Guide to Cement-Modified Soil (CMS)

By Gregory E. Halsted, Wayne S. Adaska, William T. McConnell
**Abstract:** Cement-modified soil (CMS) is a soil/aggregate material that has been treated with a relatively small proportion of portland cement in order to amend its undesirable properties so that they are suitable for use in subgrade or foundation construction. This guide to CMS discusses its applications, benefits, design, construction, testing, and performance.

**Keywords:** Cement-modified soil, CMS, modification, stabilization, pavement, subgrade, subbase, base, soil/aggregate, pavement structure, portland cement, cation exchange, flocculation, agglomeration, hydration, pozzolanic reaction, plasticity index, PI, volume change, expansion, California Bearing Ratio, CBR, Sand Equivalent, SE, Resistance Value, R-Value, soil-cement, cement-treated base, CTB, pulverization, gradation, mixed-in-place, scarification, pre-wetting.


**About the Authors:**
- Gregory E. Halsted, P.E., Program Manager, Portland Cement Association, Post Office Box 5113, Bellingham, Washington 98227-5113, USA.
- Wayne S. Adaska, P.E., Director of Public Works, Portland Cement Association, 5420 Old Orchard Road, Skokie, Illinois 60077-1083, USA.
- William T. McConnell, P.G., Pavements Engineer, Portland Cement Association, 1195 Black Valley Farm Road, Walnut Cove, North Carolina 27052, USA.

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**WARNING:** Contact with wet (unhardened) concrete, mortar, cement, or cement mixtures can cause SKIN IRRITATION, SEVERE CHEMICAL BURNS (THIRD DEGREE), or SERIOUS EYE DAMAGE. Frequent exposure may be associated with irritant and/or allergic contact dermatitis. Wear waterproof gloves, a long-sleeved shirt, full-length trousers, and proper eye protection when working with these materials. If you have to stand in wet concrete, use waterproof boots that are high enough to keep concrete from flowing into them. Wash wet concrete, mortar, cement, or cement mixtures from your skin immediately. Flush eyes with clean water immediately after contact. Indirect contact through clothing can be as serious as direct contact, so promptly rinse out wet concrete, mortar, cement, or cement mixtures from clothing. Seek immediate medical attention if you have persistent or severe discomfort.

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Definition

Cement-modified soil (CMS) is a term used to describe native soils and/or manufactured aggregates that have been treated with a relatively small proportion of portland cement. Cement application rates for CMS typically vary from 2 to 6 percent by dry weight of the soil/aggregate being modified with the majority of cases being between 3 and 5 percent. The objective of the treatment is to amend the undesirable properties of problem soils/aggregates so that they are suitable for use in construction.

The amount of cement added to the soil/aggregate for a cement-modified silt-clay material is less than that required to produce a strong, frost-resistant cement-treated base (CTB) but is enough to improve their engineering properties. For information on CTB, please refer to the Portland Cement Association (PCA) publication Guide to Cement-Treated Base (CTB), EB236.

Laboratory and field work on CMS indicate that the relatively small quantities of cement bind some of the soil/aggregate particles together to form small conglomerate masses of new soil/aggregate. In addition to this slight cementing reaction, the surface chemistry of clay particles, either in clay soils or the clay fraction of granular soils, is improved by cation exchange phenomenon. As a result, the modified soils/aggregates have lower plasticity (cohesiveness), lower volume change characteristics, and greater strength than untreated soils/aggregates. Figure 1.1 shows an example of a typical CMS application.

The degree of modification increases with greater amounts of cement. Therefore, for a given soil/aggregate, a cement content can be selected that will provide a material meeting the specified level of modification, expressed in terms of plasticity, bearing capacity, or other criteria.

Field and laboratory tests show that changes in the physical characteristics of a soil/aggregate by cement modification are permanent. The soil/aggregate does not revert back to its original state, even after many cycles or years of weathering and service.

In the following discussion of cement modification, the terms subgrade, subbase, and base are mentioned to describe the uses of CMS materials in both rigid and flexible pavement systems. Figure 1.2 illustrates how these terms are used in a pavement system.

CMS is usually classified into two groups according to its combined silt and clay percentage (defined as material passing a No. 200 sieve) as follows:

Cement-Modified Silt-Clay Material

According to the American Association of State Highway and Transportation Officials (AASHTO) soil classification system, soils/aggregates containing more than 35 percent material passing a No. 200 sieve are classified as silt-clay materials. The general objective in treating these types of soils is to improve the engineering properties of the soil/aggregate which would otherwise be unsuitable for use in subgrade or...
subbase layers. Specific objectives may be to decrease plasticity and volume change characteristics, to increase the bearing capacity, or to provide a stable working platform on which pavement layers may be constructed.

Cement-Modified Granular Material

According to the AASHTO soil classification system, soils/aggregates containing less than 35 percent material passing a No. 200 sieve are considered to be granular soils. However, even granular soils can contain enough cohesive fines to cause difficulties. The usual objective in treating these types of soils is to alter the substandard fines component of the granular soils/aggregates so that they will meet requirements specified for pavement subbase layers.

These two cement-modified applications are discussed separately in Chapters 2 and 3 in this publication.

Modification Mechanisms

The improvement of soils/aggregates containing clay through the addition of portland cement involves four distinct processes discussed in the order of their occurrence:

- Cation exchange,
- Particle restructuring,
- Cementitious hydration,
- Pozzolanic reaction.

Portland cement provides all the compounds and chemistry necessary to achieve all four processes. The most important factor in the initial timely modification of clayey soils/aggregates is the ability of the additive to supply an adequate amount of calcium. Portland cement can supply this necessary ingredient and, when used properly, can effectively modify clay soils/aggregates. For detailed information on the modification mechanisms of clay soils/aggregates, please refer to PCA publication *Effectiveness of Portland Cement and Lime in Stabilizing Clay Soils*, RP126.

Cation Exchange

The plasticity of a soilaggregate is determined by the amount of expansive clay (e.g. montmorillonite) present. This 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 (H2O) 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 soilaggregate. If the cation responsible for the neutralization is monovalent, such as sodium, the soilaggregate becomes plastic. In order to reduce the plasticity, the monovalent cations present in the montmorillonite 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. Portland cement, a good calcium-based soil modifier, can provide sufficient calcium ions to replace the monovalent cations on the surfaces. This ion exchange process occurs within hours, shrinking the layer of water between clay particles, and reducing the plasticity of the soilaggregate. This phenomenon is illustrated in Figure 1.3.

Particle Restructuring

The restructuring of modified soilaggregate 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 soilaggregate. Made
possible through cation exchange, flocculation is the process of clay particles altering their arrangement from a flat, parallel structure to a more random edge-to-face orientation (Figure 1.4). Agglomeration refers to the weak bonding at the edge-surface interfaces of the clay particles, which as a result form larger aggregates from finely divided clay particles and further improve the texture of the soil/aggregate.

The reduced size of the double layer due to cation exchange, as well as the increased internal friction of clay particles due to flocculation and agglomeration, result in a reduction in plasticity, an increase in shear strength, and an improvement in texture. As with cation exchange, the particle restructuring process happens rapidly. The most significant changes occur within several hours after mixing.

Cementitious Hydration

Cementitious hydration (Figure 1.5) is a process that is unique to cement, and produces cement hydration products referred to in cement chemistry as calcium-silicate-hydrate (CSH) and calcium-aluminum-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 clay-cement bonds. This bonding between the hydrating cement and the clay particles improves the gradation of the modified clay by forming larger aggregates from fine-grained particles. This process happens between one day and one month after mixing.

Pozzolanic Reaction

In addition to CSH and CAH, hydrated portland cement also forms calcium hydroxide, or Ca(OH)₂, 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 (Figure 1.6). The pozzolanic reactions take place slowly, over months and years, and can further strengthen a modified soil-aggregate as well as reduce its plasticity and improve its gradation.
Cement modification improves the properties of certain silt-clay soils/aggregates that are unsuitable for use in subgrade construction. The objectives may be to decrease the material’s cohesiveness (plasticity), to decrease the volume change characteristics of expansive clay, to increase the bearing capacity of a weak soil/aggregate, or to transform a wet, soft subgrade into a surface that will support construction equipment.

Cement-modified silt-clay soils are not recommended for use as pavement bases. Small quantities of cement do not improve silt-clay soils sufficiently to make them satisfactory as base materials. The most effective means of utilizing such soils for base materials is to add sufficient cement to produce fully hardened CTB. Examples of the improvement of properties of silt-clay soils/aggregates are given in the following discussion.

Plasticity Index and Other Index Properties

A soil/aggregate containing clay can behave like a solid, semi-solid, plastic solid, or liquid, depending on its moisture content, as shown in Figure 2.1. The plasticity index (PI) as determined by ASTM International (ASTM) D4318, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, is a measure of a soil’s cohesive properties and is indicative of the amount and nature of clay in the soil/aggregate. The PI is defined as the difference between the plastic limit (PL) and liquid limit (LL) of a soil.

Plasticity Index (PI) = Liquid Limit (LL) – Plastic Limit (PL)

Materials with a high PI may be difficult to work with in construction because of their instability and stickiness when wet.

High PI soils also have potential for detrimental volume changes during wetting and drying, which can lead subsequently to pavement roughness. The PI is the most commonly accepted and important indicator of soil expansion characteristics. As shown in Table 1, soils with PI’s less than 15 usually cause no problems; highly expansive soils will have much higher PI’s.

Table 2 gives examples of the effect of cement modification on five clay soils. Another index property, the shrinkage limit (SL), as tested in accordance with ASTM D4943, Standard Test Method for Shrinkage Factors of Soils by the Wax Method, indicates how much moisture (percent) the soil can absorb without swelling; the higher the value, the less expansive the soil. Ideally, the SL should be higher than the optimum moisture content. The substantial reduction of PI’s and increase in SL’s indicates not only an improvement in the volume change characteristics but also modification of the soils into more stable and workable materials. In many cases, reducing the PI to a value of 12 to 15 serves as a target for selecting the appropriate cement content.

Plasticity Index (ASTM D4318) | Degree of Expansion
--- | ---
greater than 41 | Very High
25 to 41 | High
15 to 28 | Medium
less than 15 | Low

Table 2. Effect of Cement Treatment on Properties of Clay Soils *

<table>
<thead>
<tr>
<th>Soil No.</th>
<th>AASHTO Classification</th>
<th>Cement Content (percent)</th>
<th>Plasticity Index Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>None</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 A-7-6 (20)</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 A-6 (8)</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 A-6 (9)</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 A-7-6 (18)</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 A-7-6 (20)</td>
<td>43</td>
</tr>
</tbody>
</table>

* PCA publication Cement Modification of Clay Soils, RD002.

The in-service permanence of cement modification has been demonstrated by both laboratory and field investigations. An example of the effect of freezing and thawing on plasticity properties as measured on laboratory mixtures is given in Table 4. After 60 cycles of freezing and thawing the properties of the CMS showed no tendency to increase or revert back to those of the untreated soil. In fact, the Pl's after 60 cycles of freezing and thawing were less than the values after 7 days of moist curing. This is attributed to additional hydration of the cement during the 60 thaw cycles.

A field study investigating the properties of 11 cement-modified subgrades after 45 years of service between 1938 and 1983 showed that the improvements in soil properties (Pl, SL, and gradations) were permanent. Figure 2.2 shows the effect of CMS on the Pl of these study soils.

Table 3. Effect of Cement Modification on PI and SL with Time *

<table>
<thead>
<tr>
<th>Cement Content</th>
<th>0%</th>
<th>3%</th>
<th>6%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LL</td>
<td>PL</td>
<td>PI</td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>21</td>
<td>42</td>
</tr>
</tbody>
</table>

* Adapted from PCA publication Comparative Performance of Portland Cement and Lime Stabilization of Moderate to High Plasticity Clay Soils, RD125.

Table 4. Permanence of Improvement of Cement-Modified Illinois Clay *

<table>
<thead>
<tr>
<th>Cement Content</th>
<th>0%</th>
<th>2%</th>
<th>4%</th>
<th>6%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LL</td>
<td>PL</td>
<td>PI</td>
<td>SL</td>
</tr>
<tr>
<td></td>
<td>7 days</td>
<td>60 cycles F-T</td>
<td>7 days</td>
<td>60 cycles F-T</td>
</tr>
<tr>
<td>LL</td>
<td>49</td>
<td>48</td>
<td>49</td>
<td>45</td>
</tr>
<tr>
<td>PL</td>
<td>18</td>
<td>23</td>
<td>29</td>
<td>25</td>
</tr>
<tr>
<td>PI</td>
<td>31</td>
<td>25</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>SL</td>
<td>18</td>
<td>20</td>
<td>20</td>
<td>27</td>
</tr>
</tbody>
</table>

swelling” value of 4 (roughly corresponding to a PI of 20) is an approximate borderline between expansive soils and those that would usually not be troublesome.

Small quantities of cement have a greater effect on reducing swell or expansion than they do on improving the index properties discussed in the previous section. Since the latter are only indices, the CBR swell test is a better, more direct measure of this soil property.

Reduction in swell of highly expansive clay from California is shown in Figure 2.3. The laboratory specimens were molded at standard maximum dry density and optimum moisture content and cured in high humidity for 7 days before being saturated. Expansion on saturation was reduced from a high value of about 11 percent to less than 1 percent with the addition of 2 percent portland cement. Thus, the highly expansive clay was changed to a relatively nonexpansive material.

With most soils, excessive volume changes can be controlled by compacting the subgrade at a moisture content 1 to 3 percentage points above optimum moisture as determined by AASHTO T 99 (Standard Method of Test for the Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop) or ASTM D698 (Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lb/ft³ (600 kN-m/m³)).

**Strength and Bearing Tests**

As mentioned earlier in the discussion of the modification process, the cementitious reaction between cement and clay takes place as primary and secondary processes. Hydration of the cement is regarded as the primary reaction and forms the normal cement hydration products that bind particles together. In the secondary process, the fresh calcium hydroxide formed in the primary phase reacts with the silica and alumina in the clay to form additional cementitious material. (Obviously, this secondary process does not occur with clean granular materials or concrete aggregates.) Thus, in spite of the otherwise objectionable properties of untreated clay, the clay material itself contributes somewhat to the strength development of cement-clay mixtures.

While there is normally a measurable increase in the compressive strengths of materials treated through cement modification, it is important to restate that the objective of CMS is simply to amend the undesirable properties of problem soils/aggregates so that they are suitable for use in construction. For information on preparing and testing both CMS and CTB materials, please refer to PCA publication *Soil-Cement Laboratory Handbook*, EB052.

Increases in strength as measured in the CBR test are shown in Figure 2.4 for a silty clay loam. The CBR value of 2 percent for the untreated soil represents a relatively unstable material that would be difficult to work with during pavement construction operations. At a cement content of only 3 percent by dry weight of the untreated soil, the CBR value is increased to 42 percent, which would not only provide a stable working platform but would meet CBR requirements as a subbase layer in a flexible (asphalt surfaced) pavement design.

**Soil Particle Size**

One of the benefits of cement modification is that the reaction between cement and soil reduces the amount of silt- and clay-sized particles. These fine-grained particles
Subgrade Stabilization for Pavements

Poor quality subgrade soils are improved by cement modification. The primary purpose is to provide a firm, stable working table for pavement construction. Cement-treated subgrades also provide an effective solution to the problem of fatigue failures caused by repeated high deflections of asphalt surfaces where a weak subgrade exists in the pavement structure. Field tests and experience in areas of resilient subgrades, micaceous soils for example, show a marked decrease in deflection when subgrades are modified with cement. Performance indicates the cost of subgrade stabilization is well worth the modest cost involved.

Subbase for Flexible and CTB Pavements

Cement-modified silt-clay soils have been used in flexible pavement systems. Generally, the subgrade soil is treated with enough cement to provide a firm foundation for compacting the base course above it. A CTB layer constructed on top of the cement-modified subbase may be made of the same material treated with sufficient cement to produce hardened CTB, or it may be hardened CTB built with granular borrow soil.

Subbase for Concrete Pavements

Where heavy weights and volumes of truck traffic are anticipated, cement-modified silt-clay soils are not recommended for use as a subbase because they do not meet the requirements of a non-pumping subbase material. If subgrade problems exist, they may be improved by cement modification. An untreated granular or fully hardened granular CTB layer should then be utilized as a subbase if the concrete pavement is to carry heavy truck traffic.

For light-traffic facilities, a subbase is not required and the concrete may be constructed directly on a properly prepared subgrade if it is capable of supporting construction equipment and is not highly expansive. Otherwise, the
subgrade may be made suitable by cement modification. Further information can be found in the American Concrete Pavement Association publication *Subgrades and Subbases for Concrete Pavements*, EB204P.

**Correcting Unstable Subgrade Areas**

Sometimes, localized soft spots of very wet and unstable subgrades are encountered unexpectedly during construction. In addition to the difficulty of operating construction equipment, adequate compaction of base and subbase layers placed on top of these soft areas may not be possible.

These areas may be corrected by cement modification. Cement is spread and mixed into the soil to the best extent possible. If the material is too wet or cohesive to use a traveling mixer, it may be processed by several passes of a disc harrow or motor grader using its scarifier teeth. Then the material is compacted to whatever maximum density can be achieved. The drying action of the cement and its hydration will quickly improve the area sufficiently so that construction may proceed.
Portland cement has been used to improve bearing values of certain types of granular base and subbase materials, to reduce their plasticity or swell characteristics, to prevent consolidation, and to produce a firm working table as a subbase. With the rapid depletion of acceptable granular materials for use as bases and subbases, it becomes ever more important to conserve the remaining limited supply of acceptable materials. When “dirty” sands and gravels (granular materials containing a considerable amount of high plastic fines) are encountered, cement modification can be used to improve their bearing values and reduce their plasticity, resulting in a material that will meet specifications for acceptable base and subbase materials. Consequently, the limited supply of acceptable “clean” granular materials can be conserved.

Properties

Specifications for pavement base and subbase course materials place limits on the amount of fines and the plasticity (cohesiveness or stickiness) of the fines in granular materials. Excessive fines can lead to loss of stability, susceptibility to frost action, and mud-pumping under traffic loads.

The following discussion gives examples of the improvement of the properties of substandard granular soils by the addition of cement.

Plasticity Index

One common and simple way of measuring the improvement of a granular material containing an excessive amount of clay is by the reduction in its plasticity characteristics as measured by the PI. This index is a significant indicator of soil behavior—the higher the PI, the more plastic the soil will be and the more unsuitable it will be for use in construction.

An example of the effect of cement on reducing the PI of a clayey gravel is shown in Figure 3.1. For this substandard material, a cement content of about 3 or 4 percent by weight would reduce the PI sufficiently to meet specifications. The Figure also shows the permanence of the PI reduction as measured in the field over a 10-year period.

California Bearing Ratio

The highest quality base course materials will have CBR values in the range of 70 to 100 percent while suitable subbase materials will have lower values down to about 20 percent. Flexible pavement design procedures of some agencies specify a minimum CBR for each layer; for example, 80 percent for the base course, 30 percent for the subbase, and 15 percent for the subgrade.

Using the same clayey gravel represented in Figure 3.1, Figure 3.2 shows how a small amount of cement can dramatically increase the CBR values way beyond 100 percent.

The raw material (0 percent cement content) represented in Figure 3.2 has a CBR of only 10 percent due to the excessive...
clay content, which upon saturation during the test, significantly weakens the material. As shown in the Figure, a small amount of cement (less than 2 percent) increases the CBR to a level that is adequate for base and subbase courses.

Table 5 shows the permanence of the CBR increase. After many cycles of laboratory freeze-thaw tests, the CBR values did not decrease; in fact, the value at 4 percent cement increased substantially due to additional cement hydration during the thaw cycles.

### Sand Equivalent

Some agency specifications for granular base and subbase courses include a requirement for a minimum Sand Equivalent (SE) value as described in AASHTO T 176, Standard Method of Test for Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test. This test detects the presence of clay-size materials in soils and aggregates. The method tends to magnify the volume of clay in a sample somewhat in proportion to its detrimental effects. Clean crushed stones and sands have SE values of about 80; very expansive clays have SE values of 0 to 5.

The SE of a material can be increased by the addition of a small quantity of cement. Data from tests made by the Utah Department of Transportation on a soil having a PI of 11 and having 33 percent passing the No. 200 sieve are shown in Table 6. This material containing 2 percent cement would meet the SE requirement. Incidentally, the PI was correspondingly reduced from 11 to 0 for the material containing 3 percent cement.

### Resistance Value

Some agencies make use of the Resistance Value (R-Value) test in accordance with ASTM D2844, Standard Test Method for Resistance R-Value and Expansion Pressure of Compacted Soils, also called the Hveem Stabilometer test, to determine the stability of a material used as a roadway base, subbase, or subgrade. An R-Value of about 78 is considered equivalent to a good crushed stone. Some agencies specify an R-Value of 72 for base course materials.

An example of how the addition of cement increases the R-Value is shown in Table 7. The data are for a Colorado sand classified by the AASHTO system as an A-2-4, primarily a fine sand with an appreciable quantity of silt and clay making it somewhat marginal in stability. The R-Value of 65 for the untreated sand increased to 89 with the addition of 3 percent cement – a stability level suitable for a base or subbase layer.

### Triaxial Compression

The triaxial compression test as described in AASHTO T 234, Standard Method of Test for Strength Parameters of Soils by Triaxial Compression is used by a few state highway agencies

---

**Table 5. Permanence of CBR Values of an A-1-b(0) Disintegrated Granite from Riverside County, California**

<table>
<thead>
<tr>
<th>Cement Content</th>
<th>CBR (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Soil</td>
<td>43</td>
</tr>
<tr>
<td>2 percent cement by weight, age 7 days</td>
<td>255</td>
</tr>
<tr>
<td>2 percent cement by weight after 60 cycles of freeze-thaw</td>
<td>258</td>
</tr>
<tr>
<td>4 percent cement by weight, age 7 days</td>
<td>485</td>
</tr>
<tr>
<td>4 percent cement by weight after 60 cycles of freeze-thaw</td>
<td>574</td>
</tr>
</tbody>
</table>

**Table 6. SE Values of CMS**

<table>
<thead>
<tr>
<th>Percent Cement by Weight</th>
<th>Sand Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>36</td>
</tr>
<tr>
<td>3</td>
<td>59</td>
</tr>
</tbody>
</table>

Table 7. R-Values of a Cement-Modified A-2-4 Fine Sand from Colorado

<table>
<thead>
<tr>
<th></th>
<th>R-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Soil</td>
<td>65</td>
</tr>
<tr>
<td>Lab mixture</td>
<td></td>
</tr>
<tr>
<td>3 percent cement by weight</td>
<td>89</td>
</tr>
<tr>
<td>5 percent cement by weight</td>
<td>93</td>
</tr>
</tbody>
</table>

for pavement design or to classify a soil/aggregate’s suitability for use in pavement construction. The test is used to determine the shearing resistance of a material, which is the sum of two components – internal friction and cohesion.

A clean granular material derives most of its strength from internal friction, (particle to particle contact resists shearing movement) while the cohesion component of strength is very low or zero. Dirty granular materials have some cohesion but have lower total strength because the fine silt and clay particles, when wet, act as a lubricant decreasing the internal friction.

When cement is added, both cohesion and internal friction are substantially increased. An example for a dirty bank-run gravel is shown in Figure 3.3, where the vertical scale represents cohesion and the angle $\phi$ is the internal friction. This increase in stability due to the addition of cement would modify the substandard or marginal material to one of acceptable quality.

Figure 3.3. Change in triaxial compressive strength due to the addition of cement. *


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Field Load Tests

Data on the load-carrying capacity of cement-modified granular materials have been determined by tests of outdoor test panels. Figure 3.4 shows the increase in plate bearing value of a 7-inch-thick base with increasing cement contents. At 1.5 percent cement the load bearing capacity was approximately doubled. Panels were tested each spring for a period of five years. Data from these tests also show the substantial increase in load-carrying capacity obtained even at the very low cement contents. Some loss in load-carrying capacity occurred at the lower cement contents after exposure to freezing and thawing. However, after five years of exposure, even for cement contents as low as 1.5 percent, the cement-modified materials were still able to support considerably more load than the untreated material.

Applications

Substandard granular soils/aggregates can be modified with portland cement to reduce or eliminate plasticity and to increase their bearing values to a point where they are acceptable for use as a pavement base or subbase.

By the addition of relatively small quantities of portland cement, these substandard materials are improved and made usable. Although the resultant product is improved, it is still primarily a granular material rather than a fully hardened CTB material.
**Base Course for Flexible Pavements**

Cement-modified granular materials have been used extensively as pavement bases for highways, streets, and parking areas. For these uses the materials to be treated should require only a small degree of improvement to meet specification requirements. Cement-modified granular bases should always be covered with a wearing surface.

**Shoulders**

CMS has also been used to construct shoulders for flexible highway pavements. The addition of cement prevents consolidation of the shoulder adjacent to the pavement edge and helps to eliminate dangerous “drop-offs.” Like flexible CMS pavement bases, CMS shoulders are always covered with a wearing surface.

**Subbase for Concrete Pavements and Shoulders**

Cement-modified granular material subbases are used to:
- Prevent consolidation of the subbase under heavy traffic
- Increase the bearing capacity of the subbase
- Provide a firm support for paving operations (this is especially important when a slip-form paver is used)
- Prevent intrusion of subgrade soil into the granular subbase

The use of cement-treated granular materials as subbase is recommended where good quality granular subbase materials do not exist or are very expensive. Substandard granular subbase materials can be treated with just enough cement to reduce the PI and/or upgrade the materials sufficiently to meet standard subbase specifications, such as AASHTO M 155 (*Standard Specification for Granular Material to Control Pumping under Concrete Pavement*) or ASTM D1241 (*Standard Specification for Materials for Soil-Aggregate Subbase, Base, and Surface Courses*).
4 Construction

Cement-Modified Silt-Clay Material

For silt-clay materials that are not excessively cohesive or wet, the construction operations are essentially the same as those for CTB courses as described in PCA publication Soil-Cement Construction Handbook, EB003. However, some additional effort may be required in the pulverization and mixing operations. Typical spread rates are shown in Table 8.

Wet cohesive soils may require disking to cut in the cement and do the initial mixing before a rotary mixer is used. If the soil is dry, pre-wetting and allowing the water to soak in, may facilitate pulverization.

Also in contrast to normal CTB construction, the time limit between mixing and compacting is not as stringent; although all the operations should be completed in the same day.

Table 8. Cement Spread Requirements

<table>
<thead>
<tr>
<th>Percent cement by weight</th>
<th>Percent cement by volume</th>
<th>Cement spread requirements in pounds per square yard (kg/m²) for compacted thicknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5 inches (125 mm)</td>
</tr>
<tr>
<td>100 pcf (1602 kg/m³)</td>
<td>110 pcf (1762 kg/m³)</td>
<td></td>
</tr>
<tr>
<td>1.9</td>
<td>1.7</td>
<td>2.0</td>
</tr>
<tr>
<td>2.4</td>
<td>2.1</td>
<td>2.5</td>
</tr>
<tr>
<td>2.8</td>
<td>2.6</td>
<td>3.0</td>
</tr>
<tr>
<td>3.3</td>
<td>3.0</td>
<td>3.5</td>
</tr>
<tr>
<td>3.8</td>
<td>3.4</td>
<td>4.0</td>
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<tr>
<td>4.2</td>
<td>3.8</td>
<td>4.5</td>
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<tr>
<td>4.7</td>
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<tr>
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<td>5.6</td>
<td>6.5</td>
</tr>
<tr>
<td>6.6</td>
<td>6.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Figure 4.1. Distributing cement in slurry form from a distributor truck.
Often, it is not cured, although curing with a moist spray is suggested to provide maximum benefit from the cement.

Typical construction steps are given below, although they may vary somewhat depending on the wetness and cohesiveness of the soil/aggregate material.

- For initial preparation, shape the area to crown and grade and correct any soft or unsuitable areas.
- If necessary, pre-wet dry soils to aid pulverization, or dry back wet soils by aeration with disc harrow or rotary mixer with its hood open.
- Distribute cement in dry form with mechanical spreader or in slurry form from distributor truck equipped with agitation system (Figure 4.1).
- Mix with traveling rotary mixer, adding water if necessary, until a homogeneous, friable mixture is obtained that will meet the specified pulverization requirements.
- Compact with tamping (sheepsfoot) roller (Figure 4.2).
- Complete surface compaction with a steel drum, pneumatic tire, or other appropriate type of roller.
- With grader, shape area to final crown and grade.
- Seal surface with pneumatic-tire roller.

Experience has shown that pulverization requirements (the allowable amount of unpulverized lumps and clods in the mix) for CMS need not be as strict as those for CTB construction. Specifications from different agencies vary somewhat, but a common gradation requirement for CMS is for 100 percent to pass a 1-½-inch sieve and a minimum of 60 percent to pass a No. 4 sieve exclusive of any gravel or stone retained on the No. 4 sieve.

All processing in an area can be completed within one day rather than the more restrictive limits of two to four hours typically applied for CTB. Following the processing period, an all-weather working platform is provided with no waiting period. The operation of construction equipment to place base or subbase courses, or concrete pavement can commence at any time.

**Cement-Modified Granular Material**

With a few exceptions, these base and subbase courses are constructed in essentially the same manner as CTB courses. The steps include:

- Shape the area to crown and grade and correct any soft subgrade areas.
- Add specified amounts of cement in either dry or slurry form and the required amount of water, and mix thoroughly with mixed-in-place traveling rotary mixers (in rare cases, cement-modified granular materials may also be mixed in a central mixing plant).
- Compact, finish to crown and grade.

Also in contrast to normal CTB construction, the time limit between mixing and compacting is not as stringent; although all the operations should be completed in the same day. Often, it is not cured, although curing with a moist spray is suggested to provide maximum benefit from the cement.
5 Suggested Construction Specification for Cement-Modified Soil

1. GENERAL

1.1 Description. Cement-modified soil (CMS) shall consist of soil/aggregate, portland cement, and water proportioned, mixed, compacted, and cured in accordance with these specifications; and shall conform to the lines, grades, thicknesses, and typical cross sections shown in the plans.

1.2 Caveat. These specifications are intended to serve as a guide to format and content for normal CMS construction. Most projects have features or requirements that should be incorporated in the project documents.

2. REFERENCED DOCUMENTS

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

- ASTM C150 Specification for Portland Cement (AASHTO M 85)
- ASTM C595 Specification for Blended Hydraulic Cements (AASHTO M 240)
- ASTM C618 Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete (AASHTO M 295)
- ASTM C989 Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars (AASHTO M 302)
- ASTM C1157 Performance Specification for Hydraulic Cement (AASHTO M 240)
- ASTM C1240 Specification for Silica Fume Used in Cementitious Mixtures (AASHTO M 307)
- ASTM D558 Moisture-Density (Unit Weight) Relations of Soil-Cement Mixtures (AASHTO T 134)
- ASTM D1556 Density and Unit Weight of Soil in Place by the Sand-Cone Method (AASHTO T 191)
- ASTM D2167 Density and Unit Weight of Soil in Place by the Rubber Balloon Method
- ASTM D2922 Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth) (AASHTO T 310)

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 CMS:

- 3.1.1 Certifications. Certifications for portland cement and supplementary cementitious materials as required by the engineer.
- 3.1.2 Specifications. Manufacturers’ data and specifications for equipment including capacities to be used in mixing and compacting CMS.
- 3.1.3 Proposed CMS Mix Design. If the proposed mix design is developed by the contractor or there is a suggested change to the mix design, it must be submitted to the engineer for approval at least two weeks prior to CMS construction. This mix design shall include details on soil/aggregate gradation, cementitious materials, and 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; (3) waste material from aggregate production plants; (4) high-quality crushed stone and gravel base course aggregates; or (5) old flexible
pavements, including the bituminous surface and stone or gravel base course.

The soil/aggregate shall not contain roots, topsoil, or any material deleterious to its reaction with cement. The soil/aggregate as processed for construction shall be such that 100% passes a 1-½-inch sieve and at least 60% passes a No. 4 sieve, exclusive of any gravel or stone retained on the No. 4 sieve.

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

4.3 Water. Shall be free from substances deleterious to the processing of the CMS material.

4.4 Pozzolans. If used, pozzolans including fly ash, slag, and silica fume shall comply with the appropriate specifications (ASTM C618, AASHTO M 295 for fly ash; ASTM C989, AASHTO M 302 for slag; and ASTM C1240, AASHTO M 307 for silica fume).

5. EQUIPMENT

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

5.2 Mixing Methods. Mixing shall be accomplished in-place, using single-shaft or multiple-shaft mixers. Agricultural disks, graders, or other scarifying equipment may be used to initially blend the cement into the soil/aggregate material.

5.3 Cement Proportioning. The cement spreader for in-place mixing shall be capable of uniformly distributing the cement at the specified rate. Cement may be added in a 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 CMS processing begins, the area to be mixed shall be graded and shaped to lines and grades as shown in the plans or as directed by the engineer. During this process, any unsuitable material shall be removed and replaced with acceptable material.

6.1.2 Mixing. CMS material shall not be mixed when the soil/aggregate is frozen, or when the air temperature is below 40°F.

6.2 Processing

6.2.1 Preparation. The surface of the soil/aggregate to be processed into CMS shall be at an elevation so that, when mixed with cement and water and re-compacted 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 surface conditions shall be approved by the engineer before the next phase of construction is begun.

6.2.2 Pulverization. Before cement is applied, initial pulverization or scarification may be required to the full depth of mixing.

For cohesive soils with a plasticity index greater than 20, the soil/aggregate shall be damp at the time of pulverizing to reduce dust and aid in processing.

For slurry application of cement, initial pulverization or scarification may be required to the full depth of mixing.

6.2.3 Application of Cement. The specified quantity of cement shall be applied uniformly in a manner that minimizes dust, runoff, and ponding, and is satisfactory to the engineer.

6.2.4 Mixing. Mixing shall begin as soon as possible after the cement has been spread and shall continue until a uniform mixture is produced. The final mixture shall be pulverized such that 100% passes the 1-½-inch sieve and at least 60% passes the No. 4 sieve, exclusive of any gravel or stone retained on the No. 4 sieve.
The final pulverization test shall be made at the conclusion of mixing operations. Mixing shall be continued 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. CMS material shall be uniformly compacted to a minimum of 98% of maximum dry density based on a moving average of five consecutive tests with no individual test below 96%. Field density of compacted CMS material can be determined by the 1) nuclear method in the direct transmission mode (ASTM D2922, AASHTO T 310); 2) sand cone method (ASTM D1556, AASHTO T 191); or 3) rubber balloon method (ASTM D2167). Optimum moisture and maximum dry density shall be determined prior to start of construction and also in the field prior to and during construction by a moisture-density test (ASTM D558 or AASHTO T 134).

6.4 Finishing. As compaction nears completion, the surface of the CMS shall be shaped to the specified lines, grades, and cross sections. Compaction shall then be continued until uniform and adequate density is obtained. Compaction and finishing shall be done in such a manner as to produce a dense surface free of compaction planes, cracks, ridges, or loose material.

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

If required by the engineer, after completion of final finishing, the surface may be moist-cured with a fog-type water spray.

6.6 Traffic. Completed portions of CMS can be opened immediately to construction equipment provided any moist-curing operations are not impaired.

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

6.8 Maintenance. The contractor shall maintain the CMS material in good condition until all work is completed and accepted. Such maintenance shall be done by the contractor at his own expense.

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

7. INSPECTION AND TESTING

7.1 Description. The engineer, with the assistance and cooperation of the contractor, shall make such inspections and tests as 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:

1. Obtaining test samples of the CMS material and its individual components at all stages of processing and after completion.
2. Observing the operation of all equipment used on 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 provided specifically in the contract documents, shall be in accordance with the latest applicable ASTM or AASHTO specifications in effect as of the date of advertisement for bids on the project.

8. MEASUREMENT AND PAYMENT

8.1 Measurement. This work will be measured:

1. In square yards of completed and accepted CMS material as determined by the specified lines, grades, and cross sections shown on the plans.
2. In tons or cwt of cement incorporated into the CMS material in accordance with the instructions of the engineer.

8.2 Payment. This work will be paid for at the contract unit price per square yard of CMS material and at the contract unit price per ton or cwt 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 complete the CMS material, including watering, curing, inspection and testing assistance, and all other incidental operations.
An organization of cement companies to improve and extend the uses of portland cement and concrete through market development, engineering, research, education and public affairs work.