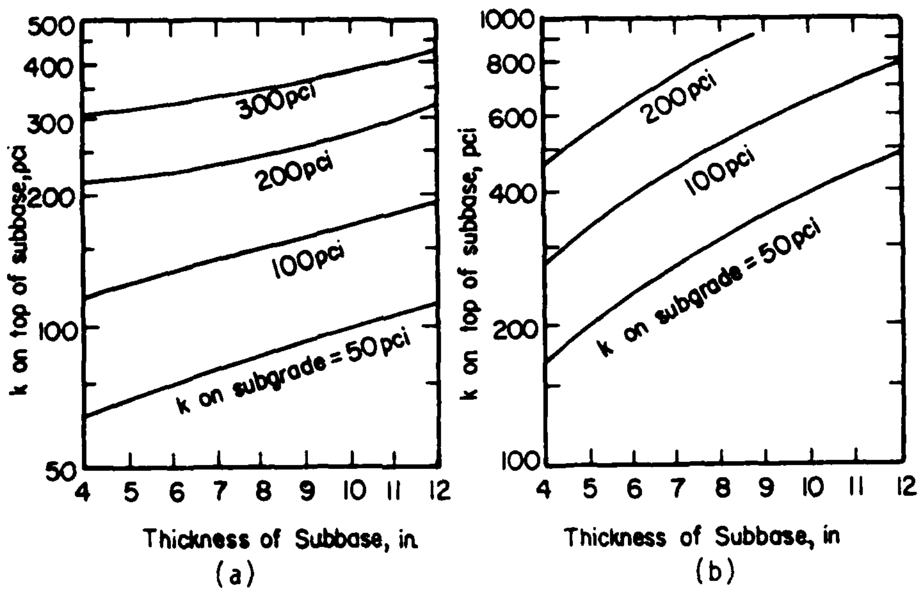
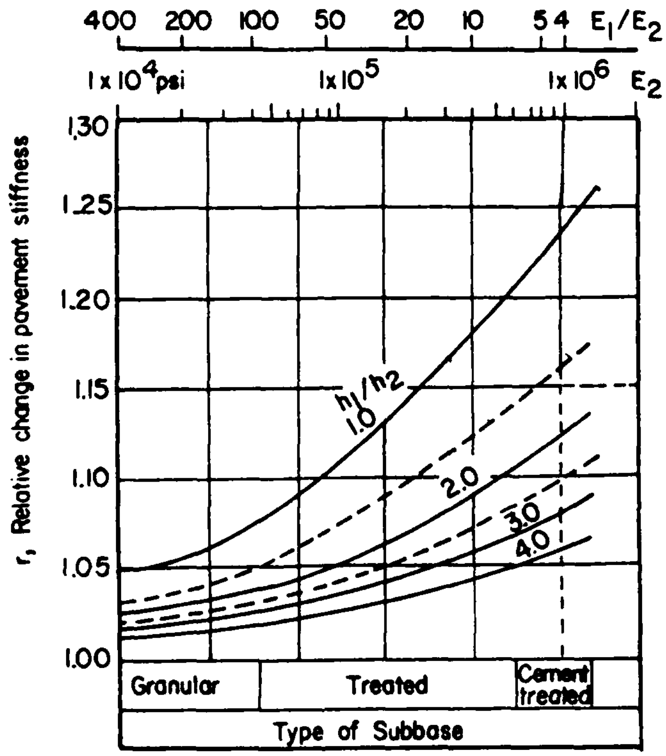
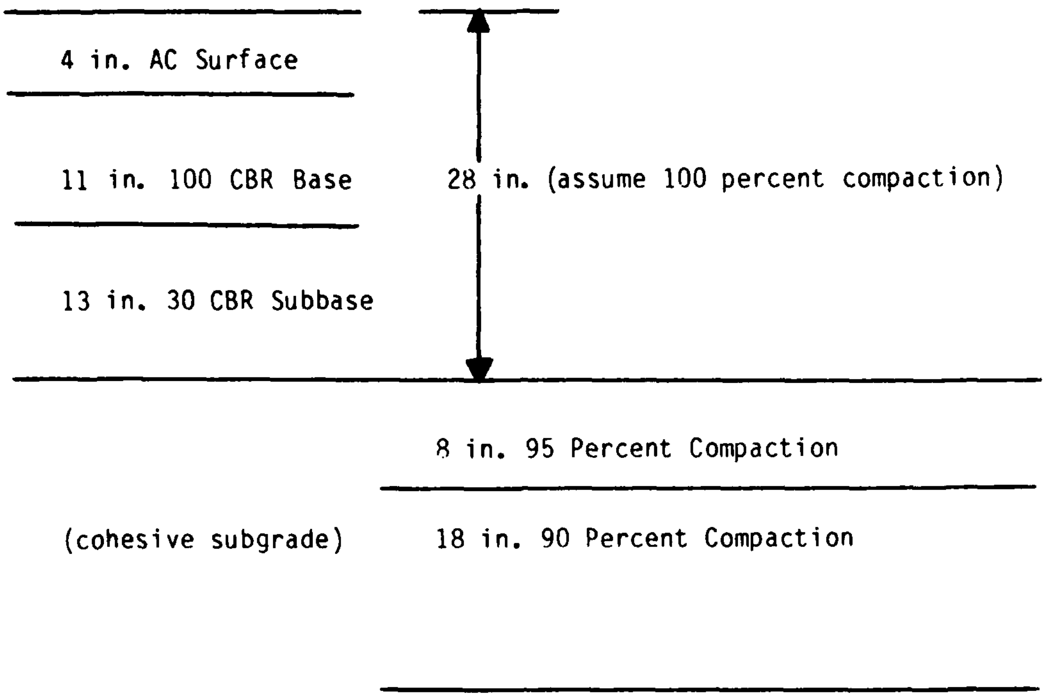


Figure 47. Effect of Subbase Thickness on Modulus of Subgrade Reaction. (a) Nontreated and (b) Cement-Treated. (After Reference 19.)



Note: The r, relative stiffness, is raised to the 1.5 power and the resulting value multiplied by the portland cement concrete slab thickness (h_1) to give the effective thickness due to the stabilized subbase. (k of natural subgrade is used.)

Figure 48. Changes in Pavement Stiffness Due to Base Course. (After Ref. 19.)



b. Example 2

(1) Suppose that in the preceeding example an asphalt concrete base is to be substituted for the conventional base and subbase courses. The asphalt concrete base material meets the requirements established in Table 27.

(2) The equivalency factor of the all-bituminous concrete base is 1.15 (Table 28). Thus, the required thickness to replace the existing base is 11 in./1.15 = 9.56 inches. Use 10 in.

(3) The revised thickness of unbound subbase is 28 inches minus 4 inches of asphalt concrete surface and 10 inches of all-bituminous concrete base or 14 inches. The equivalency factor for the subbase is 2.0. The required thickness for an all-bituminous GC subbase to replace the 14 inches thick subbase is 14 in./2 or 7 inches. The total thickness of the pavement with stabilized layers is 21 inches.

c. Example 3

(1) Assume that the subbase material in design Example 1 is stabilized with lime-fly ash which meets the requirements of Table 27.

(2) The appropriate equivalency factor from Table 28 is 1.30. Thus, the new subbase thickness is 13 in./1.30 or 10 inches.

A summary of the pavement thicknesses required in Examples 1 through 3 is presented below:

Conventional Thicknesses Example 1	Conventional Base and Subbase Replaced by All-Bituminous Concrete	Conventional Subbase Replaced by Lime-Fly Ash Stabilized Subbase
AC Surface - 4 in.	AC Surface - 4 in.	AC Surface - 4 in.
Crushed Stone Base - 11 in.	All-Bituminous Base - 10 in.	Crushed Stone Base-11 in.
GC Subbase - 13 in.	All-Bituminous Subbase - 7 in.	Lime-Fly Ash Stabilized - 10 in. GC
Total Thickness = 28 in.	Total Thickness = 21 in.	Total Thickness = 25 in.

d. Example 4

(1) Design a rigid airfield pavement thickness to support a gross aircraft weight of 480,000 pounds for 15,000 passes. The pavement is to be designed for a Type A traffic area and the natural subgrade has a modulus of subgrade reaction, k-value, of 300 pci. The flexural strength of the portland cement concrete to be used in construction is 700 psi (modulus of rupture).

(2) From AFM 88-6, Chapter 3, the required thickness of the portland cement concrete slab is 18.5 inches.

(3) Assume that the natural subgrade is stabilized with portland cement and that the thickness of the stabilized layer is 8 inches. An estimate of the changes in modulus of subgrade reaction can be obtained by means of Figure 47. The resulting k value is 800 pci. However, a maximum k-value of 500 pci is allowed.

(4) Based on the new k-value, the required thickness of the portland cement concrete pavement is (from AFM 88-6, Chapter 3) 13 inches.

D. ROADWAY THICKNESS DESIGN USING STABILIZED LAYERS

1. Role of Stabilized Layer

The role of the stabilized layers in roadway pavements is essentially the same as their role for airfield pavements, paragraph C.1.a.

One notable exception between the role of stabilized layers in airfield and roadways is under rigid pavements. The base or subbase is always necessary in a roadway to prevent pumping. Hence, a stabilized base must be highly resistant to the erosive action of water.

2. Material Properties

See the discussion of material properties in paragraph C.1.b.

3. Traffic Considerations

Traffic for roadways differs greatly from airfields in that it is much less varied. Thus, it is easier to transform the effects of a variety of traffic types to a standard design load or standard design vehicle. Generally, the 18,000 pound single axle, dual tire load is used as the standard.

For both flexible and rigid roadway pavements the Air Force transforms all traffic into equivalent applications of 18,000 pound axle dual tire loads. This is done by a parameter identified as the design index.

A designer can arrive at a design index by knowing only the letter classification of the road or street appropriate for the volume of traffic and the appropriate traffic category based on the distribution of traffic by vehicle type. The design index represents all traffic expected to use the pavement during its life.

The design index may be easily determined for flexible roadway pavements in AFM 88-7, Chapter 3, and for rigid roadway pavements in AFM 88-7, Chapter 1. The road or street class may be determined from AFM 88-7, Chapter 5.

Due to the differences inherent in relating mixed traffic to an equivalent number of coverages of the basic loading for both rigid and flexible pavements, the designer is cautioned that the values of design index may be different for the two pavement types.

4. Thickness Design

a. Flexible Pavements

(1) General Considerations. Thickness design for flexible roadway pavements is explained in AFM 88-7, Chapter 3. This manual provides the necessary background information to design thicknesses of subbase, base and surface layers.

Flexible pavements containing stabilized soil layers are designed through the use of equivalency factors. A conventional flexible pavement is first designed and the equivalency factors applied to the thickness of the layer to be stabilized.

To qualify for application of equivalency factors, the stabilized layer must meet appropriate strength and durability requirements set forth in Table 27. An equivalency factor represents the number of inches of conventional base or subbase which can be replaced by one inch of stabilized material. Table 28 provides equivalency factors for bituminous stabilized materials based on the aggregate type in the mix and the use of the layer, i.e., base or subbase. Equivalency factors for materials stabilized with lime, cement or a combination of fly ash mixed with cement or lime are provided as a function of unconfined compressive strength, Figure 49. These equivalency factors are for subbase only. To apply these to stabilized bases, the subbase factor from Figure 49 must be divided by 2.

(2) Minimum Thickness Requirements. AFM 88-7, Chapter 3, specified that stabilized base or subbase layers will be at least 4.0 inches thick. Minimum thickness requirements for conventional pavement layers are also presented in Table 2 of AFM 88-7, Chapter 3.

(3) Special Considerations. When portland cement is used to stabilize base course materials, the treatment level must be one that will minimize shrinkage cracking that will inevitably reflect through the bituminous concrete surface course. AFM 88-7, Chapter 3, prescribes a maximum of 4 percent portland cement by weight can be applied to soil or aggregate directly below asphalt concrete. In addition, it is imperative to provide adequate drainage for unbound granular layers which may be used between an asphalt concrete surface and a stabilized subbase course. This is to prevent excessive moisture entrapment in the layer resulting in strength reductions.

b. Rigid Pavements

Thickness design for rigid roadway pavements is explained in AFM 88-7, Chapter 1. As for airfields the support offered by the subgrade for the portland cement concrete pavement is measured by the plate bearing test (k-value).

Other parameters used to establish the thickness required for the portland cement concrete roadway pavement are flexural strength of the concrete (modulus of rupture) and design index. The design index is a method of transforming all damage caused by a certain traffic mix to a design damage index based on the standard 18,000 pound single axle, dual wheel load (see paragraph D.3.c).

As for airfield pavements, the increase in the k-value due to the use of a stabilized layer can be approximated by Figures 47 and 48. Although data are scarce, it has been suggested that k-values for asphalt and lime treated subbases are

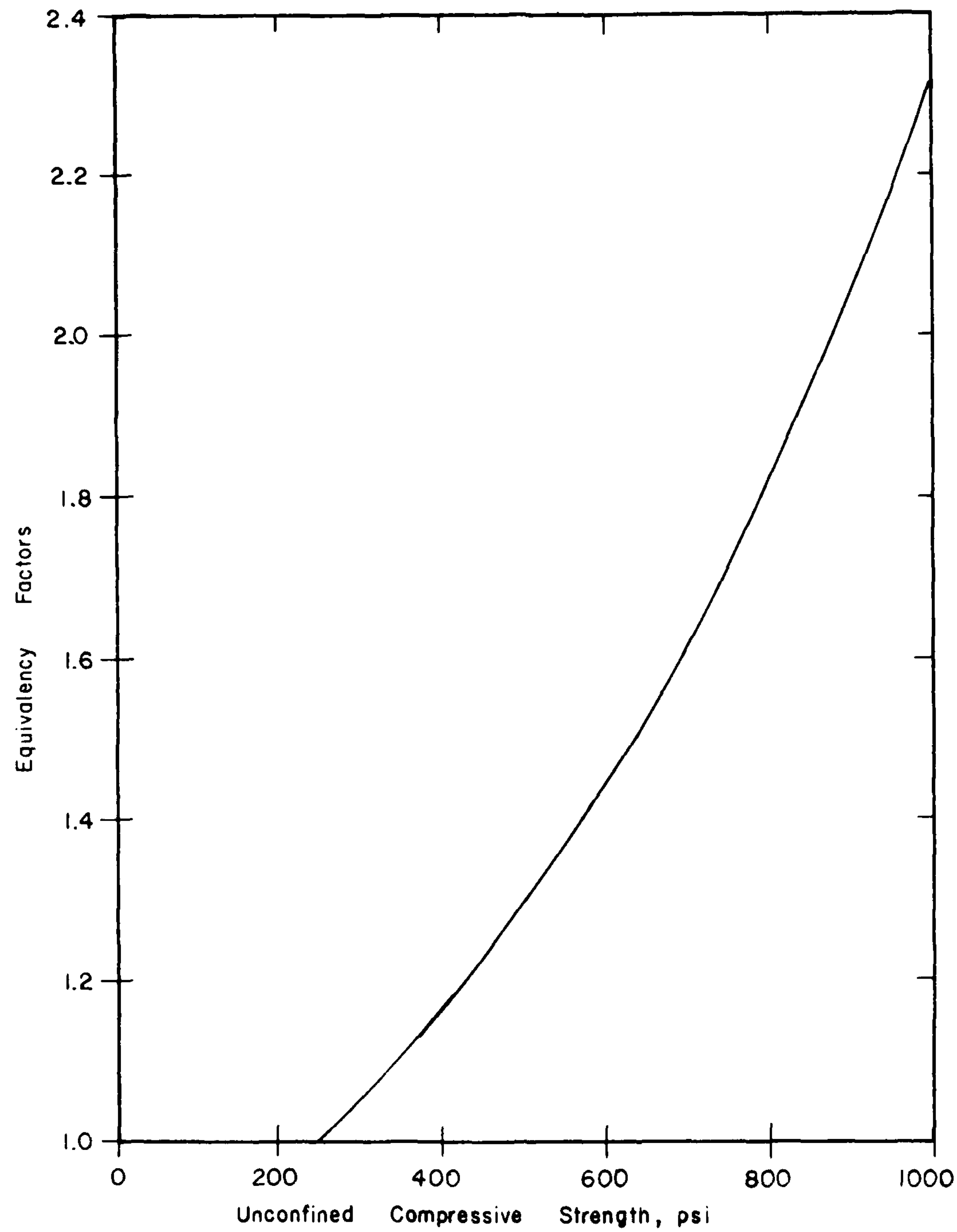


Figure 49. Equivalency Factors for Soils Stabilized with Cement, Lime or Cement and Lime Mixed with Fly Ash. (Same as Figure 4, AFM 88-7, Chapter 3.)

similar to those of cement treated bases. Hence, Figures 47 and 48 can be used for estimating. A k-value should always be determined _in situ_.

c. Alternative Design Procedures

Alternative design procedures may prove valuable as a check on those provided in AFM 88-7, Chapters 1 and 3. This is especially true for flexible pavements, AFM 88-7, Chapter 3. In the case of flexible pavements, layered elastic theory has proven very valuable in designing and analyzing pavements. In cases where more insight is required in analyzing the effects of using stabilized layers than is provided by AFM 88-7, Chapter 3, the following procedures are suggested:

DESIGN OR ANALYSIS REQUIRED	POPULAR NAME OF METHOD SUGGESTED	REFERENCES
Thickness Design of Asphalt Stabilized Bases	Chevron	18
	The Asphalt Institute	19
	Shell	20
Deformation Potential Below Asphalt Concrete Stabilized Bases	Chevron	18
	The Asphalt Institute	19
	Shell	20
Rutting Potential in Asphalt Stabilized Bases	Shell	20
Fatigue Potential in Asphalt Stabilized Bases	Chevron	18
	Shell	20
Thickness Design of Cement Stabilized Bases	PCA	19
Thickness Design of Soil-Cement Pavements for Heavy Industrial Vehicles	PCA	21

DESIGN OR ANALYSIS REQUIRED	POPULAR NAME OF METHOD SUGGESTED	REFERENCES
Thickness Design of Lime Layers	Thompson-Figueroa	23
Fly-Ash Stabilized Pavement Layers	76-16 Implementation Package	18

Where stabilized bases other than asphalt are used, the best analysis procedure is to use layered elastic computer models such as BISTRO, BISAR, CHEV5L (24) and ELSYM5 (25). The stress and strain parameter obtained from these systems under the appropriate load can be analyzed based on criteria found in References 17 through 22.

Table 26 may be used as a guide to elastic input properties for layered elastic analysis.

5. Design Examples

a. Example 1

(1) Assume a conventional flexible pavement has been designed which requires a total thickness of 16 inches above the subgrade. The minimum thicknesses of asphalt concrete surface and base are 2 and 4 inches, respectively. The thickness of the subbase is 10 inches.

(2) It is desired to replace the base and subbase with a cement-stabilized gravelly soil having an unconfined compressive strength of 890 psi. From Figure 49, the equivalency factor is 2.0. The thickness of the stabilized subbase is 5 inches (10 inches ÷ 2 = 5 inches).

(3) To calculate the thickness of the stabilized base course, divide the subbase equivalency factor by 2 and then divide the unbound base thickness by the result (4 inches ÷ 1.0 = 4.0 inches of stabilized base course).

The final section would be 2 inches of asphalt concrete and 9 inches of cement-stabilized gravelly soil.

b. Example 2

(1) Assume a conventional flexible pavement has been designed which requires 2 inches of AC surface, 4 inches of crushed stone base and 6 inches of subbase. It is desired to construct an all-bituminous pavement.

(2) The equivalency factor from Table 28 for a base course is 1.15 and for a subbase is 2.30. The thickness of asphalt concrete required to replace the base is 4 inches ÷ 1.15 = 3.5 inches and the thickness of asphalt concrete required to replace the subbase is 6 inches ÷ 2.30 = 2.6 inches.

c. Example 3

(1) Design a portland cement concrete pavement to support the following traffic:

Average Daily Volume	3,500 Vehicles per Lane
Trucks (2-axle)	150 per Lane per Day
Trucks (3 or more axle)	50 per Lane per Day

(2) In accordance with AFM 88-7, Chapter 5, and based on the definitions of the traffic categories, a Class C street for Category IV traffic is required. From AFM 88-7, Chapter 1, the design index is 5.

(3) The 28-day flexural strength of the concrete is 675 psi and a soil cement stabilized subbase of 6 inch thickness is to be used. The soil cement meets the requirements of Table 27 and was constructed according to Section I. The natural subbgrade is a silty clay with a k-value of only 100 pci.

(4) If the soil cement subbase was not used the required thickness of the portland cement concrete pavement would be 8 inches according to AFM 88-7, Chapter 1. However, the modified subgrade modulus due to the soil cement subbase (Figure 47) is 375 pci. The required portland cement concrete thickness is only 6 inches.

SECTION IX

CONSTRUCTION TECHNIQUES

A. OBJECTIVES

In the construction of stabilized soil systems the objective is to obtain a thorough mixture of a pulverized soil or aggregate material with the correct quantity of stabilizer and sufficient fluids to permit maximum compaction. Equipment must be selected, operated, and sequenced to provide:

1. The proper water content (uniformly mixed),

2. The proper stabilizer content (uniformly mixed),

3. The attainment of some minimum specified density,

4. Favorable temperature and moisture conditions for strength development during the curing period and

5. Protection of the stabilized surface from traffic to prevent abrasion and to assure adequate time for strength development.

Mixed-in-place construction methods using travelling mixing machines or central plant mixing operations can be used. The choice of the method will depend upon the local job conditions including equipment availability. If in-place soil material can be economically stabilized, the mixed-in-place method would probably be used. If the material is to be obtained from a borrow source and the project is of sufficient size, it may be economical to use central plant mixing techniques. Whatever the type of mixing equipment used, the general construction principles, procedures and objectives are the same. Construction methods and equipment are shown in Figure 50.

B. RELATED MATERIAL

The engineer, planner or inspector will require detailed information related directly to his specialized construction task. It is impossible to address all construction specifications and guides in one document. Therefore, several selected references which are excellent summaries of construction processes are suggested to supplement this section:

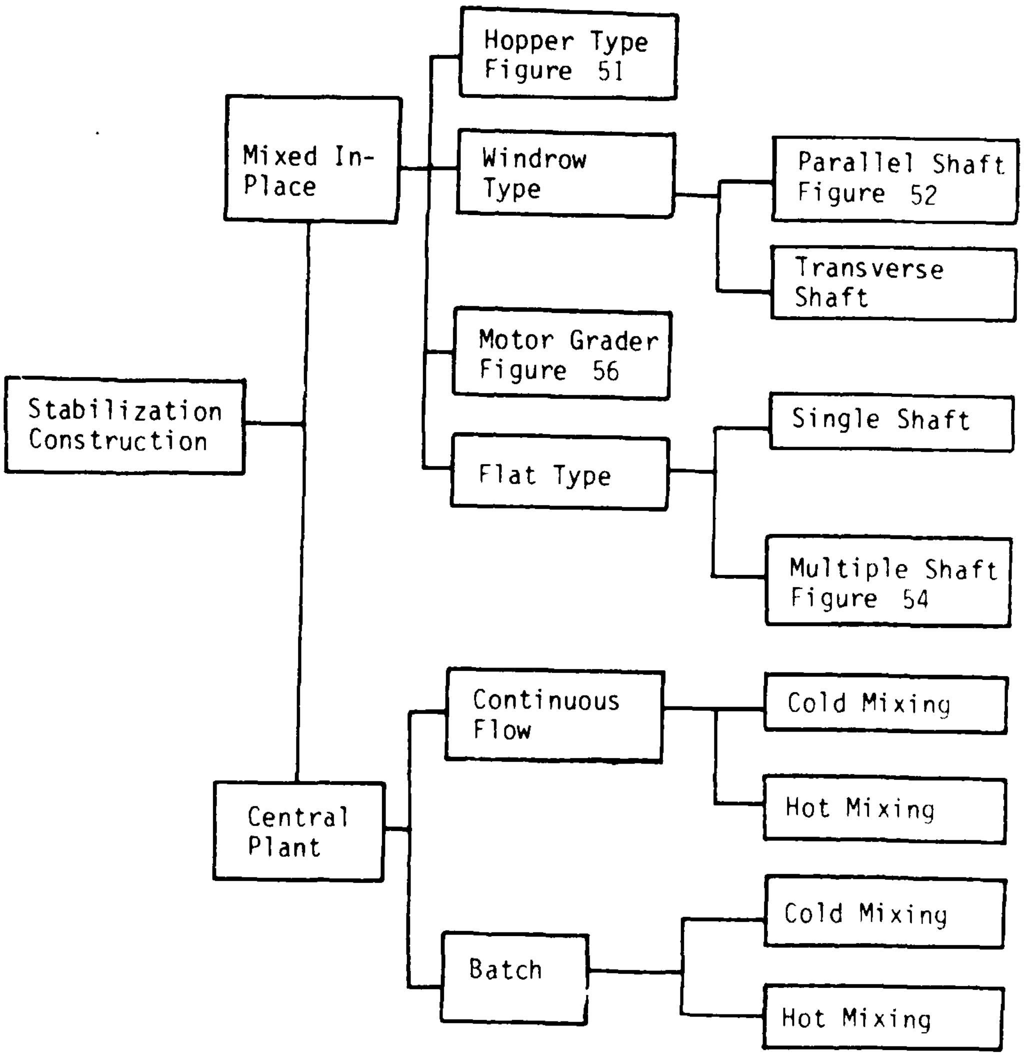


Figure 50. Soil Stabilization Construction Equipment.

STABILIZER DISCUSSED	REFERENCE IDENTIFICATION (SEE SECTION XII COMPLETE REFERENCE)	SUBJECTS OF GREATEST VALUE IN SUPPLEMENT-THIS MANUAL
Lime	Lime Stabilization Construction Manual, Bulletin 326, National Lime Assoc. (26)	Lime Spreading (Bags and Bulk), Central Mixing
Lime	State-of-the-Art: Lime Stabilization, Transportation Research Board Circular (3)	Lime Application, Compaction
Lime	Lime-Stabilized Base Course, Subbase or Subgrade, Military Construction Guide Specification 02695 (27)	Construction Details, Testing
Cement	Portland Cement Stabilized Base or Subbase Course for Airfields, Roads and Streets, Military Construction Guide Specification 02694 (28)	Construction Details, Testing
Cement	Soil Cement Construction Handbook, Portland Cement Association (29)	Spreading, Mixing and Processing Operations, Finishing, Joint Construction
Fly Ash	Fly Ash A Highway Construction Material, IP 76-16, Federal Highway Administration (18)	Spreading, Blending, Construction Sequence
Lime-Fly Ash	Lime-Fly Ash Bases and Subbases, Synthesis No. 37, National Cooperative Highway Research Program (30)	General
Asphalt	Bituminous-Stabilized Base Course, Subbase or Subgrade, Military Construction Guide Specification 02693 (31)	Construction Details, Testing
Asphalt	Asphalt Cold Mix Manual, MS-14, The Asphalt Institute (7)	Mixing, Compaction, General
Asphalt	AFM 88-6, Chapter 9, Bituminous Materials	Compaction

In addition, guide specifications are discussed in Section K and example specifications presented in Appendix A.

C. MIXED-IN-PLACE OPERATIONS

Mixture uniformity for mixed-in-place operations is usually less than that obtained using central plant mixing operations; however, satisfactory results can be obtained with road mixing equipment for all of the major chemical stabilizers. Lime and cement subgrade stabilization using mixed-in-place techniques are very popular in some parts of the United States. The major steps for mixed-in-place operations are:

1. Soil preparation,
2. Stabilizer applications,
3. Pulverization and mixing,
4. Compaction and
5. Curing.

Mixing operations with subgrade materials are often performed with single- and multiple-shaft flat type mixers or motor graders. Mixing with borrow materials is often performed with windrow type mixers or hopper type mixers if base course materials are to be produced. Photographs of mixing equipment are shown in Figures 51 to 56. A summary of mixed-in-place operations used for lime, cement, asphalt and fly ash stabilization is given in the following paragraphs. Typical subgrade, subbase and base course stabilization construction operations will be described. The subbase and base course stabilization operation will consist of borrow material mixed in a windrow because this is a common form of subbase and base course stabilization.

1. Subgrade Stabilization

The following construction steps are typically employed for subgrade stabilization operations:

(a) Soil preparation,

(b) Stabilizer application,

(c) Pulverization and mixing,

(d) Compaction and

(e) Curing.

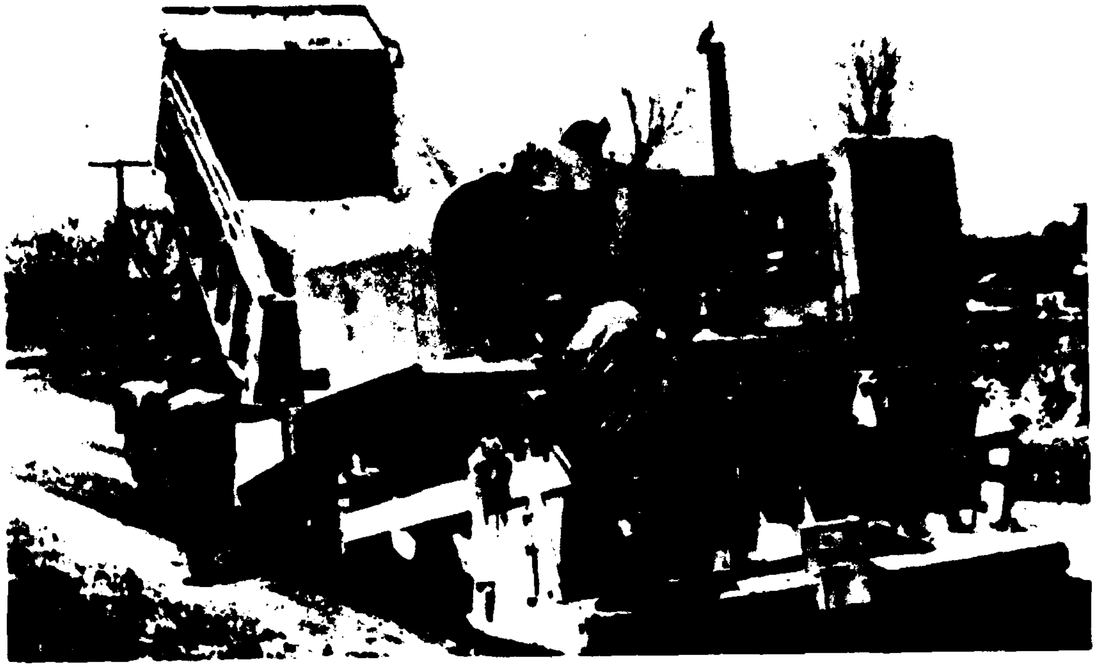


Figure 51. Hopper-Type Pugmill Travel Plant (After Ref. 7).

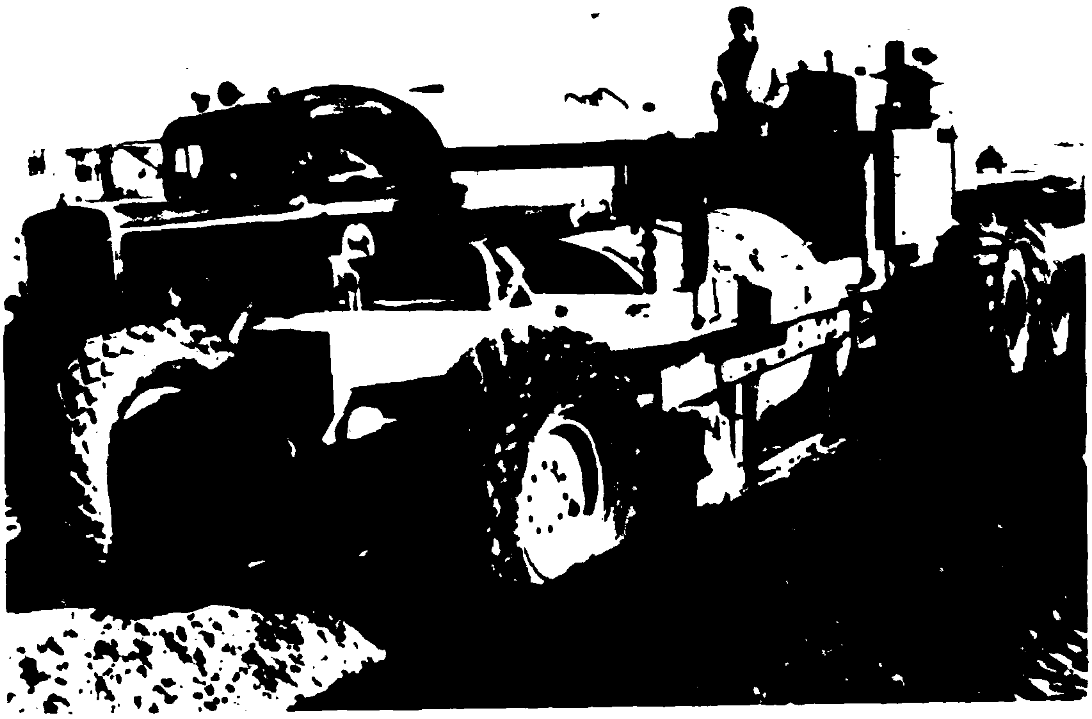


Figure 52. Windrow-Type Pugmill Travel Plant (After Ref. 7).

Figure 53. Single Transverse Shaft Rotary Mixer (Flat Type).

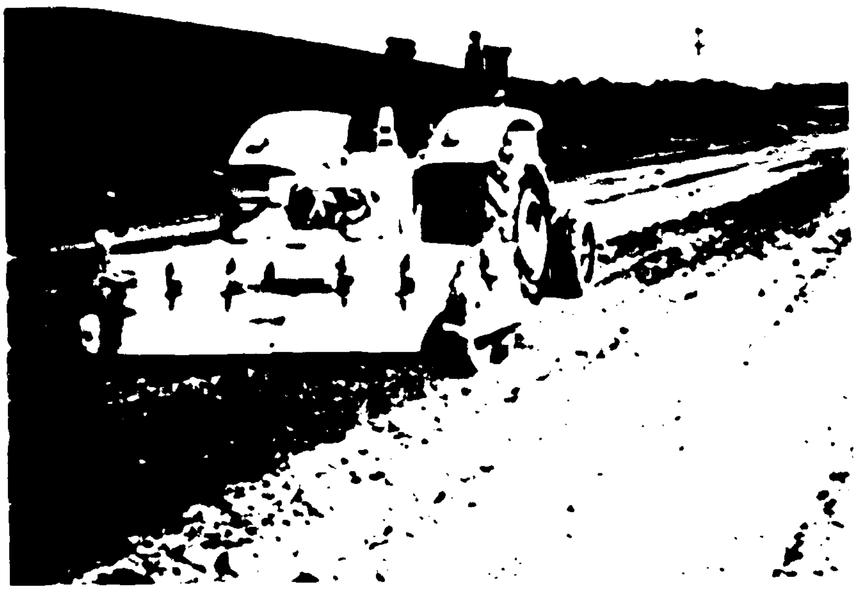


Figure 54. Multiple Transverse Shaft Rotary Mixer (Flat Type).

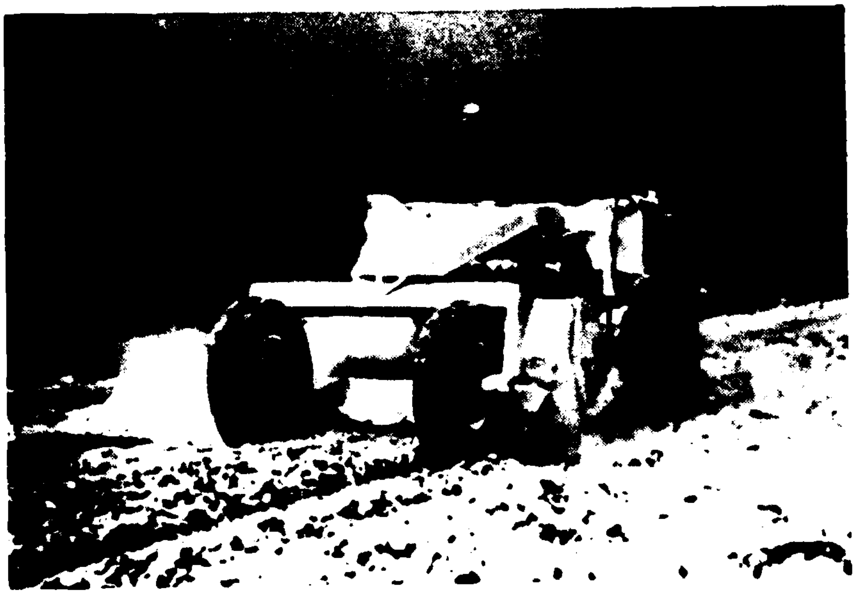


Figure 55. Single Transverse Shaft Rotary Mixer.

Figure 56. Mixing with Motor Grader.

These operations are basic to the use of lime, cement, asphalt and fly ash stabilization.

(a) Soil Preparation. After the soil has been brought to the proper line and grade as shown on the construction plans, initial scarification and partial pulverization should be performed to the specified depth and width of stabilization. During and after scarification and pulverization, all harmful materials like stumps, roots, turf, etc. and aggregates larger than 3 inches should be removed.

The grader-scarified and/or disc harrow are commonly used for initial scarification, and the disc harrow and rotary mixer for pulverization (Figures 57 and 58). Plows, various types of cultivators and other agricultural equipment can be used. When the soil is unusually dry, water is added to aid pulverization; if extremely wet, the rotary mixer or disc harrow can be used for aerating and drying the soil.

(b) Stabilizer Application. The distribution of lime and cement can be performed dry be either spotting bags on the roadway (Figure 59) or by applying bulk stabilizer from suitably-equipped self-unloading transport trucks (Figure 60) or from other bulk haul units through mechanical spreaders (Figure 61). The use of bagged lime is generally the simplest but also the most costly method. The disadvantages of the bag method over the dry bulk method are greater labor costs and a slower production. In spite of these disadvantages, bagged lime appears to be most practical for small projects, such as streets (providing dust is controlled), secondary roads and maintenance patching. The procedure for computing the number and spacing of bags of lime is presented in Reference 25.

For large stabilization projects, particularly where dusting is not a problem, the use of bulk lime distribution is a common practice. In most cases lime can be distributed from the transport truck.

In most lime-fly ash stabilization projects, lime and fly ash are spread separately. However, it is possible to preblend these two components before spreading. When the lime and fly ash are preblended, it is necessary that they be stored in a dry state. The preblend is normally spread in the dry condition. If lime and fly ash are spread separately, normal lime spreading techniques are used. Nearly all fly ash is spread in the conditioned state (i.e., residual moisture content of 15 to 25 percent). It is possible to spread dry fly ash from pneumatic trucks, but dusting is often severe. Conditioned fly ash is normally delivered in open dump trucks, dumped and spread with a motor patrol, spreader box, or other types of spreaders.

Slurry distribution methods can be used for lime distribution. Hydrated lime and water is mixed in a central

Figure 57. Scarification of Clay Subgrade with Disc Harrow (After Ref. 26).

Figure 58. Scarification with Motor Grader (After Ref. 26).

Figure 59. Bagged Lime Application.

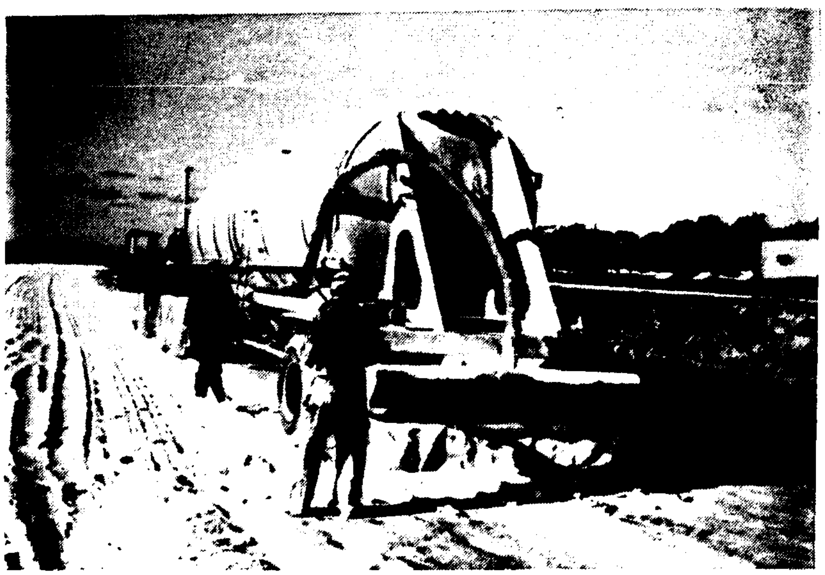


Figure 60. Spreading Bulk Lime From Pneumatic Tanker Truck Through Cyclone Spreader.

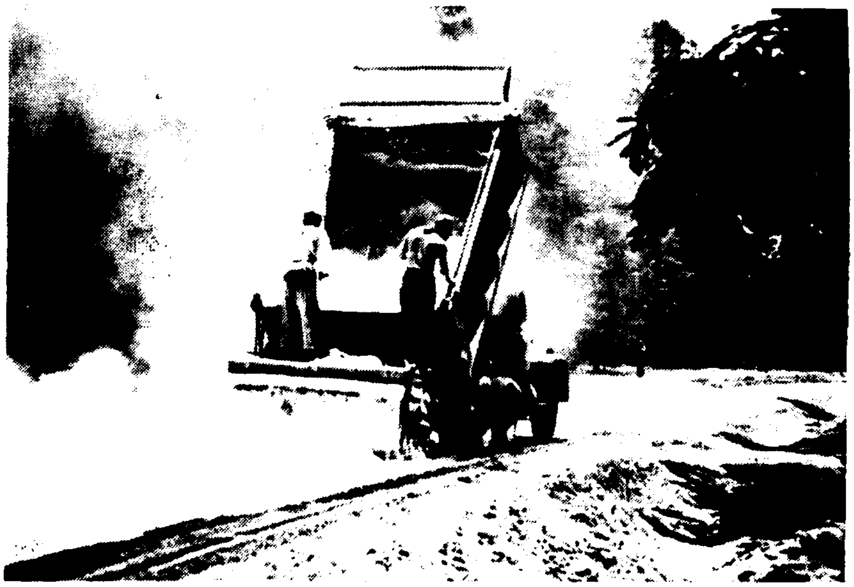


Figure 61. Mechanical Cement Spreaders (Must be Operated at Slow Speed to Provide Uniform Application).

mixing tank, jet mixer, or in a tank truck. After mixing in proportions of about 1 ton of lime to 500 gallons of water, the slurry is spread over the scarified roadbed through tank truck spray bars either by gravity or pressure (Figure 62) or the slurry can be added to the soil during the mixing operation (Figure 63). The major advantage of the slurry method is prevention of dusting. In addition, this method combines lime spreading and watering operations into one; thereby, cutting construction costs. Furthermore this method generally promotes uniform lime distribution. Disadvantages of the slurry method include purchase or rental of the slurry mixing equipment, low production and unsatisfactory use with wet soils.

Asphalt is spread or distributed from an asphalt distributor (Figure 64) or during the mixing process through the mixing machine (Figure 65). The preferred method of asphalt application is through the mixing equipment with built-in spraying systems. The asphalt application rate is matched to the thickness and width of the mixer, forward speed of the mixer and the density of the in-place soil. When rotary type mixers are used which are not equipped with spray bars, an asphalt distributor, operating ahead of the mixer, applies asphalt to the aggregate. Incremental application of asphalt and passes of the mixer are usually required to achieve the specified mixture. It is important for the soil to be at the proper moisture content prior to application of the asphalt, if uniform mixing is to be achieved.

It is important to remember that the primary objective of the stabilizer spreading operation is to achieve uniform distribution of the stabilizer in the proper proportions. Field experience has indicated that mixing by itself will not greatly improve uniformity of distribution. Hence, an important part of quality control is stabilizer spreading.

(c) Double Application. Double application of lime is often required when extremely plastic clays are encountered (PI of 50 or greater). Lime is added in two increments to facilitate adequate pulverization and obtain uniform mixing. Typically 2 to 3 percent lime is added, partially mixed, and the layer is lightly rolled to seal the surface. This surface seal not only seals out excess moisture (rain) but also retards harmful carbonation (see Section III). After a 24- to 48-hour period pulverization is attempted, the final lime application is made and the mixing of the lime and soil completed.

For maximum chemical action during curing, the clay clods should be less than two inches in diameter. Prior to curing, the soil should be sprinkled liberally to bring the moisture content to at least two percentage points above optimum. In cold, damp weather, excess watering should not be used. In hot weather, it is almost impossible to add to much water.

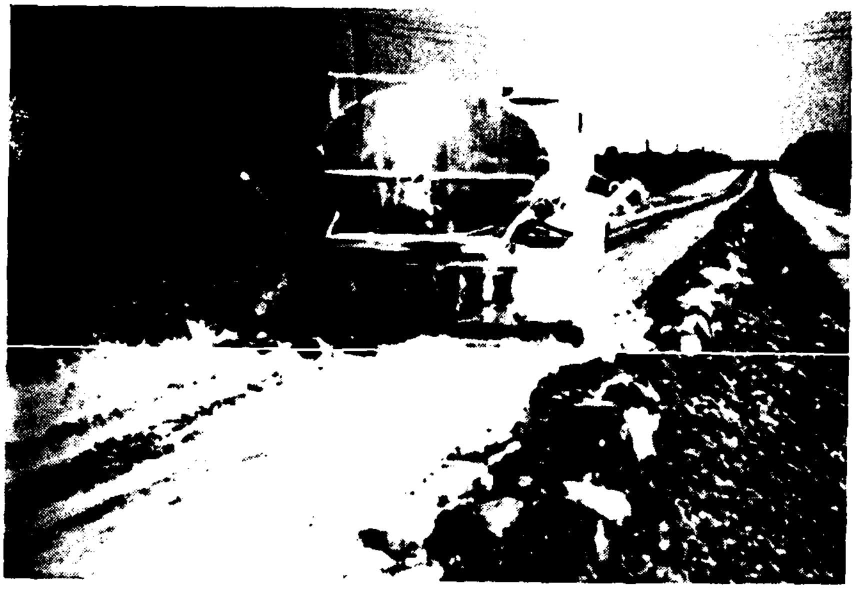


Figure 62. Transit Mixing of Lime Slurry on City Street Project, Using Recirculating Pump at Rear. Pressure and Gravity Spray Bars Distribute Lime Evenly.

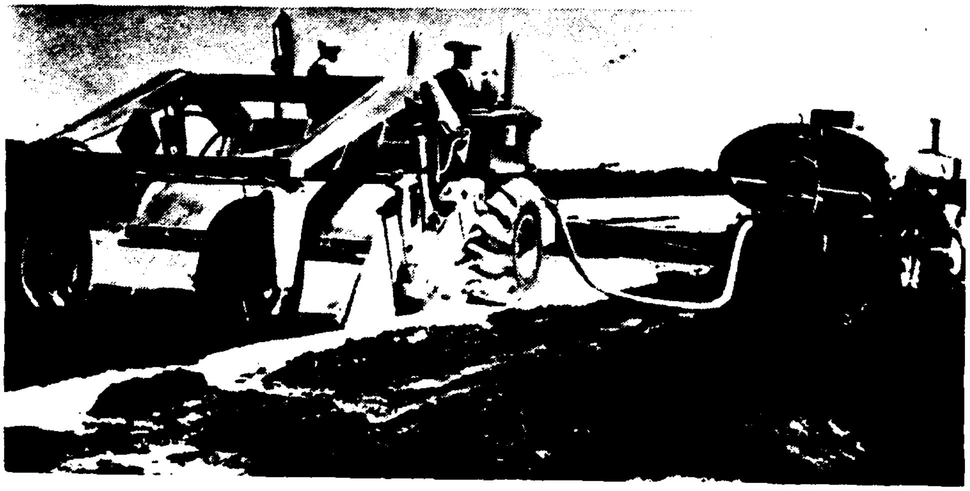


Figure 63. Rotary Mixer Used for Simultaneous Mixing of Lime and Water in Clay Subgrade Soil(After Ref. 26).

Figure 64. Distributor Applying Asphalt (After Ref. 7).

Figure 65. Single-Shaft Rotary Mixer with Asphalt Supply Tank (After Ref. 7).

(d) Pulverization and Mixing. Single- and multiple-shaft rotary (flat type) mixers are typically used to pulverize and mix lime, lime-fly ash, cement and asphalt with subgrade soils. Motor graders and agricultural type equipment can be used, however, the desired uniformity of mixing is not always obtained. Mixing difficulty increases with increasing fineness and plasticity of the soils being treated. In-place mixing efficiency, as measured by the strength of the treated soil, may be only 60 percent to 80 percent of that obtained in the laboratory. This reduced efficiency is sometimes accounted for by increasing the stabilizer content from that determined in the laboratory testing program by 1 or 2 percent. Windrow and hopper type mixers are not typically used in subgrade stabilization operation.

When high-speed rotary mixers or one-pass travel plant mixers are used with lime, the lime is generally spread evenly on the entire roadway, and mixing starts from the top down. Depending upon the type of equipment used and the soil involved, complete mixing can be accomplished in one to three passes. If needed, water is added during mixing to obtain the desired moisture content, generally optimum. The water may be added by sprinkling trucks or by spraying into the mixing chamber of the mixer. The latter method has considerable merit, since the intimate contact of lime, water and soil facilitates chemical breakdown and pulverization.

A travelling windrow-mixing type machine may also be used for one-stage mixing if adequate pulverization and mixing can be achieved in one pass.

When blade-mixing is used in conjunction with dry lime, the material is generally bladed into two windrows, one on each side of the roadway. Lime is then spread on the inside of each windrow or down the center line of the road. The soil is then bladed to cover the lime. After the lime is covered, the soil is mixed dry by blading across the roadway. After dry mixing is completed, water is added to slightly above the optimum moisture content and additional mixing is performed. To assure thorough mixing by this method, the material should be handled on the mold board at least three times.

When blade-mixing is used with the slurry method, the mixing is done in thin lifts which are bladed to windrows. One practice is to start with the material in a center windrow, then blade aside a thin layer after the addition of each increment of slurry, thereby, forming side windrows. The windrowed material is then bladed back across the roadway and compacted, provided that its moisture content is at optimum.

For lime stabilization, pulverization and mixing should continue until 100 percent of the soil binder passes a 1-inch screen and at least 60 percent passes the Number 4 sieve. Water contents consistent with good compaction should be obtained during the pulverization and mixing operation. For soil cement mixtures, most specifications require that fine grained soils be pulverized such that at the time of compaction 100 percent of the soil-cement mixture will pass a 1-inch sieve and that a minimum of 80 percent will pass a Number 4 sieve, exclusive of any gravel or stone.

Mixing and pulverization requirements for lime-fly ash and cement-fly ash mixtures are typically those for lime and cement stabilization. It is important that uniform mixing be achieved because two stabilizers are being used and both must be mixed uniformly to achieve the desired result.

In-place mixing of cement or cement-fly ash and dry uniform, fine sand is impractical for trafficability reasons.

Mixing of asphalt with soil and water should continue until a uniform mixture is obtained. When flat-type rotary mixers and motor graders are used, the asphalt spreading and mixing operation requires several repetitions of asphalt distribution and mixing.

(e) Compaction. Compaction should commence as soon as possible after uniform mixing of water and the stabilizer when lime-fly ash, cement-fly ash and cement are used as stabilizers. Most specifications require that materials be compacted within 4 hours of mixing. Compaction should always be complete on the same day the soil is mixed with the stabilizers.

For maximum strength, lime-stabilized soils should be compacted soon after mixing, provided uniform mixing is achieved. Since the reactions associated with lime stabilization are long term compared to cement stabilization, additional time is available for mixing and pulverizing lime stabilized soils. This additional time is particularly useful when highly plastic soils are being treated and pulverization is difficult. Delays up to 4 days long have been acceptable in certain cases when long delays cannot be avoided, it may be necessary to incorporate a small amount of additional lime (about ½) into the soil to compensate for losses due to carbonation and erosion.

Lime-soil and soil cement mixtures should be compacted to high density (at least 95 percent of maximum density according to MIL-STD-621A, Method 100). This necessitates compacting at no less than the optimum moisture content with approved compaction equipment.

Experience has shown that breakdown rolling of emulsified asphalt mixes should begin immediately before, or at the same time as, the emulsion starts to break. At about this time, the moisture content of the mixture is sufficient to act as a lubricant between the aggregate particles, but is reduced to the point where it does not fill the void spaces. This allows air void reduction under compactive forces. Also, by this time, the mixture should be able to support the roller without undue displacement.

When using cutback asphalt, correct aeration will be achieved when volatile content is reduced to about 50 percent of that contained in the original asphaltic material, and the moisture content does not exceed 2 percent by weight of the total mixture (refer to ASTM D-1461 or AASHTO T-110).

Various types of rollers and layer thicknesses have been used in stabilization operations. For example, in lime stabilization the most common practice is to compact in one lift, using the sheepsfoot roller (for fine-grained soils) until it "walks out." The sheepsfoot is often followed by a multiple-wheel pneumatic roller; the flat wheel roller is used for finishing. Single lift compaction can also be accomplished on some of the more granular soils with vibrating impact rollers or heavy pneumatic rollers, with pneumatic or steel rollers used for finishing. When light pneumatic rollers (less than 8 tons) are used alone, compaction is generally done in thin lifts, usually 1 and ½ to 2 inches. Slush rolling of lime-stabilized materials with steel wheel rollers is not recommended. During compaction, light sprinkling may be required, particularly during hot, dry weather, to compensate for evaporative losses.

Since lime-fly ash and cement-fly ash materials often behave as if they are basically granular in nature, with little or no cohesion at the time of compaction, pneumatic-tired rollers, steel and vibratory rollers are usually most effective in providing initial densification of the mixes. Lift thicknesses of 6 inches are common.

Cement stabilization of fine-grained soils sometimes makes use of sheepsfoot rollers. Typically, pneumatic and steel wheel rollers and vibratory rollers are adequate for the granular cement stabilized materials.

Asphalt-stabilized materials are granular. Thus, pneumatic, steel wheel, and vibratory rollers can be used. Typical types of compaction equipment are shown in Figures 66 to 69.

Placement of multiple lifts of stabilized materials create certain problems that must be recognized by the engineer. Consecutive lifts of lime-stabilized materials can be placed successively provided the top approximatley ¼ of inch is removed prior to placing the next layer. Carbonation of top of lime stabilized layers often results when sprinkling is used for the curing. The carbonation created a weak interlayer.

Figure 66. Initial Compaction of Lime-Soil Mixture with Sheepsfoot Roller (After Ref. 7).

Figure 67. Pneumatic-Tired Roller.

Figure 68. Steel-Wheel Tandem Roller (After Ref. 7).

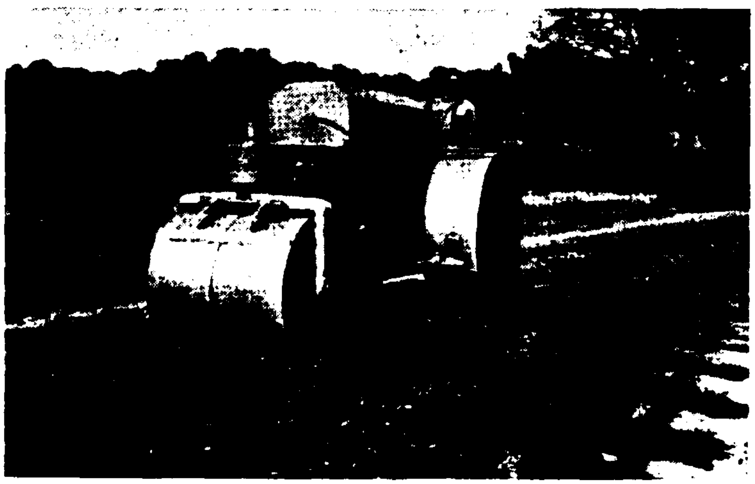


Figure 69. Flat Three-Wheel Roller Used for Final Compaction of Lime-Treated Base (After Ref. 26).

When liquid asphalts are used it is important that the lifts have sufficient time to cure prior to placement of the next layer. One week delays in hot, dry weather normally result in the desired curing.

General compaction requirements for bases, subbases and subgrades are specified in AFM 88-6, Chapters 2 and 3 and 88-7, Chapters 1 and 3. Compaction requirements for bituminous materials are also discussed in AFM 88-6, Chapter 9. General compaction procedures are discussed in Military Construction Guide Specifications 02693, 02694 and 02695, References 31, 26 and 27, respectively.

(f) Curing. Proper curing of the lime, lime-fly ash, cement-fly ash and cement stabilization is important because the strength gain is dependent upon time, temperature and the presence of water. Generally a 3 to 7 day curing period is required, during which time equipment heavier than pneumatic rollers is kept off. Two types of curing are employed to ensure that the moisture is retained in the stabilized layer: sprinkling (Figure 70) and membrane (Figure 71). Sprinkling with water to keep the surface damp, together with light rolling to keep the surface knitted together, has proven successful. However, the preferred method is membrane curing. In membrane curing, the stabilized soil is either sealed with one shot of cutback asphalt (0.10 to 0.25 gal/sq. yd.) within 1 day after final rolling or primed with increments of asphalt emulsion, applied several times during the curing period. In some cases, curing may not be extensive or not needed if the overlying pavement layer is placed shortly after construction of the stabilized layer.

If traffic is to use emulsion or cutback stabilized materials, it is desirable to place a sand or aggregate seal. A protective layer should not be used soon after construction if traffic will not immediately use the facility as strength gain of cutback and emulsion-stabilized materials is based on loss of volatiles. A protective seal will reduce the rate of loss of volatiles.

(g) Deep Plow - Lime Stabilization. The area is first brought to proper line and grade. Disc the grade and distribute lime uniformly on the grade. Usually three percent of dry weight of soil is used. Disc the lime into the upper eight to ten inches. Plow the grade to 24 inches depth or greater with a dozer drawn plow. Disc the plowed material to eight to 10 inch depth. Shape the mixture to proper cross section and grade. Compact the processed mixture in one lift; a Cat 834 self-propelled tamping foot roller has been used successfully. Water is added as needed for compaction at optimum moisture content. Density in the lower half of the layer should be 90 percent of maximum and in the upper half of 95 percent of maximum (MIL-STD-621A, Method 100). Using this technique, no undercutting and wasting of material is required, additional sources of borrow

Figure 70. Sprinkling Lime-Treated Subgrade on Military Runway (After Ref. 7).

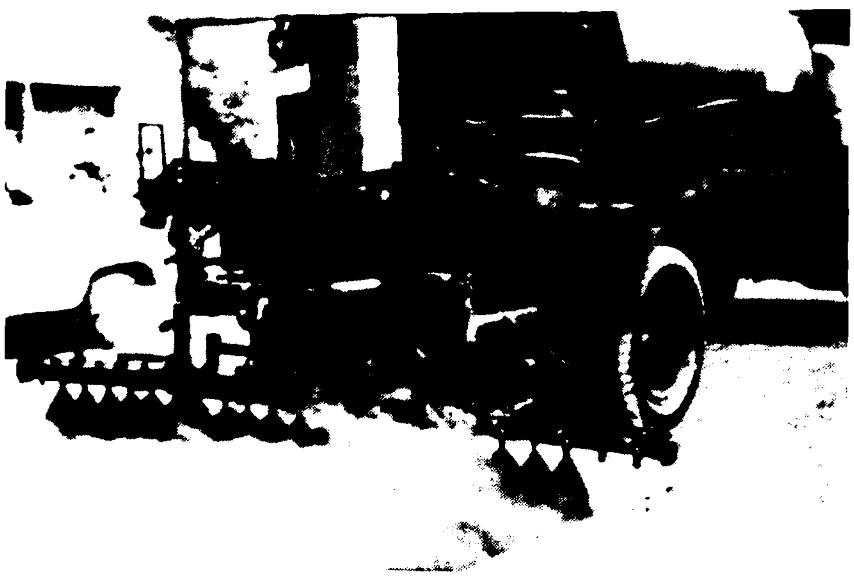


Figure 71. Membrane Curing with Asphalt.

material are not required, equipment requirements are nominal, immediate soil improvement is obtained and the modified layer is water-resistant, minimizing loss of working days in wet weather.

2. *Subbase and Base Course Stabilization*

Stabilization of subbase and base course materials in-place is very similar to subgrade stabilization. The major difference in the two operations is the usual use of borrow material and thus the opportunity to distribute the stabilizer and perform mixing with the aid of a windrow. The following construction steps are typically employed for subbase and base stabilization where windrows are employed:

a. Soil preparation,

b. Stabilizer application,

c. Pulverization and mixing,

d. Compaction and

e. Curing.

Most of the construction operations are identical to those for subgrade stabilization. Thus, details will not be restated.

(a) Soil Preparation. The most important element of this operation is to assure that the underlying course is compacted and prepared to the proper grade and cross slope. The desired density of stabilized subbase cannot be obtained if a soft or undercompacted subgrade is present. A compaction platform, therefore, must be created and soft spots removed and reworked.

Another important element of the soil preparation operation is the formation of a uniform windrow. A windrow sizer may have to be used to achieve the desired uniformity (Figure 72).

If the stabilized layer is of sufficient thickness to require multiple lifts, partial surface scarification of the bottom lift is often required for lime, lime-fly ash, cement-fly ash and cement stabilization. For some lime stabilization jobs, it may be necessary to remove the top ½ to 1 inch of material, as this area may be weakly cemented with calcium carbonate rather then the desired pozzolanic action.

Since most borrow materials are granular, pulverization prior to the addition of the stabilizer is not required. If clay soils are encountered or of the stabilized borrow contains clay, partial pulverization may be required prior

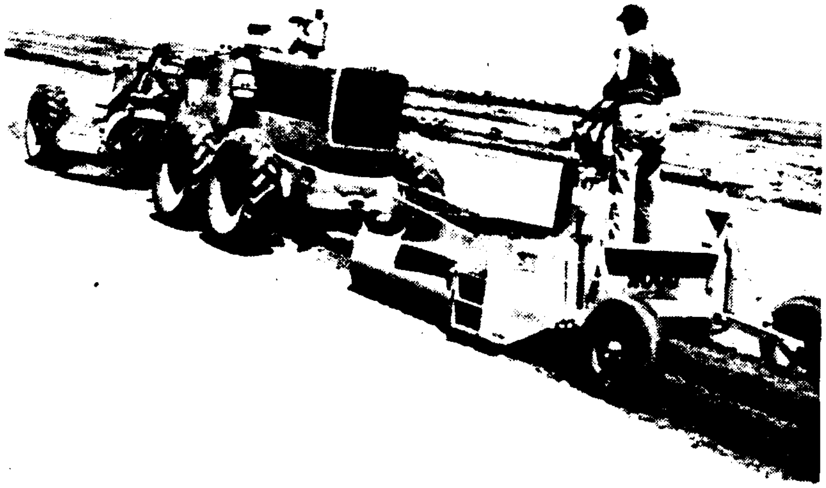


Figure 72. Windrow Sizer (After Ref. 7).

to the addition of the stabilizer.

(b) Stabilizer Application. The most common form of stabilizers for use in windrows is bulk. Lime and cement can be distributed conveniently with bulk trucks or with specially designed trucks as shown in Figure 73. Fly ash is normally conditioned with moisture prior to spreading; however, dry distribution is possible if windrows are used.

Asphalt can be distributed through the mixes (Figure 65) or by distributors as shown in Figure 64. Lime slurries can be used to distribute the lime in mixers (Figure 63).

The addition of water prior to the introduction of asphalt into the windrow is often necessary in asphalt stabilization operations. This water (usually three to five percent) will aid mixing. Dry soil and cement or lime should be premixed prior to the addition of water for best uniformity. The higher plasticity index soils will require an increase in water.

(c) Pulverization and Mixing. Mixing of materials in windrows can best be performed by parallel-shaft travelling pugmill mixers. The machine moves along the windrow, picking up the material, mixing it with stabilizer (and water as needed) in the pugmill and depositing the mixture in a windrow ready for spreading and compaction. It is not unusual to require more than single-pass mixing. Additional mixing can often be performed with the motor grader prior to spreading and compaction.

The hopper-type travel plants are sometimes used for subbase and base course stabilization. Aggregate is deposited in the hopper and mixed with the proper amount of stabilizer in the mixing chamber. Good stabilizer distribution is normally obtained if the operation is carefully controlled.

When asphalt is used in combination with lime, cement or fly ash; water should be added and mixed before the asphalt is entered into the system.

(d) Compaction and Curing. These operations are identical to those used in subgrade stabilization. It is important, however, to recognize that additional aeration of emulsion, and cutback stabilized materials may be required if windrow or hopper-type mixers are used because the mixing operation affords only limited opportunities for the volatiles to escape.

D. CENTRAL PLANT MIXING OPERATIONS

Central plant mixing operations afford the best opportunity to produce uniform stabilized materials and can achieve close to 100 percent mixing efficiency as measured by the strength of the treated soil measured after field versus after laboratory mixing.

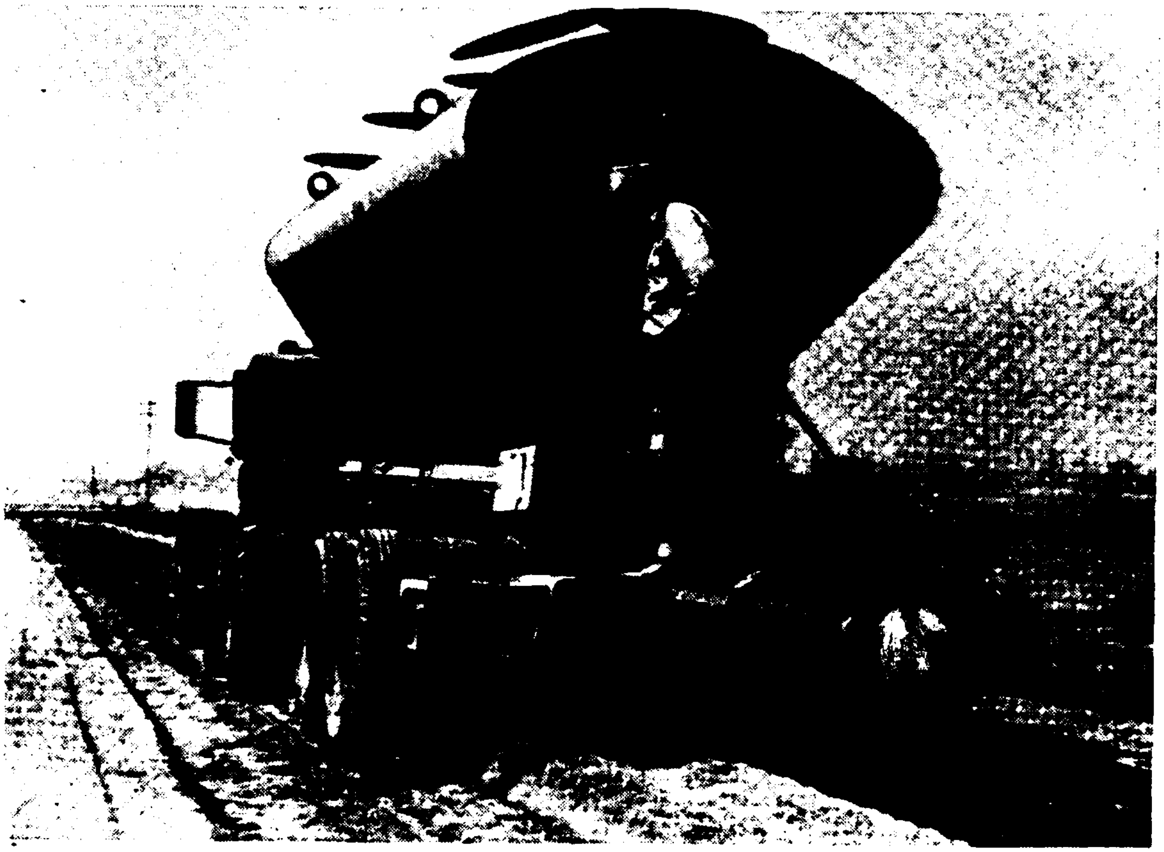


Figure 73. Windrow-Type Mechanical Spreader Used to Place Cement on Top of Windrow of Soil (After Ref. 29).

Of the two major types of central plants, the batch plant will normally have better uniformity and control than the continuous plant.

Both the hot and cold mixing operations can be performed with central plants. Asphalt cements normally require hot central plants for mixing, although soft asphalt cements and foamed asphalt cements have been used on mixed-in-place operations. Emulsified asphalts and cutback asphalts have been used in hot processes where temperatures are typically in the range of 150 to 220°F. Emulsions and cutbacks, however, can be used in central plants without the use of heated aggregates. Both continuous and batch type hot plants are available and are used extensively (see Reference 3 for a detailed discussion of these plants).

Cold central plant mixing operations have been used for lime, lime-fly ash, cement-fly ash and cement stabilization. Continuous plants are used more often than batch type plants due to their high production capabilities. Pugmill type mixing chambers on the continuous and batch plants are most popular, although central mix portland cement concrete plants have been used for cement and lime-fly ash stabilization projects.

Typical central plant mixing construction operations consist of the following:

1. Receiving and storage of materials,
2. Mixing,
3. Hauling,
4. Spreading and
5. Compaction.

The primary difference between hot and cold central plant mixing operation is the heating of the aggregates and stabilizers prior to mixing. Typical central plant operations are summarized below.

1. Receiving and Storage of Materials

Stabilizers and borrow material (aggregates) must be stored at the plant site. Typically lime and cement are stored in vertical silos and delivered to the plant by gravity and compressed air. For continuous plants where lime and cement are metered volumetrically, the stabilizer is usually transferred from the large storage silos to small feed trucks capable of supplying a continuous, calibrated feed.

Asphalt materials are normally stored in heated storage tanks. The temperatures of these tanks are adjusted to provide the correct asphalt viscosity for mixing.

Fly ash is normally stored in open stockpiles which have been conditioned with sufficient water to prevent dusting (usually 15 to 25 percent moisture). During dry weather, the stockpile surfaces must be kept moist or the stockpile covered to prevent dusting. Conditioned fly ash is normally charged into a feed hopper prior to mixing.

Aggregate materials are normally stored in stockpiles and fed through a belt, cold feed system. Sufficient stockpiles to provide the desired gradations should be used. They may vary from one to four in number. Variable speed feeder belts are desirable at the cold feed.

A water storage tank or well with pressure system can be used to handle the water required for mixing and compaction.

2. Mixing

Mixing must be accomplished in such a way that the proper amount of stabilizer is uniformly distributed. Plants suitable for this purpose have been discussed previously.

3. Hauling

Lime, lime-fly ash, cement-fly ash and cement stabilized mixtures which are blended in a central plant location can be hauled to the road site in conventional, open-bed dump and bottom dump trucks. If haul distances are long or drying of the material enroute poses a problem, then provisions should be made to cover the trucks with tarpaulins or other suitable covers to prevent loss of moisture or scattering of environmentally objectionable dust along the haul routes.

Dusting is rarely a problem with asphalt stabilization operations. However, tarpaulins or other suitable covers are used to prevent heat loss when long hauls are required on cold days.

Sufficient trucks should be made available so that all equipment such as the mixing plant, spreaders, rollers, etc., can operate at a steady, continuous pace rather than on a stop-and-go basis.

4. Spreading

Spreading should be accomplished as uniformly as possible and with a minimum of segregation. Spreader boxes (Figures 74 and 75), laydown machines (Figure 76) and other equipment with automated grade control are recommended. An alternate method of spreading (sometimes used but not recommended) is to place the stabilized material in windrows from trucks and spread with road

Figure 74. Towed-Type Spreader (After Ref. 7).

Figure 75. Placing Lime-Fly Ash-Gravel Mixture with Shoulder Base Spreader.

Figure 76. Spreading Cold Mix with Conventional Mixer. (After Ref. 7).

graders. With the windrow operation, care must be taken not to over manipulate the stabilized material, which may cause segregation and drying.

Layers of stabilized mixtures are normally spread to a thickness of between 15 and 30 percent greater than the desired final thickness to attain the required compacted thickness. The amount of excess thickness is a function of the aggregate type and source, as well as the method of spreading. Some experimentation may be necessary to determine the proper spread thickness for each operation, because some types of spreading operations provide a degree of initial consolidation. The maximum recommended thickness for a single stabilized layer after compaction is 8 to 10 inches. If thicknesses of lime, lime-fly ash, cement-fly and cement layers greater than the specified maximum are needed to develop an adequate pavement design, the material should be spread and compacted in lifts. If the material is placed in lifts, the time between lifts should be kept as short as possible so that the lower layer has not "set up" before the next layer is placed. If the stabilized material in the lower layer is fresh and the surface free of loose material, the next layer can be spread without scarifying the lower layer. As a general rule, subsequent layers should be placed the same day, but with multiple-layered pavements this is not always possible. If the stabilized mixture in the lower layer has taken on an initial set, steps should be taken to ensure the development of a bond between the two layers.

Specifically, steps should be taken to assure that there is no loose material on the lower layer and that the surface is moist before placing the material for the subsequent layer.

If multiple layers of emulsion or cutback stabilized layers are required to satisfy pavement thickness requirements, a time delays betwen layers is beneficial to allow for the escape of volatiles and thus for a gain in strength. If multiple layers must be placed with little delay, a longer curing period should be considered for thickness design considerations.

5. Compaction

This operation is identical to that used for mixed-in-place operations with the exception of the urgency of compaction where hot, asphalt stabilization operations are used. Breakdown rolling of asphalt cement stabilized mixtures should be complete before the temperature reaches about 175^{o}F. However, low internal friction mixtures may require lower temperatures. Refer to AFM 88-6, Chapter 9 and Military Construction Guide Specification 02693 (34) for further guidance on compaction of asphalt stabilized, central plant materials.

E. CLIMATIC LIMITATIONS

1. Lime and Cement

a. General. Lime stabilization and, with some soils, cement stabilization is relatively slow setting and requires some warm weather to harden properly. Therefore, in cold weather climates, construction generally should not be permitted after the first of October. Slight exceptions can be made locally, however, subject to engineering judgement. These exceptions would depend upon current weather conditions, urgency of the project and degree of stabilization required. Where lime is used solely to dry up wet soils for compaction and not for complete stabilization, the operation can be carried out in cold weather. In no case, however, should hydrated lime or cement be applied to frozen soil. As a general rule, the "40 degrees F in the shade and rising" is the logical criterion to follow for lime and cement stabilization.

This limitation on the cutoff date for construction can be lessened slightly (by about two weeks longer in the fall) in the case of subgrade stabilization as compared to base stabilization. This is due to the lime or cement stabilized subgrade not being expected to develop the higher strength of the base course, and further, it is partially protected by the subsequent base course application. The same exception applies to lime modified base courses since the lime is applied primarily for improved stability and PI reduction rather than strength. It is important in fall construction to cover the treated subgrade immediately after final compaction.

b. Rainfall. Wet weather need not be a serious construction hazard in either lime or cement stabilization. Attention to a few simple precautions ahead of processing greatly reduces the possibility of serious damage. For example, any loose or pulverized soil should be crowned so it will shed water, and low places in the grade where water may accumulate should be trenched so they will drain freely.

A light drizzle causes no harm. Light rains are beneficial in lime stabilization as they reduce the amount of sprinkling water needed for compaction. Even in heavy rains, there is no damage after the lime is spread unless flooding conditions cause some erosion loss. If rain falls during cement spreading operations, spreading is stopped and the cement already spread is quickly mixed into the soil mass. However, a heavy rainfall that occurs after most of the water has already been added may be serious. Generally, the best procedure is to obtain rapid compaction by using every available piece of equipment so that the section will be compacted and shaped before too much damage results from the rain. In such instances, it may be necessary to complete final blading later; any material bladed from the surface then is wasted.

After the mixture has been compacted and finished, rain will do no harm. Thus, in rainy climates it is advantageous to proceed with lime or cement stabilization during fair weather. Subsequent rains will cause little (if any) delays.

Excessively wet soil is difficult to mix and pulverize. Experience has shown that cement can be mixed with sandy soils when the moisture content is as high as two percent above optimum. For clayey soils, the moisture content should be below optimum for efficient mixing. Only rarely is it necessary to dry out a soil by aeration, but if necessary, efficient aeration can be obtained by using single-shaft travelling mixers operated with the hood raised.

The maintenance of good crown and surface grade to permit rapid runoff of surface water before soil-cement processing is the best insurance against excessive amounts of wet soil.

c. Cold Weather. When premature freezes occur or when jobs have been badly delayed into cold weather, damage from frost can be minimized by:

(1) Rerolling the freshly compacted lime base the next day after a freeze and possibly again the following day (should it freeze again the next night). Experience has shown that subsequent intermittent freezes have little effect on the base. The first freeze usually causes some "puckering" or distortion in the top one inch of base.

(2) Sealing the base as soon as possible after it cures with a bituminous prime coat. In cold weather, it might be desirable to shorten the curing period to three days or even less. If it is shortened, however, traffic should be kept off for several days, in order to permit the base to harden properly.

If spring "breakup" occurs as a result of late fall construction, distressed sections can be reworked and recompacted into permanent, durable sections. Most of the lime is still active and "free," and will readily react during the ensuing warm spring weather. Usually in reworking, it is desirable to add 1 percent of lime to compensate for partial loss of lime due to carbonation over the winter months.

While lime slow set is disadvantageous in shortening the fall construction season in colder climates, there are several compensating advantages. First, the use of lime lengthens the spring construction period by permitting operations to start much earlier - just as soon as the frost is out of the ground. Early spring freezes are not damaging since they are short-lived. Construction can proceed with lime even when the ground is saturated with moisture. This is due to lime's drying effect which ultimately permits the saturated soil to be worked without heavy equipment bogging down. Without lime, the contractor is obliged to wait for nature's drying action, causing weeks of lost construction schedules. The contractor can count on just as many months of construction (possibly more) with lime stabilization than with other methods of base and foundation construction.

Flexibility in construction is also possible since in event of contingencies causing delays while lime stabilization is in progress, the soil-lime mixtures can be retempered and reworked if necessary even after the cementing or hardening action commences.

2. Fly Ash

The general guideline for determining the construction cut-off date for stabilized fly ash base course is that the ambient air temperature should not fall below 50^{o}F for a period of seven days following completion of the base course. The pozzolanic reaction in the base course material ceases at temperatures below 40^{o}F, although it continues once the temperature is increased. If construction takes place early or late in the season, or if unseasonably cold weather occurs during the curing period, the base course should be protected from freezing by a covering of suitable material, such as hay or straw and consideration should be given to delaying the opening of the finished pavement to traffic.

3. Asphalt

The primary restraint in the use of asphalt stabilization is the requirement for above-freezing temperatures during construction. When cutbacks and emulsions are used, the temperature must be above freezing to permit the required aeration before compaction. Asphalt cements are impossible to compact once the temperature of the mix decreases due to its viscosity characteristics. An air temperature of 40^{o}F is required for thin lifts. Thick lifts may be placed in freezing temperatures. Hot, dry weather is preferred in all types of bituminous stabilization.

TABLE 29. EQUIPMENT TYPICALLY ASSOCIATED WITH MIXED-IN-PLACE SUBGRADE STABILIZATION OPERATIONS (AFTER REF. 1).

	Construction Operation				
Stabilizer	Soil Preparation	Stabilizer Application	Pulverization and Mixing	Compaction	Curing
Lime[1]	Single-shaft rotary mixer (flat type) Motor grader Disc harrow Other agricultural-type equipment	Dry-bagged Dry bulk Slurry Slurry thru mixer	Single- and multi-shaft rotary mixers Motor graders Other agricultural-type equipment	Sheep's foot Pneumatic Steel wheel	Asphalt membrane Water sprinkling
Lime or Cement, Fly Ash[2]	Single-shaft rotary mixer (flat type) Motor grader Disc harrow Other agricultural-type equipment	Separate application Lime--dry or slurry Fly ash--conditioned Combined application Dry--bagged Dry bulk	Same as lime	Steel wheel Pneumatic Vibratory	Asphalt membrane Water sprinkling
Cement[3]	Single-shaft rotary mixer (flat type) Motor grader Disc harrow Other agricultural-type equipment	Dry--bagged Dry bulk	Same as Lime	Sheep's foot Pneumatic (clay soils) Vibratory (granular soils)	Asphalt membrane Water sprinkling
Asphalt[4]	Motor grader Single-shaft rotary mixer (flat type)	Asphalt spray distributor During mixing process	Single- and multi-shaft rotary mixer (flat type) Motor grader	Pneumatic Steel wheel Vibratory	Volatiles should be allowed to escape and/or the pavement to cool

Comments	Safety Procedures
[1]Double application of lime may be required to facilitate mixing. The soil and air temperature should be greater than 40°-50°F to insure adequate strength gain. Construction should be completed early enough in summer or fall so that sufficient durability will be gained to resist freeze-thaw action.	Lime spreading should be avoided on windy days. Proper clothing should be worn so that workmen can avoid skin contact with quicklime. Workmen should avoid prolonged contact with lime and breathing lime dust.
[2]Fly ash must be conditioned with moisture prior to distribution to prevent dusting. Mixing and compaction should be completed shortly after stabilizer application. The soil and air temperature should be greater than 40°-50°F to insure adequate strength gain. Construction should be completed early enough in summer or fall so that sufficient durability will be gained to resist freeze-thaw action.	Fly ash, lime and cement spreading should be avoided on windy days. Workmen should avoid prolonged contact with the stabilizers and breathing the stabilizers.
[3]Mixing and compaction must be completed shortly after stabilizer application. The soil and air temperatures should be greater than 60°F to insure an adequate rate of strength gain. Construction should be completed early enough in summer or fall so that sufficient durability will be gained to resist freeze-thaw action.	Cement spreading should be avoided on windy days. Workmen should avoid prolonged contact with cement and breathing the cement dust.
[4]Proper soil moisture content must be achieved to aid distribution and mixing. Stabilized material should be properly aerated prior to compaction. The soil and air temperature should be above 40°F to allow for proper curing and sufficient time for compaction if hot mix processes are utilized. Thick lifts of hot, asphalt cement stabilized materials can be placed below 32°F.	Proper clothing should be work so that workmen can avoid skid contact with quicklime.

SECTION X

QUALITY CONTROL

A. PURPOSE

Quality control is essential to assure that the final product will be adequate for its intended use. It must also ensure that the contractor has performed in accordancce with the plans and specifications, as this is a basis for payment.

This section identifies those control factors which are most important in soil stabilization construction with lime, lime-fly ash, cement and asphalt. Inspection and testing requirements for each of those factors will also be discussed.

Statistical quality control will be discussed in light of its applicability to soil stabilization construction.

B. RELATED MATERIAL

Several references provide invaluable supplementary information to this section on quality control. These references are documented in the Reference Section but are also presented here for convenience.

Subject	Title and Reference Number
Soil-Lime Quality Control	Lime Stabilization Construction Manual, Bulletin 326, National Lime Association (26)
	State of the Art: Lime Stabilization, Transportation Research Board Circular (25)
Soil-Cement Quality Control	Soil-Cement Inspector's Manual, Portland Cement Association (32)
Soil-Asphalt	Asphalt Cold-Mix Manual, The Asphalt Institute, MS-14 (7)
Statistical Quality Control	Statistically Oriented End Result Specifications, Transportation Research Board (33)
	Statistical Quality Control in Highway Construction, Journal of Const. Engineering, ASCE (34)
	Principles of Pavement Design, Yoder and Witczak, pp. 405-442 (35)

C. SCOPE

Development of laboratory methods for soil stabilization will be of little value if the results of these methods cannot be successfully applied in the field. The success, at least in part, is more likely if some plan is available to assure the quality of the final product. The engineer in the field encounters highly variable conditions such as climate, efficiency of equipment and soil type. These items can have a major impact during construction. Therefore, field personnel must be aware of those factors which control the quality of the final product. The use of lime, lime-fly ash, cement and asphalt in soil stabilization can present significant problems unless the field engineer has some familiarity with those factors which must be controlled to assure that an investment of time and money will not be wasted.

The quality of stabilized mixtures, as produced and placed, must be monitored on a continuing basis to assure a quality product. The general tests normally conducted on these materials listed below in their order of importance or frequency of testing are:

1. In-place density (AASHTO T-238, AASHTO T-205, AASHTO T-191 or MIL-STD-621A, Method 102).

2. Stabilizer content (lime-fly ash and cement - ASTM C-117) (Asphalt - AASHTO T-164)

3. Gradation (ASTM C-117 or MIL-STD-619B).

4. Moisture content (ASTM D-2216, AASHTO T-239 or MIL-STD-621A, Method 100).

In addition, frequent checks should be made on all batch and continuous feeds of mixing plants to assure that the metering of the components is progressing uniformly.

D. SOIL LIME

The most important factors to control during soil-lime construction are:

1. Pulverization and scarification,

2. Lime content,

3. Uniformity of mixing,

4. Time sequence of operations,

5. Compaction and

6. Curing.

These are described in detail in the following paragraphs.

1. Pulverization and Scarification

Before application of lime, the soil is scarified and pulverized. To assure the adequacy of this phase of construction, a sieve analysis is performed. Most specifications are based upon a designated amount of material passing the 1-inch and Number 4 sieves. The depth of scarification or pulverization is also of importance as it relates to the specified depth of lime treatment. For heavy clays, adequate pulverization can best be achieved by pretreatment with lime, but this method is used, agglomerated soil-lime fractions may appear. These fractions can be easily broken down with a simple kneading action and are not necessarily indicative of improper pulverization.

2. Lime Content

When lime is applied to the pulverized soil, the rate at which it is being spread can be determined by placing a canvas of known area on the ground and, after the lime has been spread, weighing the lime on the canvas. Charts can be made available to field personnel to determine if this rate of application is satisfactory for the lime content specified (26).

To accurately determine the quantity of lime slurry required to provide the desired amount of lime solids, it is necessary to know the slurry composition. This can be done by checking the specific gravity of the slurry, either by a hydrometer (AFM 89-3) or volumetric-weight procedure.

3. Uniformity of Mixing

The major concern is to obtain a uniform lime content throughout the depth of treated soil. This presents one of the most difficult factors to control in the field. It has been reported that mixed soil and lime has more or less the same outward appearance as mixed soil without lime. The use of phenophthalein indicator solution for control in the field has been recommended. This method, while not sophisticated enough to provide an exact measure of lime content for depth of treatment, will give an indication of the presence of the minimum lime content required for soil treatment. The soil will turn a reddishpink color when sprayed with the indicator solution, indicating that free lime is available in the soil (pH = 12.5). Short cut methods of performing strength tests are available to determine the efficiency of the mixing (32).

4. Compaction

Primarily important is the proper control of moisture-density. Conventional procedures such as sand cone, rubber balloon and nuclear methods have been used for determining the density of compacted soil lime mixtures. Moisture content can be determined by either oven dry methods or nuclear methods (MIL-STD-621A, Method 105, AFM 89-3 or ASTM D-2216 or ASTM D-3017). The influence of time between mixing and compacting has been demonstrated to have a pronounced effect on the properties of the treated soil. Compaction should begin as soon as possible after final mixing has been completed. The National Lime Association recommends an absolute maximum delay of 1 week. The use of phenopthalein indicator solution has also been recommended for lime content control testing (26). The solution can be used to distinguish between areas that have been properly treated and those that have received only a slight surface dusting by the action of wind. This will aid in identifying areas where density test samples should be taken.

5. Curing

Curing is essential to assure that the soil lime mixture will achieve the final properties desired. Curing is accomplished by one of two methods: (1) moist curing, involving a light sprinkling of water and rolling, or (2) membrane curing, which involves sealing the compacted layer with a bituminous seal coat. Regardless of the method used, the entire compacted layer must be properly protected to assure that the lime will not become nonreactive through carbonation. Intermittent sprinkling which allows the stabilized soil surface to dry will promote carbonation.

6. Other Considerations

The National Lime Association provides specifications for hydrated lime and information on storage and handling requirements (26). Field personnel should insure that the lime used in the treatment process has not been rendered nonreactive through improper storage and handling. A simple pH test capable of indicating a pH of at least 12.4 in a lime-water slurry is adequate for this purpose.

E. SOIL-LIME FLY ASH

The nature of lime-fly ash stabilization is similar to that for lime only. Consequently, the same factors involved for quality control are suggested.

F. SOIL CEMENT

Detailed procedures have been identified for soil-cement construction (29,32). Those factors which are most important from a quality control standpoint are:

1. Pulverization,

2. Cement content,

3. Moisture content,

4. Uniformity of mixing,

5. Time sequence of operations,

6. Compaction and

7. Curing.

These are described in detail below.

1. Pulverization

Pulverization is generally not a problem in soil cement construction unless clayey or silty soils are being stabilized. A sieve analysis is performed on the soil during the pulverization process with the Number 4 sieve used as a control. The percent pulverization can then be determined by calculation. Proper moisture control is also essential in achieving the required pulverization (32).

2. Cement Content

Cement content is normally expressed on a volume or dry weigth basis. Tables and graphs (see Reference 32) can be made available to field personnel which will enable them to determine quantities of cement per linear foot or per square yard of pavement. Spot check can be used to assure that the proper quantity of cement is being applied, by using a canvas of known area or, as an overall check, the area over which a known tonnage has been spread.

3. Moisture Content

The optimum moisture content determined in the laboratory is used as an initial guide when construction begins. Allowance must be made for the in situ moisture content of the soil when construction starts. The optimum moisture content and maximum density can then be established for field control purposes. Shortcut methods are available for performing field moisture density tests (32). Mixing water requirements can be determined on the raw soil or on the soil-cement mix before addition of the mixing water. Graphs and tables can be made available to field personnel as an aid in determining the proper quantities of mixing water to be added (32). Nuclear methods can also be used to determine moisture content at the time construction starts and during processing.

4. Uniformity of Mixing

To assure the uniformity of the mixture throughout the treated depth, a visual inspection is made. Uniformity must be checked across the width of the pavement and to the desired depth of treatment. Trenches can be dug and then visually inspected. A satisfactory mix will exhibit a uniform color throughout, while a streaked appearance indicates a nonuniform mix. Special attention should be given to the edges of the pavement.

5. Compaction

Equipment used for compaction is the same that would be used if no cement were present in the soil, and is therefore dependent upon soil type. Several methods can be used to determine compacted density: sand-cone method, ballon method, oil method and nuclear method (MIL-STD-621A, Method 102, Method 106 or AFM 89-3 or ASTM D-2922, ASTM D-2937, ASTM D-2167 and ASTM D-1556). It is important to determine the depth of compaction and special attention should be given to compaction at the edges.

6. Curing

To assure proper curing a bituminous membrane is frequently applied over large areas. The surface of the soil cement should be free of dry loose material and in a moist condition. It is important that the soil-cement mixture be kept continuously moist until the membrane is applied. The recommended application rate is 0.15 to 0.30 gallon per square yard.

G. SOIL-ASPHALT

Detailed procedures have been identified for soil-asphalt construction (7). The factors that seem most important to control during construction are:

1. Surface moisture content,

2. Viscosity of the asphalt,

3. Asphalt content,

4. Uniformity of mixing,

5. Aeration,

6. Compaction and

7. Curing.

These are described in detail in the following paragraphs.

1. Surface Moisture Content

The surface moisture of the soil to be stabilized is of concern. Surface moisture can be determined by conventional methods, such as oven-drying, or by nuclear methods. The Asphalt Institute recommends a surface moisture of up to three percent or more for use with emulsified asphalt and a moisture content of less than three percent for cutback asphalt. The gradation of the aggregate has proven to be of significance as regards moisture content. With dense graded mixes, more water is needed for mixing than compaction. Generally, a surface moisture content that is too high will delay compaction of the mixture. Higher plasticity index soils require higher moisture contents.

2. Viscosity of the Asphalt

The Asphalt Institute recommends that cold-mix construction should not be performed at temperatures below 50°F. The asphalt will rapidly reach the temperature of the aggregate to which it is applied and at lower temperature difficulty in mixing will be encountered. On occasion some heating is necessary with cutback asphalts to assure that the soil aggregate particles are thoroughly coated.

3. Asphalt Content

Information can be provided to field personnel which will enable them to determine a satisfactory application rate. The asphalt content should be maintained at optimum or slightly below for the specified mix (7). Excessive quantities of asphalt may cause difficulty in compaction and result in plastic deformation in service during hot weather.

4. Uniformity of Mixing

Visual inspection can be used to determine the uniformity of the mixture. With emulsified asphalts, a color change from brown to black indicates that the emulsion has broken. The Asphalt Institute recommends control of three variables to assure uniformity for mixed-in-place construction: (1) travel speed of application equipment, (2) volume of aggregate being treated and (3) flow rate (volume per unit time) of emulsified asphalt being applied. In many cases, an asphalt content above design is necessary to assure uniform mixing.

5. Aeration

Prior to compaction, the diluents (cutbacks) that facilitated the cold-mix operation must be allowed to evaporate. If the mix is not sufficiently aerated, it cannot be compacted to acceptable limits. The Asphalt Institute has determined that the mixture has sufficiently aerated when it becomes tacky and appears to "crawl." Most aerating occurs during the mixing and spreading stage, but occasionally additional working on the roadbed is necessary. The Asphalt Institute has reported that overmixing in central plant mixes can cause emulsified asphalts to break early, resulting in a mix that is difficult to work in the field (3).

6. Compaction

Compaction should begin when the aeration of the mix is completed. The Asphalt Institute recommends that rolling begin when an emulsified asphalt mixture begins to break (color change from brown to black). Early compaction can cause undue rutting or shoving of the mixture due to overstressing under the roller. The density of emulsion stabilized bases has often been found to be higher than that obtained on unstabilized bases for the same compaction effort.

7. Curing

Curing presents the greatest problem in asphalt soil stabilization. The Asphalt Institute has determined that the rate of curing is dependent upon many variables: quantity of asphalt applied, prevailinng humidity and wind, the amount of rain and the ambient temperature. Initial curing must be allowed in order to support compaction equipment. This initial curing, the evaporation of diluents (cutbacks), occurs during the aeration stage. If compaction is started too early, the pavement will be sealed, delaying dehydration, which lengthens the time before design strength is reached. The heat of the day may cause the mixture to soften, which prohibits equipment from placing successive lifts until the following day. This emphasizes the need to allow sufficient curing time when lift construction is employed. The Asphalt Institute recommends a 2- to 5-day curing period under good conditions when emulsified bases are being constructed (3). Cement has been used to accelerate curing.

H. USEFUL TESTS

1. Rapid Test Method for Soil-Lime Construction to determine the efficiency of mixing:

a. Secure a sample of the field mixed soil-lime material,

b. Halve the sample,

c. Prepare stength specimens (unconfined compression) form one portion,

d. Completely "remix" the other portion of the field mixture to ensure almost 100 percent mixing,

e. Prepare strength specimens from the "remixed material,"

f. Cure both samples and test and

g. Calculate mixing efficiency as follows:

$$\text{Percent} = \frac{\text{Field Mixed Strength}}{\text{Lab Mixed Strength}} \times 100$$

(For mixed-in-place, expect 60-80 percent.)

2. Determination of percent pulverization for soil cement construction:

$$\text{Percent} = \frac{\text{Dry Weight of Soil Cement Mixture Passing the No. 4 Sieve}}{\text{Dry Weight of the Total Sample Exclusive of Gravel Retained on the No. 4 Sieve}} \times 100$$

To improve pulverization:

a. Slower forward speed of mixing machine,

b. Additional passes, if using multiple pass mixer,

c. Replacing worn mixing teeth and

d. Prewetting and premixing the soil before processing begins.

3. Short cut method of moisture density test:

a. Obtain field sample near optimum moisture,

b. Split sample in three parts,

c. Use one portion to establish a point near the peak of the moisture density curve,

d. Add a small increment of water to a second portion to obtain a point on the wet sude of the curve and

e. Third portion, which has dried slightly, is used to obtain a point on the dry side of the moisture-density curve.

I. STATISTICAL QUALITY CONTROL

In recent years the trend towards End Result Specifications has led to the implementation of Statistical Quality Control (SQC) in highway construction.

Statistical quality control can readily be applied to soil stabilization construction. Many of the control factors discussed previously under stabilization with lime, lime-fly ash, cement and asphalt can be tested under the SQC method. The SQC method could be used to determine both the number of samples to be tested and the locations from which the samples should be taken. The Asphalt Institute has devised a random sampling plan for selecting sampling locations in trucks handling asphalt mixtures and for the selection of sampling locations at the paving site. This plan, although designed for asphalt cold-mix construction, can be used for other types of soil stabilization whether central mix or mixed-in-place methods are used. The procedure is explained in Section IX, Paragraph K.

In establishing an SQC plan, it must be recognized that there are risks involved for both the buyer and the seller. The seller's risk involves the rejection of material that is good on the basis of samples that are bad. The buyer's risk involves the acceptance of material that is bad on the basis of samples that are good. One approach for determining acceptable buyer's and seller's risk is to consider the criticality of the characteristic of the material or construction for which the acceptance plan is intended. Acceptance plans must then be developed by the contracting agency to assure that it receives the most satisfactory product with the fewest possible defects for the inspection effort specified.

J. FACTORS TO CONSIDER IN STATISTICAL QUALITY CONTROL

1. Classification of Criticality:

a. Critical. The defect will make the product dangerous to use,

b. Major. This defect will seriously impair performance of the item,

c. Minor. This defect may impair performance, but not seriously and

d. Contractual. This defect is likely to have insignificant effect on performance.

2. Acceptable Buyer's and Seller's Risks

When designing an acceptance plan, a decision must be made as to what is the appropriate buyer's risk (accepting unacceptable material or construction) and seller's risk (rejecting acceptable material or construction). Based on the classification of criticality the following risks are assigned:

Classification Characteristic	Buyer's Risk, Percent (β Value)	Seller's Risk, Percent (α Value)
Critical	0.5	5.0
Major	5.0	1.0
Minor	10.0	0.5
Contractual	20.0	0.1

The seller's risk is usually established as 5 or 1 percent for roadway or airport construction. Buyer's risks are much more difficult to establish because they involve selecting mean values determined important to detect along with associated risks.

3. Essential Elements of a Complete, Statistically Oriented Lot Acceptance Plan:

a. Specifications should define the size of the lot in terms of appropriate units of measure such as tons, square yards, or linear feet of lane,

b. The point of sampling should be stated,

c. The method of random sampling should be stated,

d. The number of samples to be taken or the number of measurements to be made on each lot or sublot should be stated,

e. The method test (AASHTO, ASTM, MIL-Standard or agency) by which the material or construction will be evaluated should be stated,

f. The target or desired value of the measured characteristic of the material or construction should be stated,

g. Realistic tolerances should be placed on the target value and

h. The action to be taken in case the material or construction does not fully comply with the specified quality requirements given.

This usually takes the form of a table of graduated reductions in price with some cutoff point beyond which the material or construction must be removed and replaced or may be left in place for only a token payment, if agreed to by the engineer.

4. Acceptance Procedures

The statistical procedures used in quality control requires a fundamental knowledge of statistics, especially hypothesis testing. The necessary background may be found in any basic statistics text. Reference 35 will certainly be helpful. This section assumes a basic understanding of statistical terms and hypothesis testing.

A procedure is outlined here to aid in identifying the Acceptance-Rejection value (R) of a test and the number of sampling units (n) required.

a. Identify the mean value for acceptable performance, μ_1.

b. Identify the acceptable probability, α, of rejecting a material whose mean performance is at least μ_1. This is called the seller's risk.

c. Identify the mean value, μ_2, at which the user would like to establish a risk, β, associated with acceptance. This risk is called buyer's risk.

d. Determine if the standard deviation, σ, is known or unknown. The standard deviation is usually based on historic data summaries.

e. Calculate K_α, K_β, R and n as defined in paragraph 5.

5. Definitions

a. $P_R\ (\bar{X} < R) = \alpha$ (for μ_1). This expression states that the probability is α that the mean value of n sampling units is less than R. R is an acceptance-rejection value. This is for the population whose mean is μ_1.

b. $P_R\ (\bar{X} > R) = \beta$ (for μ_2). This expression states that the probability is β that the mean value of n sampling units is greater than R. This is for a population whose mean is μ_2.

c. $K_\alpha = \dfrac{|R - \mu_1|}{(\sigma/\sqrt{n})}$. Thus,

$$R = \mu_1 - K_\alpha\ (\sigma/\sqrt{n})\ .$$

d. $K_\beta = \dfrac{|R - \mu_2|}{(\sigma/\sqrt{n})}$. Thus,

$$R = \mu_2 + K_\beta\ (\sigma/\sqrt{n})\ .$$

e. $n = \dfrac{(K_\beta - K_\alpha)^2 \sigma^2}{(\mu_1 - \mu_2)^2}$, solving

Equations (c) and (d) simultaneously.

6. Example

It is desired to determine the number of sampling units (n) and the rejection-acceptance value (R) what will comprise the statistical quality control specifications for percentage compaction for stabilized base course layers.

a. Historic data show that successfully performing layers have been compacted to 99 percent of density (μ_1). These data also show a standard deviation of 3.00 percent (σ).

b. The acceptable probability of rejecting a base whose mean compaction was at least 99 percent was agreed upon to be 2 percent (α).

c. The Air Force would like to limit their risk to only 5 percent (β) of accepting a compacted base whose density is 94 percent (μ_2).

d. Since σ is known

$$K_\alpha = \frac{|R - \mu_1|}{(\sigma|\sqrt{n})} \text{ and } K_\beta = \frac{|R - \mu_2|}{(\sigma|\sqrt{n})}$$

or $R = \mu_1 - K_\alpha\ (\sigma|\sqrt{n})$ and $R = \mu_2 + K_\beta\ (\sigma|\sqrt{n})$.

$$\text{Thus, } n = \frac{(K_\beta - K_\alpha)^2\sigma^2}{(\mu_1 - \mu_2)}$$

For $\alpha = 0.02$, $K_\alpha = 2.055$; and for $\beta = 0.05$, $K_\beta = 1.645$ (Table 30).

$$\text{Thus, } n = \frac{(2.055 + 1.645)^2\ (3.00)^2}{(99.0 - 94.0)^2} = 4.9 \text{ say, 5 tests.}$$

Since $R = \mu_2 + K_\beta\ (\sigma|\sqrt{n})$

$$R = 94 + 1.645\ (3.00|\sqrt{5}) = 96.2 \text{ percent.}$$

K. RANDOM SAMPLING PLANS*

1. Definitions:

a. Lot. A quantity of material that one desires to control. It may represent a day's production, a specified ton-

*Source: The Asphalt Institute, "Asphalt Cold-Mix Manual", Manual Series No. 14, February, 1974 (Reference 3).

TABLE 30. AREAS UNDER THE NORMAL CURVE FROM K_α TO ∞.

K_α	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
0.0	.5000	.4960	.4920	.4880	.4840	.4801	.4761	.4721	.4681	.4641
0.1	.4602	.4562	.4522	.4483	.4443	.4404	.4364	.4325	.4286	.4247
0.2	.4207	.4168	.4129	.4090	.4052	.4013	.3974	.3936	.3897	.3859
0.3	.3821	.3783	.3745	.3707	.3669	.3632	.3594	.3557	.3520	.3483
0.4	.3446	.3409	.3372	.3336	.3300	.3264	.3228	.3192	.3156	.3121
0.5	.3085	.3050	.3015	.2981	.2946	.2912	.2877	.2843	.2810	.2776
0.6	.2743	.2709	.2676	.2643	.2611	.2578	.2546	.2514	.2483	.2451
0.7	.2420	.2389	.2358	.2327	.2296	.2266	.2236	.2206	.2177	.2148
0.8	.2119	.2090	.2061	.2033	.2005	.1977	.1949	.1922	.1894	.1867
0.9	.1841	.1814	.1788	.1762	.1736	.1711	.1685	.1660	.1635	.1611
1.0	.1587	.1562	.1539	.1515	.1492	.1469	.1446	.1423	.1401	.1379
1.1	.1357	.1335	.1314	.1292	.1271	.1251	.1230	.1210	.1190	.1170
1.2	.1151	.1131	.1112	.1093	.1075	.1056	.1038	.1020	.1003	.0985
1.3	.0968	.0951	.0934	.0918	.0901	.0885	.0869	.0853	.0838	.0823
1.4	.0808*	.0793	.0778	.0764	.0749	.0735	.0721	.0708	.0694	.0681

*Enter table with α or β values and select K_α or K_β. K values are given in the first column and first row. For example, the K_α for $\alpha = 0.0808$ is 1.400.

TABLE 30. AREAS UNDER THE NORMAL CURVE FROM K_α TO ∞ (CONCLUDED).

K_α	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
1.5	.0668	.0655	.0643	.0630	.0618	.0606	.0594	.0582	.0571	.0559
1.6	.0548	.0537	.0526	.0516	.0505	.0495	.0485	.0475	.0465	.0455
1.7	.0446	.0436	.0427	.0418	.0409	.0401	.0392	.0384	.0375	.0367
1.8	.0359	.0351	.0344	.0336	.0329	.0322	.0314	.0307	.0301	.0294
1.9	.0287	.0281	.0274	.0268	.0262	.0256	.0259	.0244	.0239	.0233
2.0	.0228	.0222	.0217	.0212	.0207	.0202	.0197	.0192	.0188	.0183
2.1	.0179	.0174	.0170	.0166	.0162	.0158	.0154	.0150	.0146	.0143
2.2	.0139	.0136	.0132	.0129	.0125	.0122	.0119	.0116	.0113	.0110
2.3	.0107	.0104	.0102	.0099	.0096	.0093	.0091	.0088	.0086	.0084
2.4	.0082	.0079	.0077	.0075	.0073	.0071	.0069	.0067	.0065	.0063
2.5	.0062	.0060	.0058	.0057	.0055	.0053	.0052	.0050	.0049	.0048
2.6	.0046	.0045	.0044	.0042	.0041	.0040	.0039	.0037	.0036	.0035
2.7	.0034	.0033	.0032	.0031	.0030	.0029	.0028	.0028	.0027	.0026
2.8	.0025	.0024	.0024	.0023	.0022	.0021	.0021	.0020	.0019	.0019
2.9	.0018	.0018	.0017	.0016	.0016	.0015	.0015	.0014	.0014	.0013
3.0	.0013	.0013	.0013	.0012	.0012	.0011	.0011	.0011	.0010	.0010

nage, a specified number of truck loads, a specified time period during production.

b. Sample. A segment of a lot chosen to represent the total lot. It may represent any number of subsamples.

c. Subsample. A segment of a sample, taken from a unit of the lot, i.e., a specified ton, a specified truck load.

d. Sample Unit. A portion of subsample taken from a unit of a lot and combined with one or more other sample units to make up a subsample.

2. Selecting Sampling Location (Procedure 1)

In this procedure the following steps are necessary to select the sampling locations:

a. Select the lot size - it can be time (hours), an average day's production (tons), a selected tonnage (Example: 2,000 tons), or a selected number of truck loads. A lot size of a day's production is recommended for these procedures as being convenient and easy to randomize.

b. Select the number of samples desired per lot. One sample per lot, made up of four subsamples, is the minimum recommended.

c. Select the number of locations in each truck load from which sampling units of asphalt mixtures will be taken to combine into one subsample. Two sampling units per subsample are recommended.

d. Assign each truck load of mixture in the lot a number, beginning with one for the first truck load and number then consecutively to the highest number in the lot. Find the truck load numbers for sampling by the following procedure:

(1) Place consecutively numbered 1-inch square pieces of cardboard, equal to the number of truck loads in the lot, into a container (such as a bowl). Mix them thoroughly before each drawing.

(2) Draw a number of cardboard squares from the container equal to the number of subsamples desired for the lot.

The numerals on the cardboard squares will be the truck loads to be sampled.

e. Choose for each subsample desired the location in the truck load for each of the sampling units. Use the following steps:

(1) Divide the truck beds into equal quadrants and number them 1 through 4 in any order desired.

(2) Place four consecutively numbered (1 through 4) 1-inch square pieces of cardboard into a container (such as a bowl). Mix them throughly before each drawing.

(3) Draw out an amount of cardboard squares equal to the number of sample units desired. The numerals on each square drawn represent the quadrants from which the sample unit will be taken. Replace the cardboard squares and repeat this step for each sample unit subsample to be taken.

3. Selecting Sample Locations at Pavement Site (Procedure 2)

Table 31 contains random numbers for the general sampling procedure. To use this table for selecting locations for sampling or testing, the following steps are necessary:

a. For compacted pavement sampling to testing locations, use each day's run as a separate section.

b. Determine the number of sampling locations within a section by selecting the maximum average longitudinal distance desired between samples and dividing the length of the section by the maximum average longitudinal distance.

c. Select a column of random numbers in Table 31 by placing 28 one-inch square pieces of cardboard, numbered 1 through 28, into a container (such as a bowl), shaking them to get them thoroughly mixed, and drawing one out.

d. Go to the column of random numbers identified with the number drawn from the container. In subcolumn A, locate all numbers equal to and less than the number of sampling locations per section desired.

e. Multiply the total length of the section by the decimal values in subcolumn C, found opposite the numbers located in sub-column A. Add the result to the station number at the beginning of the section to obtain the station of the sampling location.

f. Multiply the total width of the proposed pavement in the section by the decimal values in sub-column C, found opposite the numbers located in subcolumn A, then subtract one-half the total width of the proposed pavement from the result to obtain the offset distance from the centerline to the sampling location. A positive (+) number will be the distance to the right of the centerline and a negative (-) number will be the distance to the left of the centerline. If only one lane of pavement is involved, the total width will be the lane width and the offset distance will be measured from the left edge of the lane.

TABLE 31. RANDOM NUMBER FOR GENERAL SAMPLING PROCEDURE.

COL. NO. 1			COL. NO. 2			COL. NO. 3			COL. NO. 4			COL. NO. 5			COL. NO. 6			COL. NO. 7		
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
15	.033	.576	05	.048	.879	21	.013	.220	18	.089	.716	17	.024	.863	30	.030	.901	12	.029	.386
21	.101	.300	17	.074	.156	30	.036	.853	10	.102	.330	24	.060	.032	21	.096	.198	18	.112	.284
23	.129	.916	18	.102	.191	10	.052	.746	14	.111	.925	26	.074	.639	10	.100	.161	20	.114	.848
30	.158	.434	06	.105	.257	25	.061	.954	28	.127	.840	07	.167	.512	29	.133	.388	03	.121	.656
24	.177	.397	28	.179	.447	29	.062	.507	24	.132	.271	28	.194	.776	24	.138	.062	13	.178	.640
11	.202	.271	26	.187	.844	18	.087	.887	19	.285	.899	03	.219	.166	20	.168	.564	72	.209	.421
16	.204	.012	04	.188	.482	24	.105	.849	01	.326	.037	29	.264	.284	22	.232	.953	16	.221	.311
08	.208	.418	02	.208	.577	07	.139	.159	30	.334	.938	11	.282	.262	14	.259	.217	29	.235	.356
19	.211	.798	03	.214	.402	01	.175	.641	22	.405	.295	14	.379	.994	01	.275	.195	28	.264	.941
29	.233	.070	07	.245	.080	23	.196	.873	05	.421	.282	13	.394	.405	06	.277	.475	11	.287	.199
07	.260	.073	15	.248	.831	26	.240	.981	13	.451	.212	06	.410	.157	02	.296	.497	02	.336	.992
17	.262	.308	29	.261	.087	14	.255	.374	02	.461	.023	15	.438	.700	27	.311	.144	15	.393	.488
25	.271	.180	30	.302	.883	06	.310	.043	06	.487	.539	22	.453	.635	05	.351	.141	19	.437	.655
06	.302	.672	21	.318	.088	11	.316	.653	08	.497	.396	21	.472	.824	17	.370	.811	24	.466	.773
01	.409	.406	11	.376	.936	13	.324	.585	25	.503	.893	05	.488	.118	09	.388	.484	14	.531	.014
13	.507	.693	14	.430	.814	12	.351	.275	15	.594	.603	01	.525	.222	04	.410	.073	09	.562	.678
02	.575	.654	27	.438	.676	20	.371	.535	27	.620	.894	12	.561	.980	25	.471	.530	06	.601	.675
18	.591	.318	08	.467	.205	08	.409	.495	21	.629	.841	08	.652	.508	13	.486	.779	10	.612	.859
20	.610	.821	09	.474	.138	16	.445	.740	17	.691	.583	18	.668	.271	15	.515	.867	26	.673	.112
12	.631	.597	10	.492	.474	03	.494	.929	09	.708	.689	30	.736	.634	23	.567	.798	23	.738	.770
27	.651	.281	13	.499	.892	27	.543	.387	07	.709	.012	02	.763	.253	11	.618	.502	21	.753	.614
04	.661	.953	19	.511	.520	17	.625	.171	11	.714	.049	23	.804	.140	28	.636	.148	30	.758	.851
22	.692	.089	23	.591	.770	02	.699	.073	23	.720	.695	25	.828	.425	27	.650	.741	27	.765	.563
05	.779	.346	20	.604	.730	19	.702	.934	03	.748	.413	10	.843	.627	16	.711	.508	07	.780	.534
09	.787	.173	24	.654	.330	22	.816	.802	20	.781	.603	16	.858	.849	19	.778	.812	04	.818	.187
10	.818	.837	12	.728	.523	04	.838	.166	26	.830	.384	04	.903	.327	07	.804	.675	17	.837	.353
14	.985	.631	16	.753	.344	15	.904	.116	04	.843	.002	09	.912	.382	08	.806	.952	05	.854	.818
26	.912	.376	01	.806	.134	28	.969	.742	12	.884	.582	27	.935	.162	18	.841	.414	01	.867	.133
28	.920	.163	22	.878	.884	09	.974	.046	29	.926	.700	20	.970	.582	12	.918	.114	08	.915	.538
03	.945	.140	25	.939	.162	05	.977	.494	16	.951	.601	19	.975	.327	03	.992	.399	25	.975	.584

COL. NO. 8			COL. NO. 9			COL. NO. 10			COL. NO. 11			COL. NO. 12			COL. NO. 13			COL. NO. 14		
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
09	.042	.071	14	.061	.935	26	.038	.023	27	.074	.779	16	.073	.987	03	.033	.091	26	.035	.175
17	.141	.411	02	.065	.097	30	.066	.371	06	.084	.396	23	.078	.056	07	.047	.391	17	.089	.363
02	.143	.221	03	.094	.228	27	.073	.876	24	.098	.524	17	.096	.076	28	.064	.113	10	.149	.681
05	.162	.899	16	.122	.945	09	.095	.568	10	.133	.919	04	.153	.163	12	.066	.360	28	.238	.075
03	.285	.016	18	.158	.430	05	.180	.741	15	.187	.079	10	.254	.834	26	.076	.552	13	.244	.767
28	.291	.034	25	.193	.469	12	.200	.851	17	.227	.767	06	.284	.628	30	.087	.101	24	.262	.366
08	.369	.557	24	.224	.572	13	.259	.327	20	.236	.571	12	.305	.616	02	.127	.187	08	.264	.651
01	.436	.386	10	.225	.223	21	.264	.681	01	.245	.988	25	.319	.901	06	.144	.068	18	.285	.311
20	.450	.289	09	.233	.838	17	.283	.645	04	.317	.291	01	.320	.212	25	.202	.674	02	.340	.131
18	.455	.789	20	.290	.120	23	.363	.063	29	.350	.911	08	.416	.372	01	.247	.025	29	.353	.478
23	.488	.715	01	.297	.242	20	.364	.366	26	.380	.104	13	.432	.556	23	.253	.323	06	.359	.270
14	.498	.276	11	.337	.760	16	.395	.363	28	.425	.864	02	.489	.827	24	.320	.651	30	.387	.248
15	.503	.342	19	.389	.064	02	.423	.540	22	.487	.526	29	.503	.787	10	.328	.365	14	.392	.694
04	.515	.693	13	.411	.474	08	.432	.736	05	.552	.511	15	.518	.717	27	.338	.412	03	.408	.077
16	.532	.112	20	.447	.893	10	.476	.468	14	.564	.357	28	.524	.998	13	.356	.991	27	.440	.280
22	.557	.357	22	.478	.321	03	.508	.774	11	.572	.306	03	.542	.352	16	.401	.792	22	.461	.830
11	.559	.620	29	.481	.993	01	.601	.417	21	.594	.197	19	.585	.462	17	.423	.117	16	.527	.003
12	.650	.216	27	.562	.403	22	.687	.917	09	.607	.524	05	.695	.111	21	.481	.838	30	.531	.486
21	.572	.320	04	.566	.179	29	.697	.862	19	.650	.572	07	.733	.838	08	.560	.401	25	.678	.360
13	.709	.273	08	.603	.758	11	.701	.605	18	.664	.101	11	.744	.948	19	.564	.190	21	.725	.014
07	.745	.687	15	.632	.927	07	.728	.498	25	.674	.428	18	.793	.748	05	.571	.054	05	.797	.595
30	.780	.285	06	.707	.107	14	.745	.679	02	.697	.674	27	.802	.967	18	.587	.584	15	.801	.927
19	.845	.097	28	.737	.161	24	.819	.444	03	.767	.928	21	.826	.487	15	.604	.145	12	.836	.294
26	.846	.366	17	.846	.130	15	.840	.823	16	.809	.529	24	.835	.832	11	.641	.298	04	.854	.982
29	.861	.307	07	.874	.491	25	.863	.568	30	.838	.294	26	.855	.142	22	.672	.156	11	.884	.928
25	.906	.874	05	.880	.828	06	.878	.215	13	.845	.470	14	.861	.462	20	.674	.887	19	.886	.832
24	.919	.809	23	.931	.659	18	.930	.601	08	.855	.524	20	.874	.625	14	.752	.881	07	.929	.932
10	.952	.555	26	.960	.365	04	.954	.827	07	.867	.718	30	.929	.056	09	.774	.560	09	.932	.206
06	.961	.504	21	.978	.194	28	.963	.004	12	.881	.722	09	.935	.582	29	.921	.752	01	.970	.692
27	.969	.811	12	.982	.183	19	.988	.020	23	.937	.872	22	.947	.797	04	.959	.099	23	.973	.082

TABLE 31. RANDOM NUMBER FOR GENERAL SAMPLING PROCEDURE (CONCLUDED).

COL. NO. 15			COL. NO. 16			COL. NO. 17			COL. NO. 18			COL. NO. 19			COL. NO. 20			COL. NO. 21		
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
15	.023	.979	19	.062	.588	13	.045	.004	25	.027	.290	12	.052	.075	20	.030	.881	01	.010	.946
11	.118	.465	25	.080	.218	18	.086	.878	06	.057	.571	30	.075	.493	12	.034	.291	10	.014	.939
07	.134	.172	09	.131	.295	26	.126	.990	26	.059	.026	28	.120	.341	22	.043	.893	09	.032	.346
01	.139	.230	18	.136	.381	12	.128	.661	07	.105	.176	27	.145	.689	28	.143	.073	06	.093	.180
16	.145	.122	05	.147	.864	30	.146	.337	18	.107	.358	02	.209	.957	03	.150	.937	15	.151	.012
20	.165	.520	12	.158	.365	05	.169	.470	22	.128	.827	26	.272	.818	04	.154	.867	16	.185	.455
06	.185	.481	28	.214	.184	21	.244	.433	23	.156	.440	22	.299	.317	19	.158	.359	07	.227	.277
09	.211	.316	14	.215	.757	23	.270	.849	15	.171	.157	18	.306	.475	29	.304	.615	02	.304	.400
14	.248	.348	13	.224	.846	25	.274	.407	08	.220	.097	20	.311	.653	06	.369	.633	30	.316	.074
25	.249	.890	15	.227	.809	10	.290	.925	20	.252	.066	15	.348	.156	18	.390	.536	18	.328	.799
13	.252	.577	11	.280	.898	01	.323	.490	04	.268	.576	16	.381	.710	17	.403	.392	20	.352	.288
30	.273	.088	01	.331	.925	24	.352	.291	14	.275	.302	01	.411	.607	23	.404	.182	26	.371	.216
18	.277	.689	10	.399	.992	15	.361	.155	11	.297	.589	13	.417	.715	01	.415	.457	19	.448	.754
22	.372	.958	30	.417	.787	29	.374	.882	01	.358	.305	21	.472	.484	07	.437	.696	13	.487	.598
10	.461	.075	08	.439	.921	08	.432	.139	09	.412	.089	04	.478	.885	24	.446	.546	12	.546	.640
28	.519	.536	20	.472	.484	04	.467	.266	16	.429	.834	25	.479	.080	26	.485	.768	24	.550	.038
17	.520	.090	24	.498	.712	22	.508	.880	10	.491	.203	11	.566	.104	15	.511	.313	03	.604	.780
03	.523	.519	04	.516	.396	27	.632	.191	28	.542	.306	10	.576	.659	10	.517	.290	22	.621	.930
26	.573	.502	03	.548	.688	16	.661	.836	12	.563	.091	29	.665	.397	30	.556	.853	21	.629	.154
19	.634	.206	23	.597	.508	19	.675	.629	02	.593	.321	19	.739	.298	25	.561	.837	11	.634	.908
24	.635	.810	21	.681	.114	14	.680	.890	30	.692	.198	14	.749	.759	09	.574	.599	05	.696	.459
21	.679	.841	02	.739	.298	28	.714	.508	19	.705	.445	08	.756	.919	13	.613	.762	23	.710	.078
27	.712	.366	29	.792	.038	06	.719	.441	24	.709	.717	07	.798	.183	11	.698	.783	29	.726	.585
05	.780	.497	22	.829	.324	09	.735	.040	13	.820	.739	23	.834	.647	14	.715	.179	17	.749	.916
23	.861	.106	17	.834	.647	17	.741	.906	05	.848	.866	06	.837	.978	16	.770	.128	04	.802	.186
12	.865	.377	16	.909	.608	11	.747	.205	27	.867	.633	03	.849	.964	08	.815	.385	14	.835	.319
29	.882	.635	06	.914	.420	20	.850	.047	03	.883	.333	24	.851	.109	05	.872	.490	08	.870	.546
08	.902	.020	27	.958	.856	02	.859	.356	17	.900	.443	05	.859	.935	21	.885	.999	28	.871	.539
04	.951	.482	26	.981	.976	07	.870	.612	21	.914	.483	17	.863	.220	02	.958	.177	25	.971	.369
02	.977	.172	07	.983	.624	03	.916	.463	29	.950	.753	09	.863	.147	27	.961	.980	27	.984	.252

COL. NO. 22			COL. NO. 23			COL. NO. 24			COL. NO. 25			COL. NO. 26			COL. NO. 27			COL. NO. 28		
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
12	.051	.032	26	.051	.187	08	.015	.521	02	.039	.005	16	.026	.102	21	.050	.952	29	.042	.039
11	.068	.980	03	.053	.256	16	.068	.994	16	.061	.599	01	.033	.886	17	.085	.403	07	.105	.293
17	.089	.309	29	.100	.159	11	.118	.400	26	.068	.054	04	.088	.686	10	.141	.624	25	.115	.420
01	.091	.371	13	.102	.465	21	.124	.565	11	.073	.812	22	.090	.602	05	.154	.157	09	.126	.612
10	.100	.709	24	.110	.316	18	.153	.158	07	.123	.649	13	.114	.614	06	.164	.841	10	.205	.144
30	.121	.744	18	.114	.300	17	.190	.159	05	.126	.658	20	.136	.576	07	.197	.013	03	.210	.054
02	.166	.056	11	.123	.208	26	.192	.676	14	.161	.189	05	.138	.228	16	.215	.363	23	.234	.533
23	.179	.529	09	.138	.182	01	.237	.030	18	.166	.040	10	.216	.565	08	.222	.520	13	.266	.799
21	.187	.051	06	.194	.115	12	.283	.077	28	.248	.171	02	.233	.610	13	.269	.477	20	.305	.603
22	.205	.543	22	.234	.480	03	.286	.318	06	.255	.117	07	.278	.357	02	.288	.012	05	.372	.223
28	.230	.688	20	.274	.107	10	.317	.734	15	.261	.928	30	.405	.273	25	.333	.633	26	.385	.111
19	.243	.001	21	.331	.292	05	.337	.844	10	.301	.811	06	.421	.807	28	.348	.710	30	.422	.315
27	.267	.990	08	.346	.085	25	.441	.336	24	.363	.025	12	.426	.583	20	.362	.961	17	.453	.783
15	.283	.440	27	.382	.979	27	.469	.786	22	.378	.792	08	.471	.708	14	.511	.989	02	.460	.916
16	.352	.089	07	.387	.865	24	.473	.237	27	.379	.959	18	.473	.738	26	.540	.903	27	.461	.841
03	.377	.648	28	.411	.776	20	.475	.761	19	.420	.557	19	.510	.207	27	.587	.643	14	.483	.095
06	.397	.769	16	.444	.999	06	.557	.001	21	.467	.943	03	.512	.329	12	.603	.745	12	.507	.375
09	.409	.478	04	.515	.993	07	.610	.238	17	.494	.225	15	.640	.329	29	.619	.895	28	.509	.748
14	.465	.406	17	.518	[illegible]	09	.617	.041	09	.620	.081	09	.665	.354	23	.623	.333	21	.583	.804
13	.499	.651	05	.539	.620	13	.641	.648	30	.623	.106	14	.680	.884	22	.624	.076	22	.587	.993
04	.539	.972	02	.623	.271	22	.664	.291	03	.625	.777	26	.703	.622	18	.670	.904	16	.689	.339
18	.560	.747	30	.637	.374	04	.668	.856	08	.651	.790	29	.739	.394	11	.711	.253	06	.727	.298
26	.575	.892	14	.714	.364	19	.717	.232	12	.715	.599	25	.759	.386	01	.790	.392	04	.731	.814
29	.756	.712	15	.730	.107	02	.776	.504	23	.782	.093	24	.803	.602	04	.813	.611	08	.807	.983
20	.760	.920	19	.771	.552	29	.727	.548	20	.810	.371	27	.842	.491	19	.843	.732	15	.833	.757
05	.847	.925	23	.780	.662	14	.823	.223	01	.841	.726	21	.870	.435	03	.844	.511	19	.896	.464
25	.872	.891	10	.924	.888	23	.848	.264	29	.862	.009	28	.906	.367	30	.858	.299	18	.916	.384
24	.874	.135	12	.929	.204	30	.892	.817	25	.891	.873	23	.948	.367	09	.929	.199	01	.948	.610
08	.911	.215	01	.937	.714	28	.943	.190	04	.917	.264	11	.956	.142	24	.931	.263	11	.976	.799
07	.946	.065	25	.974	.398	15	.975	.962	13	.958	.990	17	.993	.989	15	.939	.947	24	.978	.633

SECTION XI

GUIDE SPECIFICATIONS

A. GENERAL

There are many similarities in construction methods. The methodology for evaluation of soils and binders and their optimum proportioning is an important part of the design process. The construction requirements for each type of stabilization are equally important. There are somewhat different needs for mixing, curing, etc., for each stabilizer, and these should be carefully noted.

During the design stage of a given project, the Air Force must also prepare plans, write specifications and prepare contract proposals. The Air Force must be concerned with several major aspects of the project, including:

1. General description of the project,

2. Materials to be used,

3. Special equipment that may be required,

4. Construction methods to be employed including mixing, placement, compaction and curing and

5. Quality control/quality assurance with regard to sampling, testing and method of measurement or payment.

The Air Force must also establish limits or criteria for quality. Laboratory evaluations coupled with experience and such factors as local climate and soil materials will strongly influence these criteria. Many agencies have already standardized specifications for most conventional road and air-field construction. These should be used wherever possible. Often a specification that is currently in force may be modified slightly to guide construction. Other instances, particularly when a soil stabilization procedure is new to the Air Force, will require the development of entirely new and perhaps unique specifications.

B. IMPORTANT FACTORS

The intent of this section is to illustrate the major factors to be considered in developing specifications for stabilizing pavement layers. It would be impractical to attempt complete coverage of the subject; therefore, a selection of five examples are included in Appendix A to aid the engineer in preparing his own. Those included are:

1. Lime treatment for materials in-place,

2. Lime-fly Ash-Aggregate Stabilization for Base and Subbase Courses,

3. Road-mixed Asphalt Stabilized Base and Surface Courses,

4. Travel Plant for Asphalt Base Treatment and

5. Soil Cement-Stabilized Base Courses.

Many agencies have developed specifications and special provisions for soil stabilization. A listing of some of those currently in use that may be helpful are:

1. AASHTO - Guide Specifications for Highway Construction 1968 (36),

2. U.S. Department of Transportation (FAA) 150/5370A, "Standard Specifications for Construction of Airports," 1968 (37),

3. U.S. Corps of Engineers, "Engineering and Design Manual - Soil Stabilization for Roads and Streets," 1969 (38),

4. National Lime Association, "Lime Stabilization Construction," Bulletin 326, 1972 (26),

5. The Asphalt Institute, "Asphalt Cold Mix Manual", Manual Series No. 14, 1977 (7),

6. Portland Cement Association, "Soil Cement Construction Handbook," (29); "Soil-Cement Inspector's Manual," (32),

7. Portland Cement Association, "Suggested Specifications for Soil-Cement Base Course," (39),

8. American Road and Transportation Builders Association, "Materials for Stabilization," 1977 (40),

9. Chevron, U.S.A., Inc., "Bitumuls Mix Manual," 1977 (10),

10. The Asphalt Institute, "Model Construction Specifications for Asphalt Concrete and Other Plant Mix Types," Specification Series SS-1, 1975 (41),

11. Transportation Research Board, "State of the Art: Lime Stabilization," Circular No. 180, 1976,

12. Federal Highway Administration, "Fly Ash A Highway Construction Material," Implementation Package No. 76-16, 1976 (18) and

13. Many state highway agency Standard Specifications.

SECTION XII

EXAMPLE PROBLEMS

A. GENERAL

Seven example problems are presented to illustrate the use of this manual. The example problems illustrate manual use as follows:

1. Example 1, Lime Stabilization;

2. Example 2, Portland Cement Stabilization;

3. Example 3, Portland Cement Stabilization;

4. Example 4, Lime-Fly Ash Stabilization;

5. Example 5, Asphalt Stabilization;

6. Example 6, Combination Stabilization and

7. Examply 7, Asphalt Emulsion Stabilization.

Example problems are also included in Section VIII, Thickness Design and in Appendix B, Cost and Economic Analysis.

B. EXAMPLE 1

It is desired to construct a roadway on an Air Force Base over a weak natural subgrade soil which is high in clay content. The following data were gathered:

Sieve Size	Percent Passing
No. 4	100
No. 10	100
No. 40	90
No. 60	75
No. 200	62

Atterberg Limits

Liquid limit -	55
Plastic limit -	37

CBR = 3.

Based on traffice data, AFM 88-7, Chapter 3, identifies a traffic index of 4 for this area and a total thickness of pavement above the subgrade of 21 inches. It was decided to use a 3-inch asphalt concrete surface, a 6-inch base course (CBR = 80) and a stabilized subgrade layer instead of the normally required 12-inch subbase (21 - 9 = 12).

1. Stabilizer Selection

From Section II and Figure 9, lime or a lime-cement combination are selected as the optimum stabilizers. Lime is selected in lieu of a combination of stabilizers in this case.

Section III is next used to verify the adequacy of lime as a stabilizer and to select the optimum percentage.

2. Mix Design

The procedure outlined in Section III, Paragraph D and Figure 15 is used to establish the optimum percentage of lime.

The natural soil when molded at optimum moisture and maximum dry density possesses an unconfined compressive strength (Appendix C - Section I) of 50 psi. The addition of 4 percent lime and curing increased the unconfined compressive strength to 160 psi (an increase of 110 psi). Thus, the soil is lime-reactive.

Next, specimens were molded and cured at 6, 8 and 10 percent lime in accordance with details in Figure 15. The strength increased to 450 psi at 8 percent lime and no further strength increase occurred with increase in lime content. Thus, 8 1/2 percent lime was selected for field application. The unconfined strength of 450 psi is suitable for use as a subbase according to Table 5.

3. Thickness Determination

Section VIII is a summary of the thickness design procedures employed by the Air Force for payment thickness designs using stabilized pavement layers. From Figure 49 and Section VIII, Paragraph D, we find that thickness of the lime stabilized layer required to replace the granular subgrade is 12/1.2 = 10 inches.

4. Economic Considerations

The ultimate decision of which pavement cross-section to use will probably be made based on economic factors. Appendix B - Section I is designed to aid in such decisions. One must consider not only first costs but total life cycle costs (see Section I, Paragraph E).

C. EXAMPLE 2

In this example the same soil discussed in Example 1 is to be stabilized. This time combination stabilization, lime-cement, is selected.

1. Mix Design

In accordance with paragraph 38, one to three percent lime was added to the natural soil in the laboratory and Atterberg limits obtained to identify the percentage of lime required to reduce the plasticity index to less than 30 (see Figure 45). Two percent lime was required to reduce the PI to less than 30.

Next, the proper percentage of cement is selected for stabilization of the lime-modified soil. The optimum percentage of cement was identified based on the percentage required to meet brushing weight loss criteria following cyclic freeze-thaw testing (ASTM C-593).

Specimens were prepared at 8, 10 and 12 percent cement, cured and subjected to cyclic freeze-thaw. Ten percent cement was required to meet the post twelve cyclic freeze-thaw weight loss criteria (ASTM C-593).

2. Thickness Determination

The unconfined compressive strength of the lime-cement stabilized soil tested in accordance with ASTM C-1633 is 650 psi. From Figure 49 of Section VIII, the appropriate equivalency factor is 1.5. Thus, the allowable reduction in the granular subbase thickness from Example 1 is to 12/1.5 = 8 inches of lime-cement stabilized subbase.

D. EXAMPLE 3

An Air Force Base roadway is to be built over a subgrade soil which appears primarily sandy in nature and is classified according to the unified soil classification system as SM (MIL-STD-619B). From the unified classification we know that the percent material smaller than the Number 200 sieve is between 12 and 50 percent. We also know that the plasticity of the fines plots below the A-line.

It is desired to select the best stabilizer and the optimum percentage of the stabilizer to provide proper stabilization. Figures 1 and 2 direct the reader in selecting the stabilizer and in designing the mix.

1. Stabilizer Selection

Section B describes how to select the proper stabilizer based on two parameters: percent smaller than the 200 sieve (percent - 200) and plasticity index (PI). By returning to the data used to classify the soil, the values of percent minus 200 and PI may be found. In this case these values are 30 percent and 9, respectively.

From Figure 9, cement is selected as the optimum stabilizer. Figure 2 directs the reader to proceed to Section IV, paragraph C.17. It shows that an SM soil is highly suitable for cement stabilization provided that it does not possess excessive organic or sulfate contents.

2. Mix Designs

Figure 2 guides the reader to paragraphs E of Section IV for mix design considerations.

Table 7 indicates that approximately 6 percent cement should be used to stabilize this soil. Figure 20 outlines the design procedure.

The pH test for organics and gravimetric tests for sulfates indicate that the soil is free of problem organics and sulfates.

The soil classification indicates that the soil can be treated as a sandy soil. Thus, paragraph E.7 is followed.

A gradation analysis is necessary to complete the procedure. The results are:

Percent passing No. 4 sieve	=	100
Percent passing No. 10 sieve	=	70
Percent passing No. 40 sieve	=	45
Percent passing No. 60 sieve	=	35
Percent passing No. 200 sieve	=	30
Percent smaller than 0.05 mm	=	25

Figure 21 is used to estimate average maximum density. The estimated maximum density is 122 lbs/ft^3. Next, Figure 22 yields the approximate cement content. The value obtained is 6 perc[illegible]t.

Finally, specimens are molded in accordance with Section IV, Paragraph E. The resulting unconfined compressive strength is 350 psi, above the criteria line in Figure 23.

E. EXAMPLE 4

The soil in Example 3 is to be stabilized with lime-fly ash (LFA) instead of cement. Figure 1 gives guidance in the use of the manual to assess the suitability of LFA for this particular soil and to identify the proper mixing proportions.

Section II, Paragraph B explains that LFA is a suitable stabilizer for a SM type material. Paragraph C explains the role of each constituent in the proportional mix as well as selected ASTM tests that the constituents must meet.

Section VI, Paragraph F and Figure 43 guide the user in mix proportioning and design. As a first step the suitability of the fly ash was evaluated based on its reactivity and gradation (ASTM C-593). The fly ash was deemed satisfactory. The next step was to mold specimens of aggregate and fly ash at optimum moisture content and at various percentages of fly ash. The maximum density occurred at a fly ash content of 12 percent by weight.

Next, specimens were prepared (ASTM C-593) at optimum moisture content, 12 percent fly ash and lime percentages of 2 1/2, 3, 3 1/2 and 4 percent by weight (see Figure 43). These specimens were cured and tested in accordance with ASTM C-593 and Figure 43.

The results of the strength and durability study was a mixture with 12 percent fly ash and 3 percent lime by weight.

F. EXAMPLE 5

An asphalt concrete runway is to be built to accommodate a 480-kip gross load twin gear assembly aircraft in a Type B traffic area for 15,000 passes. The subgrade is a SM material with a design CBR of 13.

A boring program was conducted and the following data obtained:

Percent passing No. 4 sieve	=	90
Percent passing No. 10 sieve	=	80
Percent passing No. 40 sieve	=	45
Percent passing No. 60 sieve	=	40
Percent passing No. 200 sieve	=	15
Liquid limit, $\omega \ell$	=	20
Plasticity Index, PI	=	9

1. Selection of Asphalt Type

Figure 1 identifies cement or asphalt as suitable stabilizers. Section V, paragraph E verifies that the SM subgrade can be adequately stabilized with asphalt (see Table 10). If cement is used under an asphalt concrete surface, shrinkage cracks in the soil cement may propagate through the asphalt concrete surface unless the percentage of cement is less than 4 percent by weight. This small percentage of cement may be inadequate to suitably stabilize the soil for structural purposes. Thus, it was elected to go with a "full-depth" asphalt concrete pavement.

Section V, paragraph C, explains the various types of asphalt available. It has been determined that in-place mixing of the soil and asphalt will be pursued in lieu of a central plant operation.

Section V, paragraph G indicates that an asphalt emulsion is the best type of asphalt for stabilization due the method of construction and ecological considerations.

The combination of asphalt and the soil is identified as a soil bitumen (Table 10). Table 13 and Figure 31 are used as a guide in selecting the type and amount of asphalt.

Table 15 indicates that a slow setting emulsion is preferred for the SM aggregate. The in-place mixing will be done with a travel plant.

The aggregate is primarily siliceous and should mix better with a cationic emulsion according to Figure 34. A CSS-1 is selected.

2. Determination of Asphalt Quantity

The estimated percentages of emulsified asphalt to be used is found from Table 18 and is 7.8 percent. This is based on the fractions passing the Numbers 200 and 10 sieves.

Mixtures were prepared at 7.8 percent emulsion content and cured in accordance with Appendix C, Section VI. These mixtures were next tested for Marshall stability, total voids in the compacted mix and percent absorbed moisture after 4-day soak (Table 26). The results were as follows:

Marshall Stability	800 pounds
Air Voids	5 percent
Stability Loss (following 4-day soak)	30 percent

Absorbed Moisture 3 percent

3. Thickness Design

AFM 88-6, Chapter 2, is used for pavement thickness design. Table 3 from that manual requires a minimum of 4 inches of surface quality asphalt concrete over 9 inches of 100-CBR base and 15 inches of subbase (30-CBR). Asphalt emulsion stabilized SM cannot be used as a base (Table 28). Thus, all bituminous concrete is substituted for the 9 inches of base: 9/1.15 = 7.8 say, 8 inches is required.

The asphalt emulsion-stabilized soil can be substituted for the 15 inches of required subbase (28 - 13 = 15 inches) using the substitution ratio of 1.5 (Table 28). Thus, the asphalt-stabilized soil thickness is 15/1.5 = 10 inches.

The pavement cross-section is

4 inches all bituminous concrete (surface)

8 inches all bituminous concrete (base)
10 inches asphalt emulsion stabilized soil (subbase)

22 inches.

4. Construction

The proper quality control and construction procedures is essential to a satisfactory product. Section X identifies control of the following factors as being essential:

a. Surface moisture content,

b. Asphalt viscosity,

c. Asphalt content,

d. Uniformity of mixing,

e. Aeration,

f. Compaction and

g. Curing.

Section XI provides general guidelines and references necessary to develop construction specifications.

Section III of Appendix A presents a guide specification for inplace stabilization of roadbed material.

G. EXAMPLE 6

The emulsion asphalt-stabilized base designed in Example 5 is suitable for the design traffic once the mix is fully cured. However, curing times can vary quite a bit based on climatic conditions. The mission of the proposed runway requires immediate high traffic service and thus rapid maximum strength gain.

To speed the development of maximum strength, cement may be added to the mix. After the optimum percentage of asphalt emulsion is added as discussed in Example 5, the effect of various percentages of cement is evaluated. Specimens of various percentages of cement and the optimum percentage of emulsified asphalt were cured for 24 hours using the procedure in Appendix C, Section VI. This represents early or initial cure. The specimens were then soaked in accordance with Appendix C, Section V, paragraph H. Diametral resilient moduli, Reference 7, values were determined at 77°F and 100°F following soaking.

A graph of the change in resilient modulus (modulus of cement-emulsion mix minus modulus of emulsion control mix) was made versus increasing percent of cement. A substantial increase in modulus occurred with the addition of 3 percent cement. Larger percentages added little to the early strength. Hence, a mixture of 3 percent cement and 7.8 percent CSS-1 was selected.

H. EXAMPLE 7

An emulsified asphalt-aggregate mixture design is required for a base course of a low traffic volume road. The base thickness required is 6 inches and is to be placed in two lifts with a conventional paver over a compacted granular subbase. A seal coat will be placed over the base course after compaction and curing.

Appendix C, Section VI, was selected to design the mix.

1. Materials

A crushed limestone aggregate and CSS-1 emulsified asphalt is considered for the product. Standard tests were conducted on the aggregate and emulsion which indicated both are within specifications.

2. Trial Residual Asphalt Content

The washed aggregate gradation shows the following:

Retained No. 4 = 55 percent,

Passing No. 4 = 37 percent and

Passing No. 200 = 8 percent.

The trial residual asphalt content is computed as follows:

$$R = 0.00138AB + 6.358 \log C - 4.685$$

$$= 0.00138 \times 55 \times 37 + 6.358 \log 8 - 4.685$$

$$= 3.90, \text{ use 4 percent.}$$

3. Coating

Coating tests were conducted, using the trial residual asphalt content and a range of mixing water contents (1 to 7 percent). Results showed the following:

Mixing Water Content	Estimated Coating (Percent)
1	90
2	90
3	85
4	80
5	75
6	60
7	35

Thus, a mixing water content up to 6 percent for this specific emulsion and aggregate will provide adequate coating.

4. Water Content

Specimens were compacted at varying water contents at compaction ranging from 2 to 6 percent (3 specimens at each water content). The specimens contained 4 percent residual asphalt content and were mixed at 2, 3, 4, 5 and 6 percent water and compacted immediately. After 24 hours of dry curing they were extruded and tested in Marshall stability at 72°F. The optimum stability occurred at a water content of 4 percent. This is within the 0-6 percent range of acceptable mixing water contents.

5. Varying Residual Asphalt Content

Specimens were compacted at varying residual asphalt contents ranging over 2, 3, 4, 5 and 6 percent (6 specimens at each content). The specimens were dry-cured for 3 days. Three specimens from each asphalt content were tested in Marshall stability, bulk density and water content. Three other samples were placed in the moisture soak test for 4 days and then tested for modified Marshall stability and moisture content. A peak stability occurred at about 4 percent.

The following plots were made:

a. Dry stability versus moisture content at compaction,

b. Dry bulk density versus residual asphalt content,

c. Modified Marshall stability (dry and soaked) versus residual asphalt content,

d. Percent absorbed moisture versus residual asphalt content,

e. Stability change (dry minus soaked) versus residual asphalt content and

f. Total voids versus residual asphalt content.

6. Selection of Optimum Residual Asphalt Content

The residual asphalt content at peak soaked stability is 4 percent. The following values of other parameters were obtained from the graphs for this content:

MIXTURE PARAMETER	VALUE AT FOUR PERCENT ASPHALT	LIMITING CRITERIA
Percent Stability Loss	5	50 max
Total Voids	7.6	2-8
Percent Moisture Absorption	2.2	4 max
Modified Marshall Stability, lbs.	1,050	500 min
Percent Aggregate Coating	80	50 min

Therefore, all of the criteria are achieved at a residual asphalt content of 4 percent.

The following mixture design and construction recommendations are obtained:

a. Residual asphalt content = 4.0 percent by weight of dry aggregate.

b. Asphalt emulsion content (for an asphalt residual of 65 percent) = $\frac{4.0}{0.65}$

= 6.1 percent by weight of dry aggregate.

c. Mixing water content = 4-6 percent by weight of dry aggregate.

d. Optimum water content at compaction = 4.0 percent by weight of dry aggregate.

In summary, an adequate emulsified asphalt-aggregate mixture will be obtained if the recommended residual asphalt content is used (4 percent), the mixing process provides at least 50 percent coating, the mix is compacted at approximately 4 percent water content to an adequate density, and the compacted layer is allowed to cure for a time sufficient to remove most of the remaining water before it is sealed or overlayed.

REFERENCES

A. LITERATURE CITED

The literature cited are listed in the sequential order of their appearance within this manual and are referred to by this numerical designation in the manual.

1. Soil Stabilization in Pavement Structures - A User's Manual, FHWA-IP-80-2, Federal Highway Administration, October, 1979.

2. Suddath, L. P. and Thompson, M. R., "Load Deflection Behavior of Lime Stabilized Layers," Technical Report M-11B, USACDE, Construction Engineering Research Laboratory, 1975.

3. State of the Art: Lime Stabilization, Transportation Research Circular Number 180, Transportation Research Board, 1976.

4. Raad, L., Monismith, C. L. and Mitchell, J. K., "Tensile Strength Determinations for Cement-Treated Materials," Transportation Research Record No. 641, pp. 7-11, 1977.

5. Soil Cement Laboratory Handbook, PCP, 1969.

6. "Mix Design Methods for Liquid Asphalt Mixtures," MISC-74-2, The Asphalt Institute, February, 1974.

7. "Asphalt Cold-Mix Manual," Manual Series No. 14 (MS-14), The Asphalt Institute, February, 1977.

8. "Mix Design Methods for Asphalt Concrete," Manual Series No. 2, The Asphalt Institute, 1974.

9. "A Basic Asphalt Emulsion Manual," FHWA-IP-79-1, Volume 1, Federal Highway Administration, January, 1979.

10. "Bituminous Mix Manual," Chevron, U.S.A., 1977.

11. Herrin, M., "Bituminous-Aggregate and Soil Stabilization," <u>Highway Engineering Handbook</u>, Section III, Editor, K. B. Woods, McGraw-Hill Book Company, 1960.

12. Santucci, L. E., "Thickness Design Procedure for Asphalt and Emulsified Asphalt Mixes," Fourth International Structural Conference on Asphalt Concrete, Ann Arbor, Michigan, August, 1977.

13. Terrel, R. L. and Wang, C. K., "Early Curing Behavior of Cement Modified Asphalt Emulsion Mixtures," Proceedings, AAPT Meeting, Vol. 40, 1971.

14. The Asphalt Institute, "Interim Guide to Full Depth Asphalt Paving Using Various Asphalts Mixes," The Asphalt Institute Pacific Coast Division, PCD-1, 1976.

15. United States Navy, "A Guide to Short-Cut Procedures for Soil Stabilization with Asphalt," U.S. Navy Civil Engineering Laboratory, Technical Note N955, 1968.

16. Mertens, E. W. and Wright, J. R., "Cationic Asphalt Emulsions: How They Differ From Conventional Emulsions in Theory and Practice," Proceedings, HRB, Vol. 38, 1959.

17. "Superintendents' Manual on Compaction of Hot Mix Asphalt Pavements," Training Aid Series 12, NAPA, 1978.

18. "Fly-Ash, A Highway Construction Manual," Implementation Package 76-16, Federal Highway Administration, June, 1976.

19. Santucci, L. E., "Thickness Design Procedure for Emulsified Asphalt Mixes," Chevron Research Company, 1976.

20. "Thickness Design - Asphalt Pavement for Highways and Streets," Manual Series No. 1 (MS-1), The Asphalt Institute, September, 1981.

21. Shell Pavement Design Manual-Asphalt Pavements and Overlays for Road Traffic, Koninklijke/Shell Laboratorium, Amsterdam, Holland, 1978.

22. "Thickness Design for Concrete Pavements," Portland Cement Association, 1966.

23. Thompson, M. R. and Figueroa, J. L., "Mechanistic Thickness Design Procedure for Soil-Lime Layers," TRR 754, 1980.

24. Chevron Layered Elastic Computer Program, Chevron U.S.A., Richmond, California, 1979.

25. ELSYM5 Layered Elastic Computer Program, University of California at Berkeley, 1979.

26. "Lime Stabilization Construction," National Lime Association, Washington, D.C., Bulletin 326, 1976.

27. Lime Stabilized Base Course, Subbase or Subgrade, Military Construction Guide Specification 02695, February, 1976.

28. Portland Cement Stabilized Base or Subbase Course for Airfields, Roads and Streets, Military Construction Guide Specifications 02694, March, 1976.

29. "Soil Cement Construction Handbook," Portland Cement Association, 1969.

30. "Lime-Fly Ash Stabilized Bases and Subbases," Synthesis No. 37, NCHRP, 1976.

31. Bituminous Stabilized Base Course, Subbase or Subgrade, Military Construction Guide Specification 02693, February, 1976.

32. Soil, Cement Inspector's Manual, Portland Cement Association, 1963.

33. "Statistically Oriented End Result Specifications," National Cooperative Highway Research Program 38, Transportation Research Board, 1976.

34. Beaton, John L., "Statistical Quality Control in Highway Construction," Journal of the Construction Division, Proceedings, ASCE, Vol. 94, No. C01, January, 1968.

35. Yoder, E. J. and Witczak, M. W., Principles of Pavement Design, John Wiley, New York, 1975.

36. "AASHTO - Guide Specifications for Highway Construction," Transportation Research Board, 1968.

37. "Standard Specifications for Construction of Airports," U.S. Department of Transportation, Federal Aviation Administration, 1968.

38. "Engineering and Design Manual - Soil Stabilization for Roads and Streets," U.S. Army Corps of Engineers, 1969.

39. "Suggested Specifications for Soil-Cement Base Course," Portland Cement Association, 1969.

40. "Materials for Stabilization," American Road and Transportation Builders Association, 1977.

41. "Model Construction Specifications for Asphalt Concrete and Other Plant Mix Types," Specification Series SS-1, The Asphalt Institute, 1975.

42. Texas Standard Specifications for Construction of Highways, Streets and Bridges, Spec. No. 261, 1982.

43. Shahin, M. Y. and Kohn, S. D., "Development of a Pavement Condition Rating Procedure for Roads, Streets and Parking Lots - Volume 1: Condition Rating Procedure," Technical Report M-268, Construction Engineering Research Laboratory, July, 1979.

44. Shanin, M. Y., Darter, M. I. and Kohn, S. D., "Development of Pavement Maintenance Management System - Volume 3, Maintenance and Repair Guidelines for Airfield Pavements," Construction Engineering Research Laboratory, 1976.

45. Epps, J. A. and Wootan, C. V., "Economic Analysis of Airport Pavement Rehabilitation Alternatives," prepared for Federal Aviation Administration and the Naval Facilities Command, October, 1981.

46. Woods, K. B., Highway Engineering Handbook, McGraw Hill Book Company, 1960.

B. ASTM BIBLIOGRAPHY

1. C-42, "Drilled Cores and Sawed Beams of Concrete, Obtaining and Testing."

2. C-88, Soundness of Aggregates by Use of Sodium or Magnisium Sulfate."

3. C-114, "Chemical Analysis of Hydraulic Cements."

4. C-117, "Materials Finer Than No. 200 Sieve in Material Aggregates by Washing."

5. C-127, "Specific Gravity and Absorption of Coarse Aggregate."

6. C-128, "Specific Gravity and Absorption of Fine Aggregate."

7. C-131, "Resistance to Abrasion of Small Size Coarse Aggregate by Use of Los Angeles Machine."

8. C-136, "Sieve Analysis of Fine and Coarse Aggregates."

9. C-150, "Specification for Portland Cement."

10. C-207, "Specification for Hydrated Lime for Masonry Purposes."

11. C-593, "Specifications for Fly Ash and Other Pozzolans for Use With Lime."

12. C-168, "Fly Ash and Raw or Calcinated Natural Pozzolans for Use in Portland Cement Concrete."

13. D-422, "Particle Size Analysis of Soil."

14. D-423, "Tests for Liquid Limit of Soils."

15. D-424, "Test for Plastic Limit and Plasticity Index of Soils."

16. D-588, "Test of Moisture-Density Relation for Soil-Cement Mixture."

17. D-599, "Wetting-Drying Tests of Compacted Soil-Cement."

18. D-560, "Freezing-Thawing Tests of Compacted Soil Cement."

19. D-698, "Moisture-Density Relations of Soils, Using a 5.5 Lb. Hammer and 12 Inch Drop."

20. D-946, "Asphalt Cement for Use in Permanent Construction."

21. D-977, "Emulsified Asphalts."

22. D-1461, "Moisture of Volatile Distillates in Bituminous Paving Mixtures."

23. D-1556, "Density of Soil-In-Place by Sand Cone Method."

24. D-1557, "Moisture Density Relations of Soils Using 10 Lb. Hammer and 18 Inch Drop."

25. D-1632, "Making and Curing Soil Cement Compression Specimens."

26. D-1633, "Compressive Strength of Molded Soil-Cement Cylinders."

27. D-2026, "Liquid Asphalt (Slow Curing)."

28. D-2027, "Liquid Asphalt (Medium Curing)."

29. D-2028, "Liquid Asphalt (Rapid Curing)."

30. D-2167, "Density of Soil In-Place by the Rubber Balloon Method."

31. D-2216, "Laboratory Determination of Moisture Content of Soil."

32. D-2397, "Specification for Cationic Emulsified Asphalt."

33. D-2922, "Density of Soil and Soil-Aggregate In-Place by Nuclear Methods."

34. D-2937, "Density of Soil In-Place by the Drive Cylinder Method."

35. D-3017, "Moisture Content of Soil and Soil-Aggregate In-Place by Nuclear Methods."

36. D-3515, "Hot-Mixed, Hot-Laid Bituminous Paving Mixtures."

37. D-3381, "Viscosity Graded Asphalt Cement for Use in Pavement Construction."

38. D-3497, "Dynamic Modulus of Asphalt Mixtures."

39. D-3551, "Laboratory Preparation of Soil-Lime Mixtures Using a Mechanical Mixer."

40. D-3688, "Bearing Ratio for Laboratory Compacted Soil Lime Mixtures."

C. AASHTO METHODS AND TEST CITED

1. M-20, "Penetration Graded Asphalt Cement."

2. M-81, "Cut-Back Asphalt (Rapid Curing)."

3. M-82, "Cut-Back Asphalt (Medium Curing)."

4. M-140, "Emulsified Asphalt."

5. M-141, "Cut-Back Asphalt (Slow Curing)."

6. M-208, "Cationic Emulsified Asphalt."

7. M-216, "Lime for Soil Stabilization."

8. M-226, "Viscosity Graded Asphalt Cement."

9. T-99, "Moisture-Density Relations of Soils, Using a 5.5 Lb. Rammer and a 12 Inch Drop."

10. T-110, "Moisture of Volatile Distillates in Bituminous Paving Mixtures."

11. T-119, "Slump of Portland Cement Concrete."

12. T-164, "Quantitative Extraction of Bitumen from Bituminous Paving Mixtures."

13. T-191, "Density of Soil In-Place by the Sand-Cone Method."

14. T-205, "Density of Soil In-Place by the Rubber Balloon Method."

15. T-238, "Density of Soil and Soil-Aggregate In-Place by Nuclear Methods."

16. T-239, "Moisture Content of Soil and Soil-Aggregate In-Place by Nuclear Methods."

D. MILITARY STANDARDS CITED

1. MIL-STD-619B, "Unified Soil Classification System for Roads, Airfields and Foundations."

2. MIL-STD-620A, "Test Methods for Bituminous Paving Materials" (Methods 100-104).

3. MIL-STD-621A, "Test Methods for Pavement Subgrades, Subbases and Base-Course Materials" (Methods 100-106).

E. AIR FORCE MANUALS CITED

1. AFM 86-2, Standard Facility Requirements.

2. AFM 86-8, Airfield and Airspace Criteria.

3. AFM 88-5, Chapter 1, Surface Drainage Facilities for Airfields and Heliports.

4. AFM 88-6, Chapter 1, General Provisions for Airfield Design.

5. AFM 88-6, Chapter 2, Airfield Flexible Pavements.

6. AFM 88-6, Chapter 3, Rigid Pavements for Airfields.

7. AFM 88-6, Chapter 4, Pavement Design for Frost Conditions.

8. AFM 88-6, Chapter 8, Standard Practice for Concrete Pavements.

9. AFM 88-6, Chapter 9, Bituminous Pavements Standard Practice.

10. AFM 88-7, Chapter 3, Flexible Pavements for Roads, Streets, Walks and Open Storage Areas.

11. AFM 88-7, Chapter 1, Rigid Pavements for Roads, Streets, Walks and Open Storage Areas.

12. AFM 88-24, Chapter 2, Flexible Airfield Pavement Evaluation.

13. AFM 88-24, Chapter 3, Rigid Pavement Evaluation.

14. AFM 88-24, Chapter 4, Pavement Evaluation for Frost Conditions.

15. AFM 89-3, Materials Testing.

16. AFM 93-5, Airfield Pavement Evaluation Program.

17. AFM 96-2, Airfield Geometric Design.

APPENDIX A

GUIDE SPECIFICATIONS

SECTION I

LIME TREATMENT FOR MATERIALS IN-PLACE

A. DESCRIPTION

This item shall consist of treating the subgrade, existing subbase or existing base by pulverizing, addition of lime, mixing and compacting the mixed material to the required density. This item applies to natural ground, embankment or existing pavement structure and shall be constructed as specified herein and in conformity with the typical sections, lines and grades as shown on the plans or as established by the Engineer.

B. MATERIALS

1. The lime shall meet the requirements of the Item, "Hydrated Lime and Lime Slurry," for the type of lime specified.

When Type B, Commercial Lime Slurry, is specified, the Contractor shall select, prior to construction, the grade to be used and shall notify the Engineer in writing before changing from one grade to another.

2. If the minimum design strength or percent of lime to be used for the treated subgrade, existing subbase or existing base is specified, it will be determined by preliminary tests performed in accordance with Test Method Tex-121-E.

C. EQUIPMENT

1. The machinery, tools and equipment necessary for proper prosecution of the work shall be on the project and approved by the Engineer prior to the beginning of construction operations.

All machinery, tools and equipment used shall be maintained in a satisfactory and workmanlike manner.

2. Hydrated lime shall be stored and handled in closed weatherproof containers until immediately before distribution on the road. If storage bins are used they shall be completely enclosed. Hydrated lime in bags shall be stored in weatherproof

---

[1] Source: Texas Standard Specifications for Construction of Highways, Streets and Bridges, Spec. No. 261, 1982 (Reference 42).

buildings with adequate protection from ground dampness.

3. If lime is furnished in trucks, each truck shall have the weight of lime certified on public scales or the Contractor shall place a set of standard platform truck scales or hopper scales at a location approved by the Engineer.

Scales shall conform to the requirements of the Item, "Weighing and Measuring Equipment."

4. If lime is furnished in bags, each bag shall bear the manufacturer's certified weight. Bags varying more than 5 percent from that weight may be rejected and the average weight of bags in any shipment, as shown by weighing 50 bags taken at random, shall not be less than the manufacturer's certified weight.

D. CONSTRUCTION METHODS

1. General

The primary requirement of this specification is to secure a completed course of treated material containing a uniform lime mixture, free from loose or segregated areas, of uniform density and moisture content, well bound for its full depth and with a smooth surface suitable for placing subsequent courses. It shall be the responsibility of the Contractor to regulate the sequence of his work, to use the proper amount of lime, maintain the work and rework the courses as necessary to meet the above requirements.

The roadbed shall be constructed and shaped to conform to the typical sections, lines and grades as shown on the plans or as established by the Engineer. The material, either before or after lime is added, shall be excavated to the secondary grade (proposed bottom of lime treatment) and removed or windrowed to expose the secondary grade. Any wet or unstable materials below the secondary grade shall be corrected, as directed by the Engineer, by scarifying, adding lime, and compactinng until it is of uniform stability.

If the Contractor elects to use a cutting and pulverizing machine that will remove the subgrade material accurately to the secondary grade and pulverize the material at the same time, he will not be required to expose the secondary grade nor windrow the material. However, the Contractor shall be required to roll the subgrade, as directed by the Engineer, before using the pulverizing machine and correct any soft areas that this rolling may reveal. This method will be permitted only where a machine is provided to insure that the material is cut uniformly to the proper depth and which has cutters that will plane the secondary grade to a smooth surface over the entire width of the cut. The machine shall be of such design that a visible indication is given at all times that the machine is cutting to the proper depth.

2. Application

Lime shall be spread only on that area where the first mixing operations can be completed during the same working day.

The application and mixing of lime with the material shall be accomplished by the methods hereinafter described as "Dry Placing" or "Slurry Placing." When Type A, Hydrated Lime, is specified, the Contractor may use either method.

a. Dry Placing. The lime shall be spread by an approved spreader or by bag distribution at the rates shown on the plans or as directed by the Engineer.

The lime shall be distributed at a uniform rate and in such manner as to reduce the scattering of lime by wind to a minimum. Line shall not be applied when wind conditions, in the opinion of the Engineer, are such that blowing lime becomes objectionable to traffic or adjacent property owners. A motor grader shall not be used to spread the lime.

The material shall be sprinkled as directed by the Engineer, until the proper moisture content has been secured.

b. Slurry Placing. The lime shall be mixed with water in trucks with approved distributors and applied as a thin water suspension or slurry. Type B, Commerical Lime Slurry, shall be applied with a lime percentage not less than that applicable for the grade used. The distribution of lime at the rates shown on the plans or as directed by the Engineer shall be attained by successive passes over a measured section of roadway until the proper moisture and lime content have been secured. The distributor truck shall be equipped with an agitator which will keep the lime and water in a uniform mixture.

3. Mixing

The mixing procedure shall be the same for "Dry Placing" or "Slurry Placing" as hereinafter described.

a. First Mixing. The material and lime shall be thoroughly mixed by approved road mixers or other approved equipment, and the mixing continued until, in the opinion of the Engineer, a homogeneous, friable mixture of material and lime is obtained, free from all clods or lumps. Materials containing plastic clays or other material which will not readily mix with lime shall be mixed as thoroughly as possible at the time of the lime application, brought to the proper moisture content and left to cure 1 to 4 days as directed by the Engineer. During the curing period the material shall be kept moist as directed.

b. Final Mixing. After the required curing time, the material shall be uniformly mixed by approved methods. If the soil binder-lime mixture contains clods, they shall be reduced in size by raking, blading, discing, harrowing, scarifying or the use of other approved pulverization methods so that when all nonslaking aggregates retained on the Number 4 sieve are removed the remainder of the material shall meet the following requirements when tested dry by laboratory sieves:

	Percent
Minimum Passing 1 3/4 inch Sieve	100
Minimum Passing Number 4 Sieve	60

During the interval of time between applications and mixing, hydrated lime that has been exposed to the open air for a period of 6 hours or more or to excessive loss due to washing or blowing will not be accepted for payment.

4. Compaction

Compaction of the mixture shall begin immediately after final mixing and in no case later than 3 calender days after mixing, unless approval is obtained from the Engineer. The material shall be aerated or sprinkled as necessary to provide the optimum moisture. Compaction shall begin at the bottom and shall continue until the entire depth of mixture is uniformly compacted by the method of compaction hereinafter specified as the "Ordinary Compaction" method or the "Density Control" method as indicated on the plans.

If the total thickness of the material to be treated cannot be mixed in one operation, the previously mixed material shall be bladed to a windrow kust beyond the area to be treated and the next layer mixed with lime. The first layer of the treated material shall be compacted in such a manner that the treated material will not be mixed with the underlying material.

When the "Ordinary Compaction" method is indicated on the plans the following provisions shall apply:

The material shall be sprinkled and rolled as directed by the Engineer. All irregularities, depressions or weak spots which develop shall be corrected immediately by scarifying the areas affected, adding or removing material as required and reshaping and recompacting by sprinkling and rolling. The surface of the course shall be maintained in a smooth condition, free from undulations and ruts, until other work is placed thereon or the work is accepted.

When the "Density Control" method of compaction is indicated on the plans the following provisions shall apply:

The course shall be sprinkled as required and compacted to the extent necessary to provide the density specified below as determined by the use of the compaction ratio method:

Description	Density, Percent
For lime-treated subgrade, existing subbase or existing base that will receive subsequent subbase or base courses.	Not less than 95 except when otherwise shown on the plans.
For lime-treated existing subbase or existing base that will receive surface courses.	Not less than 98 except when otherwise shown on the plans.

The testing will be as outlined in Test Method Tex-114-E or other approved methods. In addition to the requirements specified for density, the full depth of the material shown on the plans shall be compacted to the extent necessary to remain firm and stable under construction equipment. After each section is completed, tests as necessary will be made by the Engineer. If the material fails to meet the density requirements, it shall be reworked as necessary to meet those requirements. Throughout this entire operation the shape of the course shall be maintained by blading, and the surface upon completion shall be smooth and in conformity with the typical section shown on the plans and to the established lines and grades. Should the material due to any reason or cause, lose the required stability, density and finish before the next course is placed or the work is accepted, it shall be recompacted and refinished at the sole expense of the Contractor.

E. FINISHING, CURING AND PREPARATION FOR SURFACING

After the final layer or course of the lime treated subgrade, subbase or base has been compacted, it shall be brought to the required lines and grades in accordance with the typical sections. The completed section shall then be finished by rolling as directed with a pneumatic tire or other suitable roller sufficiently light to prevent hair cracking. The completed section shall be moist-cured for a minimum of 7 days before further courses are added or any traffic is permitted, unless otherwise directed by the Engineer. In cases where subgrade treatment or subbase sets up sufficiently to prevent objectionable damage from traffic, such layers may be opened to traffic 2 days after compaction. If the plans provide for the treated material to be sealed or covered by other courses of material, such seal or course shall be applied within 14 days after final mixing is completed, unless otherwise directed by the Engineer.

F. MEASUREMENT

Lime treatment of the subgrade, existing subbase, and existing base shall be measured by the square yard to neat lines as shown on the typical sections.

When Type A, Hydrated Lime is used, the quantity of lime will be measured by the ton of 2,000 pounds, dry weight.

When Type B, Commercial Lime Slurry is used, the quantity of lime shall be calculated from the required minimum percent solids based upon the use of Grade 1, Grade 2, or Grade 3 as follows:

Grade 1: The "Dry Solids Content" shall be at least 31 percent by weight of the slurry and the quantity of lime will be calculated by the ton of 2000 pounds based on the 31 percent, as delivered on the road.

Grade 2: The "Dry Solids Content" shall be at least 35 percent by weight of the slurry and the quantity of lime will be calculated by the ton of 2000 pounds based on the 35 percent, as delivered on the road.

Grade 3: The "Dry Solids Content" shall be at least 46 percent by weight of the slurry and the quantity of lime will be calculated by the ton of 2000 pounds based on the 46 percent, as delivered on the road.

G. PAYMENT

Work performed and materials furnished as prescribed by this item and measured as provided under "Measurement" will be paid for as follows:

Lime will be paid for at the unit price bid per ton on 2,000 pounds for "Lime" of the type specified which price shall be full compensation for furnishing all lime.

"Lime-Treated Subgrade (Ordinary Compaction)," "Lime-Treated Existing Subbase (Ordinary Compaction)," and "Lime-Treated Existing Base (Ordinary Compaction)" or "Lime Treated Subgrade (Density Control)," "Lime-Treated Existing Subbase (Density Control)" and "Lime-Treated Existing Base (Density Control)" will be paid for at the unit price bid per square yard. The unit priced bid shall be full compensation for all correction of secondary subgrade, for loosening, mixing, pulverizing, spreading, drying, application of lime, water content of the slurry, shaping and maintaining, for all manipulations required, for all hauling and freight involved, for all tools, equipment, labor, and for all incidentals necessary to complete the work except as specified below:

When "Ordinary Compaction" is indicated on the plans, all sprinkling and rolling performed as required will be measured and paid for in accordance with the provisions governing the Items of "Sprinkling" and "Rolling," respectively.

When "Density Control" is indicated on the plans, sprinkling and rolling will not be paid for directly but the cost of all sprinkling and rolling will be sibsidiary to other bid items.

APPENDIX A

SECTION II

TYPICAL SPECIFICATIONS FOR LIME-FLY ASH--AGGREGATE BASE/SUBBASE COURSES [1]

A. DESCRIPTION

This item shall consist of constructing a base course by mixing, spreading, shaping and compacting mineral aggregate, lime fly ash and water. It shall be placed on the prepared underlying course in accordance with the requirements of this specification and shall conform to the dimensions and typical cross sections shown on the plans and to the lines and grades established by the Engineer.

B. MATERIALS

1. Lime-Fly Ash Cementitious Filler Material

The lime and fly ash shall be supplied either separately or as a manufactured blend. The lime, fly ash, or blend may contain admixtures such as water-reducing agents, portland cement, or other materials that are known to provide supplementary properties to the final mix. When admixtures are to be included, they are to be used in the laboratory mixture selection process.

The lime shall meet ASTM Specification C 2-7, Type N, Sections 2 and 3(a) when sampled and tested in accordance with Sections 6 and 7. The fly ash shall meet ASTM Specification C 593, Section 3.2, when sampled and tested in accordance with Sections 4, 6 and 8. The water-soluble fraction shall not be determined. The preceding requirements may be waived if it is demonstrated that a mix of comparable quality and reliability can be produced with lime and/or fly ash that do not meet these criteria. If portland cement is blended with either lime or fly ash, or both, or added at the mixer, it shall be a standard brand and shall conform to the requirements specified in AASHTO M 85 for the type specified.

2. Water

The water for the base course shall be clean, clear, and free from injurious amounts of sewage, oil, acid, strong alka-

[1]Source: NCHRP, "Lime-Fly Ash--Stabilized Bases and Subbases," Synthesis of Highway Practice Report No. 37, 1976 (Reference 30).

lies, or vegetable matter, and it shall be free from clay or silt. If the water is of questionable quality, it shall be tested in accordance with the requirements of AASHTO T-26. Water known to be of potable quality may be used without tests.

3. Aggregate

The aggregate may be either stone, gravel, slag, or sand, crushed or uncrushed, or any combination thereof. In addition to the fine aggregate naturally contained in the coarse material, supplementary fly ash may be used as a mineral filler to provide the desired fines content.

The crushed or uncrushed mass shall consist of hard, durable particles of accepted quality (crushed if necessary to reduce the largest particles to the largest accepted size and free from an excess of flat, elongated, soft, or disintegrated pieces, or dirt or other deleterious materials.

The methods used in processing such as crushing, screening, blending, and so forth, shall be such that the finished product shall be as consistent as practicable. If necessary to meet this requirement or to eliminate an excess of fine particles, the materials shall be screened before and during processing, and all stones, rock, boulders, and other source materials of inferior quality shall be wasted.

The aggregate shall show no evidence of general disintegration nor show a total loss of more than 12 percent when subjected to five cycles of the sodium sulfate accelerated soundness test specified in AASHTO T 104; however, if an aggregate source that fails to meet this requirement can show an acceptable performance record in service, it may be accepted.

All material passing the Number 4 (4.75 mm) sieve and produced during crushing or other processing may be incorporated in the base material to the extent permitted by the gradation requirements, unless it is known to contain significant deleterious material.

A wide range of aggregate gradations are permitted with these base materials provided appropriate mixture proportion procedures are followed. If the maximum particle size in the aggregate exceeds 0.75 inch (19 mm), the aggregate shall meet the gradation requirements given in Table A-1 when tested in accordance with AASHTO T 11 and T 27.

The gradation in the table sets limits that shall determine the general suitability of the aggregate from a source of supply. The final gradations selected for use shall be within the limits designated in the table, and shall also be well graded from fine to coarse and shall not vary from high to low limits on subsequent sieves.

TABLE A-1. REQUIREMENTS FOR GRADATION OF AGGREGATE FOR THE PLANT-MIX BASE COURSE.

Sieve Designation (square openings)		Percentage by Weight Passing Sieves		
		A	B	C
2 inch	(50 mm)	100	-	-
1-1/2 inch	(38.1 mm)	-	100	-
1 inch	(25 mm)	55-85	70-95	100
3/4 inch	(19 mm)	50-80	55-85	70-100
No. 4	(4.75 mm)	40-60	40-60	40-65
No. 40	(425 μm)	10-30	10-30	15-30
No. 200	(75 μm)	5-15	5-15	5-15

TABLE A-2. BITUMINOUS CURING MATERIALS FOR LFA BASES.

Type and Grade	Specification	Application Temperature, F (C)
Curback Asphalt MC-30	AASHTO M 82	120-150 (49-65)
Emulsified Asphalt	Fed. Spec. SS-A-674	75-130 (23-54)

In addition to the gradations given in Table A-1, clean sands and sand-sized materials, such as boiler slags, can be used. Also, if the aggregate has a substantial portion (75 percent) passing the Number 4 (4.75 mm) mesh sieve the gradations in Table A-1 can be waived and the aggregate gradation adjusted with the fly ash and fines contents to produce the maximum dry density in the compacted mixture.

The portion of the base material including any blended material passing the Number 40 (425 μm) mesh sieve shall have a liquid limit of less than 25 and a plasticity index of less than 6 when tested in accordance with AASHTO T 89 and T 90.

4. Bituminous Material

The types, grades, controlling specifications and application temperatures for the bituminous materials used for curing the lime-fly ash-aggregate-treated base course are given in Table A-2. The Engineer shall designate the specific material to be used.

C. LABORATORY TESTS AND LIME-FLY ASH CONTENT

1. Lime Content

The quantity of lime (approximately 2 to 5 percent by weight) to be used with the aggregate, fly ash and water, shall be determined by tests for the materials submitted by the contractor, at his own expense, and in a manner satisfactory to the Engineer.

2. Fly Ash Content

The quantity of fly ash (approximately 9 to 15 percent by weight) to be used with the aggregate, lime and water, shall be determined by tests for the materials submitted by the contractor, at his own expense, and in a manner satisfactory to the Engineer.

3. Manufactured Blend Content

The quantity of manufactured blend to be used with the aggregate and water (and any supplemental fly ash) shall be determined by tests for the materials submitted by the contractor, at his own expense, and in a manner satisfactory to the Engineer.

4. Laboratory Tests

Specimens of the lime-fly ash-aggregate base course material shall develop a minimum compressive strength of 400 psi (2700 kPa) and demonstrate freeze-thaw resistance of a maximum of 14 percent weight loss as specified in ASTM Specifications C 593.

Section 3.2, when tested in accordance with Section 9 of that specification except that all compaction shall be done in accordance with FAA T 611, Section 2.2(a) and (b).

D. CONSTRUCTION METHODS

1. Sources of Supply

All work involved in clearing and stripping pits, including handling unsuitable material, shall be performed by the contractor. All costs involved in clearing and stripping pits, including labor, equipment and other incidentals shall be included in the price of the material. The contractor shall notify the Engineer sufficiently in advance of the opening of any designated put to permit staking of boundaries at the site, to take elevations and measurements of the ground surface before any material is produced, to permit the Engineer to take samples of the material for tests to determine its quality and gradation, and to prepare a preliminary base mixture proportion. All materials shall be obtained from approved sources.

The pits, as used, shall be opened immediately to expose vertical faces of the various strata of acceptable material and, unless otherwise directed, the material shall be secured in successive vertical cuts extending through all the exposed strata in order to secure a uniform material.

2. Equipment

All methods employed in performing the work and all equipment, tools, and other plans and machinery used for handling materials and executing any part of the work shall be subject to the approval of the Engineer before the work is started. If unsatisfactory equipment is found, it shall be changed and improved. All equipment, tools, machinery and plants must be maintained in a satisfactory working condition.

3. Preparing Underlying Course

The underlying course shall be checked and accepted by the Engineer before placing and spreading operations are started. Any ruts or soft, yielding places caused by improper drainage conditions, hauling, or any other cause, shall be corrected and rolled to the required compaction before the base course is placed thereon.

Grade control between the edges of the pavement shall be accomplished by grade stakes, steel pins, or forms placed in lanes parallel to the centerline of the runway and at intervals sufficiently close that string lines or check boards may be placed between the stakes, pins or forms.

To protect the underlying course and to ensure proper drainage, the spreading of the base shall begin along the centerline of the pavement on a crowned section or on the high side of the pavement with one-way slope.

4. Mixing

a. General Requirements. Lime-fly ash-treated base shall be mixed at a central mixing plant by either batch or continuous mixing. The capacity of the mixing plant should not be less than 50 tons per hours (45 metric tons per hour). The aggregates, lime, and fly ash may be proportioned either by weight or by volume.

In all plants, water shall be proportioned by weight or volume and there shall be means by which the Engineer may readily verify the amount of water per batch or the rate of flow for continuous mixing. The discharge of the water into the mixer shall not be started before part of the aggregates are placed into the mixer. The inside of the mixer shall be kept free from any hardened mix.

In all plants, lime and fly ash (and portland cement when used in the mix) shall be added in such a manner that they are uniformly distributed throughout the aggregates during the mixing operation.

The charge in a batch mixer, or the rate of feed into a continuous mixer shall not exceed that which will permit complete mixing of all the material. Dead areas in the mixer, in which the material does not move or is not sufficiently agitated, shall be corrected either by a reduction in the volume of material or by other adjustments.

b. Batch Mixing. In addition to the general requirements as provided in Section II, paragraph D,1, batch mixing of the materials shall conform to the following requirements:

(1) The mixer shall be equipped with a sufficient number of paddles of a type and arrangement to produce a uniformly mixed batch,

(2) The mixer platform shall be of ample size to provide safe and convenient access to the mixer and other equipment. The mixer and batch-box housing shall be provided with hinged gates of ample size to permit easy sampling of the discharge of aggregate from each of the plant bins and of the mixture from each end of the mixer.

(3) The continuous feeder for the aggregate may be mechanically driven or electrically driven. Aggregate feeders that are mechanically driven shall be directly connected with the drive on the lime feeder, and

(4) The pugmill for the continuous mixer shall be equipped with a surge hopper containing sufficient baffles and gates to prevent segregation of material discharged into the truck and to allow for closing of the hopper between trucks without requiring shutdown of the plant.

5. Placing, Spreading and Compacting

The use of mixers having a chute delivery shall not be permitted excelt as approved. In all such cases the arrangement of chutes, baffle plates, etc., shall ensure the placing of the lime-fly ash-treated base without segregation.

The prepared underlying course shall be free of all ruts or soft yielding places. The surface, if dry, shall be moistened but not to an extent that causes a muddy condition at the time the base mixture is placed.

Any dusting or surface revelling caused by traffic on the sealed base course material shall be the responsibility of the contractor and shall be taken care of as directed by the Engineer.

6. Construction Joints

The protection provided for construction joints shall permit the placing, spreading and compacting of base material without injury to the work previously laid. Care shall be exercised to ensure thorough compaction of the base material immediately adjacent to all construction joints.

7. Protection and Curing

After the base course has been finished as specified herein, it shall be protected against drying until the surface course is applied by the application of bituminous material or other acceptable methods, such as frequent light applications of water by a pressure water distributor. A double seal shall be used for the small projects where a surface course layer is not required.

The bituminous material specified shall be uniformly applied to the surface of the completed base course at the rate of approximately 0.15 gallons per square yard (0.68 liters per square meter) using approved heating and distributing equipment. The exact rate and temperature of application to give complete coverage without excessive runoff shall be as directed by the Engineer. At the time the bituminous material is applied, the surface shall be dense, free of all loose and extraneous material, and shall contain sufficient moisture to prevent penetration of the bituminous material. All surfacces shall be cleaned of all dust and unsound materials to the satisfaction of the Engineer. Cleaning shall be done with rotary brooms and/or blowing the surface with compressed air, with the surface reasonably moistened to prevent air pollution. Water shall be applied in sufficient quantity to fill the surface voids immediately before the bituminous curing material is applied.

If it becomes necessary for construction equipment or other traffic to use the bituminous-covered surface before the bituminous material has dried sufficiently to prevent pickup, sufficient granular cover shall be applied before such use.

No traffic shall be allowed on the pozzolan base course other than that developing from the operation of essential construction equipment unless otherwise directed by the Engineer. Any defects that may develop in the construction of the base course or any other damage caused by the operation of the job equipment is the responsibility of the contractor and shall be immediately repaired or replaced at no expense to the sponsor.

Other curing materials, such as moist straw or hay, may be used upon approval. Upon completion of the curing period, the straw shall be removed and disposed of as directed by the Engineer.

Trucks for transporting the mixed base material shall be provided with protective covers. The material shall be spread on the prepared underlying course to such depth that, when thoroughly compacted, it will conform to the grade and dimensions shown on the plans. No time limit is required for placing the base material; however, it is suggested that the base material be placed within several hours to avoid the necessity of replacing moisture that may be lost.

The materials shall be spread by a spreader box, self-propelled spreading machine, or other method approved by the Engineer. It shall not be placed in piles or windrows without the approval of the Engineer. If spreader boxes to other spreading machines are used that do not spread the material the full width of the lane or the width being placed in one construction operation, care shall be taken to join the previous pass with the last pass of the spreading machine. The machine shall be moved back approximately every 600 feet (180 meters) when staggered spreading machines are not used. The first pass shall not be compacted to the edge and, if necessary, the loose material shall be dampened just prior to joining the next pass. When portland cement is used in the mixture, if the temperature is 70°F (21°C) or more, the materials must be spread within four hours and reworked into the adjacent material. When portland cement is used in the mixture, and the temperature is less than 70°F (21°C), the materials must be spread within 8 hours and worked into the adjacent material. Additional moisture may be required during the reworking operations as directed by the Engineer.

The equipment and methods employed in spreading the base material shall ensure accuracy and uniformity of depth and width. If conditions arise where such uniformity in the spreading cannot be obtained, the Engineer may require additional equipment or modification in the spreading procedure to obtain satisfactory results. Spreading equipment shall be no more than 30 feet (90 meters) nor less than 9 feet (2.7 meters) in width unless approved by the Engineer.

After spreading, the material shall be thoroughly compacted by rolling. The rolling shall progress gradually from one side toward previously placed material by lapping uniformly each preceding rearwheel track by one-half the width of such track. Rolling shall continue until the entire area of the course has been rolled by the rear wheels. The rolling shall continue until the material is thoroughly compacted, the interstices of the material reduced to a minimum, and until creeping of the material ahead of the roller is no longer visible. Rolling shall continue until the base material has been compacted to not less than 97 percent density, as determined by the compaction-control tests specified in ASTM C 593. Blading and rolling shall be done alternately, as required or directed, to obtain a smooth, even, and uniformly compacted base. Finishing operations shall continue until the surface is true to the specified cross section and until the surface shows no variations of more than 0.38 inches (9.5 mm) from a 16 feet (4.9 meters) straightedge laid in any location parallel with, or at right angles to, the longitudinal axis of the pavement.

8. Cold Weather Protection

During cold weather, if the air temperature unexpectedly drops below 35°F (1°C) and remains there for a period of several days or more, the completed base course shall be protected from freezing by any approved method, if required by the Engineer, before application of the bituminous surface course. Any light surface frost caused by overnight below-freezing temperatures shall be treated by rolling the surface with a light steel-wheel roller as directed by the Engineer.

9. Thickness

The thickness of the base course shall be determined from measurements of cores drilled from the finished base or from thickness measurements at holes drilled in the base at intervals so that each test shall represent no more than 300 square yards (250 square meters). The average core thickness shall be the thickness shown on the plans, except that if any one thickness shown by the measurements made in 1 day's construction is not within the tolerance given, the Engineer shall evaluate the area and determine if, in his opinion, that section shall be reconstructed at the contractor's expense or the deficiency is to be deducted from the total material in place.

E. METHODS OF MEASUREMENTS

1. Quantity of Base

The quantity of one course, lime-fly ash-treated base, to be paid for will be determined by measurement of the number of square yards of base actually constructed and accepted by the Engineer as complying with the plans and specifications.

a. The mixer shall be equipped with a timing device that will indicate by a definite audible or visual signal the expiration of the mixing period. The device shall be accurate to within 2 seconds. The plant shall be equipped with an automatic device suitable for counting the number of batches.

b. The mixing time of a batch shall begin after all ingredients are in the mixer and shall end when the mixer is half emptied. Mixing shall continue until a homogeneous mixture of uniformly distributed and properly coated aggregates of unchanging appearance is produced. In general, the time of mixing shall be not less than 30 seconds; however, the time may be reduced when tests indicate that the requirements for lime-fly ash content and for compressive strength can be consistently met.

2. Weight Proportioning

When weight proportioning is used, the discharge gate of the weight box shall be arranged to blend the different aggregates as they enter the mixer.

3. Volumetric Proportioning

When volumetric proportioning is used for batch mixing, the volumetric proportioning device for the aggregate shall be equipped with separate bins, adjustable in size, for the various sizes of aggregates. Each bin shall have an accurately controlled gate or other device designed so that each bin shall be completely filled and accurately struck-off in measuring the volume of aggregate to be used in the mix. Means shall be provided for accurately calibrating the amount of material in each measuring bin.

4. Continuous Mixing

In addition to the general requirements as provided in Section B-4 d (1), continuous mixing of the materials shall conform to the following requirements:

a. The correct proportions of each aggregate size introduced into the mixer shall be drawn from the storage bins by a continuous feeder, which will supply the correct amount of aggregate in proportion to the lime-fly ash and will be arranged so that the proportion of each material can be separately adjusted.

The bins shall be equipped with a vibrating unit, which will effectively vibrate the side walls of the bins and prevent any "hang up" of material while the plant is operating. A positive signal system shall be provided to indicate the level of material in each bin, and as the level of material in any one bin approaches the strike-off capacity of the feed gate, the device shall automatically and instantly close down the plant. The plant shall not be permitted to operate unless this automatic signal is in good working condition.

b. The drive shaft on the aggregate feeder shall be equipped with a revolution counter accurate to 1/100 of a revolution and of sufficient capacity to register the total number of revolutions in a day's run.

F. BASIS OF PAYMENT

Payment shall be made at the contract unit price per square yard for lime-fly ash base course. This price shall be full compensation for furnishing all materials and for all preparation, manipulation, and placing of the materials and for all labor, equipment, tools and incidentals necessary to complete the item.

G. TESTING AND MATERIAL REQUIREMENTS

1. Test and Short Title:

AASHTO T 26 - Water
AASHTO T 96 - Abrasion
AASHTO T 11 and T 27 - Gradation
AASHTO T 89 - Liquid Limit
AASHTO T 90 - Plastic Limit and Plasticity Index
AASHTO T 136 - Freeze-Thaw Compressive Strength

2. Material and Short Title:

ASTM C 207 - Lime
ASTM C 593 - Fly Ash
AASHTO M 85 - Portland Cement, ASTM C 150
AASHTO M 134 - Air-Entrained Portland Cement, ASTM C 226
AASHTO M 82 - Asphalt MC, ASTM D 2027
AASHTO M 140 and M 208 - Asphalt Emulsion, ASTM D 977 and D 2397.

APPENDIX A

SECTION III

TYPICAL SPECIFICATION FOR ROAD-MIXED ASPHALT FOR BASE AND SURFACE COURSES [1]

A. GENERAL REQUIREMENTS

1. Preparation of Roadway

This type of construction may be performed either with the natural material occurring in the roadbed or by importing materials from pits or other sources.

When the material to be treated is that already in the roadbed, it shall be scarified with approved equipment to a depth 2 inches (50 mm) greater than the specified depth of pavement to be constructed and to a width 2 feet (0.6 meters) outside the proposed edge of the pavement. After the material has been scarified it shall be thoroughly mixed and processed. All foreign substances shall be removed and discarded. Any particles of aggregate or agglomerations of aggregate that will not pass a 2 inch (50 mm) square opening screen shall be removed and discarded. If needed, imported material shall be thoroughly mixed with the in-place material.

2. Equipment

As many as necessary of the following named pieces of equipment shall be used to complete the specified work: scarifiers; pulverizing equipment; rotary mixers or travel plants, motor graders; windrow devices; aggregate spreaders; power brooms or power blowers, or both; self-propelled vibratory or steel-tired tandem and pneumatic-tired rollers capable of attaining the required density; a pressure distributor designed and operated to distribute the asphaltic material in a uniform spray without atomization; equipment for heating the asphaltic material; and a water distributor. Other equipment may be used in addition to, or in lieu of, the specified equipment when approved by the Engineer.

3. Samples

Samples of all materials proposed for use shall be submitted by the contractor to the Engineer. If any portion of the in-place road materials are to be used in the construction,

---

[1] Source: The Asphalt Institute, "Asphalt Cold Mix Manual," Manual Series Number 14, 1977 (Reference 7).

the Engineer will furnish the contractor with the test results and improvement requirements, if any, for the in-place materials. Samples of all other materials proposed for use under these the specifications shall be submitted to the Engineer for test and analysis. The material shall not be used until it is approved by the Engineer.

Sampling of asphaltic materials shall be in accordance with the latest revision of AASHTO Designation T 40 (ASTM Designation D 140). Sampling of mineral aggregate shall be in accordance with the latest revision of AASHTO Designation T 2 (ASTM Designation D 75).

4. Methods of Testing

a. Asphaltic materials will be tested by the methods of test of the American Association of State Highway and Transportation Officials (AASHTO). If an AASHTO method of test is not available, the American Society for Testing and Materials (ASTM) method will be used.

b. Mineral aggregates will be tested, as designated in the detailed requirements of these specifications, by one or more of the following methods of test of the American Association of State Highway and Transportation Officials (AASHTO). If an AASHTO method of test is not available, the American Society for Testing and Materials (ASTM) method will be used.

	Method of Test	
Characteristic	AASHTO	ASTM
Sieve Analysis, Fine and Coarse Aggregates	T 27	C 136
Unit Weight of Aggregate	T 19	C 29
Sand Equivalent	T 176	D 2419
Plasticity Index of Soils	T 90	D 424

5. Weather

Asphalt shall not be applied to the aggregate when the air temperature in the shade is less than 50^{o}F (10^{o}C) unless otherwise permitted by the Engineer. Work shall be suspended during rain or when the mix is wet.

6. Traffic Control

Traffic shall be directed through the project with warning signs, flagmen and pilot trucks or cars in a manner that provides maximum safety for the workmen and traffic and the least interruption of the work.

Traffic shall be kept off of freshly sprayed asphalt or mixed materials.

If it is necessary to route traffic over the new work, speed shall be restricted to 25 miles/hr (40/km/hr) or less until rolling is completed and the asphalt mixture is firm enough to take high-speed traffic.

7. Safety

Safety precautions shall be used at all times during the progress of the work. As appropriate, workmen shall be furnished with hard hats, safety shoes, asbestos gloves, respirators, and any other safety apparel that will reduce the possibility of accidents and minimize health hazards. All Occupational Safety and Health Act requirements shall be observed.

8. Method of Measurements

The quantities, as applicable, to be paid for will be as follows:

a. Preparation of Surface. Total number of square yards (square meters) of surface actually prepared for covering by the asphalt treatment.

b. Asphaltic Materials. Total number of gallons (liters) at 60°F (15°C) or tons (tonnes) of each asphaltic material incorporated into the work.

c. Mineral Aggregate. Total number of tons (tonnes) of mineral aggregate incorporated into the work.

d. Mixing and Placing. Total number of square yards (square meters) to specified depth of road mix laid.

e. Water. Total number of gallons (liters) of water incorporated into the work.

9. Basis of Payment

The quantities described above in Section VIII will be paid for at the contract unit price bid for each item. Payment will be in full compensation for furnishing, hauling and placing materials for mixing, for rolling and for all labor and use of equipment, tools and incidentals necessary to complete the work in accordance with these specifications.

In adjusting volumes of asphaltic material to the temperature of 60°F (15°C) ASTM Designation D 1250, ASTM-IP Petroleum Measurement Tables, will be used.

B. MATERIALS

1. Asphalt Binder

The asphalt will be specified by the Engineer from the following table prior to letting the contract.

Asphalt	AASHTO Specs.	ASTM Specs.
SS-1, SS-1h	M 140	D 977
CSS-1, CSS-1h	M 208	D 2397
RC-70, RC-250, RC-800	M 81	D 2028
MC-70, MC-250, MC-800	M 82	D 2027

The Engineer will specify the temperature at which the material shall be used.

2. Mineral Aggregate

The mineral aggegate shall consist of material naturally occurring in the roadbed; material imported from local pits or other sources, with or without mineral filler; or any combination of these aggregates that will meet the following requirements:

a. Passing a 75 m (Number 200) U.S. Standard Sieve, not more than 25 percent.

b. Sand equivalent, not less than 30, or Plasticity Index, not more than 6.

C. CONSTRUCTION

1. Methods of Mixing

Where mixing of the aggregate is to be done by means other than a travel mixer, any mineral filler or other aggregate to be blended with the natural material shall be spread over the surface of the scarified material in a uniform quantity, and in such quantity as will provide a mixture meeting the requirements of Section C-2 b. Such applications shall be made immediately after the scarifying operations; mixing with a rotary-type mixer shall continue until a uniform mixture is obtained.

Where a travel mixer is to be used, the prepared in-place material shall be bladed into one or more windrows suitable for the type of travel mixer. Any additional aggregate required to be blended with the windrowed material shall be uniformly distributed over the windrows as directed by the Engineer. Windrows shall contain sufficient material to produce the required thickness of compacted pavement.

If all aggregate material is to be imported from local pits or other sources, this shall be spread on the prepared subgrade or placed in windrows (depending on the method of mixing that will be used) in quantities sufficient to produce the required pavement thickness.

2. Alternative Number 1 - Travel Mixing

a. Application of Asphalt (Alternative 1). Asphalt shall not be applied when the moisture content of the aggregate material exceeds 3 percent, unless laboratory tests indicate that a moisture content in excess of 3 percent at the time the asphalt is added will not be harmful. If the travel mixer is not equipped to measure and apply the asphalt during the mixing operation, the asphalt shall be applied directly on the measured windrows with the asphalt distributor. When the travel mixer is equipped to measure and apply the asphalt the application will be made during the mixing process.

When the travel mixer is equipped to measure and apply the asphalt, the asphalt shall be carefully heated, if needed, by means of heating coils in tanks designed to provide uniform heating of the entire contents. The contractor shall provide all necessary facilities for determining asphalt temperature during heating and prior to use, and shall take all usual precautions incidental to handling these materials.

b. Mixing Operation (Alternative 1). The aggregate material and asphalt shall be thoroughly mixed until the asphalt is uniformly distributed throughout and all aggregate particles are completely coated. The mixture shall be placed in a windrow for later spreading, aeration and compaction.

3. Alternative Number 2 - Blade Mixing

a. Application of Asphalt (Alternative 2). When the aggregate material is to be mixed with a motor grader, the windrow shall be flattened and the asphalt applied from a distributor. Asphalt shall not be applied when the moisture content of the aggregate exceeds 3 percent, unless laboratory tests indicate that a moisture content in excess of 3 percent at the time the asphalt is added will not be harmful.

The asphalt shall be applied uniformly upon the layer of aggregate material at the rate of 0.50 to 0.75 gal/yd^2 (2.3 to 3.5 liters/m^2) the specified temperature. The asphalt shall then be initially mixed into the layer. Successive applications of asphalt shall then be applied and mixed in quantities not exceeding 0.75 gal/yd^2 (3.5 liters/m^2).

b. Mixing Operation (Alternative 2). As soon as the total specified amount of asphalt is applied to the aggregate material, mixing shall be continued with motor graders until a thorough uniform mixture is produced.

4. Aeration

Regardless of the mixing method used, manipulation of the mix shall continue until volatiles or water, or both, are removed in quantity sufficient to provide a compactable mix.

When mixing and aerating are complete, the mix may be laid and compacted in accordance with Section III, paragraph D 1, or it may be placed in windrows along the edges of the area to be paved for laydown at a later time.

5. Speading and Compaction

After the material has been aerated it shall be spread to a uniform grade and cross-sectioned and compacted with a pneumatic-tired roller for the full width of the roadway. Rolling shall continue until the entire depth is compacted to the specified density. Test holes shall be dug at specified intervals to determine the compacted thickness of the layers being placed. Areas in which a deficiency of more than 13 mm (1/2 inch) compacted thickness is indicated shall be reworked with added mixed material sufficient to increase the layer to the depth specified. All irregularities that develop in the surface shall be corrected by blading while the pavement is still soft. Blading and compaction shall continue until the surface is true to grade and cross section.

6. Application of Seal Coat

Upon the thoroughly-cured asphalt course, emulsified asphalt or cutback asphalt, RS-1, RS-2, CRS-1, or CRS-2, RC-250, or RC-800, shall be applied uniformly at the rate of 0.10 to 0.15 gal/yd^2 (0.45 to 0.68 liters/m^2). The asphalt shall be covered immediately with Size Number 9 (see AASHTO Designation M 43) aggregate at the rate of 10 to 15 lb/yd^2 (5.5 to 8 kg/m^2). The procedure for this operation shall be in accordance with Specification ST-1, Asphalt Surface Treatments (MS-13), The Asphalt Institute.

D. NOTES TO THE ENGINEER

The foregoing specifications for road-mixed asphalt courses are recommended for use under average conditions. It is realized, however, that no singly standard specification will cover all variations in local conditions which may prevail for individual jobs. Before adopting these specifications verbatim, the Engineer, therefore, should give particular attention to the items listed below and, if necessary, make the changes suggested.

Asphalt-sand and asphalt-soil mixed-in-place courses are usually laid to a compacted thickness of from 3 to 6 inches (75 to 150 mm) depending upon traffic conditions. However, greater thicknesses may sometimes be advisable.

Prior to letting the contract the Engineer should select the particular asphaltic material he wishes to use, deleting the requirements for all other asphaltic materials shown in these specifications.

Asphalt-sand or soil mixes normally serve better as base courses. But in some localities, because of lack of aggregate and in the interest of economy, they may be used as surface courses.

The loose grading requirement in Section II, paragraph A-2, is included in this specification to allow the use of local sands and soils that may vary widely in grading but are still suitable for mixing with asphalt.

APPENDIX A

SECTION IV

TYPICAL SPECIFICATION FOR TRAVEL PLANT MIX BITUMULS BASE TREATMENT[1]

A. DESCRIPTION

Travel plant mix mitumuls base treatment is a cold mixed, cold laid base course mixture of mixing asphalt and suitable aggregate used for highways, streets, roads, airport runways, parking areas, storage yards and similar paved areas. The aggregate may be any noncohesive inert material meeting the specified gradation and test criteria. These base course aggregates are mixed by the travel plant and are then either laid down in a continuous windrow for spreading or are continuously spread out mechanically into a uniform, level mat. The travel plant meters and proportions the aggregate and the emulsion in a confined pug mill mixer. The travel plant may be either of two general types: one type mechanically picks up the aggregate from a prepared windrow, the other type is fed by dumping the aggregate (by dump truck) into the receiving hopper of the travel plant.

From an air quality and environmental point of view, bitumuls travel plant mixes have been very satisfactory. There is a minimum of noise, dust, smoke or fumes, generated because the paving mixture is produced from aggregates which are damp or moist and, therefore, almost dustless. The emulsified asphalt for the cold travel plant paving mixtures is not hot enough to create any objectionable odors, fumes, or smoke. For small rural or scattered projects, travel plants, such as the Moto-Paver, or the Midland Mixer-Paver, seem well adapted.

B. MATERIALS

1. Aggregate

Aggregate may be any suitable sand, blast furnace slag, coral, volcanic cinder, gravel ore tailings, crushed ledge stone or rock, or other inert mineral meeting the gradation, stability and test criteria outlined in Table A-3.

2. Asphalt

The class, type and grade of emulsified asphalt selected

---

[1]Chevron U.S.A., Inc., "Bitumuls Mix Manual," 1977 (Reference 10).

TABLE A-3. AGGREGATE SUITABLE FOR TREATMENT WITH BITUMULS EMULSIFIED ASPHALTS IN TRAVEL PLANTS.

CATEGORY	ASTM TEST METHOD	PROCESSED* DENSE GRADED AGGREGATES	POORLY GRADED	WELL GRADED	SILTY SANDS	SEMI PROCESSED CRUSHER, PIT OR BANK RUN AGGREGATES	PROCESSED COMMERCIAL AGGREGATE (1)
Gradation:							
1 1/2"	C-136	100				100	100
% Passing:							
1"		90-100				80-100	80-100
3/4"		65-90				-	-
1/2"		-	100	100	100	-	-
* 4		30-60	75-100	75-100	75-100	25-85	-
16		15-30	-	35-75	-	-	-
50		7-25	-	15-30	-	-	-
100		5-18	-	-	15-65	-	0-3
200		4-12	0-12	5-12	12-25	3-15	0-1
Sand Equivalent, %	D-2419	30 Min.	30 Min.	30 Min.	30 Min.	30 Min.	-
Plasticity Index	D-424	-	NP	NP	NP	-	-
Untreated Resistance R Value	T-190	78 Min.	60 Min.	60 Min.	60 Min.	60 Min.	-
Loss L.A. Rattler (500 Revolutions)	T-96	50 Max.	-	-	-	60 Max.	40 Max.

*Must have at least 65% by weight crushed particles.

(1) Notes:
(a) *The Processed Commercial Aggregate shown* is normally a graded aggregate with essentially no material passing the No. 200 sieve and having a nominal top size of 3/4". (For example, ASTM sizes 6, 7, or 8 or combinations of these sizes would be a suitable grading.)

(b) Normally when the graded processed commercial aggregate with substantially no material passing the No. 200 sieve is used in the travel plant, the emulsion selected will be the coarse mixing, CH-h or CM-Kh grades.

1 in. = 2.54×10^{-2} m

shall meet the requirements as specified in Table A-4.

C. REQUIREMENTS FOR THE MIXTURE

The asphalt mixture shall meet the following test criteria when tested in the laboratory:

Design Requirements

Test Property	Method of Test	Test Requirement
Moisture Pickup During Moisture Vapor Susceptibility Test, Percent	67B-307**	5.0 Max.
Resistance R_t Value $R_t = (R + 0.05\ C)$	67B-307**	
(a) For Light and Medium Traffic (DTN Under 100)*		70 Min.***
(b) For Heavy to Very Heavy Traffic (DTN Over 100)*		78 Min.***

*The Asphalt Institute Thickness Design Manual (MS-1).

**Chevron Asphalt Company Test Method.

***Should the sampled aggregate mixture fail to meet the requirements, it will be acceptable - if by the addition of an acceptable admixture the specified minimum Resistance R_t Value is developed. The admixture such as lime, cement, mineral filler, etc., should be economically available near the job site.

D. EQUIPMENT

1. Travel Plant

Travel plant shall preferably be of the twin shaft pug mill type. The travel plant continuous mixers may be one of the following types:

a. Pick-Up Type. Self-loading by pick-up from windrows measured, sized and laid out ahead on the grade.

b. Dump-Fed Type. Dump truck supplied into receiving hopper, self-propelled, equipped with spreading augers and screed strike-off mechanisms (for example, the Moto-Paver or the Midland Mixer-Paver).

TABLE A-4. CHEVRON ASPHALT COMPANY PRODUCT SPECIFICATIONS FOR BITUMULS EMULSIFIED ASPHALT MIXING GRADES*

BITUMULS CLASS				ANIONIC				CATIONIC					
BITUMULS GRADE DESIGNATION				CM-h		DM-h		CM-Kh		SM-Kh		DM-Kh	
ASTM GRADE DESIGNATION (CLOSEST)				(MS-2h)		(SS-1h)		(CMS-2h)		(CMS-2h)		(CSS-1h)	
	TEST METHOD			MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
	AASHO	ASTM	CHEVRON										
Test on Emulsion (a)													
Vis. Saybolt Furol--77°F (25°C) sec.	T-59	D244	-	-	-	-	100	-	-	-	-	-	100
Vis. Saybolt Furol--122°F (50°C) sec.	T-59	D244	-	-	500	-	-	-	500	-	500	-	-
Storage Stability Test, 1 day, %	-	D244		-	1.0	-	1.0	-	1.0	-	1.0	-	1.0
Aggr. Coating--Water Resistance Test													
Dry Std. Ref. Aggr., % coated, min.	-		C-5	80	-	-	-	80	-	-	-	-	-
Wet Std. Ref. Aggr., % coated, min.	-		C-5	60	-	-	-	60	-	-	-	-	-
Cement Mixing Test, %	T-59	D244	-	-	-	-	2.0	-	-	-	-	-	2.0
Sieve Test, %	T-59	D244	-	-	0.10	-	0.10	-	0.1	-	0.1	-	0.1
Particle Charge Test (b)	T-59	D244	-	Negative		Negative		Positive		Positive		Positive	
pH (b)	T-200	E70	-	-	-	7.3	-	-	-	-	-	-	6.7
Dehydration, ratio	-		B-15	-	-	0.5	-	-	-	-	-	0.7	-
Adhesion	-		S-4	-	-	Pass	-	-	-	-	-	Pass	-
Residue by Distillation, %	T-59	D-244		60	-	57	-	65	-	60	-	57	-
Oil distillate, vol. emulsion, %	T-59	D-244		5	15	-	-	5	15	-	20	-	-
Tests on Residue from Distillation Test													
Penetration at 77°F, 100 gm, 5 sec.	T-49	D5	-	40	100	40	100	60	110	60	150	60	110
Ductility at 77°F, cm.	T-51	D113	-	40	-	40	-	40	-	40	-	40	-
Solubility in Trichloroethylene, %	T-44	D2042	-	97	-	97	-	97	-	97	-	97	-

a) All tests shall be performed within 30 days from the date of emulsified asphalt shipment.
b) Must meet pH Test if inconclusive Particle Charge Test.
* These specification requirements may vary in different locations dependent on local construction practices, aggregates, and climatic conditions. Please check with your nearest Chevron Asphalt Company District Office for grades available in your area.

The Dump-Fed type travel plant shall be equipped with a hopper for receiving aggregate from standard dump trucks. The travel plant shall be equipped with a conveyor and aggregate metering device for maintaining a uniform regulated flow of aggregate to the mixing chamber. The travel plant shall have a twin shaft continuous type pug mill mixer with adequate power and capacity for mixing approximately 2 tons or more per minute. The machine shall have one or more emulsion tanks with a minimum total capacity of approximately 1000 gallons and shall be equipped with suitable devices (burners and flues) for heating the emulsified asphalt. There shall be a dial thermometer in the emulsion line to mixing chamber having a range of 50°F to 300°F (10°C to 150°C). The machine shall be equipped with a suitable variable capacity positive displacement pump, piping and control devices for maintaining a uniform regulated flow of asphalt mixture to the mixing chamber and suitable piping and valve arrangement to permit recirculation, loading and unloading of the mixture. There shall be a mechanical, electrical or hydraulic (or other suitable) interlock between the drive of the aggregate metering conveyor feed belt and the asphalt metering pump. It shall be equipped with a suitable variable capacity positive displacement pump, piping and control devices for maintaining a uniform regulated flow of Bitumuls Emulsified Asphalt to the mixing chamber and suitable piping and valve arrangement to permit recirculation, loading and unloading of the Bitumuls Emulsified Asphalt. There shall be a mechanical, electrical or hydraulic (or other suitable) interlock between the drive of the aggregate metering conveyor feed belt and the asphalt metering pump. It shall be equipped with adjustable width screed and with lateral spreading devices for maintaining adequate mixture directly in front of the strike-off screed. The screed shall be readily adjustable vertically. The travel plant shall be equipped with a gallons-per-minute indicator and a totalizing meter on the emulsion line to the mixing chamber. The aggregate regulating devices and the emulsion metering devices shall be so designed that the percentage of emulsion in the mix can be varied within a range of from 4 to 10 percent of the aggregate by weight.

2. Spreading Equipment

Suitable spreading equipment must be on the project for use following those travel plants (Pick-up type) which deposit the base mixture into a windrow rather than into a full width mat ready for immediate compaction. The spreading equipment must be capable of laying out the windrowed mixture to the proper uncompacted crown, cross section and profile to produce a uniform compacted thickness as specified.

3. Compaction Equipment

The compacting equipment shall be of the standard steel wheel, pneumatic tire, or vibratory steel wheel types meeting the minimum requirements of the following tables:

Roller Type	Three Wheel	Tandem	Three Axle Tandem	Trench	Vibratory Steel
Total Weight, Tons	10	8-12	12-20		5
Compression Rolls Pounds per Inch Width (Min.)	300	200	240	300	

Pneumatic Tire Rollers

Tire Size Minimum	9.00 x 20
Total Weight Minimum	8 Ton

Pneumatic tire rollers shall be self-propelled, reversible units, with vertical oscillation on all wheels on at least one axle. The tires shall be smooth tread and of equal size and diameter. The tires shall be spaced so that the entire gap between adjacent tires will be covered by the smooth tread of the following tire. The steel wheel and pneumatic tire rollers shall be in good mechanical repair and shall be equipped with water sprinkling devices for wetting the rollers. The steel wheel rollers shall be equipped with suitable loaded scrapers covering the full width of all rollers.

4. Bituminous Distributor

The bituminous pressure distributor should be of an approved type equipped with modern devices for adequate control of pumped application rates. The tank should be well insulated and equipped with suitable heating devices (burners and flues) to assure a uniform, specified, spraying viscosity and temperature. The distributor should be equipped with a fifth wheel tachometer that registers truck speed in feet per minute and a positive displacement pump techometer that registers in gallons per minute. The spray bar should be of the full circulating type with hydraulic lift and shift capabilities and be equipped with a pressure gauge. The tank should be equipped with suitable pencil or dial thermometers calibrated from 50^{o}F to 300^{o}F (10^{o}C to 150^{o}C) and a tank contents gauge with a minimum of a 10 inch (25mm) diameter dial.

E. CONSTRUCTION

1. Subgrade

Adequate drainage shall be provided to prevent undue weakening or damage to the subgrade by moisture or water. The subgrade shall be smoothed, trimmed and compacted to the required line, grade and cross section. During grading, all roots, sod and vegetation shall be removed. The finished subgrade shall be compacted to a density of not less than 90 percent of the maximum density as determined by AASHTO T 180 to a depth of at least 6 inches (150 mm).

The finished subgrade shall have the specified line, grade, cross section and density just prior to placing of the base material. Should the subgrade become rutted or disturbed in any manner, it shall be reshaped and recompacted.

If a sandy subgrade is encountered which is by nature unstable when dry, it shall be kept sufficiently damp to support equipment until covered with base mixture or subbase. Other types of subgrade shall be firm, showing no signs of damage by equipment until covered by the subbase or base mixture.

2. Subbase

Select aggregate of acceptable quality shall be furnished for construction of a subbase when required under a base course.

To be of acceptable quality the subbase material shall meet the minimum requirements of the local Highway Department; or one of the three alternates specified below:

Alternates	Test Property	Method of Test	Test Requirements
(1)	California Bearing Ration, % (CBR)	ASTM D 1883	20 Min.
(2)	Untreated Resistance R Value	AASHTO T 190	55 Min.
	Sand Equivalent, %	ASTM D 2419	25 Min.
(3)	Plasticity Index	ASTM D 424	6 Max.
	Liquid Limit, %	ASTM D 423	25 Max.

Aggregates for subbases shall be delivered to the subgrade as uniform mixtures and shall be placed in uniform layers. Segregation shall be avoided.

The subbase material shall be evenly spread, moistened or dried (as required), and compacted to full depth to not less than [illegible] percent maximum density as determined by AASHTO T 180.

The subbase shall be smoothed, trimmed and compacted so as to conform to the established line, grade and cross-section. The subbase shall be free from pockets of coarse or fine material. It may be placed in one lift providing the depth of the layer does not exceed 6 inches compacted thickness.

3. Prime Cost

A prime cost shall be required:

a. When the asphalt treated base course will be less than 3 inches (75 mm) thick and placed on a loose untreated aggregate subbase,

b. When the asphalt treated base course will be placed on dry, untreated, lean or loose, pulverized salvaged base material from the old road,

c. When the asphalt-treated base course will be placed over old deteriorated portland cement concrete slabs, and

d. When required by the Project Engineer.

4. Bituminous Material for Prime

Any suitable grade of bituminous material (such as MC-30 cutback or diluted 1:1 SS-1h or CSS-1h asphalt emulsion) shall be applied, by an approved bituminous distributor, at the rate specified by the Engineer. The prime shall penetrate and cure until the surface is free from pools and resists pick-up before proceeding with the pavement construction.

5. Bituminous Material for Tack

Existing pavements to be leveled or resurfaced shall receive a light tack coat of suitable bituminous material. The dryness, texture and porosity of the old surface shall be considered for estimating the preferred quantity of tack coat. A popular tack is SS-1h or CSS-1h diluted 1:1 with pure and applied at the rate of 01 to 0.25 gallons (0.5 to 1.2 liters^2) of the dilution per square yard; the exact amount depending on the absorptive conditions of the old pavement.

If traffic conditions through the project warrant, the tack coat may be lightly sanded to prevent hazards to traffic during construction.

6. Preparation of Aggregate for Mixing (When aggregate is hauled directly to travel plant)

When the aggregate to be mixed through the travel plant is a "one-sized" macadam type aggregate with essentially no fraction passing the Number 200 sieve (for example, ASTM Sizes

6,7 or 8) no preparation may be required if the asphalt selected is the medium setting type. When dense graded aggregate is to be used (containing minus #200 fines) and the asphalt selected for mixing is the medium setting type, the aggregate shall be pre-wetted to the optimum mixing moisture content. The optimum mixing moisture content must be maintained by spraying the stock-piled aggregate several hours before hauling to the dump-fed type travel plant.

7. Preparation of Aggregate for Mixing (When aggregate is windrowed for pick-up type travel plant).

When the aggregate to be mixed through the travel plant is to be windrowed for pick-up for the travel plant, the windrowed aggregate shall be maintained at or near optimum mixing moisture content. Water shall be added, as needed, to the windrowed aggregate by sprinkler bar truck, spray-bar distributor or hose and nozzle. The windrowed aggregate shall be maintained uniformly moist by mixing or other means as required.

The volume content of the aggregate windrow per linear foot shall not vary more than 5 percent.

Admixtures, if required, shall be throughly and uniformly blended into the aggregate windrows. The admixture shall be spread uniformly throughout the aggregate by blade mixing and other methods approved by the Engineer.

8. Travel Plant Mixing and Placement

The job should be organized in such a manner that construction traffic over freshly placed mix is avoided whenever possible and is held to an absolute minimum in all cases. Delivery of asphalt and aggregate to the travel plant shall be scheduled to hold shutdowns to an absolute minimum.

The aggregate feeding device (conveyor and adjustable metering gate) should be calibrated at several different settings in the anticipated operating range to determine the quantity fed per minute. The asphalt pump and regulating device shall be calibrated at several different settings in the expected operating range to determine the gallons per minute delivered to the mixing chamber. Throughout construction the aggregate feed rate and the asphalt feed rate shall be controlled and adjusted to maintain the specified gallons of asphalt per ton of aggregate.

The position of the spray-bar nozzles which spary asphalt into the mixing chamber should be positioned far enough forward to achieve uniform coating of the aggregate. It should not be in the extreme forward position if there is any evidence of overmixing. Temperature of the asphalt should be raised (if necessary) to assure easy and uniform pumping and delivery to the mixing chamber. In no case, however, should the temperature exceed 160°F during heating, the asphalt should be circulated and shall be maintained at a level such that the heating flues are always completely covered.

The transverse spreading devices (augers) should be operated as necessary to maintain an adequate supply of mix in front of the screed. Vertical position of the screed should be adjusted so as to provide the specified mat thickness of mix and/or maintain proper grade. The strike-off screed may ride on skis, runners or wheels.

Guide string lines should be established by the Engineer parallel to the center line of the roadway for the travel plant to follow in placing initial lanes. Longitudinal pavement edges should closely parallel these established string lines.

Any surface irregularities in the freshly placed mat should be corrected directly behind that travel plant. Excess mix material shall be removed. Low areas or torn spots should be brought to grade and smoothed with rakes or lutes.

When placing travel plant mix adjacent to a lane which already has been laid and rolled, irregularities in the existing edge should be remedied by removing excess mix or placement of additional fresh mix, as necessary. Vertical position of the screed should be controlled carefully to allow for compaction of the loose mix to required density and thickness and to insure a smooth longitudinal joint. Both transverse and longitudinal joints should be staggered in multilift jobs.

When delays or shutdowns are necessary the aggregate feed and butumuls feed should be stopped simultaneously, the pug mill should continue to operate until all of the mixture has been discharged, the travel plant machine shall move forward until all of the mixture has been spread, and the potential transverse joint should be squared and leveled. The screed shall be cleaned as often as necessary to prevent streaking or tearing of the fresh loose mat.

9. Compacting the Mixture

Compaction of the treated base material shall commence immediately after it has been spread on the subgrade or at the direction of the Engineer. Each lift of the mixture shall be compacted to at least 95 percent of the laboratory density.

Rolling shall commence at the outer edges of the base course and progress toward the center.

Breakdown andd intermediate rolling may be by pneumatic tire, vibratory steel wheel, three wheel steel wheel or tandem steel wheel roller as best suits the particular grading, type and richness of the mixture. Finish rolling shall be by tandem steel wheel, three axle tandem steel wheel or self-propelled vibratory steel wheel roller. Rolling shall continue until all ruts, roller marks and tire prints of the initial breakdown rolling are smoothed to a true cross section.

The steel wheels should be kept wet during rolling and spring loaded scraper blades shall be maintained in proper adjustment to keep the wheels clean. Sudden stops and starts and sharp turns should be avoided. Rollers should not be left standing upon the fresh mixture. Small quantities of detergent in the roller wetting water may be beneficial for preventing pick-up on the rollers.

10. Dry Choke

If a layer of travel plant mixture is subjected to traffic prior to placement of a succeeding course, it should receive a uniform application of 5 to 10 pounds per square yard (2.7 to 5.4 kg/m^2) dry choke aggregate (coarse sand or fine chips) to avoid pickup. The dry choke should be spread just after the initial rolling.

11. Secondary Rolling

After the mixture has developed sufficient mat cohesion to avoid undue displacement under the roller it may be rolled again following the normal rolling procedures.

12. Tolerance

No portion of the completed base should vary more than 1/4 inch (6 mm) from a 10-foot (3-meter) straightedge placed in any direction where the planned grade or cross section is in one plane, or from a 10-foot (3-meter) template, laid transversely and conforming with the specified crown.

13. Black Seal

It if is necessary to open the new base course or leveling course to temporary traffic before the succeeding layer (or surface course) is constructed, the cured base course may be sealed by applying 0.15 to 0.25 gallons per square yard (1.7 to 1.2 liters/m^2) of one to one (1:1) diluted asphalt emulsion grades SS-1h or CSS-1h. The application shall be allowed to cure until no pick-up occurs before traffic is permitted on the base course.

(Caution: To avoid pick-up and whip-off the base mixture should be cured throughout its depth before the seal is applied.)

F. METHODS OF MEASUREMENT

1. The amount of select aggregate furnished and placed as subbase material under Section D-5 shall be measured in cubic yards (m^2), compacted, in place, on the grade.

2. The "Bituminous Material for Prime" furnished, applied and accepted as prime coat under Section IV, paragraph F,3 shall be measured in U.S. gallons (liters) at 60°F (15°C), or in tons.

3. The "Bituminous Material for Tack" furnished, applied and accepted as Tack Coat under Section IV, paragraph F shall be measured in undiluted U.S. gallons (liters) at 60°F (15°C), or in tons.

4. The "Bituminous Emulsified Asphalt for Travel Plant Mixing" furnished and mixed through the travel plant for the base course mixture shall be measured in U.S. gallons (liters) at 60°F (15°C), or in tons.

5. The aggregate hauled to the jobsite, dumped into the receiving hopper of the travel plant or placed in sized windrows, as the case may be, shall be measured in tons to the nearest tenth of a ton, no deduction being made for moisture. Truckload net weights may be tallied for this measurement.

6. The diluted asphalt emulsion furnished and applied and used and accepted as seal on the cured base course shall be measured in undiluted U.S. gallons at 60°F (15°C) or undiluted tons (kg) to the nearest one hundredth ton (kg).

The volume measured or weighed and reported shall be the undiluted emulsion.

7. The water used for prewetting the stockpiled aggregate or the windrowed aggregate as directed will be measured in thousands of U.S. gallons (liters) either volumetrically or by weight.

8. Admixture such as hydraulic cement, hydrated lime, soil or clay, etc., if required to be blended into the aggregate either at the stockpile loading operation or in the windrows on the grade will be measured in tons to the nearest hundredth of a ton. It will be necessary to define the exact admixture material and the exact percentages to be blended if this item is required.

9. The crushed aggregate (such as ASTM Size Number 8 or Number 9 or dry coarse sand) furnished, hauled, spread, accepted and used as dry choke will be measured in tons to the nearest tenth of a ton.

G. BASIS OF PAYMENT

1. The cubic yardage of select aggregate furnished, accepted

and placed for subbase material, shall be paid for at the contract unit price per cubic yard bid for "Select Aggregate for Subbase Material."

2. The "Bituminous Material for Prime" used for prime coat furnished, accepted and used on the project shall be paid for at the contract unit price per gallon (liter) or per ton bid for "Bituminous Material for Prime."

3. The "Bituminous Material for Tack" used for Tack Coat furnished, applied and accepted shall be paid for at the contract unit per gallon (liter) or per ton bid for "Bituminous Material for Tack."

4. The "Emulsified Asphalt for Travel Plant Mixing" furnished and mixed through the travel plant for bitumuls treated base course mixture shall be paid for at the contract unit price per gallon (liter) or per ton bid for "Bitulums Emulsified Asphalt for Travel Plant Mixing" and as measured under Section IV, paragraph F, 3.

5. For the aggregate used for the asphalt-treated base mixture through the travel plant, the contractor will be paid the contract unit price per ton bid for "Aggregate for Travel Plant Mixing." This pay item will be measured in tons as specified in Section IV, paragraph F, 3 and payment will constitute full compensation for furnishing, hauling, mixing, spreading, aerating if required, and compacting the base mixture, as well as all tools, signs, barricades, flagman, traffic control, and equipment not otherwise included in pay items necessary to complete the work in a workmanlike manner according to the plans and as directed by the Engineer.

6. The emulsion used for seal on the cured base course will be paid for at the contract unit price per undiluted gallon (liter), or per undiluted ton bid for "Emulsified Asphalt for Seal."

Payment will be full compensation for diluting the emulsion, for suitable water for dilution, for heating, and application of the seal.

7. The water used for prewetting aggregate will be paid for at the contract unit price per thousand gallons (liter) bid for "Water and Prewetting Aggregate."

8. Any admixture used and accepted on the project will be paid for at the contract unit price per ton bid for "Admixture."

9. The chips for dry choke as measured under article 6.9 shall be paid for at the contract unit price bid for "Chips for Dry Choke."

H. SEASONAL AND TEMPERATURE LIMITATIONS

1. There should be no travel plant mixing operations when the ambient air temperature is below 50°F (10°C), nor when rain is imminent, or when other conditions are obviously unsuitable.

2. There should be no prime or tack coating operations when the surface temperature of the pavement is below 50°F (10°C), nor when rain is imminent.

I. LIMITATION OF WARRANTY AND LIABILITY

This specification reflects successful performance experience, and is intended to provide a guide to approved construction practices and materials. However, as workmanship, weather conditions, construction equipment, quality of other materials and other variable factors affecting results are all beyond our control, there is NO WARRANTY OF FITNESS OR MARKETABILITY, EXPRESS OR IMPLIED, THAT FOLLOWING THIS SPECIFICATION OR USING THE MATERIALS COVERED THEREBY WILL ASSURE SATISFACTORY RESULTS IN ALL CASES.

APPENDIX A

SECTION V

SUGGESTED SPECIFICATION FOR SOIL-CEMENT BASE COURSE

A. GENERAL

Soil-cement base course shall consist of soil material, portland cement and water uniformly mixed, compacted, finished and cured in accordance with these specifications. It shall conform to the lines, grades, thicknesses and typical cross section shown on the plans.

B. MATERIALS

1. Portland Cement

Portland cement shall comply with the latest specifications for portland cement (ASTM C150, CSA Standard A5, or AASHTO M85) or blended hydraulic cements (ASTM C595 or AASHTO M240, excluding slag cements Types S and SA) for the type specified.

2. Water

Water shall be free from the substances deleterious to the hardening of the soil-cement.

3. Soil Material

Soil material shall consist of the material existing in the area to be paved, of approved borrow material, or of a combination of these materials proportioned as directed. The soil shall not contain gravel or stone retained on a 2-inch sieve.

C. EQUIPMENT

Soil-cement may be constructed with any combination of machines or equipment that will produce the results meeting these specifications.

D. CONSTRUCTION METHODS

1. Preparation

Before other construction operations are begun, the area to be paved shall be graded and shaped as required to construct the soil-cement in conformance with grades, lines, thicknesses and typical cross section shown on the plans. Unsuitable soil material shall be removed and replaced with acceptable material.

The subgrade shall be firm and able to support without displacement the construction equipment and the compaction hereinafter specified. Soft or yielding subgrade shall be made stable before construction proceeds.

2. Pulverization

Before cement is applied the soil material shall be so pulverized that at the completion of moist-mixing, 100 percent by dry weight passes a 1 inch sieve, and a minimum of 80 percent passes a Number 4 sieve, exclusive of gravel or stone retained on these sieves.

3. Cement Application, Mixing and Spreading

Mixing of the soil material, cement and water shall be accomplished either by the mixed-in-place or the central-plant-mixed method.

No cement or soil-cement mixture shall be spread when the soil or subgrade is frozen or when the air temperature is less than 40^{o}F in the shade.

The percentage of moisture in the soil material, at the time of cement application, shall be the amount that assures a uniform and intimate mixture of soil material and cement during mixing operations. It shall not exceed the specified optimum moisture content for the soil-cement mixture.

The operations of cement application, water application, mixing, hauling, spreading, compacting and finishing shall be continuous and completed in daylight. The total elapsed time between the addition of water to the soil-cement mixture and the completion of finishing shall not exceed 4 hours.

Any soil-and-cement mixture that has not been compacted and finished shall not remain undisturbed for more than 30 minutes.

a. <u>Central-Plant-Mixed Method</u>. The soil material, cement and water shall be mixed at an approved central mixing plant by either continuous-flow or batch-type mixers using revolving blades, or rotary-drum mixers.

The plant shall be equipped with feeding and metering devices that will add the soil material, cement and water into the mixer in the specified quantities. Soil material and cement shall be mixed sufficiently to prevent cement balls from forming when water is added.

The mixing time shall be that which is required to secure an intimate, uniform mixture of soil material, cement and water.

Free access to the plant shall be provided to the engineer at all times for inspection of the plant's operation and for sampling of the soil-cement mixture and its components.

The mixture shall be hauled to the paving area in trucks or other equipment having clean beds. The contractor shall protect the soil-cement mixture whenever it is transported during unfavorable weather.

Haul time shall not exceed 30 minutes.

The mixture shall be placed on a moist subgrade without segregation at a quantity per linear foot that will produce a uniformly compacted base conforming to the required grade and cross section. The mixture shall be spread by either one or several approved spreaders. Not more than 30 minutes shall elapse between placement of soil-cement in adjacent lanes at any location except at longitudinal and transverse construction joints.

Compaction shall start as soon as possible after spreading and the elapsed time between the addition of water to the soil-cement mixture and the start of compaction shall not exceed 60 minutes.

b. Mixed-in-Place Method. Soil material to be mixed with cement and water in a travelling pugmill mixer shall be formed into windrows of the required size with a sizing device. The tops of windrowed soil material shall be flattened or slightly trenched to receive the cement.

The specified quantity of cement shall be spread uniformly on the area to be paved or on the top of the windrowed material. Spread cement that has been displaced shall be replaced before mixing is started.

After the cement is spread it shall be mixed with the soil material and water with a travelling pugmill, single or multiple transverse shaft mixer.

The water may be applied through the mixing machine or separately by approved pressure-distributing equipment. The soil material and cement shall be mixed sufficiently to prevent cement balls from forming when water is added. Mixing shall be continued until the mixture is uniform in color and at the required moisture content throughtout. Operations of cement spreading, water application, mixing and spreading mixed material from a windrow, if required, shall result in a uniform soil, cement and water mixture for the full depth and width.

4. Compaction

At the start of compaction, the percentage of moisture in the mixture and in unpulverized soil lumps shall not be below or more than two percentage points above the specified optimum moisture content, and shall be less than that quantity which will cause the soil-cement mixture to become unstable during compaction and finishing. The specified optimum moisture content and density shall be determined in the field by a moisture-density test, AASHTO T134 or ASTM D558, on representative samples of soil-cement mixture obtained from the area being processed at the time compaction begins.

Prior to compaction, the mixture shall be in a loose condition for its full depth. The loose mixture shall then be compacted uniformly to the specified density. During compaction operations, initial shaping may be required to obtain uniform compaction and required grade and cross section.

5. Finishing

When initial compaction is nearing completion, the surface of the soil-cement shall be shaped to the required lines, grades and cross section. The moisture content of the surface material shall be maintained at not less than its specified optimum moisture content during finishing operations.

If necessary, the surface shall be lightly scarified to remove any tire imprints or smooth surfaces left by equipment. Compaction shall then be continued until uniform and adequate density is obtained. Rolling shall be supplemented by broom-dragging if required.

The soil-cement shall be uniformly compacted to a minimum of 96 percent of maximum density.

Compaction and finishing shall be done in such a manner as to produce, in not longer than 2 hours, a smooth, dense surface free of compaction planes, cracks, ridges or loose material.

6. Curing

After the soil-cement has been finished as specified herein, it shall be protected against drying for 7 days by the application of bituminous materials. The finished soil-cement shall be kept continuously moist until the bituminous curing material is placed. The curing material shall be applied as soon as possible and not later than 24 hours after completing finishing operations.

At the time the bituminous material is applied, the soil-cement surface shall be dense, shall be free of all loose and extraneous material and shall contain sufficient moisture to prevent excessive penetration of the bituminous material.

The bituminous material specified shall be uniformly applied to the surface of the completed soil-cement at the rate of approximately 0.2 gallons per square yard with approved heating and distributing equipment. The exact rate and temperature of application for complete coverage without undue runoff will be specified by the engineer.

Should it be necessary for construction equipment or other traffic to use the bituminous-covered surface before the bituminous material has dried sufficiently to prevent pickup, sufficient granular cover shall be applied before such use.

The curing material shall be maintained by the contractor during the 7-day protection period so that all of the soil-cement will be covered effectively during the period.

Other methods of curing may be authorized by the engineers.

Finished portions of soil-cement that are travelled on by equipment used in construction an adjoining section shall be protected in such a manner as to prevent equipment from marring or damaging completed work.

Sufficient protection from freezing shall be given the soil-cement for 7 days after its construction and until it has hardened.

7. Construction Joints

At the end of each day's construction a straight transverse construction joint shall be formed by cutting back into the completed work to form a true vertical face.

Soil-cement for large, areas shall be built in a series of parallel lanes of convenient length and width meeting approval of the engineer. Straight longitudinal joints shall be formed at edge of each days's construction by cutting back into completed work to form a true vertical face free or loose or shattered material.

Special attention shall be given to joint construction to ensure a vertical joint, adequately mixed material and compaction up against the joint. On mixed-in-place construction using transverse shaft mixers, a longitudinal joint constructed adjacent to partially hardened soil-cement built the preceding day may be formed by cutting back into the previously constructed area during mixing operations. Guide stakes shall be set for cement spreading and mixing.

8. Traffic

Completed portions of soil-cement may be opened immediately to local traffic and to construction equipment provided the curing material is not impaired. The section may be opened to all traffic after the 7-day curing period, provided the soil-cement has hardened sufficiently to prevent marring or distorting of the surface by equipment of traffic.

9. Maintenance

The contractor shall be required, within the limits of his contract, to maintain the soil-cement in good condition until all work has been completed and accepted. Maintenance shall include immediate repairs of any defects that may occur. This work shall be done by the contractor at his own expense and repeated as often as necessary to keep the area continuously intact.

Faulty work shall be replaced for the full depth of treatment rather than by adding a thin layer of soil-cement to the completed work.

E. MEASUREMENT AND BASIS OF PAYMENT

1. Measurement

This work will be measured in square yards of completed and accepted soil-cement base course, or by tons of soil-cement mixture on a dry-weight basis placed in the completed and accepted soil-cement base course and in hundredweight of cement.

Unsuitable soil or material removed and the replacement material in accordance with Section E-4a will be measured in cubic yards in its original position by the method of average end areas.

2. Basis of Payment

This work will be paid for at the contract unit price per square yard of completed and accepted soil-cement base course, or at the contract unit price per ton of soil-cement mixture placed in completed and accepted soil-cement base course, and at the contract unit price per hundredweight of cement used as authorized for incorporation into the work.

Soil moved in accordance with Section E-4a, will be paid for at the contract unit price per cubic yard for common excavation.

Contract unit prices will be full payment for furnishing all materials, equipment, tools, labor and incidentals necessary to complete the work and to carry out the maintenance provisions in these specifications.

No allowance will be made for any materials used or work done outside the lines established by the engineer.

APPENDIX B

SECTION I

COST AND ECONOMIC ANALYSIS

A. GENERAL

The engineer responsible for the construction rehabilitation and maintenance of a road network is responsible for allocating his monetary resources in an optimum manner. Thus, he must decide on what portion of the pavement network he intends to construct, rehabilitate and maintain as well as what specific rehabilitation and/or maintenance action is most appropriate for a particular pavement segment. Project feasibility is determined at the network level by comparing the needs of the entire pavement system. Selection of a specific construction rehabilitation or maintenance alternative for a given project requires that a variety of alternatives be considered from an economic standpoint. The economic tools used by the Engineer to make those "network" and "project" decisions are nearly the same, with the amount of detailed information required as the major difference.

This appendix considers only the techniques suitable for selection of a construciton, rehabilitation and/or maintenance strategy for a particular project. The techniques available use the principles of engineering economy and methods of economic evaluation. Thus, cost information is required together with information concerning the life of various rehabilitation alternatives. Cost information must be projected for the life of the project, and techniques utilized to reduce these costs at various ages after reconstruction to some "common denominator." Hence, the term, "life cycle analysis," is often utilized. These "common denominator" costs can be compared and the least-cost solution selected.

B. RELATED MATERIAL

The Engineer is directed to the following publications for assistance in determining costs and analysis techniques associated with pavement construction, rehabilitation and maintenance.

1. Shahin, M. Y. and Kohn, S. D., "Development of a Pavement Condition Rating Procedure for Roads, Streets and Parking Lots - Volume 1: Condition Rating Procedure," Technical Report M-268, Construction Engineering Research Laboratory, July, 1979, (43).

2. Shahin, M. Y., Darter, M. I. and Kohn, S. D., "Development of Pavement Maintenance Management System - Volume 3, Maintenance and Repair Guidelines for Airfield Pavements,"

Construction Engineering Research Laboratory, 1976, (44).

3. Epps, J. A. and Wootan, C. V., "Economic Analysis of Airport Pavement Rehabilitation Alternatives," prepared for Federal Aviation Administration and the Naval Facilities Command, Report No. DOT/FAA/RD-81/78, October, 1981, (45).

C. COSTS

Data included in this appendix define prices associated with pavement construction, reconstruction, recycling and maintenance operations. These prices are intended to be representative only and are updated prices for 1980. If prices for these operations are available from local agencies' historical records or local contractors, they should be substituted appropriately because a large price variation can be expected depending on the location of the project and the time of construction.

The engineer should be aware that the term "pavement price" refers to the total amount of monies that an agency, or the public, must spend to have a pavement structure constructed, rehabilitated or maintained. Pavement price includes pavement cost, general contractor overhead and contractor profit. Pavement cost is defined as the amount of monies that a contractor must spend for labor, materials, equipment, subcontracts and overhead to construct, rehabilitate or maintain a pavement structure.

1. Construction Prices

Prices for common pavement construction operations are shown in Table B-1. These prices are considered representative of average in-place prices in the United States. Prices are based on pavement layers in the range of 4 to 8 inches of untreated base and stabilized layers. Asphalt concrete prices are typical of 1.5 to 3 inch lifts while portland cement concrete prices are typical for pavements 8 to 10 inches in thickness. These thicknesses are typical of those found on general aviation airports and highway pavements.

2. Rehabilitation and Pavement Recycling Prices

Prices associated with selected rehabilitation and pavement recycling operation prices are shown in Tables B-2, B-3 and B-4. The common rehabilitation activities of asphalt concrete overlays, chip seal costs, etc., can be found in Table B-2. Recycling prices are shown in Tables B-3 and B-4.

3. Maintenance Costs

Costs associated with flexible pavement maintenance operations are shown in Table B-5 and with rigid pavement maintenance operations in Table B-6. Costs were obtained from

TABLE B-1. PRICE OF COMMON PAVEMENT CONSTRUCTION OPERATIONS - 1980.

Construction Operation	Representative Price Dollars - Per Square Yard - Inch	
	Average	Range
Crushed Stone Base	0.65	0.35 - 0.85
Gravel Base	0.55	0.25 - 0.85
Lime-Stabilized Subgrade	0.35	0.20 - 0.55
Cement-Stabilized Subgrade	0.45	0.25 - 0.60
Cement-Treated Base	1.10	0.70 - 1.60
Asphalt Treated Base	1.40	0.75 - 1.90
Lime-Fly Ash-Aggregate Base	1.00	0.65 - 1.25
Chip Seal	0.60*	0.40 - 0.90*
Asphalt Concrete	1.65	0.90 - 2.50
Portland Cement Concrete	1.85	1.00 - 2.75

*Price per square yard of surface.

TABLE B-2. PRICE OF PAVEMENT REHABILITATION OPERATIONS - 1980.

Rehabilitation Operation	Approximate Thickness, Inch	Representative Price Dollars - Per Square Yard	
		Average	Range
Chip Seal Coat	1/2	0.60	0.40 - 0.90
Fabric Interlayers	1/4	1.20	0.75 - 1.75
Asphalt-Rubber Interlayer	1/2	1.25	0.90 - 1.50
Open Graded Friction Course	5/8	1.50	1.00 - 2.50
Asphalt Concrete (Dense-Graded)	1	1.65	0.90 - 2.50
Asphalt Concrete (Dense-Graded)	2	3.15	1.80 - 4.75
Asphalt Concrete (Dense-Graded)	3	4.75	2.60 - 7.00

TABLE B-3. PRICE OF COMMON RECYCLING OPERATIONS - 1980.

Recycling Operations	Representative Price Dollars - Per Square Yard - Inch*	
	Average	Range
Heat and Plane Pavement - 3/4 inch depth	0.40	0.20 - 0.70
Heat and Scarify Pavement - 3/4 inch depth	0.50	0.20 - 0.90
Cold Mill Pavement	0.85	0.30 - 1.25
Rip, Pulverize and Compact - Existing Pavement less than 5 inches of Asphalt Concrete	0.30	0.20 - 0.50
Rip, Pulverize, Stabilize and Compact - Existing Pavement less than 5 inches of Asphalt Concrete	0.50	0.25 - 0.70
Rip, Pulverize and Compact - Existing Pavement greater than 5 inches of Asphalt Concrete	0.35	0.15 - 0.50
Rip, Pulverize, Stabilize and Compact - Existing Pavement greater than 5 inches of Asphalt Concrete	0.55	0.30 - 1.00
Remove and Crush Portland Cement Concrete	0.70	0.40 - 1.10
Remove and Crush Asphalt Concrete	0.50	0.25 - 1.00
Cold Process - Remove, Crush, Place, Compact, Traffic Control - (Cold Process) without Stabilizer	0.55	0.30 - 0.90
Cold Process - Remove, Crush, Mix, Place, Compact, Traffic Control - (Cold Process) with Stabilizer	0.65	0.40 1.00
Hot Process - Remove, Crush, Place, Compact, Traffic Control - without Stabilizer	0.80	0.50 - 1.40
Hot Process - Remove, Crush, Mix, Place, Compact, Traffic Control - with Stabilizer	1.10	0.75 - 1.65

*Costs are for a square yard inch except where listed.

TABLE B-4. REPRESENTATIVE PRICE FOR ASPHALT PAVEMENT RECYCLING OPERATIONS - 1980.

Type	Operation	Option or Expected Results		Representative Price Per Square Yard: Average	Representative Price Per Square Yard: Range	Assumptions
A. Surface	Heater Planer	Without additional aggregate	A1	0.40	0.35 - 0.90	Heat, plane, clean-up, haul, traffic control.
		With additional aggregate	A2	0.55	0.30 - 0.80	Spread aggregate, heat, roll, traffic control and clean-up.
	Heater Scarify	Heater scarify only	A3	0.40	0.25 - 0.90	Heat, scarify, recompact, traffic control (3/4 inch scarification).
		Heater scarify plus thin overlay of asphalt concrete	A4	1.25	0.80 - 1.50	Heat, scarify, recompact, add 50 lbs. of asphalt concrete per square yard, compact, traffic control (3/4 inch scarification).
		Heater scarify plus chip seal or slurry seal	A5	1.00	0.60 - 1.50	Heat, scarify, recompact, place slurry seal or chip seal and traffic control (3/4 inch scarification).
		Heater scarify plus thick overlay	A6	5.00	3.00 - 6.50	Heat, scarify, recompact, add 300 lbs. of asphalt concrete per square yard, compact, traffic control (3/4 inch scarification).
	Surface Milling or Grinding	Surface milling only	A7	0.85	0.30 - 1.50	Milling, cleaning, hauling, traffic control (one inch removal).
		Surface milling plus thin overlay	A8	4.00	2.50 - 5.00	Milling, cleaning, hauling, 200 lbs. of asphalt concrete, traffic control (one inch removal).
		Surface milling plus thick overlay	A9	6.85	4.25 - 8.00	Milling, cleaning, hauling, 400 lbs. of asphalt concrete, traffic control (one inch removal).

TABLE B-4. REPRESENTATIVE PRICE FOR ASPHALT PAVEMENT RECYCLING OPERATIONS - 1980 (CONTINUED).

Type	Operation	Option or Expected Results		Representative Price Per Square Yard: Average	Representative Price Per Square Yard: Range	Assumptions
B. In-Place	Asphalt Concrete Surface Less Than 5 Inches	Minor structural improvement without new binder	B1	4.40	2.50 - 6.00	Rip, pulverize and remix to 4 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	B2	3.65	2.10 - 4.10	Rip, pulverize and remix with stabilizer to 4 inch depth with 1 inch of asphalt concrete, traffic control.
		Major structural improvement	B3	8.10	5.00 - 10.00	Rip, pulverize and remix to 6 inch depth with 4 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	B4	6.25	4.00 - 8.00	Rip, pulverize and remix with stabilizer to 6 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement without new binder	B5	3.50	2.50 - 4.50	Rip, pulverize and remix to 4 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	B6	3.80	2.50 - 4.75	Rip, pulverize and remix with stabilizer to 4 inch depth with 1 inch of asphalt concrete, traffic control.
		Major structural improvement without new binder	B7	6.25	5.00 - 7.50	Rip, pulverize and remix to 6 inch depth with 4 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	B8	6.40	5.00 - 7.50	Rip, pulverize and remix with stabilizer to 6 inch depth with 2 inches of asphalt concrete, traffic control.

TABLE B-4. REPRESENTATIVE PRICE FOR ASPHALT PAVEMENT RECYCLING OPERATIONS - 1980 (CONCLUDED).

Type	Operation	Option or Expected Results		Representative Price Per Square Yard		Assumptions
				Average	Range	
C. Central Plant	Cold Mix Process	Minor structural improvement without new binder	C1	4.60	4.00 - 5.25	Remove, crush and replace to 4 inch depth with 2 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	C2	3.90	2.75 - 5.00	Remove, crush, mix and replace to 4 inch depth with 1 inch of asphalt concrete, traffic control.
		Major structural improvement without new binder	C3	8.00	6.00 - 10.00	Remove, crush and replace to 6 inch depth with 4 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	C4	6.50	5.00 - 8.00	Remove, crush, mix and replace to 6 inch depth with 2 inches of asphalt concrete, traffic control.
	Hot Mix Process	Minor structural improvement without new binder	C5	6.25	5.00 - 8.00	Remove, crush and replace to 4 inch depth with 1.5 inches of asphalt concrete, traffic control.
		Minor structural improvement with new binder	C6	6.20	5.00 - 8.00	Remove, crush, mix and replace to 4 inch depth with 1/2 inch of asphalt concrete, traffic control.
		Major structural improvement without new binder	C7	8.75	7.00 - 10.00	Remove, crush and replace to 6 inch depth with 3 inches of asphalt concrete, traffic control.
		Major structural improvement with new binder	C8	10.00	8.00 - 12.00	Remove, crush, mix and replace to 6 inch depth with 1 inch of asphalt concrete.

the states of California, Florida, Iowa, Louisiana, Nevada, New Jersey and North Dakota and are representative of costs in 1980.

A general description for each maintenance activity has been prepared and is shown in the tables together with the average, low and high unit costs for these activities. The reported suggested costs are the author's best estimate of representative unit costs for the stated maintenance activity. The wide range of reported unit costs for this condensed list of activities is due in part to:

a. Different crew sizes utilized in the various areas,

b. Different equipment requirements for various areas,

c. Differences in maintenance work activity as defined by various agencies,

d. Variety of traffic conditions under which maintenance is performed,

e. Type of facility on which maintenance activities are performed and

f. Amount of work performed per square yard or other unit of measurement.

Maintenance unit cost information has been converted to costs per square yard of total pavement surface area treated (Table B-7). To develop these costs, assumptions were made as to the thickness and extent of the area treated. Costs associated with maintenance activities of different thicknesses and extent can be calculated from Tables B-5 and B-6.

The summary of maintenance information contained in the previous tables is for 11 flexible and five rigid highway pavement activities. Costs representative of airport pavement maintenance operations are not available in summary form. As a first approximation, highway maintenance costs can be used to represent airport maintenances costs. If there is a need for determining maintenance costs for activities other than those listed in Tables B-5, B-6 and B-7, it will be necessary to obtain data from local state, county or city governments or contractors that perform those activities.

4. Airport Versus Highway Prices

Price data reported in this manual are based primarily on information obtained from highway construction projects. Highway prices and costs are readily available to the engineer in summary form. Price data for airport construction, rehabilitation, recycling and maintenance operations are not available in summary form. Bid tabulation forms from 25 airport reconstruction and

TABLE B-5. UNIT COSTS FOR FLEXIBLE PAVEMENT MAINTENANCE OPERATIONS - 1980.

Descriptive Title	General Description	State	Reported Average Unit Cost, Dollars	Suggested Cost, Dollars				Adjusted Average Unit Cost, Dollars
				Average	Low	High	Unit Measured	
Fog Seal - Full Width	Light application of diluted emulsion or a proprietary material over a full lane width in a continuous section.	CAL	126.35/ton	0.12	0.06	0.21	yd^2	$0.063/yd^2$
		NEV	$0.08/yd^2$					$0.08/yd^2$
		MD	$0.21/yd^2$					$0.21/yd^2$
Chip Seal - Partial Width	Application of asphalt and cover aggregate to a limited area.	CAL	36.15/ton	0.47	0.24	1.91	yd^2	$0.45/yd^2$
		CAL	46.41/ton					$0.57/yd^2$
		CAL	48.93/ton					$0.61/yd^2$
		CAL	47.73/ton					$0.59/yd^2$
		CAL	153.98/ton					$1.91/yd^2$
		LA	$48.86/yd^2$					$0.41/yd^2$
		NEV	$0.24/yd^2$					$0.24/yd^2$
		MD	$0.42/yd^2$					$0.42/yd^2$
Chip Seal - Full Width	Application of asphalt and cover aggregate to a full lane width in a continuous section.	CAL	45.74/ton	0.40	0.23	0.57	yd^2	$0.57/yd^2$
		IWA	$0.45/yd^2$					$0.45/yd^2$
		LA	3179/mile					$0.23/yd^2$
		NEV	$0.31/yd^2$					$0.31/yd^2$
		MD	$0.44/yd^2$					$0.44/yd^2$
Surface Patch - Hand Method Pothole Type	Application of a premix to fill small depressions.	CAL	142.59/ton	250.00	144.00	343.00	yd^3	$269.50/yd^2$
		FLA	181.67/ton					$343.35/yd^3$
		LA	76.33/ton					$144.25/yd^3$
Surface Patch - Hand Method	Application of a premix material to the surface of the pavement by hand method	FLA	65.39/ton	150.00	90.45	295.60	yd^3	$123.60/yd^3$
		LA	47.86/ton					$90.45/yd^3$
		LA	54.71/ton					$103.40/yd^3$
		NEV	$156.39/yd^3$					$295.60/yd^3$

TABLE B-5. UNIT COSTS FOR FLEXIBLE PAVEMENT MAINTENANCE OPERATIONS - 1980 (CONTINUED).

Descriptive Title	General Description	State	Reported Average Unit Cost, Dollars	Suggested Cost, Dollars: Average	Low	High	Unit Measured	Adjusted Average Unit Cost, Dollars
Surface Patch - Machine Method	Application of a premix material to the surface of the pavement with machine	CAL	49.16/ton					92.90/yd^3
		CAL	34.97/ton					66.10/yd^3
		CAL	23.41/ton					44.25/yd^3
		CAL	30.20/ton					57.10/yd^3
		CAL	29.16/ton					55.10/yd^3
		FLA	60.48/ton	60.00	30.27	114.20	yd^3	114.30/yd^3
		IA	20.05/ton					37.90/yd^3
		LA	32.82/ton					62.00/yd^2
		NEV	30.27/yd^3					30.27/yd^3
		NJ	25.25/ton					47.70/yd^3
		MD	35.28/yd^3					35.28/yd^3
Digout and Repair - Hand Method	Removal and repair of limited areas by use of hand tools.	CAL	130.75/ton					238.30/yd^3
		FLA	60.11/ton	160.00	109.55	238.30	yd^3	109.50/yd^3
		MD	127.52/yd^3					127.52/yd^3
Digout and Repair - Machine Method	Removal and repair of limited areas by use of mechanized equipment.	CAL	44.94/ton					81.90/yd^3
		CAL	40.81/ton					74.40/yd^3
		FLA	60.11/ton					109.55/yd^3
		LA	31.41/yd^3	90.00	26.11	151.05	yd^3	31.41/yd^3
		NEV	26.11/yd^3					26.11/yd^3
		NJ	77.41/ton					141.10/yd^3
		NJ	82.89/ton					151.05/yd^3
Crack Pouring	Pouring cracks in flexible pavement with asphalt material (may include cleaning with compressed air and covering with sand).	CAL	6.71/gal					6.71/gal
		CAL	10.03/gal	6.25	2.37	10.03	gal	10.03/gal
		NEV	0.73/lb					6.10/gal
		NJ	314.91/ln/mi					6.00/gal
		MD	2.37/gal					2.37/gal

TABLE B-5. UNIT COSTS FOR FLEXIBLE PAVEMENT MAINTENANCE OPERATIONS - 1980 (CONCLUDED).

Descriptive Title	General Description	State	Reported Average Unit Cost, Dollars	Suggested Cost, Dollars				Adjusted Average Unit Cost, Dollars
				Average	Low	High	Unit Measured	
Slurry Seal	Sealing the roadway with a mixture of emulsion, cement and aggregate and placed by machine.	IA	0.24/yd^3	0.25			yd^2	0.24/yd^2
Heater Planing	Heating and planing the surface to remove lumps, ripples, wheel ruts, etc.	IA LA NEV	0.90/yd^2 34.60 each 0.28/yd^2	0.70	0.28	0.90	yd^2	0.90/yd^2 0.85/yd^2 0.28/yd^2

TABLE B-6. UNIT COSTS FOR RIGID PAVEMENT MAINTENANCE OPERATIONS - 1980.

Descriptive Title	General Description	State	Reported Average Unit Cost, Dollars	Suggested Cost, Dollars				Adjusted Average Unit Cost, Dollars
				Average	Low	High	Unit Measured	
Mudjacking	Drilling and pumping concrete slurry under slab to fill the voids and raise the slab to grade.	CAL	370.50/yd^2					370.50/yd^2
		FLA	255.13/Slab	6.00	4.00	370.50	yd^2	8.70/yd^2
		FLA	144/ft^3					-
		IA	82.23/yd^3					-
		NJ	117.73/Slab					4.00/yd^2
Temporary Patching	Patch with bituminous material	CAL	172.26/ton					325.55/yd^3
		CAL	38.23/ton	180.00	72.25	325.55	yd^3	72.25/yd^3
		IA	126.77/ton					239.60/yd^3
		IA	78.72/ton					148.80/yd^3
		NEV	123.44/yd^3					123.45/yd^3
Permanent Patching	Patch with P.C.C.	IA	33.54/yd^2					123.15/yd^3
		NEV	402.24/yd^3	270.00	134.15	402.24	yd^3	402.24/yd^3
Joint Sealing	Cleaning joint, pour joint and apply sand as required.	CAL	7.91/gal					7.91/gal
		CAL	6.50/gal					6.50/gal
		FLA	318.00/mile	7.50	3.06	12.40	gal	-
		IA	3.05/gal					3.06/gal
		NEV	1.49/lb					12.40/gal
		NJ	167.61/unit					-
Expansion Joint Repair	Cut along distressed area, clean out area, place filler material.	NEV	23.91/lin ft	24.00			lin ft	23.81/lin ft

TABLE B-7. REPRESENTATIVE COSTS FOR FLEXIBLE PAVEMENT MAINTENANCE AND REHABILITATION ACTIVITIES - 1980.

Maintenance Activity	Cost Dollars* Per		Cost Dollars Per Square Yard of Maintenance Performed	Total Pavement Area Treated
	Square Yard	Lane Mile		
Fog Seal - Partial Width	0.09	640	0.18	50 percent
Fog Seal - Full Width	0.12	845	0.12	100 percent
Chip Seal - Partial Width	0.07	500	0.47	15 percent
Chip Seal - Full Width	0.40	2,820	0.40	100 percent
Surface Patch - Hand Method Pothole Type	0.14	1,000	13.90	100 percent 2 inch thick
Surface Patch - Hand Method	0.10	730	4.20	2.5 percent 1 inch thick
Surface Patch - Machine Method	0.17	1,170	1.70	10 percent 1 inch thick
Digout and Repair - Hand Method	0.36	2,500	17.80	2 percent 4 miles thick
Digout and Repair - Machine Method	0.75	5,280	15.00	5 percent 6 inch thick
Crack Pouring	0.23	1,630	-	250 lin ft per station

*Costs are for square yards of total pavement surface maintained. For example, surface patching by the hand method may have been applied over only 5 percent of total pavement surface area, yet costs reported are for the total pavement.

rehabilitation projects have been obtained however, and are summarized in Table B-8. The variability in prices associated with highway and airport projects is so large when defining national average prices that, in all probability, a statistically significant difference could not be ascertained between prices for these two types of pavements.

5. Price Updating Procedures

As price information is obtained from various sources at various times, it is necessary to bring these prices to a common time frame. In order to convert price figures contained in this manual to a current date, the price or cost index method is suggested. The following equation can be used.

$$C_c = C_o \left(\frac{I_c}{I_o} \right)$$

where C_c = Current estimated cost,

C_o = Cost at other time "O",

I_c = Current index number and

I_o = Index number at other time "O".

The index number to use depends upon the type of cost being estimated. Four indices are commonly available and can be used.

a. The ENR Construction Cost Index,

b. Bid Price Trends on Federal-Air Highway Contracts,

c. The ENR Equipment Price Index and

d. The Cost Trends on Highway Maintenance and Operations.

The ENR Construction Cost Index was designed as a general purpose construction cost index to chart basic costs with time. It is a weighed index of constant quantities of structural steel, portland cements, lumber and common labor, valued at $100 in 1913.

The Bid Price Trends on Federal-Aid Highway Contracts is compiled by the Federal Highway Administration as reported by state transportation agencies. The base year for this index is 1967.

The ENR Equipment Price Index is compiled from Bureau of Labor statistics and is published periodically by Engineering News Record (for a base year of 1967).

TABLE B-8. SUMMARY OF SELECTED 1980 FAA BID PRICES.

Description	Unit	Price, Dollars Low	High	Representative	No. of Projects
Pavement Milling 0-1.5"	yd^2	2.50	14.00	3.00	3
Pavement Pulverization	yd^2	0.80	1.25	1.00	2
Removal of AC Pavement	yd^2	0.50	4.60	2.00	5
Removal of PCC Pavement	yd^2	1.90	7.50	4.00	4
Removal of Pavement	yd^2	0.35	4.75	2.00	3
Subbase Course	yd^2-in	0.10	0.57		2
Lime Treated Subgrade	yd^2-in	0.32	0.45	0.40	3
Bituminous Base Course	yd^2-in	1.53	2.47	2.05	6
Aggregate Base Course	yd^2-in	0.31	0.56	0.42	9
Lime Rock Base Course	yd^2-in	0.31	0.93	0.55	12
Shell Base Course	yd^2-in			0.70	1
Sand/Clay Base Course	yd^2-in			0.32	1
Soil Cement Base	yd^2-in	0.45	0.53	0.50	3
Cement Treated Base	yd^2-in			1.45	1

TABLE B-8. SUMMARY OF SELECTED 1980 FAA BID PRICES (CONCLUDED).

Description	Unit	Price, Dollars			No. of Projects
		Low	High	Representative	
Asphalt Concrete Surface	yd^2-in	1.20	2.64	1.70	22
Recycled Asphalt Concrete	yd^2-in			1.35	1
PCC Pavement - Non-Reinforced	yd^2-in	1.58	2.64	2.00	7
PCC Pavement - Reinforced	yd^2-in	2.22	3.67	3.00	4
Bituminous Prime Coat	yd^2	0.16	0.69	0.22	13
Bituminous Tack Coat	yd^2	0.04	0.14	0.06	13
Chip Seal	yd^2	0.85	3.95	1.10	6
Slurry Seal	yd^2	1.05	2.00	1.25	2
Fabric Interlayers	yd^2	1.00	2.25	1.50	3

The Cost Trends for Highway Maintenance and Operations are available from the Federal Highway Administration. Index summary information can be found in Reference 46.

D. ECONOMIC ANALYSIS METHOD

A review of the literature suggests that the best method for measuring economic worth for pavement rehabilitation alternatives is that of present worth (present value). The present worth of construction, rehabilitation and maintenance strategies is the amount of money that must be available to pay for the immediate construction or rehabilitation that is scheduled and the anticipated future rehabilitation and maintenance operations.

Before the present worth of rehabilitation and maintenance can be determined, several key items of information need to be determined and/or established. These factors include a definition of costs, selection of a discount rate, selection of an analysis life, development of a methodology for determination of salvage value and establishment of the life of various rehabilitation alternatives.

1. Cost Associated with Pavement Rehabilitation

The initial and recurring costs that an agency may consider in the economic evaluation of alternative rehabilitation strategies have been defined in Reference 40 and include the following:

a. Agency costs

(1) Initial capital costs of rehabilitation,

(2) Future capital costs of reconstruction or rehabilitation (overlays, seal costs, etc.),

(3) Maintenance costs, recurring throughout the design period,

(4) Salvage return or residual value at the end of the design period and

(5) Engineering and administration costs.

b. User costs

(1) Travel time,

(2) Vehicle operation,

(3) Accidents,

(4) Discomfort and

(5) Time delay and extra vehicle operating costs during resurfacing or major maintenance.

c. Nonuser costs. Certainly all of these costs should be included if a detailed economic analysis is desired. However, definition of many of these costs is difficult while other costs do not significantly affect the analysis of alternatives for a given pavement segment. For the sake of simplicity the method of analysis usually only considers the following costs:

(1) Initial capital costs of rehabilitation,

(2) Future capital costs of reconstruction or rehabilitation,

(3) Maintenance costs and

(4) Salvage value.

It is suggested, however, that certain user costs such as time delay costs during rehabilitation be considered on certain facilities. Factors that must be considered when determining these costs include:

(a) Will the runway, taxiway, apron, etc. be closed over a lengthy period of time,

(b) Are alternate runways, taxiways, etc. available,

(c) Can operations be moved to a different facility and

(d) What are the costs of traffic delays (aircraft and personnel) associated with closing the facility.

2. Discount Rate

The discount rate selected must be based on an analytical method which is consistent in its use of either constant dollars (cost stated at price levels prevailing at a particular date in time) or current dollars (costs stated at price levels prevailing at the time the costs are incurred). A discount rate based on the market rate of return is consistent with the use of current dollars in estimating future costs. One using the real rate of return is consistent with the use of constant dollars.

The practice of using constant dollars for economic analysis together with market rate of return (current interest rate) for discounting future costs to present values is a rather common practice. However, this methodology is in error and should not be used since the market rate of return includes: (1) an allowance for expected future inflation as well as (2) a return that represents the real cost of capital. (In private investment decisions there is also included an allowance for risk; however, in Federal investments this is considered to be negligible and generally ignored.) The use of constant dollars for costing future rehabilitation and maintenance alternatives, on the other hand, makes no provision for anticipated inflation. Thus, if future costs and salvage values are calculated in constant dollars, only the real cost of capital should be represented in the discount rate used.

Comparison of pavement construction and rehabilitation alternatives should be based on the use of constant dollars for estimating present and future costs together with salvage values. A discount rate of four percent is suggested for present value calculations associated with the use of this manual.

Because the results of present value are sensitive to the discount rate, the analyst may want to perform the economic calculations at two or three alternative discount rates. Rehabilitation alternatives with large initial costs and low maintenance or user costs are favored by low interest rates. Conversely, high interest rates favor strategies that combine low initial costs with high maintenance and user costs.

A discount rate of 4 percent has been used for examples in this manual. Present worth factors and capital recovery factors for discount rates of 3.5, 4.0, 4.5 and 5.0 percent are shown in Table B-9. Values for other discount rates can be found in textbooks on engineering economy. Both present worth and the uniform annual cost methods are illustrated in the manual. Costs are estimated in terms of dollars per square yard.

3. Analysis Life

In economic studies, projects under consideration are defined as having a service life, an economic life and an analysis life. Service life estimates the actual total usage of a facility. It is the time span from installation of a facility to retirement from service. The ending of service life of a pavement (except by disaster) is by manmade decision.

The economic life if the life in which a project is economically profitable or until the service provided by the project can be provided by another facility at lower costs. The economic life may be less than the service life. Shortage of capital often extends a project service life beyond the end of its economic life.

Analysis life may not be the same as the service life or economic life of a project, but it represents a realistic estimate to be used in economic analysis. The analysis period utilized should be long enough to include the time between major rehabilitation actions for the various rehabilitation activities under study. However, the analysis period should not be excessive as the analysis becomes more uncertain due to changes in technology and/or events not occurring as predicted. The Highway Engineering Handbook (49) "stresses that use of an analysis life not to exceed 40 years on the basis that a sound investment should return its costs within that length of time."

An analysis period of 20 years is suggested for use when evaluating pavement rehabilitation alternatives unless the life of a selected alternative is expected to exceed 20 years. An analysis period of 20 years has been utilized for examples in this manual.

4. Salvage Value

Salvage value is the economic residual value of the facility at the end of the analysis period for the project. The present value of this residual value is used to partially offset the present worth of the project costs. In a broad sense, the salvage value is the remaining value of the land, equipment and facility of the project that has continued or alternative uses at the end, or terminal year of the analysis period.

In several studies made on salvage value of pavements it was considered valid to assume zero salvage value at the end of the analysis period. However, the evaluation of pavement rehabilitation alternatives requires that some consideration be given to salvage value. The residual value of rehabilitation action based on its anticipated remaining life appears to be the best method for determining salvage value in this manual. A simplified but adequate method is described by the equation given below:

$$SV = \left(1 - \frac{L_A}{L_E}\right) C$$

where SV = Salvage value or residual value of rehabilitation alternative,

L_A = Analysis life of the rehabilitation alternative in years i.e., difference between the year of construction and the year associated with the termination of the life cycle analysis,

L_E = Expected life of the rehabilitation alternative and

C = Cost or price of rehabilitation alternative.

For example, if an analysis period of 20 years is utilized on a project where a rehabilitation alternative has a life cycle of 7 years, the residual or salvage value of the second rehabilitation action is equal to the straight-line depreciated value of the alternative at the end of the analysis period as given by the equation above. Thus, the residual value at the 20th year would be

$$SV = (1 - \frac{6}{7})\ 2.50 = \$0.36$$

if the cost of the rehabilitation alternative was $2.50.

5. Life of Construction and Rehabilitation Alternatives

The expected life of construction and rehabilitation alternatives must be based on the engineer's experience with consideration given to local materials, environmental factors and contractor capability. For example, overlay design lives of 20 years are utilized for thickness design calculations. In practice the life is usually of the order of 12 to 15 years.

6. Analysis Procedures

Based on the information presented above, present worth or present value economic evaluation methods appear to be the best methods to utilize for evaluating airport pavement rehabilitation and maintenance strategies. A discount rate of 4 percent is suggested for use in this manual, together with an analysis period of 20 years. Salvage values should be calculated based on the residual value equal to the straight-line depreciated value of the rehabilitation alternative at the end of the analysis period. The life and initial price of the various rehabilitation, recycling and maintenance alternatives should be based on the engineer's experience, with consideration given to local materials, environmental factors and contractor capability. Typical price and cost data have been included for reference purposes. Cost-updating procedures included will allow the engineer to predict prices for planned rehabilitation projects.

The basic equation for determining present worth of rehabilitation and maintenance for a given facility is shown below:

$$PW = C + M_1 \left(\frac{1}{1 + r}\right)^{n_1} + \ldots M_i \left(\frac{1}{1 + r}\right)^{n_i} - S \left(\frac{1}{1 + r}\right)^{z}$$

where: PW = Present worth or present value,

C = Present cost of initial rehabilitation activity,

M_i = Cost of the ith maintenance or rehabilitation alternative in terms of present costs, i.e., constant dollars,

r = Discount rate (4 percent suggested for use in this manual),

n_i = Number of years from the present to the ith maintenance or rehabilitation activity,

S = Salvage value at the end of the analysis period and

z = Length of analysis period in years (20 years suggested for use in this manual).

The term

$$\left(\frac{1}{1 + r}\right)^n$$

is commonly called the single-payment present worth factor in most engineering economic testbooks. From a practical standpoint, if the difference in the present worth of costs between two rehabilitation alternatives is 10 percent or less, it is normally assumed to be insignificant and the present worth of the two alternatives can be assumed to be the same.

E. EXAMPLE PROBLEM

A 9-mile pavement section is to be constructed as a major access roadway at an Air Force Base in central Texas. Two pavement sections have been suggested for use on this roadway. Plan 1 consists of construction of a pavement containing 6 inches of lime stabilized subgrade, eight inches of crushed stone base, and 2 inches of asphalt concrete surfacing. Overlays are scheduled on a 7-year cycle (Table B-9). Plan 2 consists of constructing a pavement containing 6 inches of lime stabilized subgrade, 6 inches of asphalt treated base and 2 inches of asphalt concrete. Overlays will not be required during the 20-year life cycle (Table B-10).

The following cost estimates were used for the initial construction:

1. Lime stabilization - \$0.35 per yd^2-in.

2. Asphalt stabilization - \$1.40 per yd^2-in.

3. Crushed stone base - \$0.65 per yd^2-in.

4. Asphalt concrete - \$1.65 per yd^2-in.

Initial construction costs for Plan 1 are therefore \$10.60 per yd^2, and \$13.80 per yd^2 for Plan 2. Routine maintenance costs were forecast based on experience of the local highway department district and costs shown in Tables B-5 and B-6.

From both a present worth and uniform annual cost basis with a 4 percent rate of return, Plan 2 is favored (\$14.37 versus \$15.81) over Plan 1.

---

*Only English units will be used in the example problem for the sake of clarity.

TABLE B-9. ECONOMIC ANALYSIS OF PLAN 1.

Year	Cost, Dollars Per Square Yard	Present Worth Factor, 4 Percent	Present Worth, Dollars
Initial Cost	10.60 Initial Construction	1.0000	10.60
1			
2			
3	0.10 routine maintenance	0.8890	0.089
4	0.12 routine maintenance	0.8548	0.103
5	0.15 routine maintenance	0.8219	0.123
6	0.15 routine maintenance	0.7903	0.119
7	3.30 two-inch overlay	0.7599	2.508
8		0.7307	
9			
10	0.10 routine maintenance	0.6756	0.068
11	0.12 routine maintenance	0.6496	0.078
12	0.15 routine maintenance	0.6246	0.094
13	0.15 routine maintenance	0.6006	0.090
14	3.30 two-inch overlay	0.5775	1.906
15			
16			
17	0.10 routine maintenance	0.5134	0.051
18	0.12 routine maintenance	0.4936	0.059
19	0.15 routine maintenance	0.4746	0.071
20	0.15 routine maintenance	0.4564	0.068
Salvage Value	0.00	0.4564	-0.215
		Total =	15.812

Uniform Annual Cost = Present Worth x Capital Recovery Factor
= 15.812 x 0.07358
= 1.163

TABLE B-10. ECONOMIC ANALYSIS OF PLAN 2.

Year	Cost, Dollars Per Square Yard	Present Worth Factor, 4 Percent	Present Worth, Dollars
Initial Cost	13.80 Initial Construction	1.0000	13.80
1			
2			
3			
4			
5			
6			
7			
8	0.12 routine maintenance	0.7307	0.088
9			
10	0.12 routine maintenance	0.6756	0.081
11			
12	0.15 routine maintenance	0.6246	0.094
13			
14	0.15 routine maintenance	0.5775	0.087
15			
16	0.15 routine maintenance	0.5339	0.080
17			
18	0.15 routine maintenance	0.4936	0.074
19			
20	0.15 routine maintenance	0.4564	0.068
Salvage Value	0.00	0.4564	
		Total =	14.372

Uniform Annual Cost = Present Worth x Capital Recovery Factor

= 14.372 x 0.07358

= 1.057

TABLE B-11. PRESENT WORTH AND CAPITAL RECOVERY FACTORS.

	Present Worth Factor				Capital Recovery Factor			
	Interest Rate				Interest Rate			
Years	3.5	4.0	4.5	5.0	3.5	4.0	4.5	5.0
1	0.9662	0.9615	0.9569	0.9524	1.03500	1.04000	1.04500	1.05000
2	0.9335	0.9246	0.9157	0.9070	0.52640	0.53020	0.53400	0.53780
3	0.9019	0.8890	0.8763	0.8638	0.35693	0.36035	0.36377	0.36721
4	0.8714	0.8548	0.8386	0.8227	0.27225	0.27549	0.27874	0.28201
5	0.8420	0.8219	0.8025	0.7835	0.22148	0.22463	0.22779	0.23097
6	0.8135	0.7903	0.7679	0.7462	0.18767	0.19076	0.19388	0.19702
7	0.7860	0.7599	0.7348	0.7107	0.16354	0.16661	0.16970	0.17282
8	0.7594	0.7307	0.7032	0.6768	0.14548	0.14853	0.15161	0.15472
9	0.7337	0.7026	0.6729	0.6446	0.13145	0.13449	0.13757	0.14069
10	0.7089	0.6756	0.6439	0.6139	0.12024	0.12329	0.12638	0.12950
11	0.6849	0.6496	0.6162	0.5847	0.11109	0.11415	0.11725	0.12039
12	0.6618	0.6246	0.5897	0.5568	0.10348	0.10655	0.10967	0.11283
13	0.6394	0.6006	0.5643	0.5303	0.09706	0.10014	0.10328	0.10646
14	0.6178	0.5775	0.5400	0.5051	0.09157	0.09467	0.09782	0.10102
15	0.5969	0.5553	0.5167	0.4810	0.08683	0.08994	0.09311	0.09634
16	0.5767	0.5339	0.4945	0.4581	0.08268	0.08582	0.08902	0.09227
17	0.5572	0.5134	0.4732	0.4363	0.07904	0.08220	0.08542	0.08870
18	0.5384	0.4936	0.4528	0.4155	0.07582	0.07899	0.08224	0.08555
19	0.5202	0.4746	0.4333	0.3957	0.07294	0.07614	0.07921	0.08275
20	0.5026	0.4564	0.4146	0.3769	0.07036	0.07358	0.07688	0.08024
21	0.4856	0.4388	0.3968	0.3589	0.06804	0.07128	0.07460	0.07800
22	0.4692	0.4220	0.3797	0.3418	0.06593	0.06920	0.07255	0.07597
23	0.4533	0.4057	0.3634	0.3256	0.06402	0.06731	0.07068	0.07414
24	0.4380	0.3901	0.3477	0.3101	0.06227	0.06559	0.06899	0.07247
25	0.4231	0.3751	0.3327	0.2953	0.06067	0.06401	0.06744	0.07095
26	0.4088	0.3607	0.3184	0.2812	0.05921	0.06257	0.06602	0.06956
27	0.3950	0.3468	0.3047	0.2678	0.05785	0.06124	0.06472	0.06829
28	0.3817	0.3335	0.2916	0.2551	0.05660	0.06001	0.06352	0.06712
29	0.3687	0.3207	0.2790	0.2429	0.05545	0.05888	0.06241	0.06605
30	0.3563	0.3083	0.2670	0.2314	0.05437	0.05783	0.06139	0.06505

APPENDIX C

SPECIAL TESTS

SECTION I

COMPRESSIVE STRENGTH OF MOLDED SOIL-LIME CYLINDERS

A. SCOPE

This method covers the procedures for making and testing molded cylinders of soil-lime mixture to determine their compressive strength. This method provides for specimens 2.0 inches in diameter by 4 inches in length.

Note: The suggested procedure may be used for molding and testing larger or smaller specimens. The height-to-diameter ratio should preferably be between 2 and 3.

B. APPLICABLE DOCUMENTS

ASTM Standards: D3551 Method for Laboratory Preparation of Soil-Lime Mixtures Using a Mechanical Mixer and D2216, Laboratory Determination of Moisture Content of Soil.

C. APPARATUS

1. Compression Test Specimen Molds

Molds having an inside diameter of 2 inches and a height of 4 inches for molding test specimens. The mold shall have an extension collar assembly made of rigid metal and constructed so it can be securely attached to or detached from the mold. The extension collar assembly shall have a height extending above the top of the mold of at least 2 inches, which may include an upper section that flares out to form a funnel provided there is at least a 1/2-inch straight cylindrical section beneath it.

2. Compaction Hammer

A manually operated metal hammer having a 1.94 + .01 inch diameter circular face equipped with a 4-pound rammer that slides freely on a metal rod attached to the circular compaction face. The rammer shall have a drop of 12 inches.

3. Compression Specimen Extruder

A device consisting of a piston, jack and frame or similar equipment suitable for extruding specimens from the mold.

4. Scarifying Tool

A sharp-edged or sharp pointed device suitable for scarifying the surface of a compacted soil-lime layer.

5. Miscellaneous Equipment

Tools such as spatulas, trowels, scoops, etc., for use in preparing the specimens.

6. Compression Device

The compression device may be any device with sufficient capacity and control to provide a constant strain rate which may range from 0.50 to 2.0 percent per minute. The device shall be equipped in such a manner that compressive load can be applied to the specimen without producing eccentric loading conditions. The compression device shall be capable of measuring the unit load to the nearest 2 psi.

D. PREPARATION OF SOIL-LIME MIXTURE

1. The mixture shall be prepared in accordance with ASTM D3551.

E. MOLDING SPECIMENS

1. Three specimens shall be prepared.

2. Compact the mixture into the mold in three approximately equal layers using the compaction hammer. The surfaces of the first two layers should be scarified to promote bonding between adjacent layers. The compaction effort (number of blows per layer) is selected to provide the desired density.

Note: A compactive effort of 20 blows per layer produces densities approximately equal to ASTM D698.

3. Trim the compacted soil-lime mixture even with the top of the mold by means of a straightedge.

4. Extrude the specimen from the mold, determine the mass of the specimen and record the mass.

5. Take a moisture content sample from the remaining soil-lime mixture after the second specimen has been compacted.

6. Cure the specimen in the manner desired. Constant temperature curing for a designated time period is normally used. Typically, curing is carried out in sealed containers to avoid moisture loss and lime carbonation.

F. COMPRESSION TEST

1. Place the specimen in the compression device making certain that the specimen is properly aligned.

2. Apply the load continuously and without shock so as to produce axial strain at a rate of 0.5 to 2.0 percent per minute. Record the maximum load sustained by the specimens to the nearest 6 pounds.

3. Determine the moisture content of a representative sample from the three specimens tested.

G. CALCULATION

1. Calculate the compressive strength by dividing the maximum load by the cross-sectional area of the specimen.

2. Determine the average compressive strength of the three specimens tested.

H. REPORT

1. The report shall include the following:

a. Mixture identification (percent lime, soil sample identification, lime identification).

b. Length of mellowing period used in mixture preparation in accordance with ASTM D3551.

c. Specimen diameter and length, in inches and cross-sectional area, in square inches.

d. Strain rate used, percent per minute.

e. Average compressive strength, calculated to the nearest 2 psi.

f. Curing conditions (time, hours; temperature, degree Fahrenheit; nature of curing container).

g. Moisture content, percent and dry density pcf, at molding.

h. Moisture content, percent, of the specimens after test.

APPENDIX C

SECTION II

SOIL-LIME pH TEST

A. SCOPE

The pH test is used to estimate the optimum lime content for maximum cured strength development. The optimum lime percentage is the percentage of lime which maintains a soil-lime pH at its highest value.

1. Weigh to nearest 0.01 gram, representative sample of air-dried soil passing Number 40 sieve equal to 20 grams of oven-dried soil.

2. Use the following formula and previously determined values for moisture content to establish the required amount of soil:

$$1 + \frac{\text{Water Content}}{100} \times 20 \text{ grams} = \begin{array}{l}\text{Weight of natural soil} \\ \text{required to approximate} \\ \text{20 grams of dry soil}\end{array}$$

3. Place soil samples in 150-200 mL bottles insuring that no soil is lost in the transfer.

4. Add percentages of lime, weighed to nearest 0.01 gram, to the soil samples (suggested lime percentages are 0,2,4,5,6,8 and 10 percent based on dry weight of soil).

5. Add 100 mL of distilled or demineralized water to each bottle.

6. Shake the mixture vigorously for a minimum of 30 seconds or until there is no evidence of dry material on the bottom of the bottle.

7. Shake the bottles for 30 seconds at 10-minute intervals for 1 hour. At the last interval, shake the bottle and immediately transfer the mixture into a clear 250 mL beaker.

8. Calibrate the pH meter (should be equipped with an electrode suitable for high pH determinations) using a buffer solution with a known pH of approximately 12.0.

9. Take pH reading after swirling for 50 seconds.

10. Repeat the above process for all samples.

11. Record the pH for each of the soil-lime mixtures.

12. The lowest percentage of lime yielding the highest pH is the estimated optimum lime content.

Note: The basic thrust of the pH procedure is to add sufficient lime to the soil to insure a pH of 12.4 for sustaining the strength-producing, soil-lime pozzolanic reaction. There are limitations to the pH procedure. The technique does not establish whether the soil will react with lime to produce a substantial strength increase. Thus, compressive strength testing is required to establish if the soil is reactive (cured strength increase greater than 50 psi). More extensive compressive strength testing may be required to confirm that the pH lime content estimate is appropriate for maximum cured strength development.

APPENDIX C

SECTION III

pH TEST ON SOIL-CEMENT MIXTURES

A. MATERIALS

1. Portland cement to be used for soil stabilization.

B. APPARATUS

1. pH meter (the pH meter must be equipped with an electrode having a pH range of 14)

2. 150 mL plastic bottles with screw-top lids

3. 50 mL plastic beakers

4. Distilled water

5. Balance

6. Oven

7. Moisture cans

C. PROCEDURE

1. Standardize the pH meter with a buffer solution having a pH of 12.00.

2. Weigh to the nearest 0.01 grams, representative samples of air-dried soil, passing the Number 40 sieve and equal to 25.0 grams of oven-dried soil.

3. Pour the soil samples into 150 mL plastic bottles with screw-top lids.

4. Add 2.5 grams of the portland cement.

5. Thoroughly mix soil and portland cement.

6. Add sufficient distilled water to make a thick paste. (Caution: Too much water will reduce the pH and produce an incorrect result).

7. Stir the soil-cement and water until thorough blending is achieved.

8. After 15 minutes, transfer part of the paste to a plastic beaker and measure the pH.

9. If the pH is 12.0 or greater, the soil organic matter content should not interfere with the cement stabilizing mechanism.

APPENDIX C

SECTION IV

DETERMINATION OF SULFATE IN SOILS (GRAVIMETRIC METHOD)

A. SCOPE

Applicable to all soil types with the possible exception of soils containing certain organic compounds. This method should permit the detection of as little as 0.05 percent sulfate as SO_4.

B. REAGENTS

1. Barium chloride, 10 percent solution of $BaCl_2 \cdot 2H_2O$. (Add 1 ml two percent HCl to each 100 ml of solution to prevent formation of carbonate.)

2. Hydrochloric acid, two percent solution (0.55 N)

3. Magnesium chloride, 10 percent solution of $MgCl_2 \cdot 6H_2O$

4. Demineralized water

5. Silver nitrate, 0.1 N solution

C. APPARATUS

1. Beaker, 1000 mL

2. Burner and ring stand

3. Filtering flask, 500 mL

4. Buchner funnel, 9 cm

5. Filter paper, Whatman Number 40, 9 cm

6. Filter paper, Whatman Number 42, 9 cm

7. Saranwrap

8. Crucible, ignition or aliminum foil, heavy grade

9. Analytical balance

10. Aspirator or other vacuum source

D. PROCEDURE

1. Select a representative sample of air-dried soil weighing approximately 10 grams. Weigh to the nearest 0.01 gram. (Note:

When sulfate content is anticipated to be less than 0.1 percent, a sample weighing 20 grams or more may be used.) (The moisture content of the air-dried soil must be known for later determination of dry weight of the soil.)

2. Boil for 1 1/2 hours in beaker with mixture of 300 ml water and 15 mL HCl.

3. Filter through Whatman Number 40 paper, wash with hot water, dilute combined filtrate and washings to 50 mL.

4. Take 100 ml of the solution and add $MgCl_2$ solution until no more precipitate is formed.

5. Filter through Whatman Number 42 paper, wash with hot water, dilute combined filtrate and washings to 200 mL.

6. Heat 100 ml of this solution to boiling and add $BaCl_2$ solution very slowly until no more precipitate is formed. Continue boiling for about five minutes and let stand overnight in warm place, covering beaker with Saranwrap.

7. Filter through Whatman Number 42 paper. Wash with hot water until free from chlorides (filtrate should show no precipitate when a drop of $AgNO_3$ solution is added).

8. Dry filter paper in crucible or on sheet of aluminum foil. Ingite paper. Weigh residue on analytical balance as $BaSo_4$.

E. CALCULATION

$$\text{Percent } SO_4 = \frac{\text{Weight of residue}}{\text{Oven-dry weight of initial sample}} \times 411.6$$

where

$$\text{Oven-dry weight of initial sample} = \frac{\text{Air-dry weight of initial sample}}{1 + \dfrac{\text{Air-dry moisture content (percent)}}{100 \text{ percent}}}$$

NOTE: If precipitated from cold solution, barium sulfate is so finely dispersed that it cannot be retained when filtering by the above method. Precipitation from a warm, dilute solution will increase crystal size. Due to the adsorption (occlusion) of soluble salts during the precipitation of $BaSO_4$ a small error is introduced. This error can be minimized by permitting the precipitation to digest in a warm, dilute solution for a number of hours. This allows the more soluble small crystals of $BaSO_4$ to dissolve and recrystallize on the larger crystals.

APPENDIX C

SECTION V

DETERMINATION OF SULFATE IN SOILS TURBIDIMETRIC METHOD

A. REAGENTS

1. Barium chloride crystals (grind analytical reagent grade barium chloride to pass a 1 mm sieve.)

2. Ammonium acetate solution (0.5N). (Add dilute hydrochloric acid until the solution has a pH of 4.2.)

3. Distilled water

B. APPARATUS

1. Moisture can
2. Oven
3. 200 ml beaker
4. Burner and ring stand
5. Filtering flask
6. Buchner funnel, 9 cm
7. Filter paper, Whatman Number 40, 9 cm
8. Vacuum source
9. Spectrophotometer and standard tubes (Bausch and Lomb Spectronic 20 or equivalent)
10. pH meter

C. PROCEDURE

1. Take a representative sample of air-dried soil weighing approximately 10 grams and weigh to the nearest 0.01 grams. (The moisture content of the air-dried soil must be known for later determination of dry weight of the soil.)

2. Add the ammonium acetate solution to the soil. (The ratio of soil to solution should be approximately 1:5 by weight.)

3. Boil for about five minutes.

4. Filter through Whatman Number 40 filter paper. If the extracting solution is not clear, filter again.

5. Take 10 mL of extracting solution (this may vary depending on the concentration of sulfate in the solution) and dilute with distilled water to about 40 mL. Add about 0.5 gram of barium chloride crystals and dilute to make the volume exactly equal to 50 ml. Stir for 1 minute.

6. Immediately after the stirring period has ended, pour a portion of the solution into the standard tube and insert the tube into the cell of the spectrophotometer. Measure the turbidity at 30-second intervals for 4-minutes. Maximum turbidity is usually obtained within 2-minutes and the readings remain constant thereafter for 3-10 minutes. Consider the turbidity to be the maximum reading obtained in the 4-minute interval.

7. Compare the turbidity reading with a standard curve and compute the sulfate concentration (as SO_4) in the original extracting solution. (The standard curve is secured by carrying out the procedure with standard potassium sulfate solutions.)

8. Correction should be made for the apparent turbidity of the samples by running blanks in which no barium chloride is added.

D. SAMPLE CALCULATION

Given: Weight of air-dried sample = 10.12 grams

Water content = 9.36 percent

Weight of dry soil = 9.27 grams

Total volume of extracting solution = 39.1 mL

Ten ml of extracting solution was diluted to 50 mL after addition of barium chloride. The solution gave a transmission reading of 81.

E. CALCULATION

From the standard curve, a transmission reading of 81 corresponds to 16.0 ppm (see following figure).

Concentration of original extracting solution =

$$16.0 \times 5 = 80.0 \text{ ppm}$$

$$\text{Percent } SO_4^{--} = \frac{80.0 \times 39.1 \times 100}{1000 \times 1000 \times 9.27} = 0.0338 \text{ percent}$$

F. DETERMINATION OF STANDARD CURVE

1. Prepare sulfate solutions of 0, 4, 8, 12, 16, 20, 25, 30, 35, 40, 45 and 50 ppm in separate test tubes. The sulfate solution is made from potassium sulfate salt dissolved in 0.5 N ammonium acetate (with pH adjusted to 4.2).

2. Continue Steps 5 and 6 in the procedure as described in Determination of Sulfate in Soil by Turbidimetric Method.

3. Draw standard curve as shown in following figure by plotting transmission readings for known concentrations of sulfate solutions.

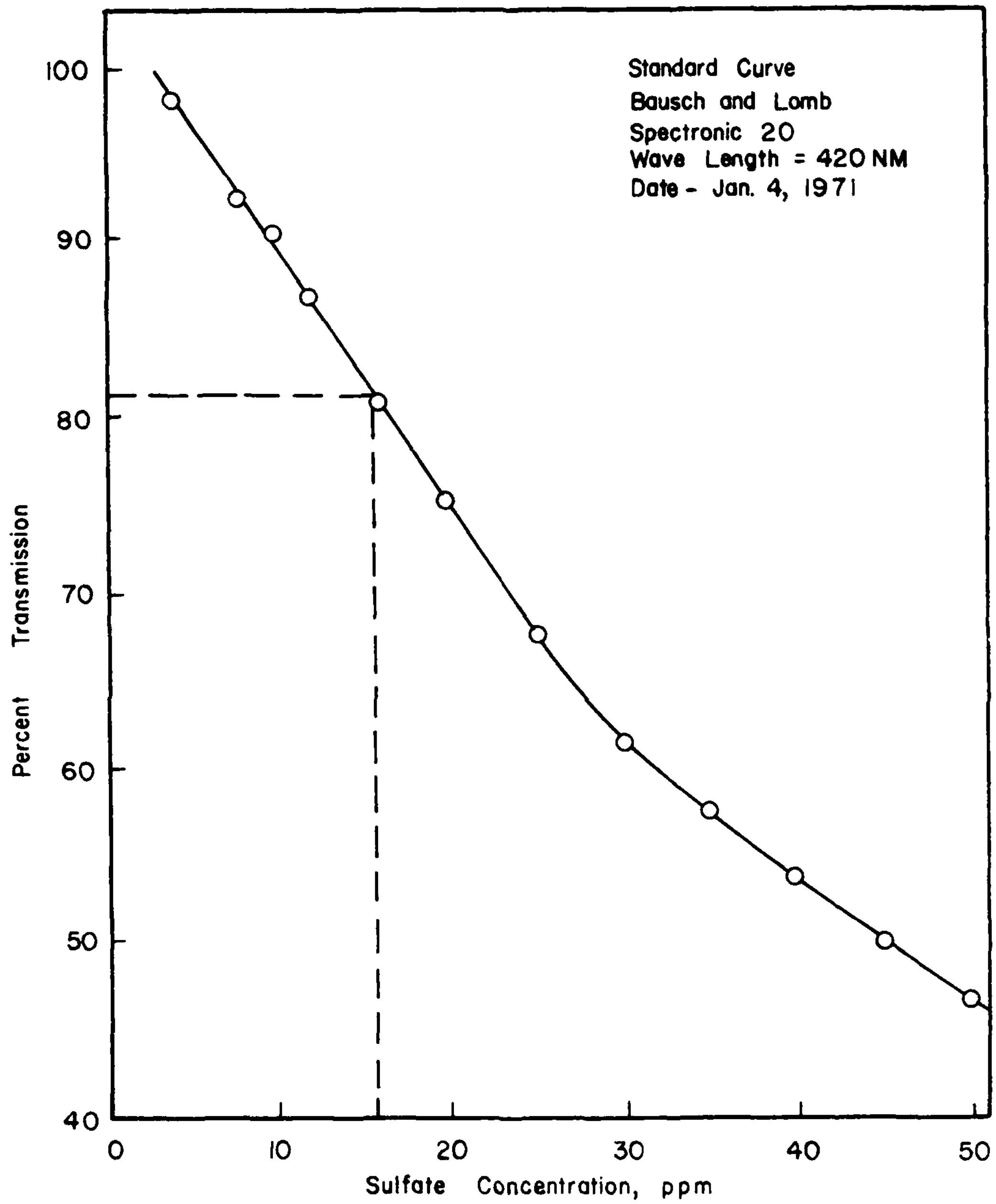


Figure C-1. Example Standard Curve for Spectrophotometer.

APPENDIX C

SECTION VI

EMULSIFIED ASPHALT MIX DESIGN - ILLINOIS METHOD

A. GENERAL

This design method for cold-mix-emulsified asphalt-aggregate paving mixtures is based on research conducted at the University of Illinois using a modified Marshall method of mix design and a moisture durability test. The method and recommended test criteria are applicable to paving base course mixtures for low traffic volume pavements containing any grade of emulsified asphalt and dense graded mineral aggregates with maximum sizes of one inch or less. This design is recommended for road mixes or plant mixes prepared at ambient temperatures.

B. EMULSIFIED ASPHALT

Approximately one gallon of the emulsified asphalt to be used for the project is required for each aggregate type during mixture design.

The emulsion must meet ASTM or AASHTO specifications (see Table 9).

C. TRIAL RESIDUAL ASPHALT CONTENTS

The method for calculating the trial residual asphalt content is as follows:

$$R = 0.00138AB + 6.358 \log_{10}C = 4.655$$

where R = percentage of trial residual asphalt content by weight of dry aggregate,

A = percentage of aggregate retained on Number 4 sieve,

B = percentage of aggregate passing a Number 4 sieve and retained on the Number 200 sieve and

C = percentage of aggregate passing on the Number 200 sieve.

The gradation is based only on washed sieve gradations. The R is rounded off to the nearest half percent to yield the trial residual asphalt content. For example:

Retained on Number 4 sieve = 35 percent,

Passing Number 4 and Retained

on Number 200 sieve = 57 percent and

Passing Number 200 sieve = 8 percent.

$R = 0.00138 \times 35.0 \times 57.0 + 6.3581 \log_{10} (8.0) - 4.655 = 3.84.$

Use $R \cong 4.0$ percent.

Trial residual asphalt content R = 4.0 percent by weight of dry aggregate. To obtain an emulsified asphalt content, it is necessary to divide the trial residual asphalt content R by the fraction of residual asphalt contained in the emulsion. The following is an example for a CSS-1 emulsion:

Trial Residual Asphalt Content = 4.0,

Residual Asphalt in CSS-1 Emulsion = 65 percent and

$$\text{Trial Emulsion Content} = \frac{4.0}{.65} = 6.15 \text{ percent.}$$

Selection of emulsified asphalt type and grade for use on a particular project is based in part on the ability of the emulsion to adequately coat the job aggregate. This is explained in Section V, paragraph G.

D. COATING TEST

Preliminary evaluation of each emulsion selected for mixture design is accomplished through a coating test. The trial residual asphalt content as determined from Section V is combined with the job aggregate, and coating is visually estimated as a percentage of the total area. Emulsions which do not pass the coating test are not considered further. Detailed procedures for the coating test are listed below.

1. Equipment

a. Balance, 5,000 g minimum capacity and accurate to within $\pm$ 0.5 grams.

b. Laboratory mixing equipment, preferably mechanized and capable of producing intimate mixtures of the job aggregate, water and asphalt emulsion material. Hand mixing, if used, must be sufficiently thorough to uniformly disperse the water and emulsion throughout the aggregate.

c. Hot plate or $230^{o}F \pm 9^{o}F$ oven.

d. Supply of round bottom mixing bowls (approximately 5-quart capacity).

e. Supply of metal kitchen mixing spoons (approximately

10-inches).

f. A one-hundred milliliter glass graduate.

2. Procedure

a. Obtain representative samples of each emulsion considered for the project.

b. Obtain representative samples of the job aggregate or aggregate blend.

c. Prepare the aggregate by air drying until it is easily separated into sizes using the following sieves: 1-inch, 3/4-inch, 1/2-inch, 3/8-inch and Number 4. Dry until the portion passing the Number 4 sieve has a free-flowing consistency. Any suitable means of drying which does not heat the aggregate in excess of 140^{o}F or cause degradation of the particles may be used. The aggregate should be stirred frequently to prevent crusting or formation of hard lumps.

d. Determine the moisture content of the air-dried aggregate according to MIL-STD-621A, Method 105 or ASTM D-2216.

e. Weigh out a sufficient number of batches of the air-dried job aggregate for trial mixes. The batch weight should be approximately 2000 grams (oven-dried basis). These batches should be prepared by reblending exact fractions of material retained on 1-inch, 3/4-inch, 1/2-inch, 3/8-inch and Number 4 sieve with material passing the Number 4 sieve to match the grading analysis of the whole sample.

f. Place one batch of aggregate in the mixing bowl of the mechanical mixer. Incorporate X percent of water by dry weight of aggregate in excess of the air dried water content. Water should be added in a thin stream and the aggregate mixed until the water is thoroughly dispersed. Select the initial X percentage water by the following criteria.

(1) <u>Anionic emulsion</u>. Initial trial may be mixed without the addition of any water (i.e., air dry condition).

(2) <u>Cationic emulsion</u>. Often requires a higher water content to produce satisfactory mixes; start the coating test at about 3 percent added water.

With aggregate containing clay, the aggregate should be placed in a sealed container for a minimum of 15 hours prior to the addition of emulsion.

g. Add the amount of emulsified asphalt (percent by weight of dry aggregate) as determined in paragraph C. The emulsion should be added in a thin stream to minimize the tendency of the asphalt to ball up with the fine aggregate. A 5-minute mixing process is usually satisfactory. If hand-mixing is used, it should be sufficiently thorough to disperse the asphalt throughout the mixture.

h. Calculate the free water content of the aggregate at mixing by combining the moisture content of the aggregate as determined in Step 4 with the percentage of water added in Step 6. For example:

Water content of (air-dried) aggregate	= 0.5 percent,
Percentage of water added prior to addition of emulsion	= 3.0 percent and
Premix water before mixing with emulsion	= 3.5 percent.

i. Allow the mixtures to air-dry with the aid of an electric fan or place the mixtures in a drying oven at $230^{o} \pm 10^{o}F$. Prepare a new batch by repeating Steps 6, 7, and 8 with an additional increment of 1 percent water by weight of dry aggregate. Mixes which become soupy or segregate or standing are considered unacceptable. When this occurs, proceed to Step 10.

j. Rate the appearance of the surface dry mixtures by visually estimating the total aggregate surface area that is coated with asphalt. For each premix water content at mixing, record the estimate of the coating as a percentage of the total area. Aggregate coating in excess of 50 percent shall be considered acceptable (see Note 1). If the mixture does not attain 50 percent at any water content, the emulsion shall be rejected from further consideration. If the coating appears borderline, the mixture may be evaluated by the full mixture design procedure.

k. For anionic emulsions, record the following water contents:

(1) Minimum premix water content to attain 50 percent coating.

(2) Premix water content to attain optimum coating.

(3) Maximum premix water content to attain 50 percent coating.

NOTE 1: It is important to recognize that 100 percent coating common to hot mixed materials is desirable but not required. Sufficient asphalt to produce 100 percent coating may result in an excessively high asphalt content.

The range of minimum to maximum premix water content to attain 50 percent coating shall be the acceptable range of mixing water contents for field construction. All subsequent mixing shall be done at the water content which produces optimum coating (see Note 2).

The range of minimum to maximum premix water content to attain 50 percent coating shall be the acceptable range of mixing water contents for field construction. All subsequent mixing shall be done at the water content which produces optimum coating (see Note 2).

1. Cationic emulsified asphalt mixtures generally exhibit increased coating as the premix water content is incrementally increased. At some point, sufficient water is available for optimum dispersion of the asphalt and additional increments of water do not improve coating. The result shall be the minimum premix water content required for mixing. All subsequent mixing in the design process shall be done at the minimum premix water content.

E. SAMPLE PREPARATION

The mixture design procedure uses standard Marshall specimens in the evaluation of mixture properties. To obtain adequate reliable results, triplicate specimens are prepared for both the stability and capillary moisture soak tests.

1. Equipment

The equipment required is that detailed in MIL-STD-620A, Methods 100 and 101 with one addition. A water bath compaction mold with outside threads on both ends is specified. These molds are screwed into threaded base plates. See Figure F-1.

2. Preparation of Samples

a. Number of Specimens. Prepare three specimens for each destructive test to be performed.

b. Molds and Hammer. Thoroughly clean the specimen mold assemblies and the face of the compaction hammer. Place a piece of filter paper toweling cut to size in the bottom of the mold before placing mixture in the mold.

c. Aggregate. Recombine each size fraction of the

NOTE 2: Some combinations of aggregate and emulsion are not significantly affected by a variation of water content at mixing. In these cases, mixing may be allowed at or above the optimum water content as determined for compaction.

aggregate to produce a total aggregate weight of 3.6 kg. Place the pans in a well ventilated area and determine the temperature of the aggregate. The temperature should be adjusted to 72 $\pm$ 3°F prior to mixing.

d. Calculations. Four calculations are required for each combination of aggregate and asphalt: weight of aggregate, weight of emulsion, weight of added premixing water and weight of water loss for compaction. The following formulas are used for the calculations:

(1) Weight of air dried aggregate added

$$= \frac{a}{100 - b} \times 100,$$

(2) Weight of emulsion = $\frac{a \times c}{d}$,

(3) Weight of premixing water added

$$= a\ (f - b - \frac{e \times c}{d})/100 \text{ and}$$

(4) Weight of water loss for compaction = $a\ (\frac{f - g}{100})$

where a = weight of dry aggregate,

b = percent water content of air dried aggregate,

c = desired residual asphalt content, percent weight of dry aggregate,

d = percent residual asphalt in the emulsion,

e = percent water in emulsion = 100 - d,

f = percent premix water content at mixing (weight of dry aggregate) and

g = percent water content at compaction (weight of dry aggregate).

For example:

weight of dry aggregate = a = 7200 grams,

percent water content of air dried aggregate = b = 0.5 percent,

desired residual asphalt content = c = 4.0 percent,

percent residual asphalt in the emulsion = d = 65 percent,

percent water in emulsion = e = 35 percent,

percent premix water content at mixing = f = 5.0 percent,

percent water content at compaction = g = 3.5 percent,

(a) Weight of air dried aggregate added

$$= \frac{7200}{100 - 0.5} \times 100 = 7236 \text{ grams},$$

(b) Weight of emulsion $= \frac{7200 \times 4.0}{65} = 443$ grams,

(c) Weight of added premixing water

$$= 7200\ (5.0 - 0.5 - \frac{35 \times 4.0}{65})/100 = 169 \text{ grams and}$$

(d) Weight of water loss for compaction $= 7200\ (\frac{5.0 - 3.5}{100})$
$= 108$ grams.

Appropriate input values for the previous formulas are discussed in subsequent sections.

e. Preliminary Water. Place the air-dried aggregate in the mechanical mixer. Calculate the total amount of free water that needs to be added to achieve the optimum premixing water as determined in the coating test. Measure the volume of added water in a graduated cylinder. The temperature of the water shall be $72 \pm 3^{o}F$. Add the water in a slow stream and mix for 2 $\pm$ .5 minutes or until the water is thoroughly dispersed throughout the aggregate. For aggregates containing clay the material shall be placed in a sealed container for a minimum of 15 hours (see note below). Weigh the emulsified asphalt container and record. Subtract the required weight of emulsion to determine the final weight of the container to produce the desired residual asphalt content. Add the emulsion to the moistened aggregate in a thin stream as the material is mixing. Reweigh the emulsified asphalt container periodically to insure the required weight of emulsion is not exceeded. The mixing process may require 5 minutes. Excessive mixing tends to strip the asphalt from the aggregate and should be avoided.

f. Aeration. If the desired water content at compaction differs from the optimum mixing water content, aeration is required. Remove all material from the mixing bowl and blade and place in an aeration pan. Distribute the mixture in the pan such that the depth does not exceed 1 inch. Record the weight of the mixture and pan. The required weight loss to reach the desired compaction water content is calculated by Equation 4d in this paragraph. The required weight loss is subtracted from the recorded weight of mixture and pan and that weight recorded. Place the mixture in the curing oven ($200 \pm 5^{o}F$). Stir and weigh the mixture every 15 $\pm$ 0.5 minutes until the weight is within 20 grams of the required weight loss. Remove the mixture from the oven and place in a well ventilated area. Cool the mixture to 72 $\pm$ $3^{o}F$ and weigh the mixture. A fan may be used to accelerate the cooling process. Stir and weigh the mixture every 10 + 0.5 minutes until the calculated required water loss is complete. The mixture is now ready for compaction.

g. Compaction. For specimens to be soaked in the water bath use specially threaded Marshall forming molds, Figure C-2. Assemble the base plate, Marshall forming mold and collar extension. Cover the base plate with a piece of filter paper cut to size and place 1200 ± 5 grams of mixture in the mold assembly (see Note). Spade the mixture with a small spatula 15 times around the perimeter and 10 times over the interior. Place a second piece of filter paper cut to size over the top of the mixture. Repeat this process for the remaining mold assemblies.

Place the first mold assembly on the compaction pedestal in the mold holder and apply 75 blows with the compaction hammer. Remove the collar and base plate, reverse the mold and reassemble. Apply the same number of compaction blows to the face of the reversed specimen. Repeat the process for the remaining mold assemblies. Remove the collars, base plates and filter paper from all specimens. Specimens are now ready for curing.

h. Curing. Specimens are cured at 72 ± 3.0°F in the forming mold for a specified curing period of 24 or 72 hours. The specimens must be set on their edge for equal ventilation on both sides. Remove the specimens from the mold approximately 2 hours prior to the intended testing time and warm to 72 ± 2°F. A water bath should not be used unless the specimens are sealed in a plastic bag to prevent moisture absorption.

F. OPTIMUM WATER CONTENT AT COMPACTION

1. Equipment

The equipment required to optimize the water content at compaction is listed in paragraph E.1.

2. Preparation of Specimens

Use the Procedure for Preparation of Specimens, paragraph E. Additional instructions and clarifications listed below correspond to the appropriate sections of paragraph E.

a. Number of Specimens. Prepare three specimens for each water content at compaction to be evaluated. Generally, four increments of water content 1 percent apart are sufficient to define the stability/water content at compaction curve.

b. Molds and Hammer. No change.

c. Aggregate. Use a total aggregate weight of 3.6 kg for three specimens.

d. Calculations. No change.

e. Mixing Water. The desired residual asphalt content shall be the trial residual asphalt content as determined in paragraph F-3a.

f. Aeration. Aerate successive batches to 1 percent increment water contents generally between 2 to 7 percent by dry weight of aggregate. If the total mixing water content is not greater than the desired water content at compaction, the mixing water content may be increased provided the mixture passes the coating test requirements.

g. Compaction. Use standard Marshall forming molds in the compaction of specimens.

h. Curing. Cure for 24 hours in the compaction mold at $72 \pm 3^{\circ}$F in air as stated in paragraph E.

3. Test Procedure

Test the specimens for modified Marshall stability, MIL-STD-620A, Method 104. However, the conditions of specimen fabrication, compaction and curing for emulsified asphalts described in this appendix must be followed. Prepare a plot of modified Marshall stability vs. water content at compaction. Select the peak of the curve as the optimum water content at compaction. If further definition of results is required, an additional water content at compaction shall be used on all subsequent compaction regardless of the residual asphalt content.

G. VARIATION OF RESIDUAL ASPHALT CONTENT

In determining the optimum residual asphalt content for a particular aggregate and asphalt combination, a series of test specimens are prepared over a range of residual asphalt contents. Test mixtures are prepared in 1-percent increments of residual asphalt content with two increments on either side of the trial asphalt content determined. If further definition of test results is required, increments farther away from the trial residual asphalt content are prepared.

1. Equipment

The equipment required for preparation of specimens is listed under Preparation of Specimens, paragraph E.

2. Preparation of Specimens

Use the Procedure of Preparation of Specimens listed in paragraph E. Additional instructions and clarifications presented below correspond to the appropriate paragraph E.

a. Number of Specimens. Prepare six specimens for each residual asphalt content.

b. Preparation of Molds and Hammer. No change.

c. Preparation of Aggregate. Us a total aggregate weight of 7.2 kg.

d. Calculations. No change.

e. Addition of Mixing Water. Note that the optimum total compaction water is used for all asphalt contents. As the residual asphalt content increases, the amount of water contributed by the emulsion increases. Thus, the amount of pre-mix water added will be reduced as the residual asphalt content is increased. Vary the residual asphalt content on successive batches to yield five 1 percent increments (the trial residual asphalt content and 1 and 2 increments both sides of the trial).

f. Aertion to Reduce the Water Content of the Mixtures. No change.

g. Compaction of Specimens. Use three standard Marshall molds and three specially threaded Marshall molds.

h. Curing of Specimens. Use a 72-hour cure time.

H. TEST PROCEDURES

1. General

To complete the mix design, the following tests and analyses are made from data obtained from the compacted specimens:

a. Bulk specific gravity (MIL-STD-620A, Method 105),

b. Modified Marshall stability and flow of dry specimens at 72 $\pm$ 2^{O}F (MIL-STD-620A, Method 104),

c. Soaked stability and flow at 72 $\pm$ 2^{O}F after 4-day soak (paragraph H),

d. Density and voids analysis (MIL-STD-620A, Method 101) and

e. Moisture absorption during soak (MIL-STD-620A, Method 106).

2. Bulk Specific Gravity

Bulk specific gravities are determined as required to compute air voids (MIL-STD-620A, Method 101).

3. Modified Marshall Stability

Three specimens are tested in accordance with MIL-STD-620A, Method 104. These specimens are prepared and cured as prescribed in paragraph G and tested at 72 $\pm$ 2^{O}F.

4. Soaked Stability and Flow Tests

Three specimens are placed in capillary soak in the apparatus shown in Figure C-2.

a. The specimens in the specially threaded molds are brought flush to the end of the mold by use of the extrusion jack.

b. Specially threaded brass or aluminum plates, Figure C-2, are then screwed on either end of the molds. The whole assemblies are then placed with the flush ends down in a water bath with water at a depth of 1 inch. The depth of water is maintained at 1 inch and at a temperature of 72^{O}F + 3.0^{O}F. The top of the mold is covered to prevent evaporation of moisture.

c. After 48 hours, the assemblies are removed from the water bath. The brass plates are removed, the specimens are brought flush with the opposite end of the mold. The brass plates are again threaded on either end, and the whole assemblies are placed with the flush ends down in the water bath, and the top is again covered.

d. After 48 hours, the specimens are removed and extruded from the specially threaded molds.

e. The specimens are then tested for Marshall stability (MIL-STD-620A, Method 104) and moisture content determination (MIL-STD-620A, Method 106).

H. INTERPRETATION DATA

1. General

Prepare a separate graphical plot for the following factors:

a. Dry stability at one day vs. compaction moisture,

b. Dry and soaked stability vs. residual asphalt content,

c. Dry bulk density (corrected for moisture) vs. residual asphalt content,

d. Percent total voids vs. residual asphalt content,

e. Percent moisture absorbed vs. residual asphalt content and

f. Percent stability loss vs. residual asphalt content (calculated as [Dry Stability-Wet Stability] 100/Dry Stability).

In each graphical plot, connect the data with a smooth curve that provides the best fit for all values.

2. Trends

General trends are described as follows:

a. The 1-day dry stability will generally show a peak at a particular moisture content at compaction. Sometimes this curve is very flat and no peak is apparent, indicating a range of possible compaction moisture content. If this occurs the moisture content resulting in maximum dry bulk density may be used as long as stability does not drop off significantly.

b. Soaked stability will generally show a peak at a particular residual asphalt content while dry stability will generally show a continually decreasing curve with increasing residual asphalt content. Some mixes may show a continual increase in soaked stability over the range of asphalt content evaluated, which indicates the increased beneficial effect of additional asphalt content on soaked stability.

c. Percent loss of stability (computed by [dry stability-soaked stability] 100/dry stability) generally decreases as residual asphalt content increases.

d. Dry bulk density usually peaks at a particular residual asphalt content.

e. Percent moisture absorbed during the soak test decreases with increased residual asphalt content.

f. Percent toal voids (air plus moisture) decreases as residual asphalt content increases.

3. Optimum Asphalt Content

a. Mixture must provide an adequate stability when tested in a "soaked" condition to provide adequate resistance to traffic load during wet seasons.

b. The percent loss of stability of the mixture when tested "soaked" as opposed to "dry" should not be excessive. A high loss is indicative of the mixture having high moisture susceptibility and may cause disintegration during wet seasons.

c. The total voids within the mixture should be within a specified range to prevent either excessive permanent deformation and moisture absorption (for too high void content), or bleeding of the residual asphalt from the mixture (for a low void content).

d. Moisture absorption into the mixture should not be excessive to minimize the potential of stripping or weakening the bond between residual asphalt and aggregate.

e. Residual asphalt should provide adequate coating of the aggregate and should be resistant to stripping or abrasion.

The optimum residual asphalt content for the paving mixture is determined from the data obtained as presented. The optimum residual asphalt content is chosen that provides maximum soaked stability, but is adjusted either up or down depending on moisture absorption, percent loss of stability, total voids and coating of aggregates. Design criteria for each of these values is given in Table 25. If the residual asphalt content at the peak of the soaked stability curve provides for adequate moisture absorption, percent loss of stability, total voids and aggregate coating, it is selected as the optimum asphalt content. This value must meet minimum stability requirements, however, as given in Table 25, or the mix is rejected. If one or more criteria cannot be met, the mix should be considered inadequate.

The moisture contents of the aggregate at mixing and at compaction may have a significant effect on the above criteria for emulsified asphalt aggregate mixtures. While there is a fairly broad range of moisture which may be acceptable, it is generally desirable to use a minimum of water. This minimum amount of moisture is determined by the coating of the aggregate by the residual asphalt. The optimum moisture contents at mixing and compaction, therefore, need to be determined and then controlled to help achieve the desired criteria previously listed.

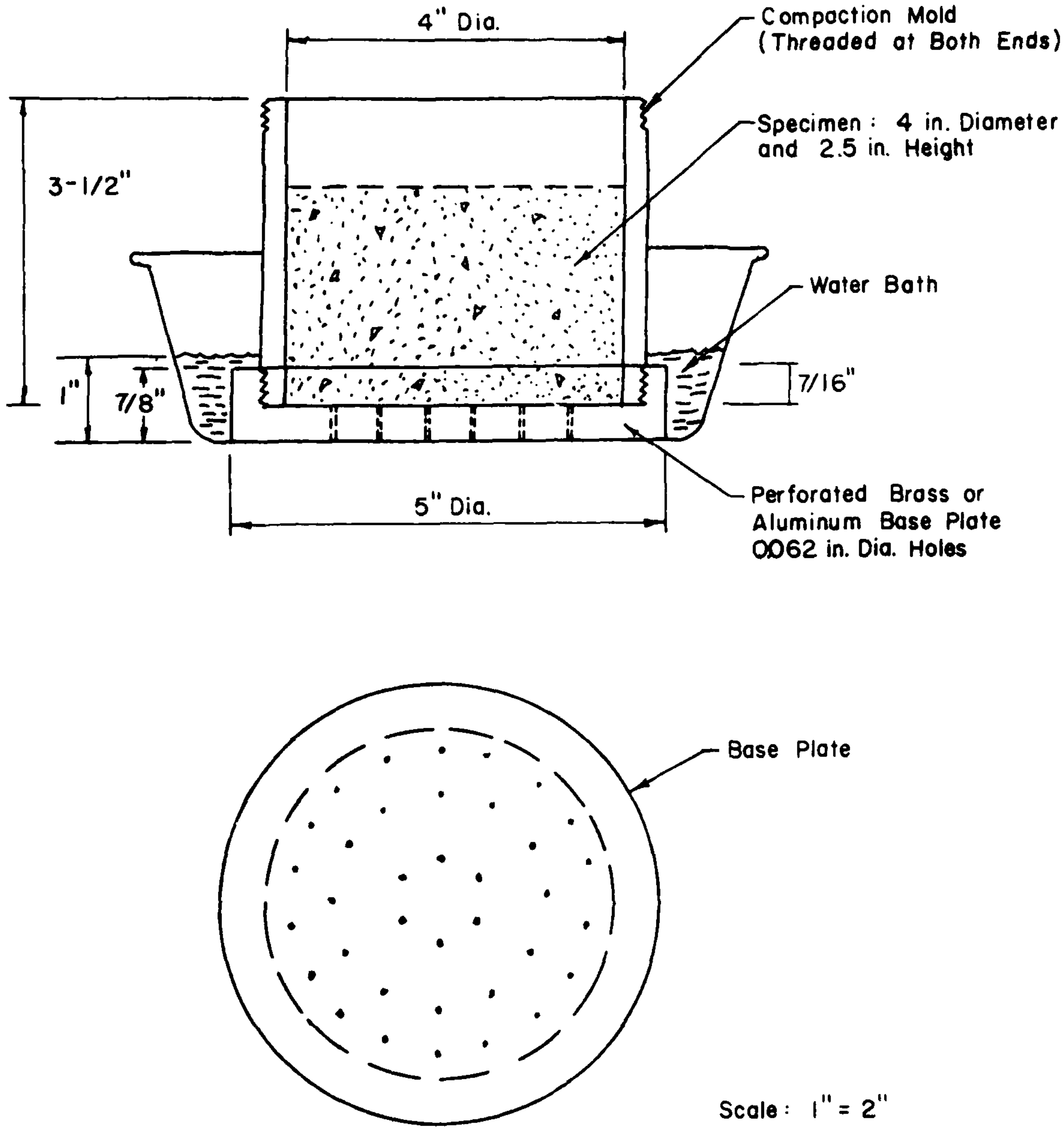


Figure C-2. Capillary Soak Mold.

END
9-87
DTIC