Design Procedures for Soil Modification or Stabilization

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DESIGN PROCEDURES FOR SOIL MODIFICATION OR STABILIZATION

1.0 General

The Indiana Department of Transportation's policy is to minimize the disruption to motorists due to changes in traffic patterns and traffic delays caused during the construction or reconstruction of the State's roads and bridges. The Indiana Department of Transportation (INDOT) is often faced with the difficulty of constructing roadbeds on or with soils, which do not possess the sufficient strength to support wheel loads imposed upon them during the construction or the service life of the pavement. At times it is necessary to treat these soils to provide a stable subgrade or a working platform for the construction of the pavement. These treatments require less time and energy in the production, handling, and the placement of road and bridge fills and subgrades, therefore, reducing the disruption and delays to traffic.

These treatments are generally classified into two processes, soil modification and soil stabilization. The purpose of subgrade modification is to create a working platform for construction equipment. A small credit is accounted for this modification in the pavement. 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. Subgrade stabilization requires a more thorough design methodology during construction compared to subgrade 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 geosynthetics or undercutting and replacement. The treatment also includes chemical processes such as mixing with cement and lime. 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 alteration, 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 all subgrade soils with a resilient modulus of less than 5,000 psi based on laboratory testing.

INDOT Standard Specifications provide several options for subgrade treatment types which include chemical modification, replacement with aggregates, geosynthetic reinforcement in conjunction with the aggregates, density, and moisture control. The geotechnical engineer shall evaluate the needs of the subgrade and include where necessary, specific types of treatment beyond the requirements of Sec. 207 specification.

Various soil modification or stabilization guidelines are discussed below. Project location, local economic factors, as well as environmental conditions shall be considered in order to make prudent decisions for design. It is important to note that modification and stabilization terms are not interchangeable.

2.0 Soil Modification and Stabilization

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 granular material to a predetermined depth below the grade lines. The compacted granular layer distributes the wheel loads over a wider area and serves as a working platform.

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 in. to 24 in. of granular material shall be adequate for subgrade stabilization. However, deeper undercut and replacement may be required in certain areas. Drainage improvements shall also be considered, such as ditches or French drains.

The undercut and backfill option is widely used for construction traffic mobility and to establish a suitable work 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 Geosynthetic Reinforcement

Geosynthetics have been used to reinforce road sections on INDOT projects. The inclusion of geosynthetics in the subgrade has been shown to improve the performance of the roadway in many ways. Tensile reinforcement, confinement, lateral spreading reduction, separation, construction uniformity, and reduction in strain have been identified as primary reinforcement mechanisms. INDOT Standard Specification Section 207 and Section 214 specify the use of geotextile and geocell. Empirical design and post-construction evaluation have lumped the benefits into better pavement performance during the design life. The use of geotextile, geogrid, and geocell with a reduced aggregate thickness option has been successfully designed in urban areas with high water conditions. Geotextiles, geogrids, and geocells shall be in accordance with 918 and be placed directly over exposed soils to be modified or stabilized and then overlapped in accordance with the following table.

Table 1. DCP Blow Counts per 6 Inches and Geogrid Overlap

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

Once the geotextile, geogrid or geocell is installed, the layer of coarse aggregate subgrade shall be placed in accordance with 207. This reinforced coarse aggregate will provide a stable working platform.

2.3 Chemical Modification and Stabilization

The addition of chemicals such as cement, fly ash, or lime alters the physical and chemical properties of the soil. There are 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 of moisture and chemical binding that will facilitate compaction.

3.0 Design Procedures of Chemical Modification and Stabilization

3.1 Criteria for Chemical Selection

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

1. Chemical Selection for Stabilization.
   a. Quicklime or Hydrated Lime: Clay content >30 % and PI > 20. The lime shall have a soluble sulfate content < 5%. Quick lime should be used in a slurry mixture.
   b. Cement: Clay content ≤ 30% and PI ≤ 20.

2. Chemical Selection for Modification
   a. Lime or Class C Fly ash: Clay content > 30% and PI >20.
   b. Cement: Clay content ≤ 30% and PI ≤ 20.

Lime treated soils may not provide immediate stability due to presence of high–moisture. Geotechnical consultants may recommend cement as a modifier for faster strength gain in these conditions. In lieu of lime class C fly ash with a soluble sulfate content < 5% may be used. Use of fly ash is not permitted between October 15 and April 15. When fly ash class C is substituted in lieu of lime, a minimum corresponding strength of 50 psi gain should be obtained. Appropriate tests showing the improvements in the strength gain and the swell reduction are essential.

3.2 Chemical Quantities for Modification and Stabilization

The recommended quantity of chemicals is shown in the following table.

Chemical	Chemical Modification	Chemical Stabilization
Quicklime or Hydrated Lime	5% - 7%	5% - 7%
Lime By-product	6% - 7%	Not recommended
Cement	5% - 8%	5% - 8%
Fly ash	12% - 15%	Not recommended

3.3 Strength Requirement for Modification and Stabilization

The reaction of soil with lime, cement, or fly ash is important for stabilization and modification. Design methodology shall be based on an increase in the unconfined compressive strength of the mixture. To determine the increase of unconfined compressive strength, two samples of the soil without chemical incorporation should be prepared in 3-inch diameter by 6-inch in height molds. These two samples should be compacted to 95% standard proctor maximum dry density at the optimum moisture content. In addition, two samples of soil with the appropriate chemical (either 5% cement, 6% lime, or 12% fly ash by dry unit weight) should be prepared in the same fashion (3-inch diameter by 6-inch in height molds compacted to 95% standard proctor maximum dry density at the optimum moisture content). When the contractor chooses to use slurry, the soils-chemical modifier specimens should be molded at the natural moisture content of the subgrade soils. All specimens shall be cured for 48 hours at 70 degrees F in the laboratory and then tested in accordance with AASHTO T-208.

The minimum strength gain required for chemical modification and the target design strength for stabilization are as follows.

Chemicals	Strength Gain for Chemical Modification	Target Design Strength for Chemical Stabilization
Quicklime or Hydrated Lime	50 psi	150 psi
Lime By-product	50 psi	Not recommended
Cement	100 psi	300 psi[1]
Fly ash	50 psi	Not recommended

Note 1: Strength tested at 7 days

When the contractor chooses to use a slurry, the chemically modified specimens should be molded at the natural moisture content of the subgrade soils.

4.0 Laboratory Test Requirements

Soil modification or stabilization mix design shall be performed in accordance with the following: AASHTO T 88, T 89, T 90 T 89, T 90, T 99, T 208, T 265, T 289, T 307, and ITM 510. All the tests shall be performed in AASHTO Accredited Laboratories.

4.1 Soil Sampling

A qualified 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 recommendations, along with the current material safety data sheet and evidence that the modifier is from the 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. Following properties shall be checked prior to any modification or stabilization.

1. Soil Classification as A1, A2, A3, A-4, A-5, A-6, and A-7 in accordance with AASHTO M 145
2. Moisture content
3. pH for optimum lime content determination
4. Maximum dry density of 90 pcf or greater
5. Loss on Ignition[1] (LOI) not more than 6 % dry weight of soil
6. Sulfate content not greater than 1,000 ppm
7. Two unconfined compressive strength at 95% compaction on natural soils
8. Two unconfined compressive strength at 95% compaction on chemically modified specimen
9. Two resilient modulus[2] on chemically stabilized soils

Note 1: Loss on Ignition tests shall be performed when required.

Note 2: For chemical stabilization only. M_r Test should be performed during the design phase and two specimens shall be sent to the Geotechnical Engineering Division 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.

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

Lime reacts with fine silts and clay to improve soil plasticity, workability, swell potential and strength. As a general guide, treated soils shall increase in particle size by cementation, reduction in plasticity, increased internal friction among the agglomerates, greater shear strength, and increased workability due to the textural change from plastic clay to a friable, sand-like material. Moisture is critical for chemical modification to succeed. 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. The clayey soils shall be tested by the Eades & Grim test and not solely based on the results of unconfined compressive strength results.

The following procedures shall be utilized to determine the amount of lime required to chemically treat the subgrade. Hydrated quicklime or lime by-products 5 to 7% by weight, shall be used for soil modification or stabilization. The following procedures shall be used to determine the optimum lime content.

1. The sieve analyses on the soils shall be performed.

2. The separate pH of soil and lime samples shall be determined.

3. The optimum lime content using the 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 ensure, 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 CO_2-free distilled water shall be added to the bottles of soil-lime mixture.

    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 whereas 2 percent lime produces the same reading, the lowest percent which gives a pH of 12.30 is 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. An 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 lime.

j. A pair of lime treated specimens compacted at 95% of Proctor shall be tested for strength at 70º F after curing for 48 hours. The strength gain shall be at least 50 psi over the natural soils.

In the case of stabilization, two prepared specimens shall be delivered to the Geotechnical Engineering Division for Resilient Modulus testing.

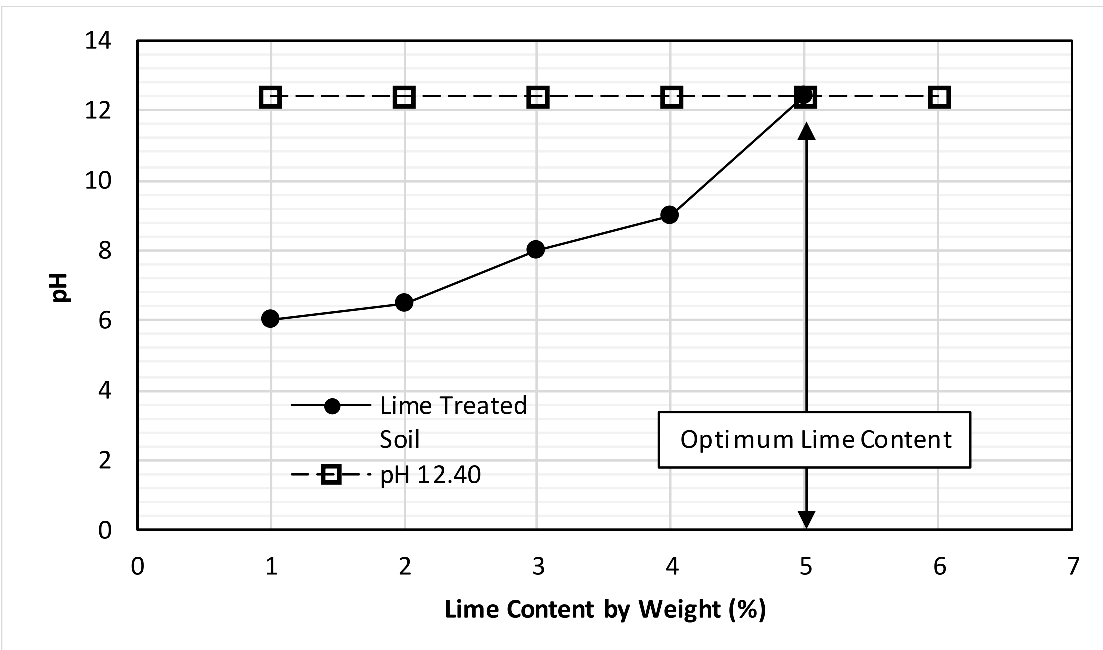

Figure 1. pH vs. Lime Content

4.3 <u>Cement Required for Stabilization or Modification</u>

The following methodology shall be used for quality control of cement modification or stabilization.

1. Perform the standard Proctor on soil-cement mixture.
   Prepare 2 specimens, as per Section 3.3. The minimum strength gain and target design

strength for cement modification or stabilization shall meet the requirement described in Section 3.3.

2. The resilient modulus (M_r) shall be determined on the two specimens compacted at 95% of the standard Proctor for cement stabilization.

4.4 Fly Ash Required for Modification

The following methodology shall be used for soil modification with fly ash.

1. Standard Proctor shall be performed to determine the maximum dry density and optimum moisture content of the soil.
2. 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.
3. The compaction of mixes shall be completed within 2 hours of mixing.
4. 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.
5. The 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 70º F for 48 hours. The strength gain shall be a minimum of 50 psi.
6. Two specimens of optimum fly ash mix sample shall be molded for standard Proctor. The swell test shall be performed for an extended period in accordance with AASHTO T 193. The swelling shall be observed daily for 7 days. If the swell exceeds 3%, the chemical shall not be allowed to treat the tested soils.

4.5 Mix Design Submittal of Chemical Modification and Stabilization

The mix design shall be prepared by the INDOT Qualified Geotechnical Consultant. The mix design report shall be signed and sealed by an Indiana Licensed Professional Engineer. The laboratory shall be accredited by AASHTO. The summarized results of the mix design, along with details, shall include the following information:

1. Subgrade and its foundation recommendations available in the project's geotechnical report
2. Textural and AASHTO Classifications of soils
3. Natural moisture content of 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 % compaction of soil
11. Standard Proctor of chemically treated soils
12. Unconfined compressive strength of chemically treated soil specimens prepared at 95% compaction
13. Recommendations for mixing, pulverization, compaction and curing
14. 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 groundwater. Water shall meet the requirement of Section 913.
16. Specific limits of unstable foundation soils by reviewing the project geotechnical recommendations.

4.6 Soils Drying with Chemical Modifiers

Lime is an effective chemical modifier in soil moisture reduction. The presence of free calcium in chemical modifiers makes soils drier and increases the optimum moisture content of the soils, which makes this application very attractive for designers to plan ahead and allow for an expedited construction schedule. Lime application affects soils in the following manner,

- Dilution: adding dry chemical to wet soils
- Calcium Oxide Hydration: Rapid hydration of calcium oxide to calcium hydroxide,
- Evaporation: The exothermic reaction of lime hydration increases moisture reduction.
- Pozzolanic Reaction: Moisture combines calcium hydroxide with alumina silica compounds as pozzolanic reaction begins. This reduces the free moisture.
- Optimum Moisture Content (OMC) Change: An increase of OMC 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 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 testing shall be performed at room temperature or at the 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 sieve analysis and Atterberg limits tests on the predominant soil sample. Loss on Ignition test should also be performed, if required.
4. Perform the sulfate test on each soil sample.

5. Determine the pH of soil and lime samples separately.
6. Perform a standard Proctor moisture-density test on the predominant soil type.
7. When wet soils with field moisture of greater than 10% over OMC are encountered, the soils should be spread and mixed with rotary speed mixers for moisture reduction.
8. Perform the moisture content tests on the soil-lime mixture with 3%, 4%, and 5% lime at the field moisture. After soils are mixed with lime, moisture content tests shall be performed each hour for up to 2 hours. For a soil drying application, the lime by-products shall not be greater than 5%.
9. 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 following table shows an example of moisture reduction based on different lime contents. The OMC of the untreated soil is 15%. Depending on the field moisture, the lime content and time for treatment can be adjusted.

Table 2. Example of Moisture Reduction vs. Lime Contents

% Above OMC (Untreated)	Untreated MC	Treated MC (By Dry Weight) After one Hour		
		3%	4%	5%
2	17.0	16.0	-	-
4	19.0	18.0	16.0	-
6	21.0	20.0	18.0	16.0
8	23.0	22.0	21.0	19.0

Chemical modifier, mix design, test results, and the geotechnical consultant's recommendations shall be submitted to the Engineer and to the Department's Geotechnical Engineering Division for approval.

5.0 Construction Considerations

The chemical modification of soils with lime, cement, and fly ash used 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 constraints, and availability of chemicals. Furthermore, when a 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 the modification and 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 the chemical necessary to produce the desired results.
2. Gradation and moisture tests shall be performed in accordance with ITM 516 and ITM 506.
3. More chemicals do not guarantee the best results.
4. When mixed with calcium, sulfate will expand. Soils having over 1,000 ppm sulfate content shall not be mixed with chemicals.
5. Soluble sulfate in lime and fly ash shall not be greater than 5%.
6. Chemical modifiers shall be from the INDOT approved list.
7. One type of chemical is recommended to produce a working platform.
8. Dynamic cone penetrometer (DCP) or Light Weight Deflectometer (LWD) shall be used in accordance with ITM 508 or ITM 509. Compaction acceptance shall be in accordance with 215.
9. Proofrolling shall be performed in accordance with 203.26 prior to placing a subsequent layer.
10. Set the grade low to account for the swell in the lime. A swell factor of 10% is an approximate estimate.
11. Uniform distribution of chemicals throughout the soil is very important.
12. Uniform spreading and mixing are very important for chemical modification or stabilization. Gradation shall be checked in accordance with Section 215.08.
13. For stabilization, the surface should be maintained in a moist condition for seven days in accordance with Section 219.13. No heavy construction equipment shall be allowed on the stabilized grade during the curing period.
14. The maximum dry density of the soil-lime mixture decreases when compared to the untreated soils, whereas the OMC of the soil-lime mixture increases. Generally, lime or lime by-products reduce the soil moisture by dilution, lime hydration, evaporation, and pozzolanic reactions. See Figure 2.
15. Cover the modified or stabilized roadbed with pavement before suspending work for the winter.
16. Cement treated soils may exhibit shrinkage cracks when exposed to the atmosphere for a long period. It is recommended to provide surface sealing on stabilized subgrade after the curing period.
17. Moisture content of modified or stabilized subgrade shall be maintained above the optimum moisture content of modified subgrade during curing.
18. 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 3.
19. Lime and cement can cause chemical burns. Safety gear, such as gloves, eye protection, etc., shall be used during construction and inspection.

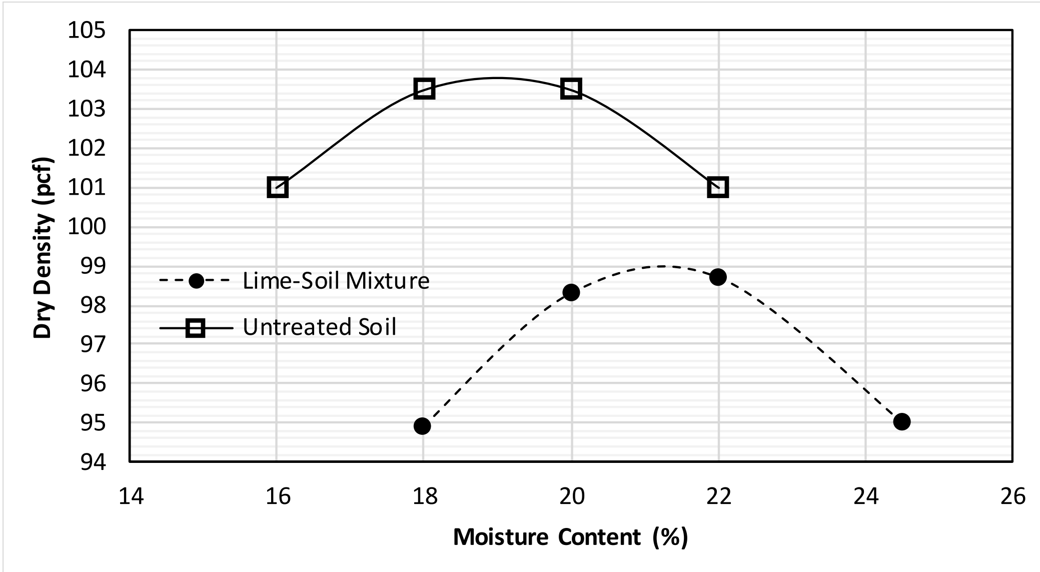

Figure 2. Moisture Content – Density Relationship

(a) Well mixed lime-soil modified soil **(b) Poorly mixed lime-soil modified soil**

Figure 3. Lime Modified Subgrade Uniformity Determination by Phenolphthalein

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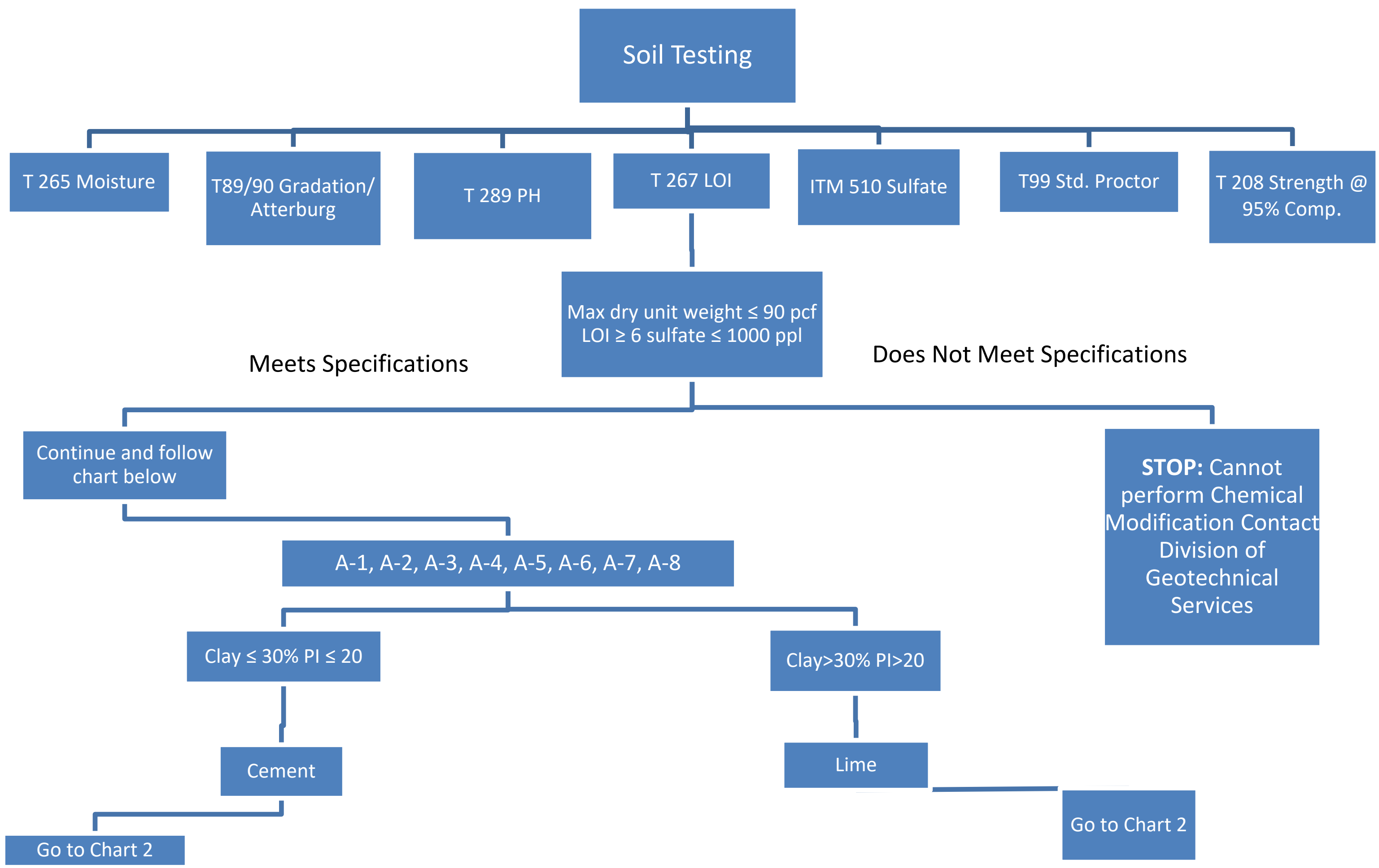
Chemical Modification Flow Chart 1

Appendix



Chemical Modification Flow Chart 2