



Design Procedures for Soil Modification or Stabilization

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Table of Contents

<u>Section</u>	<u>Page</u>
1.0 General.....	3
2.0 Modification or Stabilization of Soils.....	4
2.1 Mechanical Modification or Stabilization	4
2.2 Geogrid Reinforcement	4
2.3 Chemical Modification or Stabilization	5
3.0 Design Procedures.....	5
3.1 Suggested Criteria for Chemical Selection.....	5
3.2 Suggested Chemical Quantities for Modification or Stabilization.....	6
3.3 Suitable Soils for Modification/Stabilization.....	6
4.0 Laboratory Test Requirements	7
4.1 Soil Sampling	7
4.2 Lime or Lime By-Products Required for Modification or Stabilization.....	8
4.3 Cement Required for Stabilization or Modification.....	9
4.4 Fly Ash Required for Modification	10
4.5 Combination of Cement Fly Ash and Lime Mixtures	10
4.6 Soils Drying.....	11
4.7 Requirements for Geotechnical Submittals to INDOT	12
5.0 Construction Considerations	13
References.....	16
Tables	
1. DCP Blow Counts per 6 inches and Overlap.....	5
2. AASHTO Classifications for Cement Requirements	10
3. Moisture Reduction vs. Lime.....	13
Figures	
1. pH vs. Lime Content.....	9
2. Optimum Moisture Content vs Lime Content	12
3. Moisture Density Relationship	14
4. Lime Modified Subgrade Uniformity Determination by Phenolphthalein	15
Appendices	
1. Chemical Modification Flow Chart, Appendix 1.....	17
2. Chemical Modification Flow Chart, Appendix 2.....	18

DESIGN PROCEDURES FOR SOIL MODIFICATION OR STABILIZATION

1.0 General

It is the policy of the Indiana Department of Transportation to minimize the disruption of traffic patterns and the delay caused today's motorists whenever possible during the construction or reconstruction of the State's roads and bridges. INDOT Engineers are often faced with the problem of constructing roadbeds on or with soils, which do not possess sufficient strength to support wheel loads imposed upon them either in construction or during the service life of the pavement. It is, at times, necessary to treat these soils to provide a stable subgrade or a working platform for the construction of the pavement. The result of these treatments are that less time and energy is required in the production, handling, and placement of road and bridge fills and subgrades and therefore, less time to complete the construction process thus reducing the disruption and delays to traffic.

These treatments are generally classified into two processes, soil modification or soil stabilization. The purpose of subgrade modification is to create a working platform for construction equipment. A small credit is provided for this modification in the pavement design process. The purpose of subgrade stabilization is to enhance the strength of the subgrade and this increased strength is taken into account in the pavement design process. Stabilization requires more a thorough design methodology during construction than modification. The methods of subgrade modification or stabilization include physical processes such as soil densification, blending with granular material, the use of reinforcement such as Geogrids, undercutting and replacement, etc.. The treatment also includes chemical processes such as mixing with cement, fly ash, lime, and blends of any these materials. Soil properties such as strength, compressibility, hydraulic conductivity, workability, swelling potential, and volume change tendencies may be altered by various soil modification or stabilization methods. When designers require fast construction, soils with higher moisture contents can be dried with the use of chemical modifiers. When soil properties require alterations, these soils can be altered by performing chemical soil stabilization.

Subgrade modification shall be considered for all the reconstruction and new alignment projects. When used, modification or stabilization shall be required for the full roadbed width including shoulders and curbs. Subgrade stabilization shall be considered for prepared subgrade soils with a resilient modulus less than 5,000 psi based on laboratory testing.

INDOT Standard Specifications provide the geotechnical engineer several options for subgrade treatment type that includes chemical modification, replacement with aggregates, geosynthetic reinforcement in conjunction with the aggregates, and density and moisture control. **The geotechnical engineer has to evaluate the needs of the subgrade and include where necessary, specific types of treatment above and beyond the Standard Specifications.**

Various soil modification or stabilization guidelines are discussed below. It is necessary for geotechnical engineers to take into consideration the project location, local economic factors, local economic factors, as well as environmental conditions in order to make prudent decisions for design. It is important to note that modification and stabilization terms are not interchangeable.

2.0 Modification or Stabilization of Soils

2.1 Mechanical Modification or Stabilization

Mechanical modification or stabilization is the process of altering soil properties by changing the gradation through mixing with other soils, densifying the soils using compaction efforts, or undercutting the existing soils and replacing them with granular material.

A common remedial procedure for wet and soft subgrade is to cover it with granular material or to partially remove and replace the wet subgrade with a granular material to a pre-determined depth below the grade lines. The compacted granular layer distributes the wheel loads over a wider area and more evenly distributes wheel loads serves as a working platform. (1).

To provide a stable working platform using granular material, the following conditions shall be met.

1. The thickness of the granular material must be sufficient to develop acceptable pressure distribution over the wet/soft soils.
2. The backfill material must be able to withstand the wheel load without rutting.
3. The compaction of the backfill material shall be in accordance with the Standard Specifications.

Based on the results from research, usually 12 to 24 in. of granular material shall be adequate for subgrade stabilization. However, deeper undercut and replacement may be required in certain areas.

The undercut and backfill option is widely used for construction traffic mobility and a working platform. This option could be used either on the entire project or as a spot treatment. The equipment needed for construction is normally available on highway construction projects.

2.2 Geogrid Reinforcement

Geogrid has been used to reinforce road sections in INDOT projects. The inclusion of geogrid in subgrade changes the performance of the roadway in many ways (5). Tensile reinforcement, confinement, lateral spreading reduction, separation, construction uniformity and reduction in strain have been identified as primary reinforcement mechanisms. Empirical design and post-construction evaluation have lumped the benefits into better pavement performance during the design life. The use of geogrid with aggregate option has been designed for urban areas. A 12 in. of subgrade shall be excavated and reconstruct with aggregate No. 53 over a layer of geogrid. When foundation soils moisture are several points above the optimum a six to twelve inches No 2 aggregate may used in lieu of additional excavation. Choking of NO. 2 is important and shall be looked into. When the soils are cohesive, a separation layer is necessary between No 2 and soils. . This geogrid reinforced coarse aggregate shall provide a stable working platform.

Geogrid shall be in accordance with 918.05(a) and be placed directly over exposed soils to be modified or stabilized and then overlapped in accordance with the following table.

Dynamic Cone Penetrometer Blow Counts per 6 inches	Overlap
> 5	12 in.
3 to 5	18 in.
less than 3	24 in.

Table 1: DCP Blow Counts Per 6 Inches and Geogrid Overlap

2.3 Chemical Modification or Stabilization

The additions of chemicals such as cement, fly ash, lime or a combination of these, alter the physical and chemical properties of the soil. There are the two primary mechanisms by which chemicals alter the soil into a stable subgrade:

1. Increase in particle size by cementation, reduction in plasticity index, increased internal friction among the agglomerates, greater shear strength, and lower shrink/swell potential.
2. Absorption and chemical binding of moisture that will facilitate compaction.

3.0 Design Procedures

3.1 Suggested Criteria for Chemical Selection

When the chemical stabilization or modification of subgrade soil is considered the most economical or feasible alternate, the following criteria shall be considered for chemical selection based on the index properties of the soils.

1. Chemical Selection for Stabilization.
 - a. Lime¹: Clay content > 20% and PI > 10.
 - b. Cement: Clay content \leq 20% and PI \leq 10.
2. Chemical Selection for Modification
 - a. Lime: Clay content > 20% and PI > 10.
 - b. Lime¹ - Fly ash² blends: clay content < 20 % and 20 > PI > 10.

- c. Cement - Fly ash² blends: Clay content < 20% and $5 < PI < 15$.
- d. Cement: Clay content $\leq 20\%$ and $PI \leq 10$.
- e. Cement or Fly ash: Clay content $\leq 20\%$ and $PI \leq 10$.

Note 1. Lime shall be quick or hydrated lime only and lime shall have a soluble sulfate content < 5%.

Note 2. Fly ash shall be class C only and shall have a soluble sulfate content < 5%.

Note 3. Appropriate tests showing the improvements such as the strength gain and swell percentage) are essential for the exceptions listed above.

Note 4. Lime treated A-4 and A-6 soils may not provide immediate stability due to presence of a shallow water table. Geotechnical consultants may recommend cement as modifier for faster strength gain in these conditions.

Note 5. When chemical modification is planned for silty or sandy soils and there are weather limitations on chemical modification, the consultant, may use cement/ with flyash or lime to improve rate of strength gain.

Note 6. Use of fly ash is not permitted between October 15 and April 15.

3.2 Suggested Chemical Quantities for Modification or Stabilization

- 1. Lime or Lime By-Products: 4% to 6%
- 2. Cement: 4% to 6%
- 3. Fly ash: 10% to 15
- 4. The percentage for each combination of lime-fly ash or cement-fly ash shall be established based on laboratory testing. A minimum of 2 % quick lime or cement shall be used in all combinations.

3.3 Suitable Soils for Modification/Stabilization

The reaction of a soil with lime, cement, fly ash or blends of these materials is important for stabilization and modification. Design methodology shall be based on an increase in the unconfined compressive strength of the mixture. A pair of specimens of 2 in. diameter by 4 in. height or larger diameter with a ratio of 2:1, height/diameter, is prepared at 95% of the standard Proctor and the optimum moisture content. A 4% cement, 5% lime or 10% fly ash can be used in soils mixture. These specimens are cured for 48 hours at 70° F in the laboratory and tested in accordance with AASHTO T-208. A complimentary set of two specimens are also prepared of the soil at 95 % of standard Proctor and optimum moisture content. All specimens are then subjected to unconfined compressive testing. The minimum strength gain of both samples of the lime-soil mixture shall be 50 psi over that of the natural soil.

The minimum strength gain of the cement-soil mixture shall be 100 psi over that of the natural soil mixture and minimum strength gain for the fly ash-soil mixture shall be 50 psi over that of the natural soils.

Similarly for clayey soils, A-6, mixed with a 7 % steel slag and 3 % fly ash, (pre blended mixture,) compacted to 95 % of T 99 in two specimens with 2:1 ratio and cured for 48 hours at 70 °F. A strength gain of 75 psi over natural soils shall be obtained.

4.0 Laboratory Test Requirements

4.1 Soil Sampling.

An approved Geotechnical Engineer shall visit the project during the construction and collect a bag sample of each type of soil in sufficient quantity for performing the specified tests. The Geotechnical Engineer shall review the project geotechnical report and other pertinent documents, including soil maps, etc. prior to the field visit. The Geotechnical Consultant shall submit the test results and a recommendation, along with the current material safety data sheet and evidence that modifier is from INDOT approved list to the Engineer for approval. If the Geotechnical Engineer determines the necessity of chemical-soil stabilization during the design phase, they shall design a subgrade treatment utilizing the chemical in the geotechnical report in accordance with INDOT guidelines. All the tests shall be performed in AMRL inspected laboratory. Following properties shall be checked prior to any modification or stabilization.

1. Classified as A1, A2, A3, A-4, A-5, A-6, A-7 in accordance with AASHTO T-89 and 90, and natural moisture content based on AASHTO T-265. Foundation soils shall also be checked for moisture content.
2. pH test for optimum lime determination in accordance with AASHTO T-289 with the exceptions listed below.
3. 35% passing 200 sieve and Atterberg limits ,
4. Perform the suitability test as required in Sec 3.3,
5. Max. Dry unit weight of 95 pcf (Min.) in accordance with AASHTO T-99 or greater,
6. Loss on Ignition^{*2} (LOI) not more than 6 % dry weight of soil in accordance with T-267,
7. Sulfate content shall not be more than 1,000 ppm in accordance with ITM 510.
8. Unconfined strength on 95% compacted soils (Two) in accordance with AASHTO T-208
9. Unconfined Test on 95% chemically modified specimen (Two) in accordance with AASHTO T-208
10. Resilient modulus¹ on chemically modified (For stabilization) soils in accordance with AASHTO T-307 (Two).

Note 1: M_R Test would be performed during design phase and two specimens shall be sent to the Office of Geotechnical Services for testing. The Geotechnical Consultants shall coordinate with the INDOT Geotechnical Lab Supervisor for the sample size and dimensions needed to perform M_R Test.

Note 2: Loss on Ignition tests shall be performed if required.

4.2 Lime or Lime By-Products Required for Modification or Stabilization

Lime reacts with fine grained soils, clay, to produce decreased plasticity, increased workability, reduced swell and increased strength. As a general guide, treated soils shall increase in particle size by cementation, reduction in plasticity, increased in internal friction among the agglomerates, greater shear strength, and increased workability due to the textural change from plastic clay to friable, sand like material.

The following procedures shall be utilized to determine the amount of lime required to chemically treat the subgrade. Hydrated, quick lime or lime by-products, 4 to 6 % by weight, shall be used for soil modification or stabilization. The following procedures shall be used to determine the optimum lime content.

1. The mechanical and physical tests on the soils shall be performed.
2. The separate pH of soil and lime samples shall be determined.
3. The optimum lime content using Eades and Grim pH test shall be determined as follows:
 - a. 20 g of oven-dried minus No. 40 soil shall be weighed to the nearest 0.1 g and poured into 150-ml, or larger, plastic bottles with screw tops.
 - b. A sufficient amount of lime shall be added to soils to produce a pH of 12.4 or equal to the pH of the lime before mixing. A graph shall be plotted between the pH value and the lime percentage. The optimum lime content shall be determined corresponding to the maximum pH of lime-soil mixture. See Figure 1. It is advisable to set up five bottles with lime percentages of 3, 4, 5, 6, and 7. This shall insure, in most cases, that the percentage of lime required can be determined in one hour. Weigh the lime to the nearest 0.01 g and add it to the soil. Shake to mix soil and dry lime.
 - c. 100 ml of CO₂-free distilled water shall be added to the bottles to the bottles.
 - d. The soil, lime and water mixture shall be shaken until there is no evidence of dry material on the bottom. Shake for a minimum of 30 seconds.
 - e. The bottles shall be shaken for 30 seconds every 10 minutes for one hour.
 - f. After one hour, part of the slurry shall be transferred to a plastic beaker and the pH shall be measured. The pH meter shall be equipped with a Hyalk electrode and standardized with a buffer solution having a pH of 12.00.
 - g. The pH for each of the lime-soil mixtures shall be recorded. If the pH readings reach 12.40, the lowest percentage of lime that yields a pH of 12.40 is the percent

required to stabilize the soil. If the pH does not go beyond 12.30 and 2 percent lime produces the same reading, the lowest percent which gives a pH of 12.30 is that required to stabilize the soil. If the highest pH is 12.30 and only 1 percent lime gives a pH of 12.30, additional test bottles shall be started with larger percentages of lime.

- h. Atterberg Limit test shall be performed on soil and lime mixture corresponding to optimum lime content.
- i. Compaction testing shall be performed on the optimum lime and soil mixture to evaluate the drop in maximum dry density in relation to time,
- j. A pair of lime treated specimens compacted at 95% of Proctor, AASHTO T-99, shall be tested for strength at 70° F after curing for 48 hou.s. The strength gain shall be at least 50 psi over the natural soils.

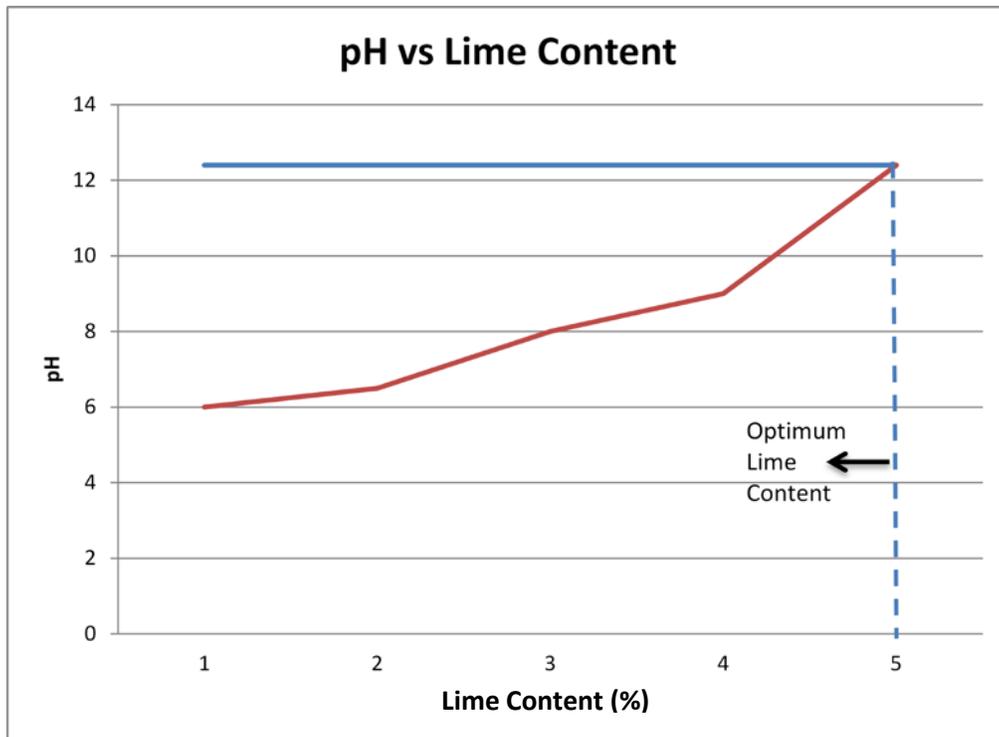


Figure 1: pH vs. Lime Content

In the case of stabilization two prepared specimens shall be delivered to the Office of Geotechnical Services for Resilient Modulus testing., Resilient Modulus, M_R tests at 95% compaction, AASHTO T-99, shall be performed in addition to the above tests corresponding to optimum lime and soil mixture of predominant soils types.

4.3 Cement Required for Stabilization or Modification

The following methodology shall be used for quality control and soil cement stabilization. 4

% of cement can be utilized to modify the subgrade.

1. Perform the mechanical and physical properties of the soils.

Table 2: AASHTO Classifications for Cement Requirements

AASHTO Classification	Typical Range Of Cement % by Dry Wt. of Soil
A-1,A-3	4 – 5
A-2, A-4	4 - 6

2. Perform the standard Proctor on soil-cement mixture in accordance with AASTO T-99. Create a pair of strength specimens, 3.3, at 95% of the standard Proctor and cure at 70° F for 48 hours. The strength gain shall be at least 100 psi when compared to the natural pills. The strength shall be in accordance with AASHTO T-208.
3. The resilient modulus shall be determined on a pair of specimens molded at 95% of the Standard Proctor for soil stabilized with cement. A strength gain of 100 psi of is adequate enough to allow for stabilization at 48 h at 70° F and % cement shall be adjusted.

4.4 Fly Ash Required for Modification

1. The in-situ soils shall meet the criteria of modifications.
2. Standard Proctor shall be performed in accordance with AASHTO T-99 to determine the maximum dry density and optimum moisture content of the soil.
3. Fly ash shall be mixed with the soils in increments of 10%, 15%, and 20% by dry weight. Each blend of the mixture shall be tested per standard Proctor to determine their respective maximum dry densities.
4. The compaction of mixes shall be completed within 2 hours of mixing.
5. A percentage of fly ash, which provides the highest maximum dry density, shall be considered as the optimum amount of fly ash for that soil.
6. Unconfined compressive strength of optimum fly ash mix sample shall be determined on a pair of specimens at 95% of the standard Proctor which have been cured at 70° F for 48 hours. The strength gain shall be a minimum of 50 psi.
7. A pair of specimens of optimum fly ash mix sample shall be molded for Standard Proctor and Resilient Modulus testing. The swell test shall be performed for extended period. The swelling shall be observed daily for 7 days. If the swell exceeds 3% then the chemical shall not be allowed to treat the soils tested.

4.5 Combination of Cement Fly Ash and Lime Mixtures

To enhance the effectiveness of lime, cement, or fly ash combinations for modification, the

subsequent guidelines shall be used. The minimum gain of 75 psi over the natural soils is required.

- Lime and Fly Ash: The ratio between lime and fly ash mixture shall be chosen from strength test. Lime shall be quick lime and shall not be less than 2 % in blend.
- Cement and Fly Ash: The ratio of cement and fly ash shall be chosen based on strength test. Cement content shall not be less than 2 % in blend.
- Lime, cement, and fly ash combinations may be used if strength criteria are met and a minimum of 2 % cement shall be used in combination.

4.6 Soils Drying

Lime and fly ash are effective chemical modifiers in soil moisture reduction. The presence of free calcium in chemical modifier makes soils drier, increases optimum moisture content of the soils in addition to changes in other soils properties. The moisture reduction by hydration and increase in optimum moisture content make this application very attractive for designers to plan ahead an expedited construction schedule. Lime and fly ash application affects soils in the following manner:

1. Dilution: adding dry chemical to wet soils,
2. Calcium Oxide Hydration: - Rapid hydration of calcium oxide to calcium hydroxide,
3. Evaporation: The exothermic reaction of lime hydration increases moisture reduction.
4. Pozolonic Reaction- Moisture combine into alumina silica compounds as pozolonic reaction begins, therefore there moisture reduction due to pozolonic reaction.
5. OMC Change: Increase of OMC, optimum moisture content, due to flocculation/agglomeration based on a change in texture from parallel alignment to edge to face attraction. The new texture will have more voids and additional room for any increase in moisture.

The following procedure shall be used to determine the appropriate modifier and as well as develop a relationship with moisture range and time delays so the modifier adjustment can be made during construction if needed.

1. All of the tests shall be performed at room temperature or at temperature desired by the Geotechnical Engineer.
2. Collect a jar soil sample of the in-situ soil and determine the in-place moisture content of the soil.
3. Perform mechanical and physical tests on each soil sample along with Loss on ignition, if required.
4. Perform the sulfate test on each soil sample.

5. Determine the pH of soil and lime samples separately.
6. Perform a typical moisture- density test on each soil type.
7. Perform a typical moisture- density test on each soil and lime mixture, such as soils with 3% lime, soils with 4% lime etc. For example: soils are 8% over OMC. After soils are mixed with 3 %, 4% and 5 % lime moisture content tests shall be performed each hour.
8. Chemical modifier % vs. moisture content relationship shall be developed and presented in a tabular or graphical form so that the chemical modifier may be adjusted in the field if needed based on the in-situ soil moisture content. The table may be expanded to include additional time.
9. Compaction shall be performed on each lime–soil mixture to evaluate the drop in maximum dry density and the rise in optimum moisture content with respect to time (depending on the delay between the lime - soil mixing and compaction:-)

Soil ID	% Above OMC (Untreated)	Untreated MC	Treated MC (By Dry Weight) After one Hour			
			3%	4%	5%	6%
Sta. 16+00	2	17.3	15.8	-	-	-
Sta. 16+00	4	19.5	18.0	16	-	-
Sta. 16+00	6	21.2	20	18	16	-
Sta. 16+00	8	23.8	22	21	19	18

Table 3: Moisture Reduction vs. Lime

4.7 Requirements for Geotechnical Submittals to INDOT

The mix design report shall be prepared by the INDOT Approved Geotechnical Consultant laboratory and duly signed by an Indiana Licensed Professional Engineer. The laboratory shall be inspected by AMRL. The summarized results of the mix design along with details shall include the following information:

1. Subgrade and its foundation (project Geotechnical report) review by Geotechnical Engineer
2. Textural and AASHTO Classifications of soils
3. Natural moisture content of subgrade and foundation soils
4. Soluble sulfate content
5. pH of soils
6. Atterberg limit of soils

7. Type and source of the chemical modifier or stabilizer
8. Mix Design proportions
9. Standard Proctor of soils, 3 points min.
10. Unconfined compressive strength at 95 % AASHTO T-99 compaction of soil
11. Standard Proctor of chemically treated soils
12. Unconfined compressive strength of chemically treated soil specimens prepared at 95% AASHTO T-99 compaction
13. Recommendations for mixing, pulverization, compaction and curing
14. Recommendations for guidance to maintain adequate moisture during mixing and curing
15. Confirmation that sulfate or other chemical constituents which may cause soil heaving are not present in the ground water. Water shall meet the requirement of Section 913.
16. Identify the specific limits of unstable foundation soils by reviewing the project geotechnical recommendations.
17. Identify the high plastic soils from the geotechnical report which needs double application or other recommendations.

Note 1: Moisture is critical for chemical modification to succeed.

Note 2: Clayey soils with high plasticity shall be tested to determine how the lime reacts with clay and how long it takes to break into smaller clay particles.

Note 3: The clayey soils shall be tested by the Eades & Grim test and not solely based on the results of unconfined compressive strength results.

Note 4: Fly ash shall not be used in a period between October 15 and April 15.

5.0 Construction Considerations

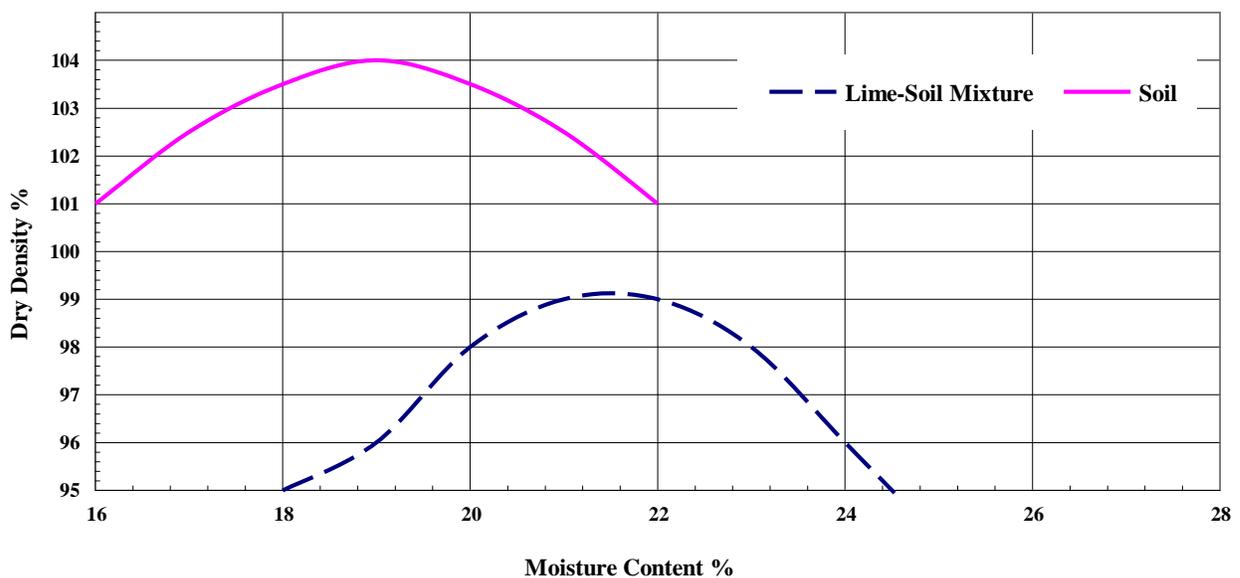
Modification of soils such as drying out of wet subgrade with lime, cement, and fly ash to speed construction is not as critical as completely stabilizing the soil to be used as a part of the pavement structure. With the growth of chemical modification throughout the state, a variety of applications are being suggested due to such factors as type of soil, percentage of modification/stabilization required, environmental restraints, and availability of chemicals. Furthermore, when chemically stabilized subgrade is used to reduce the overall thickness, the stabilized layer must be built under tight construction specifications, whereas requirements for the construction of working platforms are more lenient. Following are a few recommendations for modification or stabilization of subgrade soils.

1. Perform recommended tests on each soil to see if the soil will react with chemicals then determine the amount of chemical necessary to produce the desired results.
2. More chemicals may not give the best results.

3. The sulfate, when mixed with calcium will expand. Soils having over 1,000 ppm sulfate content shall not be mixed with chemicals.
4. Soluble sulfate in lime and fly ash shall not be greater than 5%.
5. Chemical modifier used shall be from INDOT approved list.
6. One increment of chemical is recommended to produce a working platform. Proofrolling is required before placing the base or subbase. Pavement shall not be installed before curing is completed.
7. The density of cement treated soils may likely be different than untreated soils. Standard Proctor tests shall be performed in the laboratory to estimate the appropriate target density.

Figure 3: Moisture Density Relationship

(ASTM - D698, AASHTO T 99)



8. Set the grade low to account for the swell in the lime. A swell factor of 10% is an approximate estimate.
9. Uniform distribution of chemical, throughout the soil is very important.
10. Uniform spreading and mixing are very important for chemical modification or stabilization. Gradation shall be checked in accordance with Section 215.08.
11. Curing takes 7 days of 50⁰ F + weather for stabilization. No heavy construction equipment shall be allowed on the stabilized grade during the curing period.
12. The maximum dry density of the soil-lime mixture is lower than in untreated soils. Maximum dry density reduction of 3~5 pcf is common for a given compactive effort. It is, therefore, important that the laboratory provide appropriate density. Generally lime or lime by products reduces the soils moisture by dilution, lime hydration, evaporation, and pozzolanic reactions. See Figure 3.

13. Cover the modified or stabilized roadbed with pavement before suspending work for the winter.
14. Cement or fly ash treated soils exhibit shrinkage cracks due to soil type, curing, chemical contents, etc. Therefore, it is recommended to provide surface sealing on stabilized subgrade after the curing period.
15. Moisture content of modified or stabilized subgrade shall be maintained above the optimum moisture content of modified subgrade during the curing.
16. Lime raises the pH of the soil. Phenolphthalein, a color sensitive indicator solution can be sprayed on the soil to determine the presence of lime. If lime is present, a reddish-pink color develops. See Figure 4.

Figure 4: Lime Modified Subgrade Uniformity Determination by Phenolphthalein



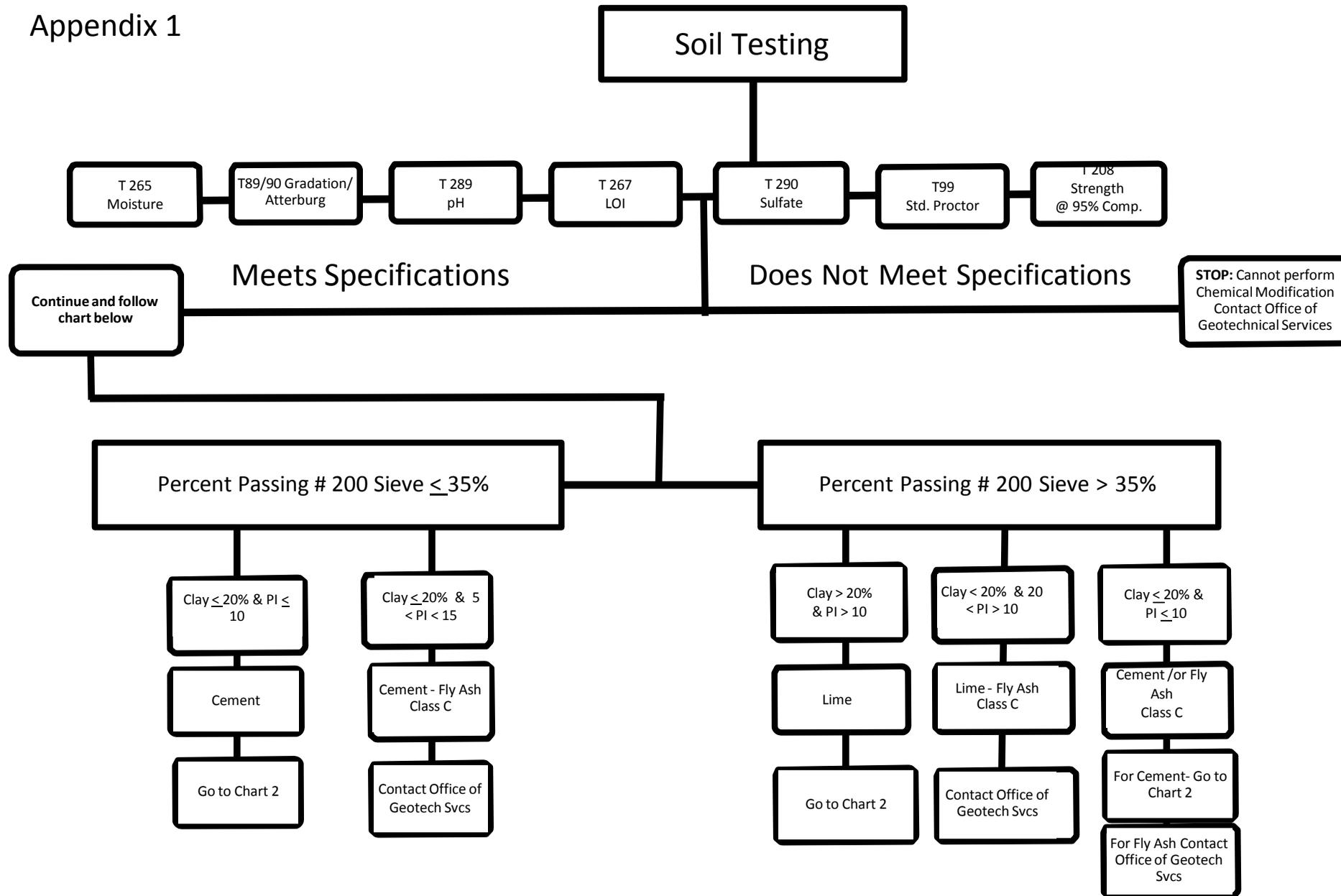
17. Because lime can cause chemical burns, safety gear, such as gloves, etc. shall be used during construction and inspection as well.

References:

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5. Zia and Fox, "Engineering Properties of Loess-Fly-Ash Mixtures For Roadbase Construction", Transportation Research Record 1714, TRB, National Research Council, Washington D. C., 2000.
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Chemical Modification Flow Chart

Appendix 1



Chemical Modification Flow Chart

Appendix 2

