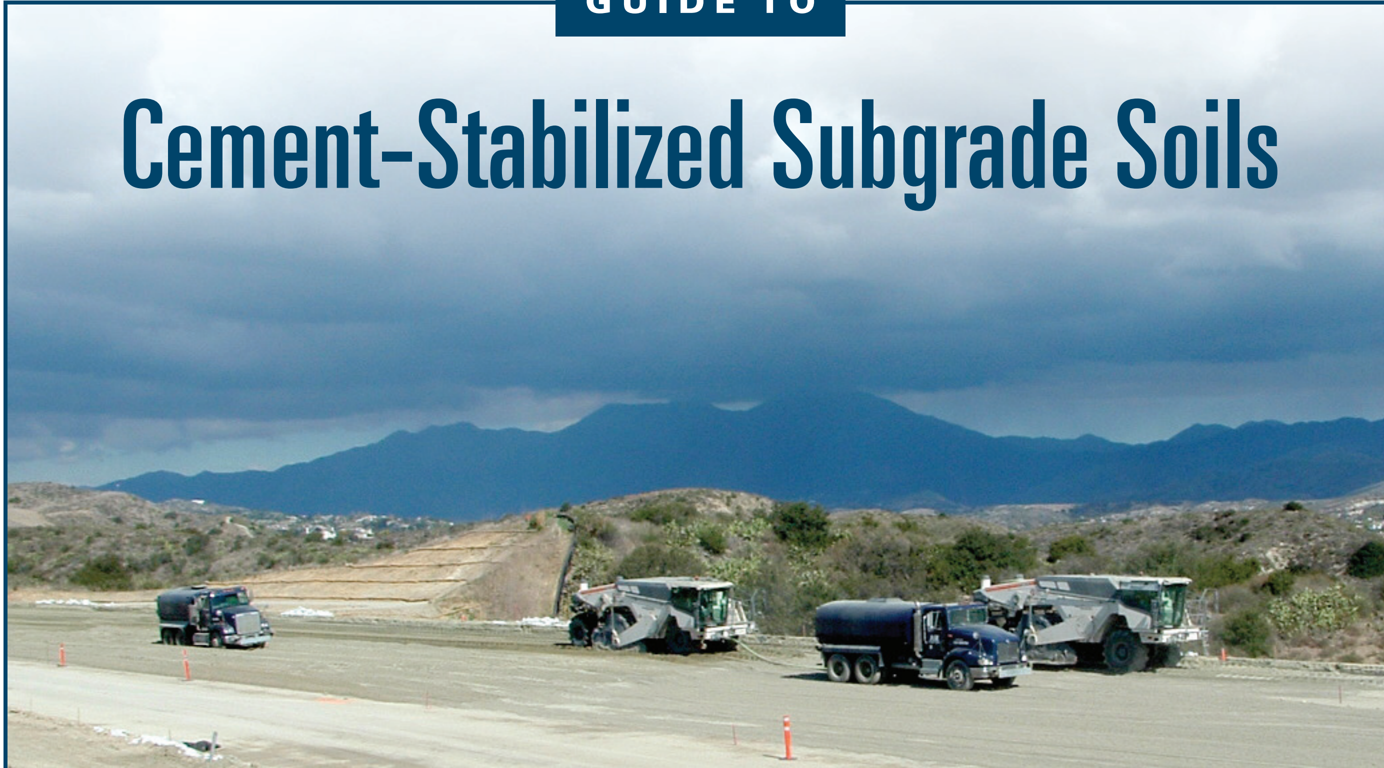
GUIDE TO

Cement-Stabilized Subgrade Soils



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The mission of the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.

About the PCA

The Portland Cement Association (PCA) is a nonprofit organization founded in 1916 that serves America's cement manufacturers through policy, research, education, and market intelligence. PCA members represent 91 percent of US cement production capacity with facilities in all 50 states. PCA promotes safety, sustainability, and innovation in all aspects of construction, fosters continuous improvement in cement manufacturing and distribution, and generally promotes economic growth and sound infrastructure investment.

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About this Guide

This document, *Guide to Cement-Stabilized Subgrade Soils*, is a product of the CP Tech Center with funding from the PCA. It provides guidance for engineers, producers, contractors, and owners to improve soil properties for construction of various types of infrastructure. The focus of this guide is roadway applications.

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16. Abstract

The primary purpose of this guide is to describe the characteristics, uses, and benefits of cement-stabilized subgrade (CSS) and present methods for geotechnical evaluation, mix design, construction, and field testing that will produce a satisfactory project. The material in this guide updates and expands on the information presented in the Portland Cement Association's 2008 publication *Guide to Cement-Modified Soil (CMS)*.

To clarify the scope of this guide, CSS is distinguished from CMS as follows. CMS describes otherwise untreated soils, particularly clayey soils, that have been treated with a relatively small proportion of portland cement to provide improved characteristics, including reduced plasticity and volume change potential and increased bearing capacity. CSS not only provides the benefits of CMS but also substantially increases soil stiffness and strength to the point where the treatment can provide structural benefits to pavement and building foundations. Unless stated otherwise, this guide primarily discusses CSS.

This guide discusses several critical aspects of CSS. The first two chapters describe the key terminology related to cement-treated soil, the effects of cement on the various material properties of the treated soil, the benefits that CSS provides, and the soil properties and classifications relevant to cement treatment. The third chapter provides a systematic procedure for conducting a geotechnical evaluation and a field sampling and testing program. The fourth chapter outlines a step-by-step mix design process for determining the proper cement content for a desired application and treated soil characteristics. The fifth chapter summarizes construction, field inspection, and testing methods, and the final chapter presents several case studies to illustrate the information provided in the guide.

Design engineers, testing laboratory personnel, contractors, and owners will find this document useful for determining whether CSS is appropriate for a particular application and the proper steps to follow to produce a satisfactory project.

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Executive Summary

The primary purpose of this guide is to describe the characteristics, uses, and benefits of cement-stabilized subgrade (CSS) and present methods for geotechnical evaluation, mix design, construction, and field testing that will produce a satisfactory project. The material in this guide updates and expands on the information presented in the Portland Cement Association's 2008 publication *Guide to Cement-Modified Soil (CMS)*.

The use of cement for subgrade soil treatment, whether through CMS or CSS, can be an economical, fast, and sustainable solution to several soil problems encountered before or during construction. Cement treatment can thus help reduce or maintain project timelines and budgets and minimize the impacts of poor soil on pavement design. Additionally, in both rural and urban environments cement treatment is usually a cost-effective and sustainable alternative to removing and replacing soil.

CMS and CSS share many characteristics and applications. Both treatments improve the physical properties of the native in situ soil, and both help extend the life of a pavement by providing uniform support via a durable, stable, and typically non-expansive subgrade.

However, to clarify the scope of this guide the two treatments are distinguished as follows:

- CMS describes otherwise untreated soils that have been treated with a relatively small proportion of portland cement to provide a stable working platform. The improvements offered by the treatment include reducing the plasticity and shrink/swell potential of unstable, highly plastic, wet, or expansive soils as well as increasing the bearing capacity.
- CSS not only provides all the benefits of CMS but also substantially increases soil stiffness and strength to the point where the treatment can provide structural benefits to pavement and building foundations.

Unless stated otherwise, this guide primarily discusses CSS.

While this document may not address all of a project's specific details, it provides guidance on the cement treatment of subgrade soils. Among other topics, this guide addresses soil classifications and properties, geotechnical evaluation, and the design, construction, and field testing of CSS. Throughout, this guide addresses the importance of geotechnical oversight at the beginning of a project, during the mix design stage, and during construction in order to ensure that the project meets its intended purpose.

The six chapters in this guide cover the following information:

- **Chapter 1. Introduction**
  Chapter 1 covers the purpose of the guide, key terminology, a comparison of soil-cement products, soil modification mechanisms, and the benefits and life expectancy of CSS.
- **Chapter 2. Materials and Properties**
  Chapter 2 covers basic information on soil types and properties and explains how cement stabilization affects engineering properties.
- **Chapter 3. Geotechnical Evaluation and Field Sampling**
  Chapter 3 covers the various types of sampling and testing required to determine soil types and properties.
- **Chapter 4. Mixture Design**
  Chapter 4 covers the process used to determine the proper cement content required to stabilize the subgrade.
- **Chapter 5. Construction, Field Inspection, and Testing**
  Chapter 5 discusses the process for constructing a cement-stabilized subgrade, the equipment required, and the necessary field inspection and testing.
- **Chapter 6. Case Studies**
  Chapter 6 includes five case studies that describe projects in which cement has been incorporated into the subgrade to improve soil properties. Each case study includes project information and a detailed discussion of improvements.

The following appendices are included at the end of this guide:

- **Appendix A. Suggested Construction Specification for Cement-Stabilized Subgrade Soils**
  Appendix A provides a guide specification covering submittals, materials, equipment, construction inspection, and testing requirements for constructing cement-stabilized subgrade soils.
- **Appendix B. Mix Design Swell Test Method for Soil Treatment Using Additives (Cement or Other)**
  Appendix B describes a test method for determining the extent to which engineering properties such as strength and shrink/swell potential are improved for soils treated with cement or other additives relative to untreated soil.

Chapter 1. Introduction

The primary purpose of this guide is to describe the characteristics, uses, and benefits of cement-stabilized subgrade (CSS) and present methods for geotechnical evaluation, mix design, construction, and field testing that will produce a satisfactory project. The material in this guide updates and expands on the information presented in the Portland Cement Association (PCA) publication *Guide to Cement-Modified Soil (CMS)* (Halsted et al. 2008).

To clarify the scope of this guide, CSS is distinguished from CMS as follows:

- CMS describes otherwise untreated soils that have been treated with a relatively small proportion of portland cement to provide a stable working platform. The improvements offered by the treatment include reducing the plasticity and shrink/swell potential of unstable, highly plastic, wet, or expansive soils and increasing the bearing capacity.
- CSS not only provides all of the benefits of CMS but also substantially increases soil stiffness and strength to the point where the treatment provides structural benefits to pavement and building foundations.

Unless otherwise noted specifically, this guide primarily discusses CSS.

This first chapter defines key terminology regarding cement-treated soil, compares four cement treatments in terms of their applications and benefits, describes the mechanisms by which cement modifies soil, and then summarizes the benefits and life expectancy of CSS.

Terminology

Soil-Cement

Soil-cement refers to a compacted engineered mixture of soil, cement, and water designed and constructed for various pavement and geotechnical applications and characteristics. The term soil-cement can be considered an umbrella term covering the four types of cement products defined in the following paragraphs.

Note that throughout this guide, the term cement always refers to portland cement, a hydraulic cement that sets and hardens by reacting chemically with water (hydration).

Cement-Modified Soil (CMS)

CMS is a compacted mixture of pulverized in situ soil, water, and small proportions of cement that results in an unbound or slightly bound material. The treated material is similar to a soil but has reduced plasticity and a lower susceptibility to moisture, resulting in a more workable material.

The principal benefits of CMS are as follows:

- Improves the workability of subgrade soils and their ability to be used in construction
- Reduces plasticity and shrink/swell volume change potential
- Reduces moisture susceptibility and migration
- Increases the speed of construction on sites due to the reduced impact of rain
- Increases bearing capacity compared to untreated soil
- Promotes soil drying
- Provides a significant improvement to the working platform
- Uses on-site soil rather than costly removal and replacement with select fill material
- Provides a permanent soil modification (does not leach)
- Does not require any mellowing period

Cement-Stabilized Subgrade (CSS)

CSS is a compacted, engineered mixture of pulverized in situ soil, water, and moderate proportions of cement (slightly more cement than CMS) that results in a semi-bound to bound material. The treated material has structural engineering properties similar to or better than those of a granular material.

In addition to all of the benefits of CMS, CSS provides improved shear and compressive strength and/or soil shrink/swell tendencies. The degree of improvement depends on the quantity of cement used and the type of soil. Therefore, by the addition of varying amounts of cement, it is possible to produce cement-stabilized subgrade with a wide range of engineering properties. Typical seven-day unconfined compressive strengths (UCS) for CSS range from 100 to 300 psi (0.7 to 2.1 MPa).

CSS provides all the principal benefits of CMS in addition to the following:

- Reduces moisture susceptibility and migration
- Improves bearing strength and increases California Bearing Ratio (CBR)
- Potentially allows for a reduction in pavement thickness or increased pavement life
- May be used to support other infrastructure, including rails, airfields, parking lots, and loading/intermodal facilities

Cement-Treated Base (CTB)

Cement-treated base (CTB) is a fully bound, compacted, engineered mixture of aggregate, water, and sufficient cement to meet the project-specified minimum durability and strength requirements. CTB can be mixed in place using on-site soils or mixed in a central plant or pugmill using selected aggregate. Because of the better aggregate selection available for CTB, it typically uses about the same quantity of cement as CSS; however, CTB results in a stronger, more durable, more frost-resistant layer within the pavement structure. Typical seven-day UCS for CTB range from 300 to 600 psi (2.1 to 4.1 MPa). More detailed information about CTB can be found in the PCA publication *Guide to Cement-Treated Base (CTB)* (Halsted et al. 2006).

The principal benefits of CTB are as follows (Halsted et al. 2006):

- Provides a stiffer and stronger base than an unbound granular base
- Requires a thinner section for roadway bases compared to an unbound granular base
- Provides a moisture-resistant base
- Provides an erosion-resistant base
- Improves freeze/thaw durability
- Provides high strength, even when saturated

Full-Depth Reclamation (FDR)

A special case of CTB, full-depth reclamation (FDR) is a process that involves pulverizing and blending an existing distressed asphalt roadway surface and its underlying base and/or subgrade materials. Cement is mixed with the pulverized material, compacted, and cured, resulting in a new homogenous and stabilized base. With respect to performance, this method compares favorably to the complete removal and replacement of a distressed asphalt pavement and underlying granular base material. More detailed information about the benefits, design, and construction of FDR can be found in the PCA publication *Guide to Full-Depth Reclamation (FDR) with Cement* (Reeder et al. 2017).

FDR provides all the principal benefits of CTB in addition to the following:

- Increases structural capacity for existing roadways compared to non-stabilized sections
- Increases durability compared to granular base materials
- Provides substantial cost savings compared to removal and replacement
- Reduces environmental impacts compared to removal and replacement
- Reduces truck traffic and improves safety compared to removal and replacement
- Allows for faster construction time compared to removal and replacement

Comparison of CMS, CSS, CTB, and FDR

Given that subgrade soils are an integral part of any pavement system design (Figure 1.1) and poor subgrade support is the principal cause of pavement distress, the benefits offered by any of the four cement treatments described above can be crucial to long-term pavement performance if undesirable subgrade soils are encountered within project limits.

CSS and CMS

Despite their similarities, CMS and CSS are different treatments. The primary purpose of CSS is to improve the engineering properties of the native in situ subgrade soil so that it behaves similarly to or better than an enhanced, untreated aggregate base with uniform support. While CMS also improves the properties of the existing subgrade, CSS provides all the benefits of CMS in addition to reducing moisture susceptibility, permeability, volume change potential, and plasticity and improving bearing strength. The improved strength that CSS provides are often considered in pavement design analysis, resulting in reduced thicknesses for the overlying pavement courses.

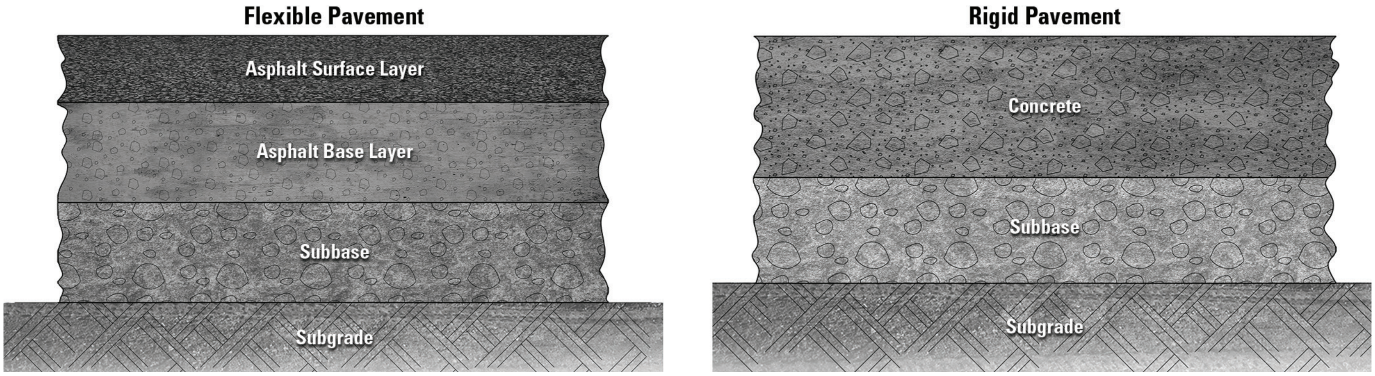

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Figure 1.1. Structural layers in flexible and rigid pavements

To determine whether CSS or CMS is a viable candidate for a project, a routine geotechnical investigation should be performed during the planning stages to determine the soil profile and various properties of the underlying material, including moisture content, plasticity characteristics, swell potential, and bearing capacity. If remediation is required, this information can also help determine the amount of cement necessary to remedy the soil. Chapter 2 discusses the recommended laboratory tests in greater depth.

CSS and CTB

The main difference between CSS and CTB is that CSS involves mixing cement into an existing fine-grained material to improve the properties of the existing subgrade soil, while CTB provides a higher end structural base layer and usually, but not always, consists of predominantly coarse-grained material. CTB is also designed to have higher strengths than CSS and to be resistant to frost and erosion.

Because CTB typically consists of select aggregate, it typically requires a similar or lower percentage of cement compared to CSS in order to achieve the desired strength and durability properties. The percentage of cement required for both CSS and CTB depends on the type of soil or aggregate, the desired engineering characteristics, and the design of the overall pavement system. For instance, a lower percentage of cement would be required to provide the desired engineering properties for a subgrade or base material that consists of a well-graded aggregate compared to a subgrade or base material that consists of a significant amount of clayey or silty soil.

In terms of applications, CSS alone may be used as the direct support material for concrete pavements, while for flexible pavements an aggregate base is typically placed upon the CSS before placement of the pavement. Like CSS, CTB may also be used as the direct support material for concrete pavements, though an interlayer of asphalt/aggregate base or a geofabric between the CTB and the concrete may also be included. Unlike CSS, CTB may be used as the direct support material for flexible pavements; however, in such cases precautions, such as limiting the strength of the CTB or incorporating microcracking into the CTB, should be considered in order to reduce the potential for reflective cracking in the surface pavement.

FDR

In some situations where an existing road that includes underlying base material is in poor condition due to an extensive amount of pavement distress, major rehabilitation or total reconstruction is necessary. If this is the case, FDR should be considered. As a form of CTB, FDR has similar engineering properties and construction requirements.

Summary

Table 1.1 lists the purposes of and the materials and construction practices used for the four primary soil-cement products discussed in this chapter: CMS, CSS, CTB, and FDR.

Although CSS has applications that extend beyond stabilizing problematic soils, the remainder of this guide focuses on the use of cement to enhance the engineering properties of subgrade soils beneath both rigid and flexible pavements as well as building floor slabs.

Table 1.1. Key features of soil-cement products

Soil-Cement Type	Cement-Modified Soil (CMS)	Cement-Stabilized Subgrade (CSS)	Cement-Treated Base (CTB)	Full-Depth Reclamation (FDR)
Purpose	• Promotes soil drying • Provides a significant improvement to the working platform • Provides a permanent soil modification (does not leach)	• Provides all the benefits of CMS plus the following: - Potentially allows for a reduction in pavement thickness or increased pavement life - Increases the bearing capacity for building slabs, footings, and other structural elements	• Provides a strong, frost-resistant base layer for asphalt or concrete pavements	• Provides a strong, frost-resistant base layer for asphalt or concrete pavements
Materials	• Primarily fine-grained soils • 2%–4% cement	• Primarily fine-grained soils • 3%–6% cement	• Primarily coarse-grained manufactured materials • 3%–6% cement	• Pulverized asphalt blended with existing pavement base, subbase, and/or subgrade • 3%–6% cement
Material Properties	• Reduced moisture susceptibility	• 100–300 psi (0.7–2.1 MPa) seven-day compressive strength	• 300–600 psi (2.1–4.1 MPa) seven-day compressive strength	• 300–600 psi (2.1–4.1 MPa) seven-day compressive strength
Construction Practices	• Minimum 95% of maximum density • Mixed in place	• Minimum 95% of maximum density • Mixed in place	• Minimum 95%–98% of maximum density • Mixed in place or at a plant	• Minimum 95%–98% of maximum density • Typically mixed in place

Source: Adapted from PCA 2005

Modification Mechanisms

CMS and CSS physically and/or chemically modify the makeup of existing subgrade soils that may be unsuitable due to high shrinkage or expansion potential, low bearing capacity, evidence of instability, or high moisture contents that will cause unstable subgrades during construction activity.

The improved engineering properties that CMS and CSS impart to the subgrade soil, including improved workability, lower plasticity, reduced volume change potential, and increased bearing strength, are achieved primarily through the four modification mechanisms of cement stabilization:

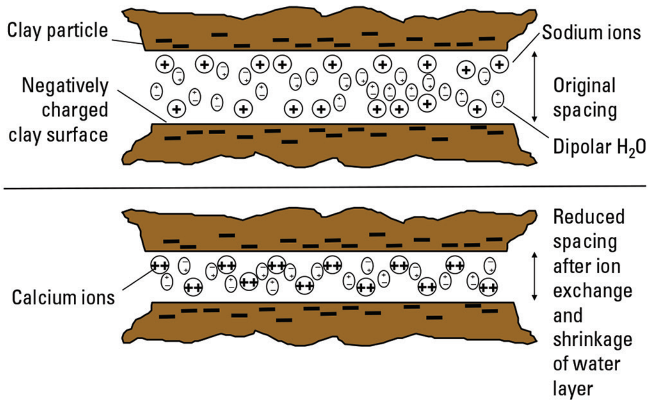
- Cation Exchange
- Particle Restructuring
- Cementitious Hydration
- Pozzolanic Reactions

Cation Exchange

Plastic soils have a high plasticity index (PI) and tend to be comprised of clay. Clay is primarily composed of aluminum silicates. The clay particles sustain net negative charges on their surfaces that are balanced by exchangeable positively charged ions (cations) held together by electrostatic attraction. Some cations are capable of only forming a single, or monovalent, bond.

The plasticity of a soil/aggregate is determined by the amount of expansive clay (e.g., montmorillonite) present. The clay mineral forms a bonded crystal structure through the stacking of silica and alumina layers. Because of the negative charge on this crystal structure, cations and water molecules (H_2O) are attracted to its negatively charged surfaces in an attempt to neutralize the charge deficiency. This results in a separation of the charged surfaces, forming a diffuse double layer. The thicker this double layer, the more plastic the soil/aggregate.

If the cation responsible for the neutralization is monovalent, such as sodium, the soil/aggregate becomes plastic. In order to reduce the soil's plasticity, the monovalent cations present in the clay surface must be exchanged so that the thickness of the double layer is reduced. Fortunately, the monovalent cations within the double layer can be easily exchanged for other cations. Cement, a good calcium-based soil modifier, can provide sufficient calcium ions to replace the monovalent cations on the surfaces of the clay particles. This ion exchange process occurs within hours, shrinking the layer of water between the clay particles and reducing the plasticity of the soil/aggregate. This phenomenon is illustrated in Figure 1.2.



Halsted et al. 2008, © 2008 PCA, used with permission

Figure 1.2. Cation exchange

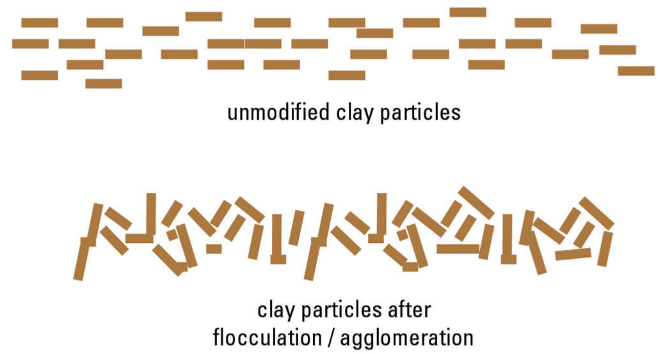


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Figure 1.3. Flocculation and agglomeration

Particle Restructuring

Typically, clay soils are lightweight, have high void ratios, and are difficult to manipulate. The addition of cement results in soil restructuring. The restructuring of modified soil/aggregate particles, known as flocculation and agglomeration, changes the texture of the material from that of a plastic, fine-grained material to one more resembling a friable, granular soil/aggregate (Halsted et al. 2008).

Flocculation is defined as the process by which clay particles form clot-like masses as a result of a chemical reaction between clay and another substance, in this case, cement. In the context of soil modification, agglomeration refers to the weak bonding at the edge-surface interfaces of the clay particles, which, as a result, forms larger aggregate-like particles from finely divided clay particles and further improves the texture of the soil/aggregate (Halsted et al. 2008).

Before soil undergoes flocculation and agglomeration, the clay particles are naturally aligned parallel to each other in layers due to their chemical composition. After undergoing flocculation and agglomeration, the clay particles are aligned randomly in an edge-to-face orientation, which gives the soil a granular-like texture (Figure 1.3). The high electrolyte content and high pH of the treated soil and the reduction in the thickness of the double layer are all attributed to dispersion.

Cementitious Hydration

Cementitious hydration (see Figure 1.4) is a process that is unique to cement and produces products referred to in cement chemistry as calcium-silicate-hydrate (CSH) and calcium-aluminate-hydrate (CAH). CSH and CAH act as the "glue" that provides structure in a cement-modified soil/aggregate by stabilizing flocculated clay particles through the formation of cement-clay bonds. This bonding between the hydrating cement and the clay particles improves the gradation of the modified clay by forming larger aggregate-like particles from fine-grained particles. The majority of this reaction occurs within the first 30 days after cement is added to the soil.

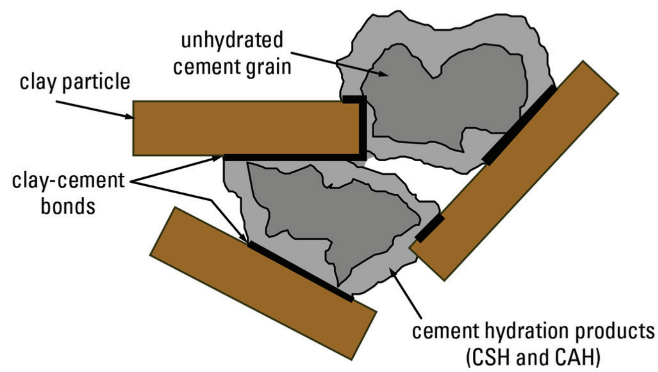

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Figure 1.4. Cementitious hydration

Pozzolanic Reactions

While cementitious hydration is the primary reaction between cement and water, secondary reactions, known as pozzolanic reactions, also occur (Figure 1.5). These reactions are created from the combination of calcium ions, silica, and alumina. Although pozzolanic reactions occur via a through-solution process, it has been claimed that they are, in fact, direct reactions between calcium hydroxide ($Ca(OH)_2$) and adjacent clay surfaces, with the pozzolanic products formed as precipitates (Prusinski and Bhattacharja 1999). These reactions can be described as follows:

$Ca(OH)_2 + SiO_2 \rightarrow$ Calcium-Silicate-Hydrate

$Ca(OH)_2 + Al_2O_3 \rightarrow$ Calcium-Aluminate-Hydrate

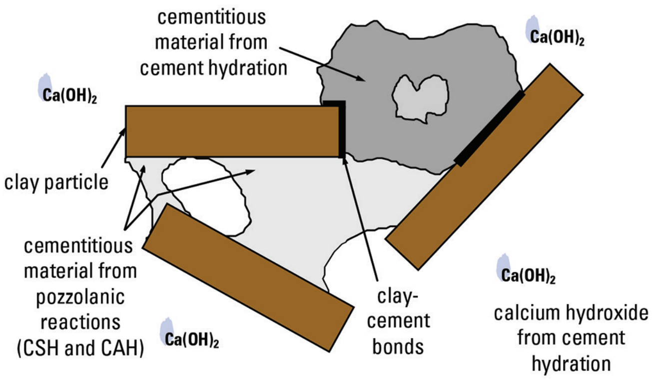

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Figure 1.5. Pozzolanic reactions

California Nevada Cement Association top; Snyder & Associates, Inc. bottom

Figure 1.6. Comparison of CSS with removal and replacement

Calcium hydroxide results from hydration, which furthers the cementing action. The process takes calcium ions (from cement) and combines them with silica and alumina (from clay) to form additional aluminates and silicates. Although pozzolanic reactions occur to a much lesser degree than cementitious hydration, they add further strength and durability to the soil and can continue for several months or years.

Benefits of CSS

Time and Cost Savings

Because it involves the application of cement to on-site soil that has undesirable characteristics, CSS is a more economical and sustainable alternative than removing and replacing unstable or expansive untreated soils. CSS reduces not only costs but also construction time. While the amount of time saved depends on the project size and the depth of the undesirable soil, CSS requires less construction time than removal and replacement for projects of any size.

Environmental Benefits

Compared to removal and replacement, CSS also reduces environmental impacts. The increased truck traffic caused by removal and replacement methods impacts the environment and the local community through increased construction time, potentially increased user delays, and reduced safety.

Figure 1.6 summarizes the benefits of CSS versus removal and replacement.

Life Expectancy

The physical characteristics of both CMS and CSS, even with low cement contents, have been demonstrated to be permanent (Halsted et al. 2008). In this regard, CSS aids in extending the service life of a pavement system by providing a non-expansive and stable subgrade that will last under different climatic conditions. The increased service life of the pavement minimizes the costs and materials that would otherwise be consumed to rehabilitate or reconstruct the pavement system.

The in-service permanence of CMS and CSS has been demonstrated by both laboratory and field investigations. For example, a study using laboratory mixtures of cement-modified clay showed that after 60 cycles of freezing and thawing, the properties of the CMS and CSS mixtures showed no tendency to change or revert back to those of the untreated soil. In fact, the PI values after 60 cycles of freezing and thawing were lower than the values after seven days of moist curing. This is most likely attributed to additional hydration in the cement that occurred during the 60 thaw cycles (PCA 2003).

At the same time, it should also be noted that very moist to wet soils within the frost zone below the cement treatment can affect the future stability of the treated soil, similarly to the way an untreated soil would be affected.

Studies based on the long-term use of CMS have also demonstrated its in-service permanence. A field study by the Oklahoma Department of Transportation investigated the properties of cement-modified subgrades after 45 years of service between 1938 and 1983. The results showed that the changes in the soil properties (PI and shrinkage limit [SL]) of the cement-modified subgrade have remained constant or improved during the nearly half-century of weathering and continued service (Roberts 1986).

Chapter 2. Materials and Properties

This chapter identifies and describes the soil materials and properties that are optimized during the chemical stabilization process. Because the construction of CSS involves adding a relatively small percentage of cement to a subgrade soil, knowledge of the soil type and its properties provides useful information for estimating the amount of cement needed to achieve the desired results. This chapter also includes the results of research demonstrating the effectiveness of cement in improving the engineering properties of a given soil.

AASHTO Soil Classification System

Determining soil classification is an important first step in determining the soil's engineering behavior (i.e., texture, plasticity, particle size distribution, and moisture sensitivity). The American Association of State Highway and Transportation Officials (AASHTO) soil classification system and the Unified Soil Classification System (USCS) are two of the most commonly used classification systems.

Because it is widely recognized by design engineers, the AASHTO classification system is used throughout this guide. Developed in 1929 by Hogentogler and Terzaghi as the Public Road Administration Classification System (Das 2010), the AASHTO classification system delineates soil into seven groups based on grain size, plasticity, and liquid limits, as shown in Table 2.1.

Table 2.2 shows the equivalent nomenclature between the AASHTO soil classification system and USCS.

In general, soils behave, by degrees, as either cohesionless or cohesive. Cohesionless soils are free flowing particles such as gravel, sands, and occasionally silts (i.e., soils with AASHTO classifications of A-1, A-2, A-3, and occasionally A-4). Cohesive soils are comprised of fine-grained soils such as clay or silty clay and have the ability to be molded without crumbling (i.e., soils with AASHTO classifications of A-5, A-6, A-7, and occasionally A-4) (Das 2010).

Table 2.1. AASHTO soil classification system

General Classification	Granular Materials (35% or less of total sample passing No. 200 [0.075 mm])							Silt-Clay Materials (More than 35% of total sample passing No. 200 [0.075 mm])				
Group Classification	A-1		A-3	A-2				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]	A-7-6 [b]
Sieve Analysis (Percent Passing)												
No. 10 (2.00 mm)	50% max.	—	—	—	—	—	—	—	—	—	—	—
No. 40 (0.425 mm)	30% max.	50% max.	51% min.	—	—	—	—	—	—	—	—	—
No. 200 (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.	36% min.
Characteristics of Fraction Passing No. 40 (0.425 mm)												
Liquid Limit	—	—	—	40 max.	41 min.	40 max.	41 min.	40 max.	41 min.	40 max.	41 min.	41 min.
Plasticity Index	6 max.	6 max.	NP	10 max.	10 max.	11 min.	11 min.	10 max.	10 max.	11 min.	11 min.	11 min.
Usual Types of Significant Constituent Materials	Stone fragments, gravel, and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils		
General Subgrade Rating	Excellent to Good							Fair to Poor				

[a] *For A-7-5, PI ≤ LL – 30*

[b] *For A-7-6, PI > LL – 30*

Source: Table 1 of M 145-91 (2017) in *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, by the American Association of State Highway and Transportation Officials, Washington, DC, used with explicit permission

Table 2.2. Comparisons between AASHTO soil classification system and USCS

AASHTO Nomenclature	USCS Nomenclature	Soil Description
A-1	GP, GW, SP, SW	Sands and gravels
A-2	SM, SM-SC	Silty or clayey sands
A-3	SP	Poorly graded sands
A-4	SM, CL-ML, ML, SM-SC	Silty sands and silty clays
A-5	SM, CL-ML, ML, SM-SC	Silty sands and silty clays
A-6	CL, ML, CL-ML	Clay loam, silty loam
A-7	CH, MH, CL-ML	Silty clay loam

CH=inorganic clays of high plasticity, fat clays, sandy clays of high plasticity

CL=inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays

GP=poorly graded gravels, gravel-sand mixtures, or sand-gravel-cobble mixtures

GW=well graded gravels, gravel-sand mixtures, or sand-gravel-cobble mixtures

MH=inorganic silts, micaceous or diatomaceous silty soils, elastic silts

ML=inorganic silts, non-plastic or slightly plastic

SC=Clayey sands, sand-clay mixtures

SM=silty sands, sand-silt mixtures

SP=poorly graded sands, gravelly sands

SW=well graded sands, gravelly sands

Soil Types Improved by the Addition of Cement

This section discusses three problematic soil types described by the AASHTO classification system and their properties that are improved by the addition of cement.

Clayey Materials

Clay soils (AASHTO classifications A-6 and A-7) have a high surface area and are susceptible to expansion and shrinkage as moisture levels vary within the soil. These soils also have a low bearing capacity and shear strength when compared to other types of soil. When clay particles adsorb and lose water, the overall volume changes and shear strengths vary.

Blending cement and water with native in situ soils chemically changes the clay particles to create a new restructured soil. These new properties result in the reduction of soil plasticity, minimization of expansion and shrinkage potential, and enhancement of strength and compaction ability.

A-6 material is typically referred to as a silty clay because it has the characteristics of both a silt and a clay. A-7 soil is predominately a clay material and is therefore more susceptible to volume change and stability issues. Compared to A-6 soil, A-7 soil typically requires a higher cement percentage to reduce volume change potential and plasticity and provide adequate bearing capacity.

The particle restructuring that occurs in clayey soils is discussed in Chapter 1 under Modification Mechanisms.

Silty Materials

Silty soils (AASHTO classifications A-4 and A-5) tend to be especially moisture sensitive. Higher moisture contents make the soil more sensitive to the disturbances caused by normal construction activity, which can cause unstable conditions. Blending cement, water, and native in situ silty soils causes a cementitious reaction to occur that reduces the amount of water in the soil. This reaction, along with the compaction of the cement-treated soil, creates stability in the silty soil and improves bearing strength.

Clayey and Silty Granular Materials

Clayey and silty granular soils with high percentages of clay and silt (AASHTO classifications A-2-6 and A-2-7) may become unstable when their moisture contents are high. These materials react like either silty soil in the case of silty granular material or clayey soil in the case of the clayey granular material; the reactions of clayey and silty soils are discussed in the previous sections. Cement is used in clayey granular material to reduce shrink/swell potential and improve the stability of the clayey granular subgrade. Cement is used in silty granular material to partially bond and realign the silt, allowing the soil to be more effectively compacted with less effort.

Soil Properties and Classification

Because CSS physically and/or chemically modifies the makeup of unsuitable subgrade soils, proper characterization of the soil is important to determine the appropriate cement content to add. Additionally, in some regions the chemical composition of the soil should be checked because it may significantly affect the performance of CSS. The key soil properties in this respect include the following:

- Atterberg limits, including liquid limit, plastic limit, plasticity index, and shrinkage limit
- Grain size analysis (gradation)
- Sand equivalent
- Strength, as characterized by resilient modulus (M_r), CBR, and UCS
- Soil pH
- Organic content, particularly for clay soils
- Sulfate content
- Expansive characteristics
- Stability

These properties and related tests are discussed in more detail in the following paragraphs.

Atterberg Limits

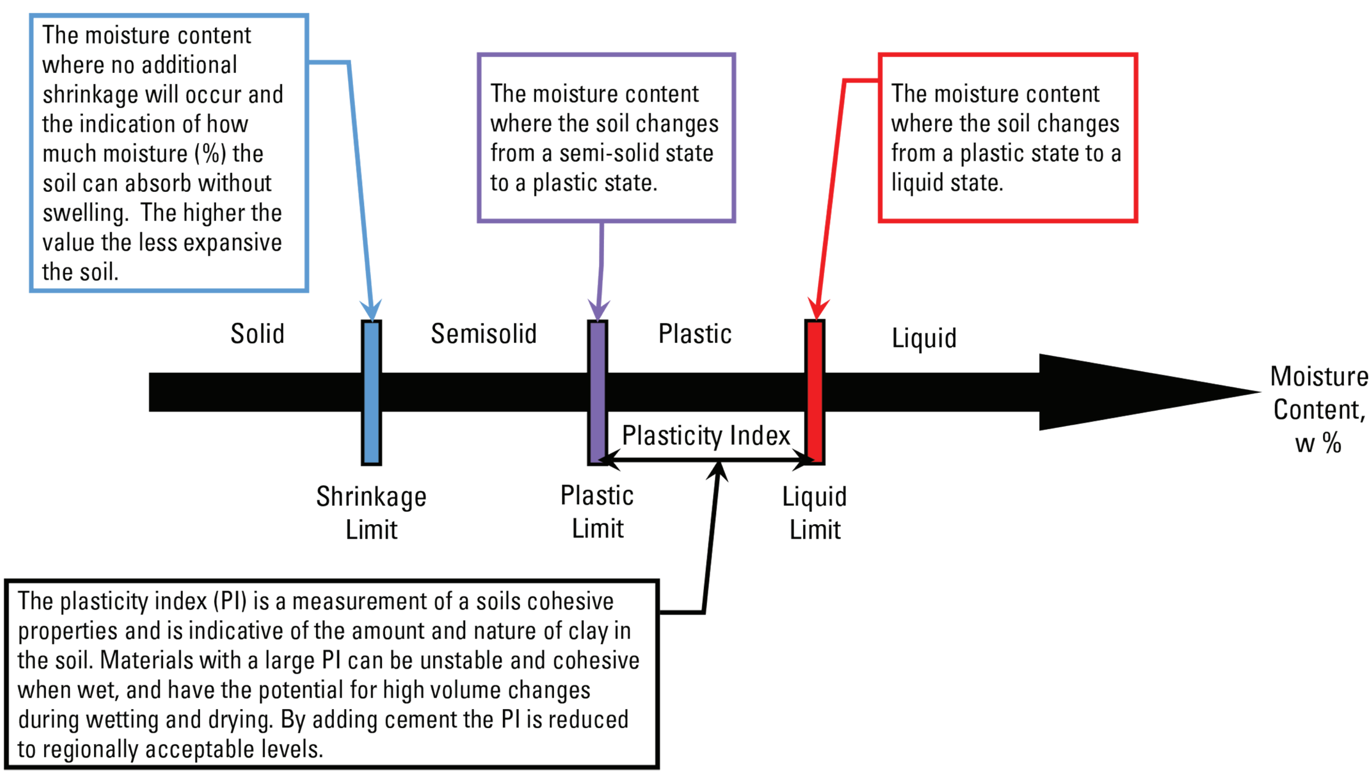
The most critical soil characteristics to analyze for clayey and silty soils are the Atterberg limits, which are indices used to classify fine-grained soils. Fine-grained soils can exhibit different physical phases, including solid, semisolid, plastic, and liquid, depending on their moisture content and the proportions of clay and silt particles present.

The properties that define the boundaries between these phases are the LL and PL, which are used to calculate the PI. The SL is not required for soil classification, and therefore the test for this property is much less commonly used than the LL and PL tests. The relationships among the four phases of fine-grained soils and the Atterberg limits are illustrated in Figure 2.1.

Atterberg limits testing determines the plasticity of a soil and its potential for shrinkage and swelling. These properties directly correlate with soil instability. The LL, PL, and PI of the soil also indicate the cohesiveness of the soil. Atterberg limits are determined using AASHTO T 90, Standard Method of Test for Determining the Plastic Limit and Plasticity Index of Soils. These tests determine whether the fines in the soil or CSS mixture are plastic clays, clay blends, non-plastic silts, or fine sands. Because the tests should only be run on the portion of a soil that passes the 425 µm (No. 40) sieve, the relative contribution of this portion of the soil to the properties of the sample as a whole must be considered to evaluate the properties of the overall soil.

A hydrometer analysis test such as AASHTO T 88, Standard Method of Test for Particle Size Analysis of Soils, can also determine the components of the fine particles. Refer to Figure 2.5 and the related discussion for more information about the hydrometer test.

A key value resulting from Atterberg limits testing is the PI. Materials with a high PI tend to be difficult to work with during construction due to their instability and cohesive properties. PI is also a commonly accepted indicator of soil expansion characteristics. Soils in the higher PI range have the potential for large volume changes during wetting and drying, which can generate pavement distress over time. In many cases, reducing the PI serves as a target when selecting the appropriate cement content.



Adapted from Halsted et al. 2008, © 2008 PCA

Figure 2.1. Atterberg limits and phases of fine-grained soils

Liquid Limit (LL)

The LL of a soil is the water content at which the soil passes from a plastic state to a liquid state. The LL is a key component in determining the PI. High-plasticity soils typically have an LL exceeding 50 percent.

Plastic Limit (PL)

The PL of a soil is the lowest water content at which the soil remains plastic. The PL is used in conjunction with the LL to determine the PI. The closer the PL is to the LL, the lower the potential for shrinkage and swelling.

Plasticity Index (PI)

The PI of a soil is the difference between the LL and the PL of a soil, as well as the range of water content, expressed as a percentage of the mass of the oven-dried soil, within which the material is in a plastic state. The PI of a soil is especially useful in classifying fine-grained soils, measuring a soil's cohesive properties, and indicating the nature of any clays in a soil. Many correlations between PI and other soil properties have been developed.

Soils with a high PI are identified as cohesive, expansive, or contractive depending on water content. Several factors affect the PI, including clay mineral type, concentration of cations, and the nature of the cations. Typically, certain types of clay exhibit high PI values, which is not ideal for performance. However, adding a small amount of cement can improve the engineering properties of soils with a high PI value.

Shrinkage Limit (SL)

SL is an indicator of the soil's moisture content. This index property is the moisture content at which the volume of the soil ceases to change (Das 2010). Low-expansion soils are indicated by higher SL values; more generally, the higher the SL value, the less expansive the clayey soil is. Ideally, the SL value should be higher than the optimum moisture content (OMC) (Bhattacharja and Bhatty 2003). Both a substantial reduction of a clayey soil's expansion potential and an increase in SL indicates not only an improvement in the volume change characteristics of the soil but also greater workability and stability.

AASHTO T 92, Standard Method of Test for Determining the Shrinkage Factors of Soils, is used to determine the SL of a soil, as well as the soil's shrinkage ratio, volumetric change, and lineal shrinkage. Determining the SL aids in determining the correct cement content to add to stabilize the soil.

Table 2.3 lists three soil index properties, including SL and PI, and the corresponding probable volume changes for plastic soils. The information listed in this table includes generalized values, so certain soils may not fall within the range of values in the table. For this reason, it is critical that testing is performed on the soil to determine its actual properties.

Table 2.3. Three soil index properties compared to degree of expansion

Data from Index Tests[1]			Estimation of Probable Expansion[2], percent total volume change (dry to saturated condition)	Degree of Expansion
Plasticity Index (ASTM D4318)	Shrinkage Limit, percent (ASTM D427)	Colloid Content, percent minus 0.001 mm (ASTM D422)		
>35	<11	>28	>30	Very high
25–41	7–12	20–31	20–30	High
15–28	10–16	13.23	10–20	Medium
<18	>15	<15	<10	Low

Original source: Holtz 1959, Bureau of Reclamation; reprinted (without ASTM standard text methods in column headings) from Young 1998, Bureau of Reclamation

[1] *All three index tests should be considered in estimating expansive properties.*

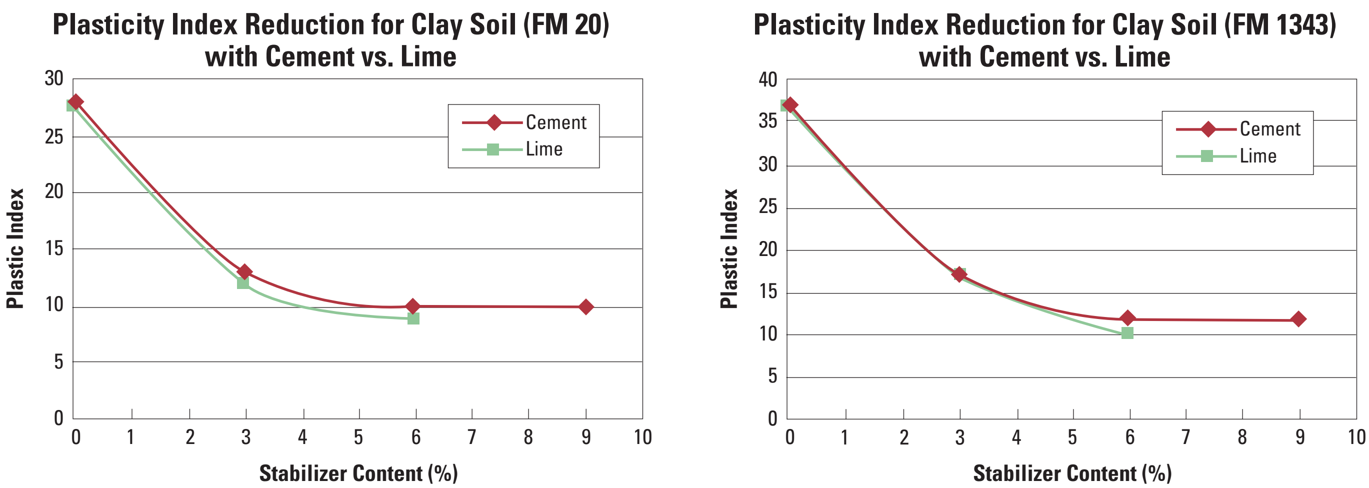
[2] *Based on a vertical loading of 1.0 psi. For higher loadings, the amount of expansion is reduced, depending on the load and the clay characteristics. In service, much less expansion would occur because these extremes of moisture variation would not occur.*

Effects of Cement Treatment on Atterberg Limits

The use of cement to effectively reduce PI in high-PI soils (i.e., soils with PI values greater than 30) has been demonstrated but is often overlooked. In a study comparing the effectiveness of cement and hydrated lime in reducing PI, Scullion et al. (2005) found that cement and lime in equal proportions yielded similar results in terms of reducing PI from values as high as 37 percent (Figure 2.2).

Note that the data from these charts are generalized. It is recommended that testing be conducted on any soils treated with cement to determine the actual reduction in PI.

Table 2.4 provides information on the effects of cement treatment on reducing the PI and increasing the SL of various clay soils.



Scullion et al. 2005, © 2005 PCA

Figure 2.2. PI of two types of clay soils after being stabilized with lime or cement

Table 2.4. Effect of cement treatment on the PI and SL of clay soils

Soil No.	AASHTO Classification	Cement Content (percent)	Plasticity Index	Shrinkage Limit
1	A-7-6 (20)	None	30	13
		3	13	24
		5	12	30
2	A-6 (8)	None	17	13
		3	2	26
		5	1	28
4	A-6 (9)	None	20	10
		3	9	21
		5	5	25
7	A-7-6 (18)	None	36	13
		3	21	26
		5	17	32
10	A-7-6 (20)	None	43	14
		3	24	24
		5	16	31

Source: Christensen 1969, PCA

The effect that cement treatment has on all four of the Atterberg limits is illustrated in Figure 2.3, which shows the positive effects of cement treatment in the LL, PL, PI, and SL of an A-7 clayey soil. This soil would be considered an unsuitable soil for a subgrade if not modified by cement (Halsted et al. 2008).

As shown in Figure 2.3, the addition of cement reduced the PI of the soil considerably. PL increased, which indicates that the soil can absorb more moisture before entering into the plastic state. SL also increased, which indicates that the material can absorb a higher percentage of moisture before it begins to swell. Alternatively, the change in SL indicates that the loss of moisture will not result in additional shrinkage at a higher percentage of moisture.

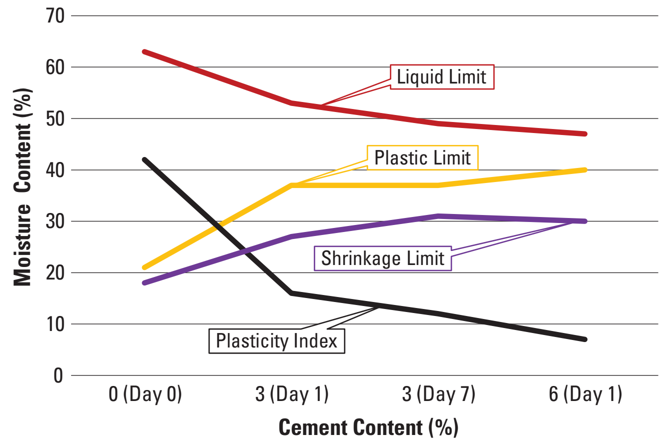
Taken together, the results shown in Figure 2.3 demonstrate that CSS improves soil properties (SL and PI) to regionally acceptable values.

Grain Size Analysis (Gradation)

In general, more cement is needed for soils with higher fine contents, such as silts and clays, than is needed for more granular soils, such as sands and gravels, to achieve the same engineering properties. Grain size analysis, or gradation, as determined by AASHTO T 27, Standard Method of Test for Sieve Analysis of Fine and Coarse Aggregates, or ASTM D6913, Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis, determines the particle size distribution of soils using sieves (Figure 2.4).

For fine-grained soils, including fine sands, silts, and clays, a hydrometer analysis test (Figure 2.5) is conducted in accordance with AASHTO T 88, Standard Method of Test for Particle Size Analysis of Soils. In this test, material passing the No. 10 (2.00 mm) sieve is used to determine the particle size distribution of the fine soils.

The information resulting from the hydrometer test is particularly useful when determining the silt and clay fraction of a fine-grained soil and the soil's permeability. ASTM C117, Standard Test Method for Materials Finer than 75 µm (No. 200) Sieve in Mineral Aggregates by Washing, is needed to accurately determine the fines content of the sample (per ASTM D6913).



Graph compiled using data from Table 3 in Halsted et al. 2008

Figure 2.3. Effects of cement treatment on the Atterberg limits of plastic soils

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Figure 2.4. Sieve analysis apparatus

© 2020 Certified Testing Services, Inc., used with permission

Figure 2.5. Hydrometer test apparatus

© 2020 Certified Testing Services, Inc., used with permission

Figure 2.6. CBR testing machine

Sand Equivalent (SE)

The sand equivalent (SE) test evaluates the amount of undesirable clay and dust materials in aggregates and soil. The SE value can be determined through AASHTO T 176, Standard Method of Test for Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test. Very expansive clays have SE values less than 5, while clean crushed stones have SE values of 80 or more. Some states have a specified minimum SE value for base and subbase layers. A small amount of cement can significantly increase the SE value.

Resilient Modulus (M_r)

The resilient modulus is a measure of subgrade material stiffness. A material's resilient modulus is actually an estimate of its modulus of elasticity (E). However, while the modulus of elasticity is stress divided by strain for a slowly applied load, resilient modulus is stress divided by strain for rapidly applied loads, like those experienced by pavements (Schaefer et al. 2008).

When a small amount of cement is added to clayey soils, the restructuring and binding of the particles results in a significant increase in the resilient modulus. This increased stiffness occurs in soils in either wet or dry condition.

California Bearing Ratio (CBR)

Similar to the resilient modulus, the CBR provides information on the stiffness and strength of a soil; however, the CBR test is less expensive to run than the resilient modulus test. The CBR test indirectly measures soil strength by penetrating a soil sample with a uniform load over a preset distance (Figure 2.6). CBR values range from 0 to 100, with 100 being a very supportive subgrade and 0 being a very poor subgrade.

Refer to Table 2.5 for correlations between CBR, M_r, and various other subgrade soil properties.

Table 2.5. Models relating material index and strength properties to M_r and CBR

Strength/Index Property	Model	Comments	Test Standard
CBR	$M_r = 2555 (CBR)^{0.64}$	• CBR = California Bearing Ratio, percent	• AASHTO T 193, The California Bearing Ratio
R-Value	$M_r = 1155 + 555R$	• R = R-value	• AASHTO T 190, Resistance R-Value and Expansion Pressure of Compacted Soils
AASHTO Layer Coefficient	$M_r = 30000 \left(\frac{a_i}{0.14}\right)$	• a_i = AASHTO layer coefficient	• AASHTO *Guide for the Design of Pavement Structures*
PI and Gradation*	$CBR = \frac{75}{1+0.728(wPI)}$	• $wPI = P_{200} \times PI$ • P_{200} = percent passing No. 200 sieve • PI = plasticity index, percent	• AASHTO T 27, Sieve Analysis of Coarse and Fine Aggregates • AASHTO T 90, Determining the Plastic Limit and Plasticity Index of Soils
Dynamic Cone Penetrometer (DCP)*	$CBR = \frac{292}{DCP^{1.12}}$	• CBR = California Bearing Ratio, percent • DCP = DCP index, mm/blow	• ASTM D6951, Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications

**Estimates of CBR are used to estimate M_r*

Source: ARA, Inc. ERES Division 2004, National Cooperative Highway Research Program

Unconfined Compressive Strength (UCS)

When the acceptance criteria include improving the existing soil either through drying or reducing the soil's plasticity in order to provide a working platform, achieving a specific compressive strength may not be an important consideration. However, if the treated soil is to be incorporated as a structural element of a pavement or building foundation, then compressive strength is typically included in the evaluation. For these situations, seven-day UCS values (see Figure 2.7) for CSS generally range between 100 and 300 psi (0.7 and 2.1 MPa).

Figure 2.7. Unconfined compressive strength testing apparatus

Expansive Characteristics

Expansive soils exhibit high clay content, high moisture content, and typically LL values greater than 50 (although some soils with LL values less than 50 may also swell). High-PI/high-swell soils have the potential for detrimental volume changes during wetting and drying cycles, which can eventually lead to pavement roughness.

As shown in Table 2.3, the PI can be a good indicator of expansion. While other factors (e.g., shrinkage limit and colloid content) can also indicate expansion potential, the PI alone is often measured to provide a simple index. Soils with PI values of 18 or less typically perform well. Highly expansive soils have much higher PI values.

Soils with these characteristics experience excessive shrink/swell movements with changes in soil moisture contents. They have very high concentrations of kaolinite and montmorillonite clay particles, which classifies them as A-5 or A-7 soils. These soils are prime candidates for CSS to alter the chemical composition of the soil and alleviate the expansive tendencies.

In contrast to the index tests discussed above, a direct measure of the expansive properties of stabilized treated soils is a one-dimensional free swell test. Appendix B provides a complete test procedure and suggested limitations on volumetric swell.

Other than the swell test, additional test methods, including the CBR test, can measure swell. In this test, a swelling value of four percent is an approximate borderline between expansive soils and those that would usually not be troublesome. Highly expansive soils have much higher values than four percent swell (PCA 2003).

Two additional tests that can be used to measure soil expansion include ASTM D4829, Standard Test Method For Expansion Index of Soils, and ASTM D4546, Standard Test Methods for One-Dimensional Swell or Collapse of Soils.

Figure 2.8 shows the effect of the addition of cement to a moderately expansive AASHTO class A-7-6 (16) clay soil. According to a CBR test, the addition of three percent cement by dry weight of soil reduced the expansion from 3.9 to 0.15 percent. The reductions in expansion can be dramatic with very low cement contents.

Stability

Unstable soils are poorly graded soils with very little cohesion to hold the individual particles together. These soils are also sensitive to moisture changes. They are typically classified as A-3, A-4, and occasionally A-5 soils. CSS that contains unstable soil can be challenging to design because too low of a dosage rate of cement only dries the soil and does not bond enough of it to create adequate soil stability and bearing capacity.

Sulfate Content

Soluble sulfates within the subgrade soil can lead to sulfate-induced heave, which is caused by an expansive mineral called ettringite that is formed when a calcium-based stabilizer (lime or cement) reacts with clay and sulfate minerals (usually gypsum) in the soil (Harris et al. 2006). In the presence of water, the soil can expand to several times its normal volume.

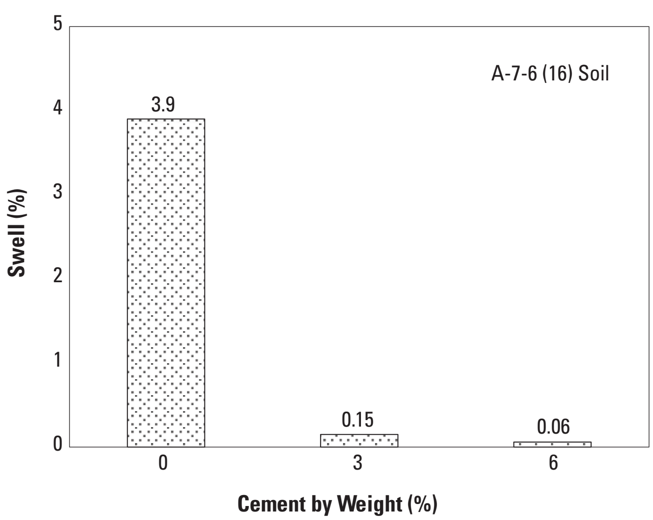

Figure 2.8. Effect of cement on swelling according to a CBR test

If the subgrade soil has a soluble sulfate content of less than 3,000 ppm (0.3 percent), sulfate-induced heave is not a problem. Higher soluble sulfate contents of up to 8,000 ppm (0.8 percent) may be satisfactorily treated with cement; however, additional testing should be conducted to confirm that sulfate-induced heave will not be an issue.

Several different cement types can be used to mitigate sulfate issues in soil. These include Type II, Type V, Type MS, and Type HS. More information on treating soils containing sulfate can be found in the Texas Department of Transportation's (TxDOT) *Guidelines for Treatment of Sulfate-Rich Soils and Bases in Pavement Structures* (TxDOT 2005) or National Cooperative Highway Research Program (NCHRP) *Web-Only Document 145: Recommended Practice for Stabilization of Sulfate-Rich Subgrade Soils* (Little and Nair 2009).

Soil pH

The pH of a soil is measured on a scale between 0 and 14 that indicates whether the material is an acid or a base. A pH of 7 is considered neutral, while lower numbers indicate increasing acidity (acid) and higher numbers indicate increasing alkalinity (base). It should be noted that an existing material with a high pH (alkaline) does not typically create constructability concerns.

Low-pH material can adversely impact the effect of cement stabilization in CSS mixtures. If the existing soil has a pH of 5.3 or lower (Robbins and Mueller 1960) the soil may not react normally with cement. Nevertheless, in such cases chemical treatments such as lime or cement can be used to neutralize the soil and raise the pH level. However, note that the cement used to neutralize the soil is in addition to the cement content used for stabilization purposes. The additional cement can help the soil attain its required strength and durability.

Organic Content

The organic content of the existing material should be evaluated during the mix design phase. Organic contents of 20,000 ppm (2.0 percent) or more (Robbins and Mueller 1960) can prevent a cement-stabilized mixture from hardening and may require that a higher cement content be added to the soil for stabilization. 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 (Army, Navy, and Air Force 1994).

Experience has shown that it is difficult to cement-stabilize certain organic soils because the low pH values of these soils cause the precipitation of an alumina-silica gel over the cement particles, which inhibits the normal hardening process (Laguros 1962). AASHTO T 267, Standard Method of Test for Determination of Organic Content in Soils by Loss on Ignition, may be performed to measure the organic content in soils.

Chapter 3. Geotechnical Evaluation and Field Sampling

Geotechnical Evaluation

A routine geotechnical evaluation should be performed early in the design process to provide the design engineer with recommendations for subsurface preparation that will be included in the final design of the project. In addition to considering these recommendations, it is important for the design engineer to fully understand all of the information resulting from the geotechnical investigation. A copy of the design plans should also be presented to the geotechnical consultant to review prior to the plans going to bid.

The first step in the evaluation process is to conduct a desktop study to collect relevant information about the site location and comparable past projects and experience. An important source of information is the soil survey reports published by the U.S. Department of Agriculture for most counties throughout the United States. These survey reports include information on the various types and properties of the soils within each county. In addition to the soil surveys, record drawings, photo surveys, and any previous subsurface reports, boring logs, and laboratory tests should be reviewed.

Either after or during the desktop study, a site visit should be made to evaluate the project's field conditions. Items that should be evaluated during the site visit include drainage conditions, the depths of existing utilities, the project's surroundings, and the extent of any structural distress and/or deterioration. If the project involves repairing an existing roadway, photos of the roadway should be taken, particularly of distressed areas, to visually document its condition prior to any repairs.

Following the site visit, field samples should be obtained for laboratory testing. The degree of sampling and the extent of laboratory testing is often determined based on whether the subgrade plays a critical role in the design and the time required for sampling and testing.

In most cases, there is sufficient time to sample and test the subgrade prior to construction. However, unanticipated situations occasionally arise during construction, such as excessive moisture resulting in an unstable subgrade or the discovery of areas of undesirable clays and silts that had not been previously reported. In addition, the degree of subgrade stability observed or assumed during the geotechnical investigation may differ from that encountered during construction due to the effects of weather and construction activity. In these situations, decisions need to be made quickly to avoid excessive construction delays. The geotechnical engineer's experience with similar situations and the nature of the application both play an important role in the decisions ultimately made. An application to simply create a working platform may require less cement stabilizing effort than an application where permanent subgrade strength is incorporated into the design.

The decision tree in Figure 3.1 outlines a commonly used approach to developing a mix design for either modification or stabilization of a subgrade soil. The approach incorporates the elements of a geotechnical evaluation. These steps are not intended to be used as a specification but rather as a framework for determining the appropriate cement content.

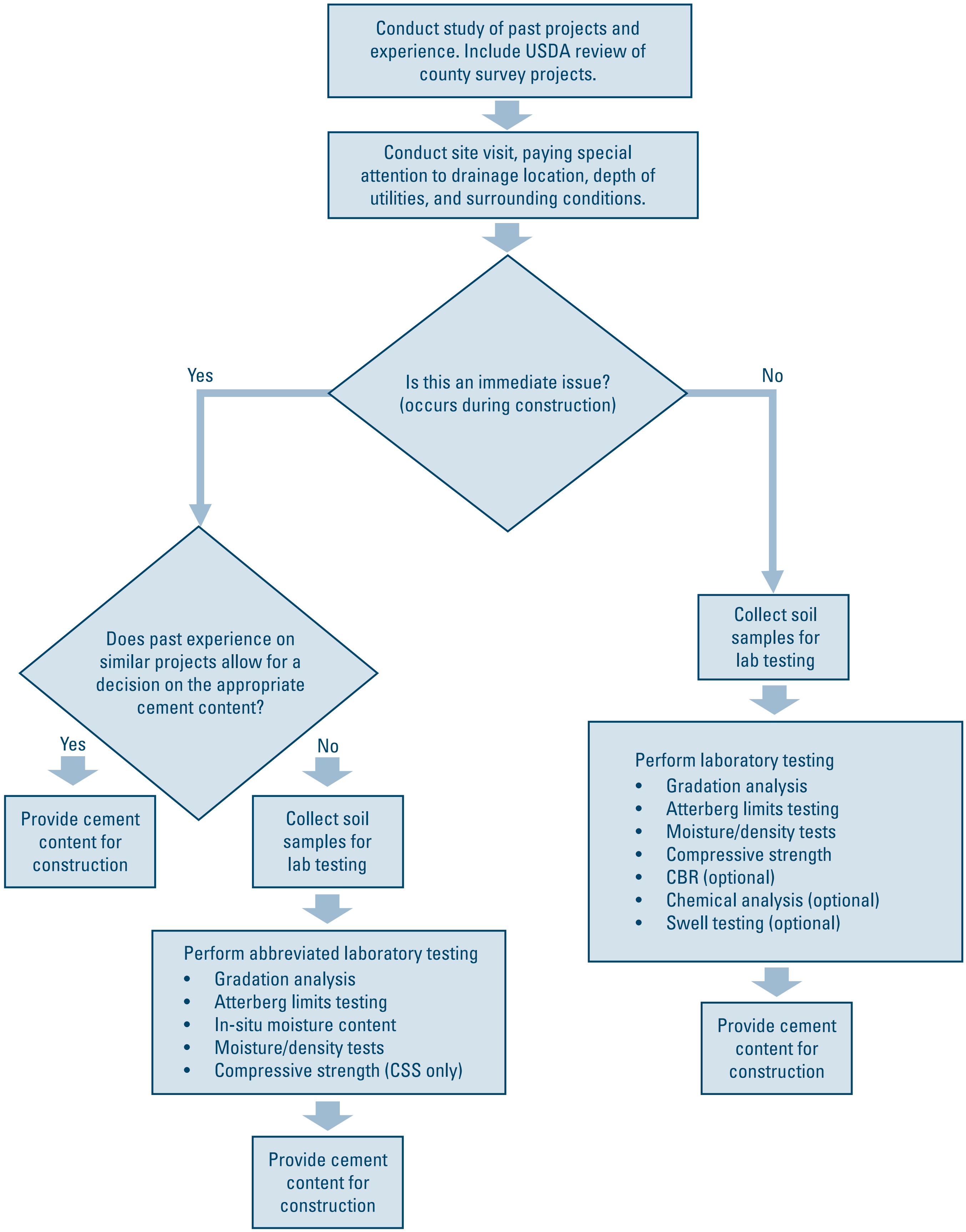

Figure 3.1. Decision tree for developing a CMS or CSS mix design

Field Sampling

A successful CSS project relies on a complete and thorough understanding of the materials that make up the existing subgrade and the cut/fill requirements along the planned alignment. The field samples obtained during the geotechnical evaluation of the existing subgrade soil can help elucidate the composition of the material that is to be treated with cement.

All material samples should be kept separate from each other with their locations recorded in a boring log. For each sample, the thickness of the subgrade strata and the depth to the water table should be identified.

If the gradations and material types of the samples vary significantly, this may indicate that several different CSS mix designs need to be developed for the project. To avoid having to design several CSS mixes, engineering judgment should be used to determine the sample(s) to serve as the representative case for the project. To this end, the project engineer must understand which soil type would be most detrimental for the project and decide how to handle the variability in the soil conditions. If necessary, the project engineer may consult with the geotechnical engineer to identify the most critical soil type present.

The remainder of this section describes field sampling and testing options.

Types of Field Sampling

There are two major types of field sampling: disturbed and undisturbed. In disturbed sampling, the natural conditions of a soil sample, such as its structure, texture, density, natural water content, or stress conditions, are altered during sampling. In contrast, undisturbed sampling retains the natural conditions of the soil mass as much as possible. The degree of disturbance depends on soil type and condition (Christopher et al. 2016). A variety of disturbed and undisturbed sampling methods can be used to obtain material samples, as described in the following paragraphs.

Table 3.1 summarizes the primary uses for disturbed and undisturbed sampling.

Common Field Sampling and Testing Methods

Test Pits

For new roadways, test pits are a common way of collecting samples to be used in CSS (see Figure 3.2). This type of testing also provides a clearer picture of the existing soil profile that lies beneath the pavement. Test pits are spaced at predetermined locations along the proposed alignment to provide adequate coverage and capture variations that may exist in the natural geologic conditions. For more information on test pit sampling, refer to the Frequency of Sampling section later in this chapter.

Table 3.1. Uses for disturbed and undisturbed soil sampling

Disturbed Sampling	Undisturbed Sampling
Soil classification	In-place stiffness and strength
Gradation	Compressibility
Triaxial shear strength	Natural moisture content
Natural moisture content	Unit weight
Consistency	Percent saturation
Moisture-density relationships	Permeability
California Bearing Ratio	Discontinuities
Stratification	Fractures or fissures of subsurface materials
Atterberg limits	Triaxial shear strength
Shrinkage limits	Unconfined compressive strength
Dynamic cone penetrometer (DCP)	—
Unconfined compressive strength	—
Chemical composition/sulfates	—

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Figure 3.2. Test pit

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Figure 3.3. Core sampling of pavement

Coring and Sampling through Existing Pavement

Soil bores provide a means to collect in situ soil samples that can be sent to a geotechnical laboratory for testing to provide the following soil property information:

- Soil classification
- Gradation
- In situ moisture and density
- Water table depth
- Chemical analysis (sulfate resistance, pH, organic content)
- Soil stiffness

Visual soil classification, relative density (if a standard penetration test [SPT] is performed), and relative moisture can be obtained in the field and reported in the boring log.

Where existing pavement is present, the most common method of field sampling is coring through the pavement (Figure 3.3) and extracting subgrade soil sample(s). Depending on the soil conditions, this method of sampling is generally limited to shallow depths below the pavement.

As Figure 3.3 shows, a rotary core drill using a core barrel placed perpendicular to the pavement is used to cut through the pavement to get access to the soil sample for testing. Common core sizes are 2, 4, and 6 in. (50, 100, and 150 mm) in diameter. The larger the core diameter, the better the representation of the in situ material.

Soil sampling through the core/drill hole may also include tube sampling, as specified in AASHTO T 207, Standard Method of Test for Thin-Walled Tube Sampling of Soils, and standard penetration testing, as specified in AASHTO T 206, Standard Method of Test for Penetration Test and Split-Barrel Sampling of Soils. These two types of sampling are discussed in detail below.

During laboratory evaluation of the samples obtained from the core, it is critical to maintain the in situ moisture content of the sample. Samples obtained in the field should be stored in air-tight containers and sent promptly to the laboratory for testing. These containers allow the in situ moisture contents of field samples to be determined more accurately.

Auger Sampling

Auger sampling in accordance with AASHTO T 306, Standard Method of Test for Progressing Auger Borings for Geotechnical Explorations, allows samples of soil or base materials to be obtained through a core/boring hole.

Auger samples are disturbed samples that are obtained from the soil brought to the surface by the flights on the auger. They are bulk samples that can be used for determining the natural moisture content of the in situ soil, Proctor compaction testing, and Atterberg limits testing, among other testing. Auger sampling can be performed by hand auger equipment, although using a truck-mounted drill rig is far more common. Machine-operated augers that are acceptable for use with AASHTO T 306 include continuous flight augers (otherwise known as solid-stem augers) and continuous hollow stem augers (Figure 3.4).

Auger samples should be obtained at a depth that represents the subgrade strata of interest or the depth of the deepest utility. Depending on the geographic location of the project, bedrock depths may also need to be noted. Traditionally, soil samples are obtained at a depth of 5 to 10 ft (1.5 to 3.0 m) below the bottom of the pavement's final design elevations.

PCA

Figure 3.4. Auger sampling

Samples should be stored in air-tight containers for later laboratory testing and in situ moisture content testing. Understanding the in situ moisture content during sampling is important, especially if the moisture content is excessive and the samples are being taken during construction.

Tube Sampling

Tube sampling, commonly referred to as Shelby tube sampling and performed according to AASHTO T 207, is a test method used to extract relatively undisturbed soil samples. Samples taken with this method can be used to determine the following in situ soil properties:

- Strength
- Compressibility
- Permeability
- Density
- Moisture content

Tube sampling involves obtaining a relatively undisturbed sample by pressing a thin-walled metal tube (Figure 3.5) into the in situ soil at the bottom of a boring, removing the soil-filled tube, and sealing the ends to prevent the soil from being disturbed or losing moisture.

Standard Penetration Test (SPT)

This test method, performed during boring operations according to AASHTO T 206, extracts soil with a split-barrel sampler (Figure 3.6) to determine the relative strength of the soil stratum. The sampler is driven into the soil stratum with an automatic or manual hammer until either the sampler has been driven 6 in. (150 mm) into the stratum in under 50 blows or 100 blows have been administered. The information obtained from this test can be extremely useful for determining the amount of cement needed to improve a soil for CSS applications (Das 2010).

Dynamic Cone Penetrometer (DCP)

The dynamic cone penetrometer (DCP) (Figure 3.7), used according to ASTM D6951, Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications, measures the strength and deformation properties of a subgrade. The concept behind the DCP test is that the resistance of a soil to penetration from a solid object is directly correlated to the strength of the soil. The test is both rapid and inexpensive and evaluates support conditions to a depth of approximately 4 ft (1.2 m).

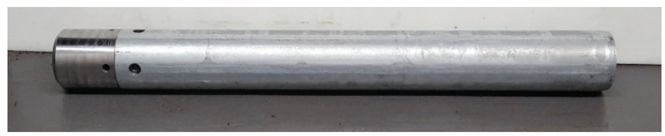

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Figure 3.5. Shelby tube sampler

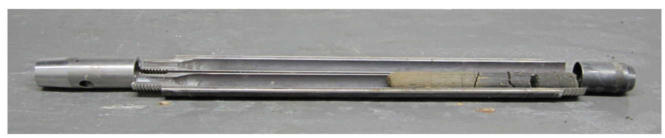

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Figure 3.6. Standard penetration sampler

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Figure 3.7. Dynamic cone penetrometer testing

In pavement areas, the DCP test must be performed after pavement core extraction but before soil samples are removed. The test uses a 17.6 lb (8 kg) drop hammer that falls from a fixed height of 22.6 in. (575 mm) along the penetrometer shaft. The hammer drives a cone attached to a steel rod into the subgrade, and the penetration rate of each drop is recorded. Variations of this test exist that are used to assess weaker soils or that utilize a disposable cone.

The DCP results can be used to identify layer boundaries and the CBR of each individual soil layer. The CBR correlates with the DCP test through Equation 1 (Tingle and Jersey 2007).

$$CBR = \frac{292}{DCP^{1.12}} \qquad (1)$$

Other Field Testing Methods

The following two field test methods for evaluating subgrade soils are generally not typical for local roads and county highways but can be very beneficial for facilities that experience higher traffic loads, such as Interstates and heavy highways. However, these test methods can also be useful for minor highway applications where occasional heavy industrial or agricultural traffic is a consideration.

Falling Weight Deflectometer (FWD)

The falling weight deflectometer (FWD), as shown in Figure 3.8, can be used to assess the level of soil support and differences in support at different locations. This test is typically used on large, heavy highway projects where traffic loading conditions warrant an extremely supportive subgrade condition.

The FWD emits a load pulse to the pavement through a load plate that is 11.8 in. (300 mm) in diameter to create a deflection basin. These deflection measurements may then be used in various back calculation methods to determine the stiffness and uniformity of both the subgrade and base support.

FWD testing can also determine the potential presence of voids beneath the slab, which may be an indication of poor soil support. When void detection is performed with the FWD, deflection is measured at three different loads: 9,000, 12,000, and 16,000 lb (40.0, 53.4, and 71.2 kN). Once testing is complete, deflection versus load is plotted graphically. Alternatively, ground penetrating radar (GPR) may also be used to determine the presence of voids beneath the slabs.

While FWD tests can be run quickly for larger projects, a smaller and more portable alternative that works well for thin pavements is the light weight deflectometer (LWD). The elastic modulus determined using the LWD correlates well with the elastic modulus determined using the FWD.

Automated Plate Load Test (APLT)

As with the FWD, the automated plate load test (APLT) is typically used on large, heavy highway projects. The APLT apparatus includes a rigid bearing plate between 6 and 30 in. (152 and 762 mm) in diameter, a loading system capable of introducing a load to the plate incrementally, and gauges or transducers to measure the applied load and resulting deflection (Figure 3.9).

The APLT is conducted according to AASHTO T 221-2, Standard Method of Test for Repetitive Static Plate Load Tests of Soils and Flexible Pavement Components for Use in Evaluation and Design of Airport and Highway Pavements. The area where the APLT is conducted should be at least twice the diameter of the bearing plate. Loading is incrementally administered. At each increment, the load and deflection are recorded. An undisturbed soil sample is also acquired at the testing location for laboratory evaluation.

Jerod Gross, Snyder & Associates, Inc.

Figure 3.8. Falling weight deflectometer

White and Taylor 2018, CP Tech Center

Figure 3.9. Automated plate load testing apparatus

The APLT system can perform several tests to evaluate pavement foundations, stabilized materials, embankments, and compacted fill:

- Modulus of subgrade reaction
- Confining stress-dependent resilient modulus
- Bearing capacity test
- Wheel rutting (proof roll)
- Borehole shear test
- Tube sampling and extrusion
- Resilient modulus (in situ)
- Strain modulus
- Shear wave velocity
- Cone penetration test
- Rapid air permeability test (in situ)

The advancement of plate load testing technology has allowed for many parameters to be tested in the field that previously could only be tested in the laboratory.

Frequency of Sampling

The locations of soil samples taken in situ and the frequency of sampling are extremely important to ensure that the different soil conditions of the horizontal and vertical profiles of a site are accurately represented. More frequent samples should be taken at sites that have variable soil types, while sites with more consistent soil types do not require as many samples. Although the sampling frequency may vary from agency to agency and is based on project size, a typical average spacing between samples for a paving project may range from 400 to 1,000 LF (122 to 305 m), or one sampling location per block in urban areas. The frequency of test pits on new roadway sites can vary, but test pits are less frequent than auger or core sampling.

Field sampling should consist of obtaining samples in clay soil and standard penetration testing in granular material. Grab samples should be obtained from an auger when large quantities of material are required for Proctor compaction and CBR testing. For each soil stratum encountered within the influence zone of the pavement, typically within the top 5 ft (1.5 m) below the pavement, 200 to 300 lb (90.7 to 136.1 kg) of soil should be collected for analysis.

The design engineer and geotechnical consultant should determine the boring layout based on previous knowledge of the existing soil and/or pavement condition. Again, consultation with a geotechnical engineer at the beginning of the project can save time and money and avoid construction issues.

Chapter 4. Mixture Design

This chapter describes a step-by-step process for determining the proper cement content to use for a given application and set of soil characteristics.

The CSS mix design process includes determining the amount of cement needed to improve a subgrade soil's engineering properties. In order to determine this amount, an assessment and understanding of the properties and materials of the existing soil is key. As discussed in Chapter 3, before beginning a mix design the geotechnical consultant should first analyze the native soil properties to determine which ones need to be altered or enhanced.

When the structural capacity of the treated soil is considered in the pavement design, as is often the case with CSS, a comprehensive laboratory testing program is necessary. In developing a mix design for CSS, the primary laboratory tests to conduct include the following:

- Gradation and Atterberg limits of the untreated soil
- Atterberg limits of the CSS
- Standard Proctor compaction
- Unconfined compressive strength (optional for CMS)
- Free swell (optional)
- Unconfined compressive dry strength and wet strength (after 10-day free swell)

The mixture design described in this chapter provides guidance for both situations that are not urgent or time dependent and situations that are urgent and time dependent (i.e., those that arise during construction). While designing for non-urgent situations involves a greater amount of testing than designing for urgent situations, gradation, Atterberg limits, and moisture and density testing should be performed in all situations when possible.

CSS Materials

When developing a mix design, it is important to understand the materials involved. The three major components of a cement-stabilized subgrade soil are cement, water, and soil.

Cement

The cement used for CSS should comply with the latest specifications for portland cement:

- ASTM C150, Standard Specification for Portland Cement
- ASTM C1157, Standard Performance Specification for Hydraulic Cement
- AASHTO M 85, Standard Specification for Portland Cement
- ASTM C595, Standard Specification for Blended Hydraulic Cements
- AASHTO M 240, Standard Specification for Blended Hydraulic Cement

When sulfate soils are present, the use of Type II, Type V, Type MS, and Type HS cement, which provide resistance to moderate and high sulfate contents, may be appropriate.

Water

Water is required to initiate several reactions that change the properties of the soil and thereby make the soil acceptable for construction, initiate cation exchange, and facilitate compaction. When cement and water are combined, the hydration process begins. During this reaction, the soil-cement mixture becomes saturated with calcium, which is a main contributor to the stabilization of clay. The process of hydration can continue to occur for many weeks (Prusinski and Bhattacharja 1999). Any water that is not utilized during hydration either remains in the soil or forms the soil's capillary system, which can induce expansion and shrinkage in a soil stratum.

Impurities in the water should be considered when water is applied to cement-stabilized subgrades. High concentrations of different impurities within the water can prolong setting time, reduce strength, increase volume instability, and even reduce durability. A few of the many examples of impurities include chloride, chemicals that cause acidity or alkalinity, and organics (Kosmatka and Wilson 2016).

The water used in CSS should meet the requirements of ASTM C1602, Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete.

Soil

Determining the soil type is crucial in the design of any pavement project, but soil type is especially important if the soil is being used as a subgrade. If the soil is highly plastic, is extremely wet, or has other unacceptable qualities, pavement distress can result. In these cases, CSS can promote soil drying, reduce plasticity and shrink/swell volume change potential, and improve bearing strength.

Step-by-Step Mixture Design

Depending on the urgency of the situation, two very different pathways can be taken to incorporate CSS into a project:

1. The first path is the design (non-urgent) path, which begins after the boring data become available and allows sufficient time for adequate field sampling and laboratory testing. The majority of this chapter focuses on the design path.
2. The second path is the construction (urgent) path, which begins during construction when excessively wet and/or unstable soils are encountered and an immediate solution is required. In the construction path, a cement content may be chosen based on engineering knowledge and previous experience or after an abbreviated laboratory testing program.

In either case, the scope of the mixture design process depends on the performance criteria that need to be met. If the only important goals are to dry the soil or simply reduce the plasticity index, then Atterberg limits testing may be sufficient. However, if there is a need to satisfy other criteria, including expansion characteristics, chemical content, bearing or compressive strength, optimum moisture, or maximum density, then a more comprehensive testing program may be required.

Once the criteria have been established, the mixture testing program can begin. Figure 4.1 illustrates the typical mixture design steps for the design path, with each of the eight steps discussed in more detail in the following paragraphs.

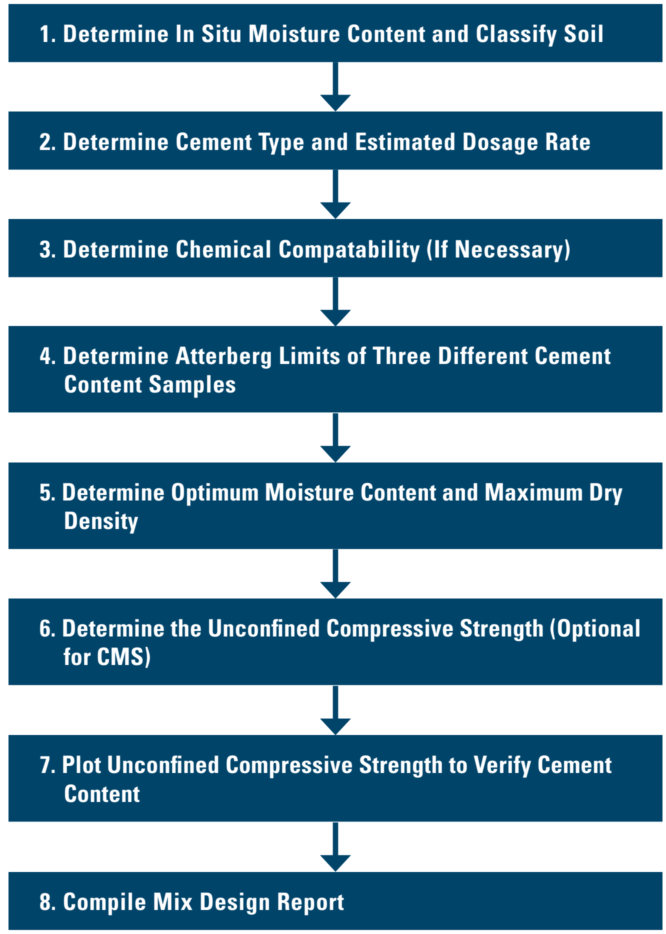

Figure 4.1. Mixture design steps for the design path

1. Determine In Situ Moisture Content and Classify Soil

Usually the first tests conducted to evaluate the soil for a CSS application are the gradation and Atterberg limits tests. The gradation test determines the percentages of fine and coarse aggregate in the soil, while the Atterberg limits test determines the plasticity of the soil. These tests are conducted on samples collected during the geotechnical evaluation described in Chapter 3, which ultimately provides information on several soil properties, including in situ moisture content and soil classification. These two properties need to be characterized before the mix design process can begin.

For CSS applications, it is also recommended that the standard Proctor test be conducted according to AASHTO T 99, Standard Method of Test for Moisture-Density Relations of Soils Using a 2.5 kg (5.5 lb) Rammer and a 305 mm (12 in.) Drop, or AASHTO T 134, Standard Method of Test for Moisture-Density Relations of Soil-Cement Mixtures.

2. Determine Cement Type and Estimated Dosage Rate

The cement type used for CSS must comply with the latest specifications for portland cement (see the CSS Materials section above). Typically, the cement is chosen based on the type that is locally available.

Although the exact cement content of the CSS mixture may not be known at this point in the mix design process, an estimated cement content can be chosen to conduct subsequent testing on the mixture. The cement content for CSS is normally between three and six percent of the dry unit weight of the untreated material. This range of cement content can be used for preliminary estimates; however, the percentage of cement should be verified or modified as additional test data become available.

Consultation with a geotechnical engineer regarding the known properties of the untreated soil can also help to define a good starting dosage rate of cement for the mix design. For example, a starting dosage rate could be selected at four percent, and specimens could then be molded with cement contents of two, four, and six percent to attempt to bracket the optimum dosage rate. It may also be helpful to check with state or local agencies to determine the cement content ranges that should be tested for the proposed project.

3. Determine Chemical Compatibility (If Necessary)

If required, the chemical compatibility between the soil and cement can be investigated. The degree of testing depends on the performance criteria that must be met. The Expansive Characteristics, Stability, Sulfate Content, Soil pH, and Organic Content sections in Chapter 2 review standard tests that can be conducted to determine the compatibility of the soil with the cement quantity and type chosen for the CSS application.

4. Determine Atterberg Limits of Three Different Cement Content Samples

Atterberg limits testing should be performed on CSS samples with varying cement contents. It is important that the testing be completed within one hour of mixing.

When determining the mix design, attempts should be made to use the same type and source of cement that will be used in the field during construction. The cement should be stored in a clean and dry environment so that it does not react with moisture prior to being incorporated into the CSS mixture.

5. Determine Optimum Moisture Content and Maximum Dry Density

The next step of the mix design process is to determine the optimum moisture content and maximum dry density (MDD) of the CSS, or the mixture's moisture-density relationship. These are important properties for estimating strength gain and compaction efforts. Determining the OMC, MDD, and percentage of cement for the subgrade to be treated is critical for obtaining the desired moisture and density of the CSS mix. This information is also critical for quality control purposes during construction because research has shown that cement-stabilized materials have better strength and performance when they are properly compacted.

Using the same cement contents as the samples in Step 4, testing traditionally follows AASHTO T 134, Standard Method of Test for Moisture-Density Relations of Soil-Cement Mixtures. This test method is a common and inexpensive procedure that can be performed by most geotechnical or construction materials laboratories. Although in most cases the MDD and OMC do not change appreciably with different cement contents, some agencies require separate moisture-density compaction tests for each of the cement contents (e.g., two, four, and six percent).

To perform this test, the required amount of cement should first be weighed out. The cement content by weight is based on the oven-dry weight of the soil/aggregate only (cement is not included) and is expressed in Equation 2.

$$cement\ content, c(\%) = \frac{weight\ of\ cement}{oven\text{-}dry\ weight\ of\ soil/aggregate\ (excluding\ cement)} \times 100 \quad (2)$$

$$water\ content, w(\%) = \frac{weight\ of\ water\ in\ mixture}{oven\text{-}dry\ weight\ of\ soil/aggregate/cement} \times 100 \quad (3)$$

The amount of water in the mix is called the water content and is defined as the weight of water in the total mixture, including the cement. The water content is expressed as a percentage of the dry weight of the material, as shown in Equation 3.

Cement should be added to the untreated, unstabilized material and thoroughly mixed prior to the addition of water. The sample should be molded within one to two hours of the time the cement is introduced to the mixture.

It is recommended that all mixing be conducted using a laboratory- or commercial-grade soil mixer to replicate actual construction practices and better represent field activities. In general, it is important to replicate the anticipated construction process as much as possible during laboratory testing. If the cement is to be added as slurry during construction, then cement should be added to the samples in slurry form to ensure that the laboratory conditions match the conditions encountered during construction.

The tests should be completed without delay to accommodate the effects of cement hydration. After the samples have been thoroughly mixed with their respective cement contents and water, the OMC and MDD should be calculated for each sample in accordance with AASHTO T 134. The OMC and MDD are defined by a best-fit curve from a minimum of four points, similar to the curve shown in Figure 4.2 for a stabilized clay soil example.

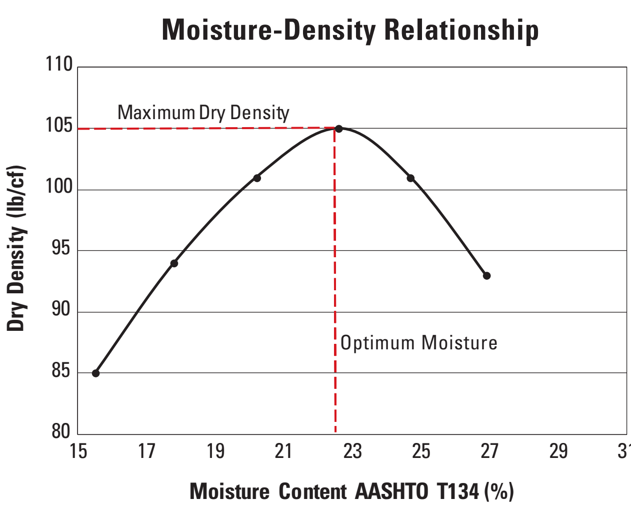

Figure 4.2. Maximum dry density and optimum moisture content curve for a stabilized clay soil

It is important to note that if the design team does not have previous experience or guidance that suggests what the OMC should be for the treated mixture, it is advisable to run a moisture-density test on the untreated soil sample prior to adding cement. The moisture-density test results from the untreated, unstabilized sample provide a range of moisture contents to use as a baseline for further moisture-density testing on the cement-treated samples.

It is strongly recommended that soil tests be performed prior to treatment due to the variability of soils and their properties. For example, when cement is applied to clay soils, the result in some instances may be a lower MDD and higher OMC than in the untreated soil.

6. Determine Unconfined Compressive Strength (Optional for CMS)

Once the material has been analyzed and the OMC, MDD, gradation, and Atterberg limits have been determined, the UCS can then be determined. (Note that for CMS this step is optional.)

Specimens for UCS are typically prepared with at least three different cement contents (e.g., two, four, and six percent by dry weight of soil). A minimum of two specimens should be prepared for each cement content. In most cases, the optimum moisture content obtained according to AASHTO T 134 in Step 5 can be used to mold the samples at the various cement contents. However, some agencies require that separate moisture-density tests be conducted for each cement content.

Immediately prior to UCS testing, the specimens should be immersed in water for four hours. At least two specimens for each of the cement contents should then be tested in accordance with ASTM D1633, Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders, Method A.

7. Plot Unconfined Compressive Strength to Verify Cement Content

The results of the UCS tests from Step 6 should be plotted on a graph, an example of which is shown in Figure 4.3.

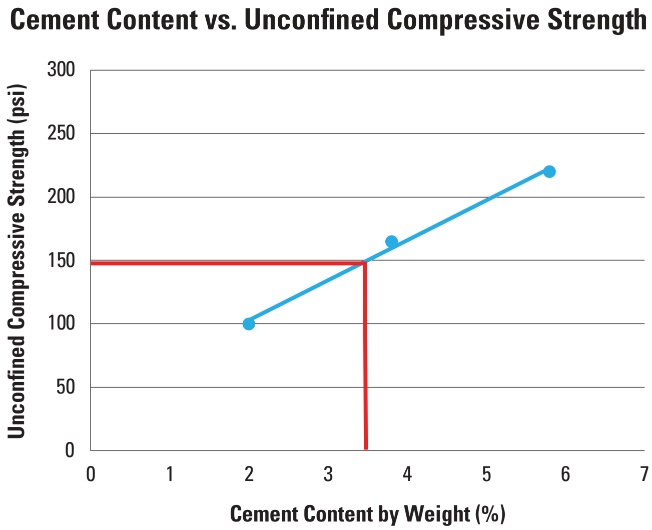

Figure 4.3. Example of unconfined compressive strength versus cement content

In this example, the target strength has been specified as 150 psi, as indicated by the horizontal red line. The results from the graph indicate that 3.5 percent cement content by dry weight will achieve the desired strength. However, a common practice is to increase the cement content by 0.5 to 1.0 percent to accommodate construction uncertainties. Therefore, a cement content of 4.0 percent would be a reasonable recommendation in this case.

Once the cement content has been established, it is recommended that a moisture-density test according to AASHTO T 134 be performed on a sample with the identified cement content to determine exactly what the OMC and MDD should be during construction.

8. Compile Mix Design Report

After the mix design process has been completed, the test results should be compiled into a report and distributed to the owner-agency. The report should contain the following information at minimum, along with the corresponding station limits and/or construction phase:

- Untreated soil properties, including in situ moisture content, gradation, Atterberg limits, and the results of moisture and density testing (when applicable)
- MDD and OMC of the CSS mixture according to AASHTO T 134 and the mixture's Atterberg limits
- Wet density of UCS test specimens before and immediately after the moist curing period
- Cement type to be used to stabilize the soil (e.g., Type I, Type II, Type I/II, or Type II/V for western states)
- Recommended cement content as a percentage of dry materials
- UCS at each trial cement content (if applicable)

In addition to these items, the graphs of UCS versus cement content for the tested cement contents and the moisture-density graph for the recommended cement content should be provided.

If the depth of treatment is known, the mix design report should include the recommended spread rate for the cement so that the correct amount of cement is applied during construction. This spread rate should be specified in pounds per square yard (kilograms per square meter) and identify whether spread rates should vary. (For an example of spread rate recommendations, refer to Table 5.1 in Chapter 5.) Station limits or other identifiable markers should be specified to ensure that the CSS layer remains consistent throughout the project area.

Chapter 5. Construction, Field Inspection, and Testing

This chapter discusses the process for constructing and field testing CSS. The material covered in this chapter includes the equipment required for construction, construction methods, environmental and safety considerations, and field inspection and testing methods.

Construction

It is important to include the geotechnical engineer in the pre-construction phase and throughout the construction process to ensure that the recommendations in the geotechnical report are being met.

Throughout this discussion, keep in mind that two paths can be taken to use cement to improve subgrade soil, as noted in Chapter 4. When marginal conditions are foreseen, that is, before construction begins and sufficient time is available for adequate field sampling and laboratory testing, the CSS application is considered to be on the design path. When unforeseen marginal conditions are encountered during construction and an immediate solution is required, cement-based mitigation can be expedited with engineering judgement, previous experience, and/or an abbreviated laboratory testing program.

Equipment

The equipment needed for CSS construction consists largely of common roadway construction machinery, though a reclaimer/mixer is also needed to uniformly mix the cement into the native material. The following equipment is recommended:

- Reclaimer/mixer
- Grader
- Cement or slurry spreader/distributor truck
- Water truck
- Tamping/sheepsfoot/padfoot roller (for clayey and silty material)
- Smooth drum roller (for granular soils)
- Pneumatic tire roller (optional)

Construction Process

The construction techniques for CSS are very similar in practice to those of mixed-in-place CTB or FDR. However, the timing of operations is less stringent when dealing with CSS.

In preparation for the mixing operation, guide stakes should be set to control the area to be stabilized with cement. This is important to ensure that each truck places the required amount of cement in the appropriate area.

The construction process begins with removal of the existing surface material, which may include vegetation, existing pavement, granular base material, or any other undesirable material identified in the geotechnical report. Based on the soil conditions at the time of construction, the percentage of cement to be added may also be adjusted at this point, if necessary.

The following steps are typical of the construction process:

1. Moisture Conditioning (If Necessary)
2. Initial Pulverization (If Necessary)
3. Preliminary Grading
4. Cement Application
5. Mixing
6. Achievement of Optimum Moisture Content
7. Compaction
8. Final Grading
9. Curing

Each of these steps is discussed in more detail in the following paragraphs.

1. Moisture Conditioning (If Necessary)

At the beginning of the construction operation, the subgrade should be tested to determine the moisture content. A moisture content near the optimum moisture content can facilitate the pulverization process, especially for highly plastic soils (expansive clays).

For soils that are too dry, water can be added immediately before or during initial pulverization (see Figure 5.1). For highly plastic soils, mixing the cement in dry or slurry form prior to adjusting the water content to bring the soil to its optimum moisture may prevent the clay from balling and failing to provide the desired results. For overly wet soils, aeration of the soil may be necessary prior to stabilization, or the soil can be pretreated with a moisture-absorbent additive.

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Figure 5.1. Moisture conditioning with a water truck

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Figure 5.2. Spreading dry portland cement

2. Initial Pulverization (If Necessary)

Before cement is applied to the subgrade, initial pulverization using a roadway reclaimer or scarifier may be required to the full depth of mixing. This step helps ensure uniform distribution.

3. Preliminary Grading

The crown and grade of the planned roadway should be noted, and grading should be completed as necessary to match the construction drawings. Special care should be taken not to remove too much material at this stage because it is easier to remove material than add material after cement is applied.

The grade at the start of mixing should be similar to the final grade after mixing. However, it should be taken into consideration that the volume of the subgrade, and therefore the grade elevation, may increase slightly with the addition of cement.

4. Cement Application

Cement is most commonly applied in a dry condition, in which case the cement should be uniformly spread in a controlled manner by a spreader truck equipped with a mechanical spreader (Figure 5.2). However, cement can also be applied in slurry form from a distributor truck equipped with an agitation system (Figure 5.3) or additives designed to keep the solids in suspension.

Halsted et al. 2008, © 2008 PCA

Figure 5.3. Spreading portland cement slurry

Most specifications call for the application of cement in terms of weight per area (e.g., pounds of cement per square yard or kilograms of cement per square meter). The percentage of cement needed is based on the in-place dry unit weight of the native soil, the application rate specified, and the depth of soil treatment. Equations 4 and 5 show how these three variables are used to determine the cement spread rate. Equation 4 uses US customary units and Equation 5 uses metric units.

Table 5.1 and Table 5.2 show typical spread rates in US customary units and metric units, respectively, based on cement percentage, depth of stabilization, and unit weight of soil.

$$Rate\left(\frac{lb}{yd^2}\right) = Percent\,\frac{Cement}{100} \times Dry\ Unit\ Weight\ \left(\frac{lb}{ft^3}\right) \times \left(9 \times \left(\frac{Depth(in.)}{12}\right)\right) \tag{4}$$

$$Rate\left(\frac{kg}{m^2}\right) = \frac{Percent\ Cement}{100} \times Dry\ Unit\ Weight\ \left(\frac{kg}{m^3}\right) \times \left(\frac{Depth\ (mm)}{1{,}000}\right) \tag{5}$$

Table 5.1. Typical cement spread rates (US customary units)

Dry Unit Weight of Soil (lb/ft³)	20 lb/yd²				30 lb/yd²				40 lb/yd²				50 lb/yd²				60 lb/yd²			
	Depth of Stabilization (in.)				Depth of Stabilization (in.)				Depth of Stabilization (in.)				Depth of Stabilization (in.)				Depth of Stabilization (in.)			
	6	8	10	12	6	8	10	12	6	8	10	12	6	8	10	12	6	8	10	12
90	5%	4%	3%	3%	7%	6%	4%	4%	10%	7%	6%	5%	12%	9%	7%	6%	15%	11%	9%	7%
100	4%	3%	3%	2%	7%	5%	4%	3%	9%	7%	5%	4%	11%	8%	7%	6%	13%	10%	8%	7%
110	4%	3%	2%	2%	6%	5%	4%	3%	8%	6%	5%	4%	10%	8%	6%	5%	12%	9%	7%	6%
120	4%	3%	2%	2%	6%	4%	3%	3%	7%	6%	4%	4%	9%	7%	6%	5%	11%	8%	7%	6%
130	3%	3%	2%	2%	5%	4%	3%	3%	7%	5%	4%	3%	9%	6%	5%	4%	10%	8%	6%	5%

Adapted from Halsted et al. 2008

Table 5.2. Typical cement spread rates (metric units)

Dry Unit Weight of Soil (kg/m³)	10.8 kg/m²				16.3 kg/m²				21.7 kg/m²				27.1 kg/m²				32.5 kg/ m²			
	Depth of Stabilization (mm)				Depth of Stabilization (mm)				Depth of Stabilization (mm)				Depth of Stabilization (mm)				Depth of Stabilization (mm)			
	150	200	250	300	150	200	250	300	150	200	250	300	150	200	250	300	150	200	250	300
1,440	5%	4%	3%	3%	7%	6%	4%	4%	10%	7%	6%	5%	12%	9%	7%	6%	15%	11%	9%	7%
1,600	4%	3%	3%	2%	7%	5%	4%	3%	9%	7%	5%	4%	11%	8%	7%	6%	13%	10%	8%	7%
1,760	4%	3%	2%	2%	6%	5%	4%	3%	8%	6%	5%	4%	10%	8%	6%	5%	12%	9%	7%	6%
1,920	4%	3%	2%	2%	6%	4%	3%	3%	7%	6%	4%	4%	9%	7%	6%	5%	11%	8%	7%	6%
2,080	3%	3%	2%	2%	5%	4%	3%	3%	7%	5%	4%	3%	9%	6%	5%	4%	10%	8%	6%	5%

Adapted from Halsted et al. 2008

For cement applied in a dry condition, dust control may be an issue. The most important time for dust control is immediately before the applied cement impacts the ground. Except on very windy days, dust is typically not a problem once the cement is on the ground. Most contractors have cement spreading equipment that adequately controls fugitive dust during the spreading operation (Figure 5.4).

With cement slurry application, it is important that the slurry be dispersed uniformly over the subgrade area so that it does not pool or run off. It is sometimes necessary to construct earthen dikes along the edge of the treated area to confine the slurry.

Figure 5.4. Dust control during portland cement application

5. Mixing

Once cement is spread over the surface of the subgrade, the next step is to mix the cement into the subgrade material using a reclaimer (Figure 5.5). Mixing should begin within 30 minutes of cement placement. It is important to sufficiently pulverize the soil to the full depth and width of mixing, especially for cohesive soils such as silty clays and clays. In the final mixture, 100 percent of the material should pass the 1½ in. (38 mm) sieve and at least 60 percent should pass the No. 4 (4.75 mm) sieve, exclusive of any gravel or stone retained on the No. 4 (4.75 mm) sieve.

Top: © 2020 Pavement Recycling Systems (PRS) Inc., used with permission
Bottom: Jeff Wykoff, California Nevada Cement Association

Figure 5.5. Mixing portland cement and native soil with a reclaimer

The more finely the soils are pulverized, the more effective the cement stabilization treatment will be. Agricultural disks, graders, rippers, and other scarifying equipment are not recommended, especially for cohesive soils, because they cannot achieve the proper degree of pulverization. In contrast, a reclaimer uses a mixing drum, operating in an upward cutting direction, to finely mix the cement, existing subgrade material, and additional water (if required). Table 5.3 lists the recommended gradation for CSS, along with the recommended gradations for FDR and CTB as a comparison. Refer to the guide specification in Appendix A for more detailed mixing guidance.

Table 5.3. Comparison of typical gradation requirements for CSS, CTB, and FDR

Type of Soil-Cement	Minimum Percent Passing			
	3 in. (75 mm) Sieve	2 in. (50 mm) Sieve	1½ in. (38 mm) Sieve	No. 4 (4.75 mm) Sieve
Cement-Stabilized Subgrade	—	—	100	60
Cement-Treated Base	100	95	—	55
Full-Depth Reclamation	100	95	—	55

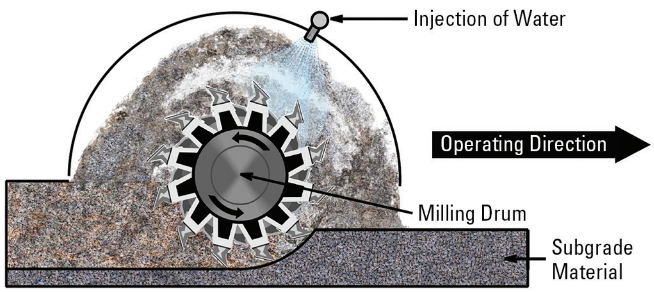
Mixing should be continued until the product is uniform in color, meets material sizing requirements, and is at a moisture content that allows compaction to the required density. The entire operation of cement spreading, water application, and mixing should result in a uniform mixture of soil/aggregate, cement, and water for the full design depth and width.

The proper depth of mixing is a function of design, site conditions, and available equipment. Reclaimers now have the capability of uniformly mixing to a depth of up to 24 in. (0.6 m). However, if greater depths are required, the subgrade can be treated (by adding cement and water and then compacting) in multiple layers. In these instances, the upper layer is removed, and CSS treatment can be completed in the bottom layer before the upper layer is replaced and treated. However, treating in multiple layers is more costly than single-layer treatment due to the effort required. One option that may be considered where deep treatment is necessary would be to add a CTB layer on top of a single deep CSS layer.

6. Achievement of Optimum Moisture Content

It is very important that the moisture content of the subgrade, particularly in expansive material, be maintained in accordance with the recommendations in the geotechnical report until the material has been covered with base material or pavement.

Water is added by injecting the proper amount of moisture into the mixing chamber of the reclaimer (Figure 5.6) or by placing water on the ground with a water truck in a separate operation (Figure 5.1). In either case, obtaining the correct amount of moisture is very important for achieving the target compaction, particularly in expansive clayey soil.



Snyder & Associates, Inc./CP Tech Center

Figure 5.6. Roadway reclaimer

7. Compaction

Once the water, cement, and existing subgrade materials have been mixed, compaction is the next step. The time limit between mixing and compacting is not as stringent for CSS as it is for CTB, although when possible compaction should occur immediately after mixing and all CSS construction operations should be completed on the same day (Halsted et al. 2008). Each compacted lift should meet the density requirements and optimum moisture content requirements in the geotechnical report or applicable specifications.

Although specified densities may be harder to achieve at greater treatment depths, meeting density requirements is important because the primary purpose of CSS is to provide stability and satisfy compressive strength requirements. If adequate compaction cannot be achieved in a single lift of CSS due to unstable conditions, multiple-lift construction may be necessary, as described in Step 5 (Mixing). In severely unstable areas, a test strip should be constructed to determine the number of lifts required. If achieving a specified density is prohibitively difficult, a stable, firm, and unyielding subgrade condition may also be accepted by the project engineer.

For applications involving silty and clayey soils, initial compaction should be done with a vibratory tamping roller (Figure 5.7) or padfoot roller that compacts from the bottom to the top of the subgrade. Compaction with this type of roller should continue until the required minimum density is achieved, which is usually indicated by the padfoot/tamping/sheepsfoot roller "walking out" of the impressions it leaves in the soil.

For compaction of sandy or gravelly material and for final compaction of silty and clayey soils, a vibratory smooth drum (Figure 5.8) or pneumatic tire roller is used.

For both silty/clayey and sandy/gravelly subgrades, the CSS material should be uniformly compacted to a minimum of 95 percent of maximum dry density.

As a final check, a proof roll by a tandem-axle truck loaded to the legal maximum weight may be performed to ensure an adequate and uniform CSS treatment.

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Figure 5.7. Vibratory sheepsfoot tamping roller

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Figure 5.8. Smooth drum roller

8. Final Grading

After compaction with the smooth drum roller, final grading should be performed using a motor grader or similar equipment. The completed subgrade should be slightly overbuilt and trimmed to avoid the need for thin fills to achieve the final crown and grade.

9. Curing

Although not always done in practice, curing with a fog water spray or bituminous emulsion is suggested to obtain the maximum benefit from the cement treatment. Refer to the guide specifications in Appendix A for additional information about finishing and curing.

Environmental and Safety Considerations

Although weather and environmental conditions are not as critical for CSS construction as they are for CTB construction, they need to be taken into consideration. CSS material must not be mixed into standing water or when the soil/aggregate is frozen or when the air temperature is below 40°F (4°C). It is further recommended that dry cement not be placed on windy days because cement content could be lost and blowing cement may cause a dust nuisance to the general public.

When handling cement, proper eye protection and proper protective clothing, including gloves, long-sleeve shirts, and long pants, are required.

Field Inspection and Testing

Inspector's Checklist

The inspector evaluating CSS construction should monitor and/or verify the following items, as discussed in further detail in the *Soil-Cement Inspector's Manual* (PCA 2001):

- Cement content
- Application rate
- Moisture content
- Mixing depth
- Compaction
- Curing

Quality Control

Quality control should be performed on site by the owner's representative with the assistance of the geotechnical consultant. At minimum, a quality control program should include the following items:

- After the site has been stripped of vegetation or existing pavement, the site should be proof rolled (refer to Step 7 of the Construction section above). Unstable areas identified during the proof rolling should be evaluated by the contractor and geotechnical consultant to determine the depth of treatment required. Samples of the unstable material should be obtained for laboratory testing at this time to determine the percentage of cement required for stabilization.
- Before cement is applied to the subgrade, all equipment should be inspected. The inspector should verify that all cutting teeth of the reclaimer are in place and in good condition, the spray bar and nozzles are working properly and not clogged, the onboard stabilizing agent system is functioning and accurate, and the water application rate is correct. If a bulk spreader is used, it should be properly calibrated (ARRA 2013).
- After the contractor's methods have been established, field observations should be performed, and a test strip may be constructed to monitor the cement application rates and depths of treatment.
- During cement application, the application rate should be monitored for accuracy. Mixing should begin within 30 minutes of cement placement (ARRA 2013). The effectiveness of mixing should be verified during the mixing operation to ensure proper gradation and pulverization depth.
- Compaction rollers should be inspected to ensure that they have a proper operating weight and working water systems, and scrapers should be inspected to ensure that they meet specifications. Compaction should occur immediately after the reclaimer mixes the cement and subgrade.
- Field density testing should be performed during construction in accordance with approved AASHTO or ASTM methods to confirm that the project specifications are being met.
- Density and moisture tests should be performed on a regular basis (for example, every 5,000 ft^2 [465 m^2]) for each compacted lift of material.
- Curing should be performed according to project specifications.

Chapter 6. Case Studies

This chapter presents five case studies that describe projects in which cement has been incorporated into the subgrade to improve soil properties. Each case study includes project information and a detailed discussion of the improvements resulting from cement treatment.

Case Study 1: Lower Muscatine Road

Project Information

Year Constructed	2013
Case Type	Construction
Facility Location	Lower Muscatine Road Iowa City, Iowa
Existing Soil Conditions	Lean clay to silty clay
Civil Firm	Foth Infrastructure & Environment, LLC Johnston, Iowa
Geotechnical Firm	GEOMAX Soil Stabilization Iowa City, Iowa
Construction Contractor	Metro Pavers, Inc. Iowa City, Iowa
Construction Subcontractor	Maxwell Construction, Inc. Iowa City, Iowa

Discussion

A pavement reconstruction project on Lower Muscatine Road in Iowa City, Iowa, involved converting a two-lane roadway to a three-lane roadway. The new road was to include a 12 in. (300 mm) CSS, a 6 in. (150 mm) rock subbase, and a 9 in. (225 mm) portland cement concrete pavement. Part of the project ran through a residential area and part through a commercial area. Areas containing shallow buried utilities were avoided for the CSS treatment.

Because the subgrade was highly saturated, it was decided to construct a CSS to remedy the saturation. Fly ash was not chosen as a solution due to potential problems with dust in the residential areas of the project, as well as the high volume of fly ash required to remedy the subgrade.

A cement content of four percent was recommended by the contractor based on previous experience, and the recommendation was reviewed by the design team and the Iowa Department of Transportation. The cement was applied in powder form and mixed with the existing subgrade using a roadway reclaimer (Figure 6.1).

The CSS was then compacted using a vibratory sheepsfoot roller (Figure 6.2) and trimmed with a skid loader. Final compaction was determined using standard Proctor testing and DCP testing. DCP testing was used in areas where the contractor felt standard Proctor testing was not applicable.

The CSS was then allowed to set for 24 hours prior to resumption of activity on the subgrade. Currently, the pavement is performing exceedingly well. The only visible cracking is directly above a deep sanitary line.

City of Iowa City

Figure 6.1. Cement and subgrade being mixed with reclaimer

City of Iowa City

Figure 6.2. Vibratory sheepsfoot roller compacting subgrade

Case Study 2: Los Patrones Parkway

Project Information

Year Constructed	2018
Case Type	Design
Facility Location	Los Patrones Parkway Rancho Mission Viejo South Orange County, California
Existing Soil Conditions	Weak and unstable, R-value of 20 (SC)
Geotechnical Firm	GMU Geotechnical, Inc. Rancho Santa Margarita, California
Soil Stabilization Contractor	Cindy Trump, Inc. DBA Lindy's Cold Planing La Habra, California
Construction Contractor	The R.J. Noble Company Orange, California
Public Agency	Orange County Public Works Santa Ana, California

Discussion

California SR-241 is a toll road that experiences high volumes of traffic and has a traffic index (TI) of 11. Los Patrones Parkway is a 5.5 mi (8.8 km) non-toll extension of SR-241 with two lanes in each direction. The 2 million ft² (186,000 m²) of CSS and pavement extend from Oso Parkway to Cow Camp Road. From top to bottom, the pavement consists of 0.2 ft (60 mm) of hot-mix asphalt, 0.6 ft (180 mm) of warm-mix asphalt, 0.5 ft (150 mm) of aggregate base, and 0.95 ft (290 mm) of CSS. Compared to the initial full-depth asphalt design, the cost savings from using CSS were estimated to be between 30 and 40 percent.

To achieve 300 psi (2.1 MPa) at seven days, a cement content of four percent was applied and mixed with the existing subgrade using two Wirtgen reclaimers (Figure 6.3). Type II/V cement was utilized.

This project received the 2018 American Society of Civil Engineers (ASCE) Orange County Branch Project of the Year Award in the Outstanding Transportation Project category.

The CSS was compacted using a steel-wheel roller (Figure 6.4).

Jeff Wykoff, California Nevada Cement Association

Figure 6.3. Reclaimers mixing the subgrade and cement

Jeff Wykoff, California Nevada Cement Association

Figure 6.4. Compacted subgrade

Case Study 3: Muhlenberg County Airport

Project Information

Year Constructed	2008
Case Type	Design
Facility Location	Greenville, Kentucky
Existing Soil Conditions	Weak and unstable
Civil Firm	Garver North Little Rock, Arkansas
Stabilization Contractor	Mt. Carmel Stabilization Group, Inc. Mt. Carmel, Illinois
Construction Contractor	Parkway Construction Lewisville, Texas
Public Agency	Kentucky Department of Aviation Frankfort, Kentucky

Discussion

The information for this case study is excerpted with minimal changes from *Cement-Modified Soil Solves Kentucky Airport Problem*, a cement-modified soil case history written by Doug Smith of the Portland Cement Association, Southeast Region.

Muhlenberg County Airport, located in Greenville, Kentucky, was in need of improvements, including a new 2,800 ft (0.85 km) partial parallel taxiway. During the design, it was discovered that the soils supporting the 1 to 3 ft (0.3 to 0.9 m) taxiway embankment were weak and would create issues with stability (Figure 6.5). Some method to improve the stability of the weak in situ soils was necessary to allow construction of the embankment.

Mt. Carmel Stabilization Group, Inc. was chosen to perform the cement modification. The design called for a six percent cement content mixed to a depth of 16 in. (400 mm) with a seven-day curing period before embankment construction could proceed. The cement modification was completed in two days in June 2008 (Figure 6.6). Stability was improved immediately, and embankment construction began one week later. Daniel Taylor, airport manager, was quoted as saying "it worked out great and appears to have been a great answer for our problem."

PCA

Figure 6.5. Weak materials evidenced during modification

PCA

Figure 6.6. Mixer incorporating portland cement to a depth of 16 in.

Case Study 4: Des Moines International Airport

Project Information

Year Constructed	2018
Case Type	Design
Facility Location	Des Moines International Airport Des Moines, Iowa
Existing Soil Conditions	Brown silty clay (A-6, CL)
Civil Firm	Foth Infrastructure & Environment, LLC Johnston, Iowa
Construction Contractor	Flynn Co., Inc. Dubuque, Iowa
Construction Subcontractor	Manatt's, Inc. Brooklyn, Iowa

Discussion

In summer 2018, the Des Moines International Airport conducted Phase 2 of Runway 13/31 reconstruction. This project involved reconstructing approximately 2,500 LF (760 m) of the runway.

The untreated soil under the runway was a brown silty clay (A-6, CL) that had a sulfate content of 0.19 percent according to ASTM C1580, Standard Test Method for Water-Soluble Sulfate in Soil. To provide a suitable soil base for the pavement structures, the design engineers elected to follow Federal Aviation Administration (FAA) specification P-157 to stabilize the soils. This FAA specification requires a soil-cement mixture to be designed at a target dosage rate to provide the specified amount of stability in the soil. In this instance, the FAA required a 125 psi (0.86 MPa) minimum unconfined compressive strength in the soil-cement mixture.

During removal of the existing pavement structure, the geotechnical laboratory working with the contractor obtained several subgrade soil samples from every 300 LF (91 m) of runway being replaced. The soil samples were homogenized under laboratory conditions, and cement dosage rates of two, three, and four percent were selected to keep the unconfined compressive strength near the 125 psi (0.86 MPa) specification requirement. The cement type selected was Type I/II. The tests conducted were Atterberg limits, grain size analysis, and Proctor tests on the samples at the three different dosage rates.

Each cement dosage rate yielded an increase in strength of approximately 100 to 300 percent over the untreated soil.

Based on the results of the study, the project utilized a cement dosage rate of four percent, which equates to approximately 38 lb/yd² (20.6 kg/m²) of cement. The cement was applied in dry form (Figure 6.7).

The cement and untreated soil were mixed using a Wirtgen reclaimer and compacted via a sheepsfoot roller (Figure 6.8) and smooth drum roller (Figure 6.9).

Figure 6.7. Subgrade after cement application

Figure 6.8. Mixing and compacting cement and subgrade

Figure 6.9. Compacting cement-stabilized subgrade

Case Study 5: Wilson Middle School and Central Elementary School

Project Information

Year Constructed	2018
Case Type	Design
Facility Location	Wilson Middle School and Central Elementary School San Diego, California
Existing Soil Conditions	Sandy fat clay
Civil Firm	Southern California Soil and Testing, Inc. San Diego, California
Construction Contractor	F.J. Willert Contracting Chula Vista, California
Soil Stabilization Subcontractor	Pavement Recycling Systems, Inc. Jurupa Valley, California

Discussion

In 2018, the Wilson Middle School was demolished and the Wilson Middle School and Central Elementary School was constructed in its place. Construction also included several additional buildings, a parking structure, hardscapes, playground areas, and a drop-off area.

Upon geotechnical exploration, it was discovered that the site consisted of a substantial amount of expansive soil. The plasticity index of the existing soil ranged from 10 to 36 while the expansion index ranged from 18 to 155, neither of which is ideal for construction.

Two options were considered to improve the site's soil. The first option was to completely remove a portion of the expansive clay soil and replace it with select granular material. The second option was to stabilize the expansive clay soil with either cement or lime. Cement stabilization proved to be the most viable option for remedying the expansive soil due to its sustainability, its lower cost versus removal and replacement, and the overall time savings that the option would provide. The decision to use CSS eliminated over 3,000 truckloads of soil compared to removal and replacement grading operations.

A geotechnical evaluation determined that an application rate of five percent cement by dry weight of soil would significantly reduce the plasticity index and the expansion index, allowing the soil to meet the low expansion criterion.

The cement was mixed into the soil using a reclaimer (Figure 6.10), and the subgrade was compacted and trimmed, allowing foundation construction to be completed (Figures 6.11 and 6.12).

Figure 6.10. Mixing cement and subgrade

Figure 6.11. Constructing foundation for the school structure

Figure 6.12. Completed foundation on cement-treated subgrade

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Appendix A. Suggested Construction Specification for Cement-Stabilized Subgrade Soils

1. General

1.1 Description. Cement-stabilized subgrade (CSS) soils shall consist of soil/aggregate, portland cement, and water proportioned, mixed, compacted, and cured in accordance with this specification and shall conform to the lines, grades, thicknesses, and typical cross sections shown in the plans.

1.2 Caveat. In terms of format and content, this specification is intended to provide information regarding typical CSS construction. Most projects have features or requirements not covered by this specification that should be incorporated into the project documents.

2. Referenced Documents

Four American Association of State Highway and Transportation Officials (AASHTO) specifications with corresponding ASTM International (ASTM) designations and one ASTM specification:

AASHTO M 85
Specification for Portland Cement (ASTM C150)

AASHTO M 240
Specification for Blended Hydraulic Cements (ASTM C595)

ASTM C1157
Performance Specification for Hydraulic Cement

AASHTO T 134
Moisture-Density Relations of Soil-Cement Mixtures (ASTM D558)

AASHTO T 310
In-Place Density and Water Content of Soil and Soil-Aggregate by Nuclear Methods (Shallow Depth) (ASTM D6938)

3. Submittals

3.1 Submittal Requirements. The contractor shall submit the following to the engineer at least 30 days before start of any production of CSS:

3.1.1 Certifications. Certifications for portland cement as required by the engineer.

3.1.2 Specifications. Manufacturers' data and specifications for equipment, including capacities to be used in mixing and compacting CSS.

3.1.3 Proposed CSS Mix Design. If the proposed mix design is developed by the contractor or a change to the mix design is suggested, the mix design must be submitted to the engineer for approval at least two weeks prior to CSS construction. This mix design shall include details on soil/aggregate gradation, cementitious materials, and the required moisture and density to be achieved during compaction.

4. Materials

4.1 Soil/Aggregate. Soil/aggregate may consist of (1) any combination of gravel, stone, sand, silt, and clay; (2) miscellaneous material such as caliche, scoria, slag, sandshell, cinders, and ash; and/or (3) waste material from aggregate production plants. No topsoil or organic content greater than two (2) percent may be present.

4.2 Portland Cement. All portland cement used shall comply with the latest specifications for portland cement (AASHTO M 85 or ASTM C150) or blended hydraulic cements (AASHTO M 240, ASTM C595, or ASTM C1157).

4.3 Water. All water used shall be free from substances deleterious to the processing of CSS material.

5. Equipment

5.1 Descriptions. CSS may be constructed with any machine or combination of machines or equipment that will produce completed CSS material meeting the requirements for gradation, cement and water application, mixing, compacting, finishing, and curing as provided in this specification.

5.2 Mixing Methods. Mixing shall be accomplished in place using a single-shaft reclaimer machine. Agricultural disks, graders, or other scarifying equipment may be used to initially blend the cement into the soil/aggregate material but should not be used for final mixing.

5.3 Cement Proportioning. The cement spreader used for in-place mixing shall be capable of uniformly distributing the cement at the specified rate. Cement may be added in dry or slurry form. If applied in slurry form, the slurry mixer and spreading equipment shall be capable of completely dispersing the cement and water and maintaining a uniform, consistent slurry without separation throughout the slurry placement.

5.4 Application of Water. Water may be applied through the mixer or with water trucks equipped with pressure-spray bars.

5.5 Compaction. The processed material shall be compacted with one or a combination of the following: tamping or grid roller, pneumatic tire roller, steel-wheel roller, vibratory roller, or vibrating-plate compactor.

6. Construction Requirements

6.1 General

6.1.1 Preparation. Before CSS processing begins, the area to be mixed shall be graded and shaped to the lines and grades shown in the plans or as directed by the engineer. During this process, any unsuitable material that cannot be stabilized using CSS shall be removed and replaced with acceptable material.

6.1.2 Mixing. CSS material shall not be mixed when the soil/aggregate is frozen or when the air temperature is below 40°F (4°C).

6.2 Processing

6.2.1 Preparation. The surface of the soil/aggregate to be processed shall be graded to an elevation such that, when the soil/aggregate is mixed with cement and water and recompacted to the required density, the final elevation will be as shown in the plans or as directed by the engineer. The material in place and the surface conditions shall be approved by the engineer before the next phase of construction is begun.

6.2.2 Application of Cement. The specified quantity of cement shall be applied uniformly in a manner that minimizes dust, runoff, and ponding and that is satisfactory to the engineer. For application of cement in slurry form, initial scoring of the surface shall be performed and soil berms installed to provide a method to uniformly distribute the slurry over the material to be processed without excessive runoff or ponding.

6.2.3 Mixing. Mixing shall begin within 30 minutes after the cement has been spread and shall continue until a uniform mixture is produced. The final mixture shall be pulverized such that 100 percent passes the 1½ in. (38 mm) sieve and at least 60 percent passes the No. 4 (4.75 mm) sieve, exclusive of any gravel or stone retained on the No. 4 (4.75 mm) sieve.

The final pulverization test shall be conducted at the conclusion of mixing operations. Mixing shall continue until the product is uniform in color, meets gradation requirements, and is at a moisture content that allows compaction to the required density. The entire operation of cement spreading, water application, and mixing shall result in a uniform soil/aggregate, cement, and water mixture for the full design depth and width.

6.3 Compaction. CSS material shall be uniformly compacted to a minimum of 95 percent of maximum dry density based on a moving average of five consecutive tests with no individual test showing a density below 93 percent. The field density of compacted CSS material shall be determined by the nuclear method in the direct transmission mode (AASHTO T 310 or ASTM D6938). Optimum moisture content and maximum dry density shall be determined prior to the start of construction and in the field prior to and during construction by a moisture-density test (AASHTO T 134 or ASTM D558).

6.4 Finishing and Curing. As compaction nears completion, the surface of the CSS shall be shaped to the specified lines, grades, and cross sections. Compaction shall then continue until uniform and adequate density is obtained. Compaction and finishing shall be performed in such a manner as to produce a dense surface free of compaction planes, cracks, ridges, or loose material. All finishing operations shall be completed within four hours from the start of mixing.

Finished portions of CSS that are traveled on by equipment used in the construction of an adjoining section shall be protected in such a manner as to prevent the equipment from damaging completed work.

If required by the engineer, the surface may be moist-cured with a fog-type water spray or bituminous emulsion after final finishing is completed.

6.5 Traffic. Completed portions of CSS can be opened immediately to construction equipment provided any curing operations are not impacted.

6.6 Covering. Subsequent subbase and base layers can be placed at any time after finishing is completed, as long as the CSS is sufficiently stable to support the required construction equipment without permanent distortion or marring of the surface.

6.7 Maintenance. The contractor shall maintain the CSS material in good condition until all CSS treatment work is completed and accepted. Such maintenance shall be performed by the contractor at their own expense.

Maintenance shall include immediate repairs of any defects in the CSS that may become apparent. If it is necessary to replace any processed material, the replacement shall be for the full depth, with vertical cuts, using fresh CSS material.

7. Inspection and Testing

7.1 Description. The engineer, with the assistance and cooperation of the contractor, shall perform any inspections and tests deemed necessary to ensure the conformance of the work to the contract documents. These inspections and tests may include, but shall not be limited to, the following:

1. Obtaining test samples of the CSS material and its individual components at all stages of processing and after processing is completed.
2. Observing the operation of all equipment used to perform the work. Only those materials, machines, and methods meeting the requirements of the contract documents shall be used unless otherwise approved by the engineer.

All testing of processed material or its individual components, unless otherwise noted specifically in the contract documents, shall be in accordance with the latest applicable AASHTO or ASTM specifications in effect as of the date of advertisement for bids on the project.

8. Measurement and Payment

8.1 Measurement. The materials yielded by or involved in CSS construction shall be measured as follows:

1. In square yards (square meters) of completed and accepted CSS material as determined by the specified lines, grades, and cross sections shown in the plans.
2. In tons (metric tons) of cement incorporated into the CSS material in accordance with the instructions of the engineer.

8.2 Payment. This work shall be paid for at the contract unit price per square yard (square meter) of completed and accepted CSS material and at the contract unit price per ton (metric ton) of cement furnished, multiplied by the quantities obtained in accordance with Section 8.1. Such payment shall constitute full reimbursement for all work necessary to construct the CSS material, including watering, curing, inspection and testing, and all other incidental operations.

Appendix B. Mix Design Swell Test Method for Soil Treatment Using Additives (Cement or Other)

Contents

Section 1. Overview

This method determines the improved engineering properties, such as strength and shrink/swell properties, of soils treated with additives relative to untreated soil. The method refers specifically to cement as the additive; however, the method may be used for other additives for comparison purposes. Some changes in sample preparation may be needed for other additives.

While a variety of compaction methods may be used (e.g., standard, modified, gyratory, vibratory hammer) to mold the specimens, this procedure follows the standard Proctor test.

The values stated in both US customary units and metric units (presented in parentheses) are to be regarded separately. The values stated in one unit shall be used independently of the values stated in the other unit. Combining values with varying units may result in non-conformance with this test method.

Section 2. Apparatus

The following apparatus is required:

- The apparatus outlined in the following test methods:
  - AASHTO T 2
  - AASHTO T 99
  - AASHTO T 134
- A compression testing machine with a capacity sufficient to break the specimens in question and meeting the requirements of ASTM D1633
- A diameter measuring device accurate to 0.05 in. (1.0 mm)

Section 3. Materials

The following materials are needed:

- A fresh sample of additive (cement or other). Ideally, this sample would be representative of the additive intended for the project in question. Consideration should be given to the delivery method of the additive (powdered, slurry, etc.), and the additive should ideally be prepared in a similar fashion.
- The soil to be stabilized. A sufficient representative quantity is required to perform index, moisture-density, swell, and unconfined compressive strength (UCS) testing. For fine-grained material, this quantity is typically greater than 200 lb (90 kg); for coarser grained material, this quantity may be 50 lb (22.7 kg) greater.
- Potable water. When water to be used in the intended project may contain contaminates, consideration should be given to using a representative water sample.

Section 4. Preparation of Sample and Additive

Secure a representative soil sample and prepare a representative bulk sample as described in AASHTO T 2 or using a minimum of 200 lb (90 kg) of material. Do not reuse soil that has been previously laboratory compacted.

Section 5. Procedure

This section lists the steps necessary to test the swelling properties of untreated soil and soil treated with cement or alternative additives.

Moisture-Density Relationship

1. Determine the optimum moisture content (OMC) and maximum dry density (MDD) for the un-treated and treated soil mixtures in accordance with AASHTO T 99, Standard Method of Test for Moisture-Density Relations of Soil.

2. Use the desired or estimated additive concentration when determining the OMC and MDD for the treated soil. Note the following:

    - While this method is used to determine an optimum cement or additive concentration for a given soil and project, the moisture-density relationship should be determined using soil containing some concentration or percentage of cement or additive. In preparing the soil for moisture-density testing, estimate an anticipated midrange for the cement or additive concentration. Small changes in cement or additive content typically have only negligible effects on moisture and density. When the original estimate is determined to be significantly different than the final determined cement or additive optimum, obtaining a new moisture-density relationship using the finalized cement additive content may be required or desired.
    - Moisture content percentages are based on the dry mass of the soil plus dry additive.
    - If the intent of testing is to simply verify that a selected amount of stabilizer will provide adequate results, it is not necessary to complete a Proctor test on the non-treated sample (i.e., a raw Proctor test).

3. Report the OMC and MDD for the untreated and treated soil.

Swell Testing

1. Prepare four untreated specimens as follows:

    - Moisture condition the untreated soil to the OMC of the untreated soil.
    - Allow the untreated soil to remain in a sealed container for at least 12 hours at room temperature (Figure B.1).
    - Record the sealed time.
    - Remove the specimens from their containers.

    NOTE: It is imperative to mix the untreated soil specimens at the same OMC as the treated soil specimens in order to determine the benefit of the treatment.

2. Prepare treated specimens as follows:

    - Prepare four specimens for each additive dosage rate in the same manner as described in Step 1.
    - After the specimens have remained for at least 12 hours at room temperature in a sealed container, record the sealed time.
    - Remove the specimens from their containers, add the additives to the respective specimens, and mix the additives into the soils (Figure B.2).

    NOTE: When mixing the treated samples, add the additive and water in a way that is as similar as possible to the way the additive and water will be mixed into the soil in the field. Some additives may require mellowing after mixing the additive into the soil and before compaction. In all cases, follow the recommended practices for the specific additive.

3. Compact four specimens for each treatment type (i.e., four untreated specimens and four specimens for each additive dosage rate) to maximum dry density. Alternatively, soils may be compacted to another density of interest, such as a project-specified percentage of MDD. Typically, compaction to within 2 lb/ft³ (32 kg/m³) or approximately 2% of a specified density is acceptable. Multiple additive percentages may be compacted during a single round of testing if desired (e.g., to determine an optimum cement or additive percentage). Figure B.3 illustrates a specimen just after compaction and prior to extrusion.

    NOTE: While a variety of compaction methods (e.g., standard, modified, gyratory, vibratory hammer) may be used to mold the specimens, the procedure outlined in this appendix follows the compaction method specified by the standard Proctor test.

    While some empirical evidence suggests that multiple lifts within a specimen may impede suction and swelling, compacting a specimen in a single lift may not be possible. Practice has shown that the gyratory compacting equipment typical in hot-mix asphalt laboratories is capable of compacting suitable samples in a single lift. However, when this equipment is not available or its use is impractical, standard soil compacting laboratory equipment (i.e., Proctor hammers and molds) may be used. If this equipment is used, multiple lifts are appropriate and acceptable. The goal of constructing the samples is to obtain uniformly compacted samples of a representative density and composition with a height-to-diameter ratio of between 1:1 and 2:1.

4. Extrude the specimens from the molds (Figure B.4)

Figure B.1. Untreated soil samples in labeled sealed containers

Figure B.2. Mixing additive and soil in the laboratory

Figure B.3. Preparing a specimen just after compaction

Figure B.4. Extruding a compacted specimen from a mold

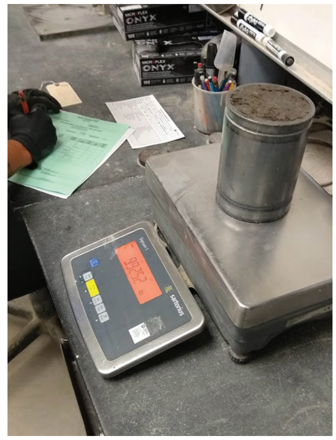

Figure B.5. Weighing a compacted specimen

Figure B.6. Measuring the diameter of a specimen

Figure B.7. Measuring the height of a specimen using a micrometer dial assembly

Figure B.8. Specimen in a sealed bag

5. Weigh each specimen immediately to the nearest 0.001 lb (0.5 g) (Figure B.5).

6. Measure the diameter of each specimen at the bottom, top, and middle of the specimen using a micrometer to the nearest 0.05 in. (1.0 mm) (Figure B.6). Mark the samples at the measurement points so that future measurements can be obtained in the same locations.

7. Measure the height of each specimen at approximately 120 degree intervals (for a total of three locations) using a micrometer dial assembly to the nearest 0.05 in. (1.0 mm) (Figure B.7). Mark the samples at the measurement points so that future measurements can be obtained in the same locations.

8. On a worksheet, record the date molded and the molded weight (W_{mold}), diameter (D_{mold}), and height (H_{mold}) for each specimen.

9. Place each specimen in a sealed bag at room temperature (Figure B.8).

10. After two days (approximately 48 hours), remove two specimens for each treatment type from their bags and place them in an oven at 110°F (43°C) for four hours (Figure B.9). The other two specimens for each treatment type will remain in their sealed bags for a total of seven days, with no additional weighing necessary.

Figure B.9. Specimen in an oven

Figure B.10. Oven-dried specimen before weighing and measuring

11. Remove the specimens from the oven (Figure B.10) and repeat the measurements described in Steps 5 through 7 on those specimens.
12. On a worksheet, record the date oven-dried and the oven-dried weight ($W_{oven\text{-}dry}$), diameter ($D_{oven\text{-}dry}$), and height ($H_{oven\text{-}dry}$) for each specimen.
13. Place a 4 in. (101 mm) diameter and 0.25 in. (6.35 mm) thick porous stone on top of each oven-dried specimen, with a 4 in. (101 mm) diameter disc or piece of plastic between the top porous stone and the soil specimen.

    NOTE: Alternatively, a 4 in. (101 mm) diameter impervious cap made of plastic or metal can be used in place of the porous stone and plastic disc. The plastic disc between the specimen and the porous stone seals the specimen to prevent moisture from evaporating from the top.
14. Mark every 120 degrees around the circumference of each porous stone or cap (for a total of three marks) to coincide with the markings on the top of the specimens.

    NOTE: These marks will be used as reference marks to ensure that the height measurements are taken at the same position each time.
15. With the porous stones or caps in place, measure the diameter and height of each specimen as described in Steps 6 and 7. On a worksheet, record the diameter and height as the Day 0 dimensions.
16. Place the specimens upside down in deep, impervious pans so that the porous stones or caps are on the bottom.

    WARNING: Do not place the treated and untreated specimens in the same pan. Additionally, keep specimens treated with various additives, if applicable, separate.
17. Fill each pan with water so that the water level in the pan is near the top of the porous stone or cap.

    WARNING: Do not overfill the pan such that water is in direct contact with the specimen.
18. Measure the height and diameter of each specimen as described in Steps 6 and 7 every 24 hours for five days, using the marks on the porous stone or cap to measure the diameter at the same location on the specimen each time.
19. Using the height and diameter measurements from Step 18, plot the percent volumetric swell over time for each specimen.
20. On a worksheet, record the ending date of the five-day soak and the weight (W_{swell}), diameter (D_{swell}), and height (H_{swell}) on that date for each specimen.
21. Test each specimen, including those left in the sealed bags, for UCS in accordance with ASTM D1633, Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders. Record the UCS from the specimens left in the bags as UC_{dry} and the UCS from the five-day soak specimens as UC_{swell}.
22. With the four specimens for each treatment type, determine the average UCS of the two five-day soak specimens and the average UCS of the two dry specimens and report these values as S_{swell} and S_{dry}, respectively.

Section 6. Calculations and Graphs

Use the following equations to determine the percent volumetric shrinkage, the percent volumetric swell, the percent change of water content, and the percent retained UCS.

Percent volumetric shrinkage after two days in a sealed bag:

$$\Delta V_{shrink} = [\ 1 - \{((\ \pi * D_{sealed\text{-}dry}^2 * H_{sealed\text{-}dry})/4)\ /\ ((\pi * D_{mold}^2 * H_{mold})/4)\ \}] * 100$$

where,

$D_{sealed\text{-}dry}$ = Diameter of specimen after two days in sealed bag.

$H_{sealed\text{-}dry}$ = Height of specimen after two days in sealed bag.

D_{mold} = Diameter of specimen after molding

H_{mold} = Height of specimen after molding

Percent volumetric swell after five days of (or intermittent) soaking:

$$\Delta V_{swell} = \{\{((\pi^* D_{swell}^2 * H_{swell}) /4)\} / ((\pi^* D_{oven\text{-}dry}^2 * H_{oven\text{-}dry}) /4)\} - 1] * 100$$

where,

$D_{sealed\text{-}dry}$ = Diameter of specimen after two days in sealed bag

$H_{sealed\text{-}dry}$ = Height of specimen after two days in sealed bag

D_{swell} = Diameter of specimen after five-day capillary soak

H_{swell} = Height of specimen after five-day capillary soak

Percent change of water content:

$$\Delta w\% = [\ (W_{swell} - W_{sealed\text{-}dry}) / W_{sealed\text{-}dry}] * 100$$

where,

W_{swell} = Weight of the specimen after five-day capillary soak

$W_{sealed\text{-}dry}$ = Weight of the specimen after two days in sealed bag

Percent retained UCS:

$$\%\ \text{Retained Strength} = (S_{swell} / S_{sealed\text{-}dry}) * 100$$

where,

S_{swell} = Average seven-day cure UCS for five-day soaked specimens

$S_{sealed\text{-}dry}$ = Average seven-day cure UCS after seven days in sealed bag

Section 7. Reporting Test Results

The laboratory report should include but is not necessarily limited to the following items:

- Soil classification (if available)
- OMC and MDD test results for both the untreated and treated soil
- Atterberg limits test results (if available)
- Graph of the percent swell versus the time in capillary soak
- Percent volumetric shrinkage after two days in sealed bag (ΔV_{shrink})
- Percent volumetric swell after five days of soaking (ΔV_{swell})
- Average UCS of the treated and untreated specimens in the following conditions:
  - After five-day capillary soak (S_{swell})
  - After seven-day cure (S_{dry})
- Percent retained strength for the treated and untreated specimens

Section 8. General Acceptance Criteria

An additive treatment can be accepted based on the following minimum material requirements:

- The volumetric swell of the treated specimens must be less than or equal to 6 percent.
- The volumetric swell of the treated specimens should exhibit a reduction of at least two to four times relative to the untreated specimens.
- The average seven-day cured UCS must be at least 150 psi (1,035 kPa) for treated specimens. A recommended subgrade value is 150 psi (1,035 kPa). However, this value can be altered by the design engineer.
- The treated specimen must retain at least 80% of its average seven-day cured strength after a five-day capillary soak.

Secondary criteria to consider acceptance of the additive treatment include the following:

- Increased bearing capacity
- Plasticity reduction
- Texture and consistency improvement

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