Cement-Modified Soil for Long Lasting 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 two to six percent by dry weight of the soil/aggregate being modified with the majority of cases being between three and five percent. The objective of the treatment is to permanently 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 long lasting and sustainable 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), making CMS a very sustainable pavement material. This paper will look at the types of CMS available, their modification mechanisms, material properties, proper construction techniques, and longevity.

DEFINITIONS

[1] Cement-modified soil, usually referred to as CMS, is a term used to describe a soil or aggregate that has been treated with a relatively small proportion of portland cement. The objective of the treatment is to amend undesirable properties of problem soils or substandard materials so that they are suitable for use in construction. The amount of cement added to the soil is less than that required to produce a hardened soil-cement mass [2 and 3] but is enough to improve the engineering properties of the soil. For the small quantities of cement generally used, CMS becomes caked or slightly hardened. However, it still functions essentially as a soil or aggregate, although an improved one.

The degree of modification increases with greater amounts of cement. Therefore, for a given soil, a cement content can be selected that will provide a material meeting the specified level of modification, expressed in terms of plasticity, strength, or other criteria. Figure 1 shows an example of a typical CMS application.

The results of field and laboratory tests, including each of the ones referenced in this paper, show that changes in the physical characteristics of a soil by cement modification are permanent. In other words, a soil modified by portland cement 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, base, and subbase are mentioned to describe the uses of CMS materials in both flexible and rigid pavement systems. Subgrade refers to the natural ground, graded and compacted, on which a pavement structure is built, while bases are used in flexible (asphalt) pavements and subbases are used in rigid (concrete) pavements [4]. 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:

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 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, base, or subbase layers. Specific objectives may be to decrease the material's plasticity and volume change characteristics, to increase its bearing capacity, or to provide a stable working platform on which pavement layers may be constructed.

Pavement applications include subgrade stabilization, subbases for flexible or cement-treated base (CTB) systems, subbases for rigid systems, and for correcting weak or unstable areas of subgrade.

Cement-Modified Granular Material

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 base and subbase layers.

Pavement applications include base courses for flexible systems, shoulders, and subbases for rigid systems.

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 [5].

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 [6]. 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 [7], 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 [8] (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 [9]; 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 permanently improves the properties of certain silt-clay soils/aggregates that are unsuitable for use in subgrade, base, and subbase 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.

Plasticity

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)) [10] as measured on laboratory mixtures of cement-modified silt-clay soils (AASHTO A-6-7 - clay and silty clay) is given in Table 1 [11]. In this study, seven sets of tests on three different soil samples were performed to determine the influence of cement in the modification process.

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 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 [12]. The original untreated 1938 subgrade soil samples classified as AASHTO A-4, A-6, and A-7 - silt, silty clay, and clay, respectively. In this study, 3 sets of tests at 11 different locations were performed to determine the influence of cement in the modification process.

Figure 8 shows the effect of CMS on the PI of these study soils over the 45-year period. It is interesting to note that the 1983 cement-modified subgrade soil samples classified as AASHTO A-1-b, A-2-4, A-4, and A-6 - sand, silty or clayey gravel and sand, silt, and silty clay, respectively. The change from all fine-grained soils in 1938 to more granular soils in 1983 is a result of the short- and long-term modification mechanisms discussed earlier. The cement hydration reaction has permanently bound some of the silt- and clay-sized particles together to form larger sand-sized particles.

Volume Change

A good way to measure the expansive properties of soils, as opposed to the plasticity index tests mentioned above, is made possible through the soaking and swelling portion of the California Bearing Ratio (CBR) test [13]. In this test, a “percent 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 of a soil, making the CBR swell test a better, more direct measure of a soil’s volume change potential.

The dramatic reduction in swell of a highly expansive (AASHTO A-7 - clay) soil from California is shown in Figure 9 [14]. The clayey soil with cement laboratory specimens were molded at standard maximum dry density and optimum moisture content and then cured in high humidity for seven days before being saturated. Expansion upon saturation was reduced from a high value of about 11 percent to less than 1 percent with the addition of only 2 percent cement. Thus, the highly expansive clay was permanently changed to a relatively nonexpansive material.

Bearing Capacity

Table 2 shows the permanence of the CBR increase for a cement-modified granular material (AASHTO A-1-b(0) - disintegrated granite) from Riverside County, California. After 60 cycles of laboratory freeze-thaw tests, the CBR values did not decrease; in fact, the value at four percent cement increased substantially due to additional cement hydration during the thaw cycles.

Similarly, in a study evaluating the effectiveness of both portland cement and hydrated lime in the modification of silt-clay soils [15], CBR values for the cement-treated specimens increased significantly with time. In this study, 20 CBR determination tests for each of 3 different soil samples were performed. Table 3 shows both the initial and 91-day CBR values for the three different fine-grained (AASHTO A-7-6 - sandy clay and clay) soils.

SUMMARY

CMS is essentially an improved soil material that has been treated with a relatively small proportion of portland cement. The objective of the treatment is to amend undesirable properties of problem soils or substandard materials so that they are suitable for use in pavement subgrade, base, and subbase construction. 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 CMS with a wide range of engineering properties.

The modification of clay soils to improve their engineering properties is well recognized and widely practiced [15 and 16]. Through stabilization, the plasticity of soil is reduced, it becomes more workable, and its compressive strength and load bearing properties are improved. Such improvements are the result of a number of modification mechanisms that take place in the presence of portland cement. While the effects of cation exchange and particle restructuring is generally within a few hours, the effects of cement hydration and its resulting pozzolanic reactions continue over a long period.

The improvement in the engineering properties of a soil due to the addition of small quantities of portland cement can be measured in several ways including reduction in plasticity characteristics as measured by PI; reduction in the amount of silt and clay size particles; increase in CBR; increase in shearing strength; and decrease in volume-change properties. Additionally, these improvements are permanent – making CMS a valuable tool for strong, durable, and sustainable pavements.

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TABLES

Table 1 – Permanence of Improvement of Cement-Modified Silt-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

Table 2 – Permanence of CBR Values for a Cement-Modified Granular Material.

	CBR (percent)
Raw Soil	43
2 percent cement by weight, age 7 days	255
2 percent cement by weight after 60 cycles of freeze-thaw	258
4 percent cement by weight, age 7 days	485
4 percent cement by weight after 60 cycles of freeze-thaw	574

Table 3 – Permanence of CBR Values for Cement-Modified Silt-Clay Soils.

Soil ID	Cement (percent)	Day	CBR (percent)
1	0	1	8
	6	91	240
2	0	1	12
	6	91	190
3	0	1	10
	6	91	130

FIGURES

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

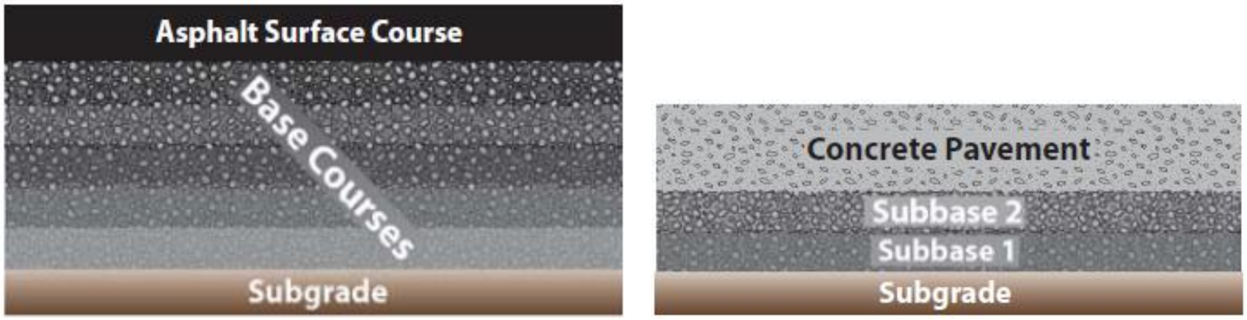

Figure 2 – Terminology used in flexible (asphalt) and rigid (concrete) pavements.

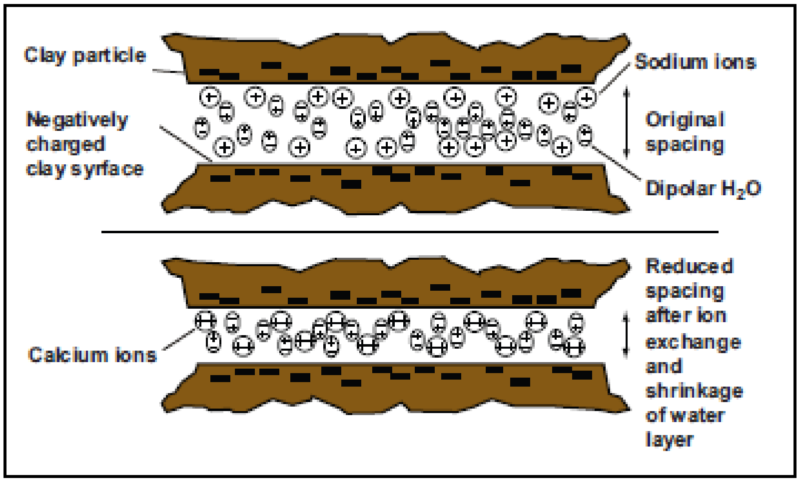

Figure 3 – Cation exchange.

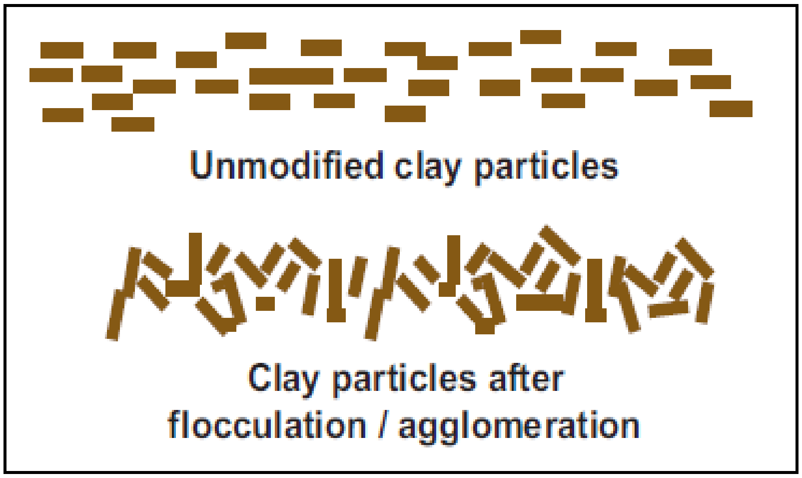

Figure 4 – Particle restructuring.

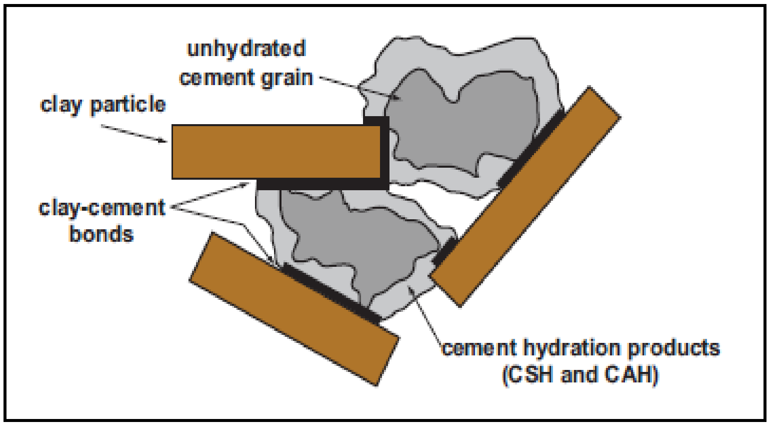

Figure 5 – Cementitious hydration.

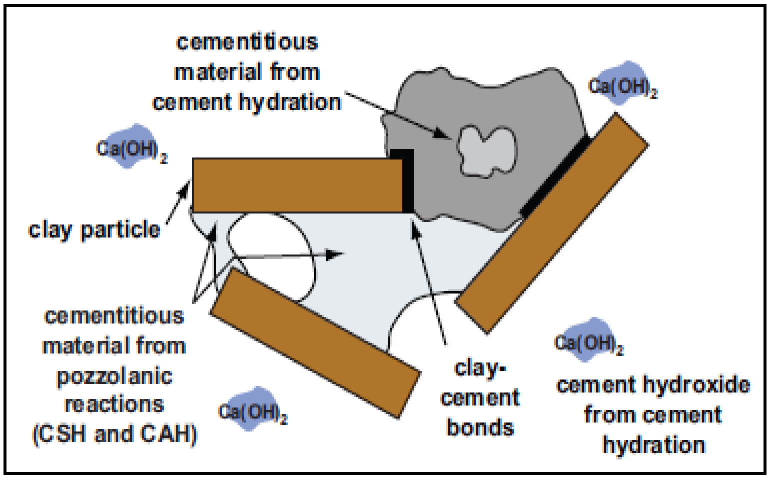

Figure 6 – Pozzolanic reaction.

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

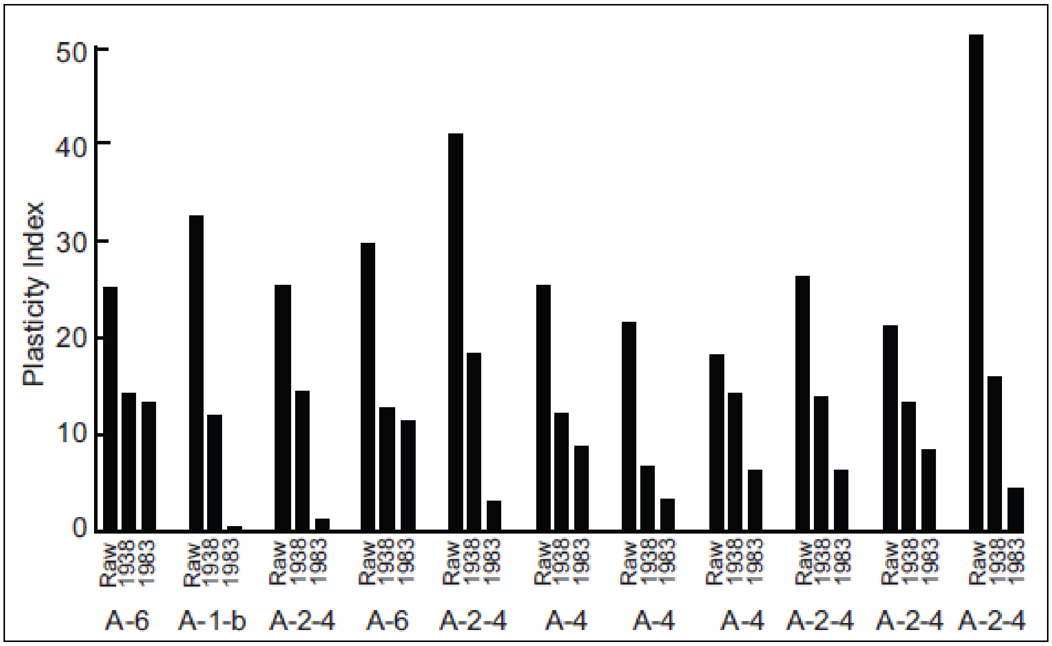

Figure 8 - Comparison of PI data for raw soil and CMS.

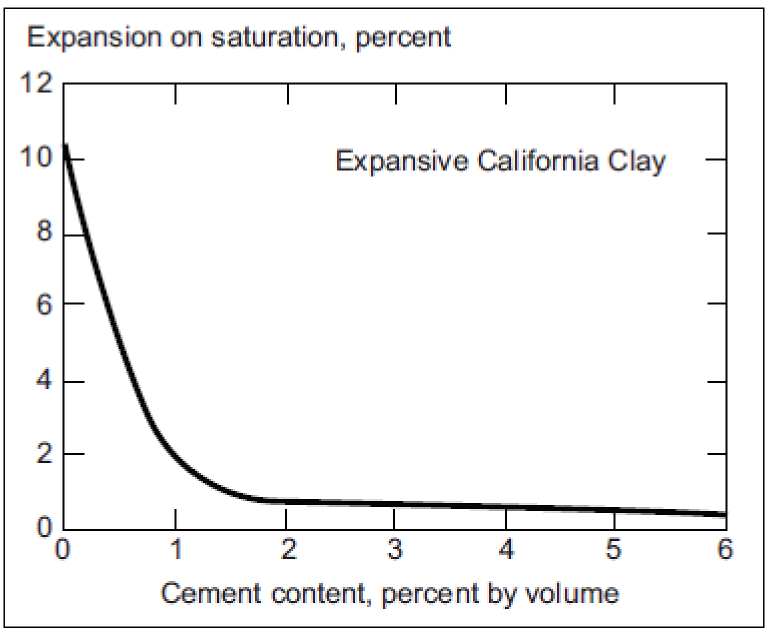

Figure 9 – Expansion versus cement content of a highly expansive clay.