SOIL-CEMENT - A CONSTRUCTION MATERIAL

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The technology of cement-treated materials is summarized. Basic properties of soil - and soil-aggregate - cement mixtures are given to help the reader understand and use the product. The use of soil and cement mixtures as pavement layers is considered. Testing and mix design methods are discussed and approximate cement requirements given. A thickness design procedure is presented. Construction procedures are outlined. Recycling of material with the addition of cement to salvage and strengthen road layers is discussed. It is concluded that cement stabilization can improve the engineering properties of materials and has wide application in pavement layers. In using soil-cement, proper consideration should be given to mix design, thickness design, and construction procedures.

Soil-cement is a compacted mixture of a soil, portland cement, and water. As the cement hydrates, the mixture becomes a hard, durable paving material.

Soil-cement is used mainly as a base for road, street, and airport paving. A bituminous wearing course is normally placed on the soil-cement base to complete the pavement.

Soil-cement was developed in an effort to save road-building money by using soils on or near the construction site.

The basic idea of soil-cement is not new. In the early 1920's, state highway departments built short sections of roads with soil and cement. However, the principles of soil compaction as applied to road building were not yet developed.

Research by the Portland Cement Association led to the development of the basic control factors for soil-cement construction: (1) an adequate cement factor, (2) proper moisture content, and (3) adequate compaction.

Compared with today's practices, the methods used to build early projects were crude at best. Although methods and equipment have been greatly improved, the engineering principles resulting from this early work have been used to build many thousands of kilometres (miles) of soil-cement pavement in the United States, Canada, and other countries.

Some other terms often applied to soil-cement are "cement-treated base", "cement-stabilized soil", and "stabilized aggregate".

The material presented here explains basic information on cement-soil reactions, testing philosophy, test methods, properties of soil-cement, thickness design and construction.

Development of Standard Tests

One of the first significant findings of the early 1935 research was that the moisture-density relationship for soils as discovered in 1929 by Proctor was also valid for mixtures of cement and soil when compacted immediately after mixing and before cement hydration. It was found that optimum moisture content provided sufficient water for cement hydration. The soil-cement moisture-density test was adopted as a standard by ASTM (D558) in 1944. It was adopted as standard by AASHTO (T134) in 1945.

The next step in the 1935 research program was to devise methods of measuring the effect that various cement contents, moisture contents and densities have on the physical properties of compacted soil-cement mixtures. Since the rate and amount of cement hydration would influence final results materially, specimens were permitted to remain undisturbed for 7 days in an atmosphere of high humidity before being tested. This permitted hydration of a significant portion of the cement.

In analyzing possible test methods that might be used for evaluating soil-cement mixtures, tests used in soil and concrete testing were analyzed. Consideration was given to various compression and tension tests that might be modified to simulate the internal forces of expansion and contraction produced by changes in moisture and temperature. It was considered that these tests were not applicable since they do not simulate the nature and magnitude of the desired forces. However, it was found that repeated wetting and drying, and freezing and thawing could induce internal forces similar to those induced by changes in moisture content.

Thus, the wet-dry and the freeze-thaw tests were evolved to reproduce in the laboratory the phenomenon of volume changes. The wet-dry test was designed primarily to simulate shrinkage forces. The freeze-thaw test was designed to simulate internal forces produced by moisture and temperature change.

Because moisture plays a predominant role in the strength of soils and road bases it is essential that water play a predominant part in both the wet-dry and freeze-thaw tests. The wet-dry test is accomplished by submerging the specimens in water during the wetting portion of each cycle. In the freeze-thaw test, specimens are permitted to absorb water by capillarity during the thawing portion of each cycle.

Early in the development of the tests, a brushing procedure was developed to remove the loosened material resulting from alternate wetting, drying, freezing, and thawing. Twelve cycles for each test produced interpretable data.

As part of the research program, data on soil gradation, surface area, physical test constants, compressive strength, organic content, pH, density, and cement-void ratio were correlated with the degree of cement reaction in search of relationships that could be used to determine cement contents for construction (1). These studies produced erratic results.

Thus, the wet-dry and freeze-thaw tests were developed to determine the minimum cement content required to produce a structural material that would resist volume changes produced by changes in moisture and temperature. Because moisture and temperature changes occur in varying degrees in all climates and geographic areas, use of both the wet-dry and freeze-thaw tests assure that a hardened, structural material is produced for any area. The wet-dry and freeze-thaw tests are standards of ASTM and AASHTO (ASTM D559, AASHTO T135; ASTM D560, AASHTO T136).

Test Criteria

Studies of laboratory test data, outdoor exposure of specimens, and field performance were used in selecting the criteria for determining minimum cement content to produce a structural material.

The selected criteria included requirements of volume change, maximum moisture content, soil-cement weight loss, and trend of compressive strength. The criterion of maximum volume increase of the specimens (not more than 2%) was chosen as an indication that the cement was holding the mass intact and preventing volume increases that would otherwise take place. The criterion of maximum moisture content (not more than that required to fill the voids) was selected as a further indication of resistance to disruptive volume changes. The criterion of maximum soil-cement loss from brushing was used as an indication that the forces of expansion and shrinkage resulting from the wetting and drying, freezing and thawing, that disrupt and disintegrate soil specimens, had been resisted. The compressive strength criterion was used because increases in strength due to increases in time and cement content were evidence that the cement is functioning normally and that the soil was not interfering with hydration of the cement.

Today, after conducting thousands of tests, weight loss, together with strength gain, are the primary criteria. The validity of these criteria has been verified by a quarter century of successful field performance of soil-cement projects in service. Invaluable as the tests (2) are, they require considerable time to obtain the factors needed for construction. The Portland Cement Association has developed a special short-cut test procedure for determining cement factors for sandy soils.

Short-Cut Test Procedures for Sandy Soils

Short-cut test procedures have been evolved to determine adequate cement contents for sandy soils (3,4). These procedures do not involve new tests or additional equipment. Instead, data from previous tests of similar soils were correlated with durability to develop charts for the short-cut test procedures. The only laboratory tests required are a grain-size analysis, a moisture-density test, and compressive-strength tests. Relatively small soil samples are needed and all tests, except the 7-day compressive-strength tests, can be completed in one day (Figures 1,2,3,4). The procedures are widely applied by engineers and builders and may largely replace the standard tests as experience increases.

Figure 1. Indicated cement contents of soil-cement mixtures not containing material retained on the 4.75-mm (No. 4) sieve - Method A.

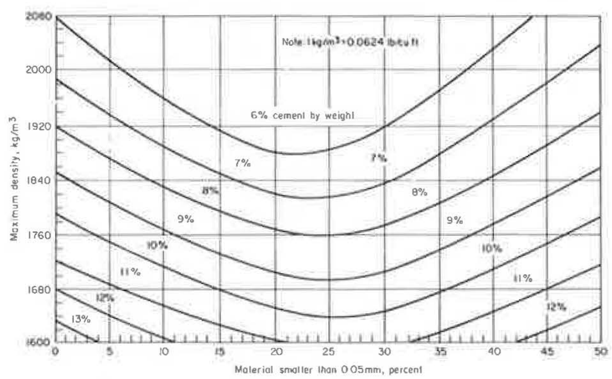
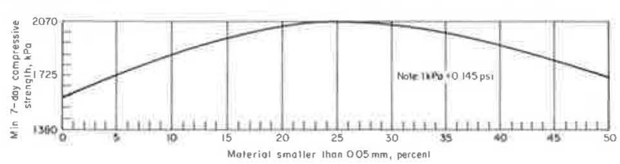


Figure 2. Minimum 7-day compressive strengths required for soil-cement mixtures not containing material retained on the 4.75-mm (No. 4) sieve - Method A.



Two procedures are used: Method A for soils not containing material retained on the 4.75-mm (No. 4) sieve and Method B for soils containing material retained on the 4.75-mm (No. 4) sieve (2).

The procedures can be used only with soils containing less than 50% material smaller than 0.05 mm (silt and clay), less than 20% material smaller than 0.005 mm (clay), and less than 45% material retained on the 4.75-mm (No. 4) sieve. Dark grey to black soils with appreciable amounts of organic impurities were not included in the correlation and therefore cannot be tested by these procedures. This is also true of miscellaneous granular materials such as cinders, caliche, chat, chert, marl, red dog, scoria, shale, and slag.

Figure 3. Indicated cement contents of soil-cement mixtures containing material retained on the 4.75-mm (No. 4) sieve - Method B.

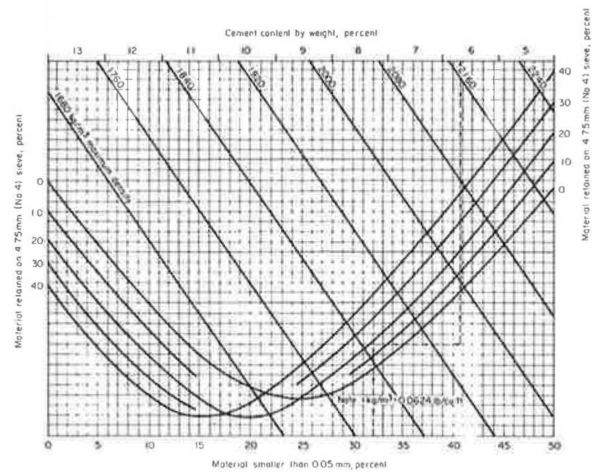
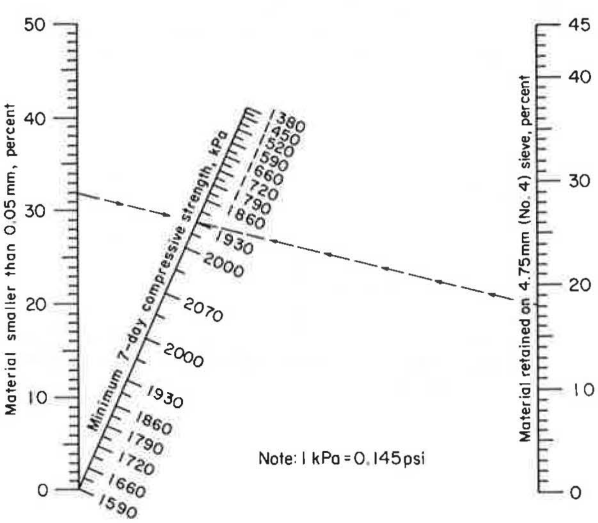


Figure 4. Minimum 7-day compressive strengths required for soil-cement mixtures containing material retained on the 4.75-mm (No. 4) sieve - Method B.



Step-by-Step Procedures

Short-cut test procedures involve:

1. Running a sieve analysis of the soil.
2. Running a moisture-density test on a mixture of the soil and portland cement.
3. Determining the indicated portland cement requirement by the use of charts.
4. Verifying the cement requirement by compressive-strength tests.

In using the short-cut test procedure, the 7-day compressive strength is usually substantially higher that the minimum allowable value. This merely indicates that the soil is reacting normally. When higher strengths are obtained, it is not correct to reduce the cement factor so that a strength value is close to the minimum allowable. Such reduction invalidates the reliability of the correlation and usually results in a cement content that is not sufficient to meet the ASTM-AASHTO freeze-thaw and wet-dry test criteria. Any reduction in the cement factor can only be made based on freeze-thaw and wet-dry tests at lower cement contents. A compressive strength value below the minimum indicates abnormal reaction and additional tests are needed to establish a cement requirement.

Compressive Strength

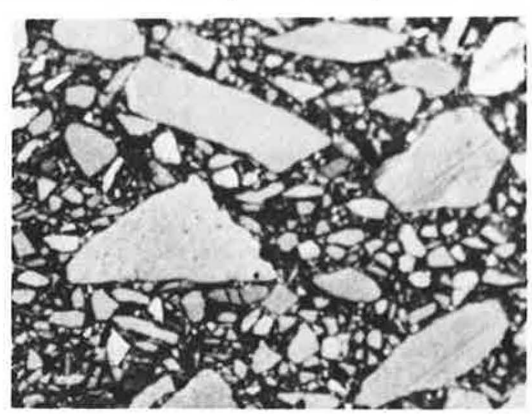
The influence of cement in producing compressive strength in soil-cement mixtures can be analyzed from two viewpoints. The cement influence is evidenced by increases in strength with age and cement content.

The 7-day compressive strengths that represent a durable soil-cement base vary with the physical and chemical properties of the soil and are generally between 2.1 and 5.5 MPa (300 and 800 psi).

Coarse-Graded Aggregates

Excessively coarse-graded aggregates, that is, more than 45% retained on the 4.75-mm (No. 4) sieve, have been used. However, the cement content to make durable soil-cement is generally increased. Up to a limit, an increase in the quantity of coarse material reduces the cement requirement, since the finer particles requiring cement to bind them together are replaced by a coarse particle. The total density of the aggregate material increases as the quantity of coarse aggregate increases, but the density of the 4.75-mm (No. 4) sieve fraction decreases. Too much coarse material interferes with compaction of the matrix of finer particles. Adequate density of the fine fraction is important for it is here that most of the cementing action takes place, forming a matrix that holds the coarser particles together (Figure 5).

Figure 5. The cemented portion of the fine fraction holds the larger particles together.



Durability criteria rather than strength criteria, should be used to establish cement requirements for durable, long-lasting soil-cement. The gradations below are compatible with the short-cut test procedure which requires only a minimum of testing. For materials that do not meet the requirements for the short-cut procedure, particularly aggregate materials that contain more than 45% retained on the 4.75-mm (No. 4) sieve, the standard wet-dry and freeze-thaw tests should be run to insure a durable mixture.

Aggregates of the following gradation limits are suggested to achieve the most economical cement factor for durable soil-cement.

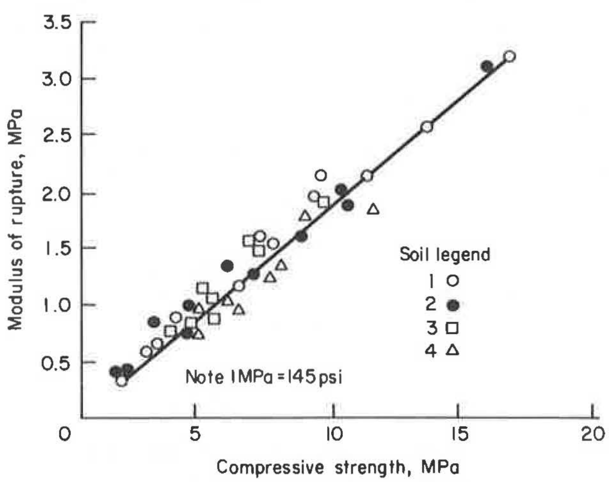
Sieve size	% by weight passing
50 mm (2 in.)	100
4.75 mm (No. 4)	55 - 90
2.0 mm (No. 10)	37 - 67
75 µm (No. 200)	0 - 30
PI	10 maximum

Engineering Properties

During construction soil-cement is compacted to a high density. As the cement hydrates, the mixture hardens in this dense state to produce a structural slab-like material. The strength and elastic properties of soil-cement depend primarily on the type of soil, age, and curing conditions.

As shown in Figure 6, a direct relationship exists between flexural strength (modulus of rupture) and compressive strength--the modulus of rupture being about 20% of the compressive strength (5).

Figure 6. Relationship between modulus of rupture and compressive strength of soil-cement.



The cement in soil-cement continues to hydrate for a long time even under traffic. Cores taken from roads after many years of use show appreciably greater strength than samples tested at 7 and 28 days (Figure 7) (6). This means that soil-cement has a "reserve" of strength to accommodate increases in volume and weight of traffic.

Because of soil-cement's slab-like character it has high load-carrying capacity. Results of bearing tests (7,8) (Figure 8) show that soil-cement can support up to three times greater loads than other low-cost base materials of the same thickness.

Cement-Modified Soils

Cement-modified soil is a soil material that has been treated with a relatively small quantity of cement--less than is required to produce soil-cement. Cement treatment changes and improves the soil's physical properties. Cement-modified soils are arbitrarily classified into two groups:

Figure 7. Strength gain with age, projects in service.

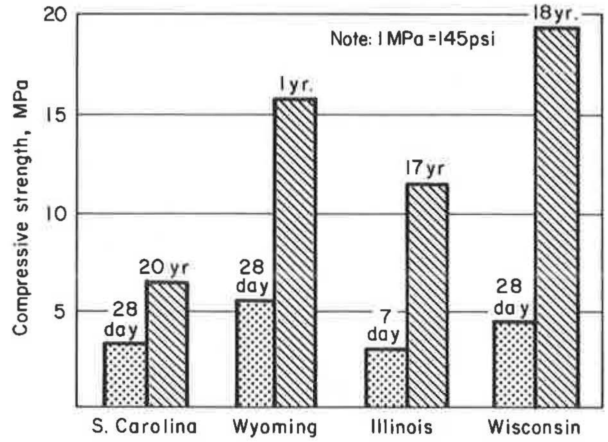
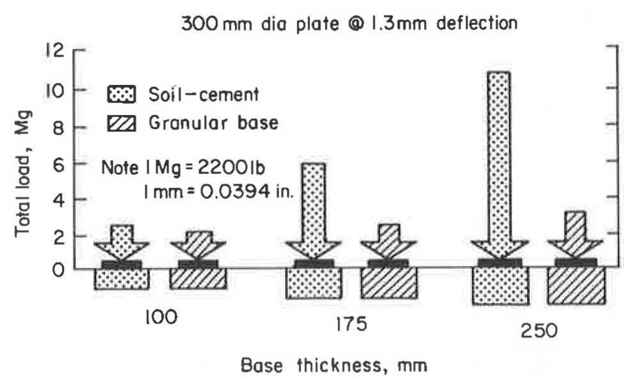


Figure 8. Load-carrying capacity of soil-cement and granular base. Plate-bearing tests on 3x3.7-m (10x12-ft) soil-cement panels made of a sandy soil with 80 kg per cubic metre (5.3% cement by volume). The k value of the clay subgrade was 18 to 33 MPa/m (66 to 122 psi/in.) under soil-cement panels and 27 to 39 MPa/m (98 to 142 psi/in.) under untreated crushed stone.



(1) cement-modified granular soils with less than 35% silt and clay, and (2) cement-modified silt-clay soils.

One common way of measuring the effect of cement on improving a granular material which contains an excessive amount of clay is by reduction in plasticity characteristics as measured by the plasticity index (PI). Figure 9 shows the reduction in PI produced by the addition of cement to a substandard granular base material. Figure 9 also shows the permanency of the PI reduction as measured over a 10-year period (9).

The Sand Equivalent test (10) used to detect the presence of undesirable clay-like materials tends to magnify the volume of the clay somewhat in proportion to its detrimental effects. Concrete sands and crushed stone have sand equivalent values of about 80; expansive clays have sand equivalents of 0 to 5. Improvement in Sand Equivalent value of a Utah granular soil having a PI of 11 and having 33% passing the 75-mm (No. 200) sieve is shown in Table 1. Three percent cement increased the value from 11 to 59. The PI was correspondingly reduced from 11 to 0 (11).

Figure 9. Plasticity index vs. time.

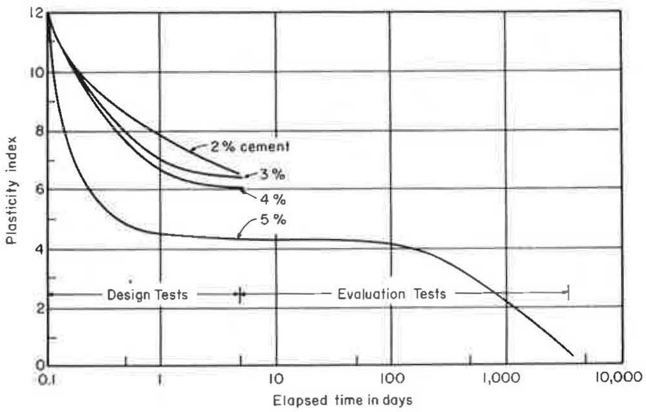


Table 1. Sand equivalent values.

Percent Cement by Weight	Sand Equivalent
0	11
1	18
2	36
3	59

Several types of laboratory strength tests are also used to measure improvement of a substandard granular material. One common test is the California Bearing Ratio test (CBR). Table 2 gives data for an A-1-b(0) disintegrated granite from California. The addition of 2% cement by weight increased the CBR from 43 to 255. The addition of 4% cement increased the value to 485. The permanency of CBR improvement is also shown in Table 2 with results of 60 cycles of laboratory freezing and thawing. Further cement hydration during the freeze-thaw test more than made up for any detrimental effect with the result that the CBR did not decrease. In fact, the CBR of the 4% mixture increased to 574 (11).

Table 2. Permanency of bearing value.

	CBR
Raw soil	43
2% cement by weight, age 7 days	255
2% cement by weight after 60 cycles of freeze-thaw	258
4% cement by weight, age 7 days	485
4% cement by weight after 60 cycles of freeze-thaw	574

Some agencies use the Stabilometer test (12) to determine the stability of a material. A stabilometer value (R value) of about 78 is considered equivalent to good crushed stone. Table 3 gives data for a fine sand. The R value increased from 65 for the untreated sand to 89 with the addition of 3% cement (11).

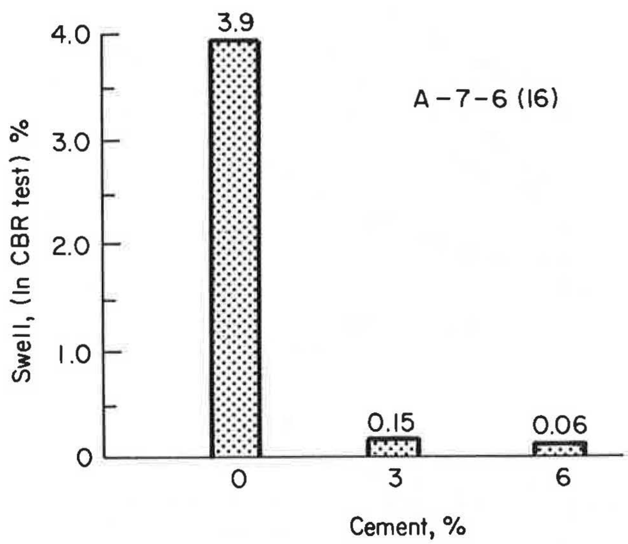
Table 3. R-values.

Raw soil	65[a]
Lab mixture	
3% cement by weight	89
5% cement by weight	93

[a] A-2-4 fine sand

Reduction in swell of an expansive clay due to the addition of cement is shown in Figure 10. The addition of 3% cement reduced the expansion from 3.9% to 0.15%, an insignificant value (8).

Figure 10. Cement treatment of expansive clay.



These examples illustrate that when cement is added to a soil material the chemical and physical properties of that material change, and when sufficient cement is added a strong structural material results.

Thickness Design

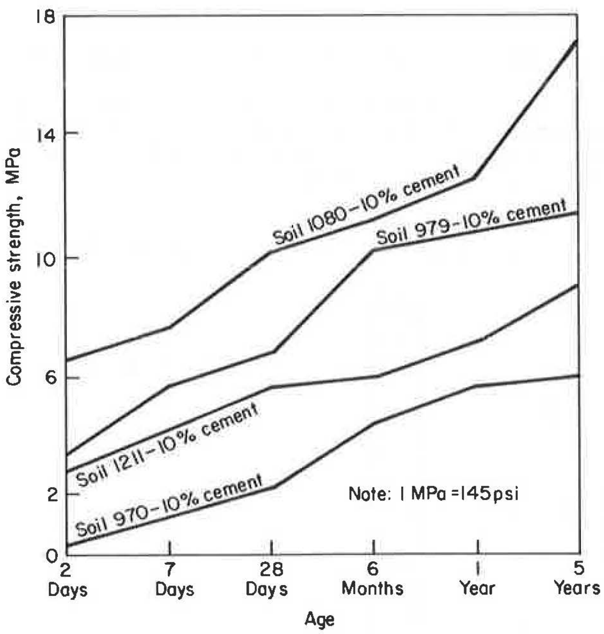
Soil-cement is a material that possesses its own unique structural characteristics.

The structural properties of soil-cement depend on soil type, curing conditions, and age. Typical ranges for a wide variety of soil-cements at their respective cement contents required for durability are:

Property	28-Day Values
Compressive strength, saturated	2.1 - 5.5 MPa (300-800 psi)
Modulus of rupture	0.5 - 1.0 MPa (70-150 psi)
Modulus of elasticity (static modulus in flexure)	4 100 - 13 800 MPa (600,000-2,000,000 psi)
Poisson's ratio	0.12 - 0.14
Critical radius of curvature on 150x150x760-mm beam	100 - 190 m (4,000-7,500 in.)

The average strength of a soil-cement pavement over the design life will be considerably greater than the 28-day values. Figure 11 shows 5-year laboratory strength gains for several soil-cements (6). These strength gains provide a margin of safety in the thickness design procedure.

Figure 11. Strength gain with age, laboratory specimens.



Studies at the Portland Cement Association laboratories (13,14) aimed toward the development of a soil-cement thickness design procedure covered these major phases of research:

1. Basic structural properties
2. Load-deflection characteristics
3. Fatigue properties

The load-deflection research on soil-cement pavements has shown that it is possible to describe the response by a single equation, regardless of soil type and cement content, as long as the final product meets the criteria for fully hardened soil-cement. Soil-cement meets specific mix design criteria (2), and the soil-cement pavements are constructed under definite specifications (15). The thickness design procedure relates to all climate areas when the quality of the soil-cement meets the above requirements.

Fatigue studies revealed that, for a given design, the number of load repetitions to failure was related to the radius of curvature of bending. This relationship proved to be similar to the known fatigue behavior of other materials.

The effect of soil type was significant in the fatigue results (Table 4). It required the division of soils into two broad textural types--granular and fine-grained soils--and the corresponding use of separate design charts (Figures 12,13) for design purposes.

Table 4. Thickness design - fatigue consumption coefficients[a].

Axle load, Mg	Granular soil-cement	Fine-grained soil-cement
Single axles		
13.6	12,500,000.	3,530.
12.7	1,270,000.	1,130.
11.8	113,000.	337.
10.9	8,650.	93.
10.0	544.	23.3
9.1	27.	5.2
8.2	1.0000	1.0000
7.3	0.0250	0.1600
6.4	0.0004	0.0200
5.4	-	0.0018
Tandem axles		
22.7	12,500,000.	3,530.
21.7	3,210.000.	1,790.
20.9	792,000.	890.
20.0	186,000.	431.
19.1	41,400.	203.
18.1	8,650.	93.
17.2	1,690.	41.1
16.3	305.	17.5
15.4	50.4	7.1
14.5	7.5	2.74
13.6	1.0000	1.0000
12.7	0.1200	0.3410
11.8	0.0120	0.1070
10.9	0.0010	0.0310
10.0	-	0.0081
9.1	-	0.0018

[a] These coefficients express the relative fatigue consumption of different axle-load magnitudes for granular and fine-grained soil-cements, respectively.

Note: 1 Mg = 2.2 kips

Design Procedure

In the design procedure, factors analyzed to determine the design thickness are:

1. Subgrade strength
2. Pavement design period
3. Traffic, including volume and distribution of axle weights (single- and tandem-axle loading configurations of conventional trucks)
4. Soil-cement base course thickness
5. Bituminous surface thickness

Subgrade Support. The support given to the soil-cement pavement by the subgrade is a major element in the thickness design procedure for soil-cement pavements. Subgrade support is measured in terms of the Westergaard modulus of subgrade reaction, k, and is determined by plate-loading tests on the subgrade or correlated to simple soil tests.

Design Period. A design period is selected for use with this procedure. Design period is not to be confused with the service life. The selection of the design period is somewhat arbitrary. The design formulation is not particularly sensitive to variations in the design period.

Figure 12. Thickness design chart for granular soil-cements.

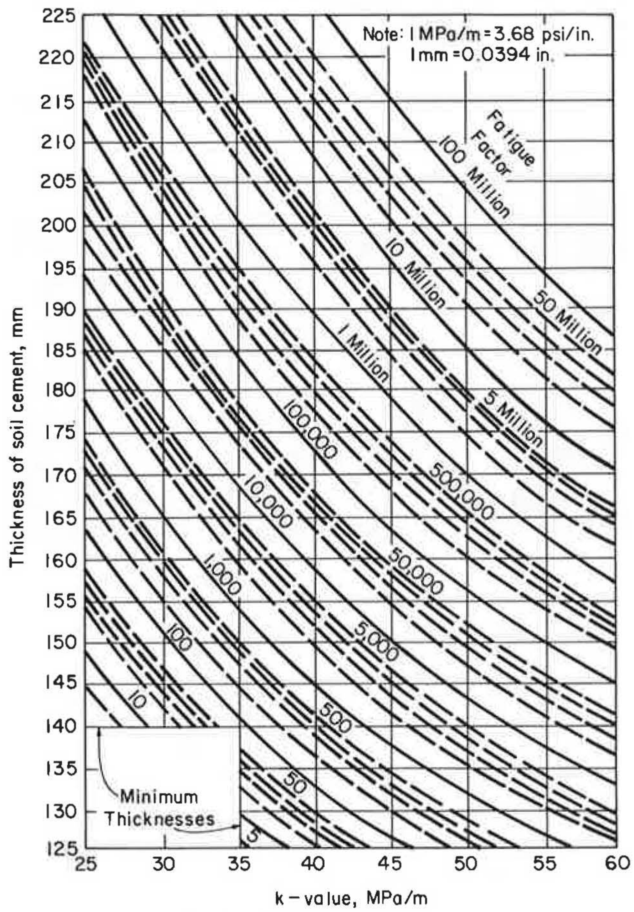
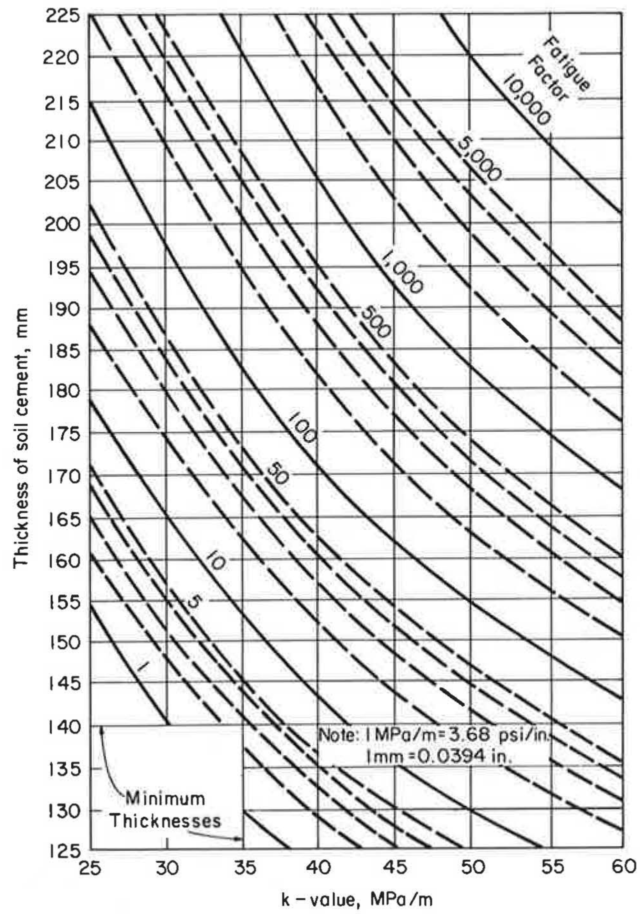


Figure 13. Thickness design chart for fine-grained soil-cements.



Traffic. The weights and volumes of axle loads expected during the design period are major factors in determination of the design thickness. The traffic analysis used in this procedure involves:

1. Determining average daily traffic in both directions (ADT) including the percentage of trucks
2. Projecting the traffic to a future design period
3. Determining the axle-load distribution
4. Computing the Fatigue Factor

Fatigue Factor. A single value that expresses the total fatigue consumption effects of the volumes and weights of single- and tandem-axle loadings for a given design problem is called the Fatigue Factor in this design procedure. It is based on coefficients showing the relative fatigue consumption of different axle-load magnitudes, the Fatigue Consumption Coefficients, which are listed in Table 4. The designer should note that different values are used for granular and fine-grained soil-cements as specified by the two equations developed from the research for the two general soil types.

The Fatigue Consumption Coefficients are multiplied by the numbers (in thousands) of axles in each weight group and then summed to give a single-value Fatigue Factor.

Materials

A proper cement content is the first requisite for soil-cement construction.

Table 5 gives the normal range of cement requirements for soils of the various AASHTO soil groups. Table 6 gives average cement requirements for a number of miscellaneous materials and special types of soil. These average cement requirements may be used for rough cost estimating and then confirmed or revised by laboratory tests (2).

Recycling Old Roadway Materials (16)

The materials usually found in old gravel or stone roads and streets make excellent soil-cement. They are generally friable, easily mixed, and require only a minimum amount of cement. Frequently the old bituminous mat, if present, can be salvaged by pulverizing it and mixing it with the old base course material for processing with cement (Figure 14). The reuse and recycling of these materials with cement is an economical way to strengthen and rebuild worn out granular base pavements. This may be specially beneficial when the level of the top of the pavement cannot be raised from a drainage standpoint.

Table 5. Normal range of cement requirements for B- and C-horizon soils[a].

AASHTO Soil Group	Cement kilograms per cubic metre of compacted soil-cement	Cement percentage by weight of soil
A-1-a	80-110	3-5
A-1-b	110-130	5-8
A-2-4		
A-2-5		
A-2-6	110-140	5-9
A-2-7		
A-3	130-180	7-11
A-4	130-180	7-12
A-5	130-180	8-13
A-6	140-210	9-15
A-7	140-210	10-16

[a] A-horizon soils (topsoils) may contain organic or other material detrimental to cement reaction and thus require higher cement factors. For dark grey to grey A-horizon soils, increase the cement contents 4 percentage points (60 kg/m^3) of compacted soil-cement); for black A-horizon soils, 6 percentage points (100 kg/m^3) of compacted soil-cement.

Table 6. Average cement requirements of miscellaneous materials.

Material	Cement, kilograms per cubic metre of compacted soil-cement	Cement percentage by weight of soil
Caliche	130	7
Chat	130	7
Chert	130	8
Cinders	130	8
Limestone screenings	110	5
Marl	160	11
Red dog	130	8
Scoria containing plus No. 4 material	180	11
Scoria (minus No. 4 material only)	130	7
Shale or disintegrated shale	160	10
Shell soils	130	7
Slag (air-cooled)	130	7
Slag (water-cooled)	140	12

Figure 14. Old bituminous mats can be broken up, pulverized, and incorporated with the old granular base material to make good soil-cement. The same machine can be used to mix the prepared material with portland cement and water.

Deposits of friable or granular materials that require less cement and little pulverizing can often be found nearby and can be used to blanket the existing soil or be combined with it. Selective grading often is used to place the most favorable soils in the top of the grade. Comparative cost estimates will indicate the most economical materials or combination of materials to use.

Construction

Soil, cement, and water can be mixed-in-place using traveling mixing machines, or mixed in a central mixing plant (17). The types of mixing equipment are:

- I. Traveling mixing machines
  - A. Flat transverse-shaft type
    - 1. Single-shaft mixer
    - 2. Multiple-shaft mixer
  - B. Windrow-type pugmill
- II. Central mixing plant
  - A. Continuous-flow-type pugmill
  - B. Batch-type pugmill
  - C. Rotary-drum mixers

Whatever type of mixing equipment is used, the general principles and objectives are the same. Modern mixing machines are very efficient and give high daily production at low cost.

Use of Borrow Materials

From a construction or cost standpoint, it is sometimes advantageous to use a borrow material instead of the soil in place. The existing soil or the soils encountered in cut sections may have a very high clay content and require a relatively high cement factor. Also, considerable effort may be required to pulverize the soils properly.

General Construction Steps

In soil-cement construction the objective is to mix a pulverized soil and cement (Figure 17) thoroughly in correct proportions with sufficient moisture to permit maximum compaction. Construction methods are simple and follow a definite procedure:

A. Initial preparation
   1. Shape the area to crown and grade
   2. If necessary, scarify, pulverize, and prewet the soil
   3. Reshape to crown and grade
B. Processing
   1. Spread portland cement and mix
   2. Apply water and mix
   3. Compact
   4. Finish
   5. Cure

During grading operations, all soft subgrade areas, springs, and frost-heave areas should be located and corrected, and stumps and other debris removed. The roadway should be shaped to approximate crown and grade.

Figure 15. Spreading portland cement in regulated quantities.

Most soil-cement is built from materials that require little or no preliminary pulverizing. If pulverization is required, it is usually done the day before actual processing. Processing operations are continuous. The moist soil-cement mix is compacted and finished immediately.

Compacted and finished soil-cement contains sufficient moisture for adequate cement hydration. A moisture-retaining cover is placed over the soil-cement soon after completion to retain moisture and permit the cement to hydrate. While most soil-cement is cured with bituminous material, but other materials and fog-type water spray are satisfactory.

Summary

When cement is added to a soil material the physical properties of the material are improved. Soil-cement is a hardened structural material possessing definite engineering properties. Outlined here are the basics of soil-cement technology: reaction, testing, properties, design, and construction. By understanding some of the basics of soil-cement an engineer can use it to advantage.

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