Soil Stabilization

General Stabilization Methods

- Mechanical Stabilization
  - Compaction
- Geosynthetics
  - Embankment Stabilization
- Chemical Treatment
  - Soil Modification (low doses)
  - Soil Stabilization (high doses)

Chemical Stabilizers

- Quicklime: CaO
- Lime Kiln Dust: CaO
- Hydrated Lime: $Ca(OH)_2$
- Cement: CaO, SiO_2, Al_2O_3
- Cement Kiln Dust: CaO, SiO_2, Al_2O_3
- Class C Fly Ash: CaO, SiO_2, Al_2O_3
- Class F Fly Ash: SiO_2, Al_2O_3

Source: PCA R&D Serial No. 2435

Lime Stabilization

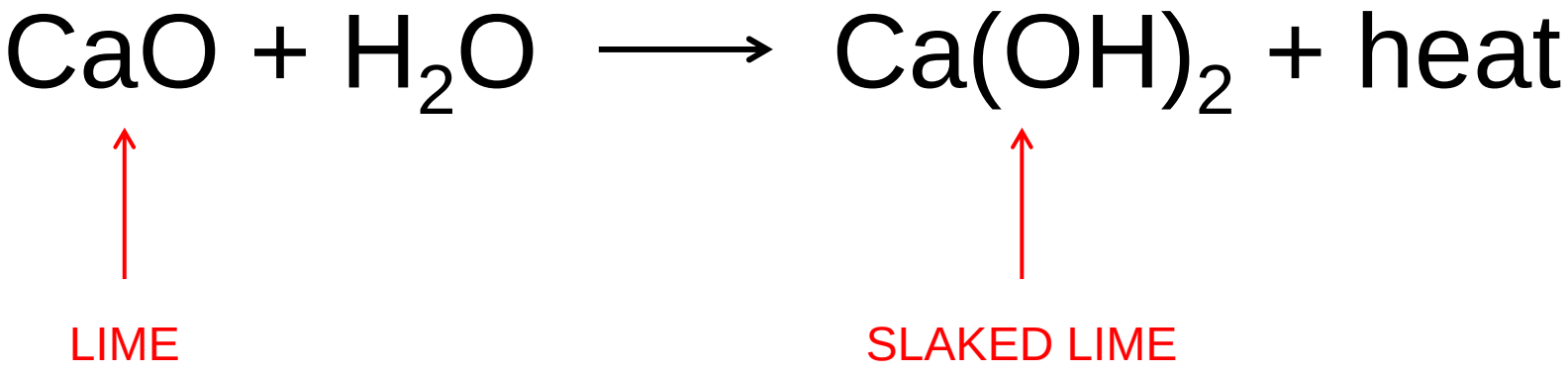
Treatment with Lime

- Drying
- Modification
- Stabilization

Lime used for Drying

- At low dosage rates, quicklime dries wet soils by
  - Removing free water from the soil to create calcium hydroxide (slaked lime)
  - Generating heat to help evaporate water from the soil
  - Chemically reacting with clayey soils to reduce their water-holding capacity

Lime Hydration



Lime Modification

- At low dosage rates, quicklime and slaked lime modify plastic soils by changing the chemistry of the soil water so the clay particles agglomerate and flocculate
- This reduces soil plasticity, decreases optimum moisture content, reduces shrink/swell potential
- The improvement in soil properties occurs over 1-2 days and may or may not be permanent

Lime Stabilization

- At higher dosage rates quicklime and slaked lime increase the pH of the soil water (making it more alkali) and the clay particles start to break down, releasing silica and alumina that combine with the Ca to produce CSH and CAH
- This reduces plasticity, increases strength and stiffness, reduces shrink/swell potential
- The improvement in soil properties occurs over weeks and lasts indefinitely

Lime Stabilization

Increasing Time

1. Flocculate and agglomerate clay particles by replacing monovalent cations such as Na^{+} with divalent cations such as Ca^{++}
2. Cement clay particles together by creating a pozzolanic reaction between CaO, SiO_2 and Al_2O_3
3. Cement clay particles together by creating $CaCO_3$ from CaO plus atmospheric CO_2

Source: PCA R&D Serial No. 2435

Cation Exchange

$$Li^{+} < Na^{+} < K^{+} < Mg^{++} < Ca^{++} < Al^{+++} < Fe^{+++}$$

Highly Expansive Clay

Moderately Expansive Clay

Moderately Expansive Clay

Pozzalanic Reaction

$$CH + S \longrightarrow CSH$$

$$CH + A \longrightarrow CAH$$

Lime Cementation

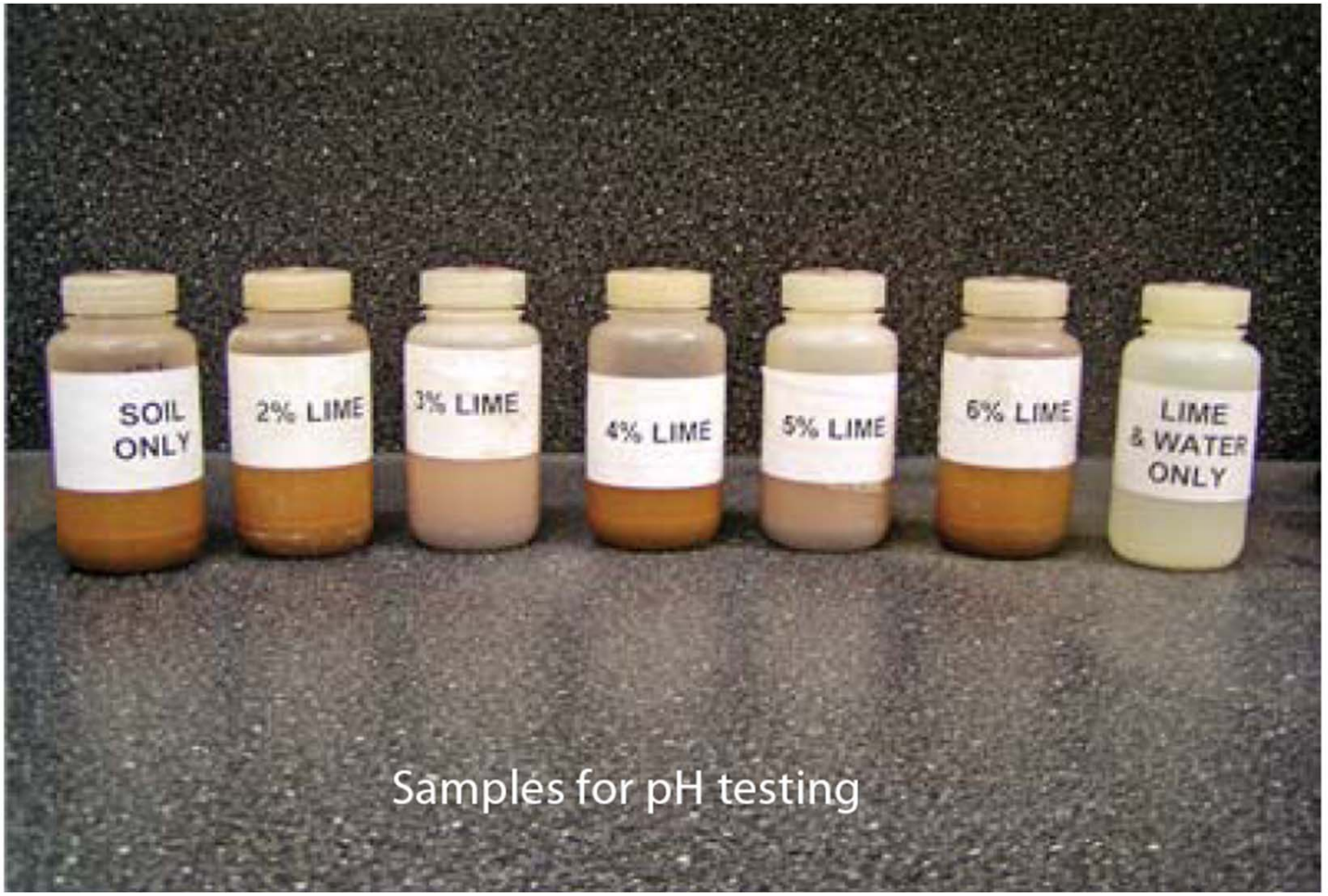
$$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O \uparrow$$

Mix Design for Lime Stabilization

Step 1 – Suitability

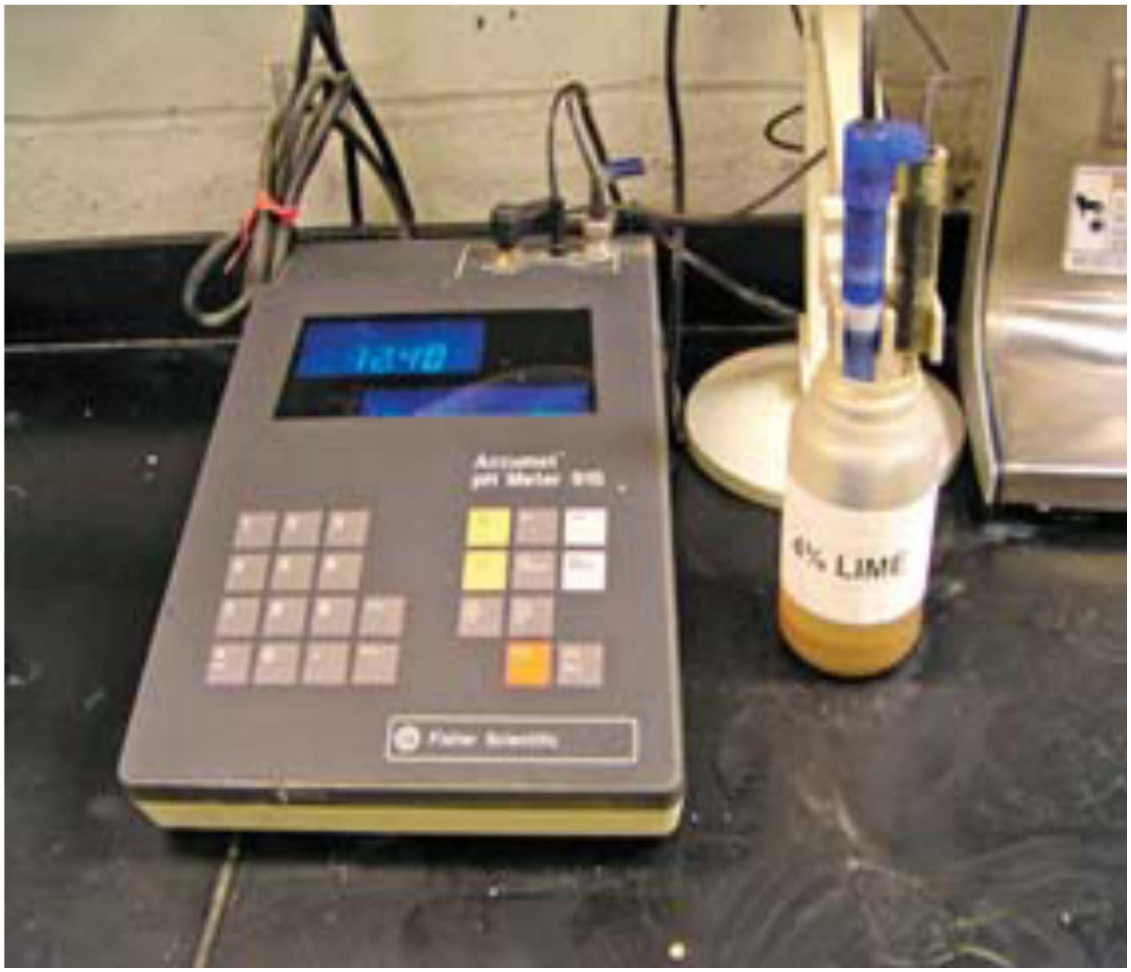
- Washed sieve analysis (ASTM C136)
- Atterberg limits (ASTM D4318)
- Organic content (ASTM D2974)
- Sulfate content (OHD L-49)

Step 2 – Initial Lime Content



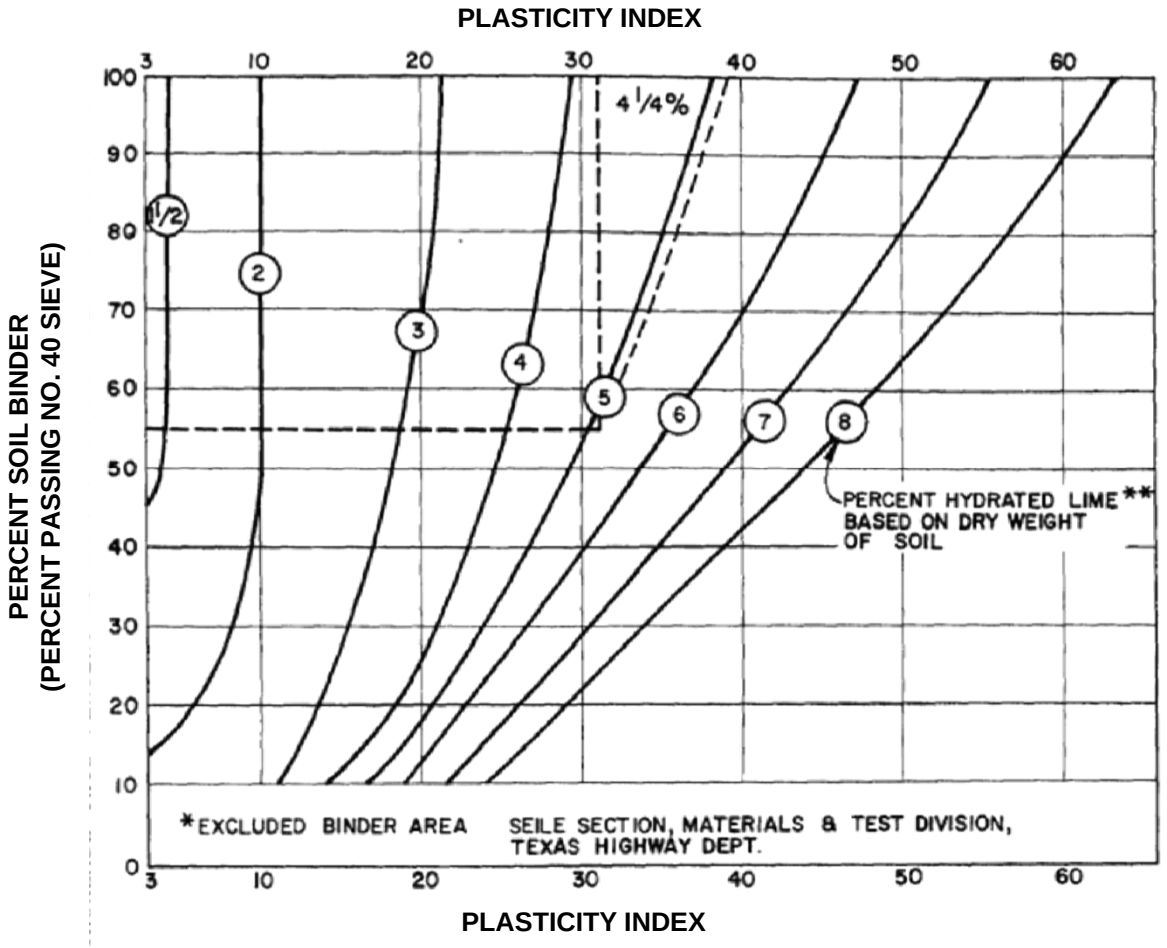
Source: **National Lime Association**

Step 2 – Initial Lime Content



Source: **National Lime Association**

Step 2 – Initial Lime Content



Source: **Army EM 1110-3-137**

Step 3 – Proctor Compaction

Source: **National Lime Association**

Step 4 – Prepare Specimens

Source: **National Lime Association**

Step 5 – Soak Specimens

Source: **National Lime Association**

Step 5 – UC Testing

Source: **National Lime Association**

Strength Criteria

Table 2-1. Minimum Unconfined Compressive Strengths for Cement, Lime, and Combined Lime-Cement-Fly Ash Stabilized Soils

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

[a]Unconfined compressive strength determined at 7 days for cement stabilization and 7 or 28 days for lime or lime-cement-fly ash stabilization (See chapter 4)

Source: **Army EM 1110-3-137**

Construction Methods

Lime Delivery

Source: **National Lime Association**

Slaker Tanks

Source: **National Lime Association**

Jet Slurry Mixer

Source: **National Lime Association**

Scarify (Optional)

Source: **National Lime Association**

Spreading Dry Lime

Source: **National Lime Association**

Spreading Lime Slurry

Source: **National Lime Association**

Scarify (Optional)

Source: **National Lime Association**

Water

Source: **National Lime Association**

Mix

Source: **National Lime Association**

Mix and Water Simultaneously

Source: **National Lime Association**

Sheepsfoot Roller

Padfoot Roller

Source: **National Lime Association**

Membrane Curing

Source: **National Lime Association**

Lime-Fly Ash Stabilization

Step 1 – Suitability

- Washed sieve analysis (ASTM C136)

  Less than 50% passing No. 200 sieve

- Atterberg limits (ASTM D4318)

  PI < 25 (for material passing No. 40 sieve)

Source: **Army TM 5822-14**

Step 2 – Initial Fly Ash Content

Source: **Army TM 5822-14**

Step 3 – Prepare Specimens

- Three specimens at 1:3 L/F ratio
- Three specimens at 1:4 L/F ratio
- Three specimens at 1:5 L/F ratio
- Add 1-2% cement by weight (optional)
- All at optimum moisture content
- All at field-specified density (usually 95%)

Step 4 – Test Samples

- Prepare one specimen each using ASTM D1632 and determine UCS using D1633
- Prepare and test two specimens each for durability using ASTM D559 (freeze/thaw) but omit the wire-brushing between cycles
- Coarse-grained soils are generally not affected by wet/dry cycles so you don’t have to test for wet/dry durability

Step 5 – Check Results

Table 2-2. Minimum unconfined compressive strength for cement, lime, lime-cement, and lime-cement-fly ash stabilized soils

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

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

Table 2-3. Durability requirements

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

Source: **Army TM 5822-14**

Mix Design for Cement Stabilization

Step 1 – Suitability

- Washed sieve analysis (ASTM C136)
- Atterberg limits (ASTM D4318)

$$PI < 20 + \frac{50 - \%\ fines}{4}$$

- Organic content (Appendix B)

  pH > 12 (10:1 soil/cement ratio)

- Sulfate content (Appendix C)

  SO < 1% by mass

Source: **Army TM 5822-14**

Step 2 – Initial Cement Content

Table 3-2. Cement requirements for various soils

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

Source: **Army TM 5822-14**

Step 3 – Proctor Compaction

Source: **National Lime Association**

Step 4 – Prepare Specimens

- Three specimens at trial cement content
- Three specimens 2% below trial content
- Three specimens 2% above trial content
- All at optimum moisture content
- All at field-specified density (usually 95%)
- All cured for 7 days in humid room

Step 4 – Test Samples

- Prepare one specimen each using ASTM D1632 and determine UCS using ASTM D1633
- Prepare and test two specimens each for durability testing using either
  - ASTM D559 (wet/dry durability)
  - ASTM D560 (freeze/thaw durability)

Step 5 – Check Results

Table 2-2. Minimum unconfined compressive strength for cement, lime, lime-cement, and lime-cement-fly ash stabilized soils

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

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

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Granular, PI < 10	11
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Silt	8
Clays	6

Source: **Army TM 5822-14**

Treatment Selection

Selecting an Admixture

SOIL MODIFICATION TABLE					
ADDITIVE (Expressed as a percentage added on oven dry basis)	**SOIL GROUP CLASSIFICATION - AASHTO M145**				
	A-4	A-5	A-6	A-7	
				A-7-5	A-7-6
PORTLAND CEMENT	3	3	3		
FLY ASH	7	7	7		
CEMENT KILN DUST (Pre-Calciner Plant)	3	3	3		
CEMENT KILN DUST (Other Type Plant)	6	6			
HYDRATED LIME*			3	3**	3**

A blank in the table indicates the additive is not recommended for that soil group. Recommended amounts include a safety factor for loss due to wind, grading, and/or mixing. Pre-Calciner plants are identified on the Materials Division approved list for cement kiln dust.

* = Reduce quantity by 20% when quick lime is used, i.e. 3% x 0.8 = 2.4%, 4% x 0.8 = 3.2%

** = Use 4% when the liquid limit is greater than 50.

Source: http://www.okladot.state.ok.us/materials/pdfs-ohdl/ohdl51.pdf

Selecting an Admixture

SOIL STABILIZATION TABLE												
ADDITIVE (Expressed as a percentage added on oven dry basis)	**SOIL GROUP CLASSIFICATION - AASHTO M145**											
	A-1		A-2				A-3	A-4	A-5	A-6	A-7	
	A-1-a	A-1-b	A-2-4	A-2-5	A-2-6	A-2-7					A-7-5	A-7-6
PORTLAND CEMENT	4	4	4	4	4	4	5	√	√	√		
FLY ASH					10	10	11	12	12	12		
CEMENT KILN DUST (Pre-Calciner Plants)	4	4	4	4	4	4	5	√	√			
CEMENT KILN DUST (Other Type Plants)	8	8	8	9	9	9	10	10	10			
HYDRATED LIME*										4	5**	5**

A blank in the table indicates the additive is not recommended for that soil group. Recommended amounts include a safety factor for loss due to wind, grading, and/or mixing. Pre-Calciner plants are identified on the Materials Division approved list for cement kiln dust.

√ = Mix Design Required

* = Reduce quantity by 20% when quick lime is used, i.e. 4% x 0.8 = 3.2%, 5% x 0.8 = 4.0%, 6% x 0.8 = 4.8%

** = Use 6% when the liquid limit is greater than 50.

Source: http://www.okladot.state.ok.us/materials/pdfs-ohdl/ohdl50.pdf

CKD and LKD

Constituent	Cement Kiln Dusts			Lime Kiln Dusts		
	Low	High	Average	Low	High	Average
SiO_2	6.0	28.5	16.5	--	--	--
Al_2O_3	3.2	9.6	4.4	--	--	--
Fe_2O_3	0.80	5.9	2.7	--	--	--
CaO	16.0	65.0	47.6	35.6	43.4	38.6
MgO	0.8	4.8	2.3	25.4	32.2	28.6
SO_3	0.7	26.3	7.1	--	--	--
Na_2O	0.08	3.2	0.8	--	--	--
K_2O	1.08	26.2	5.5	--	--	--
LOI	2.5	32.0	16.0	22.9	36.4	29.1
S	--	--	--	0.2	1.0	0.7
CO_2	--	--	--	11.0	22.3	18.0
Available Lime	--	--	--	8.3	20.2	12.6

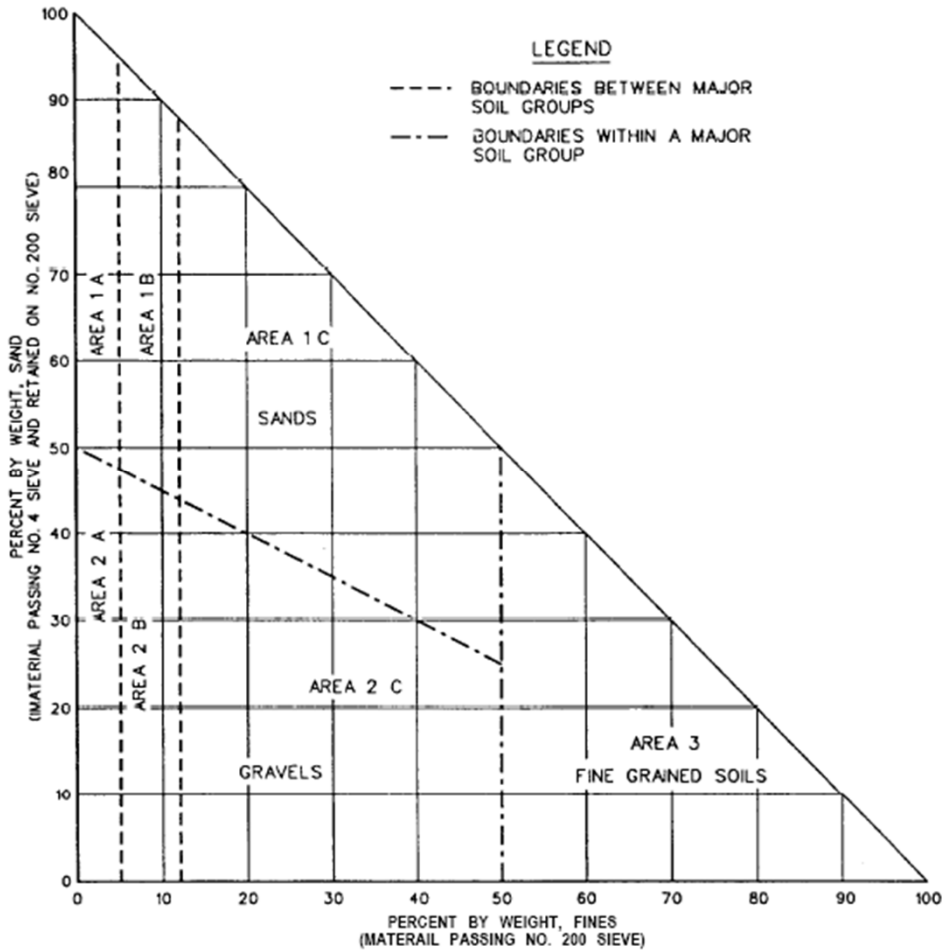
Source: TTI-2003-1

Fly Ash

	Class F	Class C	Class C
Component	Bituminous	Subbituminous	Lignite
SiO_2	20-60	40-60	15-45
Al_2O_3	5-35	20-30	10-25
Fe_2O_3	10-40	4-10	4-15
CaO	1-12	5-30	15-40
MgO	0-5	1-6	3-10
SO_3	0-4	0-2	0-10
Na_2O	0-4	0-2	0-6
K_2O	0-3	0-4	0-4
LOI	0-15	0-3	0-5

Source: http://www.tfhrc.gov/hnr20/recycle/waste/cfa51.htm

Selecting an Admixture



Source: Army TM 5-822-14

Selection Guide

Area	Soil Class.[a]	Type of Stabilizing Additive Recommended	Restriction on LL and PI of Soil	Restriction on Percent Passing No. 200 Sieve[a]	Remarks
1A	SW or SP	(1) Bituminous			
		(2) Portland cement			
		(3) Lime-cement-fly ash	PI not to exceed 25		
1B	SW-SM or	(1) Bituminous	PI not to exceed 10		
	SP-SM or	(2) Portland cement	PI not to exceed 30		
	SW-SC or	(3) Lime	PI not to exceed 12		
	SP SC	(4) Lime cement fly ash	PI not to exceed 25		
1C	SM or SC or SM-SC	(1) Bituminous	PI not to exceed 10	Not to exceed 30% by weight	
		(2) Portland cement	--[b]		
		(3) Lime	PI not less than 12		
		(4) Lime-cement-fly ash	PI not to exceed 25		

[a] Soil classification corresponds to MIL-STD-619B. Restriction on liquid (LL) and plasticity index (PI) is in accordance with Method 103 in MIL-STD-621A.

[b] $PI \leq 20 + \frac{50 - \text{percent passing No. 200 sieve}}{4}$

Source: Army TM 5-822-14

Selection Guide

Area	Soil Class.[a]	Type of Stabilizing Additive Recommended	Restriction on LL and PI of Soil	Restriction on Percent Passing No. 200 Sieve[a]	Remarks
2A	GW or GP	(1) Bituminous (2) Portland cement			Well-graded material only Material should contain at least 45% by weight of material passing No. 4 sieve
		(3) Lime-cement-fly ash	PI not to exceed 25		
2B	GW-GM or GP-GM or GW-GC or GP-GC	(1) Bituminous	PI not to exceed 10		Well-graded material only Material should contain at least 45% by weight of material passing No. 4 sieve
		(2) Portland cement	PI not to exceed 30		
		(3) Lime	PI not less than 12		
		(4) Lime-cement-fly ash	PI not to exceed 25		

[a] Soil classification corresponds to MIL-STD-619B. Restriction on liquid (LL) and plasticity index (PI) is in accordance with Method 103 in MIL-STD-621A.

[b] $PI \leq 20 + \frac{50 - \text{percent passing No. 200 sieve}}{4}$

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Selection Guide

Area	Soil Class.[a]	Type of Stabilizing Additive Recommended	Restriction on LL and PI of Soil	Restriction on Percent Passing No. 200 Sieve[a]	Remarks
2C	GM or GC or GM-GC	(1) Bituminous	PI not to exceed 10	Not to exceed 30% by weight	Well-graded material only
		(2) Portland cement	..[b]		Material should contain at least 45% by weight of material passing No. 4 sieve
		(3) Lime	PI not less than 12		
		(4) Lime-cement-fly ash	PI not to exceed 25		
3	CH or CL or MH or ML or OH or OL or ML-CL	(1) Portland	LL less than 40 and PI less than 20		Organic and strongly acid soils falling within this area are not susceptible to stabilization by ordinary means
		(2) Lime	PI not less than 12		

[a] Soil classification corresponds to MIL-STD-619B. Restriction on liquid (LL) and plasticity index (PI) is in accordance with Method 103 in MIL-STD-621A.

[b] $PI \leq 20 + \frac{50 - \text{percent passing No. 200 sieve}}{4}$

Source: Army TM 5-822-14

AASHTO Soil Classification

General Classification	Granular Materials (35% or less passing 0.075 mm)							Silty-Clay Material (More than 35% passing 0.075 mm)			
Group Classification	A-1-a	A-1-b	A-3	A-2-4	A-2-5	A-2-6	A-2-7	A-4	A-5	A-6	A-7-5 A-7-6
Sieve Analysis Percent passing:											**
2.00 mm	50 max										
0.42 mm	30 max	50 max	51 min								
0.075 mm	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
Characteristics of Fraction passing 0.42 mm											
Liquid Limit				40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
Plastic Index	6 max	6 max	N.P.	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min
Usual types of significant constitutent materials	Stone Fragments - gravel and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General rating as subgrade	Excellent to good							Fair to poor			

Soil Modification Guide

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* = Reduce quantity by 20% when quick lime is used, i.e. 3% x 0.8 = 2.4%, 4% x 0.8 = 3.2%

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Source: http://www.okladot.state.ok.us/materials/pdfs-ohdl/ohdl51.pdf

Soil Stabilization Guide

SOIL STABILIZATION TABLE												
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	A-1-a	A-1-b	A-2-4	A-2-5	A-2-6	A-2-7					A-7-5	A-7-6
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CEMENT KILN DUST (Pre-Calciner Plants)	4	4	4	4	4	4	5	√	√			
CEMENT KILN DUST (Other Type Plants)	8	8	8	9	9	9	10	10	10			
HYDRATED LIME*										4	5**	5**

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Source: http://www.okladot.state.ok.us/materials/pdfs-ohdl/ohdl50.pdf