Properties and Uses of Cement-Modified Soil for Pavements

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ABSTRACT

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 produce CMS is typically less than that required to produce a strong, frost-resistant cement-treated base (CTB) but is enough to improve their engineering properties. 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.

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.

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. This paper will look at the types of CMS available, their modification mechanisms, material properties, proper construction techniques, and longevity.

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 but is enough to improve their engineering properties.

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 shows an example of a typical CMS application.

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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 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 75 μm sieve) as follows:

<u>Cement-Modified Silt-Clay Material</u>

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 75 μm 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.

<u>Cement-Modified Granular Material</u>

According to the AASHTO soil classification system, soils/aggregates containing less than 35 percent material passing a 75 μm 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.

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, and
- 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.

Cation Exchange

The plasticity of a soil/aggregate 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 (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 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 soil/aggregate. This phenomenon is illustrated in Figure 3.

Particle 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. 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 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 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 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.

CONSTRUCTION

For silt-clay materials that are not excessively cohesive or wet, the construction operations are essentially the same as those for CTB courses; however, some additional effort may be required in the pulverization and mixing operations. 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. Often, CMS 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 7).
- 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.
- 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 37.5 mm sieve and a minimum of 60 percent to pass a 4.75 mm sieve exclusive of any gravel or stone retained on the 4.75 mm 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.

LONGEVITY / PERFORMANCE

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.

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 (liquid limit (LL), plastic limit (PL), plasticity index (PI), and shrinkage limit (SL)) as measured on laboratory mixtures is given in Table 1. 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 PI values 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 (PI, SL, and gradations) were permanent. Figure 8 shows the effect of CMS on the PI of these study soils.

TABLES

Table 1 - Permanence of Improvement of Cement-Modified Clay Soils.

Cement Content	0%	2%		4%		6%	
Age	7 days	7 days	60 cycles F-T	7 days	60 cycles F-T	7 days	60 cycles F-T
LL	49	48	49	45	47	45	45
PL	18	23	29	25	34	31	32
PI	31	25	20	20	13	14	13
SL	18	20	20	27	24	26	27

FIGURES

Figure 1 – In-place mixing for modification of clay soils at the Dallas Cowboys Stadium.

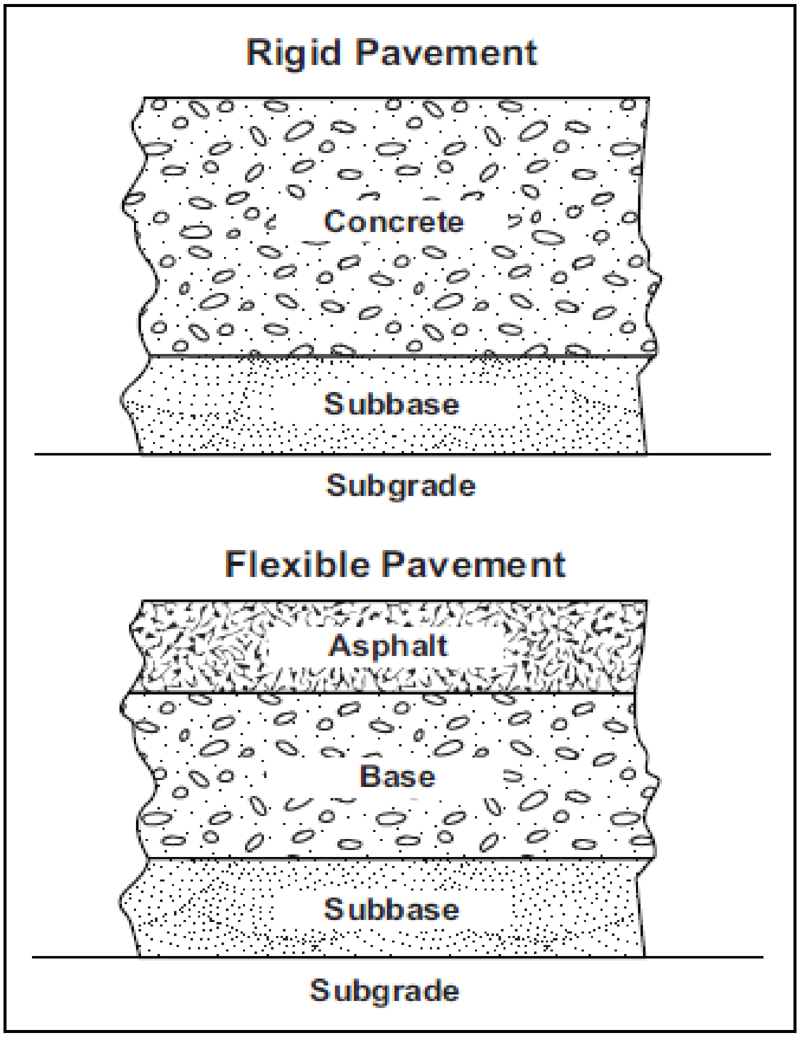

Figure 2 – Terminology used in rigid and flexible pavement systems.

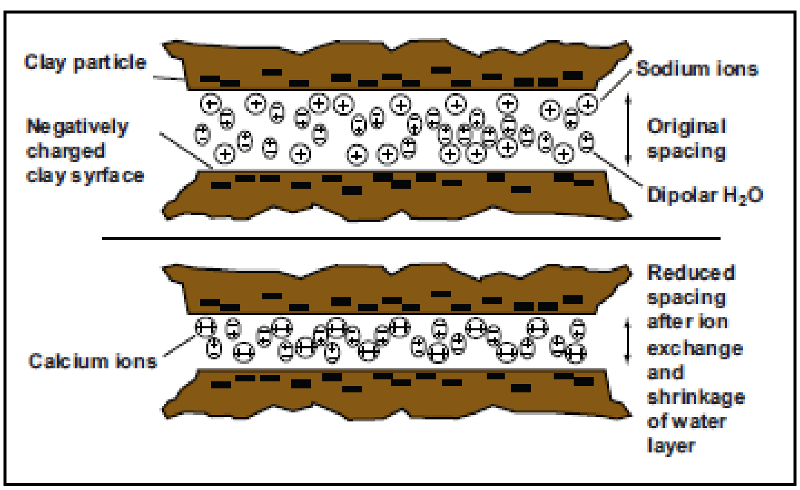

Figure 3 – Cation exchange.

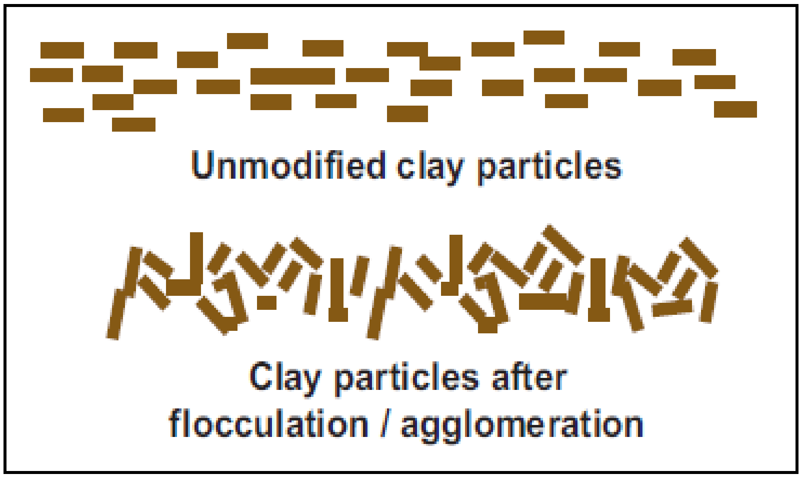

Figure 4 – Particle restructuring.

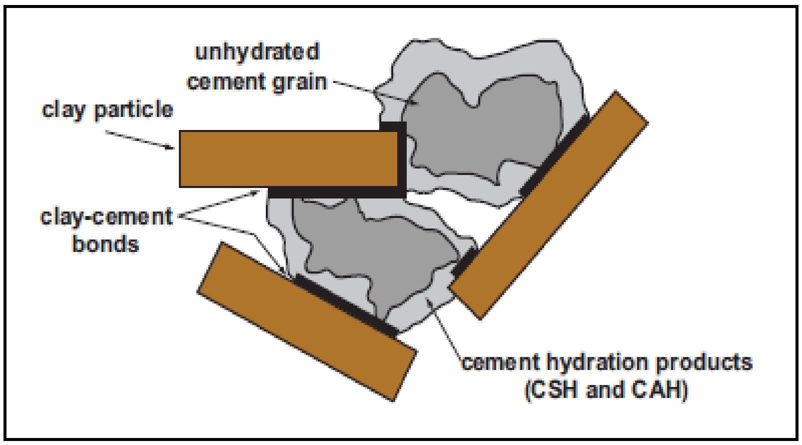

Figure 5 – Cementitious hydration.

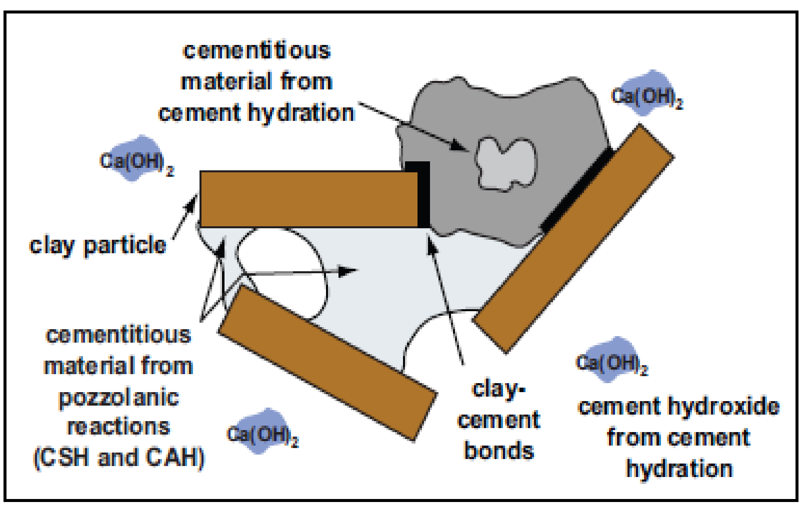

Figure 6 – Pozzolanic reaction.

Figure 7 - Distributing cement in slurry form from a distributor truck.

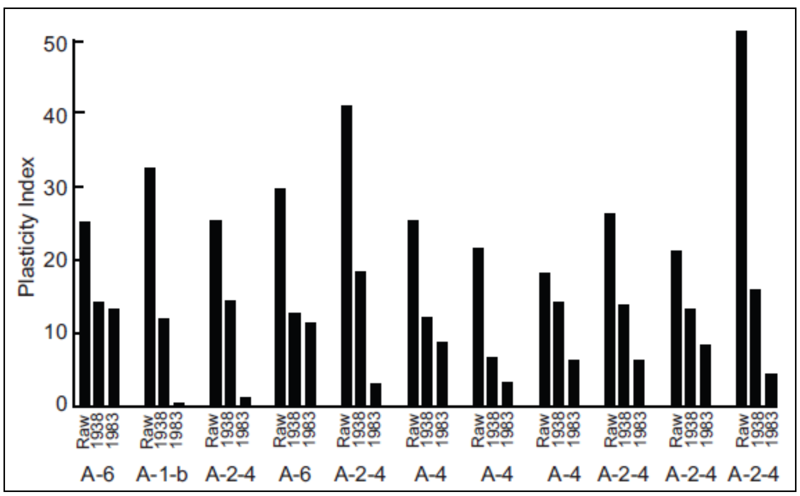

Figure 8 - Comparison of PI data for raw soil and CMS.