

**Overview of *Cement-Stabilized Subgrade Soils***

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**PROJECT TITLE**

*Overview of Cement-Stabilized Subgrade Soils*

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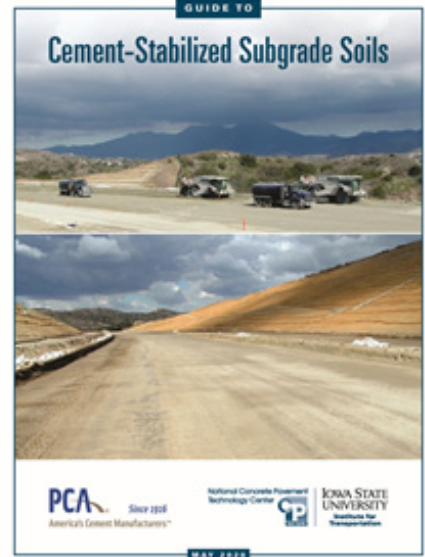
**MORE INFORMATION**

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The purpose of this MAP Brief is to provide an overview of the characteristics, uses, and benefits of cement-stabilized subgrade (CSS). It summarizes the recent *Guide to Cement-Stabilized Subgrade Soils* (Gross and Adaska, 2020) published by the National Concrete Pavement Technology Center in collaboration with the Portland Cement Association.

CSS is distinguished from Cement Modified Soils (CMS) as follows: CMS describes otherwise untreated soils that have been treated with a relatively small proportion of portland cement (approximately 2%–4%) 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 uses slightly more cement (approximately 3%–6%), provides all of the benefits of CMS, and also substantially increases soil stiffness and strength to the point where the treatment provides structural benefits to pavement and building foundations. Table 1 includes the key features of CSS and CMS.



High plastic clays may be a construction issue due to their ability to shrink or swell with changes in water content (Jones and Jefferson, 2012). Soils with a high Plasticity Index (PI) are identified as cohesive, expansive or contractive depending on water content. The Plastic Limit (PL) is the lowest water content at which the soil remains plastic. The Shrinkage Limit (SL) is the water content at which the phase of the soil changes from semi-solid to the solid state (Sridharan and Prakash 1998). As shown in

**Table 1. Key features of soil-cement products**

Soil-Cement Type	Cement-Modified Soil (CMS)	Cement-Stabilized Subgrade (CSS)
<b>Benefit</b>	<ul style="list-style-type: none"> <li>Promotes soil drying</li> <li>Provides significant improvement to working platform</li> <li>Provides a permanent soil modification (does not leach)</li> <li>Reduces plasticity index</li> <li>Improves the workability of subgrade soils</li> <li>Reduces plasticity and shrink/swell volume change potential</li> </ul>	Provides all the benefits of CMS plus the following: <ul style="list-style-type: none"> <li>Potentially allows for a reduction in pavement thickness or increased pavement life</li> <li>Increases the bearing capacity for building slabs, footings, and other structural elements</li> </ul>
<b>Materials</b>	<ul style="list-style-type: none"> <li>Primarily fine-grained clay soils</li> <li>2%–4% cement</li> </ul>	<ul style="list-style-type: none"> <li>Primarily fine-grained clay soils</li> <li>3%–6% cement</li> </ul>
<b>Material Properties</b>	Reduced moisture susceptibility	100–300 psi (0.7–2.1 MPa) seven-day compressive strength
<b>Construction Practices</b>	<ul style="list-style-type: none"> <li>Minimum 95% of maximum density</li> <li>Mixed in place</li> </ul>	<ul style="list-style-type: none"> <li>Minimum 95% of maximum density</li> <li>Mixed in place</li> </ul>

Figure 1, the SL increased with the addition of cement. The end result is when the SL increases, any additional decrease in moisture below this shrinkage limit will not result in additional shrinkage. Likewise, as the SL increases, the soil can absorb a higher percent of moisture (as a result of the increase) before any potential swelling.

## Modification Mechanisms

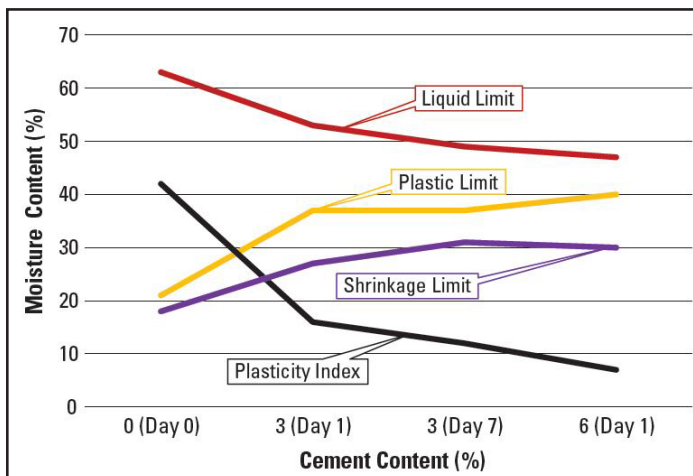
CSS physically and/or chemically modifies the makeup of existing subgrade soils that may be unsuitable due to high shrinkage or expansion potential, low bearing capacity, evidence of instability, or high moisture contents that will cause unstable subgrades during construction activity. Refer to Chapter 1 of the Guide to Cement-Stabilized Subgrade Soils for a detailed explanation of modification mechanisms.

The improved engineering properties that CSS imparts to the subgrade soil, including improved workability, lower plasticity, reduced volume change potential, and increased bearing strength, are achieved primarily through four modification mechanisms of cement stabilization illustrated in Figure 2.

In order to reduce the plasticity of a soil, the monovalent cations present in a clay surface must be exchanged so that the thickness between the clay particles is reduced. Cement 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 (Figure 2a).

The addition of cement results in restructuring of modified soil/aggregate particles, known as flocculation and agglomeration, which changes the texture of the material from a plastic, fine-grained material to one resembling a friable, granular soil/aggregate (Halsted et al. 2008).

Prior to cement treatment, clay particles are naturally aligned parallel to each other in layers due to their chemical composition. The addition of cement results in restructuring of modi-



2 Figure 1. Effect of cement treatment on Atterberg limits

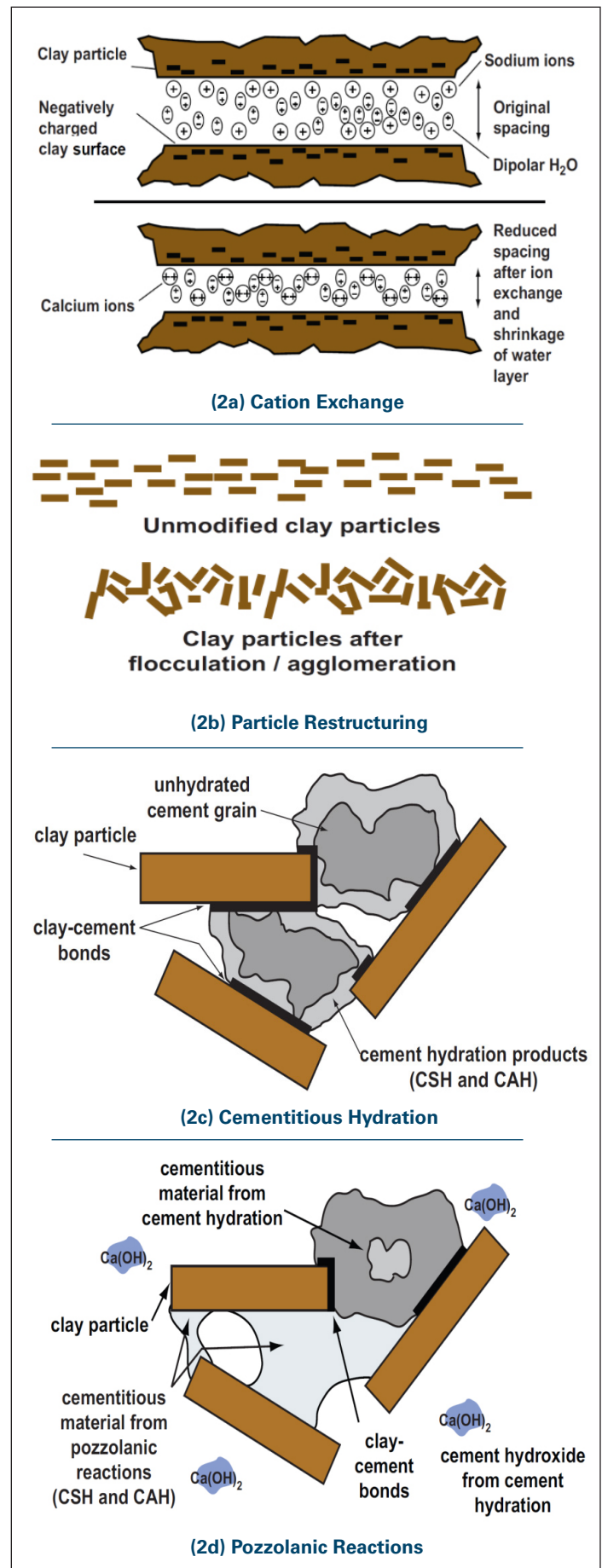


Figure 2. Modification Mechanisms (Halsted et al. 2008 ©2008 PCA, used with permission)

fied soil/aggregate particles, known as flocculation and agglomeration. Here, the clay particles are aligned randomly in an edge-to-face orientation and changes the texture from a plastic, fine-grained material to a granular-like texture (Figure 2b).

Cementitious hydration produces calcium-silicate-hydrate (CSH) and calcium-aluminate-hydrate (CAH) that acts as the “glue” to provide structure in a cement-modified soil/aggregate. The majority of this reaction occurs within the first 30 days after cement is added to the soil (Figure 2c).

In addition to CSH and CAH, hydrated portland cement also forms calcium hydroxide, which enters into a pozzolanic reaction. This secondary soil modification process takes the calcium ions supplied by the incorporation of portland cement and combines them with the silica and alumina dissolved from the clay structure to form additional CSH and CAH. (Halsted et al., 2008). 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 (Figure 2d).

## CSS Mixture Design

The CSS mix design process is straight forward. The engineering properties needed are commonly determined with a geotechnical investigation of the native soil along with laboratory testing using cement. In developing a mix design for CSS, the following laboratory tests are needed:

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

## Design Process

Depending on the urgency of the situation, two different pathways can be taken to incorporate CSS into a project. 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 (such as excessively wet and/or unstable soils) and an immediate solution is required, cement-based mitigation can be expedited with engineering judgement, previous experience, and/or an abbreviated laboratory testing program.

### Step-by-Step CSS Mixture Design

Following are the typical CSS mixture design steps for the design path:

1. Determine in situ moisture content and classify soil. The native soil’s Atterberg limits, soil classification, gradation, and standard proctor must be determined as they are needed to move forward with the next step.
2. Determine cement type and estimated dosage rate. Typically, locally available cement is utilized along with a starting range of 3%–6%.
3. Determine chemical compatibility. If required, the chemical compatibility between the soil and cement can be investigated. Standard testing, including expansion, stability sulfate content, and pH and organic content can be performed.
4. Determine Atterberg limits of the three different cement-content treated samples.
5. Determine optimum moisture content and maximum dry density (using cement content from Atterberg limits testing) (see Figure 3).
6. Determine the unconfirmed compressive strength at three different cement contents (see Figure 4).
7. Plot unconfined compressive strength to verify selected design cement content.
8. Compile CSS mixture design report.

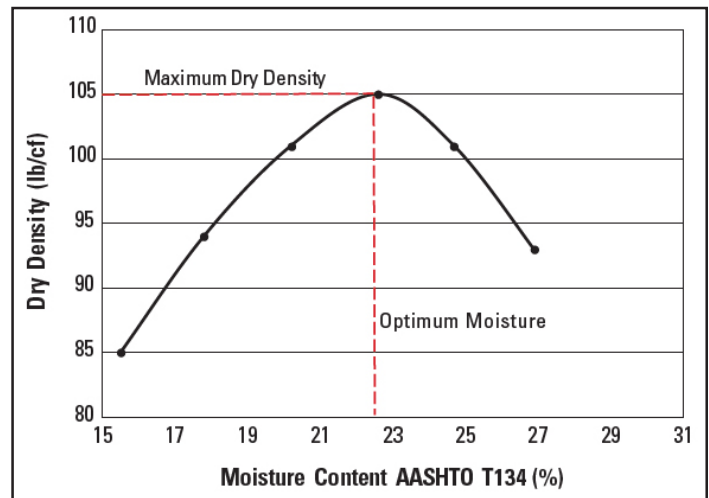


Figure 3. Moisture-density relationship graph

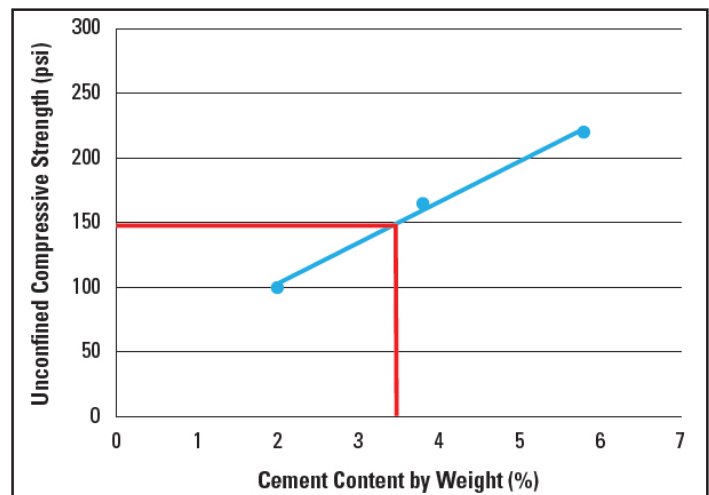


Figure 4. Example of unconfirmed compressive strength versus cement content

## Construction Process

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.

Following are the seven steps that are typical of the construction process (in some instances, initial moisture conditioning and initial pulverization may be necessary based on soil conditions at the time of construction):

1. Preliminary grading
2. Cement application
3. Mixing
4. Achievement of optimum moisture content
5. Compaction
6. Final grading
7. Curing

## Cement Application

Cement is most commonly applied in a dry condition, which may produce an issue with dust. It is important to avoid the dry application of cement on windy days. Equipment is



Figure 5. Spreader truck during portland cement application (©2020 Pavement Recycling Systems, Inc., used with permission)



Figure 6. Spreading portland cement slurry (Halsted et al. 2008, ©2008 PCA, used with permission)

available that minimizes the spread of dust in a uniform and controlled application (Figure 5). Cement can also be applied in slurry form from a distributor truck equipped with an agitation system (Figure 6) or additives designed to keep the solids in suspension.

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 1 and 2 show how these three variables are used to determine the cement spread rate. Equation 1 uses US customary units and Equation 2 uses metric units.

$$\text{Rate} \left( \frac{\text{lbs}}{\text{yd}^2} \right) = \frac{\text{Percent Cement}}{100} \times \text{Dry Unit Weight} \left( \frac{\text{lbs}}{\text{ft}^3} \right) \times \left( 9 \times \left( \frac{\text{Depth (in)}}{12} \right) \right) \quad (1)$$

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

Table 2 shows typical spread rates in U.S. customary units and metric units, respectively, based on cement percentage, depth of stabilization, and unit weight of soil.

## 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 7). 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% of the material should pass the 1 1/2 in. (38 mm) sieve and at least 60% should pass the No. 4 (4.75 mm) sieve.



Figure 7. Mixing portland cement and native soil with a reclaimer (Jeff Wykoff, California Nevada Cement Association, used with permission)

**Table 2. Typical cement spread rates (adapted from Halsted et al. 2008)**

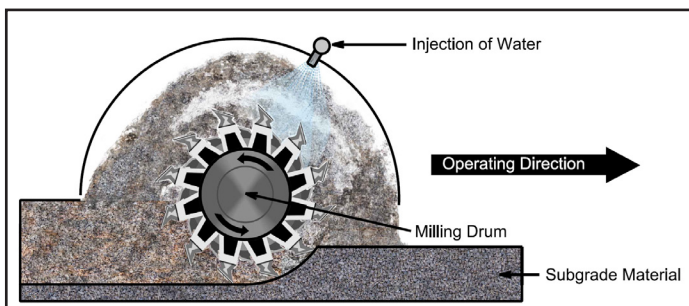
Dry Unit Weight of Soil (lb/ft <sup>3</sup> )	20 lb/yd <sup>2</sup>				30 lb/yd <sup>2</sup>				40 lb/yd <sup>2</sup>				50 lb/yd <sup>2</sup>				60 lb/yd <sup>2</sup>			
	Depth of Stabilization (in.)				Depth of Stabilization (in.)				Depth of Stabilization (in.)				Depth of Stabilization (in.)				Depth 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%

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).

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 with CSS in multiple layers starting at the bottom layer first. Treating in multiple layers is more costly than single-layer treatment due to the additional effort required. One option that may be considered where deep treatment is necessary would be to add a cement-treated base (CTB) layer on top of a single deep CSS layer.

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 8) or by placing water on the ground with a water truck in a separate operation. In either case, obtaining the correct amount of moisture is very important for achieving the target compaction, particularly in expansive clayey soil.



**Figure 8. Roadway reclaimer (Snyder & Associates, Inc./National CP Tech Center, used with permission)**

## 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.

For applications involving silty and clayey soils, initial compaction should be done with a vibratory tamping roller (Figure 9) 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 10) or pneumatic tire roller is used.



**Figure 9. Vibratory sheepsfoot tamping roller (©2020 Pavement Recycling Systems, Inc., used with permission)**



**Figure 10. Smooth drum roller (©2020 Pavement Recycling Systems, Inc., used with permission)**

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

**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.

**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 of the Guide to Cement-Stabilized Subgrade Soils (CSS) for additional information about finishing and curing.

**Case Study 1: Los Patrones Parkway**

**Project Information**

<b>Year Constructed</b>	<b>2018</b>
<b>Case Type</b>	<b>Design</b>
<b>Facility Location</b>	<b>Los Patrones Parkway Rancho Mission Viejo South Orange County, California</b>
<b>Existing Soil Conditions</b>	<b>Weak and unstable, R-value of 20 (SC)</b>
<b>Public Agency</b>	<b>Orange County Public Works Santa Ana, California</b>

**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 mile (8.8 kilometer) non-toll extension of SR-241 with two lanes in each direction. The 2 million ft<sup>2</sup> (186,000 m<sup>2</sup>) of CSS and pavement extend from Oso Parkway to Cow Camp Road. From top to bottom, the pavement consists of 2.4 inches (60 mm) of hot-mix asphalt, 7.2 inches (180 mm) of warm-mix asphalt, 6 inches (150 mm) of aggregate base, and 11.4 inches (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%.

To achieve 300 psi (2.1 MPa) at seven days, a cement content of 4% was applied and mixed with the existing subgrade using two Wirtgen reclaimers (Figure 10). 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.



**Figure 11. Reclaimers mixing the subgrade and cement (Jeff Wykoff, California Nevada Cement Association, used with permission)**



**Figure 12. Compacted subgrade ((Jeff Wykoff, California Nevada Cement Association, used with permission)**

## Case Study 2: 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

### 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.

Geotechnical exploration 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 5% 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 13), and the subgrade was compacted and trimmed, allowing foundation construction to be completed (Figures 14 and 15).

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Figure 13. Mixing cement and subgrade (©2020 Pavement Recycling Systems, Inc., used with permission)



Figure 14. Constructing foundation for the school structure (©2020 Pavement Recycling Systems, Inc., used with permission)



Figure 15. Completed foundation on cement-treated subgrade (©2020 Pavement Recycling Systems, Inc., used with permission)

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