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Soil Stabilization With Portland Cement

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Soil Stabilization With Portland Cement

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Foreword

For many years engineers have experimented with mixtures of soil and cement in an attempt to produce a low-cost durable paving material that would utilize native soils.

An enterprising paving contractor in Sarasota, Florida, probably built the world's first soil-cement in 1915 without realizing that he was making history. According to eyewitness accounts, a section of Oak Street was built by dredging shell from the bay, mixing it with sand and cement with a plow and then compacting the surface with a 10-ton steam roller. Inasmuch as the street was authorized by the city council for concrete paving, speculation is that the contractor, the late Bert Reno, resorted to the unorthodox method of construction after a breakdown of concrete mixing equipment.

As early as 1917 a patent was issued for "Soilamies" which was a mixture of soil and portland cement. In 1920 another patent was issued for "Soilcrete" for highway use. During the 1920's several state Highway departments, including Iowa, South Dakota, Ohio, California and Texas, experimented with mixtures of soil and cement for paving. However, because of lack of knowledge of the application of soil science to road building the experiments produced unpredictable results.

In 1932 the South Carolina State Highway Department began investigations of mixtures of soil and cement under the leadership of the late Dr. C.H. Moorefield, then Chief Highway Commissioner. Several test sections were built in 1933 and 1934. The performance of these test sections showed that soil and cement were compatible materials and that they could be mixed together to form a low-cost base material for roads. These early South Carolina experiments are described in two articles by Mills (1, 2).

The excellent work of the South Carolina State Highway Department stimulated more studies by them and an extensive research program by the Portland Cement Association initiated in January 1935 under the direction of F.T. Sheets, Consulting Engineer, and M.D. Catton, Development Department. An important key to soil-compaction technology and later to the development of soil-cement came with the discovery in 1929 of the moisture-density relationship in soil compaction. As a result of these studies, dependable and predictable test methods were developed which can be used to determine the quantities of soil, cement and water to use. These tests—the moisture-density, wet-dry and freeze-thaw—have since been adopted as standards by the American Society for Testing Materials and by the American Association of State Highway Officials.

To confirm results of the laboratory research, the South Carolina State Highway Department, Bureau of Public Roads, and the Portland Cement Association cooperated in construction of a 1½-mi section of pavement near Johnsonville in the fall of 1935. This project became known as the first "engineered" soil-cement road.

The success of the Johnsonville, South Carolina, test road led to additional experimental sections in 1936 in South Carolina and in Illinois, Michigan, Missouri and Wisconsin. The Portland Cement Association's laboratory experiments and construction reports on the 1935 and 1936 road work are reported in the HRB Proceedings, Vol. 17, Pt. II, and in HRB Proceedings, Vol. 18 (5). In 1937 eight more states built their first soil-cement projects. Simple, routine construction procedures were quickly learned and improvements were made as more projects were built (3, 4, 6). By 1940 over 7½ million square yards of soil-cement had been built in the United States, mostly on roads and streets. The use of soil-cement for airports received impetus during World War II. During this period, when speed was important, many notable airport construction records were set with soil-cement often under adverse conditions. During the war period, 1941-1944, 22 million square yards of soil-cement airports were built, whereas relatively few roads were built. As the long-delayed highway building program got under way after World War II, the use of soil-cement for roads and streets increased rapidly. Its use also spread to other uses such as subbases for portland cement concrete pavements, shoulders, widening, parking and storage area, and conservation uses such as linings for reservoirs, ditches and canals (7). By 1960 the annual use of soil-cement in the United States and Canada reached 46 million square yards with a total constructed yardage to that date of almost 294 million square yards.

In addition to the widespread use in the United States, soil-cement has been used extensively in England, South Africa, the Middle East, South America and Germany (8).

The rapidly expanding applications of mixtures of soil and cement have resulted in the use of several different terminologies such as soil-cement, cement-treated base, cement-modified soil and plastic soil-cement. To avoid confusion, the Highway Research Board's Committee on Soil-Portland Cement Stabilization has prepared definitions for the various uses and types of mixtures of soil and cement (9). These terminologies, which are used in this bulletin, are defined in the "Introduction."

This bulletin summarizes the available information on mixtures of soil and cement. Included are data on its properties, factors influencing these properties, soil sampling procedures, laboratory test methods, structural design practices, construction and field control procedures, and field performance records.

The rough draft which served as the starting manuscript for this committee report was prepared by A.W. Johnson, Engineer of Soils and Foundations, Highway Research Board, who used it in preparing a more condensed contribution for McGraw-Hill Book Company's "Highway Engineering Handbook," Kenneth B. Woods, Editor-in-Chief.

Sincere appreciation is expressed to all concerned for permission to use the original manuscript, which was brought up-to-date and edited by a subcommittee comprised of Donald T. Davidson and E.G. Robbins.

During 1960, the Committee circulated a questionnaire concerning the use of soil-portland cement stabilization. The replies to that questionnaire are given in the Appendix, entitled "Report on Soil-Portland Cement Stabilization Practices."

Donald T. Davidson, Chairman
Committee on Soil-Portland
Cement Stabilization

Contents

Introduction

Cement stabilization consists of a mixture of pulverized soil and measured amounts of portland cement and water, compacted to a high density and protected against moisture loss during a specified curing period.

The following definitions of materials, types of cement-treated soil and uses, prepared by the Highway Research Board's Committee on Soil-Portland Cement Stabilization, are adhered to in this bulletin (9).

DEFINITION OF TERMS RELATING TO SOIL-PORTLAND CEMENT STABILIZATION

Uses of Soil-Cement

Soil plus cement, by definition, gives a cement-treated soil. The uses of soil-cement are as follows:

Soil-Cement	Plastic Soil-Cement	Cement-Modified Soil
Base	Canal linings	Base
Subbase	Ditch linings	Subbase
Subgrade	Slope facings	Subgrade

Materials

Soil.—Stone, gravel, sand, silt, clay, or any combination thereof as defined by AASHO M145 and M146.

Note: Particle size, rather than origin of material, is the basis of the foregoing definition. Cinders, crushed stone, slag, chert, caliche, etc., are thus considered within the definition of soil.

Portland Cement.—The product obtained by pulverizing clinker consisting essentially of hydraulic calcium silicates to which no additions have been made subsequent to calcination other than water and/or untreated calcium sulfate except grinding aids and sometimes air-entraining agents and/or granulated blast-furnace slag.

Cement-Treated Soil.—An intimate mixture of pulverized soil, portland cement and water.

Note: Definition implies no quality specification and only states that portland cement and water have been added to the soil.

Soil-Cement.—A hardened material formed by curing a mechanically compacted intimate mixture of pulverized soil, portland cement and water.

Note 1: Durability and/or compressive strength are the common criteria for hardness. The standard for hardness varies.

Note 2: The term soil-cement is sometimes incorrectly used in a broad sense to include all types of cement-treated soil. (Material specified in California and some western states as Cement-Treated Base, Class A (and also most Class B and Class D mixtures) satisfies criteria for soil-cement.)

Cement-Modified Soil.—An unhardened or semihardened intimate mixture of pulverized soil, portland cement and water.

Note: Cement-modified soil contains less cement than that required to produce soil-cement. (This type includes some Class C "Cement-Treated Base" specified in some western states.) Compaction and curing are incidental to the chemical and physical process of modifying a soil with portland cement. Degree of modification is judged usually by changes in the physical test constants and/or bearing capacity of the soil, although other criteria, such as changes in permeability, are used.

Plastic Soil-Cement.—A hardened material formed by curing an intimate mixture of pulverized soil, portland cement and enough water to produce a mortarlike consistency at the time of mixing and placing.

Note: Plastic soil-cement differs from portland cement concrete in two respects—soils seldom meet specifications for concrete aggregates and the cement content for plastic soil-cement is lower. Criteria for hardness are the same as for soil-cement.

Uses of Materials

Base.—The layer used in a pavement system to reinforce and protect the subgrade or subbase (AASHO M146).

Subbase.—The layer used in the pavement system between the subgrade and the base course (AASHO M146).

Subgrade (Basement Soil).—The prepared and compacted soil below the pavement system (AASHO M146).

Cement-Treated Base.—An intimate mixture of pulverized soil, portland cement and water, used as a layer in a pavement system to reinforce and protect the subgrade or subbase.

Soil-Cement Base.—A hardened material formed by curing a mechanically compacted intimate mixture of pulverized soil, portland cement and water, used as a layer in a pavement system to reinforce and protect the subgrade or subbase.

Cement-Modified (Soil) Base.—An unhardened or semihardened intimate mixture of pulverized soil, portland cement and water, used as a layer in a pavement system to reinforce and protect the subgrade or subbase.

Cement-Treated Subbase.—An intimate mixture of pulverized soil, portland cement and water, used as a layer in a pavement system between the subgrade and the base course.

Soil-Cement Subbase.—A hardened material formed by curing a mechanically compacted intimate mixture of pulverized soil, portland cement and water, used as a layer in a pavement system between the subgrade and the base course.

Cement-Modified (Soil) Subbase.—An unhardened or semihardened intimate mixture of pulverized soil, portland cement and water, used as a layer in a pavement system between the subgrade and the base course.

Cement-Treated Subgrade.—The prepared and mechanically compacted soil, below the pavement system, that has been intimately mixed with portland cement and water.

Soil-Cement Subgrade.—A hardened material formed by curing a prepared and mechanically compacted soil, below the pavement system, that has been intimately mixed with portland cement and water.

Cement-Modified (Soil) Subgrade.—A prepared and mechanically compacted unhardened or semihardened intimate mixture of portland cement, water, and soil below the pavement system.

HOW CEMENT STABILIZES SOILS

Mechanisms

Reduction of Plasticity.—The first noticeable property change that occurs when cement is mixed with moist cohesive soils is a marked reduction in plasticity, probably caused by calcium ions released during the initial cement hydration reactions. The mechanism is either a cation exchange or a crowding of additional cations onto the clay, both processes acting to change the electrical charge density around the clay particles. Clay particles then become electrically attracted to one another, causing flocculation or aggregation. The aggregated clay behaves like a silt, which has a low plasticity or cohesion. Aggregation takes place rather quickly, and is caused by the addition of relatively small amounts of cement.

Cementation.—In compacted cement-treated soil the hydration of the different cement constituents occurs at different rates, providing cementitious amorphous and minutely crystalline hydration products responsible for the characteristic early and long-term strength gains. The cementation is mainly chemical in nature and may be visualized as due to the development of chemical bonds or linkages between adjacent cement grain surfaces, and between cement grain surfaces and exposed soil particle surfaces.

With cohesive soils, an important part of the mechanism may be the hardening of clay aggregations by lime liberated as a result of the hydration of the cement. This would explain both the hardened condition of aggregations observed where lumps of stabilized soil are removed from a road base some time after construction and the magnitude of the increase in strength after the hardening of the cement bonds would have been expected to be complete (215).

Fine-Grained Soils

The manner in which portland cement stabilizes soils to meet requirements for soil-cement differs somewhat for the two principal types of soils. In the fine-grain silty and clayey soils, the cement, on hydration, develops strong linkages among and between the mineral aggregates and the soil aggregates to form a matrix that effectively encases the soil aggregates. The matrix forms a honeycomb type of structure on which the strength of the mixture depends, because the clay aggregations within the matrix have little strength and contribute little to the strength of the soil-cement. The matrix is effective in fixing the particles so they can no longer slide over each other. Thus the cement not only destroys the plasticity but also provides increased shear strength. The surface chemical effect of the cement reduces the water affinity and thus the water-holding capacity of clayey soils. The combination of reduced water affinity and water-holding capacity and a strong matrix provide an encasement of the larger unpulverized raw soil aggregates. Because of its strength and reduced water affinity, this encasement serves not only to protect the aggregates but also to prevent them from swelling and softening from absorption of moisture and from suffering detrimental freeze-thaw effects.

Granualar Soils

In the more granular soils the cementing action approaches that in concrete, except that the cement paste does not fill the voids in the aggregate. In sands, the aggregates become cemented only at points of contact. The more densely graded the soil, the smaller the voids, the more numerous and greater the contact areas, and the stronger the cementing action. Uniformly graded (one-size) sand, which has a minimum of contact area between grains, requires a fairly high cement content for stabilization. Because well-graded granular soils generally also have a low swell potential and low frost susceptibility, it is possible to stabilize them with lesser cement contents than are needed for the uniformly graded sands, the more frost-susceptible silts, and the higher swelling and frost-susceptible clayey soils. For any type of soil, the cementing process is given the maximum opportunity to develop when the mixture is highly compacted at a moisture content that facilitates both the densification of the mix and the hydration of the cement.

Degree of Stabilization

Four major variables control the degree of stabilization of soils with cement: (1) the nature of the soil, (2) the proportion of cement in the mix, (3) the moisture content at the time of compaction, and (4) the degree of densification attained in compaction. If the moisture content and the density are controlled in accordance with standard methods (AASHO T 134 and ASTM D 558) and normal mixing and curing procedures are observed, the nature of the soil and the proportion of cement used determine the degree of stabilization. It is possible, simply by varying the cement content, to produce mixes that, after hydration of the cement, may range from those that result in only a slight modification of the compacted soil (cement-modified soil) to the product known as soil-cement, which must meet certain minimum strength and durability requirements. When moisture is increased sufficiently to produce a plastic mix, and the cement content adjusted to meet strength and durability requirements for the plastic condition, the product becomes plastic soil-cement. The ability to control the properties of the mix to suit the construction and to control the degree of stabilization to satisfy the strength and durability requirements has resulted in the development of these three principal types of cement-treated soil (soil-cement, cement-modified soil and plastic soil-cement).

Properties of Cement-Treated Soil

FACTORS INFLUENCING PROPERTIES

The properties of cement-treated soil vary with several factors: (a) the nature of and the amounts of soil, cement, and water per unit volume of the compacted mixture; (b) the conditions prevailing during the period of cement hydration; and (c) the age of the compacted mixture.

Because of the possible variation in properties due to these factors, it is not possible to list specific values representative of the several properties. However, because moisture content, density and conditions of curing are closely controlled in accordance with standard methods, it is possible to present laboratory values of the several properties for different soils. These are presented as examples indicating the range of properties of cement-treated soil. A later section presents additional data illustrating the influence of this principle and other minor factors on the properties of a wide range of cement-treated soil mixtures, including those that may be designated as cement-modified soil.

ILLUSTRATIVE EXAMPLES OF PROPERTIES

Compressive Strength

Unconfined compressive strength is the most widely discussed property of cement-treated soil. It indicates the degree of reaction of the soil-cement-water mixture, "setting" time and the rate of hardening. For normally reacting granular soils, compressive strength serves as a criterion for determining minimum cement requirements for construction of soil-cement.

Normal ranges of 7- and 28-day unconfined wet compressive strengths for soil-cement are given in Table 1. (Because of the high cohesive strength of dry, compacted clayey soil, compressive strength test data are not reliable unless tests are made on specimens properly saturated before testing. See "Wet-Dry Strength Ratio.") These data are grouped under three broad textural soil groups and include the range of soil types normally used in soil-cement construction. The ranges of compressive strength

TABLE 1

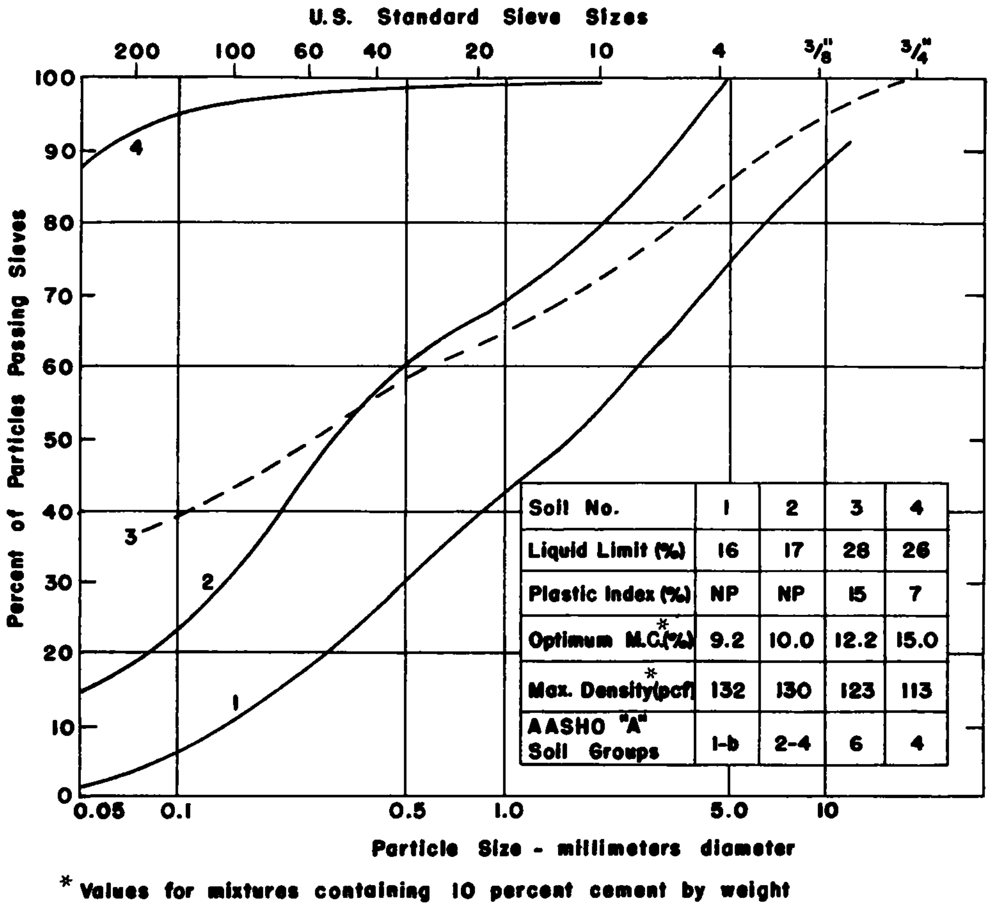
RANGES OF UNCONFINED COMPRESSIVE STRENGTHS OF SOIL-CEMENT

Soil Type	Wet Compressive Strength[a] (psi) 7-Day	28-Day
Sandy and gravelly soils:		
AASHO groups A-1, A-2, A-3		
Unified groups GW, GC, GP, GF,		
SW, SC, SP, SF	300 - 600	400 - 1,000
Silty soils:		
AASHO groups A-4 and A-5		
Unified groups ML and CL	250 - 500	300 - 900
Clayey soils:		
AASHO groups A-6 and A-7		
Unified groups MH and CH	200 - 400	250 - 600

[a]Specimens moist cured 7 or 28 days, then saturated in water prior to strength testing.

are those for the minimum cement contents that satisfy accepted criteria (10) as determined by wet-dry and freeze-thaw tests (11, 12) for soil-cement. The ranges of values given may be expected to be representative for 90 percent of soils normally used in the United States in soil-cement construction.

Illustrative examples permit a better appreciation of the ranges of the compressive



Soil No.	1	2	3	4
Liquid Limit (%)	16	17	28	26
Plastic Index (%)	NP	NP	15	7
Optimum M.C.* (%)	9.2	10.0	12.2	15.0
Max. Density* (pcf)	132	130	123	113
AASHO "A" Soil Groups	1-b	2-4	6	4

Figure 1. Gradation and plasticity of raw soils and moisture-density relations of cement-treated soil mixtures (14).

strengths as they are influenced by cement content and age for different types of soils. Four soils representative of the following types were used in the tests to obtain illustrative values of compressive strength: (1) a well-graded C-horizon nonplastic pit-run gravel with low content of fines (3 percent passing No. 200 sieve), (2) a C-horizon nonplastic sandy loam with 19 percent passing the No. 200 sieve, (3) a B- and C-horizon plastic clayey sand with 37 percent passing the No. 200 sieve, and (4) a B- and C-horizon silt loam.

The index property values and the graphs of grain size distribution are shown in Figure 1. All tests were in conformity with standard methods. Type 1 (normal) portland cement was used. Cement contents bracketed minimum values required to satisfy wet-dry and freeze-thaw criteria for soil-cement for three of the soils. The minimum values for soil-cement are given in Table 2.

The results of unconfined wet compressive strength determinations made on 2.8-in.

diameter by 5.6-in. high cylindrical specimens at various cement contents and ages are illustrated in Figure 2.

Flexural Strength (Modulus of Rupture)

Beams 3 x 3 x 11½ in. were molded at optimum moisture content and standard maximum density (11, 12) using the four soils whose index properties and grain size distributions are indicated in Figure 1. The ranges of flexural strengths obtained for each

TABLE 2

MINIMUM CEMENT CONTENTS REQUIRED TO SATISFY CRITERIA FOR SOIL-CEMENT (14)

Soil No.	Minimum Cement Content Required for Soil-Cement % by Volume	% by Weight
1	5	3.8
2	5	3.8
3	7	5.7
4	9	8.1

of the four soils when combined with various amounts of cement and tested at different ages are shown in Figure 3.

Modulus of Elasticity

Static Modulus in Compression (E_{sc}).—Figure 4 shows ranges of static moduli, computed by the Portland Cement Association (14) as secant moduli at approximately 33 percent of ultimate compressive strength of 2.8-in. diameter by 5.6-in. high cylindrical specimens. The moduli presented in Figure 4 are for the sandy soil (No. 2) and the silty soil (No. 4). Similar data computed by Reinhold (15) from strain measurements made on 2.8-in. diameter by 9.1-in. high cylindrical specimens of cement-treated sandy and clayey soils are also shown in Figure 4 for comparative purposes.

In more recent work on the shear strength and elastic properties of cement-treated soil mixtures under triaxial loadings, the Portland Cement Association (16) computed E_{sc} as a secant modulus at between 10 and 40 percent of the ultimate undrained triaxial compressive strength of 2.8-in. diameter by 5.6-in. high specimens made of cement-treated sandy and silty soils. Cement contents used with these soils ranged from 0 to 16 percent and covered the cement content required for soil-cement. The specimens at standard AASHO-ASTM density were moist-cured 7, 28, and 90 days except for a few specimens that were given special curing. The static modulus of elasticity increased with cement content; average values at 28 days varied from about 100,000 to 2,000,000 psi for the cement-treated sandy soil mixtures and from about 260,000 to 760,000 psi for the cement-treated silty soil mixtures. The modulus also increased with age. In some cases the 90-day values were double the 7-day values, but the increase averaged about 50 percent of the 7-day values. Drying cement-treated soil specimens decreased the modulus of elasticity; the decrease was slight for the sandy soil mixtures but was as much as 60 percent for the silty soil mixtures.

The ultimate elastic moduli in compression of cement-stabilized sand-shell mixtures were found by Harris (17) to be lower than values for soils. Harris used a cement content of 2.8 bags per cubic yard (approximately 10 percent by volume) and compacted some of the mix by rolling and some by vibrating in a wet state. The mix compacted by rolling had an ultimate compressive strength of 1,290 psi and a modulus (E_{sc}) of 168,000 psi.

Status Modulus in Flexure (E_{sf}).—Values of E_{sf} are shown in Figure 5. They are secant moduli at 33 percent of the ultimate load. For the cement contents tested and the ages shown, the sandy soils Nos. 1 and 2 showed values of E_{sf} ranging from

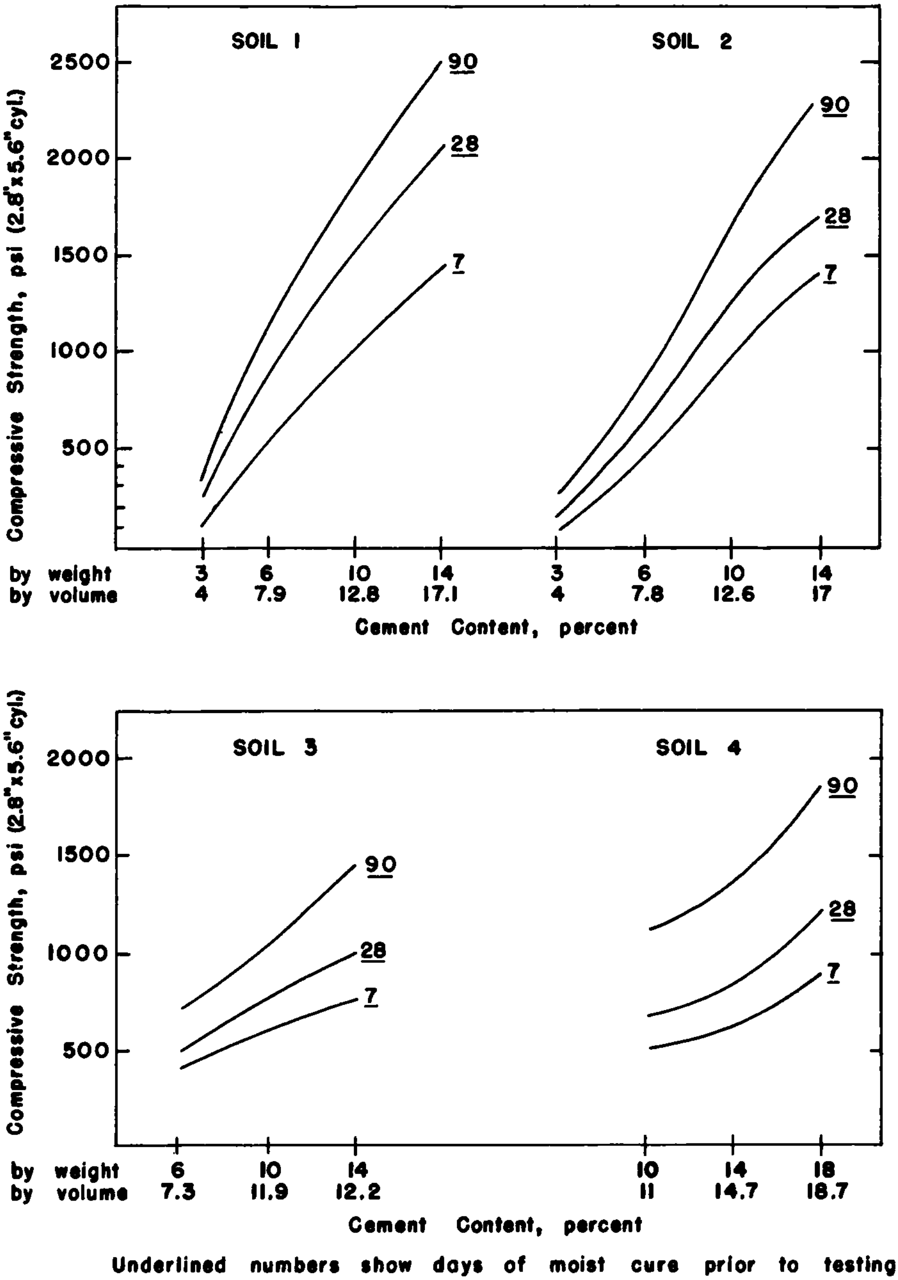


Figure 2. Compressive strength, soil type, cement content and age (14).

800,000 to 4,300,000 psi, and values for the clayey and silty soils Nos. 3 and 4 ranged from 700,000 to 2,500,000 psi.

Resonance (Dynamic) Modulus (E_d).—Values of the dynamic modulus of elasticity, computed from the fundamental transverse frequency, weight and dimensions of the beams prior to testing them in flexure, were approximately equal to those shown for the static modulus in flexure (E_{sf}) (Fig. 5). Contrary to this, researches on road materials by the British Road Research Laboratory generally have indicated an appreciable difference in values determined statically and dynamically (215).

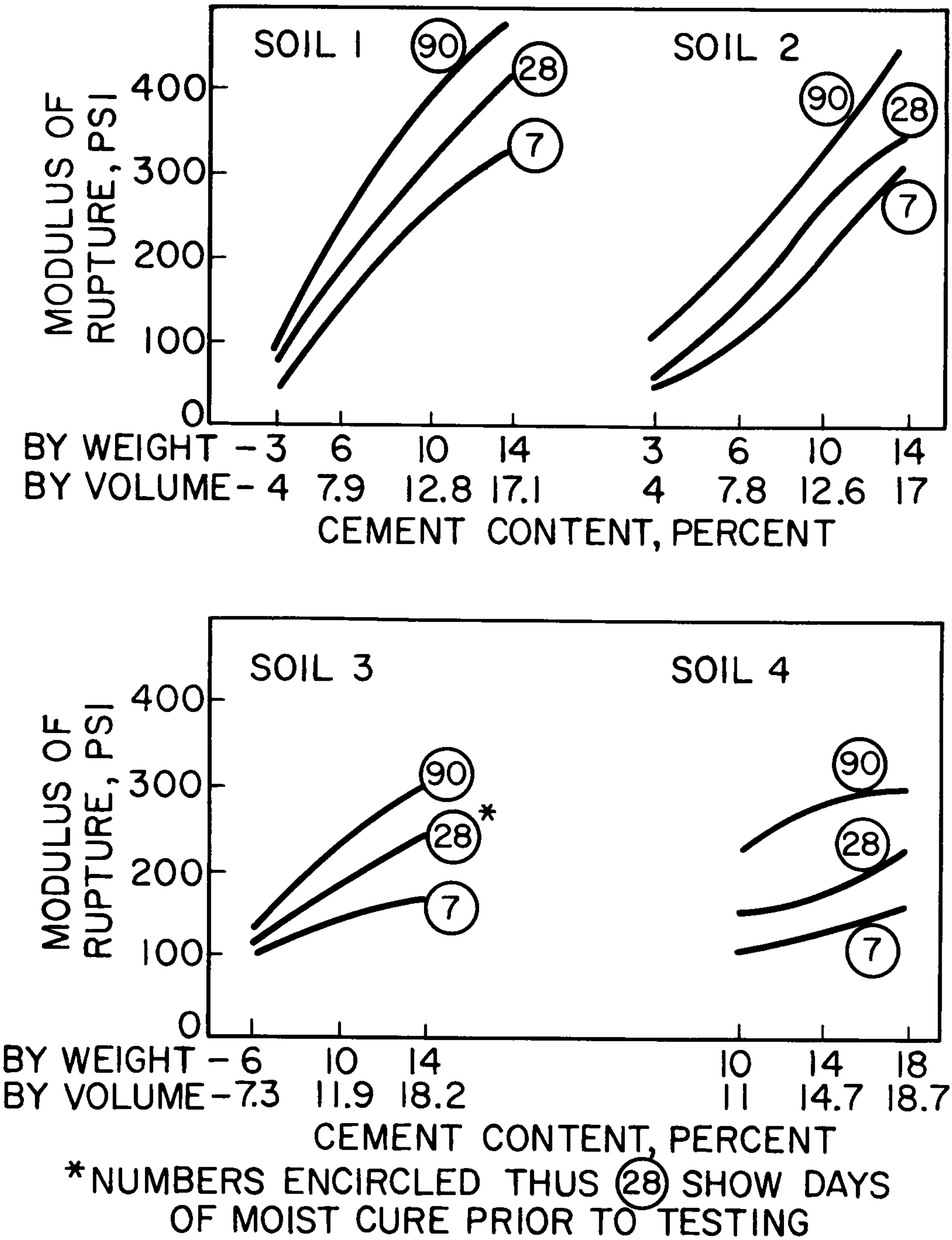


Figure 3. Modulus of rupture, soil type, cement content and age (14).

Poisson's Ratio

Computed values of dynamic Poisson's ratio, determined (14) from fundamental transverse and torsional frequencies of beams, range from 0.22 to 0.27 for granular soils Nos. 1 and 2 (Fig. 1); from 0.30 to 0.36 for clayey soil No. 3; and from 0.24

to 0.31 for silty soil No. 4. Values of static Poisson's ratio determined from compression strains were variable, ranging from 0.08 to 0.24. Indications were that variation was related to the nature of the rupture.

As a part of the Portland Cement Association's study of the shear strength and elastic properties of cement-treated sandy and silty soil mixtures under triaxial loading (16), Poisson's ratio was computed as the ratio of lateral strain to axial strain in the

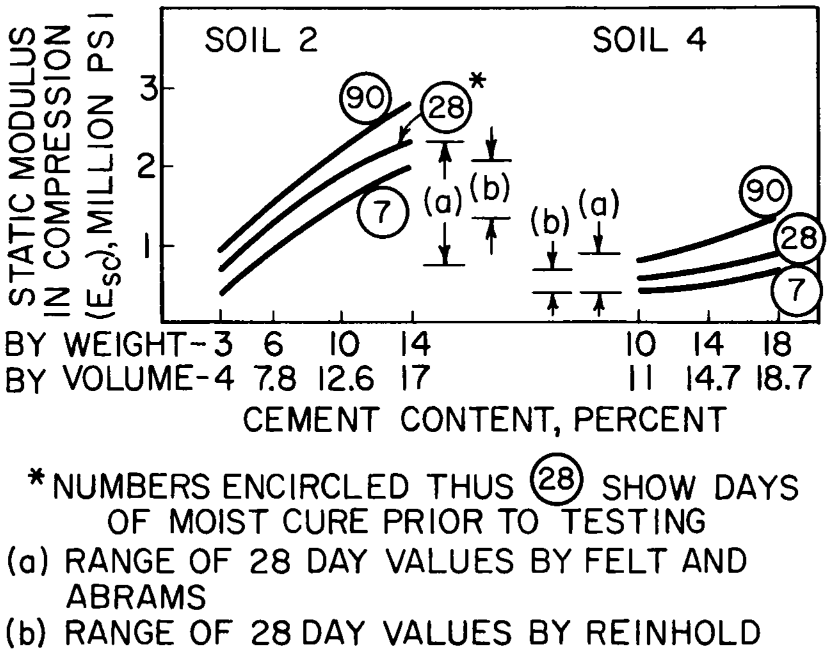


Figure 4. Static modulus of elasticity in compression, soil type, cement content and age.

elastic range (between 10 and 40 percent of ultimate strength). Poisson's ratio exhibited a random variation with cement content and age, and averaged 0.14 for the cement-treated sandy soil mixtures and 0.12 for the cement-treated silty soil mixtures.

Plate Bearing Value

Table 3 gives comparative plate bearing test data obtained on a heavy clay subgrade (19) and on four-week-old soil-cement base constructed from a heavy clay (LL = 57). Plate bearing data are for a 12-in. diameter plate seated with sand. K-values for each test were computed, loading through the range of 0- to 0.05-in. deflection. Seven-day compressive strengths of soil-cement cylinders molded from the field mix ranged from 125 to 310 psi. Seven-day strengths of laboratory mixes were as high as 550 psi. Data in Table 3 give results for the west and east ends of the experimental project. The surfacing on the west end was a single bituminous treatment, that on the east end a 2-in. thick bituminous surface. The results show that the K-values for the stabilized base-subgrade structure are about eight times that of the subgrade.

Another example illustrating plate bearing test data, obtained by loading experimental 4- x 4-ft test slabs of soil-cement on a subgrade of known K-value, is shown in Figure 6.

Additional plate bearing tests were made at Skokie, Ill., by the Portland Cement Association (21) on 4- x 4-ft outdoor test panels 4, 7 and 10 in. thick. Two substandard granular materials treated with a range of cement contents to produce both cement-modified soil and soil-cement were used in the panels. They were loaded with a 12-in.

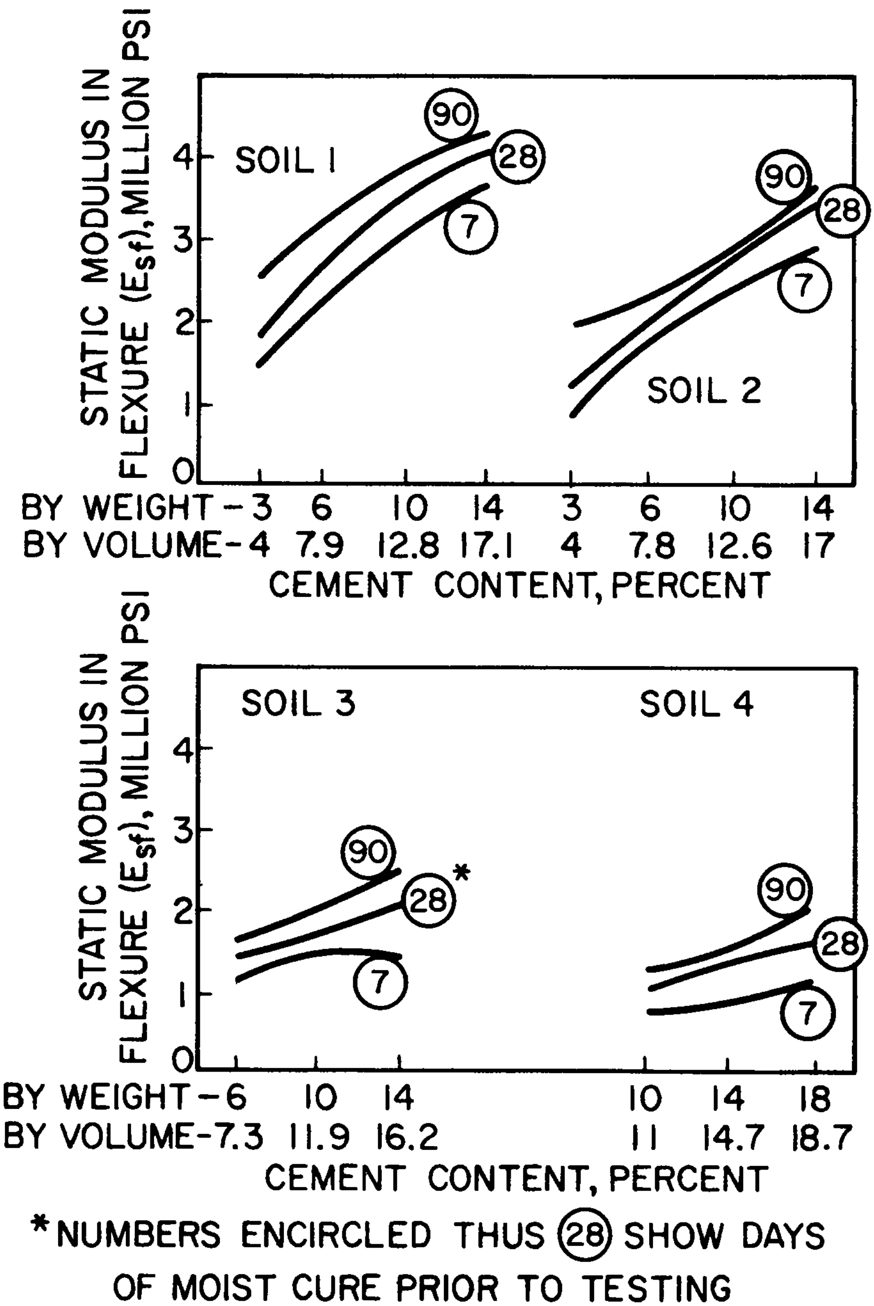


Figure 5. Static modulus of elasticity in flexure, soil type, cement content and age (14).

diameter plate over a five-year period. The results showed that an increase in cement content is accompanied by an increase in load-carrying capacity. There was little or no effect due to frost action in load-carrying capacities of the hardened soil-cement mixtures over the 5-yr period. In contrast, the load-carrying capacities of the cement-modified materials containing lower cement contents, which were reasonably high after exposure for one winter, were reduced during the 5-yr period but the capacities of these

TABLE 3

PLATE BEARING TEST DATA ON A SOIL-CEMENT ROAD (19)

Location	Subgrade Soil CBR (%)	Subgrade Soil Dry Density (pcf)	Subgrade Soil Moisture Content (%)	Soil-Cement Base K (psi)	Soil-Cement Base K (psi)
West	1	92	39	-	1,270
end	2	84	34	130	1,110
of	2	78	40	-	1,050
the	2 to 3	85	38	180	1,040
project	2	89	35	-	1,150
East	3 to 1	95	29	-	1,110
end	2 to 3	93	30	150	1,160
of	2	87	34	-	1,290
the	2 to 3	81	34	-	1,500
project	2 to 3	90	31	-	1,250
Average	2	87	34	150	1,190

materials to support load remained significantly greater than that of the untreated soils of the same thickness.

California Bearing Ratio (CBR)

The CBR has been used to a limited extent (22) as a means for measuring increase in strength resulting from the addition of cement to marginal and substandard gravels that, because of inferior grading, excessive fines or plastic fines, are not suitable for use in flexible-type base courses. The method of test used (22) was similar to that for the CBR except that a compactive effort equivalent to that of AASHO Method T 134 was used (56 blows per layer in a 6-in. diameter mold). The compacted mixture was allowed to hydrate for 7 days in the mold and then was immersed in water for 4 days before testing. Some gravel-cement mixtures became so hard that piston penetration was limited to 0.05 to 0.075 in. In tests to determine the effect of low cement contents in modifying fine-grain soils, a full 0.1-in. penetration was used.

An illustration of the relationship between CBR and cement content at various curing ages for a plastic gravel is shown in Figure 7. In comparing CBR-cement content relationships it should be noted that the maximum cement content shown (6 percent by weight) represents the minimum cement content that satisfies Portland Cement Association (PCA) criteria for soil-cement. Similar illustrative data

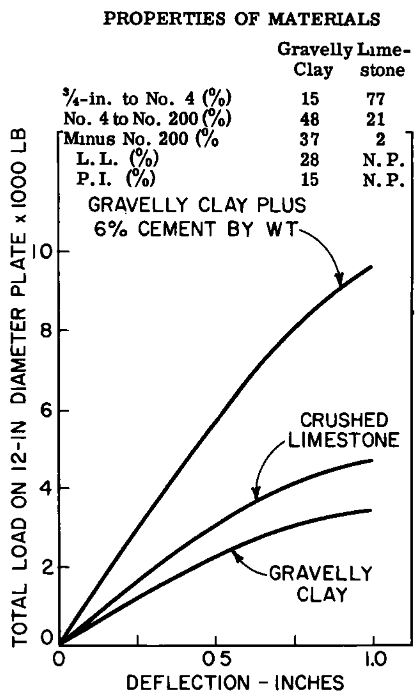


Figure 6. Plate bearing test data showing total load required to produce 0.1-in. deflection of 12-in. diameter plate on 4-ft panels 7 in. thick, built in fall of 1953 and tested in spring of 1954. K of subgrade = 100 psi/in. (20).

of CBR versus cement content used in modifying a silty clay soil are shown in Figure 8. Cement contents used in mixtures with the silty clay soil (Fig. 8) were all less than that required to produce soil-cement.

As part of the study of substandard granular materials treated with cement (21), bearing ratio tests were made. Data for specimens tested after moist curing periods of 7, 21, 37 and 87 days showed great increases in bearing ratios with increases in cement content and curing period reaching values as high as 1,200 for an A-1-b (0) substandard granular material with 6 percent cement and 600 for an A-6 (1) granular material with 10 percent cement. Bearing ratios were also determined on specimens that had been subjected to cycles of freezing and thawing. The bearing ratios of the 1.5 percent cement-treated mixtures of the A-1-b (0) substandard granular material reduced to low values in 12 cycles of freezing and thawing; the 3 percent mixture decreased somewhat after 12 cycles but did not decrease further at 48 cycles; and the bearing ratios for the 4.5 and 6 percent mixtures changed very little during the 48 cycles. The bearing ratios of the A-6 (1) cement-treated granular soil at 1.5, 3.0 and 4.5 percent cement dropped sharply during freeze-thaw cycles. The 6 percent cement-treated material showed great resistance to freezing and thawing and at the end of 12 cycles the

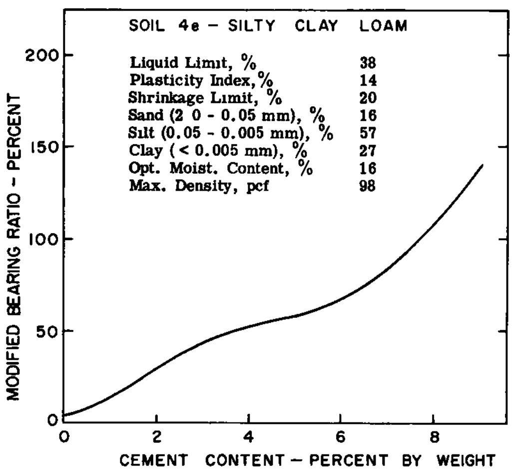


Figure 8. Relation between bearing ratio and cement content after 7 days hydration for a fine-grain silty clay soil (22). (Minimum cement content for soil-cement—15 percent.)

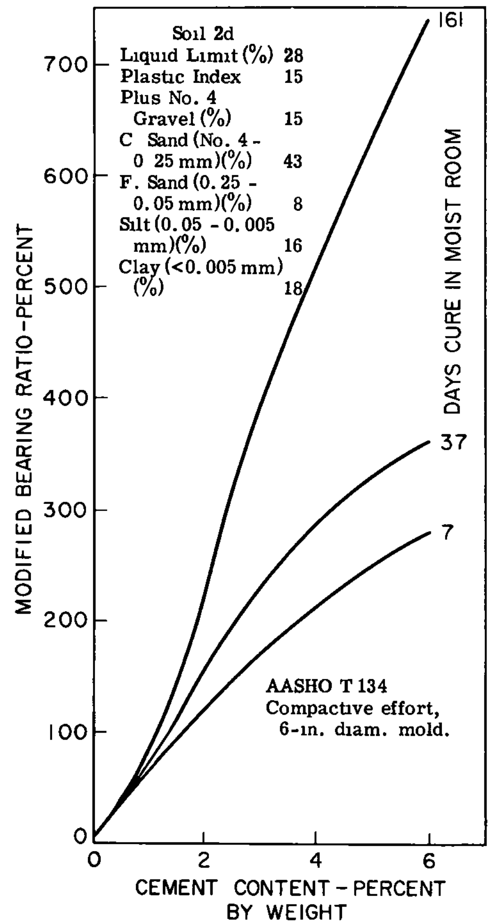


Figure 7. Bearing ratios of cement-treated soil mixtures at various ages. (Minimum cement content for soil-cement is 6 percent.) (22)

bearing ratio was still 200. The 10 percent cement-treated mixture showed a bearing ratio after 48 freeze-thaw cycles equal to or greater than the 21-day moist-cure values.

Other investigators (23, 24) have developed both CBR and compressive strength data for clayey and for gravelly soils. These data are shown under "Interrelationships Between Properties of Soil-Cement Mixtures."

The CBR test has been used for some time by many countries in Africa for evaluating soil-cement mixtures. A considerable experience is being developed in these countries in the use of the test for this purpose.

Plasticity Index (25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35)

Plasticity, a soil condition which permits deformation without rupture, is a contribution of the clay mineral colloids that exist in the fine grain fractions of practically all soils. Because the plasticity index has for years been used as an indicator of base-course quality, the influence of cement on the plastic properties is significant. On this basis it is also an indicator of cement-treated soil base-course quality, particularly for the range of cement contents below the minimum required for soil-cement; that is, for cement-modified soil in the range of cement contents below the minimum required for soil-cement (215).

The addition of cement to soil exhibiting plasticity reduces its plastic properties. This is evidenced in the manner it ruptures in simple compression, and by the increase in its elastic properties as determined by elasticity measurements. However, the decrease in plasticity usually is expressed in terms of its reduction in plasticity index, as determined on hardened cement-treated soil mixtures that have been pulverized and tested for liquid limit, plastic limit and plasticity index.

Normal procedure calls for compacting the cement-treated soil mixtures according to standard procedure (AASHO T 134 or ASTM D 558), allowing the compacted specimen to cure in an atmosphere of 100 percent relative humidity for a given period (usually 7 days), drying, repulverizing the mixture, and then performing the plasticity tests. A typical set of results for a plastic granular material is shown in Figure 9. Results for three fine-grain soils are shown in Figure 10.

Normally, cement changes the plasticity by increasing the plastic limit and thus reducing the range within which the material is plastic. Cement may also change the liquid limit, but to a lesser degree. Cement admixtures usually reduce the liquid limit of soils having a liquid limit greater than 40, and increase the liquid limit of soils having a liquid limit less than 40 (Fig. 11).

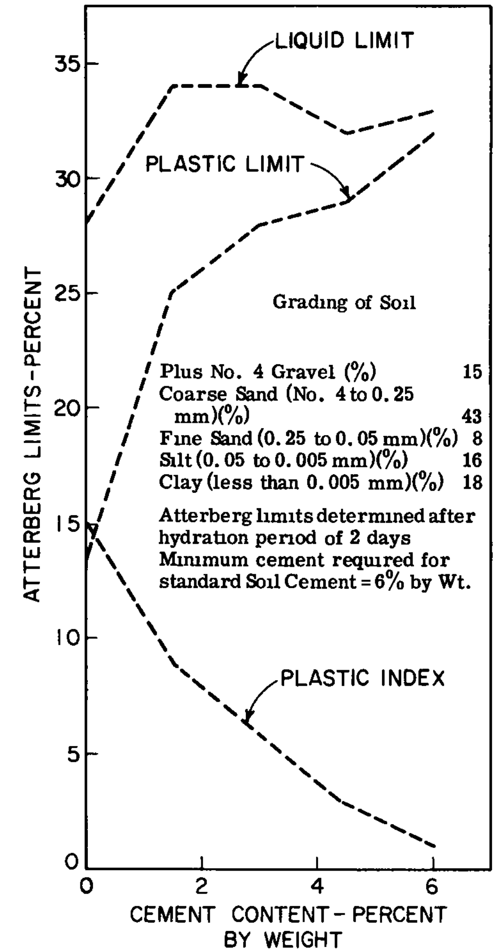


Figure 9. Cement-plasticity relationships for a plastic gravelly sand (22).

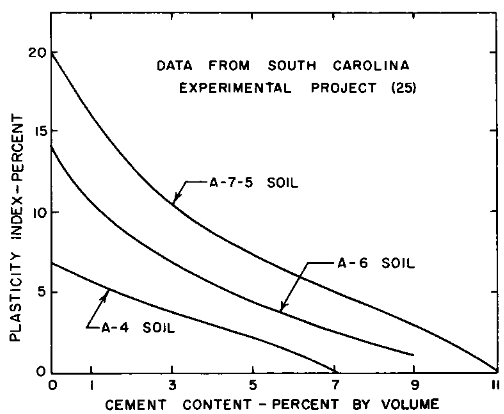


Figure 10. Effect of cement content on the plasticity indices of three South Carolina soils (25).

Volume-Change Properties of Cement-Treated Soil

Clay soils compacted at optimum moisture content to maximum density (AASHO Method T 99) usually swell on moisture gain and shrink on moisture loss. If compacted at moisture contents greater than optimum, the swell is less and the shrink is greater. If compacted to maximum density at moisture contents less than optimum, swell is greater and shrink is less. Admixing cement to soil affects both shrink and swell properties of clay soils. The manner in which cement affects the volume-change properties is complex and depends on the nature of the soil, the moisture changes, the cement content and the temperature conditions (including freezing). Limited data available on volume-change properties of cement-treated soil are considered here according to the different factors that cause volume changes:

1. Volume changes due to moisture changes (including hydration of the cement) and cementing action (increase in cohesion). These include both shrinkage and expansion.
2. Volume changes due to frost action.
3. Volume changes associated with temperature changes (coefficient of thermal expansion).

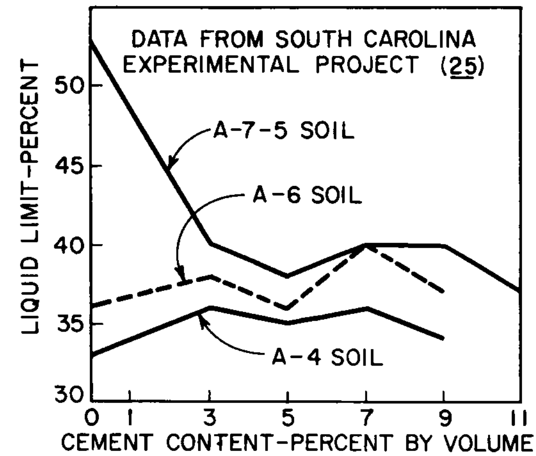


Figure 11. Effect of cement content on the liquid limits of three soils. (Data from cores taken 7 to 40 days after construction.) (25).

Volume Changes Due to Moisture Changes and Cementing Action.—Admixing cement to cohesive soils reduces shrinkage because the cement matrix tends to restrain the movement of the soil, but the admixed cement does not completely prevent shrinkage due to moisture loss. The exact proportion of the total shrinkage attributable to moisture loss (that is, water lost through hydration and water lost through evaporation) and to cementing action is not known. It is known that for a clayey sand, 1 to 1½ percentage points (about 10 percent of the total water added) is used during the first seven days in hydrating the cement (36) (Fig. 12). Admixing cement to noncohesive granular soils that in themselves exhibit little or no shrinkage results in small shrink, which is related to cohesion associated with the cementing action. Thus cement-treated mixtures made with sand exhibit some slight shrinkage and cracking.

Increasing the cement content decreases the total shrinkage (25, 35, 37, 38) of cement-treated mixtures made from soils that exhibit volume change without cement. However, the increase in tensile strength associated with the higher cement contents results in longer uncracked slabs and in wider crack openings. Decreasing the cement content and strength, while resulting in greater shrinkage, produces smaller, more closely spaced cracks.

The effect of increased cement content in producing longer uncracked slabs and thus larger crack openings holds for granular materials also (39) even though they exhibit little or no volume change without cement admixture. The significance of the effect of strength is not in the size of crack opening alone (such cracks are covered in applying the bituminous surfacing), but in the greater response of the longer slabs to expansion and contraction with changes in temperature, and the reflection of the resulting cracks through the bituminous surfacing.

Because cracking is a natural characteristic of cement-treated soil, experienced engineers carefully observe the development of cracks during the early curing period (30). When proper cracking develops, it is evident the mixture has been adequately moistened and compacted and is hardening properly. For soil-cement, each soil produces its own crack pattern. Clays develop higher total shrinkage but cracks are finer and more closely spaced—often of the hairline variety spaced 2 to 10 ft apart. Granular soils produce less shrinkage but larger cracks spaced at greater intervals, usually 10 to 20 ft or more apart. Because cracking is related to strength, some control over

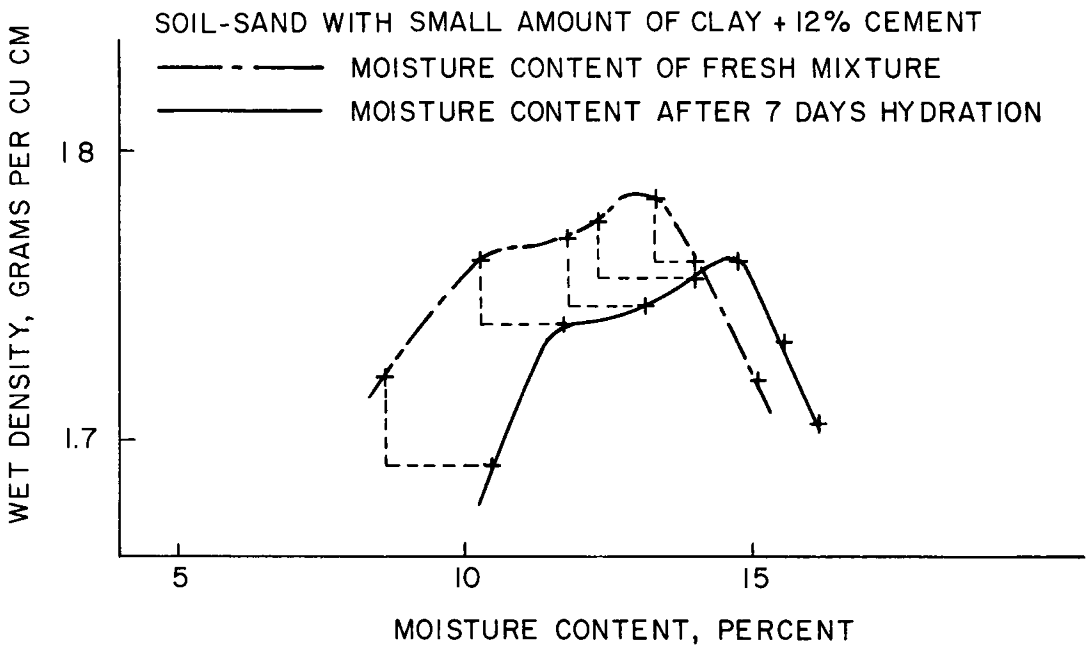


Figure 12. Moisture content lost through hydration of cement (36) (AASHO Standard Compaction Test).

size and spacing of cracks can be exercised by control of cement content; durability, however, must be kept in mind.

Measurements of size and distribution of shrinkage cracks are limited to data from three airfields in Australia (40). Soils were dominantly sandy and admixtures with 10 percent cement by weight produced soil-cement having a 7-day wet compressive strength of 450 psi and 1.8 percent loss in the wet-dry test. (Soils contained 10 to 25 percent clay (-0.002mm). Average LL = 20, PI ranged from NP to 7. Average optimum moisture content was 14 percent and maximum density (ASTM D 558) was 115 pcf.) The soil-cement was cured 7 days under Sisalkraft paper and crack measurements were observed 32 to 77 days after processing. Lineal shrinkages determined by measurement of cracks were 0.15, 0.3, and 0.4 percent for the three airfields. A relationship existed between density and cracking, the higher density resulting in less shrinkage. Measurements of the occurrence of various sizes of cracks showed that from 40 to 80 percent were less than $\frac{1}{48}$ in. in width of opening. The nature of the frequency distribution of the various sizes of crack openings observed at five test locations is shown in Figure 13.

Two methods have been used to determine the shrinkage properties of soil-cement. One of these is direct measure of the volumetric shrinkage, usually by immersion in mercury. Because shrinkage varies for different soils and for a given soil with cement content, illustrative data only are given for five soil types. Index properties of four of the soils, representative of types normally used in cement-treated soil mixtures, are given in Table 4.

Tests were made on specimens compacted by a predetermined effort (40 blows of 5.5-lb hammer dropping 15 in. on a 200-gr sample). Figure 14 shows the relationship between volumetric shrinkage and cement content for the four soils whose index properties are given in Table 4. Shrinkage decreases with increase in cement content. Shrinkage of the cement-treated soils ranges from one-third to one-half of that for the raw soils. The nature of changes in volume that take place during the wetting and drying test with the loam soil (No. 2, Table 4) is indicated in Figure 15.

The effect of mixing small quantities of cement with a heavy clay (35) to modify its

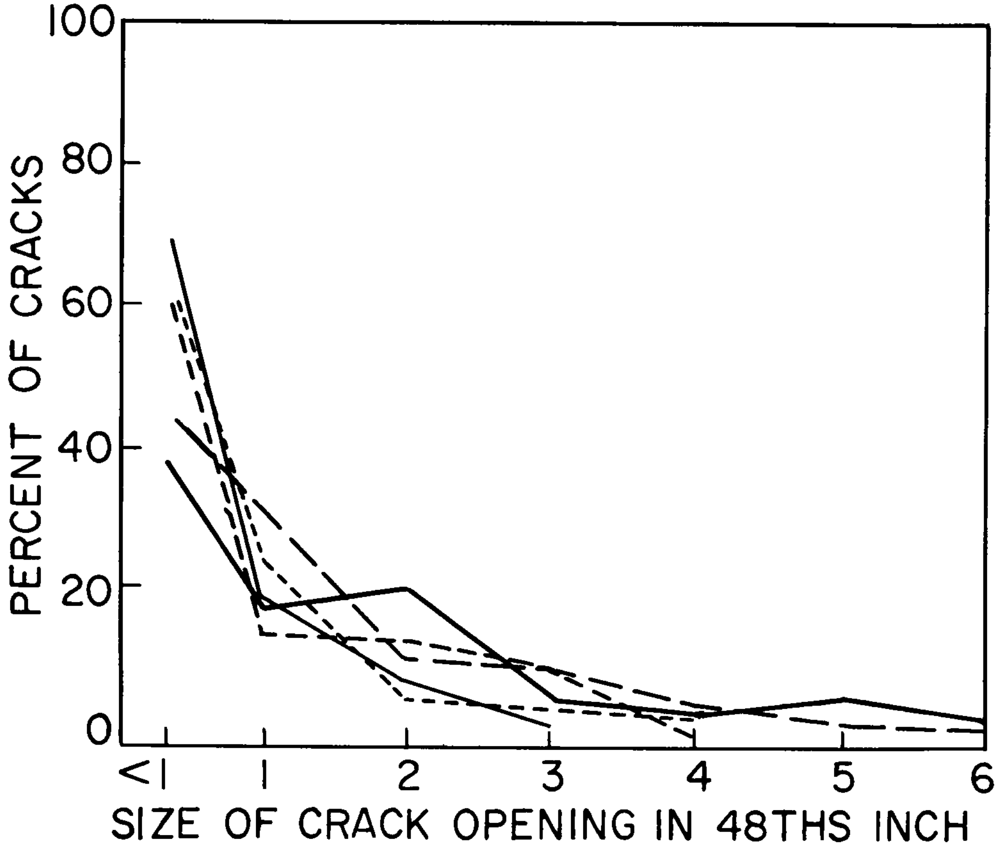


Figure 13. Frequency distribution of various sizes of shrinkage cracks in soil-cement (40).

TABLE 4

INDEX PROPERTIES OF SOILS USED IN SHRINKAGE MEASUREMENTS (37, 38)

Soil Type	Textural Type	LL	PI	Sand (%)	Optimum Moisture Content (%)	pH	Exchangeable Basis: Calcium (ME/100 gr)	Exchangeable Basis: Sodium and Potassium (ME/100 gr)
1	Sandy loam	22	5	65	13	8.7	4.2	0.9
2	Silty loam	28	9	19	12	8.4	7.0	1.6
3	Silty clay loam	37	17	8	12	8.9	14.8	1.1
4	Loam	25	10	43	12	8.1	8.7	1.1

volume-change characteristics is shown in Figure 16. Compaction was according to AASHO Method T 134 except for an 18-in. hammer drop.

During the great drought of the 1930's, clay subgrades that were compacted at low moisture contents later absorbed water and swelled, causing distortion of pavements. Cement treatments were used experimentally on some projects (27, 41) to prevent swelling of subgrade soil on gain in moisture content. Inasmuch as laboratories were equipped to perform plasticity and shrinkage tests, those tests were used to indicate the effectiveness of cement admixtures in reducing soil swell. Compacted cement-treated soil mixtures were moist cured for 7 days, repulverized, and then used to determine the relationships between volumes at the shrinkage limit (SL) and those at the field moisture equivalent (FME) and liquid limit (LL) for various cement contents. An example of the data is shown in Figure 17. Lineal shrinkage measurements were made on repulverized material remolded at the liquid limit. Illustrative data are shown in Figure 18.

The indicated decrease in shrinkage of

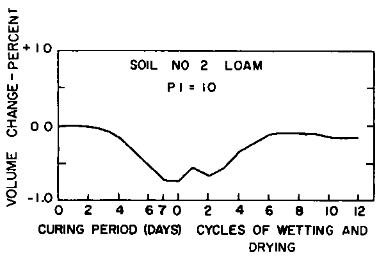


Figure 15. Changes in volume of cement-modified soil during curing and during cycles of wetting and drying (37).

the repulverized material is due to an increase in the shrinkage limit and a decrease in the liquid limit. The indirect method of determining the effect of cement on volume change does not apply to field work unless repulverization is done in construction. Even then values are only generally indicative of behavior, as the repulverized and reprocessed compacted cement-treated soil may again become hardened material. Therefore, measurements of volume change should be by direct measure of volumes and the changes should be expressed in terms of the initial compacted volume.

Treatment of soil with small percentages of cement, sometimes as low as 2 percent, may effectively prevent the occurrence of swelling (35). By PCA definition, soil-cement cannot swell more than 2 percent because one PCA criteria for soil-cement requires that the maximum volume at any time during the wet-dry

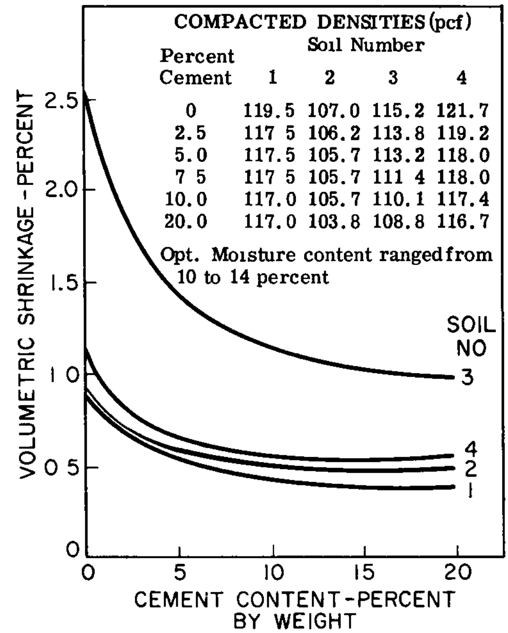


Figure 14. Effect of the addition of cement on the shrinkage of soils (37, 38).

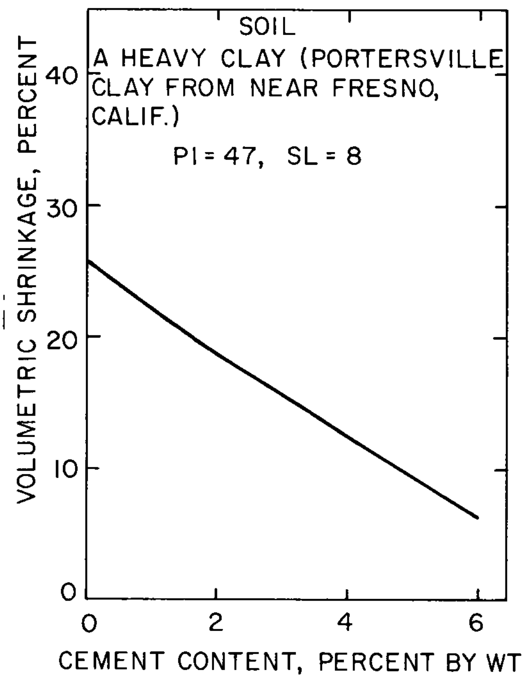


Figure 16. Effect of cement content in modifying the shrinkage properties of a heavy clay soil (35).

test shall not exceed the volume at the time of molding by more than 2 percent.

Volume Changes Due to Frost Action.—The manner and degree in which cement-treated soil expands on freezing depends on the degree of stabilization attained (cement

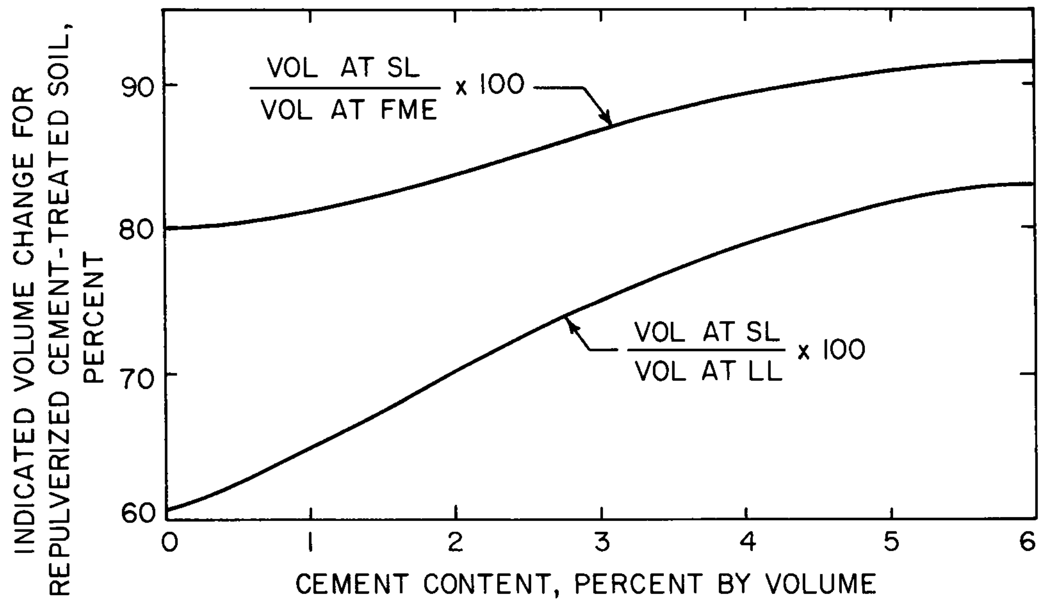


Figure 17. Volume relationships of repulverized soil-cement-treated soil (27). (Raw soil : LL = 54, PI = 30; a silty clay.)

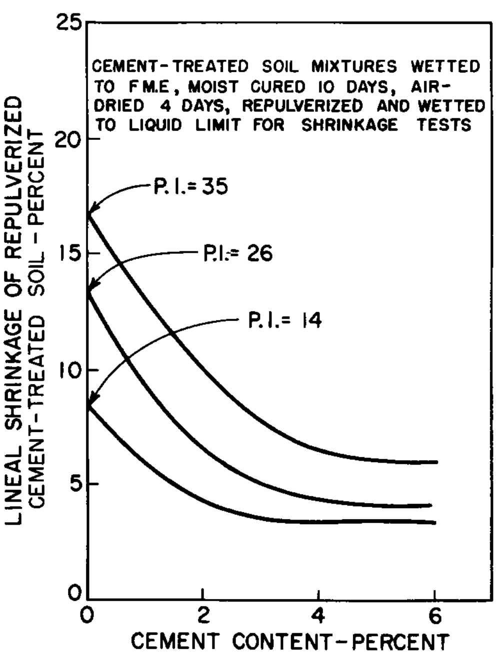


Figure 18. Influence of cement content on lineal shrinkage of repulverized cement-treated soil (26).

content) and the nature of the freezing test. The freezing test may be the closed-system test or the open-system test. The closed-system test provides for freezing the soil in a state of capillary saturation without access to additional water during freezing. The Standard Method of Freezing and Thawing Test for Soil-Cement Mixtures (ASTM Designation: D 560-57 and AASHO Designation: T 136-57) is a closed-system test. PCA criteria for soil-cement include the requirement that the maximum volume at any time during the 12 cycles of the freeze-thaw test shall not exceed the volume at the time of molding by more than 2 percent.

The open-system test consists of freezing soil-cement from the top downward. It requires that the bottom of the soil-cement is at all times in contact with free water. The test may be limited to one slow descent of the frost line or of several penetrations of the freezing isotherm. The resulting volume change is measured as heave and is expressed as a percentage of the initial thickness of the unfrozen cement-treated soil. The British Standard Test 1924: 1957, (British Standards Institution—1958 Yearbook, London, England), Determination of the Resistance of a Stabilized Soil Mixture to Damage by Frost (for fine-grained soils only), is an open-system test.

Experimental data (42) are available from two series of tests that indicate the effectiveness of cement-treated soil in resisting frost heaving. The tests were made on cylinders 3 in. in diameter and 7 in. high compacted in accordance with the original Proctor compactive effort (214) using 14 blows per layer on four layers. The soils consisted of a clay (LL = 46, PI = 26) with and without admixtures of a concrete sand and a pit-run gravel. Each test consisted of one slow descent of the frost line through the 7-in. specimen, the freezing temperature of the cabinet being lowered gradually to -10 F. One series was cured to a low moisture content before freezing. The other series was resaturated under a pressure of 30 psi before freezing.

TABLE 5

DATA ILLUSTRATING THE EFFECTIVENESS OF CEMENT IN PREVENTING HEAVING OF CLAYEY SOILS WHEN TESTED IN AN OPEN SYSTEM (42)

Soil Type	Cement (%)	Density (pcf)	Moisture Content (%) Molded	End of Curing	Start of Test	Ave. Final	Heave (%)	Frost Action Description
(a) Series 2—Cured in Lab. 1 day, 10 to 11 days in moist room								
Clay	4	108	17.9	5.1	5.1	29.2	19.8	Severe
Clay	6	107	17.0	5.0	5.0	19.0	0.85	Very slight
Clay	8	107	16.0	4.7	4.7	21.0	0.86	Very slight
Clay	10	108	15.6	4.8	4.8	20.3	0.57	Very slight
20 Cl.-80 Sand	6	131	10.4	4.2	4.2	9.1	0.0	None
20 Cl.-80 Sand	10	132	9.4	3.2	3.2	7.5	0.0	None
60 Cl.-40 Sand	6	120	11.3	5.0	5.0	12.3	0.0	None
60 Cl.-40 Sand	10	127	11.5	4.4	4.4	4.5	0.0	None
(b) Series 6—Cured in moist room 31 to 35 days, and pressure saturated (30 psi)								
Clay	4	102	18.0	20.0	26.0	57.8	65.0	Very severe
Clay	6	106	18.9	17.0	25.0	32.6	24.6	Very severe
Clay	8	103	18.7	16.0	24.5	27.6	10.0	Moderate
Clay	10	102	18.6	19.5	23.8	25.2	5.1	Moderate
Clay	12	102	18.6	19.5	24.2	28.3	8.9	Moderate
16.5 Cl.-83.5 Gr.	4	132	8.5	7.8	8.6	10.2	1.7	Very slight
16.5 Cl.-83.5 Gr.	6	132	9.0	9.1	10.0	10.5	0.0	None
16.5 Cl.-83.5 Gr.	8	132	9.0	8.6	9.8	16.2	0.0	None

The results indicate that small percentages of cement do not completely prevent heave of the clay under the severe conditions of the test but that cement contents that satisfy criteria for soil-cement hold values of heave to 2 percent or less for the clay. Heave of cement-treated sand-clay and gravel-clay mixtures was negligible. The results are given in Table 5.

In evaluating the comparative effects of freezing in the open system with that of the alternate cycles of freeze and thaw in the Standard ASTM-AASHO (closed system) test it should be borne in mind that the purposes of the two tests may be different. In the open system, the purpose may be to determine resistance to the formation of a few thick ice lenses that cause significant heave. However, in the British Standard Test, unconfined compressive strength loss due to 14 cycles of alternate freezing and thawing is also evaluated. In the ASTM-AASHO Standard Test the purpose is to determine if cycles of alternate freeze and thaw at capillary saturation have a deteriorating effect on the cement-treated soil in terms of surface softening and reduction in strength.

Volume Changes Associated with Temperature Changes—Coefficient of Thermal Expansion.—Hardened cement-treated soil changes in volume with change in temperature, decreasing in length with decrease in temperature. Volume changes due to thermal changes increase with increase in cement content and with increase in density. Experimental values of the coefficient of thermal expansion are available from tests in India (38), Africa (43), and the U.S. (17, 30). Over-all values range from a minimum of 3.5 to a maximum of 8.7×10^{-6} per inch per deg F. A summary of the experimental data is given in Table 6.

TABLE 6

SUMMARY OF DATA ON COEFFICIENT OF THERMAL EXPANSION OF HARDENED CEMENT-TREATED SOIL (17, 30, 38, 43)

Source of Data	Description of Soil	Cement Content (%)	Coefficient of Thermal Expansion (in./in. deg F) $\times 10^{-6}$
90[a]	Sandy loam	2.5 to 10	4.5 to 5.8
90[a]	Silty loam	2.5 to 10	4.1 to 5.6
90[a]	Silty clay loam	2.5 to 10	3.9 to 6.1
90[a]	Loam	2.5 to 10	4.6 to 6.3
110	Sand-shell	2.8 sks/cu yd	3.5
147	Sandy loam (A-2)	8	6.9
147	Silty clay loam	14	6.2
147	Clay (A-6-7)	12	5.7
181	Several types	Not given	5.1 to 8.7

[a]The experimental determinations made in India (38) were made on the four types of soils for which index properties are given in Table 4. The soils are: No. 1, a sandy loam; No. 2, a silty loam; No. 3, a silty clay loam; and No. 4, a loam. Determinations were made on 15-in. long by 3/4-in. diameter sticks by compacting the mixture in a metal tube with a ¼-in. diameter rod. For the same density and for all soils tested, the thermal expansion increased with increase in cement content. The sandy loam soil had the highest thermal expansion and the silty clay loam the lowest. The results of the tests are given in Figure 19. For the same proportion of cement in the soil-cement mixture, the thermal expansion increases with increase in density. The relationships for the four soils are shown in Figure 20.

Thermal Properties of Soil-Cement

Thermal properties include the coefficient of thermal conductivity, specific heat, heat of wetting, diffusivity, and volumetric heat capacity. Typical values of thermal conductivity, K in Btu/sq ft/hr/in/deg F for soil-cement of different soils are: (a)

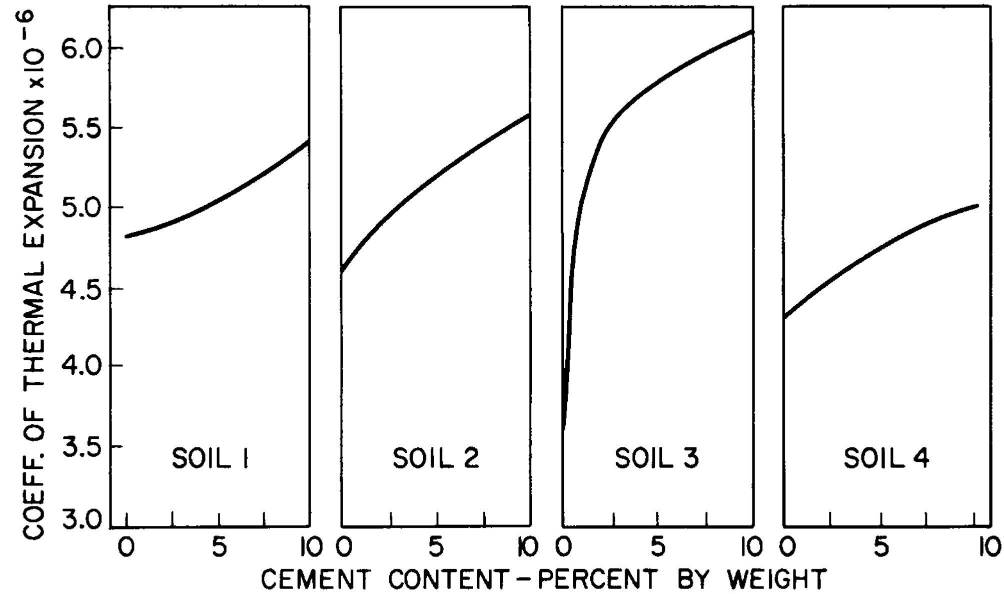


Figure 19. Effect of cement content on the thermal expansion of soils (38).

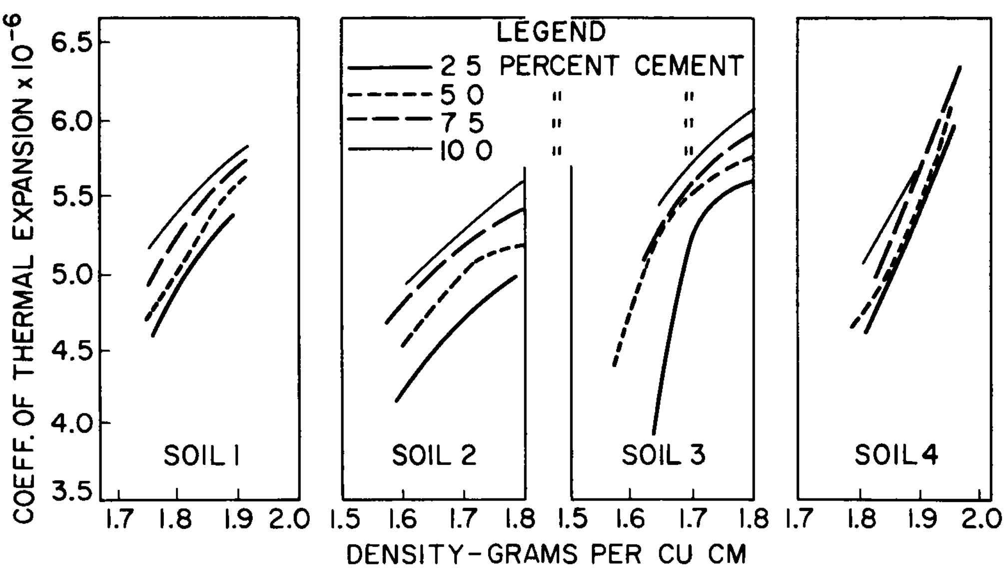


Figure 20. Effect of density on thermal expansion of soils (38).

sandy soil—.....8.0, (b) silty soil—.....4.0, and (c) clayey soil—....3.7. These results were obtained on specimens compacted to Standard ASTM-AASHO density and oven-dried at 160 F before testing.

In the absence of data on all thermal properties for a wide range of soil types, densities, and moisture contents it is necessary to use available data on thermal properties of untreated soils. The reader is referred to the following publications:

1. Kersten, M.S., "Thermal Properties of Soils." Engineering Experiment Station, Bulletin No. 28, Institute of Technology, University of Minnesota, June 1, 1949.

This bulletin contains data on thermal properties of soils and on factors of composition, moisture content, and density that influence thermal properties of soils. It also contains data on thermal properties of bituminous mixtures, portland cement concrete and other materials used in highway construction. It also includes a list of references.

2. Johnson, A.W., "Frost Action in Roads and Airfields." Highway Research Board, Special Report No. 1, National Academy of Sciences-National Research Council, Publication No. 211, Washington, D.C., 1952.

This review of the literature on factors relating to frost action includes data on thermal properties of soils and other materials of construction. A list of references is included.

Water Movement and Retention Properties

Capillary Absorption.—Soils that do not swell limit capillary absorption to the existing volume of pores having capillary properties. PCA criteria for soil-cement require that the maximum volume at any time during the 12 cycles of the wet-dry test (and also the freeze-thaw test) shall not exceed the volume at the time of molding by more than 2 percent. Thus the total volume of pore space is limited and capillary absorption cannot exceed that at time of molding by more than that permitted by the 2 percent maximum volume increase. Expansive soils treated with amounts of cement sufficiently low to permit swell will permit water absorption in proportion to the percent swell. Norm-

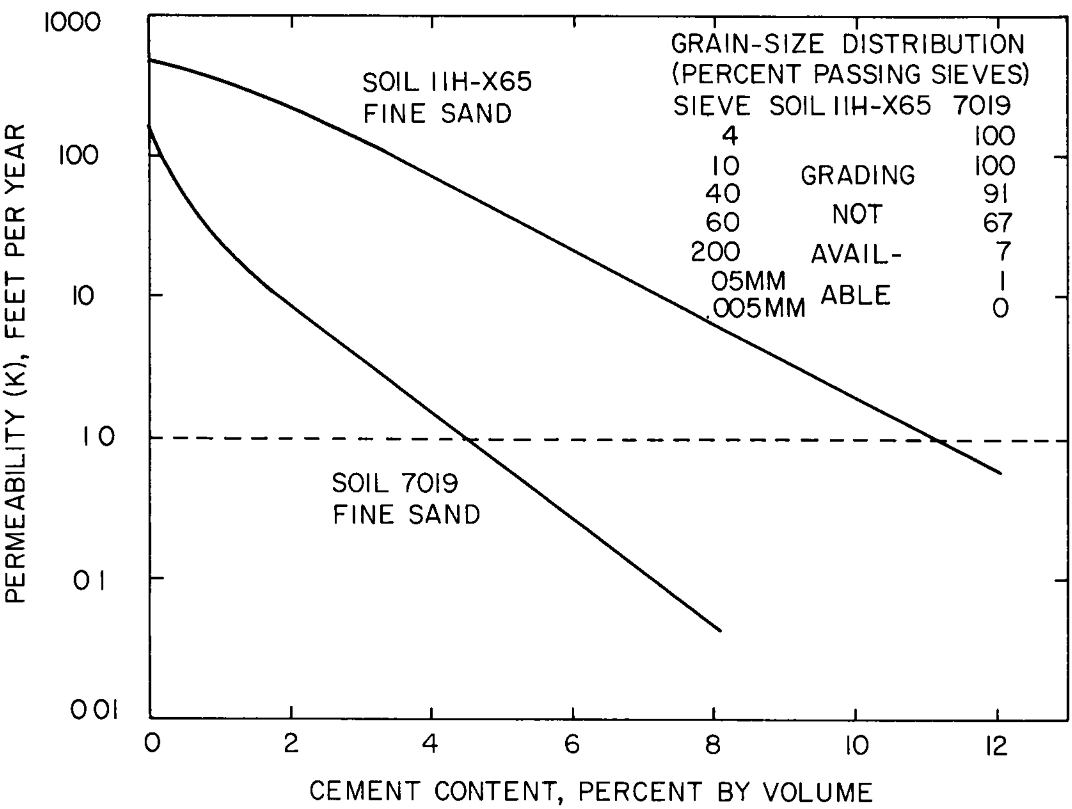


Figure 21. Permeability vs cement content of compacted cement-treated soils (33).

ally, the absorbed moisture content of soil-cement does not exceed by significant amounts the optimum moisture content at the time of compaction.

Permeability.—Most soils can be made practically impermeable by the addition of the minimum amount of cement normally needed to harden them. For sandy permeable soils, the permeability is closely related to the cement content. Two examples illustrating the relationship are shown in Figure 21.

Values of permeability for a wide range of textural soil types and for soil-cement prepared from them are given in Table 7.

Durability

Except for long-time soil profile development processes, raw soils change in volume, in strength, and in internal structure, with changes in moisture content and temperature. The magnitude of these changes in physical properties can be controlled in some degree in construction by placing soils within those limits of moisture content and density most nearly compatible with environmental requirements.

TABLE 7

PERMEABILITY OF SOIL-CEMENT MIXTURES (30, 33)[a]

Index Properties of Raw Soils: Grain-Size Distribution (% smaller than), Sieve Number 4	10	40	60	200	0.05 Mm	0.005 Mm	LL	PI	Max Dry Density (pcf)	Classification of Soils: USDA Textural Class	AASHO Soil Group	Cement Content (% by wt)	Permeability, K (ft/yr): Raw Soil	Soil-Cement
100	100	98	28	1	0	0	NP	NP	107.4	Coarse sand	A-3(0)	10	15,000	18
100	99	95	80	1	-	-	NP	NP	104.8	Fine sand	A-3(0)	9	4,500	10
100	100	77	36	4	0	0	NP	NP	114.4	Sand	A-3(0)	8	1,500	6
74	69	39	28	22	21	8	29	9	125.7	Gr. co. sa. lm.	A-2-4(0)	8	182	6
100	75	38	15	7	5	0	NP	NP	123.0	Loamy co. sa.	A-1-b(0)	7	15	0.3
100	100	99	82	40	34	12	20	2	116.2	Fi. sa. loam	A-4(0)	12	13	0.3
99	97	69	-	16	12	4	14	NP	123.0	Lo. fi. sand	A-2-4(0)	10	10	2
100	99	88	-	36	25	7	17	NP	119 2	Lo. fi. sand	A-2-4(0)	9	5	0.1
94	93	82	72	41	34	24	28	25	113.2	Sa. clay im.	A-7-6	8	1	0.5

[a]Part of data from communication with Portland Cement Association.

The same forces associated with changes in moisture content and temperature, which so strongly influence soil state, also act on cement-treated soil. Because the type of soil and the cement content each so strongly influences the degree of stabilization, it is obvious that for different soils identical cement contents may result in mixes that have different degrees of resistance to those forces. Because time is a factor associated with the forces that cause deterioration, it is again obvious that mixtures will have different lasting qualities and thus differ in durability. Because different degrees of resistance to the forces tending to deteriorate a given cement-treated soil can be built into it simply by changing cement content, values indicative of durability can be listed for mixtures only when they satisfy some standard criteria—PCA soil-cement criteria, for example.

Criteria for soil-cement mixtures require that soil-cement losses in the ASTM-AASHO standard wetting and drying test and freezing and thawing test conform to the limits listed under "Criteria for Soil-Cement Mixtures."

The standard wet-dry and freeze-thaw tests were initially devised to test the interaction due to changes in moisture content and density. Thus the tests were not initially intended as measures of durability. However, because time is an important factor in the tests (12 alternations of wetting and drying, and 12 alternations of freezing and thawing) and because laboratory results have been correlated with field experience, the tests do yield relative values indicative of the lasting quality of the mixtures tested. Thus any mixture that satisfies criteria for soil-cement must satisfy certain minimum requirements indicative of durability.

Illustrative examples showing values for the effect of age and cycles of alternate wetting and drying and freezing and thawing on compressive strength, plasticity index, and other physical properties are given in the foregoing, and under "Factors Influencing the Physical Properties of Cement-Treated Soil." (See Figs. 15, 35, 36, 37, 42, 43, 47, 48, 51, 52, 53, 62, 63, 66, 68, 70, 71, 72).

Optimum Moisture Content and Maximum Density of Soil-Cement

The optimum moisture contents and maximum densities of compacted soil-cement are approximately the same as those of the raw soil for a large proportion of the soils tested when normal mixing times are observed. Some soils do exhibit marked departures in optimum moisture content and maximum density, but they are limited in number. Most departures are of the order of 1 to 3 pcf.

TABLE 8

MAXIMUM DENSITIES AND OPTIMUM MOISTURE CONTENTS OF SOIL-CEMENT COMPARED TO CORRESPONDING VALUES FOR RAW SOILS

Soil Group and Type	Change in Maximum Density (in pcf)	Change in Optimum Moisture Content (in percentage units)
A-2 sandy loams	0 to + 3	-1 to + 1
A-3 sands	0 to + 6	0 to - 1
A-4 silts and loams	0 to - 6	0 to + 3
A-5 silts	-3 to + 1	0 to - 3
A-6 medium clays	0 to + 1	0 to - 2
A-6 heavy clays	-1 to + 2	0 to - 4

When cement is added, increases in density usually occur for sands and sandy soils and sometimes in small degree for heavy clays. Little or no change occurs for the light to medium clays. Decreases in density may occur in silts.

Decreases in optimum moisture content occur for clays. Increases occur for the silts and little or no change takes place for sands and sandy soils.

Table 8 gives typical ranges of increase and decrease in laboratory-determined values of optimum moisture content and maximum density resulting from the admixing of cement in proportions necessary to satisfy PCA criteria for soil-cement for different soil groups.

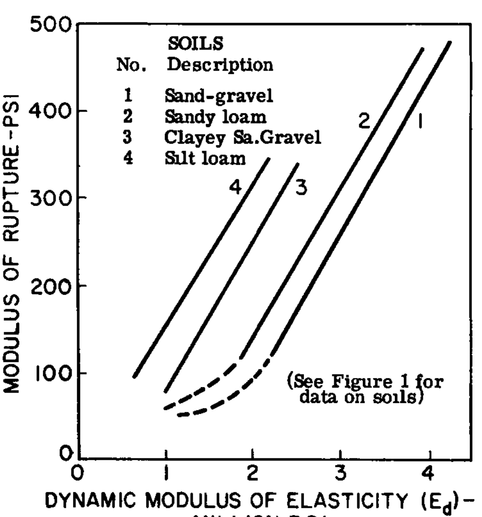


Figure 22. Relation between modulus of rupture and dynamic modulus (14).

Interrelationships Between Properties of Cement-Treated Soil

Compressive Strength vs Flexural Strength. —Examination of comparable data on unconfined compressive strength and flexural strength (14, 30) of hardened cement-treated soil shows that a nearly linear relationship exists at all cement contents, at all ages. The modulus of rupture is approximately 20 percent of the compressive strength.

Moduli of Elasticity (14). —The dynamic modulus of elasticity, E_d, and the static modulus in flexure, E_{sf}, at 33 percent of ultimate strength are equal, within limits of experimental error. Figure 5 shows data for four different soils (Fig. 1) each at several different cement contents and tested at three ages (7, 28 and 90 days).

The static modulus of elasticity in compression averages slightly more than 60 percent of the static modulus in flexure (Figs. 4 and 5).

The static moduli in compression, E_{sc}, of dry specimens of soils No. 1 and No. 3 (Fig. 1) containing 3 percent cement averaged 29 percent of those of comparable moist specimens, and the moduli of dry specimens containing 10 percent cement averaged 54 percent of those of comparable moist specimens. (Also see wet/dry strength ratio.)

Modulus of Rupture vs Modulus of Elasticity, E_d.—The relationships between modulus of rupture and dynamic modulus of elasticity, E_d, are linear except for the lower strengths for silty and clayey soils. They are linear for cement-treated soil meeting criteria for soil-cement. The illustrative examples in Figure 22 show that the relationship differs for different soils, the ratio of flexural strength to E_d being higher for the sandy soils.

Compressive Strength vs Dynamic Modulus, E_d.—The relationships are linear but the curves for different soils are in different positions as is indicated in Figure 22, which shows the relation between modulus of rupture and E_d. The ratio of compressive strength to the modulus E_d is considerably higher for the silty and clayey soils than for the sandy soils.

Illustrative Values of Elastic and Strength Properties.—For the purpose of comparison, illustrative values of properties are given in Table 9 for the four soils whose index properties are shown in Figure 1.

TABLE 9

ILLUSTRATIVE VALUES OF THE ELASTIC AND STRENGTH PROPERTIES OF SOIL-CEMENT MIXTURES (14)

Soil		Cement Cont. (%)		Compr. Strength[b]	Mod. of Rupture[b]	Mod. of Elast.[b] (psi x 10^6)	
Type	No.	By Wt.	By Vol.[a]	(psi)	(psi)	E_d	E_{sc}
Sand	1	3.8	5	450	110	2.05	-
		6.0	8	800	180	2.75	-
		8.5	11	1,225	260	3.30	-
Sandy loam	2	3.8	5	300	80	1.40	0.90
		6.1	8	650	145	2.00	1.25
		8.6	11	1,025	215	2.60	1.65
Clayey sand	3	5.7	7	475	105	1.30	-
		8.3	10	625	150	1.50	-
		11.0	13	800	195	1.75	-
Silt loam	4	8.0	9	525	125	0.90	0.55
		11.1	12	725	155	1.05	0.65
		14.2	15	900	190	1.25	0.75

[a]The lowest cement content in this column for each soil is the quantity required to produce soil-cement that will pass presently accepted criteria for base course construction.
[b]At 28 days, moisture.

Relation Between CBR and Compressive Strength.—British studies (23, 44) indicate a linear relationship between CBR and unconfined compressive strength for cement-treated soils containing a predominance of fine grains or sand. Results of comparative tests are shown in Figure 24, and for a heavy clay in Figure 23. Limited testing in the United States indicates near linear relationships for two Tennessee chert gravels as indicated in Figure 23. Both of the chert gravels contained a large proportion of gravel, which may account for the lack of linearity for these materials. The available data show that whereas the relationships vary for different cement-treated soil mixtures, those relationships are not indicated by the CBR values for the raw soils.

Relation Between Cohesion and Internal Friction.—Cement-treated soil develops

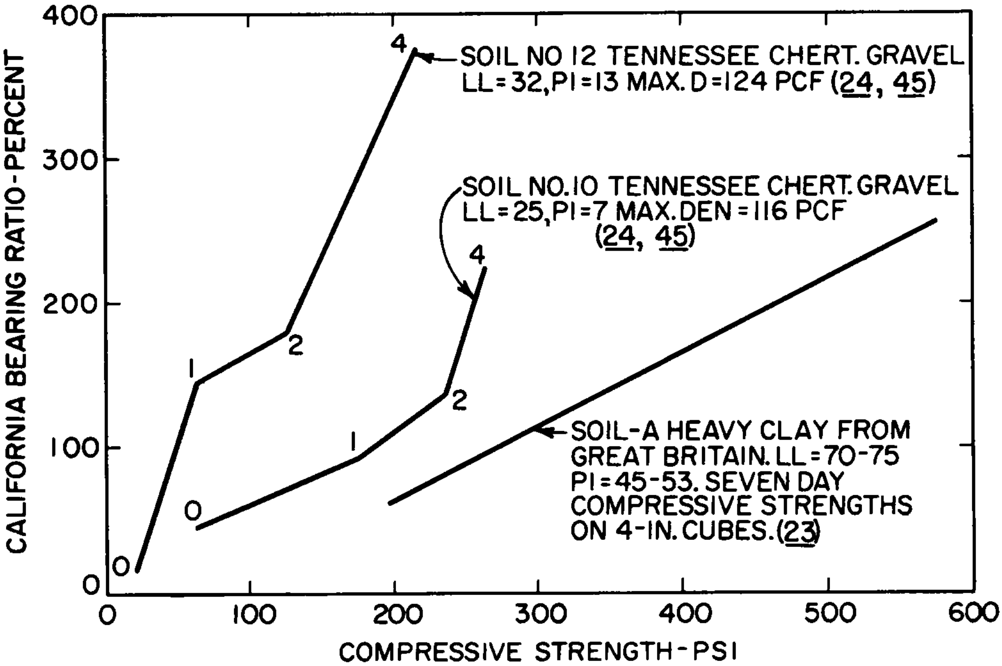


Figure 23. CBR vs compressive strength for cement-treated soil mixtures with two plastic gravels (24, 45) and a heavy clay (23). (Values of CBR and compression strength after 7 days moist cure. Numerals 0, 1, 2, and 4 are cement contents in percent of dry weight.)

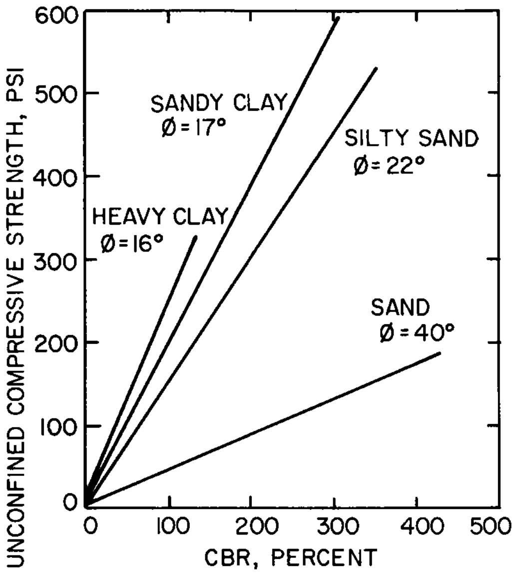


Figure 24. Relation between 7-day unconfined compressive strength and CBR for cement-treated soils (44).

values of cohesion and internal friction that are markedly higher than values for the raw soil (24). Triaxial shear tests have been performed on two soils whose index properties are shown in Figure 25. The tests were made on vacuum-saturated raw soil and cement-treated soil specimens 5 in. in diameter by 14 in. high, compacted in a split mold in nine layers under 39 blows per layer (Standard AASHO compactive effort). Lateral pressures of 10, 20, and 30 psi were used in the triaxial tests.

Data shown in Figure 26 illustrate the effect of 4 percent cement on C and ϕ for a soil considered only slightly sub-standard. The 4 percent admixture was sufficient to produce a mixture that satisfies criteria for soil-cement. The results of triaxial tests made on soil No. 13 treated with varying amounts of cement (0 to 10 percent) are shown in Figure 27. Cohesion increased with increase in cement content to a maximum at 6 percent cement and then decreased; showed a marked increase between 6 and 8 percent cement for the lateral restraining pressures used.

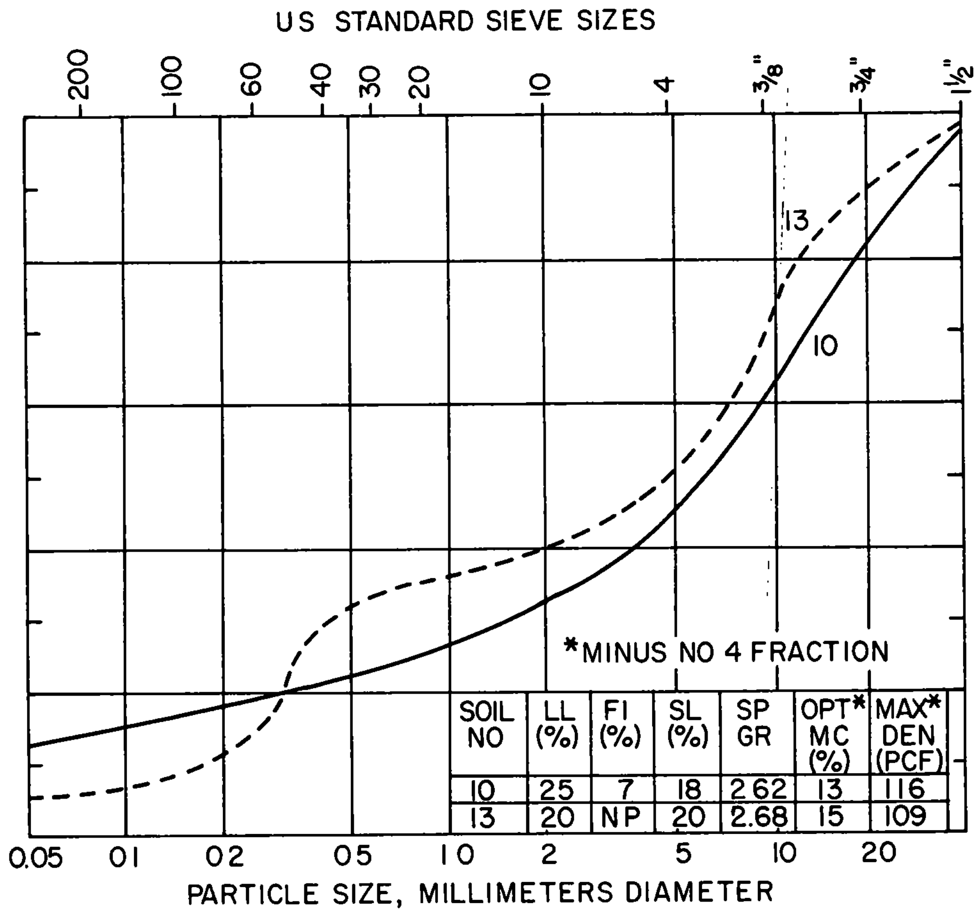


Figure 25. Grain-size distribution of chert gravels used in determination of cohesion and internal friction of cement-treated soils (24).

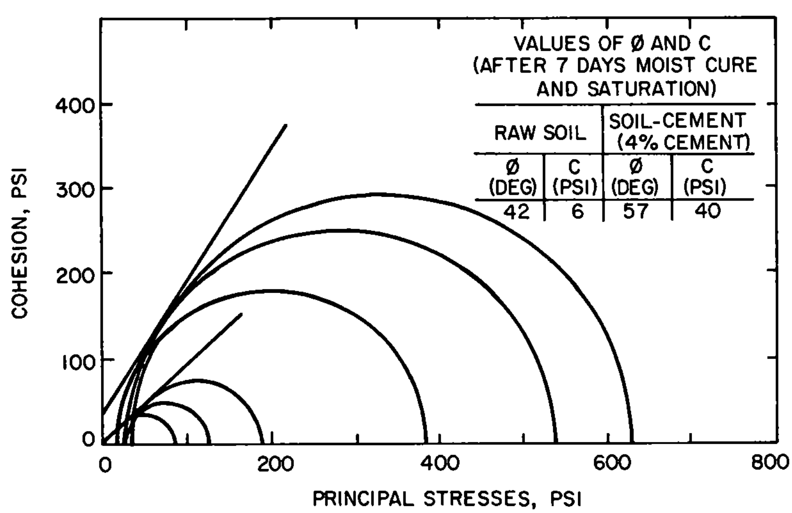


Figure 26. Triaxial test results for soil No. 10 with and without cement admixture (24).

The PCA study of the shear strength and elastic properties of cement-treated sandy and silty soil mixtures under triaxial loading (16) showed that the coefficient of internal friction (tan ϕ) was relatively constant for cement-treated specimens of each soil regardless of cement content and age. Values for moist-cured cement-treated soil specimens averaged 0.96 (ϕ = 44 deg) for the sandy soils and 0.73 (ϕ = 36 deg) for the silty soils. These average values were larger than for specimens molded from the untreated soils, as indicated by the values 0.79 (ϕ = 38 deg) for the untreated sandy soil specimens, and 0.52 (ϕ = 27 deg) and 0.43 (ϕ = 23 deg) for the untreated silty soil specimens. Specimens tested dry had considerably higher tan ϕ values than companion moist-cured specimens. Cohesive strengths (C) of moist-cured specimens at age 28 days ranged from about 35 to 530 psi and depended on cement content and type of soil. The rate of increase in C values with increase of cement content was greater for the sandy soils than for the silty soils. The cohesive strength also increased with age. In general the 90-day values were 50 percent or more than the 7-day values. Dried specimens had significantly higher cohesive strengths than moist-cured specimens; soaking specimens prior to triaxial testing lowered cohesion.

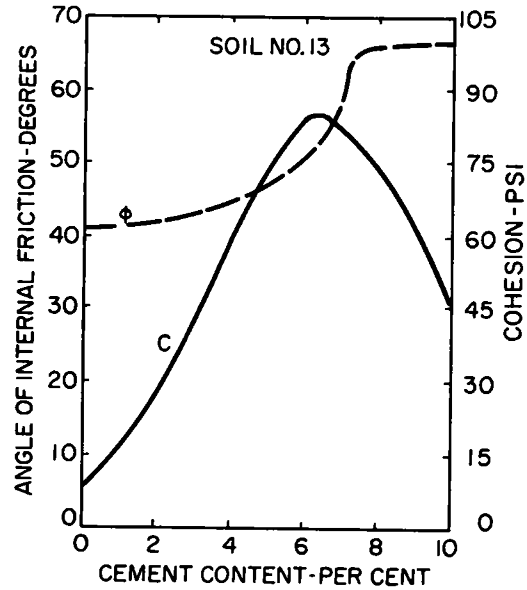


Figure 27. Influence of cement content on cohesion and internal friction of a chert gravel (24).

Triaxial tests have been performed on three sandy and two silty Georgia soils to determine the effect of 0, 7, 9, 12 and 15 percent portland cement on the cohesion and the coefficient of internal friction of specimens moist-cured for 28 days (46). Cement-treated specimens had higher tan ϕ values than untreated specimens, and for each soil tan ϕ was relatively constant at all cement treatments; average values of tan ϕ for the cement-treated sands ranged from 0.93 (ϕ = 43 deg) to 1.28 (ϕ = 52 deg), for the cement-treated silts from 0.81 (ϕ = 39 deg) to 0.93. C values increased as cement content increased; for the sands C values ranged from 0 to 245 psi, for the silts from 75 to 135 psi.

Factors Influencing Properties Of Cement-Treated Soil

GENERAL

The materials, mix proportions, construction methods and environmental conditions, natural and artificial, all have an influence on the properties of cement-treated soil. Knowledge of the nature of these influences is basic to an understanding of the behavior of cement-treated soil. The degree or extent of influence of the various factors is expressed in terms of interrelationships that are the result of measurements of cause and effect. The relationships shown are in the form of illustrative data rather than typical or average values. For the purpose of presenting a maximum of illustrative data in the space permitted, the factors that influence properties of cement-treated soil are grouped according to: (a) the nature of the materials and the proportions of the mix (soil, cement and water); (b) mixing and compacting; (c) the conditions of curing (including aging); and (d) beneficial admixtures (soil amendments and additives).

NATURE OF MATERIALS AND PROPORTIONS OF MIX

The Soil

Factors are present in soils that prevent uniform reaction with cement and water, thereby adversely affecting the strength and durability of the stabilized soil. These contributing factors—inherent nature of the soil; its composition, both physical and chemical; its texture, expressed in terms of grain-size distribution; its responses to water; its workability—are so diverse, yet so interrelated in influence, that no one has a constant, major predominating effect. The nature of and the effects of the influencing factors have not yet been fully explored. However, data that are available are shown here in the form of illustrative examples, or sources where data may be found are indicated.

Soil Identification Groups—Great Soil Groups.—The effect on cement stabilization of soil compositional variables such as the content of sand, silt, clay, and organic matter or sulphates or other constituents, are so strong within the different Great Soil Groups (Podzol, Grey-Brown Podzolic, Red and Yellow, Prairie, Chermozem, Dark Brown, Desert soils, etc.), that they overshadow the influences of the broad group effects. The susceptibility of laterite and lateritic soils to stabilization varies from excellent to poor depending on the organic content and degree of laterization (47).

Soil Series and Horizon.—The earliest correlations of soil series and cement requirements in North Carolina (48) showed that soils of the same series and horizon (as identified by the U.S. Department of Agriculture system of identification) require the same amount of cement to produce soil-cement. In other words, similar parent materials with similar topography and exposed to similar climatic conditions produce soils that have similar influence on the properties of cement-treated soil. This is discussed further under "Preliminary Surveying and Sampling for Cement-Treated Soil Construction," and under "Testing and Mix-Design for Soil-Cement."

Soil Classification Groups.—The influence of the nature of the soil is also indicated by the ranges of cement requirements to produce soil-cement for the various AASHO (M 145-49) (Standard Specifications for Highway Materials and Methods of Sampling and Testing, Part I, Specifications, pp. 45-51, 1955) and Unified System soil groups. The ranges of cement requirements for different AASHO soil groups and materials are given in Tables 30 and 31.

Aggregate Retained on No. 4 Sieve (49).—The addition of coarse aggregate (material retained on No. 4 sieve) to fine-aggregate soil (material passing the No. 4 sieve) in effect increases the cement content of the fine-aggregate soil and thus increases strength.

If the cement content by weight in the fraction passing the No. 4 sieve is held constant, the compressive strength is not affected appreciably by the proportion of coarse aggregate unless that proportion is greater than 50 percent by weight of the total material. The effect of the material retained on the No. 4 sieve is indicated in Figure 28.

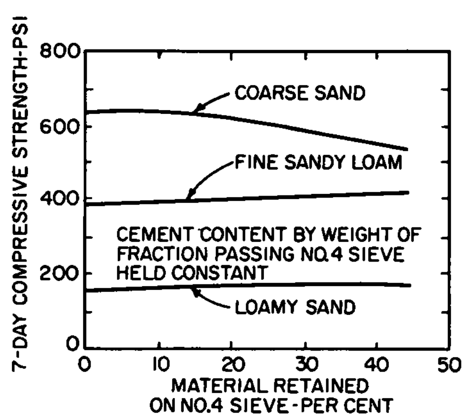


Figure 28. Effect of material retained on the No. 4 sieve on the compressive strength of soil-cement (49).

Clay Content.—Only in artificially prepared mixtures of sand and clay or in natural deposits where changes in clay content occur gradually is it possible to show clearly the influence of clay content on cement-treated soil. An example of the influence of clay content is illustrated in Figure 29 where values of modulus of elasticity in compression are given for cement-treated sand-clay mixtures ranging in proportions from 0 to 100 percent clay.

The loess soils of southwestern Iowa (32) can be used to illustrate the influence of clay content. The grain-size accumulation curves of four Iowa loess soils taken at points across the loess belt (Fig. 30) are similar in shape but show marked variance in both silt and clay contents, becoming progressively finer textured from west to east. Average sphericity of the grains is constant for various soils. Mineralogical composition of silt sizes shows little difference in quartz content but does show a decrease from west to east in feldspar content. Clay mineral tests on the minus 2 micron (0.002 mm) material shows an increase in clay content from west to east—the clay content tripling.

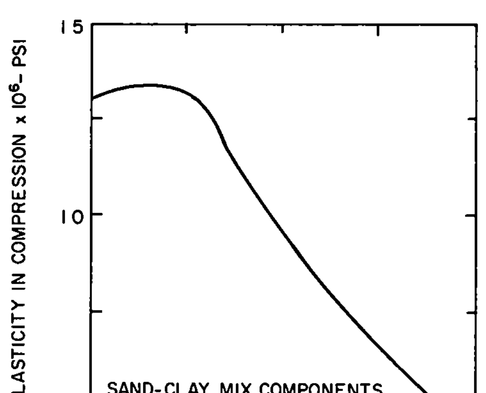


Figure 29. Influence of clay content on the modulus of elasticity in compression (15).

The influence of the increase in clay content is shown in Figure 31 in terms of the cement required to produce soil-cement. The cement requirements increase with increase in clay content. The critical criterion was weight loss after brushing in the freeze-thaw test for samples 55-1 and 20-2, and volume change in the freeze-thaw test for samples 26-1 and 43½-1, which contain the highest proportions of clay.

Surface Area.—Until the development of the glycerol retention test for measuring surface area of soils, the influence of surface area on the properties of soil-cement had not been determined with accuracy. Recently (50) correlations have been made between surface area determined by the glycerol retention method and the cement contents required for cement-treated soil mixtures that satisfy freeze-thaw test criteria for soil-cement. An illustration of the relationship between surface area and cement requirements for 18 soils having less than 45 percent silt is shown in Figure 32. The application of this correlation to testing is described under "Testing and Mix Design for Soil-Cement, Short Cut Method for Plastic Clayey Soils."

Liquid Limit and Plasticity Index (22,

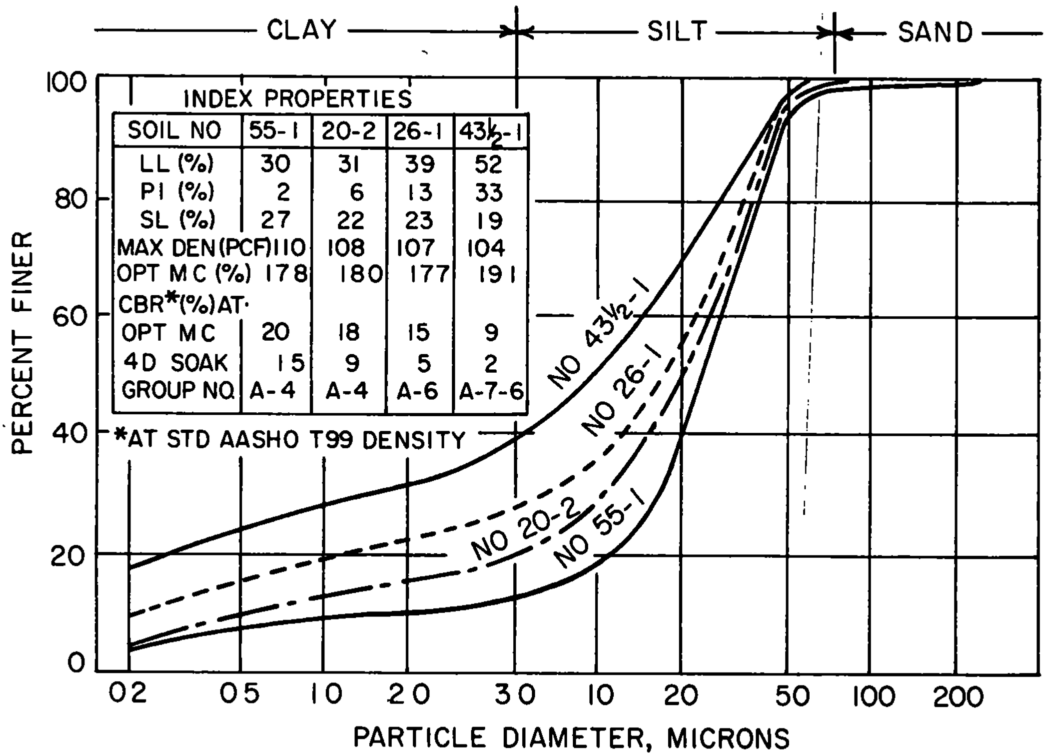


Figure 30. Grain-size distribution curves for Iowa loess soils (32).

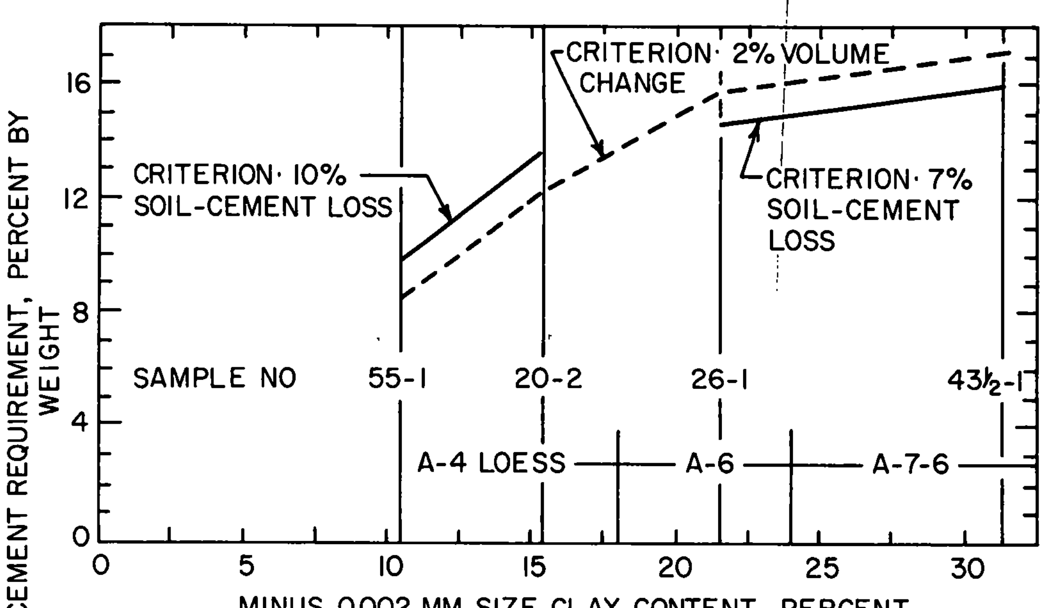


Figure 31. Relation between cement requirement and clay content of southwestern Iowa loess. Cement requirements satisfy criteria for soil-cement (32).

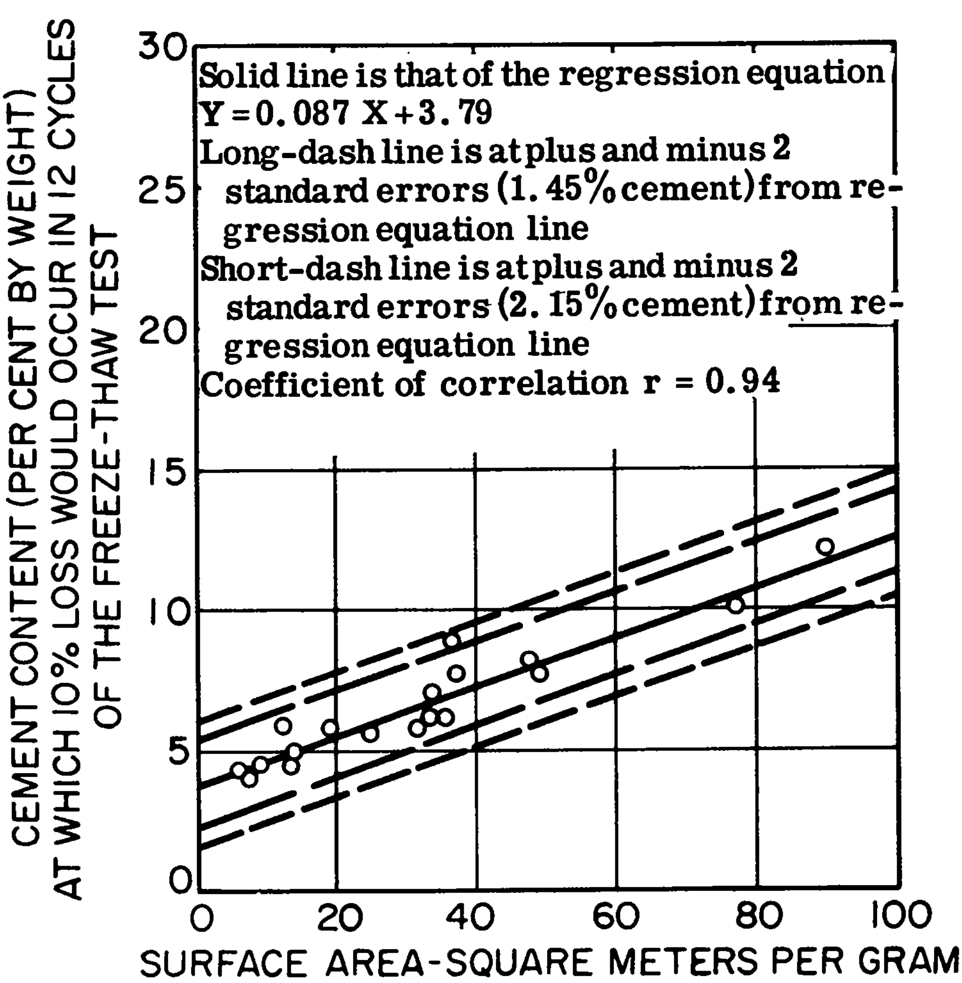


Figure 32. Cement content (by weight) at which 10 percent loss would occur in 12 cycles of the freeze-thaw test vs surface area (50).

27, 28, 29, 33, 34). —The plasticity of a soil has marked influence on the properties of cement-treated soil (28). However, other raw soil properties usually exert such strong influence that well-defined relationships between plasticity and the nature of the cement-treated soil are not always evident. General trends are evident for several types of soils, and relationships can be drawn for soils from uniform deposits of the nature of loess. The relationship for which the best correlation has been made is that between plasticity and approximate minimum cement requirements to satisfy criteria for soil-cement.

Generally, no relationship has yet been found between plasticity (LL and PI) and cement content for soils of the A-2 and A-3 groups. For soils of the A-4 group there is a noticeable trend of increasing cement requirement with increase in liquid limit (28). The trend is more marked for soils of the A-6 and A-7 groups. Nevertheless, the range in cement requirements for a given plasticity index is too great to permit the accuracy desired for practical application in determining cement requirements on the basis of plasticity alone.

Because the loess soils of southwestern Iowa (32) show a consistent increase in plasticity from west to east, they present one of the best examples of the nature of the influence of plasticity when interpreted in terms of minimum cement requirements to

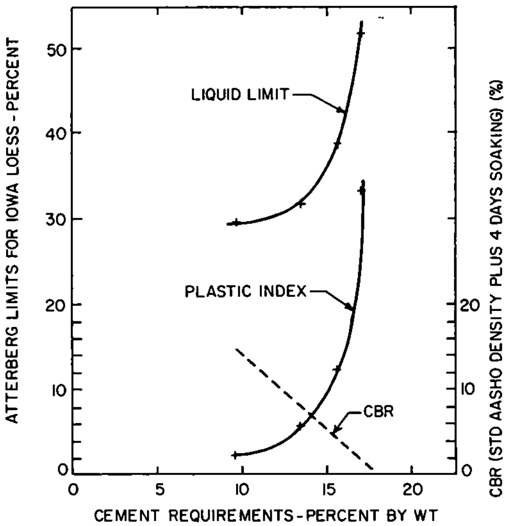


Figure 33. Influence of plasticity in terms of its relation to minimum cement requirements; also the relation between CBR of raw soil and cement requirements (32).

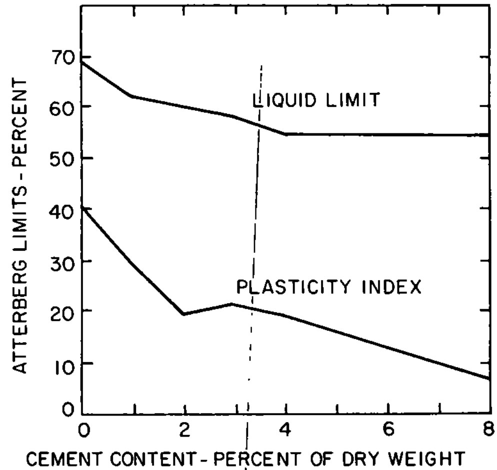


Figure 34. Atterberg limits for cement-treated Iowa gumbotil after 1-hr period of hydration (29).

satisfy criteria for soil-cement. The relationships of liquid limit and plasticity index to cement requirements are indicated in Figure 33. The soils also exhibit a correlation between CBR and cement requirements.

Age strongly influences the plasticity of cement-treated soil mixtures. Marked reductions in plasticity index occur within one hour, as indicated in Figure 34. The ef-

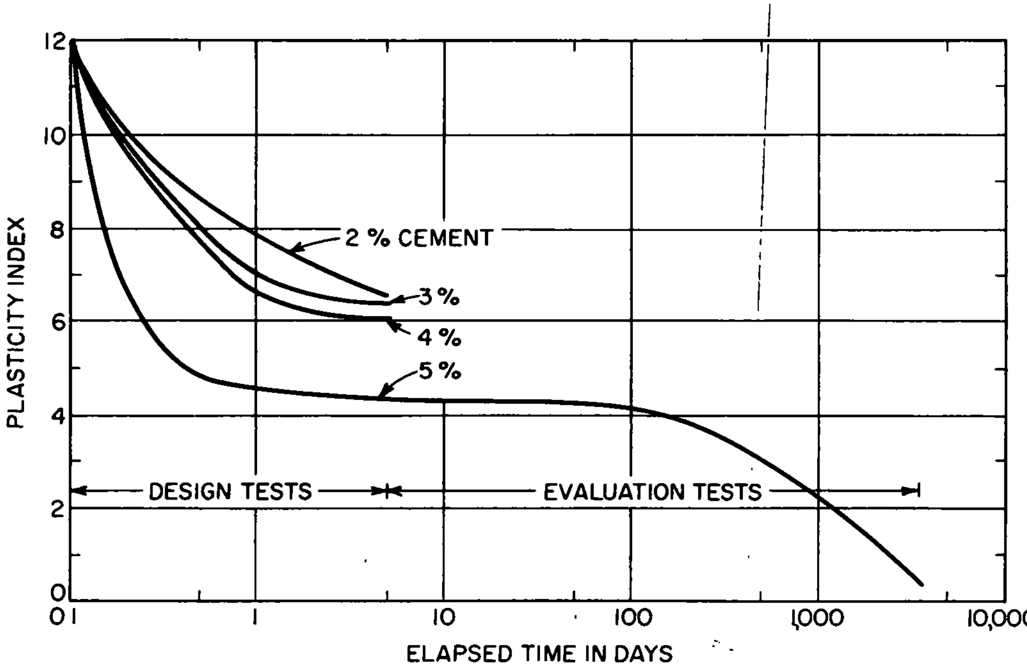


Figure 35. Plasticity index vs time (cement-treated soil mixes from Hot Springs, Ark.) (34).

fect of age on plasticity over periods up to several years is shown in Figure 35, which shows plasticity indexes after various periods of hydration for different proportions of cement admixtures to a given soil.

Inasmuch as relatively low cement contents are used to modify plastic granular soils, and the end product (cement-modified granular soil) does not necessarily satisfy criteria for soil-cement, there has been some question of the permanency of the effect on plasticity. Two series of tests (22, 33) have been made to determine the effect of alternate cycles of freezing and thawing on the reduced plasticity index of the cement-modified soil mixtures. The reduced plasticity of the mixtures is not detrimentally affected by cycles of freezing and thawing of the order indicated in Figure 36.

Chemical Composition—General.—The constituents of soils include substances that react with cement to different degrees. Normally reacting soils may differ in degree of reaction depending on the nature of the cations associated with the clay-size materials. Soils that do not react normally with cement may owe that property to the presence of a form of organic matter that causes delayed setting or to the presence of sulfates that cause swelling and/or reduction in strength in the presence of water.

Surface Chemical Factors.—The effect of surface chemical factors has not yet been sufficiently explored to permit appraisal of their influence as chemical factors. It is known that satisfactory soil-cement has been produced from soils whose pH values ranged from 4 to over 10. However, care is needed to interpret pH and organic content as separate variables because soils containing more than 5,000 ppm (parts per million) organic matter are acid (28). The nature of the dominant cation in soil clay has strong influence not only on the properties of the raw soil but also on the properties of the cement-treated soil. That has been determined experimentally for four clay soils by ionic substitution (51). A summary of the effects of various cations is given under "Beneficial Admixtures."

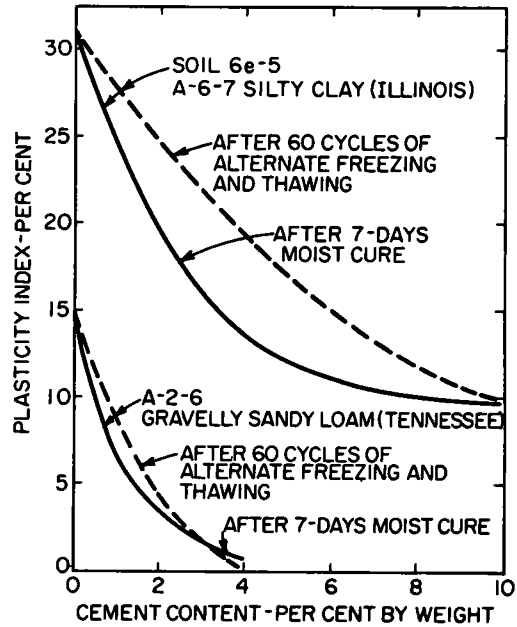


Figure 36. Effect of cycles of alternate freezing and thawing on the plasticity index of cement-treated soils (22, 33).

Organic Matter.—Undecomposed vegetation such as roots and twigs, the carbon compounds—coal, carbon, etc.—and other water-insoluble compounds derived from vegetation do not cause an unfavorable reaction with cement.

The quantity of organic matter in ppm is not a direct indication of its potential influence; some sands with only 1,000 ppm require high cement contents for hardening. However, when the Standard Colorimetric Test (52) indicates more than 2,000 ppm, the organic matter may influence the reaction with cement if measured by the compressive strength. Yet, some soils with up to 30,000 ppm (3 percent) organic matter have been hardened with 8 percent cement by volume (28). When the colorimetric test value is in excess of 4,000 ppm, it is suggested that preliminary tests be made at higher-than-normal cement contents for the texture of the soil.

The Portland Cement Association has developed a calcium absorption test for quickly identifying sandy soils that will probably react poorly in cement-treated sand mixtures (53).

Experimental work with several types of organic matter (54) has shown that organic

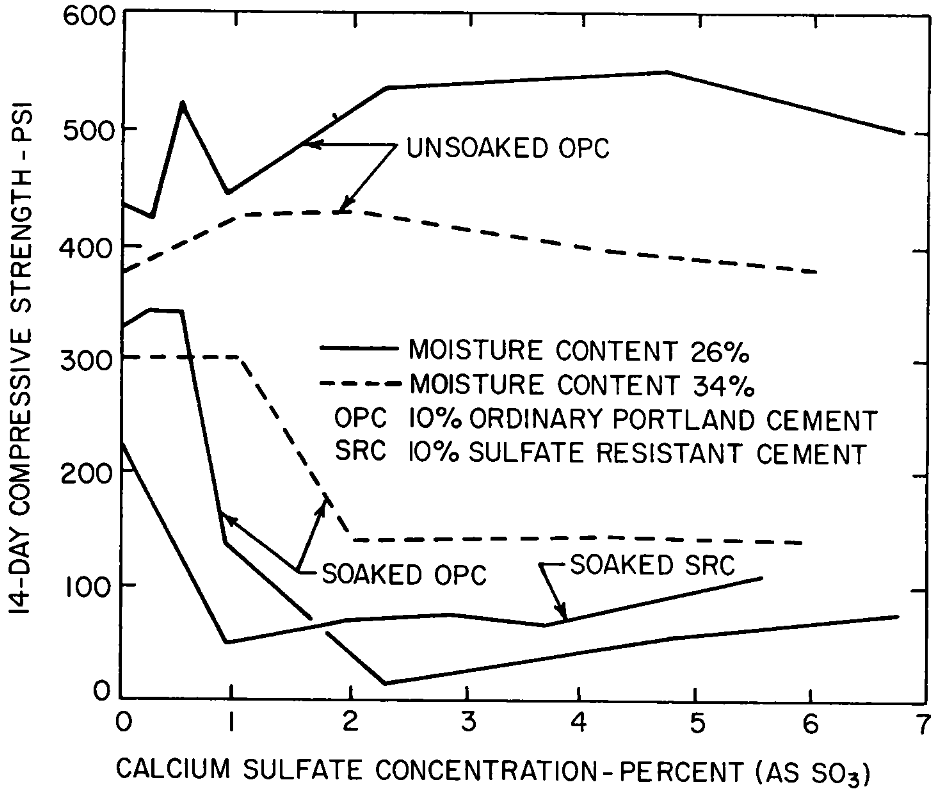


Figure 37. Influence of moisture content and calcium sulfate concentration on the strength of a clay stabilized with ordinary portland cement and sulfate-resistant cement (56).

compounds with high molecular weights such as cellulose, starch and lignen do not affect the strength of cement-treated soil, whereas those of lower molecular weights—such as nucleic acid and dextrose—act as hydration retarders and result in reduced strengths. It has been concluded from tests of organic surface soils that: retardation of setting and strength reduction are related, not to the total amount of organic matter, but probably to some active fraction of it; the activity of these surface soils is associated with their capacity to absorb calcium ions (54); the fraction particularly responsible probably contains carboxylic acid or phenolic functional groups whose existence in soil organic matter has been demonstrated.

The deleterious material occurs in the top organic layer at or below the lower black organic layer of podzol soil profiles (55). (Podzol soils develop under conditions of cool, moist climate that provide abundant vegetative cover. The soils are acidic. Leaching is intense and the organic and inorganic colloidal components are translocated from the upper horizons downward to depths up to 10 ft depending on the soil texture.)

Methods for overcoming the deleterious effects of organic matter in cement-treated soils are covered under "Beneficial Admixtures."

Sulfate Content.—When ground water carries sulfates the water can enter cement-treated soil and combine with tricalcium aluminate in the hydrated cement and produce calcium sulfo-aluminate. When the sulfate is magnesium sulfate the action is more marked in that it can also attack the calcium silicate in the hydrated cement. Both reactions are accompanied by large increases in volume of the soil-cement and in reduced strengths.

Experimental studies (56) have been made with a clay soil having 30 percent minus 0.002-mm grain-size material, a liquid limit of 45 and a plastic limit of 26. Compressive strength specimens 2 in. in diameter by 4 in. high were prepared that were subjected to different forms of sulfate attack. Specimens were coated with paraffin and stored at 25 C (77 F). One specimen was stored 14 days, the other stored 7 days, the wax coat removed and the specimen immersed in water for 7 days before testing.

The first study was made on the effect of the presence of calcium sulfate in the clay. Specimens were made with 10 percent ordinary portland cement and compacted to an air voids content of 5 percent for moisture contents ranging from 17 to 35 percent. One set contained 1 percent calcium sulfate, the other contained no sulfate. The results show that as the moisture content is increased, the strength of the normally cured cement-treated soil, both with and without sulfate, decreases and the presence of sulfate has no significant effect. However, on immersion in water, the sulfate causes significantly lower strengths. Tests were made at two moisture contents and at various sulfate concentrations to determine the effect of sulfate concentration. The results, indicated in Figure 37, show that strengths of normally cured specimens are little affected by sulfate concentration (and that the high moisture content results in reduced strengths), and that the sulfate concentrations in excess of 0.5 to 1.0 percent greatly reduced the strength of immersed specimens.

Strengths produced by sulfate-resistant cement are not significantly greater than with ordinary cement.

Specimens also were prepared (26 percent moisture and 10 percent cement) and cured for 7 days and then immersed in a solution of magnesium sulfate for 7 days. The results of those tests indicate that when the concentration of sulfate in the water exceeds 0.05 percent, significant reduction in strength occurs.

The experiments also show that in cement-treated soil made from sulfate-bearing soil, capillary movement can cause deposition of salt and detrimental action in the form of expansion in the zone where the salts crystallize.

Soil State—General.—The quality of cement-treated soil in large measure depends on the soil state during mixing and compacting. The degree of pulverization limits the degree of mixing possible. The moisture content has a major influence on not only the density, but also on the manner in which the mass is "knit" together (coheres), and it has a bearing on cement hydration. The density has a marked influence on strength. Although there is a close interrelationship between moisture content and density, they are discussed here insofar as is practicable in terms of their separate influences.

Degree of Pulverization.—Data from two series of experiments are available that illustrate the influence of the degree of pulverization on the properties of cement-treated soil. One series (22) brings out the effect of pulverization on losses in the wet-dry and freeze-thaw tests; the other shows the effect of pulverization on compressive strength after curing and immersion in water.

The first series (22) was made using 0, 20, and 40 percent unpulverized soil lumps each for an A-4 silty clay loam (LL = 37, PI = 12, SL = 20) and an A-7 clay (LL = 37, PI = 18, SL = 18). The lumps were of No. 4 sieve to 1-in. size. In one set for each soil, air-dry lumps were added to minus No. 4 sieve material that was at AASHO optimum moisture content and specimens were molded immediately. In another set, air-dry lumps were added to the minus No. 4 mix that was also air-dry. Water was then added to bring the total mix to optimum moisture content. Wet-dry and freeze-thaw tests showed that when clay lumps were dry the poorest durability was obtained. Mixes having moist clay lumps showed good resistance to the wet-dry and freeze-thaw tests. The results are given in Tables 10 and 11.

The second series (58) of tests was made on a very heavy clay (LL = 75, PI = 47). Specimens of cement-treated soil were prepared containing single-sized aggregations as follows:

1. Passing B.S. (British Standard) No. 10 sieve and retained on No. 14 sieve,
2. Passing B.S. No. 36 sieve and retained on No. 52 sieve,
3. Passing B.S. No. 150 sieve and retained on No. 22 sieve, and
4. Extruded aggregations $^3/_{16}$ in. in diameter by $^3/_{16}$ in. long.

Specimens were also prepared having a continuous grading from No. 14 to No. 200 sieves and various proportions of single-sized extruded aggregations. Mixing was by

TABLE 10

MOLDING DATA FOR SOIL 4b-6, PLUS 14 PERCENT CEMENT BY VOLUME, AASHO OPTIMUM MOISTURE CONTENT 19.8 PERCENT, MAXIMUM DENSITY 102.5 PCF (SPECIMENS MOLDED ONLY FOR FREEZE-THAW TEST) (22)

Set No.	Data on Clay Lumps: % Included	Moisture Content (%): When Added to Mix	Moisture Content (%): After Mixing	Moisture Content of Specimen (%): Minus No. 4 Mix	Moisture Content of Specimen (%): Total Mixture	Density of Specimen (pcf)	Loss Due to 12 cyc. F-T(%)
	0	-	-	19.9	19.9	102.5	2
A	20	3 to 4	4 to 5	19.8	16.4	103	8
	40	3 to 4	4 to 5	19.8	13.2	100	62
B	20	3 to 4	13 to 18[a]	-	20.1	101	6
	40	3 to 4	13 to 19[b]	-	19.7	101	8

[a]14 percent clay lumps (unpulverized soil retained on No. 4 sieve) after damp mix completed.
[b]22 percent clay lumps (unpulverized soil retained on No. 4 sieve) after damp mix completed.

TABLE 11

MOLDING DATA FOR SOIL 7h, PLUS 12 PERCENT CEMENT BY VOLUME, AASHO OPTIMUM MOISTURE CONTENT 16.8 PERCENT, MAXIMUM DENSITY 108.4 PCF (SPECIMENS MOLDED FOR WET-DRY AND FREEZE-THAW TESTS) (22)

Set No.	Data on Clay Lumps: % Included	Moisture Content (%): When Added to Mix	Moisture Content (%): After Mixing	Moisture Content of Specimen (%): Minus No. 4 Mix	Moisture Content of Specimen (%): Total Mixture	Density of Specimen (pcf)	Loss Due to 12 Cyc. (%): W-D	Loss Due to 12 Cyc. (%): F-T
	0	-	-	17.2	17.2	109	3	3
A	20	2	2	17	14.2	111	33	32
	40	2	2	17	11	109	100	100
B	20	2	9 to 13[a]	-	17.5	109.5	5	4
	40	2	11 to 16[b]	-	18	109.5	10	6

[a]20 percent clay lumps (unpulverized soils retained on No. 4 sieve) after damp mix completed.
[b]30 percent clay lumps (unpulverized soils retained on No. 4 sieve) after damp mix completed.

hand. The cement and soil was first thoroughly mixed; water was then added until optimum was obtained. Specimens 2 in. in diameter by 4 in. high were prepared at a state of compaction corresponding to an air content of 1 percent according to the method set out in British Standard, 1953. Specimens were cured for the following periods:

1. Seven days coated with wax,
2. Seven days coated with wax plus 7 days immersed in water, and
3. Seven days coated with wax plus 28 days immersed in water after removal of wax.

Results were as follows:

Specimens containing aggregations of a single size.—An illustration of data showing the relation between compressive strength and cement content after 7 days in wax plus 7 days immersion in water is given in Figure 38. The results of studies of specimens

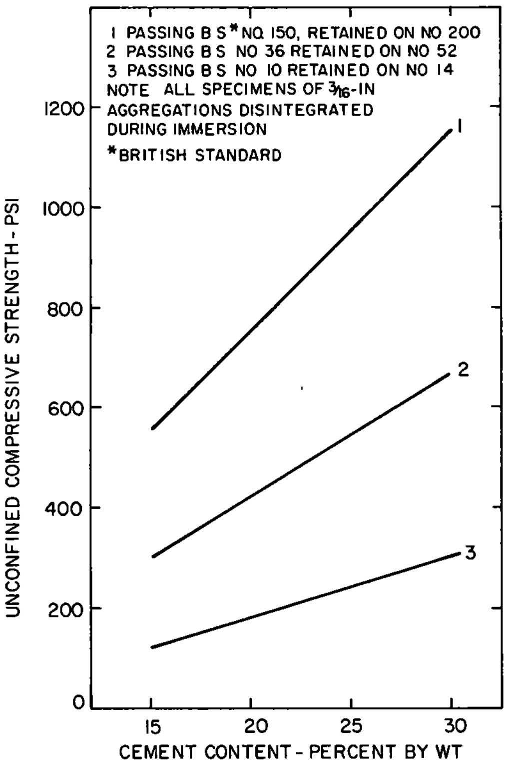


Figure 38. Relation between unconfined compressive strength and cement content for specimens containing single-size aggregations—curing: 7 days wax coated plus 7 days immersion (58).

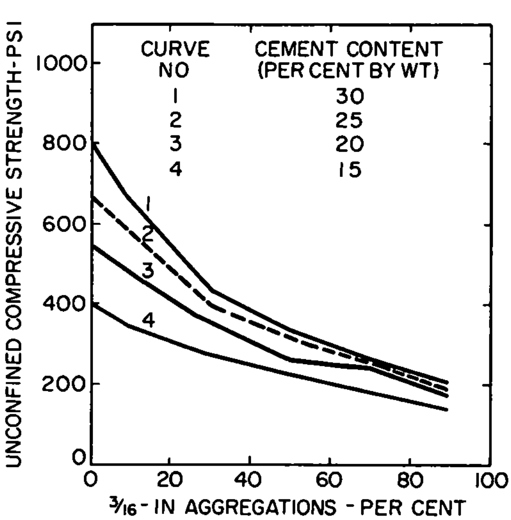


Figure 40. Relation between compressive strength and percent of 3/16-in. aggregations for various cement contents—curing: 7 days in wax coating (58).

containing single-sized aggregations showed: (a) the relation between strength and cement content is linear; (b) strength increases with decrease in aggregation size (for all three curing conditions); and (c) strength after 28 days immersion was greater in all cases than after 7 days immersion.

Specimens containing graded aggregations and various proportions of 3/16-in. ag-

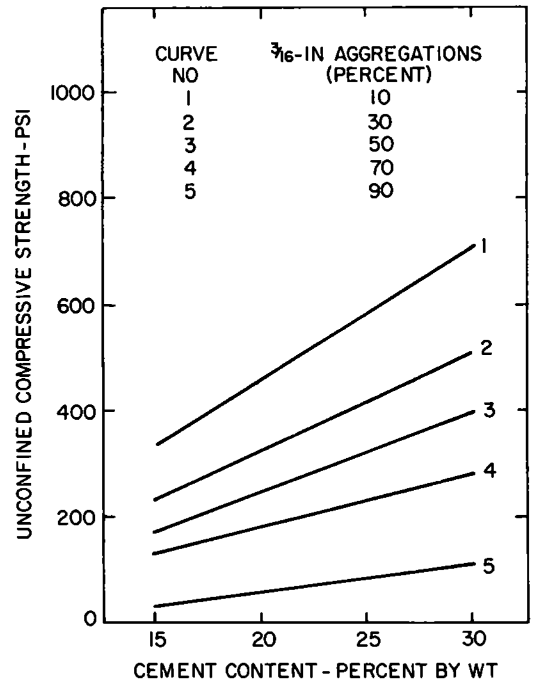


Figure 39. Relation between compressive strength and cement content for various percentages of 3/16-in. aggregations—curing: 7 days wax coated plus 7 days immersion (58).

gregations.—An illustration of data showing the relation between compressive strength and cement content for various percentages of 3/16-in. aggregations after 7 days in wax and 7 days immersion is indicated in Figure 39. The results of these tests on specimens containing graded aggregations and various percentages of 3/16-in. aggregations show that: (a) the relations between strength and cement content are linear; (b) the strength increases with decrease in percent of 3/16-in. aggregations as is illustrated in Figure 40; and (c) the compressive strength after 28 days immersion was greater in all cases than after 7 days immersion.

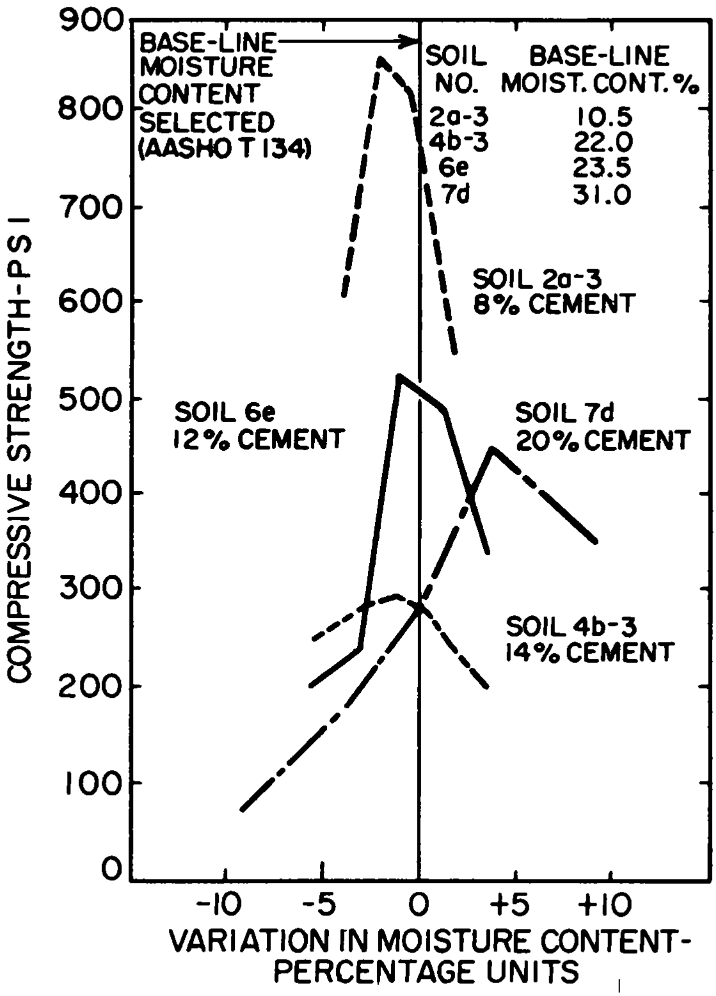


Figure 41. Effect of moisture content on 28-day compressive strength (22).

Summarizing, the quality of the cement-treated silty and clayey soils is highest when 100 percent of the soil, exclusive of gravel or stone, is pulverized to pass a No. 4 sieve. However, the quality is not seriously affected by the presence of as much as 30 percent unpulverized soil provided the lumps are moist (at or slightly above optimum) at the time of compaction of the cement-treated soil. If the lumps are dry at the time of compaction the quality of the mixture may be seriously impaired.

Moisture Content of Cement-Treated Soil at Time of Compaction (22, 23, 40, 48, 59, 60, 61, 62, 63).—Cement-treated soil exhibits the same type of moisture-density relationship as do untreated soils. Thus, the moisture content at the time of compaction has strong influence on the properties of the cement-treated soil. Moisture-density relationships also have a bearing on cement hydration. However, the influence of moisture is related more to its ability to improve workability and facilitate compaction to obtain a coherent (well-knit) mass than it is to the water requirements for hydration, because adequate water for compaction insures adequate water for hydration provided it is not lost during the curing period. The significant moisture content is that which prevails at the time of compaction and throughout the curing.

Data are available from a special study made on specific cement-treated soils to determine the effect of moisture and density on compressive strength and on losses in the wet-dry and freeze-thaw tests (22). The influence of moisture content is illustrated by using the optimum moisture content (AASHO) as a base-line moisture content and varying moisture above and below that line while holding the compactive effort constant. It was realized that with compactive effort constant, density varies; the effect

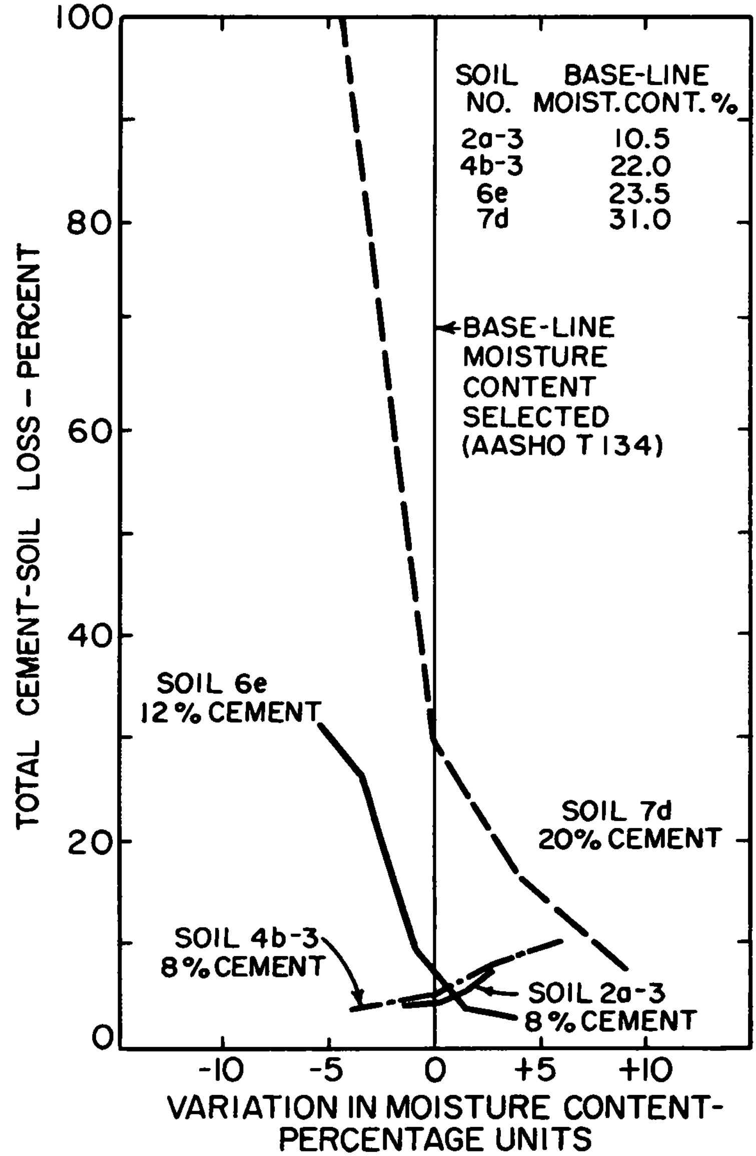


Figure 42. Effect of moisture content on cement-soil loss in the wet-dry test (22).

of moisture, however, usually overshadows the effect of density (22). The soils used in the tests are similar to those used in the density studies (Table 14). The influence of moisture content on compressive strength and on losses in the wet-dry and freeze-thaw tests are shown in Figures 41, 42 and 43. Those results may be summarized as follows:

1. Compressive strength increases to a maximum at slightly less than optimum

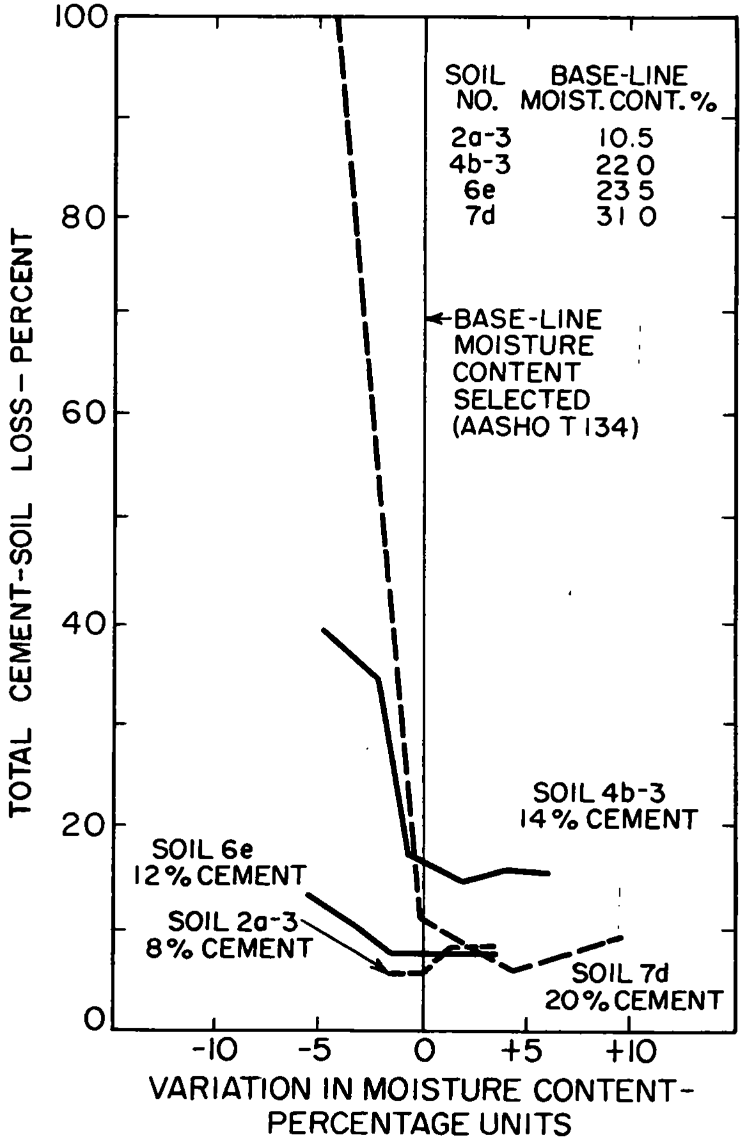


Figure 43. Effect of moisture content on cement-soil loss in the freeze-thaw test (22).

moisture for the sandy soil and the silty soil, and at greater than optimum for the clay soil. This indicates that for soil 7d (Table 14), having an irregular curve, the base-line moisture content may have been too low and should have been about 36 percent (the plastic limit is 35) instead of 31 percent. The fact that strength reaches a maximum and decreases in a manner somewhat like that of the moisture-density curve suggests that the effect of density is strong. This resulted in additional tests for all three soils in which density was held constant. The effect of holding density constant is given for three soils in Table 12. The lower moisture content coupled with density equal to AASHO maximum had no significant effect on the strength of the sandy soil, but produced inferior cement-treated soil as indicated by the reduced strengths accompanying the lower moisture content for the clayey soils.

2. Results from the wet-dry and freeze-thaw tests show that the clayey soil had

less resistance at moisture contents below AASHO optimum and the silty soil had less resistance in the freeze-thaw test at moisture contents less than optimum. Moisture contents were not so critical in either test for the sandy soil.

TABLE 12

COMPRESSIVE STRENGTHS OF CEMENT-TREATED SOILS COMPACTED ACCORDING TO AASHO COMPACTIVE EFFORT AND AT OPTIMUM MOISTURE CONTENT FOR BOTH STANDARD AND MODIFIED TESTS

Soil	AASHO Max Density[a] (pcf)	Opt. Moisture Content (%)	Cement Content (%)	Compr. Strength (psi) 7-Day	Compr. Strength (psi) 28-Day
2a—sandy loam	121	10.8[b]	8	665	800
2a—sandy loam	121	9.0[c]	8	632	769
4d—silty clay loam	108	17.0[b]	12	596	668
4d—silty clay loam	108	12.5[c]	12	277	293
6e—silty clay	102.5	18.5[b]	12	417	486
6e—silty clay	102.5	13.8[c]	12	138	149

[a]Modified AASHO maximum densities for the three soils are: 2a = 128.5 pcf, 4d = 121.5 pcf, and 6e = 115.5 pcf.
[b]AASHO standard density and AASHO optimum moisture content.
[c]AASHO standard density and Modified AASHO optimum moisture content.

Moisture Content of Cement-Treated Soil at Time of Testing—Wet-Dry Strength Ratio (14, 43, 63).—The moisture content at the time of performing a strength test has great influence on the compressive strength of cement-treated soil. One source of data (14) shows that for a nonplastic sandy loam soil (A-1-b) containing 3 and 10 percent cement, the dry strength averaged 180 percent of the strength of the moist specimens; for an A-6 sandy clay soil (PI = 15) dry compressive strengths averaged 245 percent of that of the moist specimens.

A second source (63) of data on cement-treated soil blocks made from four soils (a sandy loam having a PI of 6.5, a silty loam having a PI of 10, a silty clay loam having a PI of 19 and a loam soil having a PI of 11) showed that strengths of dry specimens ranged from 190 to 290 percent of the strength of moist specimens. The wet and dry compressive strengths for two of the soils, the sandy loam and the silty clay loam, are shown in Figure 44.

The wet-dry strength ratios of the four soils (63) increased with increase in cement content to a maximum and decreased. Relationships between wet-dry strength ratio and cement content for the same two soils indicated in Figure 44 are shown in Figure 45. Two sets of the cement-treated soil blocks were made from each of the four soils. One set was cured for one week, dried to constant weight and tested for compressive strength. The other set was similarly cured, then allowed to saturate by capillary contact with wet sand and tested after "complete saturation." It is of interest that the saturated blocks, on redrying, attained high strengths similar to those dried initially after curing.

The molding moisture content of soil-cement blocks tested (43) had some influence on the wet-dry strength ratio. The nature of the effect is indicated in Table 13.

Summarizing, the testing of cement-treated soil in a dry state evaluates the combined cohesive effect of the soil and the cementing action of the cement. In a road base course, cement-treated soil exists in the moist state. Accordingly, if realistic strength values are to be obtained, tests must be made on moist specimens as provided for in ASTM methods (43).

Density (22, 23, 28, 64).—The strength and durability of cement-treated soil are strongly influenced by density. The relationship between strength and density approaches a straight line for some soils and cement contents (23, 64). A 5 percent decrease in relative compaction may result in a greater strength reduction than a drop of 10 to 15 percent in cement content (from 10 percent cement to 9 or 8½ percent) (64). Research by the British Road Research Laboratory has established that a given moisture content the strength of soil-cement is related

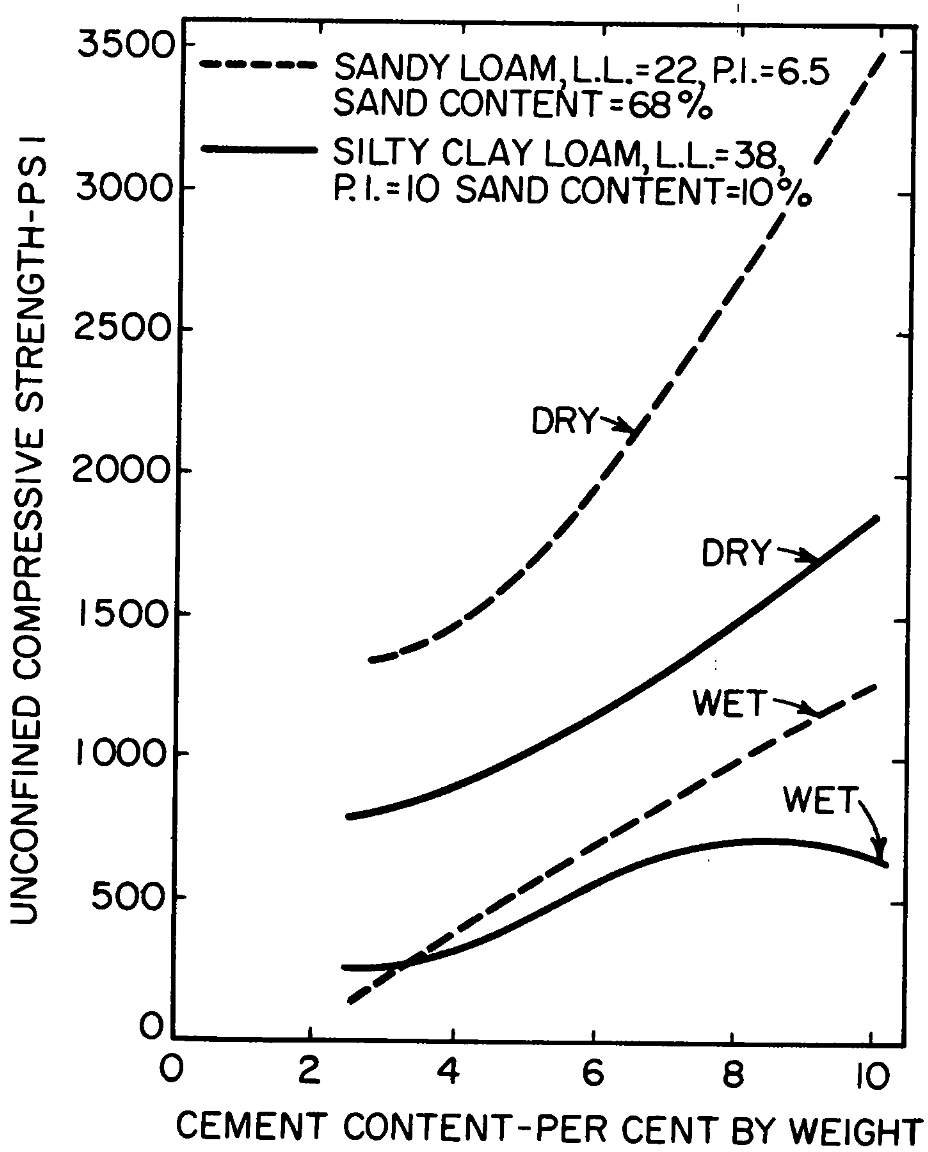


Figure 44. Compressive strengths of cement-treated sandy loam and silty clay loam soils in saturated and in dry states (63).

linearly to the logarithm of the density (215).

The nature of the influence of density has been indicated in part under "Properties of Cement-Treated Soil" and "Factors Influencing Properties of Cement-Treated Soil, Moisture Content at the Time of Compaction." It is further indicated here by the use of examples of data on different types of soils to illustrate its influence on compressive strength and durability of cement-treated soil.

Research studies (22) were conducted on four different soils to evaluate the effect of density. The index properties of the four soils are given in Table 14. Standard AASHO moisture-density tests (AASHO T 134) were performed. Two of the soils produced parabolic and two produced irregular-shaped moisture-density curves as indicated in Figure 46.

AASHO Method T 134 maximum density was used as a base-line density in molding specimens. The moisture content was held constant. The density was varied above and below the base-line values by varying the compactive effort. Cement contents are in percent by volume of the compacted mixture. Type I (normal) portland cement was used.

Results of the wet-dry, freeze-thaw and compressive strength tests are shown in Figures 47, 48, and 49. These figures permit observation of the significance of density in view of the adequacy or inadequacy of the cement content (for appropriate density) to satisfy criteria for soil-cement (See "criteria for Soil-Cement"). The results show that increasing the density: (a) decreased the brushing losses for all mixtures in both wet-dry and freeze-thaw tests but had the greatest effect on the clayey soil mix in the wet-dry test and the silty soil mix in the freeze-thaw test. Brushing losses decreased

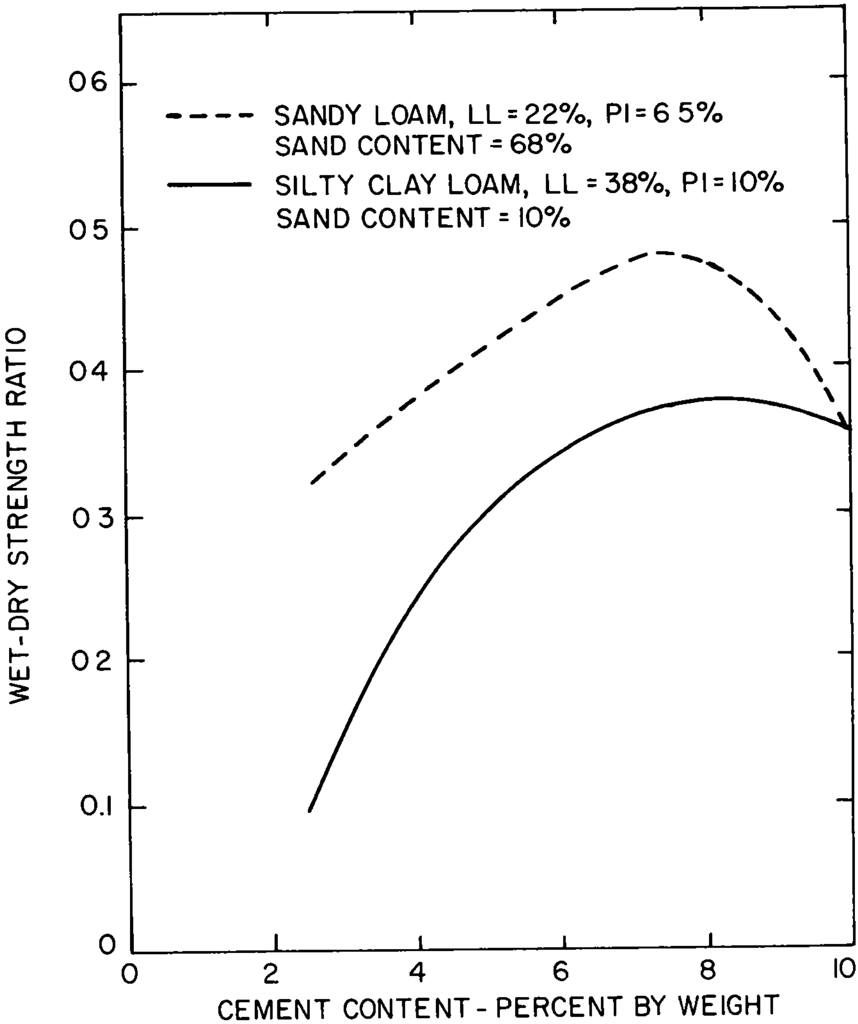


Figure 45. Ratio of wet to dry compressive strength of cement-treated soil blocks made from sandy loam and silty clay loam soils (63).

TABLE 13

EFFECT OF MOLDING MOISTURE CONTENT ON THE WET-DRY STRENGTH RATIO OF CEMENT-TREATED SOIL BLOCKS PREPARED WITH TWO SOILS (43)

Molding Moisture Content (% of Proctor opt. moisture content)	Average 28-Day Compr. Strength of Soil-Cement Blocks (psi)		Wet-Dry Strength Ratio
	Dry	Wet	
Sandy soil (PI between 0 and 5):			
80	641	285	0.445
100	599	284	0.475
120	553	242	0.440
Clayey soil (PI above 12):			
100	247	140	0.570
130	416	165	0.395
180	257	99	0.385

TABLE 14

INDEX PROPERTIES OF SOILS USED IN STUDY OF THE EFFECT OF DENSITY ON THE PHYSICAL PROPERTIES OF CEMENT-TREATED SOILS (22)

Soil No.	Gradation - Percent of Total: Sand 2.0 to 0.25 (mm)	Sand 0.25 to 0.05 (mm)	Silt 0.05 to 0.005 (mm)	Clay 0.005 to 0.000 (mm)	Atterberg Limits LL	PI	SL	Textural Glass	AASHO Soil Group
2a-3[a]	35	46	8	11	13	NP	21	Loamy sand	A-2
4b-3[b]	2	17	57	24	38	13	25	Si. cl. lm.	A-4
6-e[c]	2	10	35	53	49	26	17	Clay	A-6-7
7-d[d]	0	14	18	68	118	83	14	Clay	A-7

[a]A mixture of A-, B-, and upper C- horizons from South Carolina.
[b]A dark gray lower A-horizon soil from Illinois.
[c]A brown B- and upper C-horizon soil from Illinois.
[d]A light brown B- and C-horizon soil from Mississippi.

1 to 3½ percentage units for each pound increase in density; and (b) markedly increased the compressive strengths of all mixtures. In general, an increase in density of 1 pcf in the low density range increased compressive strengths 15 to 25 psi.

Because the quality of cement-treated soil improves as the density increases, mixtures at the proper moisture content should be compacted to the highest practical density, preferably at least equal to that obtained by AASHO Method T 134. For special construction where high compactive effort equipment is available, it may be economical to make use of increased densities with correspondingly lower optimum moisture contents.

Because of the strong effect of densities of only 5 pcf greater than Standard AASHO maximum and the interrelated effect of moisture content additional tests have been performed on three soils—a sandy soil, a silty soil, and a clay generally similar to those given in Table 14—to compare the behavior of those soils when compacted by the Modified AASHO procedure (4-in. diameter mold, 25 blows of 10-lb hammer with 18-in. drop on each of five layers).

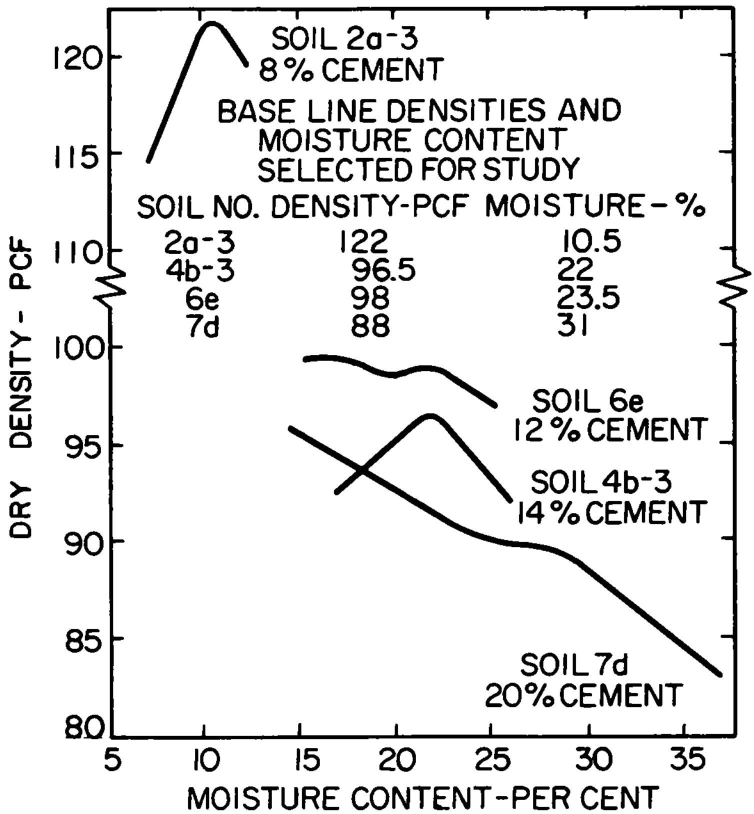


Figure 46. Moisture-density relations of cement-treated soils used in studies of the effect of moisture content and density on properties of the mixtures (22).

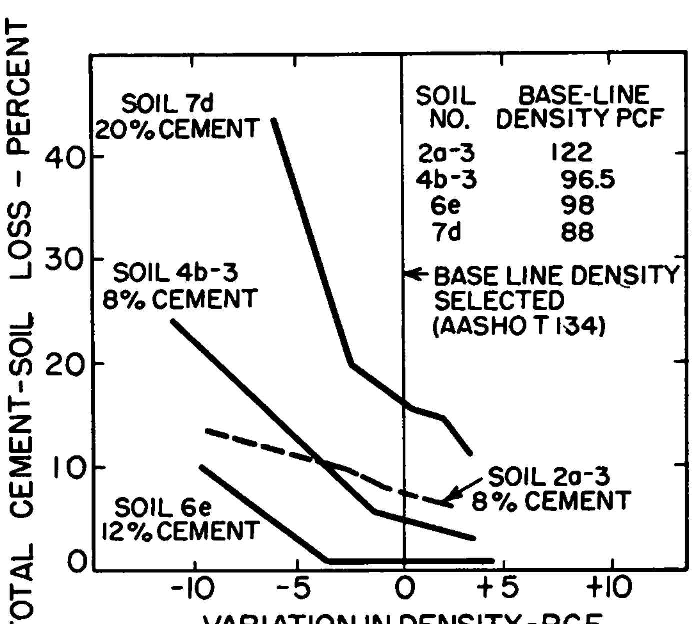


Figure 47. Influence of density on brushing losses in the wet-dry test (22).

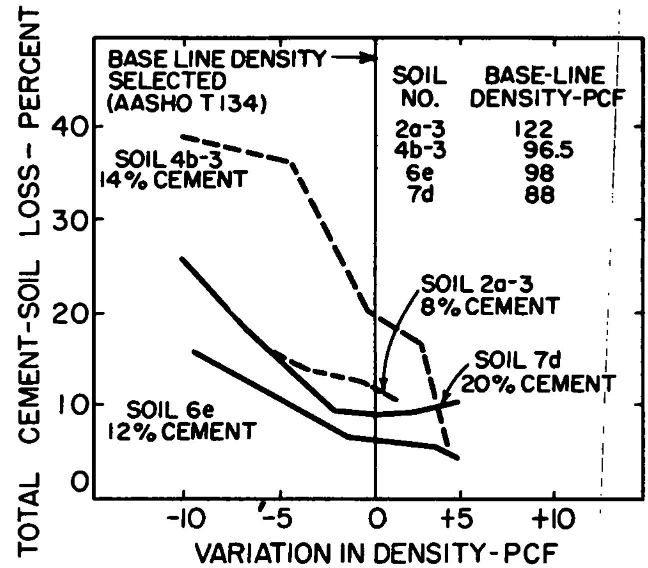


Figure 48. Influence of density on brushing losses in the freeze-thaw test (22).

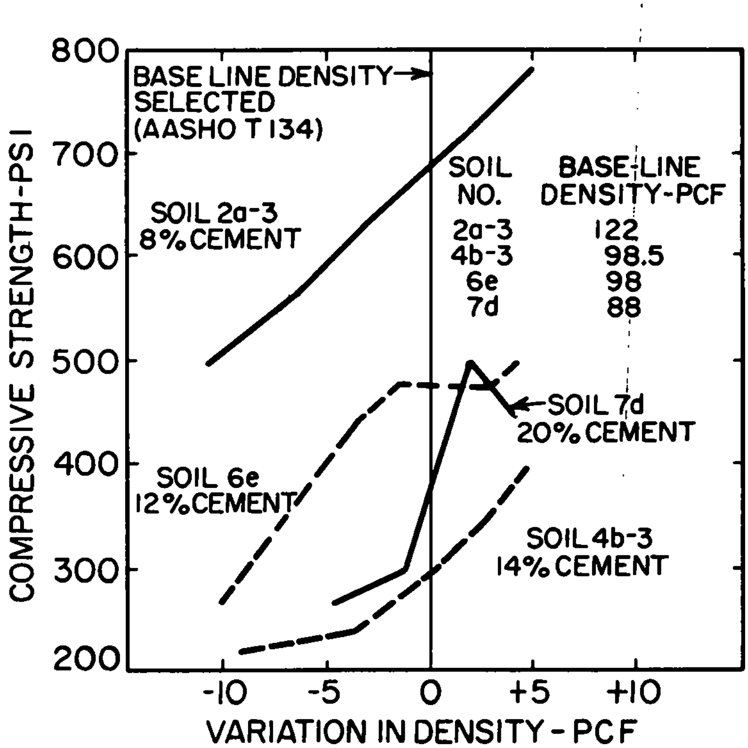


Figure 49. Influence of density on 28-day compressive strength (22).

Data given in Table 15 indicate the relative quality of the mixture produced using basic molding data from the two compaction methods but with cement content held con-

TABLE 15

COMPRESSIVE STRENGTHS AND WET-DRY AND FREEZE-THAW LOSSES OF CEMENT-TREATED SOIL COMPACTED TO AASHO STANDARD AND AASHO MODIFIED MAXIMUM DENSITIES AND OPTIMUM MOISTURE CONTENTS (22)

Soil	Compaction System[c]	Density (%)	Moisture Content (%)	Compr. Strength (psi) 7 Days	28 Days	Wet-Dry Loss (%) 12 Cycles	24 Cycles	Freeze-Thaw Loss (%) 12 Cycles	24 Cycles
2a-4[a]	A	121	10.8	665	800	3	5	5	7
	B	128.4	9	732	1,303	3	4	5	5
	C	121	9	632	769	-	-	-	-
4-d[b]	A	108	17	596	668	3	7	3	6
	B	121.5	12.5	933	1,202	3	27	3	6
	C	108	12.5	277	293	-	-	-	-
6e-4[b]	A	102.5	18.5	417	486	31	86	9	35
	B	115.5	13.8	427	709	28	97	5	6
	C	102.5	13.8	138	149	-	-	-	-

[a]8 percent cement by volume.
[b]12 percent cement by volume.
[c]A = AASHO Standard maximum density, AASHO Standard optimum moisture content;
B = AASHO Modified maximum density, AASHO Modified optimum moisture content;
C = AASHO Standard maximum density, AASHO Modified optimum moisture content.

stant on a percent by volume basis. (This means that under heavier compaction the cement had a greater weight of soil to stabilize. Had cement been based on percent of weight of soil the proportion of cement to soil would have remained constant.) Nevertheless, the cement-treated mixtures produced at the Modified AASHO density and optimum moisture content are generally higher in strength and about equal in durability to those produced at Standard AASHO values. However, when the lower moisture content of the Modified method is used and the densities are not obtained, the quality of the cement-treated mixtures may be inferior to that produced at the Standard AASHO optimum moisture and maximum density as is indicated for compaction system C in Table 15.

Summarizing, the essential relationship associated with quality of cement-treated mixtures using fine-grain soils is to compact the mixtures to the density required for adequate strength and at that moisture content that provides a minimum of air voids (23). The relationships between density, moisture content and air void content are shown in Figure 50.

Cement Content (12, 19, 24)

For a given soil that reacts normally with cement, the cement content determines the nature of the cement-treated soil. The proportion of cement alters the plasticity, volume change, susceptibility to frost heave, elastic properties, resistance to wet-dry and freeze-thaw alternations, and other properties in different degrees for different soils. Many relationships have been indicated in tabular and graphical data presented in preceding paragraphs.

The influence of cement is more apparent from tests made on three soils—a sandy loam, a silty loam and a silty clay—with cement content the only variable (22). Cement contents were varied from 6 to 30 percent to bracket the cement-modified soil type of stabilization for the fine-grain groups and to extend the cement contents well above the requirements necessary to satisfy minimum PCA criteria for soil-cement. Figures 51, 52 and 53 show cement content vs compressive strength relationships for five age periods ranging from two days to one year. The index properties of the three soils are indicated on the figures. Brushing losses in wet-dry and freeze-thaw tests ranging from 12 to 96 cycles, (Table 16) are indicative of the influence of cement content on the resistance to those tests.

Type of Cement (22, 55, 66, 67, 68)

Normal and Air-Entraining Cements.—Controlled experiments comparing the use of

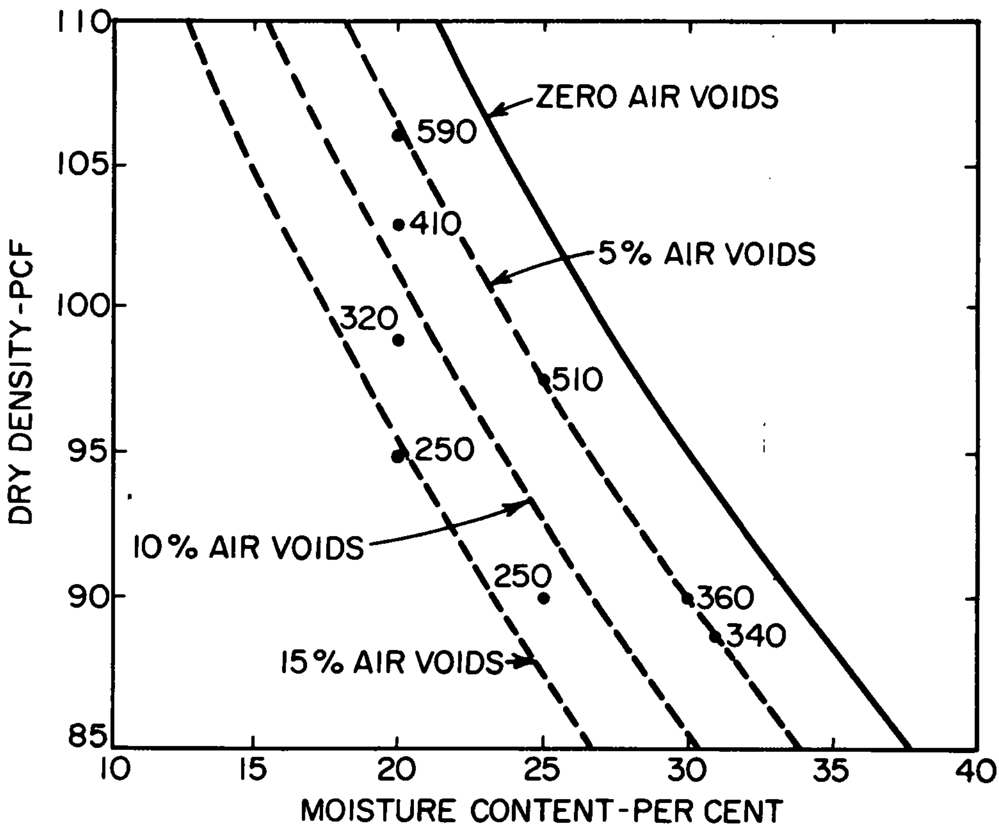


Figure 50. Influence of density and moisture content on compressive strength of clay-cement-lime mixture (15 percent cement + 2 percent lime) cured 7 days. Numbers show unconfined compressive strength, psi (LL of soil = 70 to 75 percent, PI = 45 to 53 percent (23).

normal (Type I) and air-entraining (Type IA) cements with three soils whose index properties are indicated in Figures 51, 52 and 53, have shown that moisture-density relationships, compressive strengths and brushing losses in wet-dry and freeze-thaw tests were sufficiently similar to show that the two types of cement can be used interchangeably in soil-cement construction.

Comparative compressive strength data on cement-treated soil mixtures prepared with low (0.17 percent), medium (0.48 percent) or high (0.92 percent) alkali content (total equivalent as Na_2O) Type I cements indicated that high alkali content is beneficial to strength if the soil contains a relatively high proportion of clay-free quartz surfaces (66).

High-Early-Strength Cement (Type III) (22, 55, 66, 67, 68).—Similar experiments (22) with Type III cements have shown that the optimum moisture contents and maximum densities obtained are approximately the same for Type I and Type III cements.

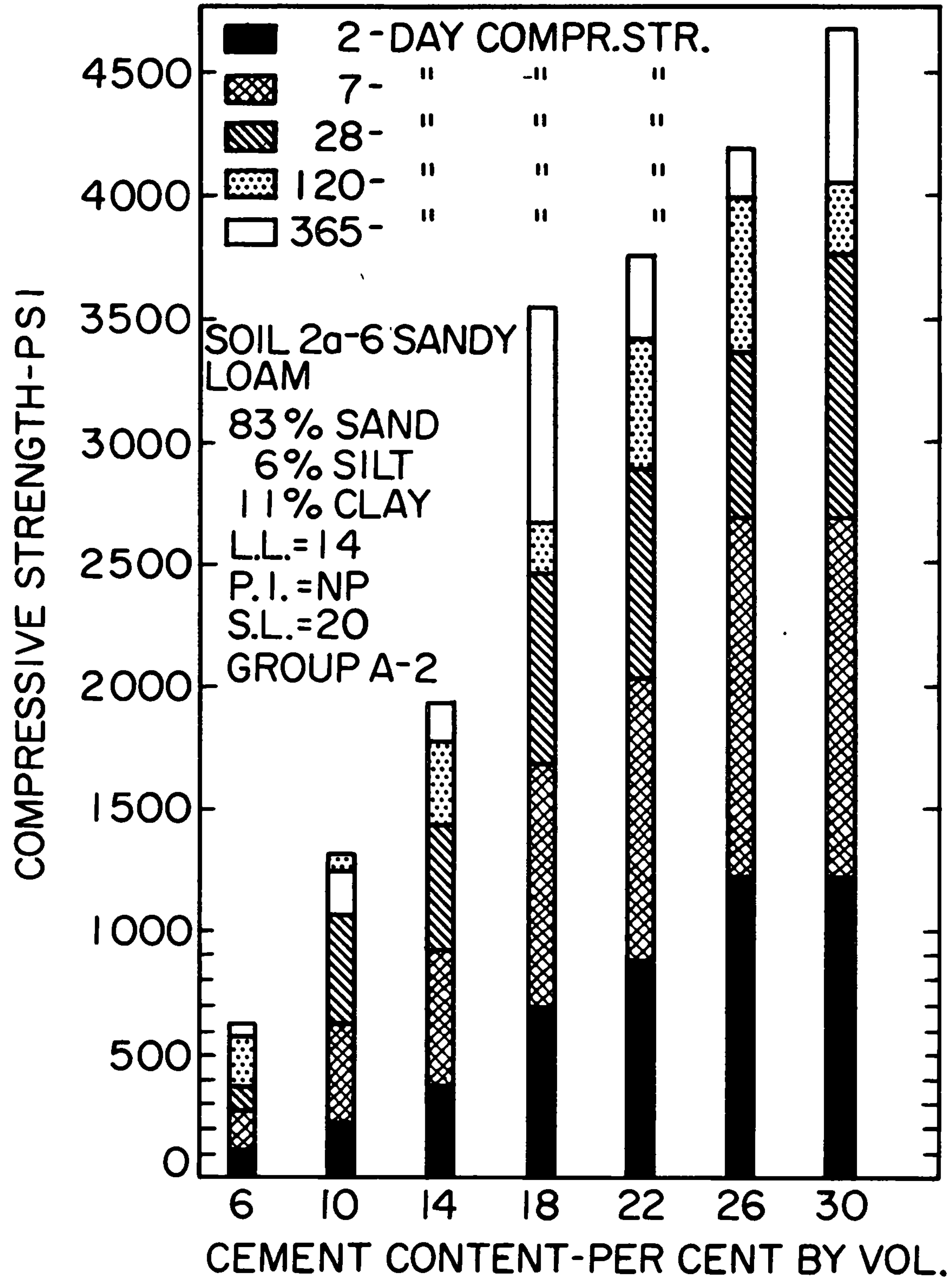


Figure 51. Effect of cement content and age on compressive strength for a loamy sand (22).

Determinations of the influence of type of cement on rate of gain of compressive strength were made on two soils in studies of the effect of prolonged mixing time (22). The results of those findings for a sandy loam and a silty clay loam are given under "Duration of Mixing Period" (Fig. 59).

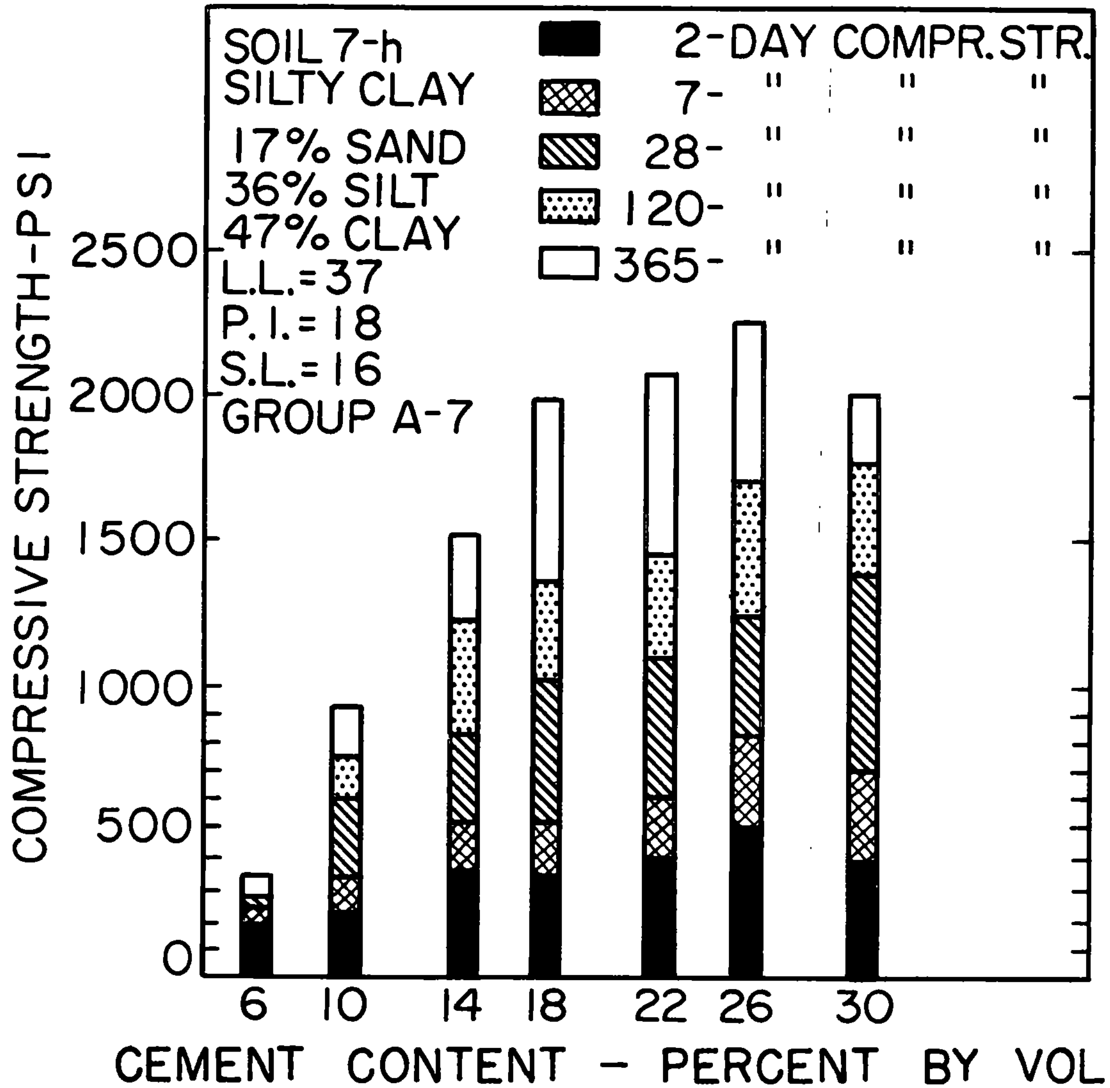


Figure 52. Effect of cement content and age on compressive strength for a medium clay (22).

Compressive strength and freeze-thaw tests on cement-treated sandy, silty and clayey Iowa soils have indicated the possibility of significant economic and/or structural advantages in using Type III cement instead of Type I cement for soil-cement road construction (66).

Type III cement does not have the same influence on strength for all soils. On loamy sand (Fig. 59) the 7- and 28-day strengths for Type III cement were about 2 and 1.4 times the strength of the values for Type I cement, respectively; for a silty clay loam the strength for Type III was only slightly greater than for Type I cement. In another series of tests (68) on a clayey sandy silt (LL = 23, PI = 9, MC = 11, and Max Den. = 125 pcf) the mixture with Type III cement was 1.5 times as strong as that with Type I at 7 days and 1.3 times as strong at 28 days. British experience (67) on three soils showed that high-alumina cement gave highest strengths at 24 hours, but the other cements gave higher strengths after 5 days with the cohesive soils. British rapid hardening cement (equivalent to Type III) yielded higher strengths than normal cement at similar ages.

The effect of sulfate-resistant cement has been discussed under "Chemical Composition—Sulfate Content."

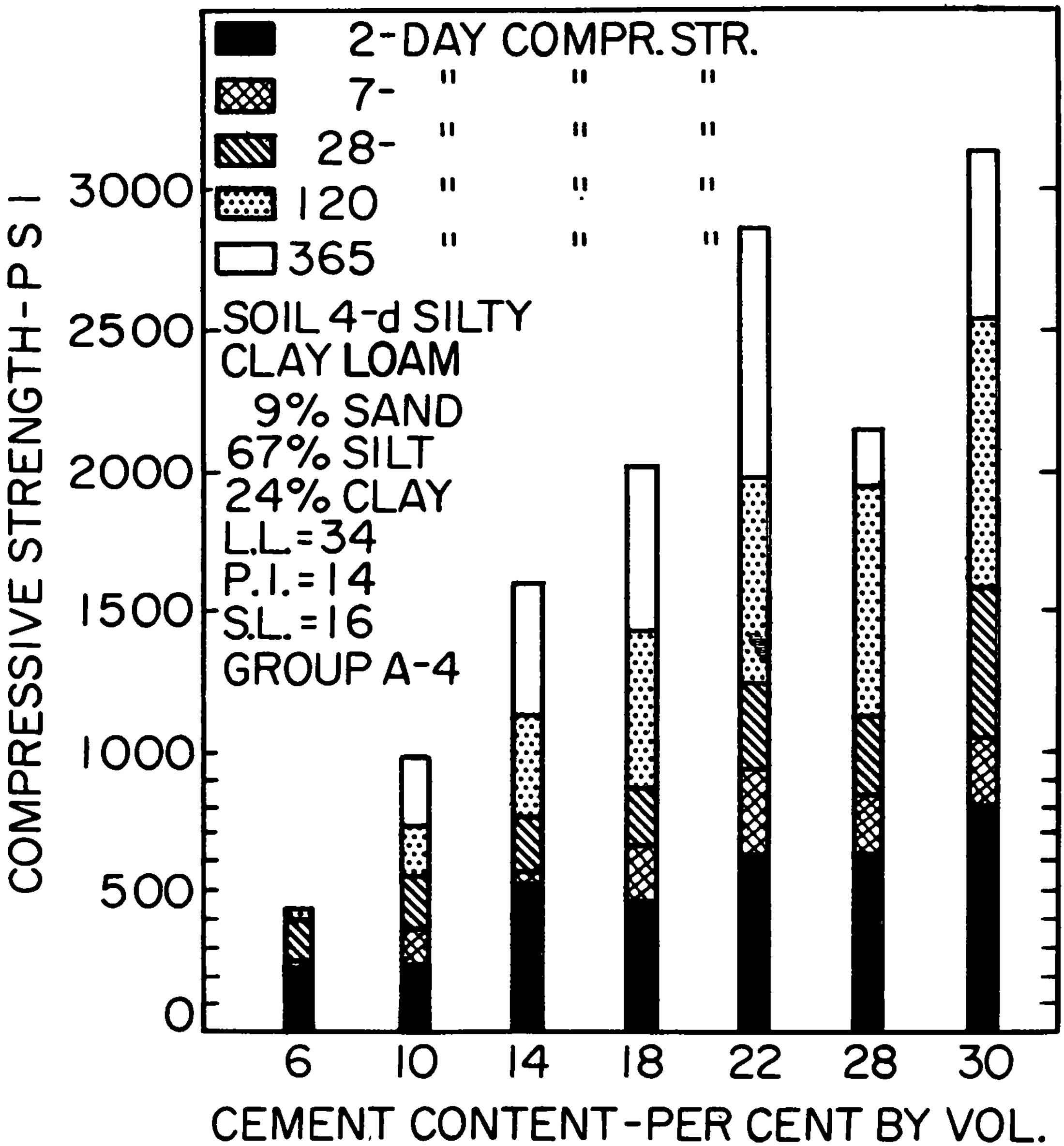


Figure 53. Effect of cement content and age on compressive strength for a silty clay loam (22).

Water

Quality.—Differences in normal potable water do not cause significant differences in the quality of cement-treated soil. Sea water has been used successfully in construction (55).

Quantity.—The influence of the proportion of water in the mix at the time of compaction has been shown under "Soil State—Moisture Content at the Time of Compaction." Further data are shown under "Conditions of Curing."

MIXING AND COMPACTING

General

The efficiency of the mixing and compacting equipment and the time required for mixing and compacting influences both the strength and the durability of cement-treated soil. Mixing involves both degree and time. The degree of mixing (62) also termed "uniformity of mixing" (70) and "efficiency of mixing" (19, 71) is a measure of the thoroughness or completeness of mixing compared to some arbitrary standard. The degree of mixing involves both the equipment and the procedures, and is closely related to the type of soil as well as its degree of pulverization and its moisture content. Degree of mixing is also a function of time. Both the degree of mixing and the time between completion of moist mixing and completion of compaction influence the properties of cement-treated soil.

Degree of Mixing

The degree of mixing has been measured experimentally by two methods. One method (62) is a direct measure of the uniformity of cement concentration by means of radio-

TABLE 16

EFFECT OF CEMENT CONTENT ON DURABILITY OF SOIL

Soil	Cement Content (Vol %)	Brushing Loss (% Orig Wt)															
		Wet-Dry Test								Freeze-Thaw Test							
		12 Cycles	24 Cycles	36 Cycles	48 Cycles	60 Cycles	72 Cycles	84 Cycles	96 Cycles	12 Cycles	24 Cycles	36 Cycles	48 Cycles	60 Cycles	72 Cycles	84 Cycles	96 Cycles
2a-6	8	6	10	14	18	21	24	27	28	12	19	25	30	37	42	46	51
	10	4	6	7	9	11	12	13	14	5	8	10	13	16	17	19	21
	12	2	3	3	4	5	6	6	6	2	4	5	7	9	10	11	12
	14	2	2	2	3	3	4	4	4	1	2	3	4	5	6	6	7
	18	1	1	1	1	1	2	2	2	0	1	1	1	2	2	2	3
	22	0	1	1	1	1	1	1	1	0	0	1	1	1	1	1	2
	26	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	1
	30	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0
4d	8	7	29	53	67	72	75	80	87	21	58	70	82	92	100	100	100
	10	5	25	43	54	63	70	76	83	7	24	33	53	66	74	88	93
	12	4	21	33	48	56	62	67	78	3	6	9	16	21	40	45	55
	14	2	9	27	35	46	47	52	60	2	4	9	14	18	20	21	24
	18	2	4	11	18	22	38	47	56	2	2	2	3	5	5	5	5
	22	1	2	7	8	9	12	17	20	2	2	2	3	5	5	5	5
	26	1	1	1	3	4	5	7	9	1	1	2	3	4	4	4	4
	30	1	1	1	2	3	4	4	5	1	1	2	2	3	4	4	4
7h	8	9	24	40	61	72	78	80	92	10	19	36	61	84	100	100	100
	10	7	18	33	45	48	49	52	56	6	18	26	41	86	100	100	100
	12	3	10	16	27	39	43	45	46	3	4	7	9	41	64	83	97
	14	2	4	9	18	24	31	33	35	3	4	7	8	10	25	43	52
	18	1	1	2	8	11	15	19	24	2	2	3	3	4	4	4	34
	22	1	1	1	2	6	7	9	11	1	1	2	2	3	3	3	27
	26	1	1	1	1	1	1	3	5	1	1	1	2	2	2	2	3
	30	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3

active tracer technique. By grinding Cobalt 60 with the cement, a scintillation counter can be used to measure the uniformity of cement distribution in the soil.

In the other method, British engineers (71) use as a measure of field mixing efficiency the ratio of the strength of specimens molded from the field mix to the strength of specimens molded from the field mix after additional laboratory mixing. The efficiency of mixing is computed from the average compressive strength of specimens mixed only by field mix, Cf, divided by the corresponding value for the remixed specimens, Cr. That is,

$$\text{Efficiency of mixing} = \frac{Cf}{Cr} \times 100 \text{ (percent)}$$

British experience indicates that 60 percent efficiency is typical of mix-in-place work by the multi-pass process for cohesive soils. That is, if the compressive strength of the laboratory re-mixed material is 400 psi, the corresponding value for the field mix is 240 psi. Higher efficiencies are obtained using the multi-pass process with granular soils and using the single-pass process with cohesive soils. Efficiencies approaching 100 percent are often obtained using plant-mix with granular soils. If the field strength

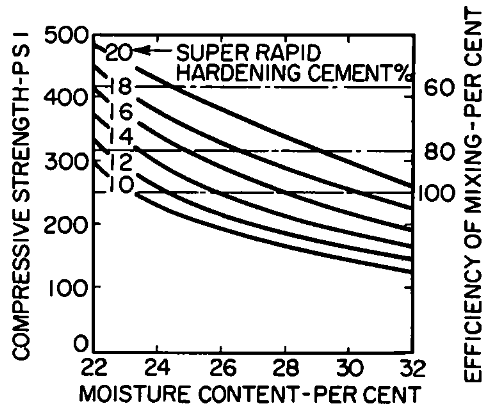


Figure 54. Efficiency of mixing vs strength (71). (Soil—clay of medium plasticity. Casagrande Classification CL.)

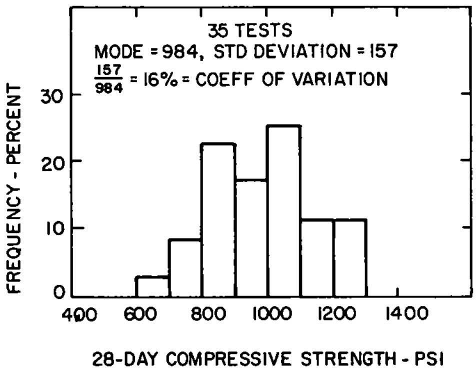


Figure 55. Uniformity of mixing Class A cement-treated base by plant-mix (pugmill) method (70) (4 to 5 percent cement).

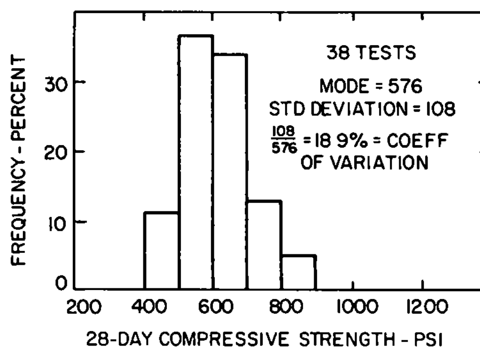


Figure 56. Uniformity of in-place mixing of Class C cement-treated base by blade method (70) (2 percent cement).

is accepted as a reliable and quick indication of stability, it can be used to advantage in judging the degree of mixing. British studies (71) show that if a given strength is desired, the cement requirements increase as mixing efficiency decreases. Figure 54 shows that a mixing efficiency of 60 percent, which is high by some standards of plant performance, means that under equal moisture conditions 5 percent more cement has to be added to obtain a field strength of 250 psi than if an 80 percent efficiency in mixing can be achieved. Field experience has shown that values as high as 90 percent have been achieved (19, 215).

Field studies have been made (70) to determine the comparative "uniformity of mixing" of Class A Cement-Treated Base. Figure 55 shows the uniformity of mixing in terms of uniformity of strength for Class A Cement-Treated Base that was plant mixed in a pugmill. Figure 56 shows similar data for a blade-mixed Class C Cement-Treated Base. These graphs show that a better grouping of test values was obtained with the Class C mix than with the Class A mix; the strengths, however, were considerably higher for the Class A mix and a greater spread of values is to be expected. The data were subjected to statistical analysis and the standard deviation and coefficient of variation (which makes allowance for the higher strength in Class A) computed. The values of 18.9 percent obtained for the Class C mix is slightly higher than the 16 percent for the Class A, indicating only slightly poorer uniformity for the Class C mix.

Duration of Mixing Period (22, 23, 40, 41)

Relative values of optimum moisture content and maximum density for laboratory-mixed soil-cement prepared from various types of soil are given in Table 8. Increasing the period of moist mixing and/or delaying compaction following completion of the moist mixing generally increases the optimum moisture content, reduces the maximum density, decreases the compressive strength, and increases the brushing losses in the wet-dry and freeze-thaw tests. The degree of the influence on each varies widely depending on the soil type, the period of mixing or period of delay (or both), and the cement content.

Prolonged intermittent mixing (up to 6 hours) may increase the optimum moisture contents for maximum compaction of cement-treated sandy loam soils about one percentage unit, silty soils one to two percentage units, and clayey soils one to three percentage units (22). Prolonged delay (up to 6 hours) may further increase the optimum moisture contents. Prolonged delay may have a similar but more or less pronounced effect on the optimum moisture content for maximum strength, the effect being less for sands, about the same for silty soils and markedly greater for clays (40).

Extended mixing reduces densities of sands in the order of 0 to 1 pcf, of sandy loams up to 3 pcf, of silty soils 2 to 4 pcf, and of clays up to 5 pcf or more. Prolonged delays without mixing may further extend these values. Maximum values recorded for extended mixing and delay for clays range from 8 pcf (23) to 11 pcf (41).

More significant is the influence of prolonged mixing and delay on compressive strength and durability. Laboratory studies (22) were made on three soils—an A-2 sandy loam (LL = 26, PI = 11), an A-4 silty clay loam (LL = 35, PI = 12), and an A-6-7 clay (LL = 47, PI = 26)—to determine the effect of prolonged intermittent mixing on compressive strength. The relationships developed are shown in Figure 57. All soils showed a decrease in strength with increase in intermittent mixing time. Prolonged intermittent mixing was found less harmful than an undisturbed delay. Australian studies (40) of the effect of delay show marked decreases in strengths for some soils and lesser effect on the strengths of others. The results of their studies are indicated in Figure 58.

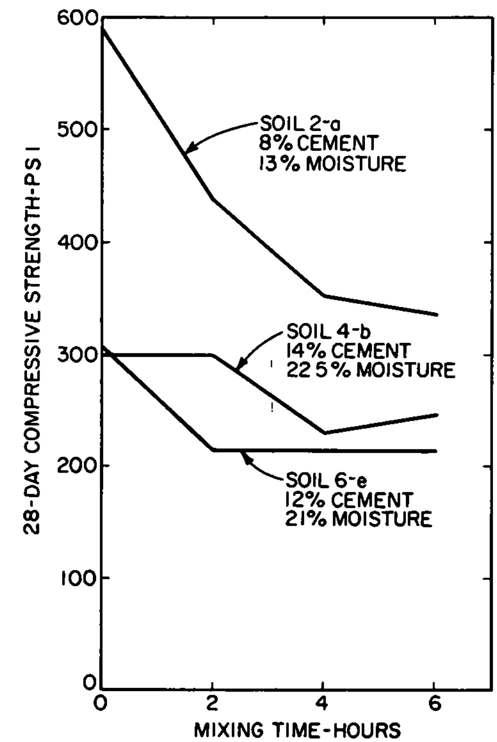


Figure 57. Effect of length of mixing time on the compressive strength of cement-treated soils (22) (intermittent mixing).

The Australian studies (40) showed that by increasing the compactive effort and thus bringing density values near to those for "no delay" the strength would be nearer to the "no delay" strength values.

Studies of prolonged intermittent mixing (22) were also made to determine its comparative effect on the compressive strengths at various ages of cement-treated soil mixtures made with Type I (normal) and Type III (high-early-strength) cements. The soils used were an A-2 nonplastic loamy sand and on an A-4 silty clay loam (samples 2a-6 and 4-d, Table 14). Strengths for both soils at all cement contents and for both mixing procedures ("zero-hour" mixing and 4-hour intermittent mixing) were consistently greater with the Type III cement. The effect of prolonged mixing period on strengths produced by the two types of cement are shown in Figure 59.

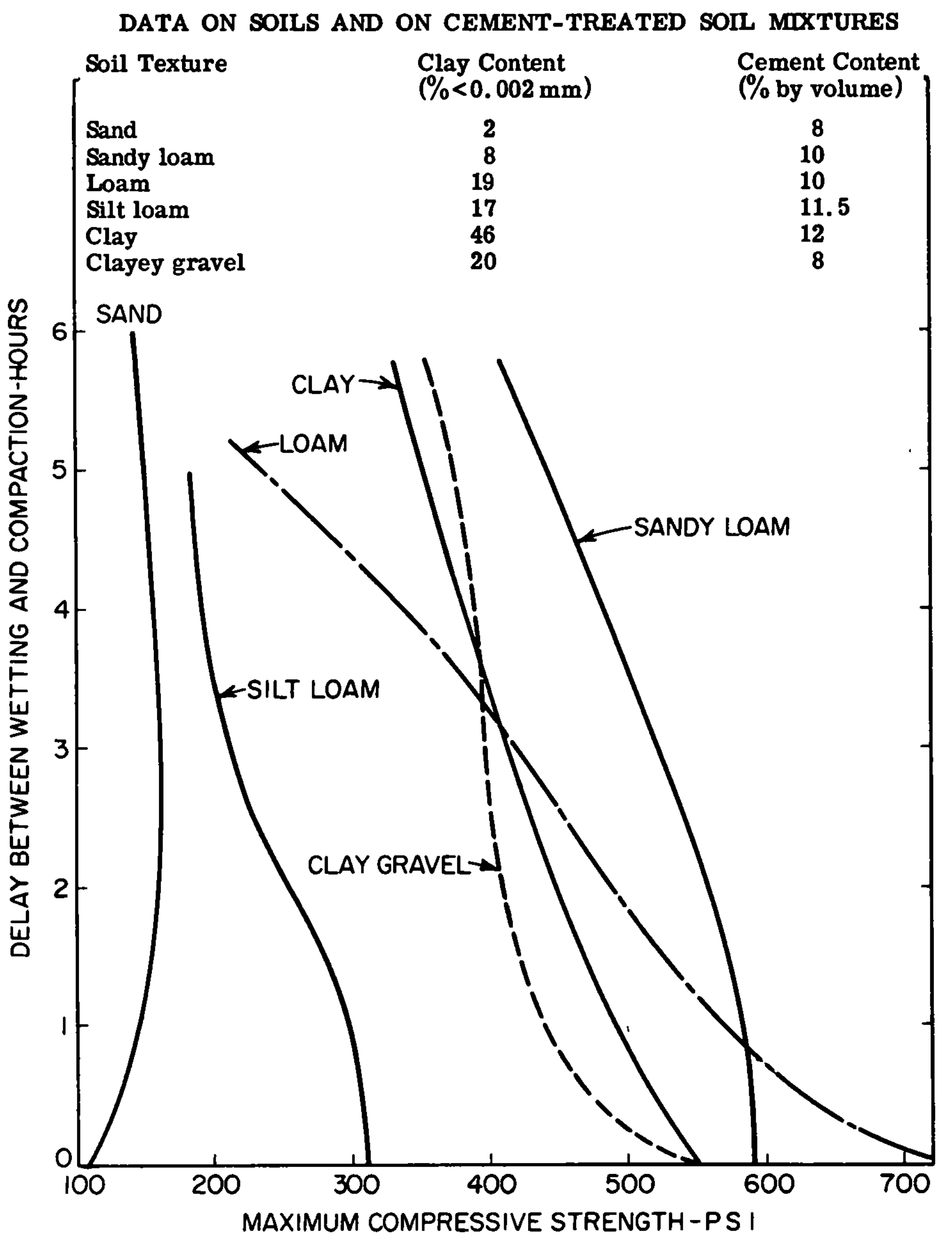
Wet-dry and freeze-thaw test brushing losses increase as the length of moist mixing increases. This is most pronounced when there is no intermittent mixing for an extended period. However, inasmuch as there is usually some intermittent mixing, data are presented here on that basis. The data shown in Figure 60 indicate that the least possible time consistent with thorough moist mixing and adequate compaction should be used. If mixing is intermittent, total mixing time up to 4 hours is not seriously detrimental.

British experience indicates that with many soils difficulties arise in obtaining adequate compaction if there has been undue delay between the commencement of mixing and compaction. This seems to conflict with the foregoing conclusion that mixing can be continued for 4 hours without detriment (215).

CONDITIONS OF CURING

Field Curing (25, 72, 73, 74)

Data on properties of cement-treated soil, on factors that influence those properties,



DATA ON SOILS AND ON CEMENT-TREATED SOIL MIXTURES

Soil Texture	Clay Content (%<0.002 mm)	Cement Content (% by volume)
Sand	2	8
Sandy loam	8	10
Loam	19	10
Silt loam	17	11.5
Clay	46	12
Clayey gravel	20	8

Figure 58. Effect of delay between wetting and compaction on compressive strength (40).

and on performance of cement-treated soil are all based on the assumption that adequate moisture is retained in the compacted mixture during the specified curing period of 7 days or longer. It is assumed also that curing in the laboratory moist room meets standard requirements of humidity and temperature.

Data on moisture retention by soil-cement under bituminous seals are available from cooperative studies in four states (72, 73). Four types of bituminous material were used: MC-2 (Illinois), RC-1 (Nebraska), MC-3 Negative Oliensis Spot test material (Kansas), and Asphalt Emulsion (Arkansas). All four types of seal materials were successful in retaining the required moisture content in the soil-cement during the 7-day field curing period. A case history of the moisture changes in soil-cement is given in Figure 61 for the project in Kansas. The effectiveness of the seals in all four states is based on the premise of a dense, tightly knit, even surface having the proper moisture content at the time of sealing. The desirable moisture content ranges from field optimum for the heavier and faster-curing bituminous types (RC-3) placed during the hot summer months to a water-saturated surface for the slower-curing bituminous types placed during the cooler spring and fall seasons. Best results are obtained when surface voids are filled with water immediately prior to application of the bituminous seal. Adequate surface moisture reduces penetration of the bituminous material. Penetration of the seal lowers the quality of the soil-cement and reduces the adherence of the bituminous cover. Effective bituminous covers are applied as soon after surface finishing of the soil-cement as construction conditions permit.

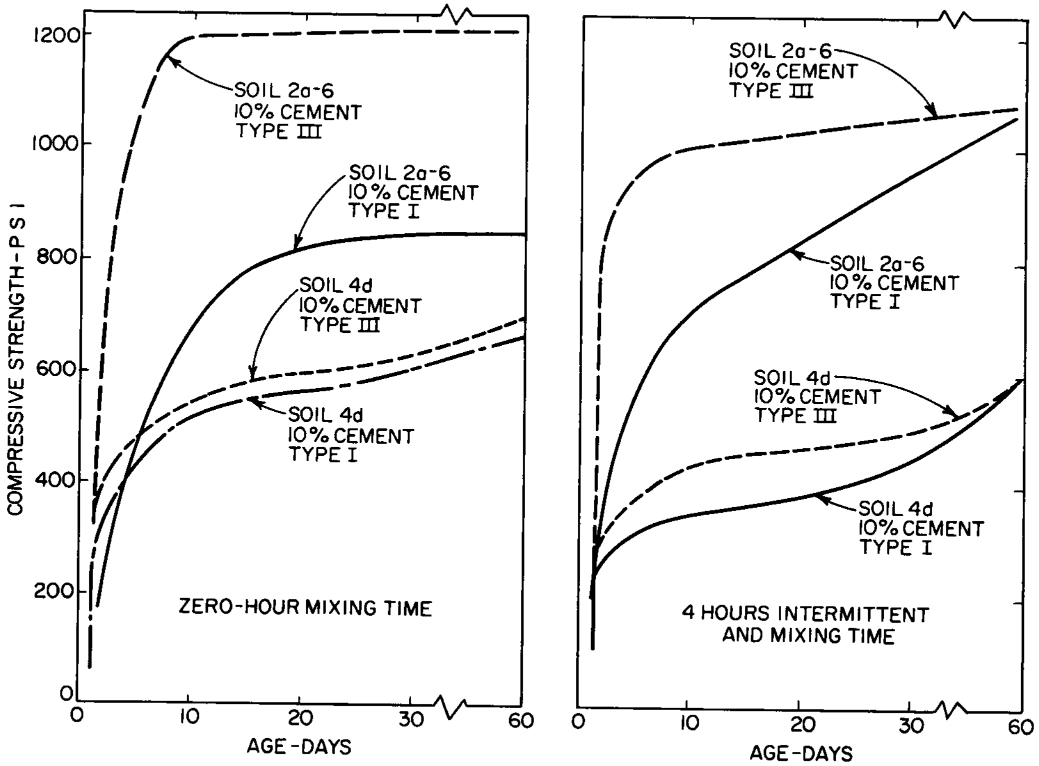
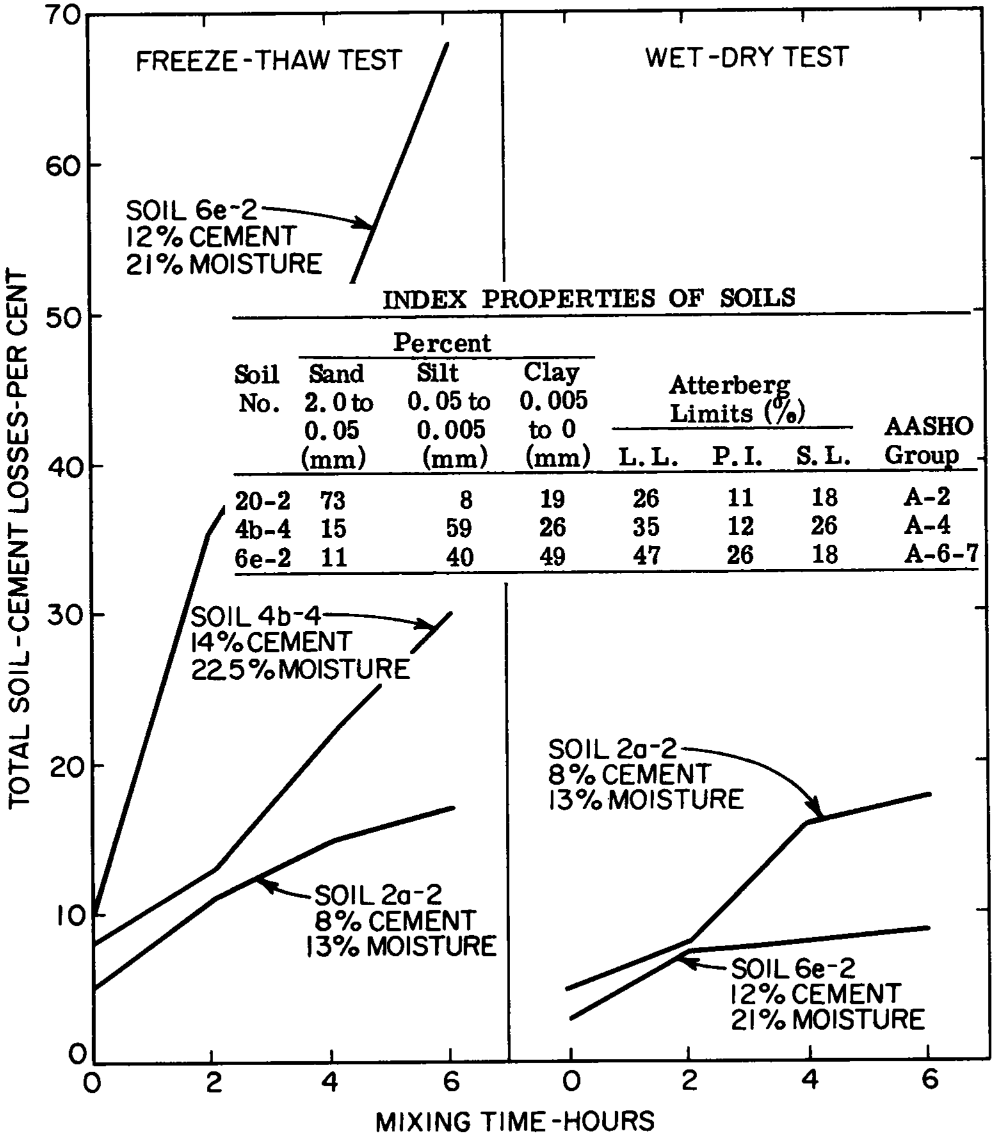


Figure 59. Comparison of strengths obtained with normal (Type I) cement and high-early-strength (Type III) cement for a loamy sand (soil 2a-6) and a silty clay loam (soil 4-d) for zero-hour and for 4-hour intermittent mixing (22).

Further data from experiments in Virginia (74) yielded results that permit comparison of the effectiveness of moist soil, waterproof paper, calcium chloride, RC-2 asphalt, tar and asphalt emulsion as curing materials for soil-cement. Initial and final moisture contents in the top ¾ in. and in the second ¾ in. of the soil-cement base for the various types of cover are given in Table 17. Humidity has strong influence on moisture retention. The three types of bituminous cover, the moist soil



INDEX PROPERTIES OF SOILS

Soil No.	Percent Sand 2.0 to 0.05 (mm)	Silt 0.05 to 0.005 (mm)	Clay 0.005 to 0 (mm)	Atterberg Limits (%) L.L.	P.I.	S.L.	AASHO Group
20-2	73	8	19	26	11	18	A-2
4b-4	15	59	26	35	12	26	A-4
6e-2	11	40	49	47	26	18	A-6-7

Figure 60. Effect of length of mixing time on cement-soil brushing losses—intermittent mixing (22).

cover, and the waterproof paper were the most effective aids to retention of moisture in the soil-cement.

Temperature (55, 75)

British researches bring out the following on the influence of temperature on the strength of soil-cement mixtures:

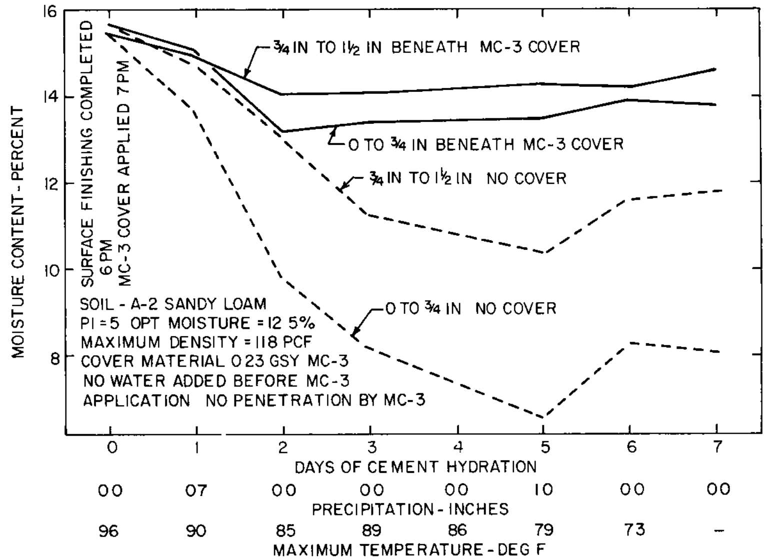


Figure 61. Moisture content of soil-cement during curing period (Washington Co., Kan. July 28 to Aug. 4, 1948) (73).

TABLE 17

AVERAGE MOISTURE CONTENT IN PERCENT IN GROUP A AND B BY DAYS

		Avg. Moisture Content (%)					
		0-¾-In. Depth			¾-1½-In. Depth		
Panel No.	Cover	7-6-51	7-12-51	Net Loss	7-6-51	7-12-51	Net Loss
(a) Group A							
1	None	15.8	5.4	10.4	13.7	9.2	4.5
2	Moist soil	16.2	12.8	3.4	13.3	12.3	1.0
3	Waterproof paper	15.5	8.2[a]	7.3	14.0	10.0[a]	4.0
4	$CaCl_2$	12.7	7.3	5.4	12.6	8.3	4.3
5	RC-2 Asphalt	15.2	11.3	3.9	13.8	11.0	2.8
6	Tar RTCB-6	13.5	11.4	2.1	12.7	11.7	1.0
(b) Group B							
10-ft	AE-2	10.3	8.8	1.5	11.0	9.1	1.9
1	None	12.1	4.7	7.4	12.0	7.3	4.7
2	Moist soil	13.0	11.1	1.9	12.7	11.2	1.5
3	Waterproof paper	13.3	10.0	3.3	12.5	10.3	2.2
4	$CaCl_2$	12.1	6.9	5.2	12.7	8.4	4.3
5	RC-2 Asphalt	12.8	10.9	1.9	12.4	10.3	2.1
6	Tar RTCB-6	12.3	10.6	1.7	12.1	10.8	1.3

[a]Waterproof paper destroyed on fifth day of curing period.

Note: Soil Type—Group A-7-5 clay, PI 15 to 25. Group A watered immediately before application of curing. Group B allowed to dry somewhat before curing. Except for one cloudy day weather was clear and hot (81 to 96 F at noon). Relative humidity at noon ranged from 41 percent to 72 percent.

1. The 7-day compressive strength increases with increasing temperature by 2 to 2½ percent per degree centigrade when the temperature is in the vicinity of 25 C (77 F).

2. Soil-cement will harden in cold weather provided the temperature is above 0 C (32 F).

3. If compressive strength is taken as the sole criterion of the quality of soil-cement, less cement is needed in warm weather than in cold weather.

4. Because of ambient temperature differences, soil-cement constructed during warm weather should be 50 to 100 percent stronger than similar construction made during cool weather, at least during the first three months of life of the construction.

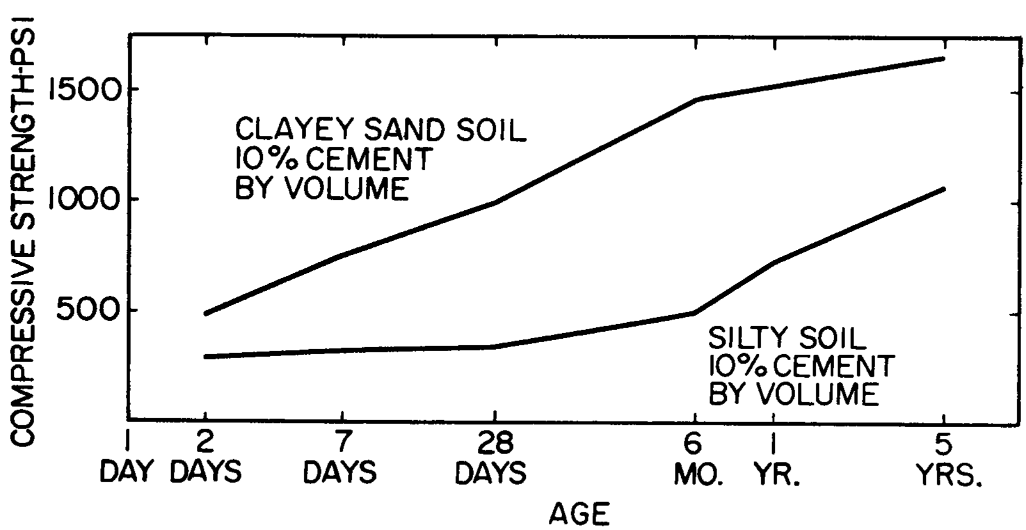


Figure 62. Compressive strengths of laboratory-molded specimens of soil-cement (33).

Age

The influence of relatively early age periods on the properties of soil-cement is indicated in Figures 2 to 5, 51 to 53, and 59. There is evidence that soil-cement continues to increase in strength with increasing age in a manner similar to concrete. This is illustrated in Figure 62 by laboratory data showing time-compressive strength relationships for two soils for a 5-yr period (33), and by more general field data from cores taken from field construction projects ranging from one to 20 years in age in four states. The data from the field projects are shown in Figure 63.

British research indicates that for normal reacting soils the relation between strength and logarithm of the age is linear over a fairly wide range of ages, although there are some departures from the relation at very early ages (up to 1 day) and at considerable ages (6 months and above) (215).

Influence of Specimen Dimensions on Compressive Strength

The results of two series of test (14, 49) permits a comparison of compressive strengths of 2-in. diameter by 2-in. high cyclinders with those of 2.8-in. diameter by 5.6-in. high cylinders and, 4-in. diameter by 4.59-in. high cylinders with those of 2.8-in. diameter by 5.6-in. high cylinders. When data for the 2 x 2 and 4 x 4.59 cylinders were plotted as ordinates and data for the 2.8 x 5.6 cylinders were plotted as abscissae, the plotted points fell above the line of equality and reasonably close to the line suggested in ASTM Designation C 42-49. For sandy soils, compressive strengths of 3 x 3-in. cubes were 25 percent higher than for 2.8-in. diameter by 5.6-in. high

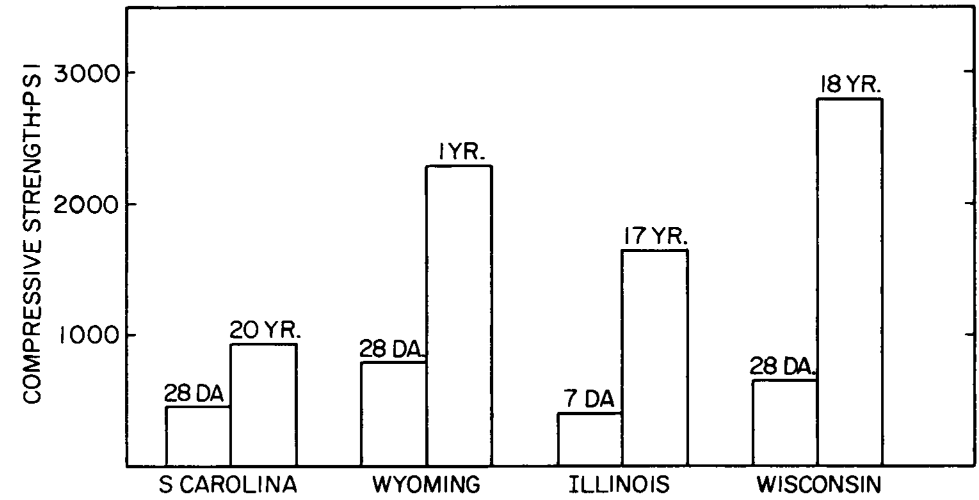


Figure 63. Gain in strength of soil-cement with age as determined from field cores (33).

cylinders. Values for the cubes were about 12 percent higher for a clayey sand and about equal for a silty soil.

BENEFICIAL ADMIXTURES

Soil and Aggregate Admixtures

Soil amendments and additives have been used to improve the reaction between the soil and the cement since the earliest projects (76). Normally reacting soils have been used to amend soils which showed poor reaction by altering the soil grading or by

TABLE 18

INDEX PROPERTIES OF SOILS USED IN SOIL-ADMIXTURES TESTS (77)

Soil No.	Soil Horizon	Gradation (% of total) Sand 2.0 to 0.25 (mm)	Sand 0.25 to 0.05 (mm)	Silt 0.05 to 0.005 (mm)	Clay 0.005 to 0.0 (mm)	Org. Cont. (ppm)	Plastic Prop. LL	Plastic Prop. PI	Textural Class and BPR Soil Group
887-2	A	16	84	0	0	36,000	21	NP	Fine sand A-3
891	B	10	90	0	0	2,500	22	NP	Fine sand A-3
578	C[a]	28	29	27	16	none	24	NP	Sandy loam A-2
902	A	52	36	7	5	10,000	16	NP	Coarse sand A-2
997	C	27	52	11	10	700	18	NP	Fine sandy loam A-2

[a]Limerock.

diluting the poorly reacting soil. Favorably reacting materials such as limestone screenings and crushed limestone have been used. Fine-grain soil has been added to clean sands and sand-gravels; conversely, sands, sand-gravels and pulverized bituminous surfaces have been mixed into clays to improve the reaction (and in many instances to reduce cement requirements).

The occurrence of detrimental types of organic matter in some sandy soils (see

"Factors Influencing Properties of Cement-Treated Soil Organic Matter") has necessitated the admixing of normally reacting soils. The results of an investigation (77) of this method serve to illustrate its effectiveness. Table 18 shows the index properties of two poorly reacting A-horizon soils and one poorly reacting B-horizon soil (887-2, 902, and 891), and two normally reacting C-horizon Florida soils (578 and 997).

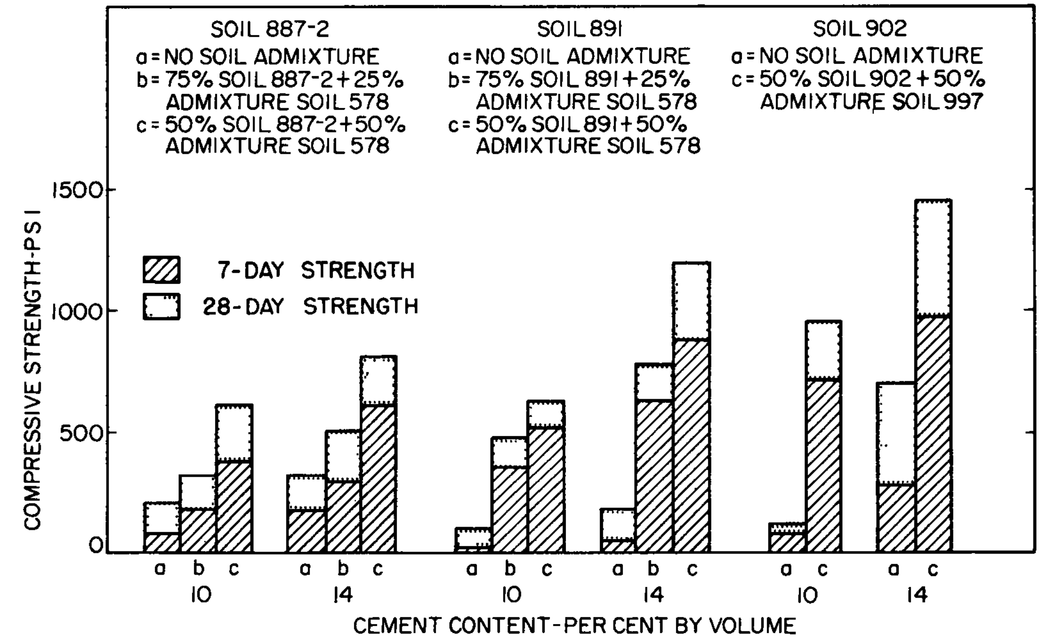


Figure 64. Effect of the addition of admixture soil on the compressive strength of cement-treated poorly reacting organic soils (77).

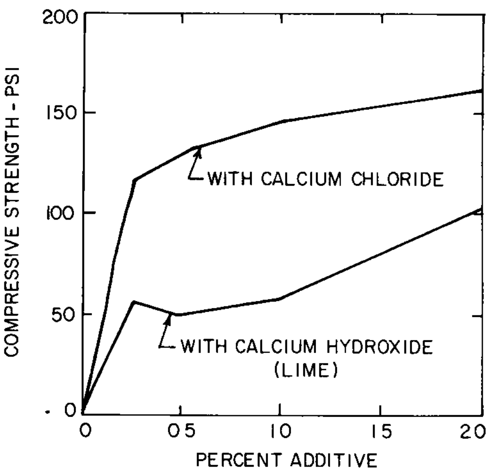


Figure 65. Effect of the addition of calcium compounds on the 7-day compressive strength of cement-treated sand containing deleterious organic matter (8 percent normal portland cement) (67) (density 106 pcf, moisture content 14 percent).

The results of compressive strength determinations on mixtures of the poorly reacting sandy soils with 10 and 14 percent cement and on admixtures of the normally reacting C-horizon soils with the poorly reacting A- and B-horizon soils are indicated in Figure 64. Admixing normally reacting soils resulted in an improvement of 200 to over 500 percent in the compressive strength. The addition of limestone screenings to soil, soil to sand, or soil to mill-run mine tailings are other examples where similar results have been obtained.

Hydrated Lime or Quicklime

Hydrated lime has been used as an admixture to cement-treated soil to improve the cement reaction with some organic soils that exhibit retarded setting or are productive of abnormally low strengths when mixed with portland cement alone. An example of this type of application is a uniformly graded fine sand (70 percent between sizes 0.1 and 0.2 mm and 3 percent silt and clay sizes) containing detrimental organic matter that was not evident on visual inspection (but showed 0.3 percent organic matter on analysis by the dichromate method) (67). Lime produced a beneficial effect in the form of early hardening of this type of mixture, which exhibited retarded setting time up to 7 days when mixed with normal portland cement alone. The addition of 2 percent hydrated lime reduced retardation to about 2 days. A comparison of the effectiveness of different percentages of lime admixture with that of calcium chloride in reducing retardation is indicated in Figure 65.

Lime has also been used as an admixture to highly plastic materials to facilitate pulverization and mixing, and to increase compressive strength and resistance to loss in the wet-dry test, for the wet-dry test is often a significant criterion for determining cement requirements for plastic high-volume-change soils. Studies by the Corps of Engineers (78) have shown that 2 percent hydrated lime was effective in reducing wet-dry losses on plastic base material. The results of tests are shown in Figure 66. British studies (23) have shown that the addition of 2 percent lime to cement-treated soil increased the compressive strength and the resistance to reduction in strength on immersion in water, but that the use of lime contents greater than 2 percent were not warranted. The relationships between lime content and strength for cement-treated soil having 15 and 30 percent cement are shown in Figure 67. The soil had a liquid limit in the range of 70 to 75 and a plastic index of 45 to 53.

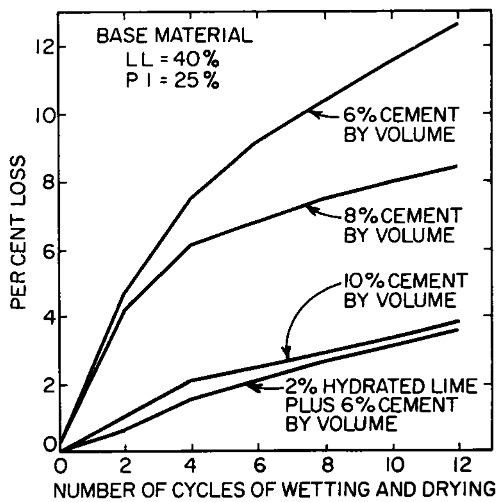


Figure 66. Influence of lime admixture in reducing brushing losses in the wet-dry test (78).

Bituminous Emulsion

A process has been developed in Britain (61) for using bituminous emulsion in conjunction with cement. The emulsion, specially developed for the purpose, will remain stable for a short time when mixed with fine-grain soils permitting good dispersion through the soil. The cement that is added subsequently: (a) causes the emulsion to break, (b) absorbs some of the resulting free moisture, and (c) gives added strength to the processed and compacted soil. The proportions of admixture generally required are 5 to 7½ percent emulsion and 3 to 5 percent cement. The final material is said to have properties intermediate between those of soil-cement and true soil-bitumen.

Fly Ash

Two investigations have been made using fly ash as a soil amendment. One of these (79) involved a coastal silty soil (18 percent sand, 56 percent silt, 26 percent clay, LL = 30, PI = 5) and mixtures of 94-3-3 and 94-4-2 parts of soil, cement and fly ash, respectively. After 28 days curing, the 94-3-3 mix showed a 5.9 percent weight gain in the freeze-thaw test and a compressive strength of 33 psi after 12 cycles of test; the 94-4-2 mix showed a weight gain of 0.70 percent and a compressive strength of 220 psi after 12 cycles of freeze-thaw. The second investigation (80) included tests on a friable loess (PI = 12), a plastic loess (PI = 12), an alluvial clay (PI = 47), and a nonplastic dune sand. Cement contents ranged upwards to 12 percent and fly ash contents ranged from 9 to 21 percent in terms of soil replacement—and then varying percentages of fly ash replacing cement. The conclusions (80) were that fly ash was not markedly beneficial as an admixture for the soils tested except as it reduced shrinkage cracking in the clay soil. It had no marked effect on the strength of cement-treated soil mixtures and was detrimental to freeze-thaw resistance.

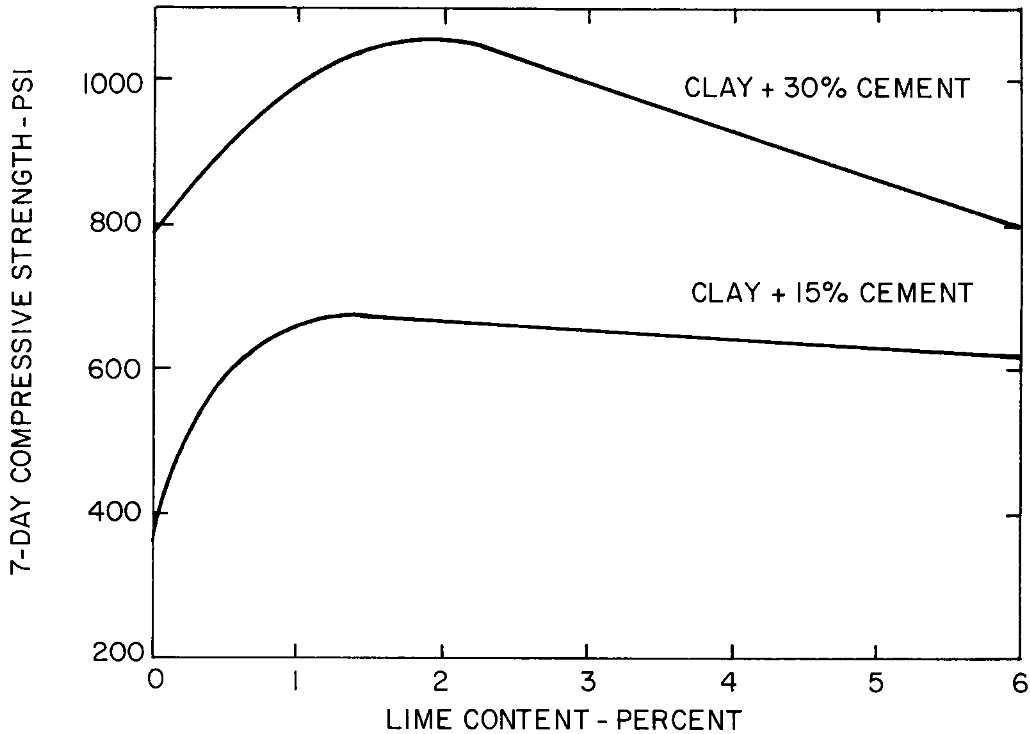


Figure 67. Influence of lime on the compressive strength of clay-cement mixtures (23).

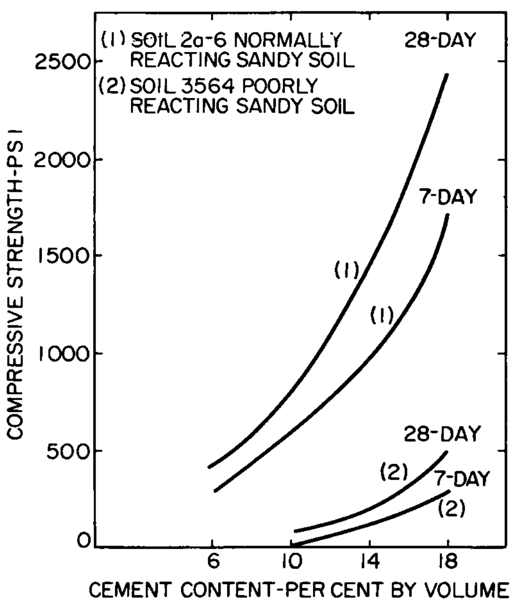


Figure 68. Comparison of compressive strengths of a normally reacting sandy soil and a poorly reacting sandy soil (77).

Calcium Chloride

The influence of calcium chloride as a beneficial admixture to mixtures of cement and organic soils has been determined both in the U.S. (17, 76, 77, 82) and in Great Britain (54, 61, 67). The nature of the effect of organic matter in retarding the set of cement-treated soil has been described in part under "Factors Influencing Properties of Cement-Treated Soil, Organic Matter." Seven-day and 28-day compressive strengths of a normally reacting soil compared to similar data for a poorly reacting soil are shown in Figure 68.

Some results of the British studies showing a comparison of the effectiveness of lime and calcium chloride in improving strength characteristics of an organic soil are indicated in Figure 65. In the U.S. tests performed on nine soils (77), four poorly reacting and five normally reacting, showed that small percentages of calcium chloride had a marked effect in improving the reaction of soils that showed poor reaction with cement alone. An example of data for one soil is shown in Figure 69;

the soil without calcium chloride treatment required more than 26 percent cement by volume for satisfactory hardening. With the addition of 0.4 to 1.0 percent calcium chloride the soil was hardened satisfactorily with 14 percent cement. It may be seen from Figure 69 that compressive strength increases to an optimum and decreases with further increase in calcium chloride. Improvement in durability, as indicated by wet-dry and freeze-thaw tests, is of the order indicated by the compressive strength data for the number of cycles tested. Generally 0.6 percent calcium chloride is an optimum value when both short period and long period effects are considered (77).

Tests made to determine the effect of calcium chloride on cement-treated Iowa loess soils (32) of very low organic content showed an increase in 7-day strength of one sample (sample 43½-1, see Figs. 30 and 31) of more than 50 percent and of another sample (sample 20-2, see Figs. 30 and 31) by more than 300 percent. After 45 days, strength gains due to calcium chloride admixture were 61 percent for sample 43½-1 and no further gain for sample 20-2. Thus calcium chloride provided merely an accelerating effect for one soil, whereas there was an over-all strength gain for the other.

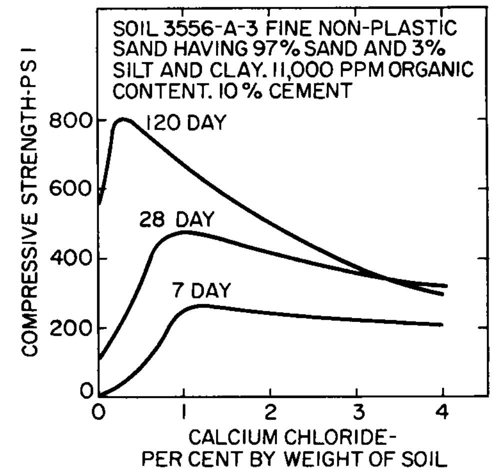


Figure 69. Effect of calcium chloride content on the compressive strength of a poorly reacting organic sand (77).

Research Studies of Additives for Improving the Properties of Cement-Treated Soil

Trace Chemicals.—A preliminary research screening test program (68, 83), has been carried out to determine the effects of 29 chemicals on the compressive strength of three soils of different composition stabilized with five percent Type I portland cement. The three soils are, a clayey silt from Massachusetts; a uniform silt from Manchester, N.H.; and a uniform loess from Vicksburg, Miss. Soil passing the No. 10 sieve was used. Specimens were molded at optimum moisture content and maximum density in the Harvard miniature mold (1.313 in. in diameter by 2.816 in. high). Specimens were cured for periods of 7 and 28 days at 100 percent relative humidity at room temperature (20 to 25 C). All specimens were subjected to complete immersion for a 24-hr period prior to testing in unconfined compression. Data given in Table 19 indicate the grain size distribution, the physical and chemical properties and mineral composition of the three soils used in the study.

Most of the dispersants, alkali reagents with sodium ions and salts with sodium ions, caused a modest increase in maximum density (1 to 7 pcf) and a small increase in optimum moisture content. Several additives had no effect on the moisture-density relations. There was no relationship between strength increase and density increase.

More than one-half of the 29 chemicals tested increased the compressive strength of the cement-treated soil mixtures. Seven of the chemicals, when used at concentrations of one percent or less, more than doubled the strength of the mixtures made with the silts. Figures 70, 71, and 72 show the 7- and 28-day compressive strength data obtained for 0.5 and 1.0 percent additives to the cement-treated soil mixtures made of the Massachusetts clayey silt, the Vicksburg loess, and the New Hampshire silt, respectively. The data show that the Massachusetts and New Hampshire silts responded to chemical treatment better than did the Vicksburg loess. The results on two of the soils showed that chemical treatments produced strengths more than double the values for cement-treated soil specimens without chemical additives, and point to the potential of this method for further improving cement-treated soil, provided durability is satisfactory.

TABLE 19

PROPERTIES OF SOILS EMPLOYED IN STUDY OF TRACE CHEMICALS (83)

Characteristic		Mass. Clayey Silt	Vicks-burg Loess	New Hamp. Silt
Textural comp.[a] (% by wt)	Gravel	0	0	0
	Sand	47	10	3
	Silt	42	86	90
	Clay	11	4	7
Eng. class.[b]		A-4(4)	A-7-6(10)	A-4(8)
Physical prop.	LL (%)	20	41	28
	PL (%)	14	26	20
	PI	6	15	8
	Sp. gr.[c] (g/cc)	2.77	2.80	2.72
	Max. dry density[d] (pcf)	122.3	104.5	99.5
	Opt. moisture[d] (%)	13.3	18.5	19.9
Chemical prop.[e]	Cat. ex. cap. (me/100 gm)	10	16	3
	pH	-	4.6	5.4
	Soluble salts (me NaCl/100 gm)	-	0.2	-
	Organic matter (%)	-	1.8 ± 0.1	0.4 ± 0.1
Mineral comp.[e] (% by wt)	Quartz	35	30	40
	Feldspar	20	30	40
	Mica	-	-	10
	Illite	30	15	10
	Montmorillonoid	-	20	-
	Fe_2O_3	2.9	1.6	1.0

[a]Based on MIT classifications: Gravel—above 2.0 mm, sand—0.06 to 2 mm, silt—0.002 to 0.06 mm, clay—below 0.002 mm.
[b]Based on HRB system.
[c]Determined on the fraction passing No. 10 sieve.
[d]Determined by Harvard Miniature compaction apparatus, compacted in three layers with a 40-lb tamper, 25 blows per layer.
[e]Determined on the fraction smaller than 0.74 mm.

Additional laboratory studies (84) of the effect of a selected group of alkali metal compounds on cement-treated soil mixtures have been made using eleven soils: well-graded clayey silt from Massachusetts, uniform loess from Vicksburg, Miss., uniform silt from New Hampshire, B-horizon clay from Illinois, A-horizon organic sand from Wisconsin, B-horizon sand from Wisconsin, two heavy clays from Texas, and three clays rich in carbonate content from Iraq. Compressive strength was used as a criteria for judging the value of the additives. The tests showed that with virtually all the soils studied, the compressive strengths were increased by the addition of small quantities of sodium compounds that form insoluble compounds with calcium. The most beneficial additives were caustic soda, soda ash, sodium sulfite, sodium sulfate, sodium metasilicate, and sodium aluminate. The lithium and potassium compounds acted similarly but to a lesser degree. The caustic soda was the most beneficial additive with the heavy clay soils and sodium sulfate in the silts. Sodium sulfate was uniquely effective with the organic sands from Wisconsin.

The effect of the alkali metal compounds on the durability of soil-cement has also been studied (85). Four of the soils reported on (organic A-horizon sand from Wisconsin, Illinois clay, New Hampshire silt, and Massachusetts clayey silt) were included. The results showed that the effects of the admixtures on durability, as measured by standard freeze-thaw and wet-dry tests, were similar to the effects of the admixtures on compressive strength. The following summarizes the results:

1. The addition of 1 percent sodium sulfate reduced the cement requirement of the Wisconsin poorly reacting sand from more than 20 percent to 9 percent. Sodium sulfate was more effective than calcium chloride in improving this poorly reacting sand.
2. The addition of 0.5 percent sodium hydroxide to the Illinois clay did not significantly reduce the cement requirement. The addition of 1.0 percent sodium hydroxide was detrimental because it increased the cement requirement from 10 percent to 12 percent.

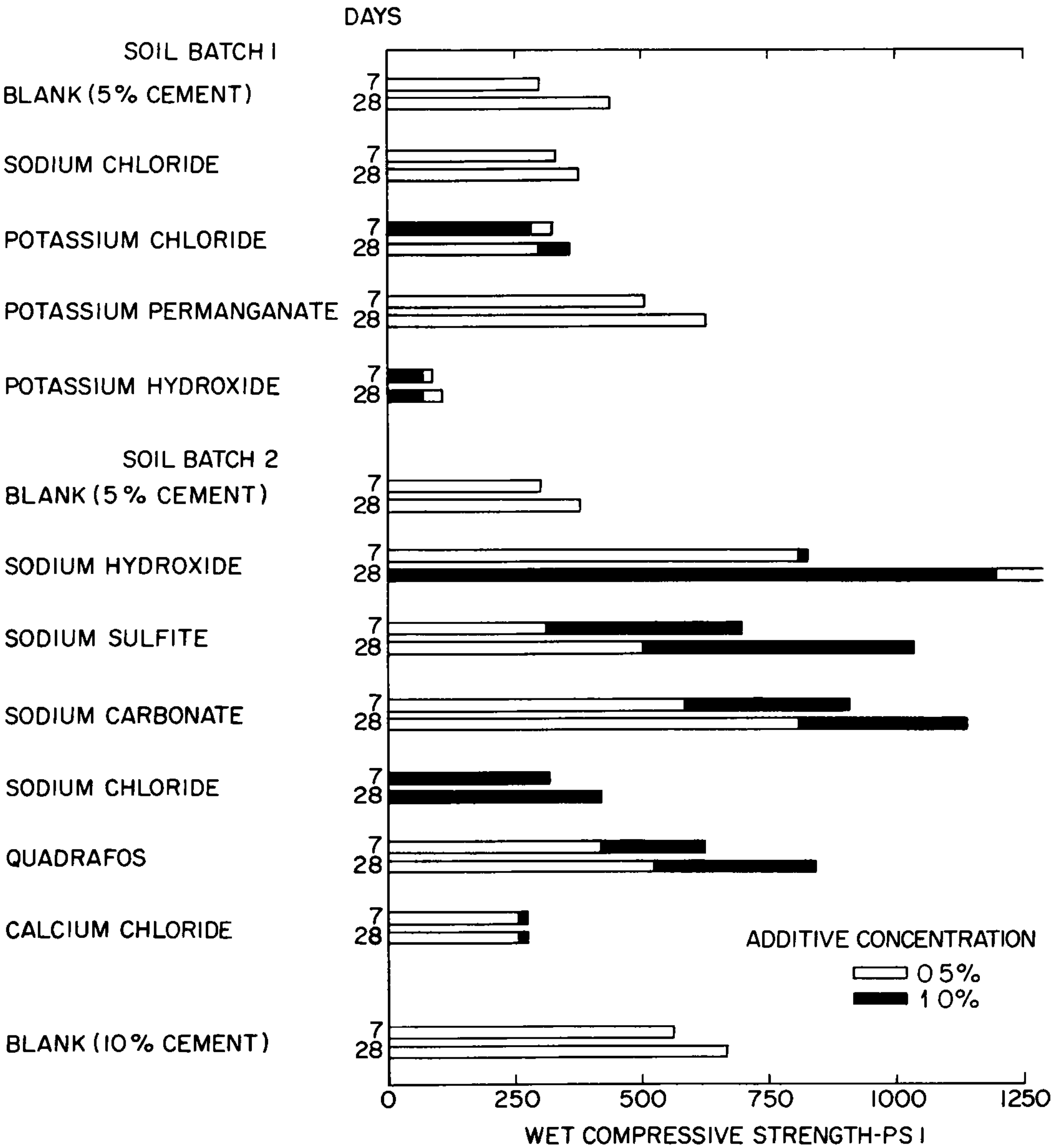


Figure 70. Effect of trace additives on the compressive strength of cement-treated Massachusetts clayey silt (83).

3. The addition of 1.0 percent sodium hydroxide to the New Hampshire silt reduced its cement requirement from 16 percent to 12 percent.

4. The addition of 1.0 percent sodium sulfate or sodium metasilicate reduced the cement requirement of the Massachusetts clay silt from 8.5 percent to less than 6 percent.

Trace Chemical Additives to Cement-Modified Soil for Control of Frost Heave.—A separate study was made of the influence of trace chemicals on cement-treated soil mixtures containin small percentages of cement as a means for further modifying the frost heave characteristics of the mixtures (86). Compacted cement-treated soil specimens were cured for 7 days in a moist room. Samples were saturated and placed in a freezing chamber with a free water surface maintained ⅛ in. above a porous stone at the bottom of each specimen. A freezing penetration of ¼ in. per day was applied. The results of freezing tests are expressed as the average rate of heave in millimeters

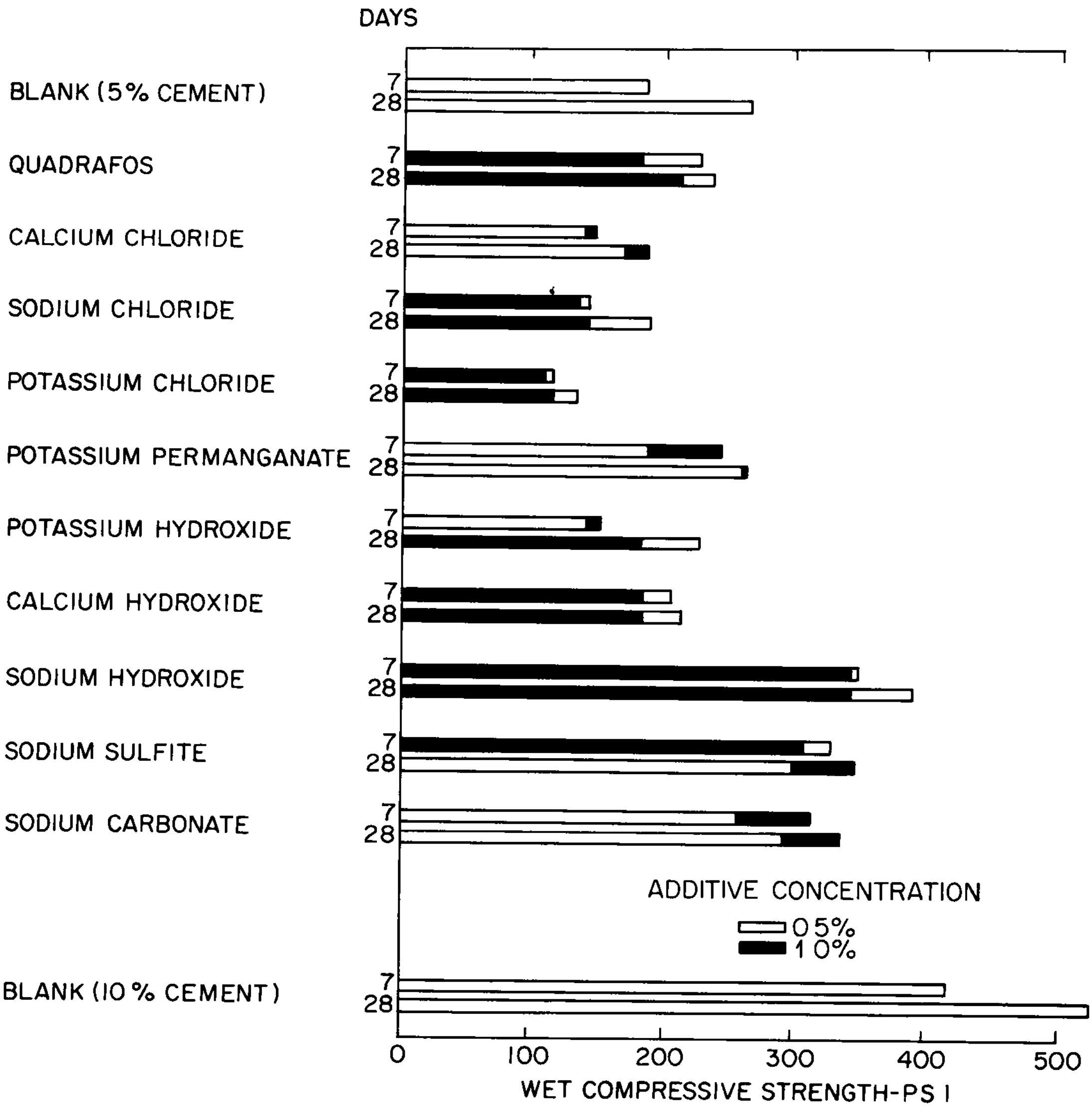


Figure 71. Effect of trace additives on the compressive strength of cement-treated Vicksburg loess (83).

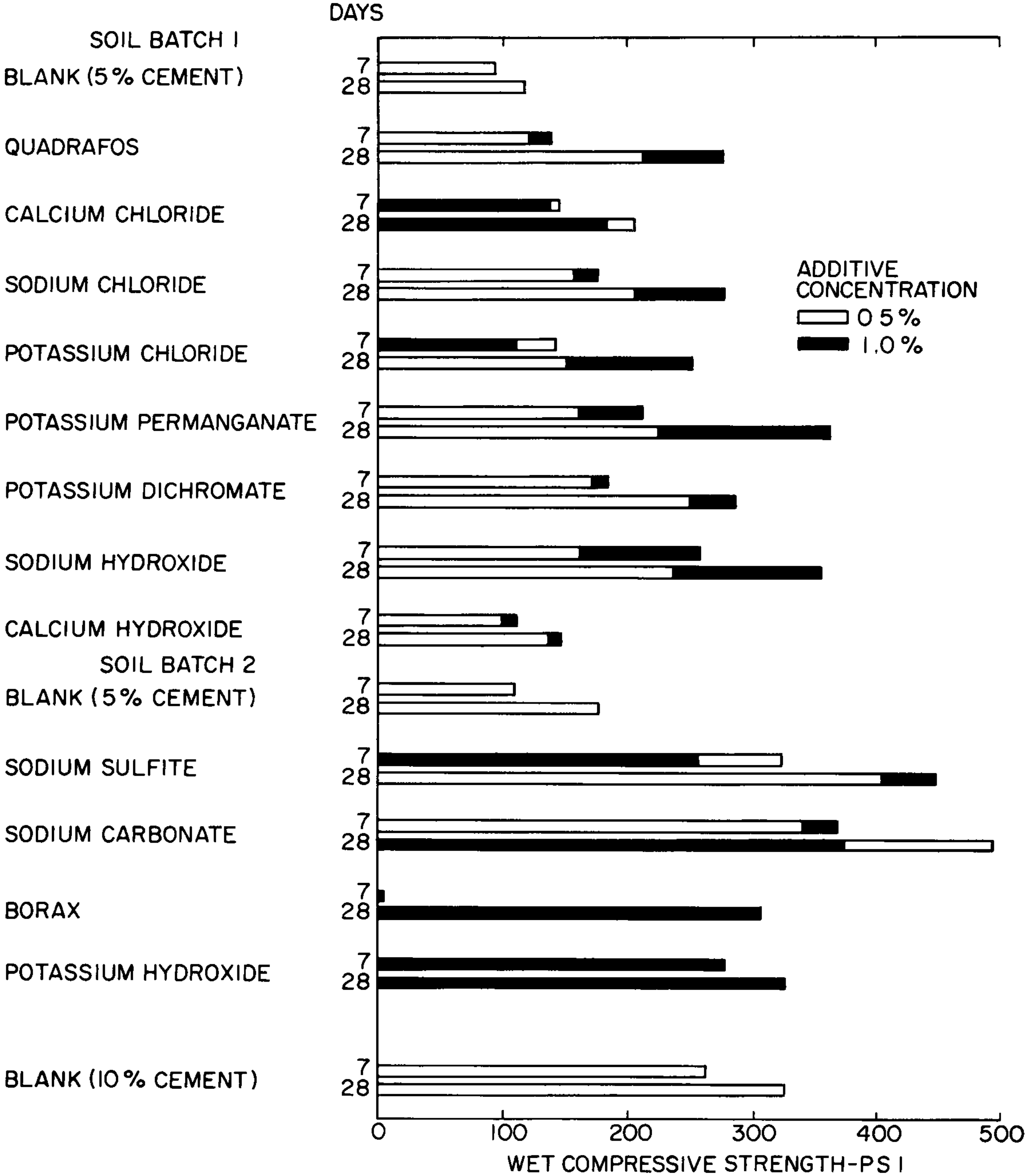


Figure 72. Effect of trace additives on the compressive strength of cement-treated New Hampshire silt (83).

per day. Because heave of a treated specimen needs to be evaluated in terms of an untreated specimen, the average rate of heave of a treated sample is divided by the average rate of heave of an untreated sample. The resulting value is a measure of the effectiveness of a treatment and is termed the "heave-ratio." A heave-ratio of less than 1 indicates improvement. Four soils susceptible to frost heave were treated with low percentages of portland cement. The nature of the soils is given in Table 20.

TABLE 20

MECHANICAL ANALYSIS AND ATTERBERG LIMITS OF SOILS USED IN FROST STUDIES (86)

Soil	Grain Size (% finer than size shown) No. 4	No. 40	No. 200	0.02 mm	LL	PI	Max[a] Den. (pcf)	Opt.[a] M.C. (%)
New Hampshire silt	100	100	99	77	24	6	110	14.7
Ft. Belvoir (Va.) sandy clay	97	88	62	46	41	19	115	16.1
Boston blue clay	100	100	100	94	53	26	106	20.2

[a]Maximum density and optimum moisture contents are by Modified AASHO method.

The heave ratios obtained on these frost-susceptible soils with the use of low cement contents with and without trace chemical admixtures are given in Table 21.

TABLE 21

EFFECT OF PORTLAND CEMENT AND TRACE CHEMICALS ON FROST HEAVE (86) (In Heave Ratios)

Additives	Percent	Boston Blue Clay	New Hampshire Silt	Fort Belvoir Sandy Clay
Portland cement	1	1.35	1.74	1.04
Portland cement	2	1.36	0.63	0.58
Portland cement	3	0.46	0.46	1.08
Portland cement + pozzolith	1 0.1	1.35	0.59	0.67
Portland cement + pozzolith	3 0.2	0.56		0.74
Portland cement + Daxad 21	1 0.1	1.41		0.82
Portland cement + Daxad 21	2 1.5	0.68	0.76	0.10
Portland cement + Daxad 21	3 0.2	0.61		1.10
Portland cement + Daxad 21	5.0 1.0	0.37	0.47	0.26

Chemical Treatments to Surface Harden Soil-Cement (87).—The chemical treatments investigated in the laboratory were calcium chloride, sodium hydroxide, sodium carbonate, and sodium silicate. Measured amounts of solutions of these chemicals were sprinkled on the surfaces of 2-in. diameter by 2-in. high soil-cement specimens confined in their molds. Solution amount, concentration, and time of application were varied. Other specimens were either moist cured or sprinkled with distilled water to provide a control. Sodium silicate application followed by daily wetting with water proved to be the best treatment, the bearing strength improvement being between 20

TABLE 22

INDEX PROPERTIES OF NATURAL SOILS STUDIED FOR SURFACE CHEMICAL EFFECTS (51)

Soil	Mechanical Analysis of Natural Soils: Sand 0.84-0.05 (mm)	Silt 0.05-0.005 (mm)	Clay 0.005-0.001 (mm)	Colloids 0.001 (mm)	Soil Constants: LL	RI	SL	Opt. M.C. (%)
Putnam	7	39	21	23	64	24	18	29
Cecil	44	28	7	21	45	30	23	21
Hagerstown	20	37	16	27	46	19	19	18
Hays	7	46	21	26	57	24	16	25

percent and 90 percent over control strengths, depending on the soil. A sandy soil-cement was most benefited. Daily wetting was beneficial to a silty soil-cement, and this alone increased the bearing strength about 30 percent over that of ordinary moist curing. However, daily sprinkling without sodium silicate pretreatment decreased the bearing strength of the sandy soil-cement.

Plaster of Paris

Admixtures of plaster of Paris (calcium sulfate) to cement-treated soils containing 2.5 percent cement by weight have been studied experimentally as a means for controlling volume change of soils (37). Shrinkage decreased as the proportion of plaster of Paris increased until at 2 to 4 percent, depending on the soil type, expansion occurred. The expansion increased with further increase in plaster of Paris content. Admixing

TABLE 23

CATION EXCHANGE CAPACITY AND CATION CONTENT OF THE NATURAL AND HOMOIONIC SOIL MATERIALS (51)

Soil	Cation Exchange Capacity[a] (me/100g)	Cation Content of the Natural Soils[b] (me/100g): H[c]	Na	K	Mg	Ca	Cation Content of the Homoionic Soils[d] (me/100g): H[e]	Na	K	Mg	Ca
Putnam	30.8	12.3	1.4	1.0	4.5	11.6	30	30.7	27.8	26.4	33.8
Cecil	4.0	1.0	0.3	0.4	0.7	1.6	4	3.0	3.0	3.4	3.8
Hagerstown	25.0	6.5	0.7	1.0	7.2	9.6	25	19.7	15.2	16.0	18.3
Hays	28.4	-	0.6	1.7	9.5	19.8	28	35.8	34.8	30.0	25.5

[a] By potentiometric titration of the H-soil.
[b] By extraction with ammonium acetate and spectroscopic analysis (V.R. Ellis, Univ. of Mo.) (the Putnam soil analysis was also checked gravimetrically).
[c] By subtraction.
[d] Amounts of cations equal to the base exchange capacity had been added in the preparation of the soils.
[e] From base exchange capacity.

plaster of Paris increased the compressive strength. However, for three of the four soils tested, plaster of Paris had a detrimental effect on durability as determined by the wetting and drying test. (Also see "Factors Influencing Properties of Cement-Treated Soil, Sulfate Content.")

Influence of Surface Chemical Factors on Cement-Treated Soil

Observations have been made on the effect of various cations (replaced by ionic substitution in the natural soils to produce homoionic soils) on the behavior of natural and cement-treated soils (51). The four soils used in the tests were:

1. Putnam clay—a grey brown podzolic soil (planosol) of mixed glacial and loessial origin having about 0.75 percent organic matter;
2. Cecil clay—a red and yellow podzolic soil (lateritic material) derived from gneiss having no organic matter;
3. Hagerstown clay—a reddish brown podzolic soil derived from limestone having no organic material; and
4. Hays clay—a chernozem soil derived from shales and limestones having 1.4 percent organic matter.

The mechanical analysis and soil constants of the natural soils are given in Table 22.

The base exchange capacities of the natural soils and of their homoionic counterparts are given in Table 23.

Ionic substitution had marked effect on the compressive strength and durability of hardened cement-treated soils. The magnitude of the effects is indicated for the different soils by the maximum and minimum values of 28-day and 120-day compressive strengths of cement-treated specimens molded with 14 percent cement (Table 24).

TABLE 24

APPROXIMATE[a] MAXIMUM AND MINIMUM VALUES OF 28-DAY COMPRESSIVE STRENGTHS OF TREATED AND UNTREATED SOILS (51) (All Specimens Contain 14 Percent Cement by Volume)

Soil	Untreated Soils (psi)	Treated Soils		
		Min. (psi)	Max (psi)	Range[b] (psi)
Cecil	780	860	1,170	390
Hagerstown	1,300	800	1,490	690
Hays	600	300	950	650

[a]Approximate because taken from charted data.
[b]Range for treated and untreated soils.

TABLE 25

APPROXIMATE[a] MINIMUM CEMENT CONTENTS (PERCENT BY VOLUME) WHICH SATISFY DURABILITY REQUIREMENTS (51) (Based on Maximum 10 Percent Brushing Loss)

Soil	Freeze-Thaw Test			Wet-Dry Test		
	Natural Soil	Treated Soils		Natural Soil	Treated Soils	
		Lowest	Highest		Lowest	Highest
Cecil	10	8	12	6	6[b]	6
Hagerstown	9	8-	13	8	7	10
Hays	16	10	16	16	10	16+
Putnam	16+	16+	-	16+	16+	-

[a]Approximate because reduced from charted data.
[b]No test with less than 6 percent cement.

Treatment to alter surface chemical properties of the clay soils also influenced the durability characteristics of the cement-treated soil mixtures as determined by the freezing and thawing tests. The effect on durability is indicated first by means of min-

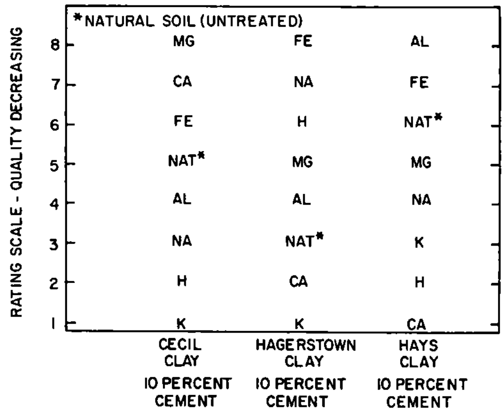


Figure 73. Relative ratings of homoionic and natural cement-treated soils when subjected to alternate cycles of freezing and thawing (51).

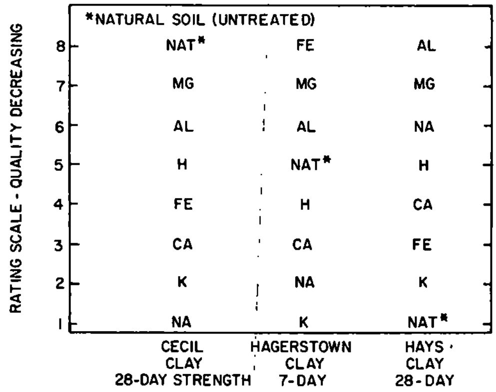


Figure 74. Relative ratings of homoionic and natural cement-treated soils as shown by 7-day or 28-day compressive strength (10 percent cement) (51).

imum cement content necessary to reduce brushing losses to 10 or less. The minimum cement requirements are given in Table 25.

It may be seen from Table 25 that the effectiveness of cationic substitution, expressed in terms of percent cement by volume saved when compared to the amount required for the natural soil, ranged from about 1 for the Hagerstown soil to 6 for the Hays soil. The freeze-thaw test was critical for the Cecil and Hagerstown soils. The wet-dry test was about equally critical on the Hays soil and may be more critical for the Putnam soil.

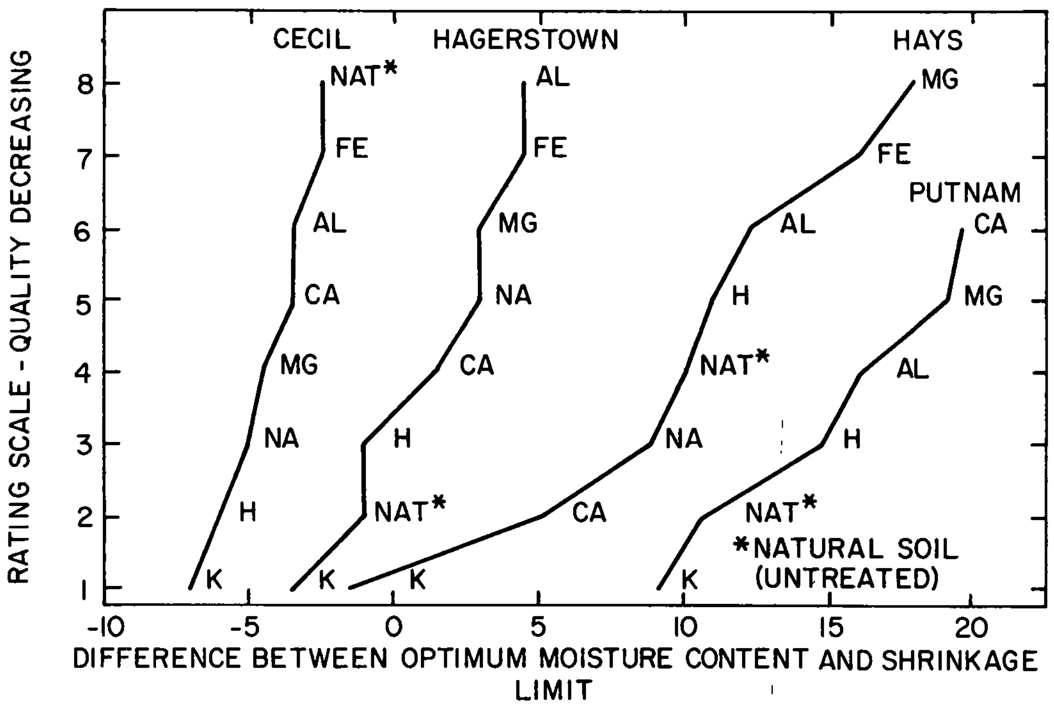


Figure 75. Quality ratings of homoionic and natural cement-treated soils related to the differences between their optimum moisture contents and shrinkage limits (10 percent cement) (51).

The general order of effectiveness of the different cations on the freeze-thaw resistance of the soils treated with 10 percent cement (by volume) is shown in Figure 73. The more beneficial cations for the Cecil soil were potassium, hydrogen, and sodium in that order; for the Hagerstown soil, potassium and calcium; and, for the Hays soil, calcium, hydrogen, and potassium.

Comparison of the ratings in Figure 73 with Figure 74, which indicates the relative ratings of the homoionic treatments based on compressive strength of specimens containing 10 percent by volume, shows that the compressive strength test alone is not the reliable indicator of the resistance of clay soils to durability tests that it is for granular soils.

Inasmuch as the homoionic treatments markedly affected the optimum moisture content and maximum density of the cement-treated soils, a separate series of tests was performed (51). Those tests demonstrated that generally compressive strength and durability of cement-treated clay soil mixtures of the types tested increased with increase in moisture content and density within the range of values affected by the treatments. Thus the results may be analyzed in terms of the nature of the cations or in terms of the physical effects of varied moisture and density control.

A significant finding as it relates to clay soils (51) was that the difference between the optimum moisture content for compaction and the shrinkage limit was large and positive for the soils requiring high cement contents (Putnam and Hays soils) and small and negative for the clay soils requiring low cement contents (Cecil and Hagerstown soils). The general order of rating of the relationship, quality-wise, for the natural soils and for the treated soils is indicated in Figure 75. Although the sequences in the order of ratings are not identical, there is a general trend of better durability for soils having small or negative differences between their optimum moisture contents and their shrinkage limits.

Uses of Cement-Treated Soil and Bituminous Surfacing Requirements

APPLICATION OF TYPES OF CEMENT-TREATED SOIL TO THE NATURE OF THE FACILITY

The various types of cement-treated soil were initially developed to serve under different conditions of use, depending on the requirements for the facility. The suggested use of each of the various types is based on the properties of each and the needs of the facility. Information pertaining to preliminary testing, to criteria for mix design, and to items of geometric and structural design of cement-treated soil facilities is given later.

Soil-Cement

Cement-treated soil mixtures that satisfy accepted criteria for compressive strength, moisture gain, volume change, and brushing losses in the wet-dry and freeze-thaw tests when each is pertinent are designated Soil-Cement. Mixtures specified in western states as "Class A Cement-Treated-Base" and most mixtures included under "Class B and Class D Cement-Treated-Base" satisfy criteria for soil-cement. Suggested uses of cement-treated soil mixtures that satisfy criteria for soil-cement include the following:

1. Base courses for roads, streets and airfields. (This item also includes subbases for rigid and flexible type pavements.)
2. Surfaced shoulders for highways and airfields (88, 89, 90).
3. Surfaced parking areas (55).
4. Surfaced storage areas for aggregates, miscellaneous materials, and equipment (91, 92).
5. Surfaced sidewalks and bicycle paths (93).
6. Unsurfaced horizontal multiple-lift thick slope facing subject to periodic or continuous inundation and wave action (30, 94, 95).
7. Earth dam cores (96).
8. Unsurfaced linings for reservoirs (95, 97, 98).
9. Foundations for some types of structures (30, 55).
10. Masonry units (brick or block) for building construction (99, 100, 101).
11. Rammed monolithic construction of small buildings (99, 100, 101).
12. Maintenance, reconstruction and granular bases (89, 102).
13. Modification of frost-susceptible soils (42, 86).
14. Miscellaneous constructions including surface drains, culverts, small arch bridges, etc., where special conditions warrant (60, 104, 105).

Cement-Modified Granular Soils (17, 22, 39, 42, 55, 64, 89, 106, 107, 108, 109, 110)

Many sandy and gravelly soils are only slightly substandard as materials for bases, subbases, and subgrades of flexible- or rigid-type pavements. These may contain excessive proportions of fine fraction material or excessively plastic fines, or both, and need improvement to bring them to a minimum acceptable quality. This may require only sufficient cement to modify the plastic properties of the soil, or it may require sufficient cement for substantial hardening to a quality only slightly less than that possessed by soil-cement. Cement-modified granular soils are used in the following facilities:

1. Base and subbase courses for flexible-type surfaces for roads, streets, and airfields where type of material, traffic, and climatic conditions permit;

2. Subgrade and subbase treatment under rigid-type pavement to prevent erosion by pumping action of the slabs;
3. Patching and reconstruction of failed granular bases;
4. Maintenance strengthening of subgrades and bases in patching operations; and
5. Modification of frost-susceptible granular soils.

Cement-Modified Silty and Clayey Soils (22, 25, 26, 27, 29, 30, 33, 35, 39, 41, 92, 107, 109, 111, 112, 113)

Cement in smaller amounts than needed to produce soil-cement is used to improve the performance of subgrade soils. The several purposes for which this type of cement-treated soil is used are:

1. Treatment to control shrinkage and expansion of high volume change subgrade soils;
2. Improvement of the strength characteristics of subgrades; and
3. Reduction of the effects of frost action on subgrades.

Plastic Soil-Cement (10, 20, 97, 114, 115)

The difficulty of placing and compacting, at optimum moisture content, the usual types of cement-treated soil mixtures in other than installations permitting the use of flat surfaces, led to the development of plastic soil-cement. This type of mix is used in the following installations:

1. Linings for roadside drainage channels (ditches);
2. Linings for irrigation canals; and
3. Sacked rip-rap for erosion protection.

Cement-Treated Soil Slurries

Slurries are used in highway work principally for maintenance purposes of "mud-jacking" to raise pavements that have subsided because of embankment settlement, or due to subgrade erosion (116, 117, 118). However, in tunnel construction it may be necessary to seal off waterflow by means of pressure grouting (119, 120, 121, 122, 123).

BITUMINOUS SURFACES FOR CEMENT-TREATED SOIL BASE COURSES FOR ROAD AND STREET CONSTRUCTION

The selection of the type and thickness of bituminous surface for cement-treated soil

TABLE 26

BITUMINOUS SURFACES FOR SOIL-CEMENT MIXTURES[a]
(Suggested Types and Minimum Thicknesses as Related to Composition of Traffic for Two-Lane Roads)

Item	ADT Less Than 100	ADT 100-400			ADT 400-1000			ADT Over 1000		
Composition of traffic (T)										
Traffic type	M	P[b]	M[c]	T[d]	P	M	T	P	M	T
Probable maximum no of trucks per day[e]	Less than 10	0	50	80	0	120	200	0	Over 120	Over 200
Bituminous surface Types[f]	2C-BST	2C-BST	RM-BST HM-CL-BP	HM-HL-BP	3C-BST RM-BST	HM-CL-BP HM-HL-BP	HM-HL-BP	4C-BST RM-BST HM-HL-BP	HM-HL-BP	HM-HL-BP
Suggested minimum surface thickness (in)	¾	¾	1	1½	1	1½	2	1½	2	3

[a]This table is based on the prevalence of the following conditions of traffic (1) that the composition of mixed traffic, M, is not likely to exceed 12 percent trucks, and that traffic containing a high proportion of trucks is not likely to exceed 25 percent, (2) that the distribution of trucks by classes is about average (national average is 15 to 16 trucks per 100 vehicles and is composed of busses = 1, single unit trucks = 8, and truck combinations = 7), (3) that the directional distribution of equivalent truck loadings throughout the day is about equal (proper consideration should be given when the number in one direction is markedly greater than in another)
[b]Passenger vehicles exclusively or passenger vehicles and commercial vehicles up to approximately 3 tons gross weight
[c]Mixed traffic containing less than average proportion of numbers of trucks
[d]Mixed traffic containing more than average proportion of numbers of trucks
[e]When truck traffic exceeds value shown for traffic type and ADT, adjust thickness to next higher thickness
[f]2C-BST = 2 course (double) bituminous surface treatment
3C-BST = 3 course (triple) bituminous surface treatment
4C-BST = 4 course (quadruple) bituminous surface treatment
RM-BST = Road-mix bituminous surface treatment
HM-CL-BP = Hot-mix, cold-lay bituminous pavement
HM-HL-BP = Hot-mix, hot-lay bituminous pavement
Consult local practice on mixes involving emulsions, and for penetration macadams

construction is a design problem. Good design practice calls for certain minimum requirements of type and thickness depending on the type of cement-treated soil and the volume and composition of traffic. Climatic conditions, types, and availability of materials as well as local experience influence minimum requirements. Where practices for an area have not been developed for a range of traffic types and volumes, the composition of traffic may be determined and the appropriate type of surface and minimum thickness given in Table 26 may be used on base courses of a quality equivalent to soil-cement. Bituminous surfaces for low-cement-content cement-modified granular base courses should be of a type and thickness normally used for base courses of crushed rock or of crushed gravel of equivalent quality.

Preliminary Surveying, Sampling, Testing And Mix Design for Cement-Treated Soil Construction

PRELIMINARY SURVEYING AND SAMPLING

Standard Methods

Standard methods of soil surveying and sampling are suggested for use in preliminary surveying and sampling for cement-treated soil construction. Regardless of the type of cement-treated soil mixture or the type of facility in which it is to be used, tests should be made that will provide needed knowledge of the properties of the subgrade soils as well as the soils available for use in the cement-treated soil mixture. Procedures for standard methods are found in "Standard Methods of Surveying and Sampling Soils for Highway Purposes" AASHO designation T 86, ASTM designation D 420. Additional procedures are found in "Suggested Methods of Surveying and Sampling Soils for Highway Purposes," by F.R. Olmstead, ASTM "Procedures for Testing Soils," 1958.

Use of the Soil Series Method

The U.S. Department of Agriculture, Soil Conservation Service, carries on a continuing program of classifying and mapping of soils. The basic unit is the soil series (124, 128). Soils of a given series have similar characteristics of subsoil (B-horizon) and parent material (C-horizon) developed under similar conditions of climate, vegetation and age. The surface soils (A-horizon) may differ in texture for a given series.

Soils of the same series and horizon have been found to require the same amount of cement for adequate hardening (125, 126). When the cement requirement for a given soil series and horizon has been determined from standard laboratory tests, no further tests for that series and horizon are needed regardless of where it may be encountered. In Iowa, however, the soil series and horizon may not be reliable indicators of cement requirements of loess and loess-derived soils and of till and till-derived soils (127).

Soil surveys using the soil series as a mapping unit have been made for a large portion of the United States. County soil survey reports are available and may be obtained from the U.S. Department of Agriculture or may be viewed at the offices of county extension agents, state colleges and universities, and many libraries. For those interested in extending their knowledge of the soil series method, numerous authentic publications are available for study (124, 125, 126, 127, 128, 129, 130, 131, 132). The Highway Research Board periodically reports (133, 134, 135, 136, 137, 138) the status of soil mapping by the U.S. Department of Agriculture and other agencies through publications sponsored by the Committee on Surveying, Mapping and Classification of Soils. These committee-sponsored publications list the soil surveys completed and those started since the preceding publication and provide the engineer with recent information on soil surveys and soil maps.

Sizes of Samples

The minimum sizes of raw soil samples required for all types of tests that are normally performed on raw soils and on cement-treated soil are indicated in Table 27.

TABLE 27

MINIMUM SIZES OF RAW SOIL SAMPLES REQUIRED FOR TESTS ON RAW SOILS AND CEMENT-TREATED SOIL MIXTURES

Tests and Test Methods	Size of Sample (gr)	Size of Sample (lb)
Standard Tests on Raw Soils		
Mechanical analysis (AASHO T 88, ASTM D 422)	115	0.25
Liquid limit (AASHO T 89, ASTM D 423)	100	0.25
Plastic limit (AASHO T 90, ASTM D 424)	25	0.1
Plasticity index (AASHO T 91)	None	None
Shrinkage factors (AASHO T 92, ASTM D 427)	30	0.1
Specific gravity (AASHO T 100, ASTM D 854)	30	0.1
Check tests	100	0.25
Compaction and density of soil (AASHO T 99, ASTM D 698)	5,000	11.0
Specific gravity and absorption of coarse aggregates (AASHO T 84, ASTM C 127)	-[a]	-[a]
Supplementary Tests on Raw Soils		
Sand equivalent test (AASHO T 176)	110[b]	0.3[b]
Swell of soils (AASHO T 116, ASTM "Procedures for Testing Soils," 1950)	650[b]	1.4[b]
Expansion pressure of soils (Test Method Calif. 301 B, January 3, 1956) 4 tests	5,000[b]	11.0[b]
Shrinkage of soil (ASTM "Procedures for Testing Soils," 1950)	1,000[c]	2.2[c]
Organic impurities (AASHO T 21)	450	1.0
Glycerol retention test (for surface area) (50)	10	0.1
Standard Tests on Cement-Treated Soil Mixtures		
Moisture-density relations (AASHO T 134, ASTM D 558)	5,000	11.0
Wetting and drying test (AASHO T 135, ASTM D 559) 2 specimens	3,000	6.6
Freezing and thawing (AASHO T 136, ASTM D 560) 2 specimens	3,000	6.6
Supplementary Tests on Cement-Treated Soil Mixtures		
Compressive strength (2.8-in. diam. x 5.6-in. high specimens) (ASTM "Procedures for Testing Soils")	250[d]	0.6[d]
Compressive strength (4-in. diam. x 4.59-in. high specimens)	1,500[d]	3.3[d]
Permeability (ASTM "Procedures for Testing Soils")	3,000[e]	6.6[e]
California Bearing Ratio (ASTM "Procedures for Testing Soils")	4,200	9.3
Cement content of soil-cement mixtures (AASHO T 144, ASTM D 806)	None	None
Inspection tests ("pick" and "click" tests) (10)	None	None
Total sample for all tests		75 to 100

[a]Depends on proportion of coarse aggregate. Test requires 5,000 grams.
[b]Minus No. 4 sieve material.
[c]Minus No. 10 sieve material.
[d]Soil required for one specimen.
[e]Size of sample ranges from 200 grams of minus No. 10 material to 3,000 grams of total material depending on method of test used.

TABLE 28

TESTING FOR SOIL-CEMENT CONSTRUCTION—OBSERVATIONS AND TESTS FOR SOIL IDENTIFICATION AND MIX DESIGN PURPOSES

Method of Observation or Test	Reference	Purpose of Method
A Commonly used methods for soil-cement		
1 Soil series and horizon determination	Soil Survey Manual, U S Dept of Agriculture, Handbook No 18, 1951 Also see Preliminary Surveying and Sampling for Soil-Cement Construction	To reduce amount of testing Once the cement requirements for a given series and horizon have been determined by tests, no further soil-cement tests are needed for soils of that series and horizon regardless of where it is encountered
2 Identification tests on raw soils a Liquid limit b Plastic limit c Mechanical analysis	 AASHO T 89, ASTM D 423 AASHO T 90, ASTM D 424 AASHO T 88, ASTM D 422	To aid in establishing the boundaries of the various roadway or borrow soils, to eliminate inferior soils, and, to select soils that appear to be the most suitable for testing as soil-cement mixtures
3 Pre-mix-design tests on raw soils a Bulk specific gravity and absorption of plus No 4 aggregates	 AASHO T 85, ASTM C 127	To furnish values for weight proportioning of soil plus 4 fractions for the moisture-density relations test on soil-cement mixtures
4 Mix-design tests on soil-cement mixtures a Moisture-density relations b Compressive strength c Wetting and drying test d Freezing and thawing test	 a AASHO T 134, ASTM D 558 b ASTM Procedures for Testing Soils, 1958 c AASHO T 135, ASTM D 559 d AASHO T 136, ASTM D 560	a To furnish values of moisture content and density for molding specimens for tests and for field control factors for starting construction b To provide data on rate and degree of hardening for all soils, for determining cement requirements for sandy soils, and for aids in selecting cement contents for wet-dry and freeze-thaw tests Also to provide a standard by which the quality of field processing can be appraised c and d To determine the minimum cement contents that will overcome disruptive forces of swelling and shrinking, as well as frost action, for use as cement factors for construction
5 Short-cut test procedures for sandy soils	(10, 49)	To determine the cement requirements and starting moisture and density values for construction
6 Inspection tests—the "pick" and "click" tests	(10)	To aid in judging the rate of hardening and in selecting cement contents for further testing
B Auxiliary and supplementary methods		
1 Identification tests on raw soils a Shrinkage limit b Sand equivalent c Specific gravity	 AASHO T 92, ASTM D 427 AASHO T 176 AASHO T 100, ASTM D 854	a When related to optimum moisture content, to aid in preliminary estimating of cement requirements b To aid in estimating cement requirements c For computation of porosity
2 Premix-design tests on raw soils a Volume change (1) Shrink (2) Swell b Frost heave susceptibility c Organic content d Surface area (glycerol retention) e Permeability	 a ASTM Procedures for Testing Soils, 1950 Page 129, except make separate computations for shrink and swell b (139) c AASHO T 21, ASTM C 40 d (140) e ASTM Procedures for Testing Soils, 1950	a To provide a basis for judging the effectiveness of low cement content mixes (cement-modified soil) in controlling volume change b To form a basis for judging the effectiveness of cement admixtures to prevent detrimental frost heave c To aid in preliminary selection of suitable soils, to establish cause of unsuitability of a soil, and to aid in determining requirements for amendments and additives d A short-cut method for plastic soils with less than 45 percent silt e To provide a basis for judging the effectiveness of cement in controlling permeability
3 Tests on soil-cement mixtures a Moisture-density relations (10-lb rammer) b Volume change (1) Shrink (2) Swell c Frost heave susceptibility d Permeability e Strength and elastic properties (1) Triaxial compression (2) Flexural (modulus of rupture) (3) Calif Bearing Ratio (CBR) (4) Punching shear (5) Plate bearing test (6) Moduli of elasticity a Static modulus in compression (E_{sc}) b Static modulus in flexure (E_{sf}) c Resonance dynamic modulus (E_d) (7) Poisson's ratio f Atterberg limits on repulverized soil-cement (LL, PL) (Also SL) g Water absorption h Thermal conductivity i Thermal expansion (coeff of) j Flow test on soil-cement slurries	 a AASHO T 180, ASTM D 1557 b Same as for B-2-a above c Test method in Reference 139 applied to Soil-Cement d ASTM Procedures for Testing Soils e -(1), e-(2), e-(3), e-(5) ASTM Procedures for Testing Soils e -(4) Reference 141 e -(6) and e-(7) Reference 14 f References 26, 27, 41, 142 g Immersion h Reference 143 i. Reference 38 j Reference 123	a Same as for B-2-a Higher density and lower moisture content can be used where these values will be obtained in construction b To determine cement requirements for control of shrink and swell within prescribed limits c. To determine cement requirements for special applications where soil-cement is in contact with free water during freezing and no heaving is permitted d To determine the cement requirements to control permeability within prescribed limits e Strength tests provide data described above under A-4-b and also for structural design purposes f To provide data that indicates effectiveness of cement in reducing plasticity in cement-modified granular soils and to indicate generally its effectiveness in controlling volume change in cement-modified clayey soils g To indicate effectiveness of cement in controlling swell h To provide data on heat losses for building purposes i To determine linear changes in soil-cement due to temperature changes j To determine proper proportion of water in mixes for mudjacking slurries and grouts

OBSERVATIONS AND TESTS FOR SOIL IDENTIFICATION AND MIX DESIGN PURPOSES

Categories of Observations and Tests

The main requirements for soil-cement of a prescribed quality are that: (a) an adequate proportion of cement is incorporated with the pulverized soil; (b) the proper proportion of water is dispersed through the soil-cement mix; (c) the soil-cement mixture is compacted to the proper density; and (d) the compacted soil-cement is protected against moisture loss and excessively low temperatures during a prescribed curing period. Control factors to aid in meeting three of these four requirements can be predetermined by commonly used tests and observations on the soils and on the soil-cement mixtures. The observations and tests are of two types: those performed on the soil for the purpose of identification, and those performed principally for controlling the design of the soil-cement mix to meet specific requirements. For each of the two categories there are several tests that are commonly used. In addition, there are auxiliary and supplementary tests of a nature that provide data on different properties of soils or soil-cement mixes or supplement the data obtained by the commonly used tests. A list of the commonly used observations and tests, and auxiliary and supplemental tests for both soil and soil-cement mixtures is given in Table 28. In addition, Table 28 gives reference to descriptions of methods and indicates the purpose of the observation or test.

Application of Observations and Tests to Projects

The need for testing, and thus the application of the individual test methods, depends on the nature of the soil, the climatic conditions involved, the type of soil-cement mix being designed, and, in some measure, on the size of the facility and the time permitted for testing. Previous test data correlated with performance make it possible to determine cement requirements for sandy soils with only limited testing. Where freezing of the soil-cement base courses does not occur, the climatic conditions lessen the need for the freeze-thaw test. Soil-cement that is designed to satisfy certain criteria requires testing that differs both in amount and nature from the testing required for cement-modified granular soils and cement-modified silt-clay soils. The size of the facility and time permitted for testing also govern the test methods permissible from the standpoint of cost and time. Major projects are planned to permit time for testing. For very small projects, the cost of extensive testing is not economical, and it is desirable to estimate cement requirements and provide a margin of safety in terms of increased requirements to insure mixtures meeting quality requirements. Figure 76 shows the manner in which tests are usually used in projects of various sizes.

The application of testing to types of cement-treated soil and size of projects is

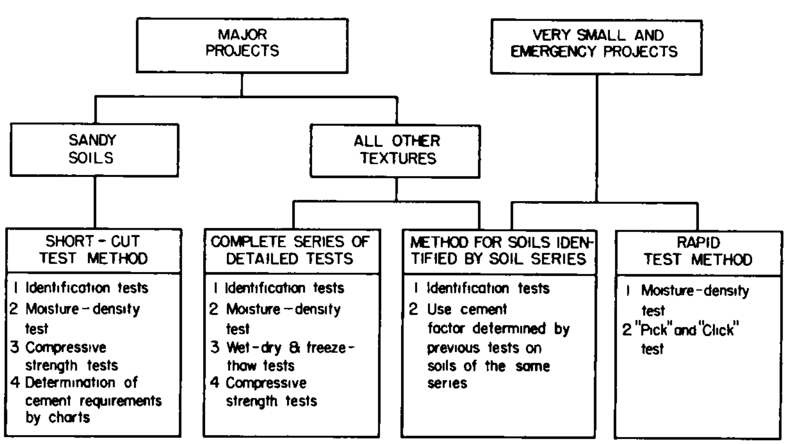


Figure 76. Interrelation of methods of testing soil-cement mixtures (144).

further indicated in Table 29, which gives the tests that are essential to insure results befitting the type of mixture used, and additional tests that may aid in designing or in evaluating the mixture.

Testing and Mix Design for Soil-Cement for Major Projects

General.—Whenever practicable the first step in making observations and tests would be to identify the soil series and horizon, then to determine if samples from a similar soil series and horizon have been tested previously. If it is not practicable to identify the series, or if on identification it is found that tests have not been made pre-

TABLE 29

APPLICATION OF TESTING TO THE VARIOUS TYPES OF CEMENT STABILIZATION

	Soil-Cement[a]		Cement-Modified Granular Soils			
Observations and Test Methods	Major Projects	Small or Emergency Projects	Major Projects	Small or Emergency Projects	Cement-Modified Silt-Clay Soils[b]	Plastic Soil-Cement (sandy soils)
I. Field soil survey						
A. Soil horizon or layer and depth in road or in borrow pit. (AASHO T 86, ASTM D 420) (3)	x	x	x	x	x	x
B. Soil series or extent	-[c]	-[c]	-	-	-[c]	-
II. Testing of raw soils						
A. Commonly used tests						
1. Mechanical analysis (AASHO T 88, ASTM D 422)	x[d]	x[d]	y	y	y	x[d]
2. Liquid limit (AASHO T 89, ASTM D 423)	y	y	y	y	y	y
3. Plastic limit (AASHO T 90, ASTM D 424)	y	y	y	y	y	y
4. Specific gravity and absorption of coarse aggregate (AASHO T 85, ASTM C 127)	x	y	x	y	y	x
B. Auxiliary and supplementary tests						
1. Sand equivalent (AASHO T 176-56 I)	y[e]	y[e]	y	y	-	y[e]
2. Volume change (shrink and swell) (ASTM Proc. for testing soils)	-	-	-	-	x[f]	-
III. Testing of cement-treated soil mixtures						
A. Commonly used tests						
1. Moisture-density relations (AASHO T 134, ASTM D 558)	x	x	x	x	x	x[g]
2. Compressive strength (ASTM Procedures for testing soils)	x	y	x	y	y	x
3. Wetting and drying test (AASHO T 135, ASTM D 559)	x[h]	y	-	-	y	x
4. Freezing and thawing test (AASHO T 136, ASTM D 560)	x[h]	y	y	-	y	x
5. Short-cut test procedures for sandy soils (40)	y[i]	y[i]	-	-	-	-
6. Inspection tests—the "pick" and "click" tests (2)	y[j]	y[j]	y[j]	y[j]	y[j]	y[j]
B. Auxiliary and supplementary tests						
1. Volume change (shrink and swell)	-	-	-	-	y	-
2. Water absorption (moisture content after swell)	y	-	-	-	y	-
3. Liquid limit and plastic limit of repulverized soil-cement mix	-	-	y	-	y	-

Note: x Observations and tests needed to insure results befitting the type of mix
y Observations and tests that may aid in designing or evaluating the mix

[a]Mixes designed to satisfy "Criteria for Soil-Cement." These may include Class A and some Class B and Class D cement-treated base mixtures used in western states.

[b]Tests needed to provide data for mix design depend on nature of facility, exposure conditions, desired properties of the cement-modified soils, and degree of permanency expected. The tests indicated will furnish data for most highway uses.

[c]When personnel qualified to identify type, series and horizon are available.

[d]Necessary when coarse aggregate (plus No. 4 sieve) is present.

[e]Most useful on granular soils.

[f]When aim is to control volume change.

[g]See Reference 159 for method of test.

[h]Except when short-cut procedures are used for sandy soils.

[i]May be used in lieu of standard tests.

[j]A useful observation on all cement-treated mixtures.

viously, the second step is to determine by mechanical analysis if the soils meet the requirements for sandy soils for which short-cut cement requirement test procedures may be used. If the short-cut procedures are not applicable, ASTM-AASHO Tests are made.

Short-Cut Methods for Determining Cement Requirements for Sandy Soils: Methods A and B.—Reports were made in 1953 (145), 1955 (144), and in 1958 (49) of short-cut methods for determining the cement requirements for mixtures made from sandy soils. During 1957 the AASHO and the ASTM revised their test procedures for the moisture-density relations test (11, 12), the wetting and drying test (11, 12), and the freezing-thawing test (11, 12) to permit the use of the total material in the mixture (with the provision that the material between ¾- and 3-in. sizes be represented by a similar proportion of No. 4 to ¾-in. sieve material). That resulted in a revision (49) of the previously reported (144, 145) procedures to conform to the latest AASHO and ASTM methods. Inasmuch as the short-cut test methods are not given in the AASHO and ASTM Standards, they are given here in detail.

Two short-cut methods have been developed for establishing cement requirements for many sandy soils. Method A is used for soils having no material retained on the No. 4 sieve. Method B is used for soils containing material retained on the No. 4 sieve.

The short-cut methods may be applied only to soils containing less than 50 percent material smaller than 0.05 mm (silt and clay) and less than 20 percent smaller than 0.005 mm (clay). The short-cut methods do not apply to slow hardening organic surface soils described under "Soil Amendments and Additives," nor to miscellaneous materials such as cinders, caliche, chat, chert, marl, red-dog, scoria, shale, slag, volcanic ash, or volcanic cinders. Method B does not apply to granular soils having material retained on the No. 4 sieve if that material has a bulk specific gravity of less than 2.45. The methods do not necessarily indicate the minimum permissible cement content, but they do indicate a safe cement factor generally near that indicated by ASTM-AASHO wet-dry and freeze-thaw tests.

Before applying the short-cut method, it is necessary (a) to determine the gradation of the soil, and (b) to determine the bulk specific gravity of the material retained on the No. 4 sieve to find if it meets the foregoing requirements. If all the soil passes the No. 4 sieve, Method A should be used. If some material is retained on the No. 4 sieve, Method B should be used.

Method A procedure is as follows:

Step 1—Determine by test the maximum density and optimum moisture content for a mixture of the soil and the cement. (Use Figure 77 to obtain an estimated maximum density of the mixture being tested. This estimated maximum density and percentage of material smaller than 0.05 mm—No. 270 sieve—may be used with Figure 78 to determine the cement content by weight to use for the test.)

Step 2—Use the maximum density obtained by test in Step 1 to determine from Figure 78 the indicated cement requirement.

Step 3—Use the indicated cement factor obtained in Step 2 to mold compressive strength specimens in triplicate at maximum density and optimum moisture content. (Specimens of 2-in. diameter by 2 in. in height or 4-in. diameter by 4.6 in. in height may be molded. The 2-in. specimen should be submerged in water one hour before testing and the 4-in. specimens four hours. The 4-in. specimens should be capped before testing.)

Step 4—Determine the average compressive strength of the specimens after 7 days moist curing.

Step 5—On Figure 79 plot the average compressive strength value obtained in Step 4. If this value plots above the curve, the indicated cement factor by weight, determined in Step 2, is adequate. For field construction use Figure 80 to convert this cement content by weight to a volume basis. (If the average compressive strength value plots below the curve of Figure 79, the indicated cement factor obtained in Step 2, is probably too low. Additional tests will be needed to establish a cement requirement. These tests generally require the molding of two test specimens, one at the indicated cement factor obtained in Step 2 and one at a cement content two percentage points higher. The specimens are then tested by ASTM-AASHO freeze-thaw test procedures.)

Method B procedure is as follows:

Step 1—Determine by test the maximum density and optimum moisture content for a mixture of the soil and portland cement. (Use Figure 81 to determine an estimated maximum density of the mixture being tested. This estimated maximum density, the percentage of material smaller than 0.55 mm (No. 270 sieve), and the percentage of material retained on the No. 4 sieve may be used with Figure 82 to determine the cement content by weight to use in the test.) The soil sample for the test should contain the same percentage of material retained on the No. 4 sieve as the original soil sample contains. However, ¾-in. material is the maximum size used. Should there be material larger than this in the original soil sample, it is replaced in the test sample by an equivalent weight of material passing the ¾-in. sieve and retained on the No. 4 sieve.

Step 2—Use the maximum density obtained by test in Step 1 to determine from Figure 82 the indicated cement requirement.

Step 3—Use total material as described in Step 1 and the indicated cement factor obtained in Step 2 to mold compressive strength specimens in triplicate at maximum density and optimum moisture content. (Specimens of 4-in. diameter by 4.6 in. in height shall be molded. They should be submerged in water four hours and should be capped before testing.)

Step 4—Determine the average compressive strength of the specimens after 7 days moist curing.

Step 5—Determine from Figure 83 the minimum allowable compressive strength for the soil-cement mixture. If the average compressive strength obtained in Step 4 equals or exceeds the minimum allowable strength, the indicated cement factor by weight obtained in Step 2 is adequate. For field construction, use Figure 80 to convert this cement content by weight to a volume basis. (If the average compressive strength value is lower than the minimum allowable, the indicated cement factor obtained in Step 2 is probably too low. Additional tests as described previously are needed.)

Accuracy of Short-Cut Methods for Determining Cement Factors for Sandy Soils.—A comparison has been made of cement requirements obtained by this method with the requirements obtained on total material by standard AASHO and ASTM wet-dry and freeze-thaw methods for 209 soils (49). Adequate cement contents or the need for further testing was indicated for 204 (97.6 percent) of the 209 soils. For five of the soils (2.4 percent) the method did not indicate adequate cement contents nor did it indicate the need for further testing. The reliability was 97.6 percent. Actual cement requirements were indicated for 59 percent of the soils. The Short-Cut Method called for a 1 percent higher cement content for 25 percent of the soils, a 2 percent higher cement content for about 9 percent of the soils and a three percent higher cement content for about four percent of the soils.

Correction for Plus No. 4 Material in Determining Maximum Density of the Soil-Cement Mix.—Past practice in all soil-cement testing (short-cut as well as standard methods) has been to determine the maximum density on the fraction passing the No. 4 sieve and then compute the theoretical maximum density of the total mixture. Those computations were based on the assumption that the addition of material retained on the No. 4 sieve increased the density of the mixture by displacing, in equal volume, the mixture passing the No. 4 sieve. That has not always held true. As a result, tests have been performed (49) to determine the relationship between the maximum density (as determined by AASHO Method T 134 or ASTM Method D 558) and the percent of material retained on the No. 4 sieve and compare the results with those obtained by computation on the basis of the following equation:

$$d = \frac{D - 0.9\ RG}{(1 - R)}$$

in which

d = the maximum density of soil-cement mixture passing the No. 4 sieve in pcf;

D = maximum density of total soil-cement mixture in pcf;
R = percent of material retained on the No. 4 sieve divided by 100; and
G = bulk specific gravity of material retained on the No. 4 sieve x 62.4.

The results of the tests on a natural gravel and sand are indicated in Figure 84. Material retained on the No. 4 sieve was separated and then recombined in the proportions indicated in the chart. It may be seen from Figure 84 that when the amount of material retained on the No. 4 sieve does not exceed about 50 percent, the maximum densities obtained by the equation approximate quite closely the maximum densities obtained by test using the total material.

Standard AASHO and ASTM Test Methods.—Standard AASHO and ASTM test methods

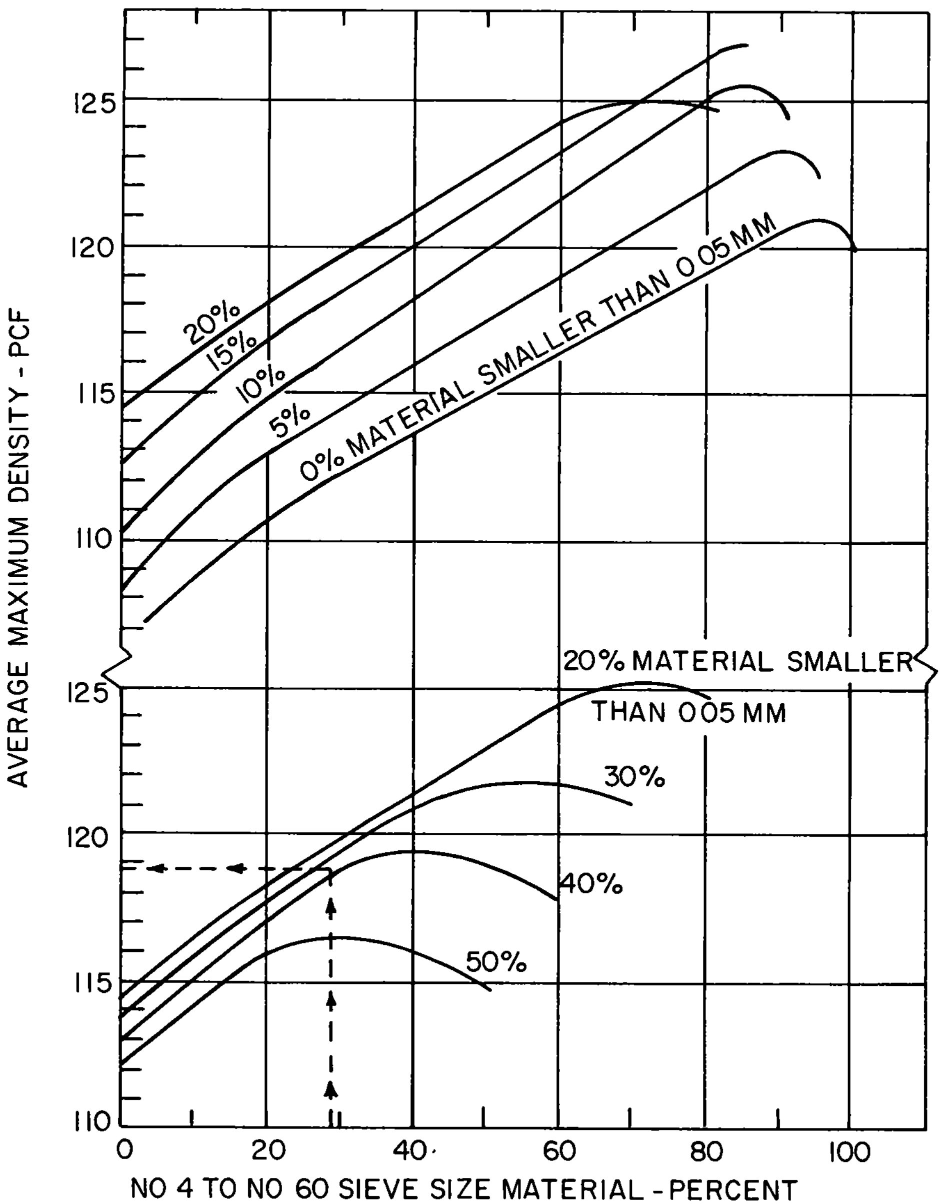


Figure 77. Average maximum densities of soil-cement mixtures having no material retained on No. 4 sieve (49).

have been recently revised to permit inclusion of the total material for soils containing coarse aggregate. References to the test methods are given in Tables 28 and 29. Sources where the descriptions of the test methods may be found are given in the references (11, 12, 103). The test methods are also described in the ASTM Book of Stand-

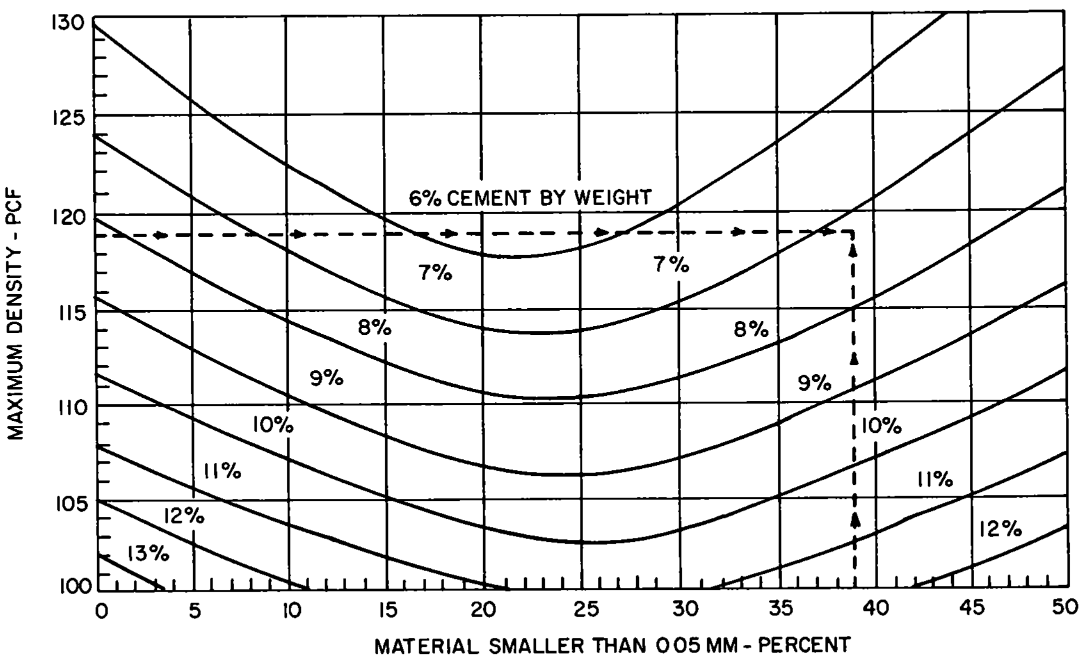


Figure 78. Indicated cement content of soil-cement mixtures having no material retained on No. 4 sieve (49).

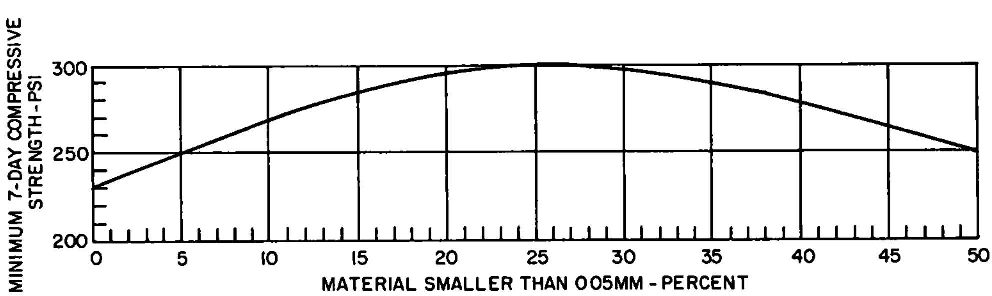


Figure 79. Minimum 7-day compressive strengths required for soil-cement mixtures having no material retained on the No. 4 sieve (49).

ards, Part 3. Additional information concerning the details of testing soil-cement are given in a Laboratory Handbook published by the Portland Cement Association (10).

For dependable results on major projects, the full set of wet-dry and freeze-thaw tests should be performed on soils that do not meet the requirements for the short-cut methods until correlation with behavior provides a background of experience for reduction in the amount and change in the type of testing.

British Standard Test Methods (36).—In British practice, the percent cement for soil-cement is determined by the unconfined compression test method described in

British Standard 1924:1953 of the British Standards Institution. Cylindrical specimens 2 in. in diameter and 4 in. high are compacted at Standard AASHO-ASTM optimum

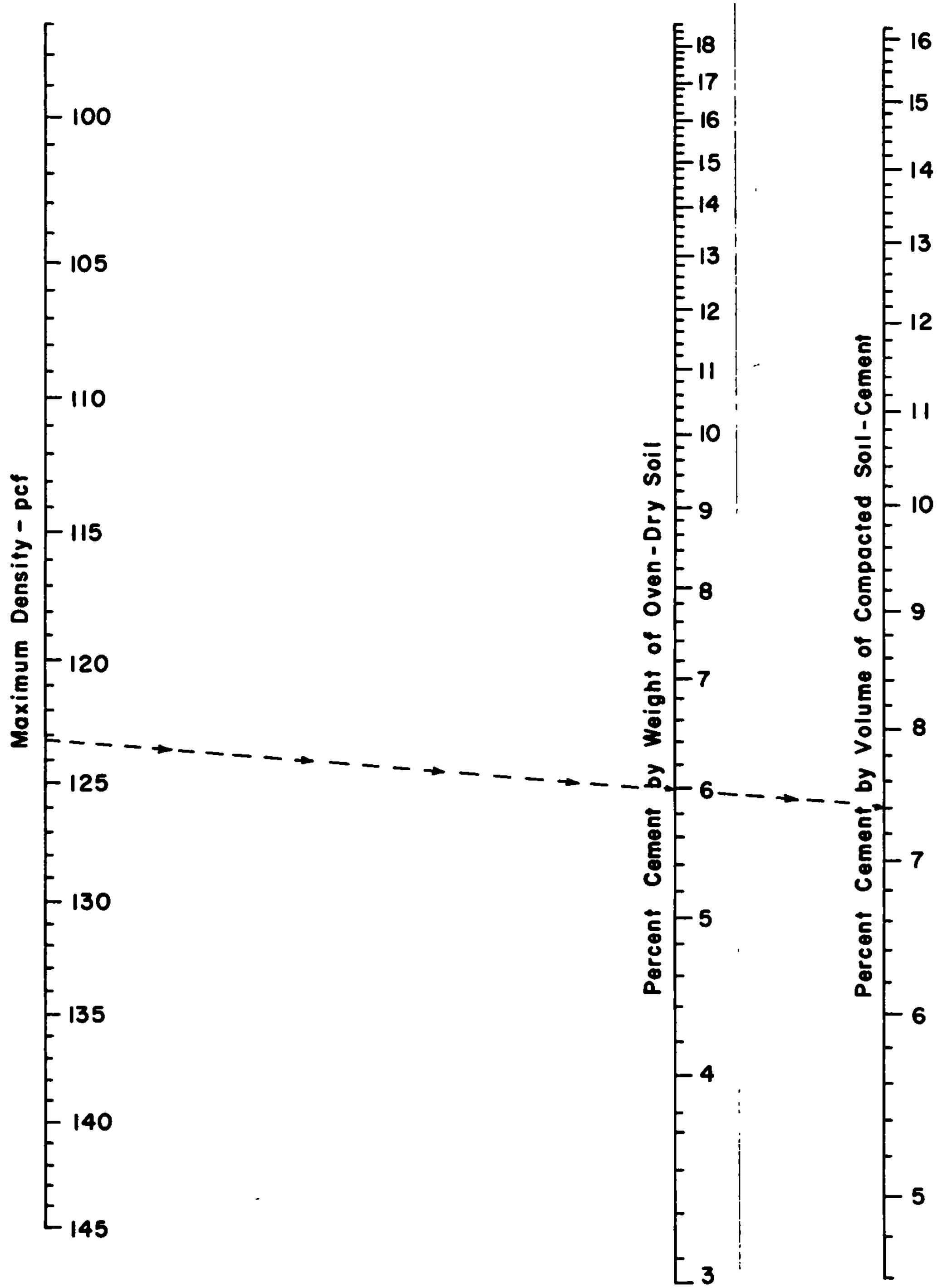


Figure 80. Relation of cement content by weight of oven-dry soil to cement content by volume of compacted soil-cement mixture (49).

moisture and dry density, moist cured at near 100 percent relative humidity and 70 F for 7 days, and then tested for unconfined compressive strength by loading at a constant rate of deformation of 0.05 in. per minute. The minimum cement content adopted is that producing a strength higher than or equal to the appropriate recommended values discussed under "British Criteria for Determining Cement Requirements."

The soil-cement mixture designed on the basis of unconfined compressive strength may not be definitely accepted until it is determined that the mixture provides adequate freeze-thaw resistance to satisfy the requirements of the durability test method described in British Standard 1924:1957 ("Determination of the Resistance of a Stabilized Soil Mixture to Damage by Frost"). For this test, two identical specimens are prepared in the same way as in B.S. 1924:1953; the percent cement used is that which provides soil-cement meeting the unconfined compressive strength criterion.

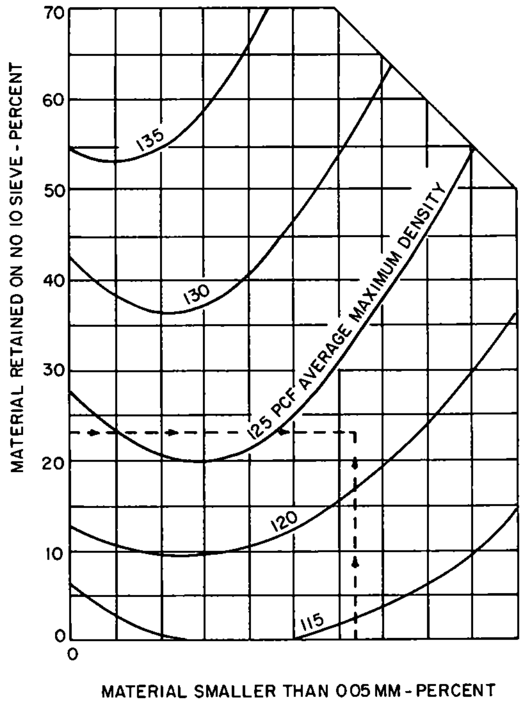


Figure 81. Average maximum densities of soil-cement mixtures having material retained on the No. 4 sieve (49).

After moist curing for 7 days, one of the specimens (the freeze-thaw specimen) is immersed in distilled water for 24 hours, then subjected to 14 cycles of alternate freezing and thawing. Each cycle consists of 24 hours and consists of 16 hours of freezing at a temperature of 23 ± 2 F (-5 + 1 C) followed by 8 hours of thawing at a temperature 77 ± 4 F (25 ± 2 C). In this test only the top surface of the specimen is exposed to extreme temperatures of 23 F and 77 F; the other surfaces of the specimen are in an insulated vacuum flask containing water at a temperature of 46 F (8 C) in contact with the base of the specimen. Freezing and thawing therefore are from the surface as in the field. The second specimen (the control specimen) is moist cured for 7 days and then immersed for 15 days. At the end of this period, the two specimens are tested for unconfined compressive strength, p_f for the freeze-thaw specimen and p_{cf} for the control specimen. The index of the resistance to the effect of freezing, p_{cf}, is calculated from the formula:

$$R_f = \frac{100\ p_f}{p_{cf}} \text{ (percent)}$$

The criterion of satisfactory freeze-thaw durability is discussed under "British Criteria for Determining Cement Requirements."

The use of the British freeze-thaw test is limited to fine-grained soils. A modification of the British freeze-thaw test is described in reference (66).

A soil-cement mixture designed on the basis of unconfined compressive strength criterion may be further evaluated by an immersion test. The preparation of two identical specimens is the same as for the freeze-thaw test. One of the specimens is moist cured for 7 days, then immersed for 7 days. The control specimen is moist cured for 14 days. At the end of this period, the two specimens are tested for unconfined compressive strength, p_i for the immersed specimen and p_{ci} for the control specimen. The resistance to the effect of immersion is calculated from the formula:

$$R_i = \frac{100\ p_i}{p_{ci}} \text{ (percent)}$$

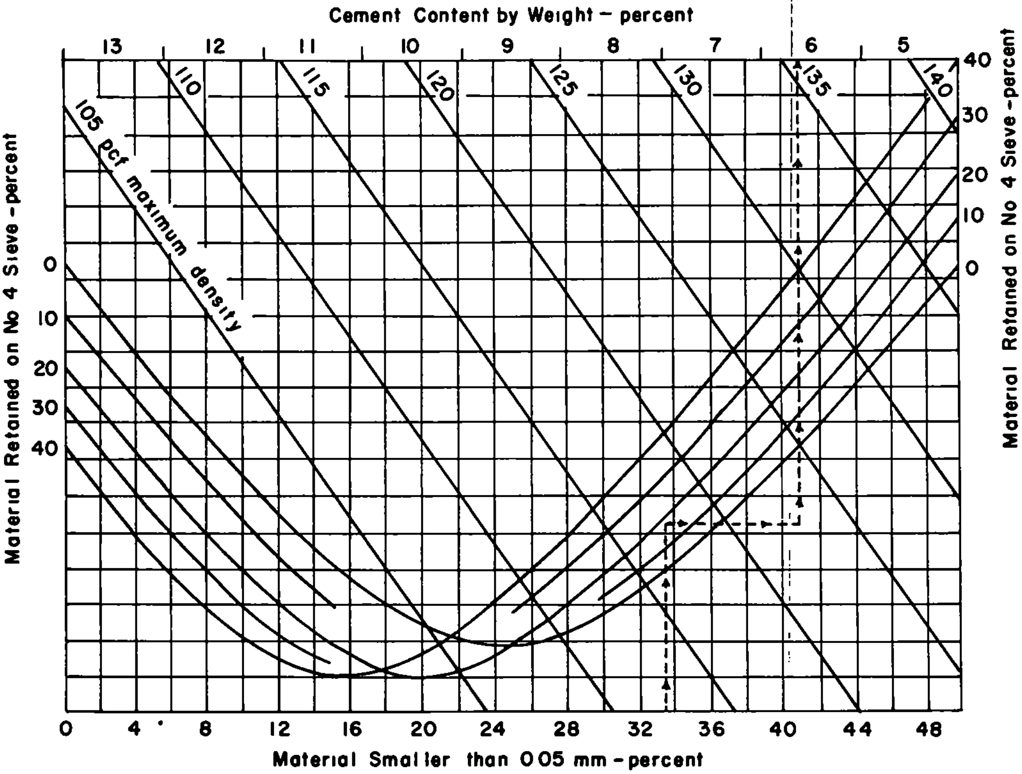


Figure 82. Indicated cement content of soil-cement mixtures having material retained on the No. 4 sieve (49).

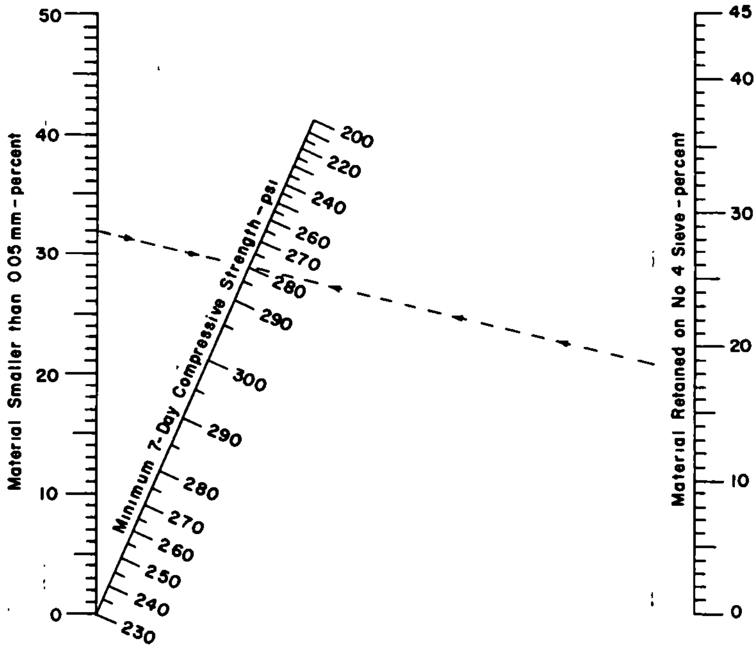


Figure 83. Minimum 7-day compressive strengths required for soil-cement mixtures having material retained on the No. 4 sieve (49).

The criterion of satisfactory immersion durability is discussed under "British Criteria for Determining Cement Requirements."

Auxiliary and Supplementary Test Methods.—The short-cut methods for determining cement requirements for sandy soils (49) and the standard AASHO and ASTM test methods are essential to insure mixtures of a quality that satisfy criteria for soil-cement. There are auxiliary and supplemental test methods that should show a high degree of reliability when used by experienced soils engineers. Among these is a new short-cut method for determining cement content for clayey soils that offers promise as a method for use on major projects, and rapid methods and inspection tests that are designed for use on small or emergency projects.

Short-Cut Procedures for Determining Cement Factors for Fine-Grained Soils—Clayey Soils.—A recent research report (50) shows a strong correlation between surface area of soils as measured by the glycerol retention test (140) and cement requirements when (1) silt clay soils contain less than 45 percent silt sizes (finer than No. 200 sieve and coarser than 0.005 mm); and (2) the cement factor in the correlation is taken as the actual cement content by weight at which 10 percent loss occurs in the freeze-thaw test, no allowance being made for AASHO soil class difference. The equation

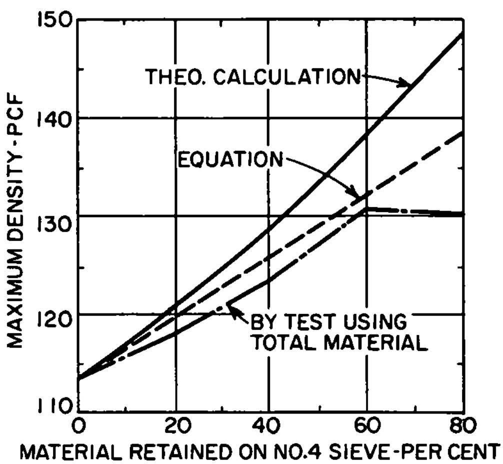


Figure 84. Effect of material retained on the No. 4 sieve on maximum density (49).

Cement Factor =
0.087 x Surface Area + 3.79

can be used to derive accurate predictions of the cement factor from measurements of surface area by the glycerol retention method.

Suitable adjustments can be made by modifying the cement factor obtained from the equation in the following ways:

1. Add 2.0 percent cement to adjust to the basis of 7 percent allowable loss in the freeze-thaw test for A-6 and A-7 soils.
2. Subtract 0.7 percent to adjust to the basis of 14 percent allowable loss for the A-1, A-2-4 and A-2-5 soils.
3. Convert the modified value to a percent by volume basis (using the density of the soil-cement mixture) for construction purposes.

$$\text{Percent cement by volume} = \frac{D-(D/C)}{94} \times 100$$

in which

D = oven-dry density of the soil-cement in pcf, and
C = 100 plus the percent cement by weight of dry soil, the quantity divided by 100.

Comparison of cement requirement values obtained by standard ASTM-AASHO wet-dry and freeze-thaw tests with values obtained by the glycerol retention surface area test for 39 samples showed an average deviation of 0.6 percent cement by volume and considerably less for the more highly plastic members of the group. The chart in Figure 85 indicates the steps taken in the use of the test and its relation to other tests on other soils for which the glycerol retention test is not applicable. As applied to this study, the glycerol retention test consists of the following steps in the determination of surface area:

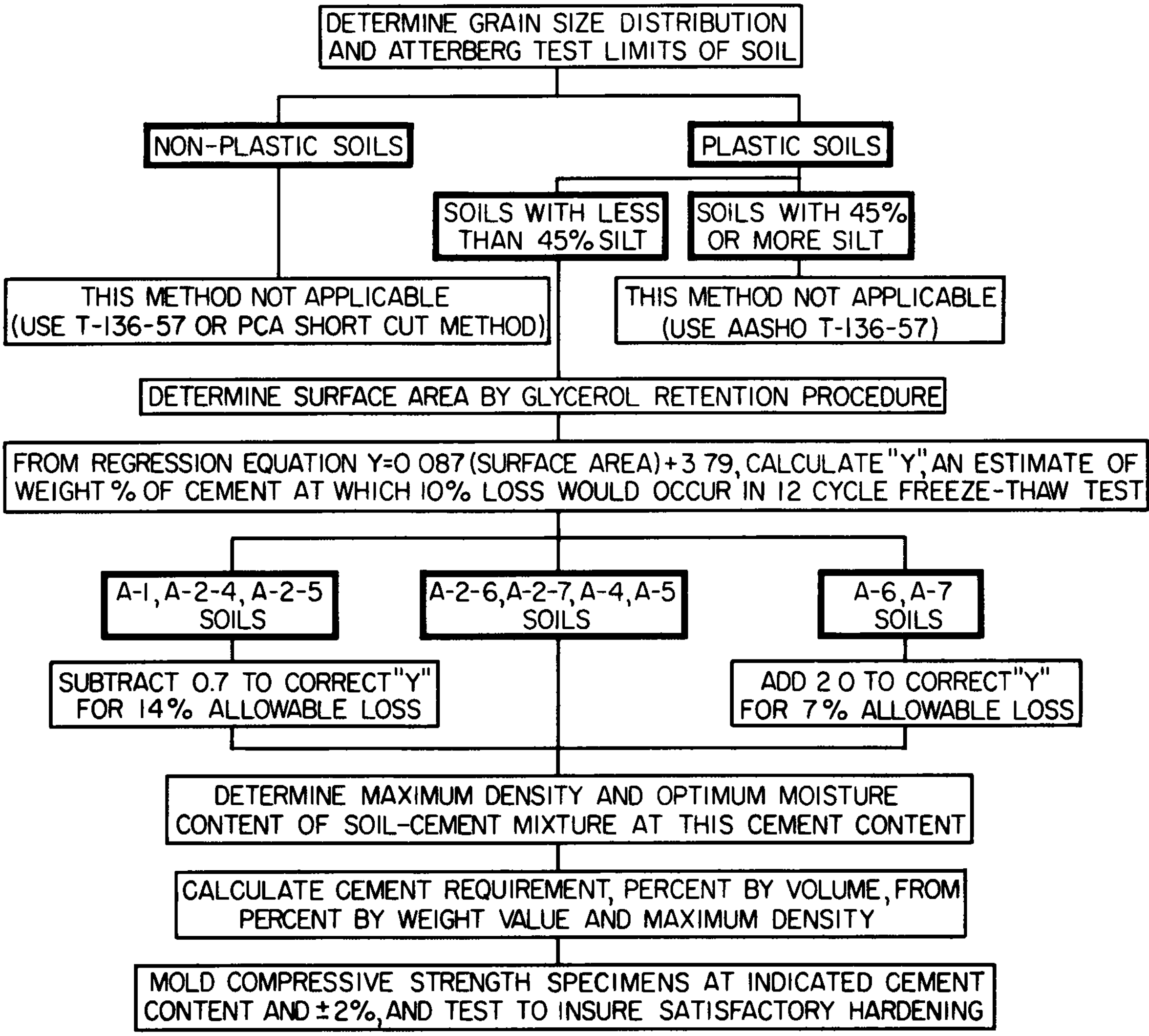


Figure 85. Flow sheet: short-cut method, using surface area to determine cement requirements of plastic soils containing less than 45 percent silt (200-mesh sieve to 0.005 mm) (50).

1. Dry duplicate small samples (about 1 gram each) of the passing 40-mesh fraction of the soil at 110 C in aluminum foil dishes, and weigh to 0.0002 gram on an analytical balance.

2. Add 10 ml of a dilute (2 percent) water solution of glycerol to the sample, and swirl the container gently to mix the contents.

3. Heat at 110 C (± 3 C) in an oven containing a supply of glycerol to provide a source of free glycerol vapor in the oven chamber; under these conditions glycerol in excess of a monomolecular layer and water are both removed.

4. Reweigh after equilibrium has been attained, normally after overnight heating; the gain in weight over the original oven-dry weight of the sample is due to the monomolecular layer of glycerol absorbed on both the internal and external surfaces; the absorbed glycerol is expressed as a percentage of the 100 C dry weight of the soil.

A distinction must be made between that portion of the glycerol retained on external surfaces of all clay minerals and that retained on internal surfaces of expanding minerals such as montmorillonite and vermiculite. On the internal surfaces both the top and bottom of the monomolecular layer of glycerol are in contact with clay surfaces. On the outside of the particles, however, only one side of the monomolecular layer is in contact with clay surface. Therefore, a given amount of glycerol on internal surfaces accounts for twice as much clay surface area as the same amount would if it were on external surfaces.

To make this distinction, a second determination is required. This is accomplished by determining the percentage of glycerol retained by replicate samples previously heated to 600 C, the glycerol retention being determined by the same procedure as previously described. Heating to 600 C normally collapses and irreversibly closes the internal spaces and thus renders them inaccessible to glycerol molecules. The difference between the original percentage of glycerol retained and that retained after heating to 600 C is attributable to internal surfaces; the percentage measured after this preliminary heating is due to external surfaces only.

Based on X-ray diffraction evidence concerning the thickness of a monomolecular layer of glycerol, it has been shown that one-hundredth of a gram of glycerol covers 35.3 square meters of internal clay surfaces; thus a glycerol retention of 1 percent on internal surfaces corresponds to 35.3 m^2/g. One square meter per gram is equal to 4,882 sq ft per pound. Similar deductions indicate that a retention of 1 percent of glycerol on external surfaces corresponds to a specific surface of 17.65 m^2/g.

For the soils used in this study the surface area value of the whole soil was computed by multiplying the surface area found for the passing 40-mesh fraction by the percentage of the whole soil which passes the 40-mesh sieve. The surface area of the particles coarser than 40 mesh is so small as to be negligible. A hypothetical example of these computations is as follows:

Glycerol retention of passing 40-mesh fraction: 3.50 percent
Glycerol retention of same after preliminary 600 C heating: 1.50 percent
Retention due to external surfaces: 1.50 percent
Retention due to internal surface: 3.50 percent - 1.50 percent = 2.00 percent
Indicated surface area of passing 40-mesh fraction:

External:	1.50 x 17.65	= 26.5 m^2/g
Internal:	2.00 x 35.3	= 70.6 m^2/g
	Total	97.1 m^2/g

Percentage of whole soil passing 40-mesh sieve: 65 percent
Surface area of whole soil: 97.1 m^2/g x 0.65 = 63.1 m^2/g

If the surface area determination method is to be used to predict cement requirements, it should be accompanied by compressive strength tests performed on small specimens made at or near the predicted cement requirements to insure that an adequate rate and amount of hardening does take place. Inasmuch as the work to date has been correlated with the freeze-thaw test, it is suggested that specimens 2 in. in diameter by 2 in. high or specimens 2.8 in. in diameter by 5.6 in. high be made, one set tested after 7 days moist cure, another set tested after 14 days moist cure, and a third set tested in compression after 7 days moist cure plus 7 days immersed in water. British experience with clay soils (44) has indicated that the comparison of the 7-day and 14-day moist cured specimen strengths with those after 7 days moist cure plus 7 days immersion are good indicators of performance of clayey soil-cement mixtures.

Silty Soils.—No acceptable short-cuts have been developed for silt clay soils having more than 45 percent silt sizes by weight, for regions where freezing of soil-cement occurs. Where freezing does not occur, the wet-dry test may be applied as the criterion of acceptability, or the compressive strength procedure described in the preceding paragraph may be used as a guide.

Testing and Mix Design for Soil-Cement for Very Small or Emergency Projects

General.—For very small or emergency projects, where complete testing is neither economical nor feasible, the following procedure is suggested:

1. Determine the maximum density and optimum moisture content for the soil-cement mixture.

2. Mold specimens for inspection of hardness.
3. Inspect specimens as curing progresses using the "pick" and "click" procedures.

The moisture-density test is made in accordance with Standard AASHO Method T 134 or ASTM D 558 if testing equipment is available. If not, a section of a 2-in. diameter filled-in gas pipe weighing 5.5 lb and a No. 2½ tin can can serve in an emergency. Maximum density and optimum moisture content are determined at 12 percent cement by weight using the standard procedure or a modified procedure (10). Optimum moisture content and maximum density are determined by "feel." When squeezed, soil-cement at optimum moisture content will stick together when it is handled.

Specimens are molded as nearly as possible in accordance with standard methods and generally contain 10, 14 and 18 percent cement by weight. They are stored in an atmosphere of high humidity for hydration. After two days hardening and after three hours immersion in water, the specimens are inspected by "picking" with a sharp pointed instrument and by sharply "clicking" each specimen against a hard object such as concrete to determine their relative hardness when wet.

"Pick" Test.—In the pick test, the specimen is held in one hand and a relatively sharp-pointed instrument, such as a dull ice pick, is lightly jabbed into the specimen (or the end of a specimen molded in a can) from a distance of 2 or 3 in. If the specimen resists this light picking, the force of impact is increased until the pick is striking the specimen with considerable force. Specimens that are hardening satisfactorily will definitely resist the penetration of the pick, whereas specimens that are not hardening properly will offer little resistance. To pass the pick test, a specimen that is not more than 7 days old and that has been soaked in water must prevent the penetration of the ice pick, which is under considerable force, to a distance greater than about ⅛ to ¼ in.

"Click" Test.—The click test is then applied to water-soaked specimens that are apparently hardening satisfactorily and that have passed the pick test. In the click test, the specimens are held perpendicular to each other and about 4 in. apart, one in each hand. They are then lightly clicked together a number of times, the force of impact being increased with each click. Specimens that are hardening satisfactorily will click together with a "ringing" or "solid" tone. As the force of impact is increased, one of the specimens may break transversely even though it is hardening adequately. The internal portion of a satisfactory specimen should then pass the pick test. Once two or three hard specimens are obtained they may be saved and one may be used in the click test with a soil-cement specimen of a soil in the process of being tested.

When a poorly hardened specimen is clicked with a satisfactory specimen, a dull sound is obtained rather than the solid sound obtained with two satisfactory specimens. After the first or second click the inferior specimens will generally break and its internal portion will not pass the pick test.

At the time the click test is made, the age of the specimens must be taken into account. For instance, specimens that are not properly hardened at an age of 4 days may be satisfactorily hardened at an age of 7 days.

These pick and click procedures are then repeated after drying out the specimens and again after a second soaking in order to test their relative hardness at both extremes of moisture content.

There is a distinct difference between satisfactorily hardened soil-cement specimens and inadequately hardened specimens. Even an inexperienced tester will soon be able to differentiate between them and to select a safe cement content to harden the soil. It is important to remember that an excess of cement is not harmful but that a deficiency of cement will result in inferior soil-cement.

If the 10 and 14 percent specimens are apparently hardening satisfactorily and compression test data are favorable, the project can immediately be started using a cement content of 12 percent by volume. If the quantities of cement available for construction are limited and if the 10 percent cement specimens are hard and have good compressive strength, additional specimens should be molded at 8 percent cement, be permitted to hydrate and then be tested in the same manner as the other specimens. If the 8 percent cement specimens are satisfactorily hardened, the cement content being used in construction can be reduced to 10 percent.

Should a 10 percent specimen be comparatively soft at 4 days hydration, while the 14 and 18 percent specimens are hardening satisfactorily, construction should be started using 16 percent cement by volume until additional data are obtained.

Additional Tests Used for Determining Cement Factors.—Tests other than those described that have been used in the determination of cement factors for cement-treated soil mixtures intended to have properties approximately similar to those of soil-cement are given in Table 28, which also gives references to methods for the shear test (141), the CBR test (22, 23, 44) and variations in the unconfined compression test that include testing cylinders lying on their side—the Brazilian test (36)—as well as variations in sizes of specimens, time, and method of curing.

Criteria for Soil-Cement

General.—Criteria used to control the quality of soil-cement depend on the nature of the soils and the tests used for mix design purposes. For sandy soils that permit the use of short-cut methods, the cement requirements are determined directly by the test procedures given under "Short-Cut Methods for Determining Cement Requirements for Sandy Soils" (49). For other soils tested in accordance with standard AASHO and ASTM methods or other methods there are limiting test values that are used as a basis for determining cement requirements.

TABLE 30

CEMENT REQUIREMENTS BY AASHO SOIL GROUPS[a] (10)

AASHO Soil Group	Usual Range in Cement Requirement (% by vol)	Usual Range in Cement Requirement (% by wt)	Estimated Cement Content and That Used in the Moisture-Density Test (% by wt)	Cement Content for Wet-Dry and Freeze-Thaw Tests (% by wt)
A-1-a	5-7	3-5	5	3-5-7
A-1-b	7-9	5-8	6	4-6-8
A-2	7-10	5-9	7	5-7-9
A-3	8-12	7-11	9	7-9-11
A-4	8-12	7-12	10	8-10-12
A-5	8-12	8-13	10	8-10-12
A-6	10-14	9-15	12	10-12-14
A-7	10-14	10-16	13	10-13-15

[a]For dark gray to gray A-horizon soils, increase the above cement contents four percentage points, for black A-horizon soils six points.

PCA Criteria for Determining Cement Requirements.—Criteria for determining cement requirements originally established by the Portland Cement Association in 1940 (28), and verified by Highway Research Board committee action in 1943 (72), remain essentially unchanged (30, 75) after performance and condition surveys throughout the United States and Canada and from outdoor weathering studies. The following limiting test values are suggested to produce soil-cement of satisfactory strength and durability:

1. Soil-cement losses during 12 cycles of either wet-dry or freeze-thaw test by the ASTM-AASHO methods shall be within the following limits: Soil Group A-1-a, A-1-b, A-3, A-2-4 and A-2-5, not more than 14 percent; Soil Group A-2-6, A-2-7, A-4 and A-5, not more than 10 percent; Soil Group A-6, A-7-5 and A-7-6, not more than 7 percent.
2. Maximum volume change during either the wet-dry or freeze-thaw test shall not exceed the volume at the time of molding by more than 2 percent.

3. Maximum moisture content during either the wet-dry or freeze-thaw test shall not exceed that quantity that will completely fill the voids of the specimen at the time of molding.

4. Compressive strengths shall increase with age and cement content in ranges of those producing results meeting requirements 1, 2 and 3 above.

These criteria usually require cement contents of the order given for the various soil groups in Table 30. Average values of cement contents required for B- and C-horizon silty and clayey soils are related to density as is shown in Figure 86. Application of these criteria to various natural and artificially produced miscellaneous materials has resulted in the average cement requirements given in Table 31.

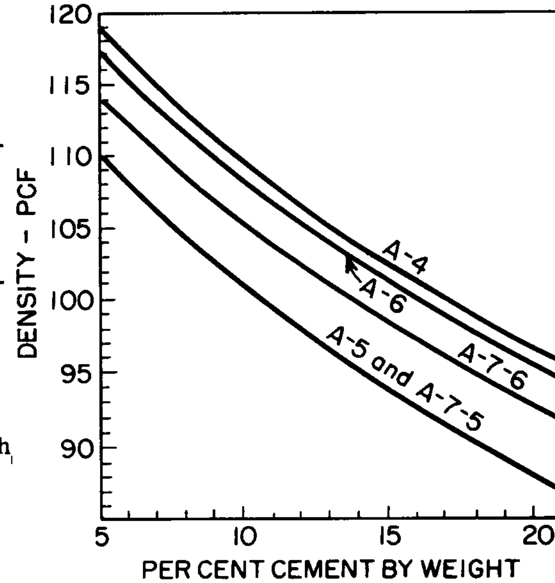


Figure 86. Average cement requirements for B- and C- horizon silt and clay soils (10).

California and Texas Criteria for Determining Cement Requirements.—California Division of Highways Standard Specifications (1960) for Class A Cement-Treated Base (150) require that the material shall be of a quality such that when mixed with portland cement in amounts not to exceed 5 percent by weight of dry material and compacted at optimum moisture content, the compressive strength shall be not less than 750 psi at 7 days. Cement requirements shall be between 3½ and 6 percent by weight. For Class B, the addition of cement not to exceed 4 percent by weight shall produce a strength of not less than 400 psi at 7 days. Cement requirements for Class B shall be between 2½ and 4½ percent by weight.

The Texas Highway Department uses the unconfined compression test and the punching shear test (141) to provide criteria for cement requirements. The compression test is performed on cylinders 6 in. in diameter and 8 in. high, using the total material, compacted at optimum moisture content under a compactive effort of 6.63 ft-lb per cubic inch, moist cured for 7 days, and immersed in water for 2 hours prior to testing. The punching shear test is made on soils passing the No. 40 mesh sieve. Approximately 8,000 grams of material are used to mold five specimens. Compaction procedure is equivalent to that of AASHO T 99. Specimens are moist cured 7 days subject to capillary absorption after the age of 2 hours. They are then tested in punching shear using a 1-in. ram over a 3-in. orifice. Tests have shown that a punching shear value of 2,000 lb or more will have a soil loss of 10 percent or less when tested by the standard ASTM-AASHO durability methods. A 2,000-lb punching shear value is considered adequate for cement stabilization. A compressive strength value of 700 psi correlates with a 2,000-lb punching shear value for minus No. 40 mesh sieve soil.

British Criteria for Determining Cement Requirements.—In the United Kingdom the stabilized material is required to have an unconfined compressive strength exceeding a specified minimum value and to a minimum loss in compressive strength, when subjected either to immersion in water or to alternate freezing and thawing, that does not exceed some specified maximum percentage of the compressive strength when cured at constant moisture content. (Discussion of reference 66 by D.J. Maclean, Head of Soils Section, Road Research Laboratory, Harmondsworth, England, December, 1959.)

A minimum unconfined compressive strength of 250 psi at 7 days has been used successfully to design soil-cement for bases of light-traffic roads, but for heavy-traffic roads, the results obtained from the performance of special experimental road sections indicate that a material with a minimum strength of the order of 400 psi at 7 days is probably required. (Discussion of reference 66 by D.J. Maclean, Head of Soils Section, Road Research Laboratory, Harmondsworth, England, December, 1959.) A soil-cement mixture designed on the basis of the unconfined compressive strength criterion shall have R_f and R_i index values (see discussion under "British Standard Test Methods") equal to or greater than 80 percent (36). If this percentage is not obtained, the cement content of the mixture shall be sufficiently increased to meet the durability criterion.

Soil Requirements for Soil-Cement

Nearly all soils can be hardened with portland cement. The general suitability of soils can be judged before they are tested, on the basis of their gradation and their position in the soil profile. On the basis of gradation, soils for soil-cement construction can be divided into three broad groups:

1. Sandy and gravelly soils, sands and gravels, crusher run limestone, caliche, limerock, and almost all granular materials are hardened with low cement contents if they contain 55 percent or more passing the No. 4 sieve and 100 percent passing the 3-in. sieve. Well-graded materials may contain up to about 65 percent retained on the No. 4 sieve and have sufficient fines for adequate hardening. Sandy and gravelly soils with about 10 to 35 percent silt and clay sizes have the most favorable characteristics for stabilization and require the lowest cement contents. These soils can be handled in construction under a wide range of weather conditions.

TABLE 31

AVERAGE CEMENT REQUIREMENTS FOR MISCELLANEOUS MATERIALS (10)

Type of Miscellaneous Material	Estimated Cement Content and That Used in Moisture-Density Test		Cement Content for Wet-Dry and Freeze-Thaw Tests
	(% by vol)	(% by wt)	(% by wt)
Shell soils	8	7	5-7-9
Limestone screenings	7	5	3-5-7
Red-dog	9	8	6-8-10
Shale or disintegrated shale	11	10	8-10-12
Caliche	8	7	5-7-9
Cinders	8	8	6-8-10
Chert	9	8	6-8-10
Chat	8	7	5-7-9
Marl	11	11	9-11-13
Scoria (containing + No. 4 material)	12	11	9-11-13
Scoria (Minus No. 4 material only)	8	7	5-7-9
Air-cooled slag	9	7	5-7-9
Water-cooled slag	10	12	10-12-14

2. Beach and some other water-laid sands, and glacial and wind-blown sands that are deficient in fines are productive of good quality soil-cement but require slightly greater cement contents than do the soils of Group 1.

3. Generally silty and clayey soils produce satisfactory soil-cement. The more

clayey the soil, the more difficult to pulverize and the higher the cement requirement. Clay soils having clay contents (finer than 0.005 mm) in excess of 35 percent, liquid limits in excess of 50, and plasticity indices in excess of 25 are difficult to pulverize and may require cement contents that make them uneconomical to construct (55, 72, 151, 152). When soils have clay contents and plasticity values in excess of these limits they should be carefully investigated prior to construction.

Specification Field Control Factors for Soil-Cement.—The essential field control factors derived from testing for mix design are: (a) Cement content, (b) Optimum moisture content, and (c) Maximum density. In addition to these factors that are included in specifications, the laboratory 7-day compressive strength values serve as a basis for judging the degree of mixing when specimens molded from the field mix are similarly compacted into specimens and cured and tested. In the case of Cement-Treated Base, the compressive strength is also a specification control factor.

Testing and Mix Design for Cement-Modified Granular Soils

The nature of the tests and the criteria derived from those tests depend on the purpose of the modification. Cement-modified granular soils are used for the following purposes as base and subbase courses:

1. To prevent pumping (erosion) under rigid-type pavements.
2. To prevent traffic densification under flexible-type pavements and at joints under rigid-type pavements.
3. To reduce volume change (shrink or swell) of plastic granular types for bases for rigid- or flexible-type pavements.
4. To increase the bearing capacity of bases for either flexible- or rigid-type pavements.
5. To provide a stable foundation for paving operations.

Criteria for determining the cement contents for certain limiting behavior characteristics have not been developed for cement-modified granular soils. Therefore the engineer must by use of strength tests, shrink or swell measurements and other applicable tests, determine the minimum cement requirements that will insure the performance expected. The nature of cement-treated granular soils is mentioned under "Properties of Cement-Treated Soil." The following remarks pertain to current practices.

It should be remembered that hardened soil-cement can also be used for all of the aforementioned uses of cement-modified granular soils. Hardened soil-cement represents a superior material and generally requires the use of only a small additional amount of cement. The use of soil-cement should be investigated whenever cement treatment is considered.

Cement Requirements to Prevent Pumping of Rigid-Type Pavements.—The purpose of cement modification is to prevent erosion of and ejection of material at joints by the pumping action of slabs. Cement-modified granular mixtures have been proved satisfactory for this purpose. Cement requirements need to be adequate to prevent deterioration by water and erosion forces. No standard test has been devised that will yield mix design criteria; experience must be used as a guide.

In California (109, 150, 153, 154) cement-treated bases ranging in quality from that of light cement-modification to that equivalent to soil-cement have been used under rigid-type pavements. Where traffic is expected to develop more than 50 million 5,000-lb wheel loads (EWL) in traffic lanes during the first ten years of service, the Cement-Treated Base mixture must provide a minimum compressive strength of 750 psi at 7 days. (This equals the requirements for Class A CTB that requires from 3½ to 6 percent cement by weight and is equivalent to soil-cement.) Where less than 50 million EWL are expected, the cement required must provide a compressive strength of 400 psi at 7 days. (This is equivalent to Class B CTB that normally requires 2½ to 4½ percent cement by weight.)

Texas practice on the Houston Expressway (17) called for 9 percent cement by volume for a sand-shell material. This resulted in hardened soil-cement.

Cement Requirements to Prevent Traffic Densification in Flexible-Type Pavement Bases.—Researches are under way (153, 154) for types of granular materials that in the untreated state are subject to increased compaction and rutting in flexible-type pavements to determine minimum cement requirements and moisture-density controls that will prevent the occurrence of detrimental densification under traffic. Data are not yet available that will serve as reliable criteria for determining cement requirements.

Cement Requirements to Reduce Volume Change and to Increase Bearing Capacity.—Because these soil properties vary for different soils and because the degree of control desired also varies, definite criteria cannot be established. In practice, cement contents of the order of 2 to 5 percent by weight usually reduce the plasticity of granular soils having indices of the order of 10 to 15 to values of the order of five or less, and control swell or shrink within limits desirable for providing smooth-riding pavements. The same range of cement content usually also increases the bearing capacity to equal that of high quality crushed gravel or crushed stone base courses. The behavior of cement-modified soils can be determined by the use of CBR or compressive strength tests and volume change tests, and is indicated in some degree by plasticity tests on the repulverized fine-grain soil fraction. The tests that may be used are indicated in Tables 28 and 29.

Properties of cement-modified soils have been discussed under "Properties of Cement-Treated Soil" and "Factors Influencing Properties of Cement-Treated Soil."

Soil Requirements.—Soils for cement-modified granular soil mixtures are those of the A-1, A-2, and A-3 AASHO Groups that have not more than 35 percent passing the No. 200 mesh sieve. These soils usually have plasticity indices of 15 or less. Soils of the other AASHO Groups are considered for treatment under cement-modified silt-clay soils.

Field control factors include cement content, optimum moisture content and maximum density. They may also include other supplementary factors as are needed for the control of construction.

Testing for Mix Design for Cement-Modified Silt-Clay Soils

Cement-modified silt-clay soils have been used experimentally in studies of means for preventing pumping and to control swell and shrink in high volume change, plastic clayey soils (22, 27, 30, 33, 35, 111, 153, 154, 155, 156) and to improve the stability of wet silt subgrades (158). Clayey soils, either hardened or modified with cement have not been proved satisfactory as a subbase to prevent pumping based on the performance of experimental projects (154, 156) and further research is needed to define limiting conditions of soil type, climatic conditions, pavement design, and traffic types and volumes. However, hardened soil-cement has proved satisfactory when made with the better A-4 soils or the granular soils. Volume change can be controlled in clayey subgrade soils by cement treatment. The proportion of cement needed can be determined by experienced engineers by means of simple swell and shrink tests of the compacted and cured cement-treated mixture (see Tables 28 and 29).

Cement also can be used to increase soil bearing value in amounts ranging upward to that for soil-cement or more, depending on the cement content used. Design for bearing value can be controlled by strength tests. An indication of the lasting properties of the treatment can be obtained from standard wet-dry and freeze-thaw tests.

The influence of cement admixtures on the nature of clayey soils is given under "Properties of Cement-Treated Soil" and "Factors Influencing Properties of Cement-Treated Soil."

Soils for cement-modified silt and clay soils include all types normally used in construction that are not included under cement-modified granular soils. Cement treatment of highly organic and peaty soils is not suggested.

Field control factors include cement content, optimum moisture content, and maximum density. They may also include supplementary factors as are needed for the control of construction.

Testing and Mix Design for Plastic Soil-Cement (95, 97, 98, 114, 115)

Cement Requirements.—Plastic soil-cement is used in lining flumes, roadside ditches, drainage channels, irrigation canals, and in sacks as sacked rip-rap. It is produced by increasing the water content of the mixture above optimum to obtain a consistency similar to that of plastering mortar. Increasing the water content increases the cement requirement. The cement requirements for plastic soil-cement are usually about four percentage units greater than those for compacted soil-cement. For example, if, for a given sandy soil, 8 percent cement by weight is required for soil-cement, about 12 percent by weight would be required for satisfactorily hardened plastic soil-cement.

In performing the laboratory tests the plastic moisture content is usually determined using 12 percent cement by weight and the wet-dry and freeze-thaw specimens are then molded at 10, 12 and 14 percent cement by weight.

The proportions of soil and cement for making the moisture-density relations test on the plastic mixture, as well as for making the computations to determine the moisture content and density, are determined in the same manner as for soil-cement, except that an allowance for soil for only one sample will be needed. Also the weight per cubic foot is about 15 pcf less than the maximum density of the compacted soil-cement mixture at optimum moisture content.

The moisture content of a plastic soil-cement mixture is determined by adding and mixing increments of water with the soil and cement mixture until the desired plastic consistency is reached. The mixture is then placed in a moisture-density mold; each layer is compacted by rodding with a $^{3}/_{4}$-in. bullet-nosed rod or with the fingers. The mold containing the mixture is then dropped three times on a firm foundation from a height of 1 ft to remove large air voids in the mixture. A moisture sample is obtained from the mixture at the time the second layer is being placed. The percentage of moisture and the wet weight of the specimen provide data for computing the plastic moisture content and the dry density. Only one trial furnishes all data needed for design of the test specimens at the plastic consistency. It is not necessary to plot a moisture-density curve.

Wet-dry and freeze-thaw test specimens are then molded in well-greased molds in the range of the estimated cement content, using the same procedure as described for making the plastic moisture-density specimen. The specimens are left in the molds overnight to permit their removal without distortion. The computations for determining the quantities of soil, cement and water needed for each specimen and the computations for checking molded specimens are similar to those for compacted soil-cement mixtures. The specimens are subjected to the standard wet-dry and freeze-thaw tests described in AASHO and ASTM methods. Brushing losses are computed in the same manner as for compacted soil-cement.

The criteria for determining the cement requirements for plastic soil-cement are the same as for compacted soil-cement. To provide a surface more resistant to erosion it is suggested that the cement contents required by these criteria be increased by two percentage units. For example, when the cement loss in the wet-dry or freeze-thaw tests indicates 12 percent cement is required, the cement content suggested for construction becomes 14 percent.

<u>Soils Requirements.</u>—The lighter textured non-plastic to moderately plastic loamy sands and sandy loams, are most satisfactory for plastic soil-cement. Soils containing more than 30 percent silt and clay sizes are difficult to pulverize and become sticky at the plastic moisture content making them difficult to mix and place. The greater the sand content the less the shrinkage. However, there is an optimum sand content for workability and strength. When practicable, tests should be made to determine the best proportions of sand and silt-clay combinations for the nature of the materials.

Testing and Mix Design for Cement-Treated Soil Slurries for Mud-Jacking (116, 117, 118, 159)

<u>Mud-Jacking Material Requirements.</u>—The suggested requirements for materials for cement-treated soil slurries for use in mud-jacking pavement slabs where faulting has occurred, or over depressed areas are as follows (159):

Cement: Type I normal, Type IA air-entraining, or Type III high-early-strength cements conforming to Standard Specifications for portland cement, AASHO Designation M 85 or ASTM Designation C 150. Type IA may be beneficial in reducing separation of sand and cement in some of the more lean and more sandy slurries. Type III facilitates pumping operations and reduces setting time.

Water: Should be free from materials that will retard the setting of the mix.

Bituminous Materials: Cut-back asphalts used in slurries should meet the following requirements:

Type	Designation for Standard Specification
RC	AASHO M 81 or ASTM D 597
MC	AASHO M 82 or ASTM D 598
SC	Specifications of the Asphalt Institute

Soils: The range in grain-size distribution of soils that have been used in mud-jacking is indicated in Figure 87. Curves 2 and 3 represent soils containing excess clay making them difficult to mix with water and causing jamming in the pump. Curves 1 and 4 represent soils that have performed satisfactorily. Curves 5 and 6 represent soils that have tended toward harshness but formed smooth easy working slurries on the addition of hydrated lime. Liquid limits of suitable soils should not exceed 35. Soils having sand contents in excess of 50 percent can be made workable by admixing lime or bituminous materials to increase fluidity. Cement-treated soil mixtures will not shrink appreciably when the shrinkage limit (SL) equals or exceeds the moisture content required for fluidity. Soils having a volumetric change of less than 10 percent and a lineal shrinkage of less than about 3 percent have performed satisfactorily.

Mixtures: A variety of mixtures have been used that have given good results. The two most widely used slurry mixtures are:

Volumes exclusive of water

Mix 1	Soil (percent)	60 to 84
	Cement (percent)	16 to 40
Mix 2	Soil (percent)	77
	Cement (percent)	16
	Cut-back asphalt (SC-2, MC-1, RC-3)	7

In general the amount of water needed to produce a slurry of creamy consistency is approximately ½ the loose volume of the other materials used. The slurry should harden at a normal rate. Slow hardening slurries are not suitable.

Fly ash has been used successfully as a filler. Also mixtures of fly ash and about 8 percent cement have been highly satisfactory as mud-jack materials (118).

Mixing Procedure: A satisfactory mixing procedure is as follows:

1. A soil-water mix is made with only sufficient water to obtain a fluid mix.
2. When bituminous material is used, it (and water as needed) are added to obtain a uniform mix.
3. Cement is added and the mix brought to a consistency that can be pumped readily.

Testing and Mix Design for Cement-Treated Soil Grouts

Cement-treated soil grouts have been used in stabilizing embankments and ballast on railroads as well as in tunneling operations and foundation work to strengthen weak rock, to fill solution channels and seal off water inflow, to fill voids in soil foundations and increase bearing capacity, to raise settle areas, and to consolidate soft foundations.

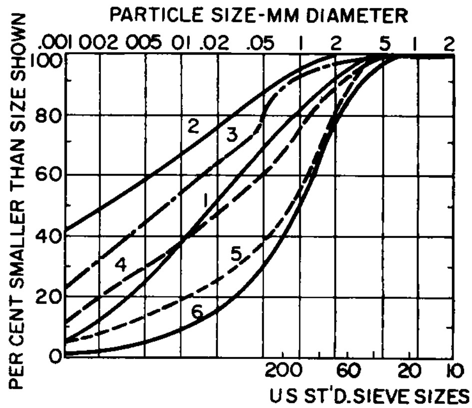


Figure 87. Grain-size distribution curves of soils used in cement-treated soil slurries for mud-jacking purposes (159).

Grouts Used by Railroads (120, 160). — Grouts have generally ranged from 1:1 to 1:4 (cement to sand) for pneumatic work and 1:12 to 1:30 for hydraulic work. The cement used has been largely Type I although air-entraining cement has been found beneficial in reducing separation of sand and cement in the slurry, particularly with pneumatic equipment. Fly ash exhibits some properties of silt and clay and increases "pump ability" of the grout or reduces the cement required to produce comparable flow characteristics. Sands used in grouts have varied in grading as is indicated in Figure 88. Two sands approaching the finer limit were used successfully in proportions of 1:7 without fly ash. One of the coarsest sands used in 1:1 proportions is also indicated in Figure 88. Another coarse sand mixed in the proportion of one part cement, one part fly ash, and 7 parts sand is also indicated in Figure 88. The computations for the curves in Figure 88 are based on volumetric proportions. To convert to weight basis, the following weights in pcf were used: cement, 94; fly ash, 100; sand, 85.

Field experience indicates a sand with 100 percent passing a No. 20 sieve and a large percentage passing a No. 40 sieve is desirable in facilitating grouting operations.

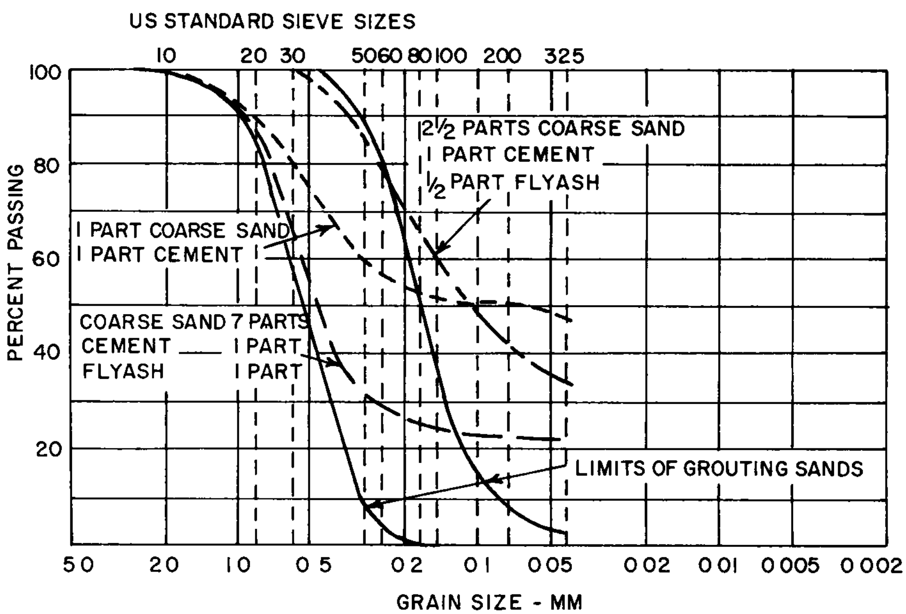


Figure 88. Mechanical analysis of sands and grouting slurries (120).

Sands from upper horizons in conifer areas may react unfavorably with cement. The use of about 1 percent calcium chloride by weight of cement usually corrects faulty reaction and slow setting. The quantity of water has ranged from 3 to 6 gallons per cubic foot of the dry material in the slurry (volume of grout has been computed as the sum of the loose volumes of dry materials).

Asphalt emulsions have been used to aid in lubricating flow and suspending solids. Amounts have ranged from 0.1 to 0.2 gal per cubic foot of sand.

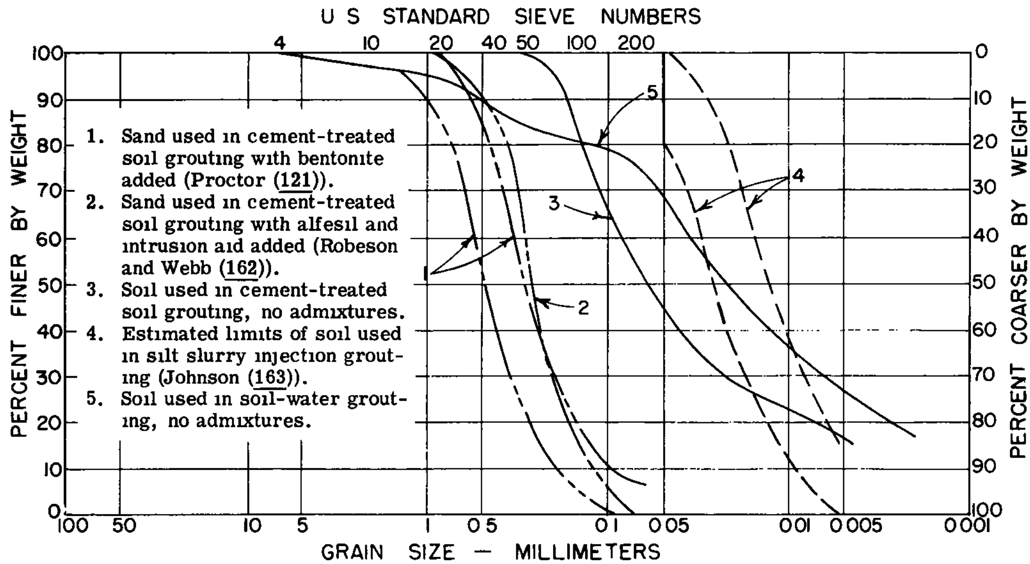


Figure 89. Soils used in cement-treated and natural soil grouts (122).

Groups Used in Strengthening and Sealing Rock and Foundations (121, 122, 162, 163). — Cement-treated soil grouts for these varied applications have been described extensively in the literature. Cement has been used with fine sandy loam in mixtures consisting of 1 part cement to 2 to 6 parts soil without significant segregation, except in some sands. Soils used for this purpose may range from fine to medium sands to lean clays as is indicated in Figure 89. When lean clays or silt are used, segregation is not a problem. With sand there is a tendency toward segregation and additives have been used to control segregation. Figure 89 indicates the grading of the following grouts using portland cement:

1. A fine sand used in a mixture consisting of one part by volume of cement to eight parts sand to which was added one-third part bentonite (121).
2. A fine sand used with admixtures of the patented products Alfesil and Intrusion Aid. The mix varied from 1 part sand and 4 parts cement to 1 part cement and 8 parts sand with 1 sack (75 lb) of Alfesil and 2.5-lb Intrusion Aid added to each mix (162).
3. Soil used in cement-treated soil grouting—no admixtures.

The Task Committees on Cement Grouting and on Clay Grouting of the Committee on Grouting of the Soil Mechanics and Foundation Division of the American Society of Civil Engineers recently sponsored publication of nine papers on Cement and Clay Grouting of Foundations (123). For further details of the present status of available information of Cement and Clay Pressure Grouting of Foundations the following references in Volume 84, No. SM 1, February 1958, Part 1, "Journal of the Soil Mechanics and Foundations Division of the American Society of Civil Engineers" are suggested for consultation:

Proc. Paper 1544, "Present Status of Pressure Grouting Foundations," by A.W. Simonds.
Proc. Paper 1545, "Grouting with Clay Cement Grouts," by S.J. Johnson.
Proc. Paper 1546, "The Use of Clay in Pressure Grouting," by G.A. Kravetz.
Proc. Paper 1547, "The Use of Admixtures in Cement Grouts," by A. Klein and M. Polivka.
Proc. Paper 1548, "Suggested Specifications for Pressure Grouting," by J.P. Elstron.
Proc. Paper 1549, "Pressure Grouting with Packers," by F.H. Lippold.
Proc. Paper 1550, "The French Grouting Practice," by A. Mayer.
Proc. Paper 1551, "Practice of the Corps of Engineers," by E.P. Burwell, Jr.
Proc. Paper 1552, "Experience of TVA with Clay-Cement and Related Grouts," by G.K. Leonard and L.M. Grant.

Structural Design of Soil-Cement Bases

There exists no nationally accepted and practiced method for structural design of flexible-type pavements (sometimes termed nonrigid type) that consist in part of a soil-cement base course or subbase course. Accordingly, the information given here covers: (1) a brief statement of general United States practice; (2) the 1949 recommendations of the Highway Research Board Committee on Flexible Pavement Design; (3) State Highway Department design procedures that evaluate the load-supporting properties of soil-cement bases in terms of thickness requirements; and (4) the results of British studies.

UNITED STATES PRACTICE

Much of the evidence in discussions and reports on flexible pavement design (reported by the Highway Research Board Committee on Flexible Pavement Design) indicates that soil-cement essentially displays characteristics of a flexible-type pavement, or in some cases, of a semi-flexible type (17). Nevertheless, design methods have been limited largely to determination of the proper cement content, and thickness design has been by arbitrary selection of thickness from within a rather narrow range of thicknesses; the range of thicknesses being dictated in the past more by capacities of the pulverizing and mixing equipment than by the thickness requirements for traffic. Thickness requirements have been satisfied by the use of granular subbases and in some instances by adjustments in the type and thickness of bituminous surfacing. The general practice in mix design has been as follows:

1. Classify the soil and select several trial cement contents.

TABLE 32

RECOMMENDED THICKNESSES OF SOIL-CEMENT BASE COURSE FOR 18,000-LB AXLE LOADS AND CORRESPONDING RECOMMENDED THICKNESSES OF GRANULAR-TYPE STABILIZED BASE COURSES

Subgrade Soil Group Classif.	Soil-Cement Base Course Thickness (in.)[a]	Granular-Type Stabilized Base Course Thickness (in.)[a]
A-1-a	0	0
A-1-b	5	5
A-3	5	5
A-2-4	5	5
A-2-5	5	6
A-2-6	5	6
A-2-7	5	6
A-4	6	8
A-5	6	8
A-6	6	8
A-7	6	8

[a]The soil-cement thicknesses were recommended at that time for highway pavements with average traffic that did not exceed 100 trucks, which range from 4,000-lb gross load to 18,000-lb axle load, per day or a total of 1,000 vehicles per day including the aforementioned truck traffic. Base courses of the thicknesses given in Table 34 may have to be supplemented by subbase when traffic exceeds the loadings for which the recommended base courses are intended.

2. Prepare trial soil-cement mixtures and determine the compaction characteristics.
3. Prepare two specimens at optimum moisture content from each trial mix.
4. Subject one specimen from each trial mix to the ASTM-AASHO wet-dry test and the other to the freeze-thaw test.
5. Select the percentage of cement by comparing the weight losses in the tests with allowable losses.

Individual variations in the foregoing procedure have been largely in the greater use of compressive strength as a criterion of mix quality in some areas and limiting testing to the wet-dry test in areas of no base freezing.

Highway Research Board Committee Recommendations

In 1949, the Flexible Design Committee (164) recommended the thicknesses of soil-cement base course given in Table 32.

California Practice (165)

The California method of calculating the design thickness of pavement sections based on stabilometer and expansion pressure measurements evaluates the cohesive resistance of bituminous surfaces and Cement-Treated-Base by means of the Hveem cohesiometer. The method evaluates the basement (subgrade) soil by means of expansion pressure and Hveem stabilometer determinations. The essentials of the design method are given in some details as follows:

Test Record Form.—Use work card (Form T-361) shown in Figure 90 for recording results of calculations.

TEST NO 60-994 REC D 3-17-60

TEST NO 992 TO 995 AND

STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS
MATERIALS AND RESEARCH DEPARTMENT
Laboratory Record of Tests Performed on
BASE, SUBBASE AND BASEMENT SOILS
FORM T-361 (REV 10 58)

UNTR STAB	✓	% CRUSHED		C GRADE	
C T B		P I		F GRADE	
OIL MIX		SP GR SSD C / F		HYDRO	✓
L A R T		SP GR C / F		MOISTURE	✓
W S T		S E	✓	SEDIMENTATION	

LETTER	COPY TO PAV T
LETTER DATE	
REC'D IN PAV T SEC	
COMPLETED	MAR 23, 1960
CALCULATED BY	G D
APPROVED BY	R B
REPORTED	MAR 24, 1960

INITIAL SAMPLE PREPARATION

COARSE GRADE

SIEVE SIZE	RETAINED WEIGHTS AS RECEIVED	RETAINED WEIGHTS CRUSHED
3"		
2½		
2		
1½		
	0	
1		
	90	
¾		
	90	
½		
⅜	210	
	300	
#4	90	
	390	

FINE GRADE

SIEVE SIZE	AS RECEIVED RET WTS	AS RECEIVED % PASS	CRUSHED RET WTS	CRUSHED % PASS
4		100		
8	3	96		
16	8	90		
30	13	84		
50	16	77		
100	24	70		
200	30	64		
5µ		20		
1µ		7		

TOTAL WEIGHT OF PASS #4 TEST SAMPLE

	WEIGHT-GMS	TEST BY	DATE
AS REC D	80	WMB	3-18-60
CRUSHED			

TOTAL WEIGHTS — GRAMS

PASS NO 4	9,590
RET NO 4	390
TOTAL WEIGHT	9,980
PREP BY W W	DATE 3-18-60

R-VALUE BATCH WEIGHTS

WEIGHT SAMPLE 1200 GRAMS

TEST NO				
1"–¾				
~~¾–⅜~~				
~~⅜–#4~~ ¾ - ⅜	24			
⅜–#4	12			
#4 DUST	1164			

INSTRUCTIONS

GRADING ANALYSIS

SIEVE SIZE	AS REC'D	RET CRUSHED	ADJ OR COND GRADE	AS USED	SPECIFIC LIMITS SOUGHT ☐					
3										
2½										
2										
1½	100									
1	99									
¾	99			100						
½										
⅜	97			98						
#4	96			97						
8	92			93						
16	86			87						
30	81			82						
50	74			75						
100	67			68						
200	61			62						
5µ	19			19						
1µ	7			7						

"AS USED" GRADING WAS OBTAINED BY COMBINING SAMPLE

% BY WT	% BY VOL	TEST NO	FIELD NO

LABORATORY COMMENTS

Figure 90. (165).

Calculations.—Before any computations for thickness of cover can be made, it is necessary to evaluate or assume the cohesiometer value of the cover overlaying the material being tested, and the traffic index of the section under consideration.

Cover material includes subbase, base, and surface courses when the basement soil is being considered. Cover would include only base and surface when the subbase material is being tested. Similarly, when the base is being evaluated, cover would mean the bituminous surface alone. If the cover consists of a single layer, the appropriate cohesiometer value may be selected from Table 33.

TABLE 33

COHESIOMETER VALUES FOR COMMON PAVEMENT AND BASE MATERIALS (165)

Type Materials	Cohesiometer Value
Cement-Treated-Base, Class A	1,500
Cement-Treated-Base, Class B	750
Asphalt concrete with paving grades of asphalt (85 to 300 penetration)	400
Asphalt concrete with liquid asphalt grades 4 and 5, open-graded mixes and road-mix asphalt surfacing	150
Bituminous surface treatment, Class C Cement-Treated-Bases and all untreated bases or subbases	100

If the cover consists of multilayer construction, the unit cohesiometer value may be determined from the procedure and formulas given in the following example:

Problem.—Determine the cohesiometer value for the 3-layer combination of asphalt concrete surfacing, Class A Cement-Treated-Base, and aggregate subbase material.

Material	Thickness, t (in.)	Cohesiometer Value, c
Data:		
AC	4	400
CTB (Class A)	8	1,500
AS	4	100

First Step.—Convert the individual thickness of AC, CTB, and AS to their respective gravel equivalents by multiplying the 5th root of the ratio of a layer's cohesion to that of untreated material by the thickness of the layer. For example, the gravel equivalent of 4-in. AC would be

$$\text{g.e.} = \sqrt[5]{\frac{400}{100}} \times 4 \text{ in.} = 5.28 \text{ in.}$$

Similarly, the gravel equivalent of 8-in. Class A CTB is 13.76 in. and for 4-in. AS would be 4 in. The sum of the gravel equivalents of the individual layers (23 in.) is the total gravel equivalent for the system.

Second Step.—Knowing the actual thickness (16 in.) of the system and having computed its gravel equivalent, determine the unit cohesiometer value by use of the following formula:

$$C = \frac{(\text{g.e.})^5}{T} \times 100$$

in which

C = unit cohesiometer value,
g. e. = gravel equivalent for system, and
T = actual thickness of system.

Thus, for the previous example

$$C = \left(\frac{23}{16}\right)^5 \times 100 = 620$$

(Alternate methods for determining the unit cohesiometer value for two or more layers of surface and base overlying soil material involve the use of Figure 91 or a table that accompanies the method.)

Traffic is expressed in terms of the number of equivalent 5,000-lb wheel loads, EWL, in one direction to be expected during the 10-yr period following construction. Calculations involve the multiplication of certain fixed constants which convert average daily traffic to yearly traffic in one direction (excluding passenger vehicles and pickup trucks) for each axle group.

TABLE 34

EWL CONSTANTS

Number of Axles	Constants
2	330
3	1,070
4	2,460
5	4,620
6	3,040

By taking a summation of the products and assuming an additional allowance of 50 percent for anticipated increase in commercial traffic at the end of a 10-yr period, the final design value for the 5,000-lb EWL repetitions is determined. For the purpose of calculating design thicknesses, the EWL is converted to a traffic index by means of the formula on the scale F portion of Figure 91. The foregoing

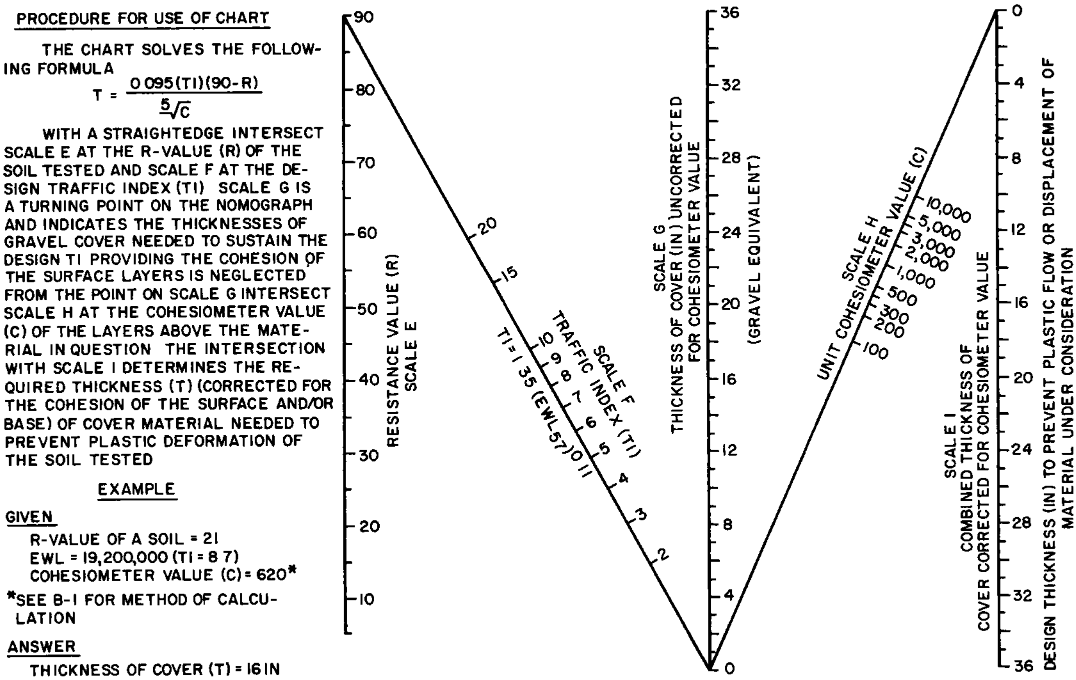


Figure 91. Design chart for thickness of increments of pavement structure (165).

method of calculation is illustrated in the following example:

No. of Axles	EWL Constants		Current ADT		Product
2	330	x	774	=	255,000
3	1,070	x	212	=	227,000
4	2,460	x	68	=	167,000
5	4,620	x	118	=	545,000
6	3,040	x	112	=	340,000
			Total Annual EWL Repetitions		1,534,000

From this example:

$$10 \times 1,534,000 \times \frac{1.0 + 1.5}{2} = 19.2 \text{ million EWL}$$

Converting to Traffic Index: 19.2 million EWL = 8.7 T.I.

Knowing the cohesiometer value of the cover material and the estimated traffic index for the road, use the design chart (Fig. 91) to determine the "thickness indicated by stabilometer" corresponding with the R-value of each specimen, and record these data on the work card shown in Figure 90.

The R-value by exudation pressure (300 psi) is interpolated by using the graph provided in Figure 92. Plot the thicknesses in inches indicated by the stabilometer for each specimen against the corresponding exudation pressure. Then determine the thickness at the intersection of the curve connecting the points with the 300-psi line, and convert to R-value using the design chart (Fig. 91).

For an example, refer to Figure 92. The thicknesses as calculated (using the cohesiometer value of 620 and traffic index of 8.7) from the individual test R-values, are plotted using the thickness scale at the left edge of the graph. It is noted that the curve crosses the 300-psi exudation line at a cover thickness of 14 in. It might be well to mention at this point, that the design chart (Fig. 91) can be used in either direction to solve either for R-value or for thickness. For instance, it is usually necessary to know the R-value for the conditions represented by the 14 in. of cover. Use a straightedge and intersect scale I at the value of 14 in. of thickness and scale H at the cohesiometer value of 620. Hold the point of a pencil at the intersection of the straightedge with scale G. Pivot the straightedge about this point and intersect the traffic index of 8.7 on scale F. The intersection of the straightedge with scale E then indicates an R-value of 29 for the given conditions. For the purposes of this example the 29 R-value is recorded on the work card as R-value by exudation pressure.

To determine the R-value by expansion pressure it is first necessary to calculate the thicknesses of cover required by expansion pressure for each specimen from the dial readings recorded on the work card. For design purposes the unit weight of cover is assumed to be 130 pcf. The expansion pressure devices are so calibrated that it is only necessary to divide the dial readings by two to obtain the cover thicknesses on the basis of this assumed unit weight. (For those who desire to determine the actual expansion pressure in psi, multiply the dial reading by 0.038.) If, in special investigations where more accurate information is available, it is desired to use a different unit weight of cover material, then the cover thicknesses may be determined from the chart in Figure 93. The determination of the R-value by expansion pressure is accomplished by first plotting thickness indicated by the stabilometer against thickness indicated by expansion pressure on the graph in Figure 92. Then note the thickness value at which the curve connecting the points crosses the 45-deg balance line. Convert this thickness to R-value with the design chart (Fig. 91) and record.

The R-value at equilibrium is established by taking the lowest value of the forego-

Test No 60-994

TEST SPECIMEN	A	B	C	D	E	F	G	H
Date Tested	3-22	3-22	3-22					
Compactor Air Press - psi	21	21	21					
Initial Moisture - %	7 5	7 5	7 5					
Water Added - ml	150	160	190					
Water Added - %	13 4	14 3	17 0					
Moisture at Compaction - %	20 9	21 8	24 5					
Wet Wt of Briquette - Gr	1009	1013	996					
Ht of Briquette - In	2 48	2 50	2 54					
Density - pcf	102	101	95					
Stabilometer PH at 1000 lb	39	46	60					
2000 lb	68	82	133					
Displacement	3 00	3 15	3 20					
R-Value	53	43	14					
Exudation Press - psi	600	450	170					
Stab Thick - In	8 6	10 9	17 5					
Expansion Press	33	13	0					
Expan Press Thick - In	16 5	6 5	0					

Material Description
Basement Soil

SP GR		FINE	COARSE
As Rec'd			
Crushed			
L L	PL	PI	Spec Max
PI x %200			Spec
SE	As Rec'd	11	Spec
SE	Crushed		Spec
SE	Combined		Spec.
Lart	100 Rev		Spec
Lart	500 Rev		Spec.
W S T			Spec
Subbase 4" AS			
Base 8" C T B Class A			
Surface 4" AC			
Cohesion Value 620			
Traffic Index 87			
R-Value	By Exud Press 39		
R-Value	By Expan Press 48		
R-Value	At Equil 29		Spec
Cover for Above Cond 14 0"			

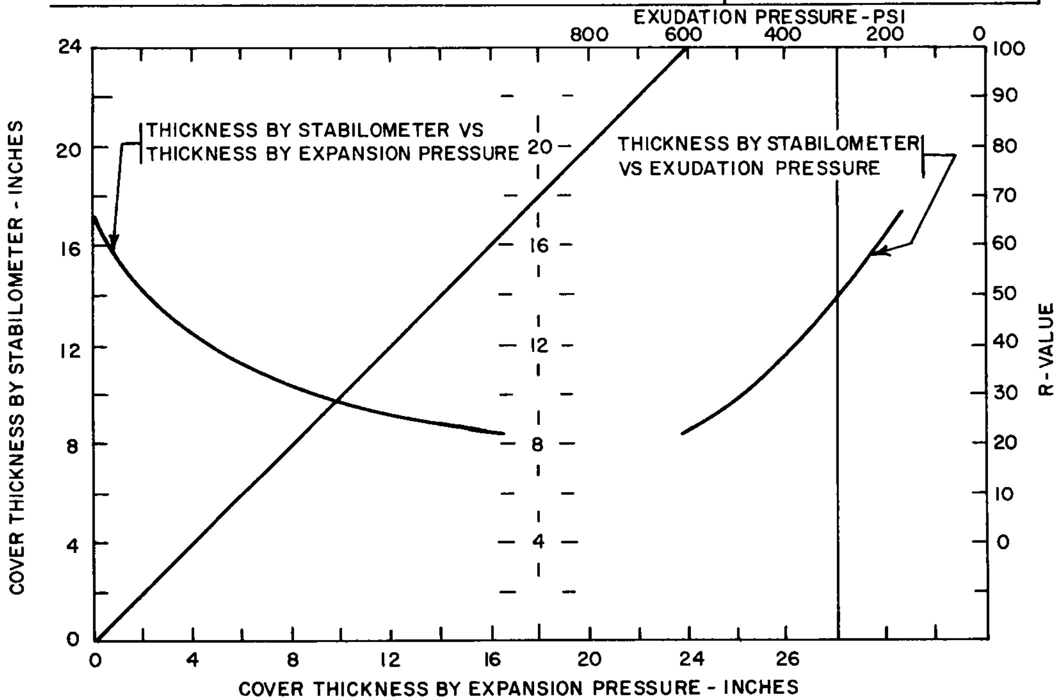


Figure 92. (165).

ing two R-values and the cover required corresponds to the R-value selected.

It is often convenient to express the thickness of cover determined from the R-value test in terms of the gravel equivalent as a temporary expedient (when the types of cover materials to be used are either unknown or uncertain). The gravel equivalent, as the name implies, is the thickness of gravel required to support a given load, and is based on a cohesion value of 100 for the cover material. One of the principal advantages in using the gravel equivalent is that it indicates to the designer what maximum thicknesses will be required to meet the conditions of the soil and traffic of the proposed project. Inasmuch as 100 cohesion is the lowest value used for design purposes, use of 100 will result in the determination of the highest thickness requirements for a given R-value and traffic index. Likewise, any subsequent increase in the cohesion will always reduce the design thickness requirement. The process of determining the gravel equivalent from the design chart (Fig. 91) merely consists of intersecting the R-value at equilibrium on scale E and the traffic index on scale F with a straightedge and reading its point of intersection of scale G.

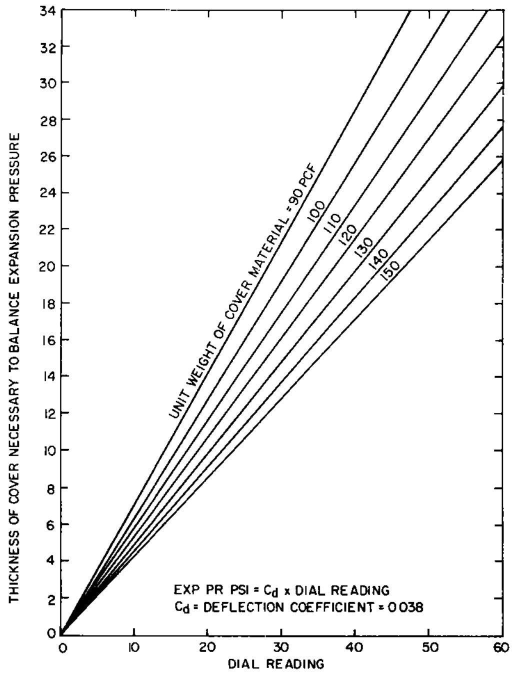


Figure 93. Thickness of cover by expansion pressure test for various unit weights of cover (165).

BRITISH STUDIES

British studies (44, 55, 166, 167, 168) of in-service behavior of soil-cement have resulted in the concept that soil-cement should be considered as a flexible type and that both mix design and structural design should be carried out accordingly. Soil-cement exhibiting a field-compressive strength of 250 psi will have a modulus of rupture of about 50 psi. That low bending strength is not sufficient to permit the material to act as a rigid material unless the pavement has great thickness. Relatively thin pavements will crack. When the cracks are closely spaced, interfacial friction is developed across the crack opening, and the material has shear strength and acts like interlocked pieces of a three-dimensional jig-saw puzzle. When the compressive strength is high, for example 1,500 psi, cracks are farther apart and the pavement tends toward discrete slabs with little or no shear strength between them. This reasoning is further tested by applying the Westergaard method of rigid pavement design. For example, a subgrade having a modulus, k, of 100 psi per in., would, by the Westergaard method, require a thickness of 24 in. of soil-cement for a wheel load of 9,000 lb (166). In practice, a 6-in. thickness has been found adequate to carry that wheel load for British conditions.

British military engineers have investigated the applicability of the shear strength method of design for cohesive subgrades, AG, having a strength essentially independent of the overburden pressure. In this method, the shear strength of the subgrade soil is compared with the maximum shear stress induced at any depth by a given wheel load and tire pressure as determined by the theory of elasticity. A thickness of soil-cement is selected such that at any depth greater than the base thickness, the induced shear stresses are less than the shear strength of the subgrade. This method has proved satisfactory for the design of pavement over very weak subgrades. British engineers have also investigated relationship between CBR and compressive strength of soil-cement mixtures. That has been discussed in part under "Properties of Cement-Treated Soil" and indicates a possibility of the use of that method provided appropriate adjustments are made in the application of the method.

Cement-Treated Soil Construction

The activities associated with construction of cement-treated soil roads, streets, airfields and accessory and miscellaneous facilities are divided broadly into three parts: (1) preconstruction needs, (2) construction equipment and procedures, and (3) engineering control of construction. Item 1 concerns specifications and cost estimates; item 2 concerns the equipment and the procedures of construction; and item 3 treats control of quantities of materials, mixing, compacting, finishing and curing to produce cement-treated soil mixtures of predetermined type and quality.

SPECIFICATIONS

Specifications for cement-treated soil construction usually require the following controls:

Materials

1. Type of cement (see "Factors Influencing Properties of Cement-Treated Soil—Type of Cement"), quality requirements for cement and cement content. AASHO Standard Specifications govern quality of cement for the type specified. Cement content of the mixture is usually specified in terms of volume of the compacted mixture. For example, 10 percent cement by volume requires 2.7 cu ft (bags) in each cubic yard (27 cu ft) of the compacted mixture. (Conversion of percent by volume to percent by weight, and vice versa may be facilitated by the use of Figure 80.)
2. Quality of water.
3. Soils. Requirements limit the maximum size to 3 in. and size distribution to 55 percent or more passing a No. 4 sieve to provide fines for the cement-soil matrix.

Equipment

Limitations on equipment require that it produce the results that satisfactorily comply with the requirements for spreading cement, applying water, mixing, compacting, finishing and curing.

Construction Methods

Requirements call for the following:

1. Pulverization of the soil so that at the completion of moist mixing 80 percent of the soil, exclusive of gravel or stone retained on the No. 4 sieve, passes the No. 4 sieve. This permits a proper mixture of fine soil grains and cement.
2. Application of the cement uniformly, but restriction of application when the moisture content exceeds the optimum. This permits efficient mixing and minimizes occurrence of cement balls.
3. Time restrictions to prevent partial hardening before compaction or strength reduction due to cement hydration before compaction.
    a. Provision for continued mixing operations so mixture does not remain undisturbed for more than 30 min, for addition of all water within a 3-hr period, for a time limit from cement spread through final compaction not to exceed 6 hours, and for a time limit for compaction not to exceed 2 hours.
4. Moisture control at time of compaction to be not below not more than one-fifth above optimum, to permit proper compaction and hydration.
5. Density control, preferably equal to the maximum density (AASHO) but not less than 5 pcf below maximum density to insure quality soil-cement.
6. Curing by protection against moisture loss for a 7-day period.
7. Placement of a bituminous cover to protect the cement-treated soil against abrasion by traffic.

8. Specifications may also provide for adequate construction joints, and for maintenance until surfacing is placed.

COST ESTIMATES

Construction costs vary with availability of equipment, materials costs, and soil and climatic conditions. Useful information to aid in determining costs may be found in the annual "Construction Costs" issue of "Engineering News-Record" and from periodicals reporting on local construction. Data on cost of equipment use and rental rates for equipment are available in the most recent revisions of publications[1] for the construction industries. An engineering estimate of detailed costs should be based on current labor rates and material costs for the locality of the project. The following blank forms cover project data and cost estimates for cement, water, curing materials, supervision, equipment and labor, and also provide for summary of data.

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[1]Booklet, "Contractors' Equipment Ownership Expense," prepared by the Associated General Contractors of America, Inc., 1227 Munsey Building, Washington, D.C., lists ownership expenses for a number of pieces of highway construction equipment.

Booklet, "Compilation of Rental Rates for Construction Equipment," prepared by the Associated Equipment Distributors, 360 North Michigan Avenue, Chicago, Illinois.

PROJECT DATA FOR PREPARING ESTIMATE

State__________ County__________ Town__________ Date__________

Project____________________

Length________ Width________ ft Depth________ in. Sq yd________

Type of soil____________________

Estimated processing days, based on 8-hour day =

$$\frac{\text{Project yardage}}{\text{Estimated average daily production}} = \underline{\hspace{6cm}}$$

Estimated days idle (rain, Saturdays, Sundays, delays) = ________________

PORTLAND CEMENT

Bulk cement is used on most jobs. For small jobs, bagged cement is commonly used. The amount of labor and equipment necessary to handle the cement depends on whether bulk or bagged cement is used.

1. Calculation of cement requirements:
   a. Cement content______% by vol
   b. Cement required per sq yd =
      $$3 \text{ ft} \times 3 \text{ ft} \times \frac{\text{depth in.}}{12} \times \frac{\% \text{ cement}}{100} = \underline{\hspace{1cm}}\text{bags/sq yd}$$
      bags/sq yd ÷ 4 = ______bbl/sq yd
   c. Total cement required =
      project yardage x bbl/sq yd = __________bbl.

WATER

The amount of water needed and the number of water trucks required to handle it will vary with the optimum moisture content of the mixture, existing moisture in the soil, rate of evaporation, length of water haul and rate of processing. Usually a minimum of two trucks will be required to handle water for mixing and finishing. Where the water haul is very long, one or more additional trucks may be necessary. On very large jobs, two or more trucks will be required to handle water for mixing and an additional one for finishing.

Calculation of water requirements:

(a) Approximate requirements of soils for 6-in. depth:

Coarse sands and sand and gravel	$5\frac{1}{2}$ gal/sq yd
Sandy soils	6 gal/sq yd
Silty and clayey soils	$6\frac{1}{2}$ gal/sq yd
Calculated quantity	____ gal/sq yd*

(b) 20% additional for evaporation = 0.20 x (a) = gal/sq yd

(c) Total requirements per sq yd = (a) + (b) = ____ gal/sq yd**

(d) Total gal/day = (c) x est. ave. daily production = ____ gal

(e) Total gal for job = (c) x total sq yd = ____ gal

Calculations:

Lb of S/C per sq yd =

$$\text{max density, pcf} \times \frac{\text{depth, in.}}{12} \times 3 \text{ ft} \times 3 \text{ ft} = \_\_\_\_ \text{lb per sq yd}$$

Percent moisture to add = optimum moisture - air-dry moisture = ____ percent

Gal/sq yd required = % moisture x lb S/C per sq yd ÷ 8.33 = ____ gal per sq yd

---

*Water requirements can be estimated more closely as follows:
Values known or estimated:
Maximum density of S/C mixture = ____ pcf
Optimum moisture of S/C mixture = ____ %
Air-dry moisture content of soil = ____ %
**If water is required for moistening curing materials, add 2 gal/sq yd

CURING MATERIALS

The following types of curing materials have been used with satisfactory results: bituminous material, moist soil, hay and sawdust, and waterproof paper. Bituminous material is usually used; the quantity required varies from about 0.15 to 0.30 gal per sq yd, averaging about 0.20.

If bituminous material is used and traffic is to be maintained, the surface should be sanded to prevent pickup. The cost of the sand, plus handling costs, should be included in the estimate as part of the curing materials.

Calculation of curing material requirements:

Total required = specified quantity/sq yd x total sq yd = ______

SUMMARY OF ESTIMATED COSTS

	Total cost	Cost/sq yd
Processing:		
Labor	______	______
Equipment	______	______
Total	______	______
Portland cement:		
Labor	______	______
Equipment	______	______
Material	______	______
Total	______	______

Handling cost:

$$\frac{\text{Total labor and equipment costs}}{\text{Bbl of cement}} = \_\_\_\_\_\_ \text{per bbl}$$

Water:

Labor

Equipment

Material

Total

Cost/1,000 gal

$$\frac{\text{Total water costs}}{\text{Total gallons required} \div 1{,}000} = \underline{\hspace{2cm}} \text{ per 1,000 gal}$$

Cure:

Labor

Equipment

Material

Total

Total estimated cost of labor, equipment and materials

Job and general overhead including moving

Contingencies and profit

Total estimated cost of soil-cement base course

APPROXIMATE COST ESTIMATE FOR CEMENT-TREATED SOIL CONSTRUCTION

State ____________ Date ____________

County ____________ Town ____________ Project ____________ Length ____________ Yardage ____________ sq yd Cement ____________ percent by volume

		Equipment						Personnel				Unit Costs and Summary							
		Est. Time Used										Processing		Water		Cement		Cure	
No.	Description	Hours Daily	Total Days	Rate Per Day Used	Est. Days Idle	Rate Per Day Idle	Cost	No.	Time on Job	Rate	Cost	Equip.	Labor	Equip.	Labor	Equip.	Labor	Equip.	Labor
	Supervision																		
	Equipment																		
	Cement Handling:																		
	Processing:																		
	Water:																		
	Cure:																		
						Total				Total									

	Processing	Water	Cement	Cure
Sub-Total				
Material				
Total				
Cost psy				

Equipment + Personnel + Material costs = ________ per sq yd Total Cost ________

Material	Quantity per Sq Yd	Total Quantity	Unit Cost	Total Cost	Cost per Sq Yd

CONSTRUCTION PROCEDURES FOR SOIL-CEMENT

Base Courses for Roads and Streets

It is intended to illustrate and to provide in summary form information of a general nature on the principal construction equipment and procedures. Details of manufacturers specifications and details of methods of operations should be obtained from those of the construction industry who provide the equipment and materials (for example, (31, 44, 65, 170, 171, 172, 173)).

The four principal types of mixing equipment and typical pieces of auxiliary equip-

TABLE 35

TYPICAL EQUIPMENT REQUIREMENTS FOR DIFFERENT TYPES OF MIXING MACHINES

Windrow-Type Traveling Mixer	Plat-Type Traveling Mixer	Multiple-Pass Rotary Mixer	Stationary Mixing Plant
For preparation 1 pulverizer—if required 1 motor grader with scarifier 1 windrow evener or spreader box For handling bulk cement 1 cement conveyor 1 cement tanker 1 portable truck scale 1 windrow-type mechanical cement spreader For mixing and water application 1 windrow type traveling mixing machine with motive power 1 water pump at water source 1 motor grader for spreading mixed windrow For compaction—see Note 1 For finishing—see Table 39 For curing—see Note 2	For preparation 1 motor grader For handling bulk cement 1 cement conveyor 2 or more cement trucks as required 1 portable truck scale 1 mechanical cement spreader of proper width For mixing and water application 1 flat-type traveling mixer 1 water pump at source 2 or more water supply trucks as needed For compaction—see Note 1 For finishing—see Table 39 For curing—see Note 2	For preparation 1 motor grader with scarifier rotary mixers for pulverizing, as needed 1 water truck for prewetting, if needed For handling bulk cement 1 cement conveyor 2 or more cement trucks as needed 1 portable truck scale 1 mechanical cement spreader of proper width For mixing and water application rotary mixers as needed 1 water pump at source 2 or more water pressure distributors or water supply trucks as needed For compaction—see Note 1 For finishing—see Table 39 For curing—see Note 2	For preparation motor grader rollers as needed For mixing 1 stationary mixing plant, batch-type or continuous-flow type with facilities for storing, handling and proportioning soil, cement and water. For placing haul trucks as needed 2 spreader boxes For compaction—see Note 1 For finishing—see Table 39 For curing—see Note 2

Note 1· Compaction equipment depends on type of soil—vibratory compactors, vibratory rollers, sheepsfoot-type rollers, three-wheel rollers and pneumatic-type rollers as needed.
Note 2 If Type RC-2, MC-3 cutback asphalts, RT-5 road tars, or asphaltic emulsions are used, pressure distributors as needed

TABLE 36

STEPS IN CONSTRUCTION PROCEDURES FOR DIFFERENT TYPES OF MIXING EQUIPMENT

Windrow-Type Traveling Mixer	Flat-Type Traveling Mixer	Multiple-Pass Rotary Mixer	Stationary Mixing Plant
A. Preparation With in-place soil 1. Shape roadway to crown and grade 2. Scarify roadway soil 3. Pulverize soil—if necessary 4. Windrow soil and even windrow With borrow soil 1. Shape subgrade to crown and grade 2 Compact subgrade 3. Place borrow soil 4. Windrow soil and even windrow B. Soil-cement processing 1 Spread portland cement 2. Mix and apply water 3. Spread mixed windrow 4. Compact 5. Finish 6. Cure	A. Preparation With in-place soil 1. Shape roadway to crown and grade 2. Loosen soil to design depth when necessary and reshape With borrow soil 1. Shape subgrade to crown and grade 2. Compact subgrade 3. Place borrow soil 4. Shape borrow soil B. Soil-cement processing 1. Spread portland cement 2. Mix and apply water 3. Compact 4. Finish 5. Cure	A Preparation With in-place soil 1. Shape roadway to crown and grade 2 Scarify roadway soil 3. Pulverize soil—if necessary 4. Pre-wet soil as needed 5. Shape prepared soil With borrow soil 1. Shape subgrade to crown and grade 2. Compact subgrade 3 Place borrow soil 4. Shape borrow soil B. Soil-cement processing 1. Spread portland cement 2. Mix, apply water, and mix 3 Compact 4 Finish 5. Cure	A Preparation With borrow soil 1. Shape subgrade to crown and grade 2 Compact subgrade B. Soil-cement processing 1. Mix, soil, cement and water in plant 2. Haul mixed soil-cement to roadway and spread 3. Compact 4 Finish 5. Cure

TABLE 37

ALTERNATE FINISHING PROCEDURES RELATED TO TYPE OF SOIL AND TYPE OF COMPACTION EQUIPMENT

For Most Soil-Cement Mixtures Compacted with Sheepsfoot-Type Roller	For Mixtures of Low Plasticity with Appreciable Quantities of Gravel and Compacted with Sheepsfoot Roller	For Sandy Soils with Few Fines[1] Compacted with Heavy Pneumatic-Tire Rollers	For Coarse Granular Mixtures Compacted with 3-Wheel, 12-Ton Steel Roller[1]
1. Remove compaction planes with weeder, nail drag or spike tooth harrow while shaping with motor grader (a)(b) 2. Roll with pneumatic-tire roller 3. "Scalp" with motor grader 4. Roll with pneumatic-tire roller (a)(c) (a) Light application of water as needed. (b) Broom drag sometimes used to level ridges. (c) Tandem steel-wheel roller may be used prior to final rolling with pneumatic-tire roller.	Alternate A 1. Shape with motor grader 2. Roll with steel-wheel roller 3. Broom drag 4. Roll with pneumatic-tire roller with light application of water as needed Alternate B (a) 1. Shape with motor grader (b) 2. Mulch and level with rotary mixer to about 2-in. depth 3. Roll with steel wheel roller 4. Roll with pneumatic-tire roller (b) (a) For very coarse granular mixes only. (b) Light application of water as needed.	1. Remove compaction planes with weeder, nail drag or spike tooth harrow while shaping with motor grader (a) 2. Roll with pneumatic-tire roller and drag with broom 3. Scalp with motor grader 4. Broom drag 5. Roll with pneumatic-tire roller (a) [1]For example—cohesionless dune sand having 0 to 10 percent passing No. 200 sieve. (a) Light application of water as needed.	1. Scalp high areas with motor grader. 2. Roll with pneumatic-tired roller (a) [1]Material should be approximately to crown and grade before compaction. The material for this procedure may contain up to 20 percent passing No. 200 sieve and have low PI. (a) Light application of water as needed.

ment used with them are given in Table 35. The principal steps in the construction procedures used for the four types of mixing equipment are given in summary form in Tables 36 and 37. The principal steps in several alternate finishing procedures related to type of soil and to type of compaction equipment are given in Table 37. Two types of cement spreading equipment are illustrated in Figures 94 and 95. Photographs of the four principal types of mixers referred to in Table 35 and 36 are shown in Figures 96, 97, 98 and 99.

Figure 94. Mechanical cement spreader delivering flat spread for flat-type mixing equipment.

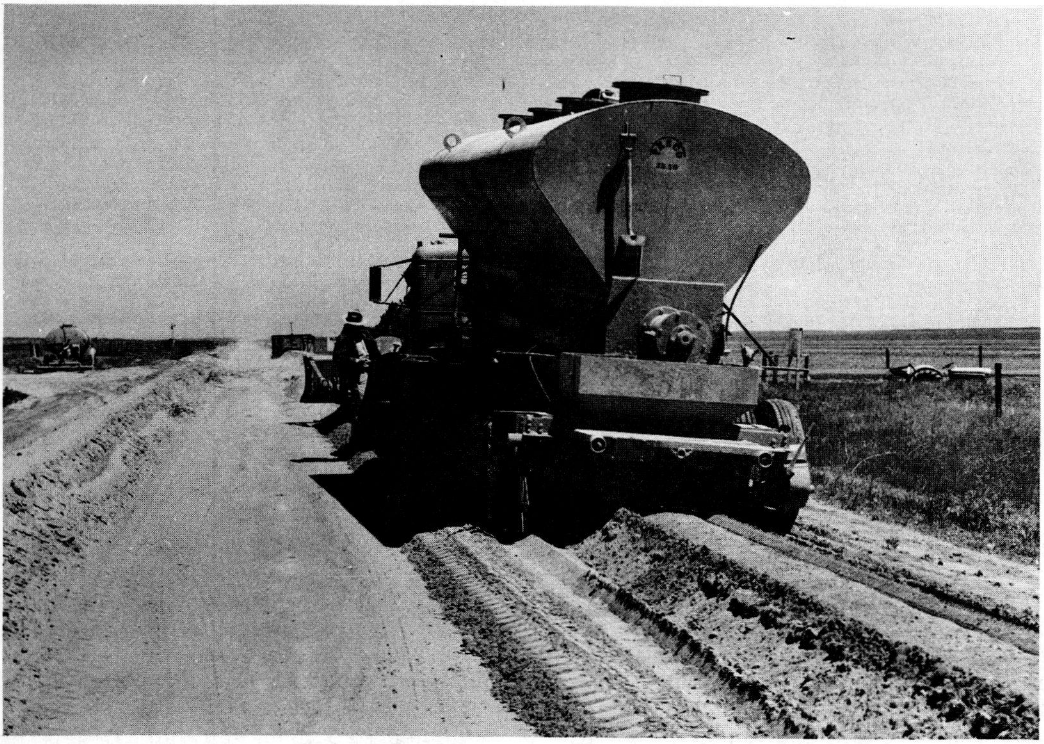


Figure 95. Windrow-type mechanical spreaders used to place cement in the soil windrow.

Figure 96. Flat-type mixing machine processing soil-cement in-place.

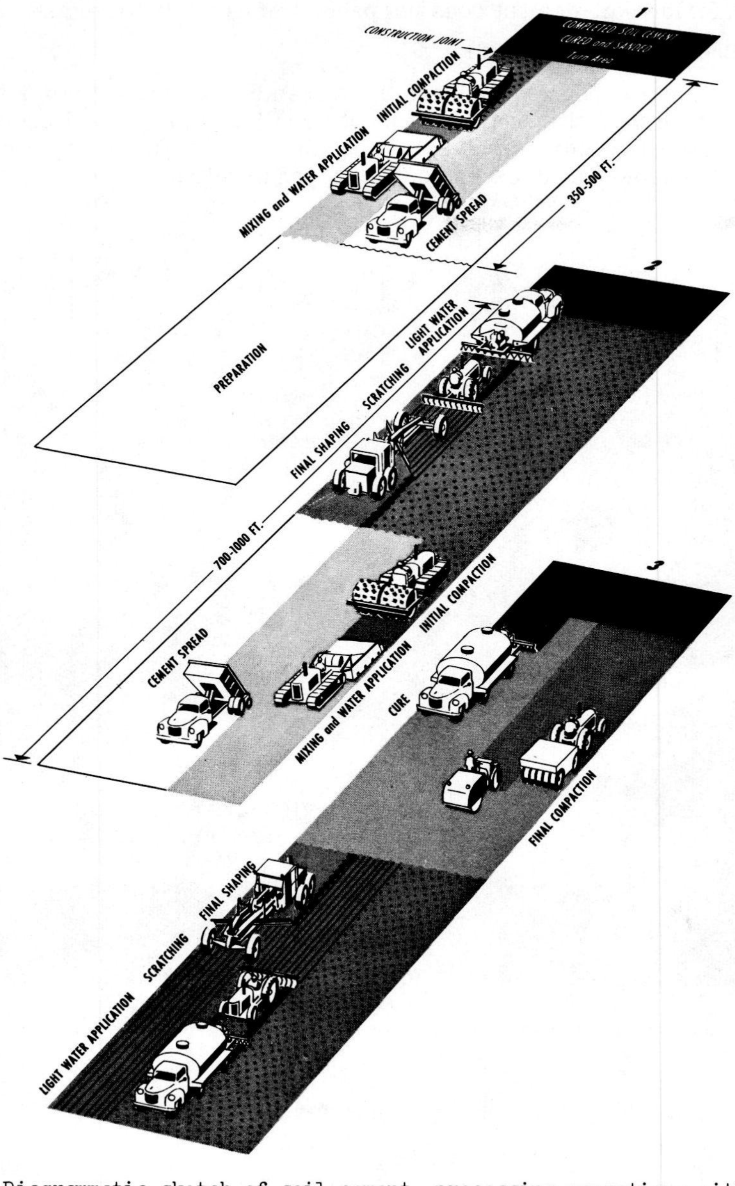


Figure 96A. Diagrammatic sketch of soil-cement processing operations with a flat-type traveling mixing machine.

Other important construction procedures not included in Tables 35, 36 and 37 include the building of a transverse vertical joint at the end of each day's work, and multiple-layer construction when the desired thickness of soil-cement exceeds the maximum thickness permitted by the types of pulverizing, mixing and compacting equipment on the job. Care is needed to insure full-depth mixing and uniform distribution of cement and moisture and proper compaction in the vicinity of the joint. When the thickness of soil-cement exceeds about 8 in., it is necessary to construct in multiple layers but no layer should be less than 4 in. thick. Final finishing of the lower layers need not be exact. Upper layers may be constructed immediately or on the succeeding day, or may be delayed until practicable. When the construction of the upper layer is delayed, the surface of the underlying layer should be properly moistened and compacted and cured so a layer of inferior soil-cement does not occur immediately under the top layer.

Widening and Shoulders (88, 89, 90)

The construction procedures for these facilities are generally similar to those for base construction, except that equipment must be tailored to fit the dimensions of the construction or a central mixing plant must be used. Where the compacted thickness for widening or shoulders is in excess of 8 in., construction should be in two or more

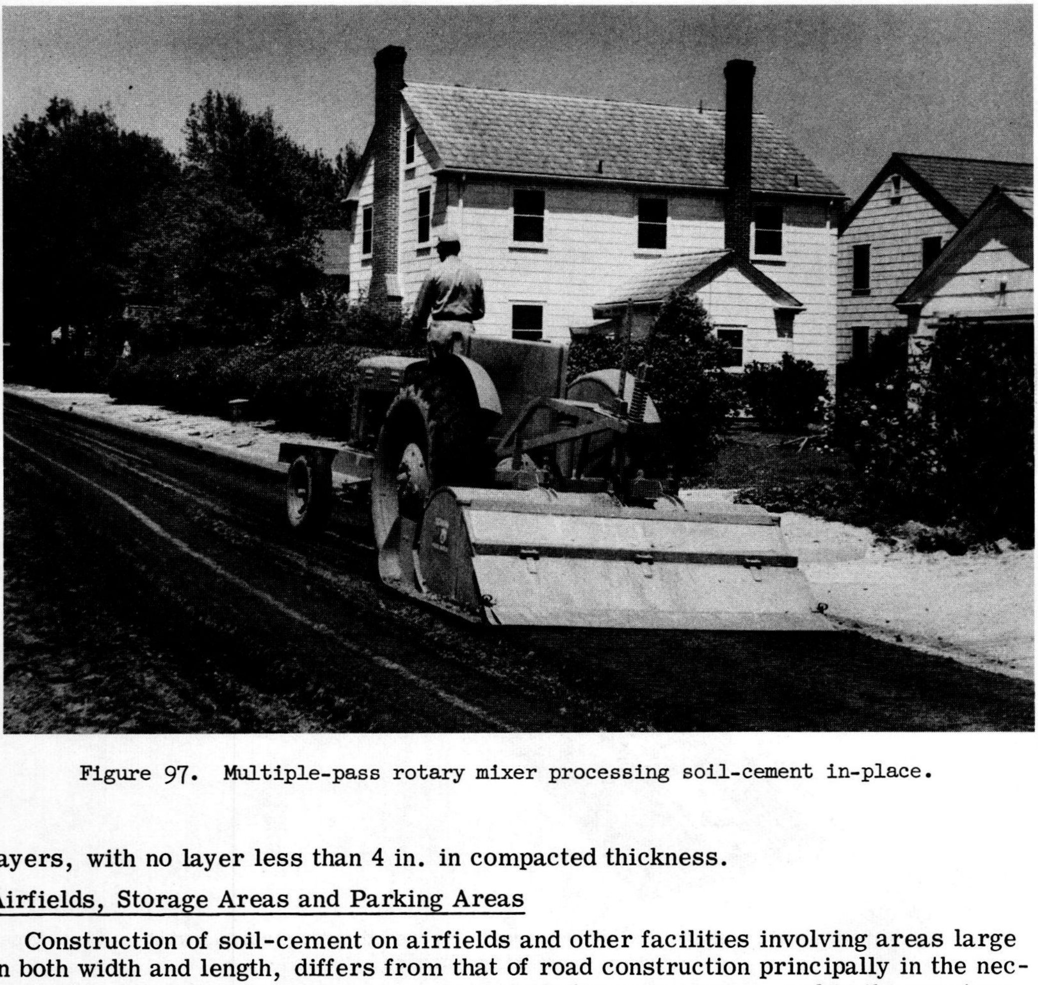


Figure 97. Multiple-pass rotary mixer processing soil-cement in-place.

layers, with no layer less than 4 in. in compacted thickness.

Airfields, Storage Areas and Parking Areas

Construction of soil-cement on airfields and other facilities involving areas large in both width and length, differs from that of road construction principally in the necessity for careful control of crown and grade before processing, and in the construction of both longitudinal and transverse joints. The control of jointing requires laying out the work into construction lanes of the proper width and length to facilitate work, carefully mixing and compacting the soil-cement adjacent to the completed work and transverse construction across the runway, taxiway or area at the turnarounds at the ends of the construction lanes. Methods adaptable to airfields are also adaptable to the construction of storage areas, parking areas and similar facilities of large area.

Slope Paving—Single Lift Construction (30, 94, 95, 185)

Construction procedures for placing soil-cement on relatively flat slopes are similar to those used in road construction, with rotary mixers or traveling mixing machines being used for mixing purposes. For slopes of about 5:1 or steeper, the use of material mixed in a central plant and hauled to the area facilitates construction. The material is spread and compacted in the usual manner except that compacting equipment is operated up and down the slope by means of tractor-powered winches located at the top of the slope, or longitudinally with self-propelled compaction equipment held up on

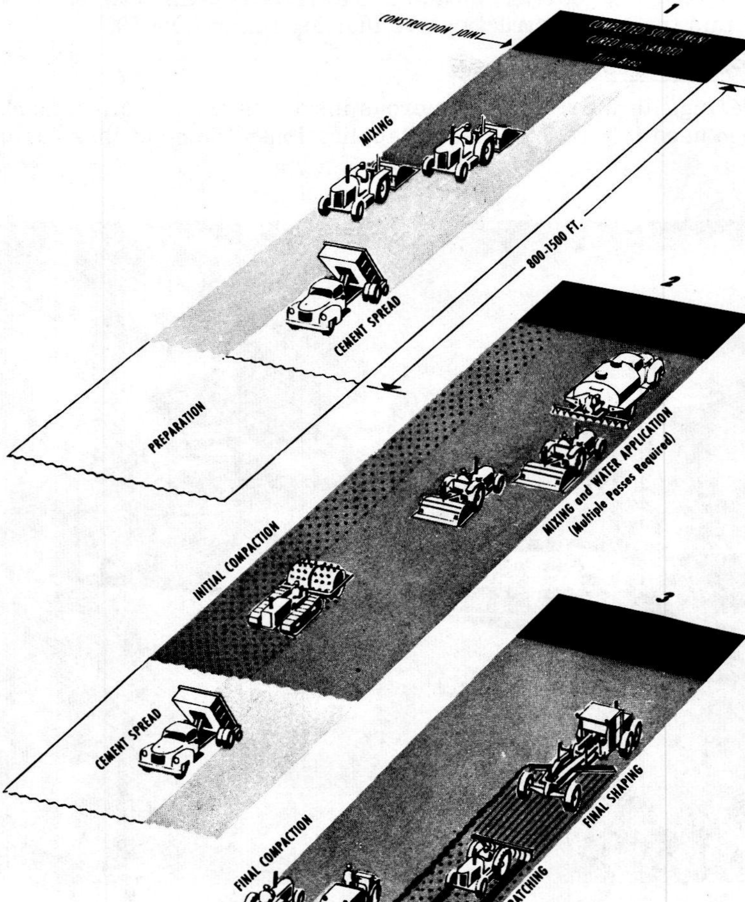


Figure 97A. Sketch of soil-cement processing operations with rotary mixers.

the slope.

Slope Paving—Thick, Multiple-Lift Facings (95, 185)

Thick facings on relatively steep slopes can be processed horizontally as the layers of the embankment are being placed and compacted. The width of processing and the offset distance for each succeeding layer of soil-cement will depend on the angle of the slope and the planned thickness of the facing normal to the slope. Construction operations are similar to those for in-place mixing for roads, and precautions are similar to those for multiple-lift construction for road bases. A principal precaution is to insure that no unmixed and poorly compacted materials remain between lifts. Some of the details of this type of construction are indicated in Figure 100.

Miscellaneous Structures

The engineering literature cites numerous instances where soil-cement of standard quality has been used in a wide variety of applications. Some of these are: bicycle

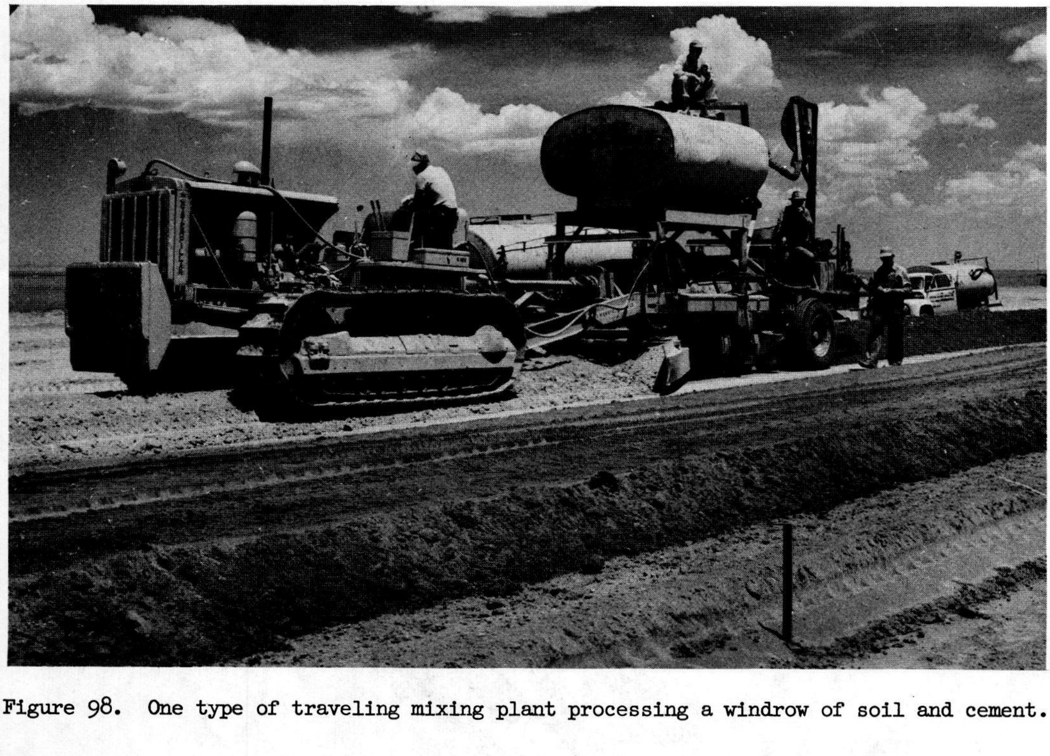


Figure 98. One type of traveling mixing plant processing a windrow of soil and cement.

pathways (93), earth dam cores (96), small culverts (104), floors for aggregate stockpiles (91, 92), building construction (99, 100, 101), small arch bridges (60), surface drains (105), foundations (55), and others. The same principles of adequate cement content, adequate mixing, proper moisture content, adequate compaction and curing that are necessary for good construction in other facilities also hold for these miscellaneous structures.

CONSTRUCTION PROCEDURES FOR CEMENT-MODIFIED SOILS FOR ROAD CONSTRUCTION

The general specification requirements (except cement content), the construction equipment and procedures that apply to soil-cement also apply in the construction of cement-modified granular and cement-modified silt-clay soils.

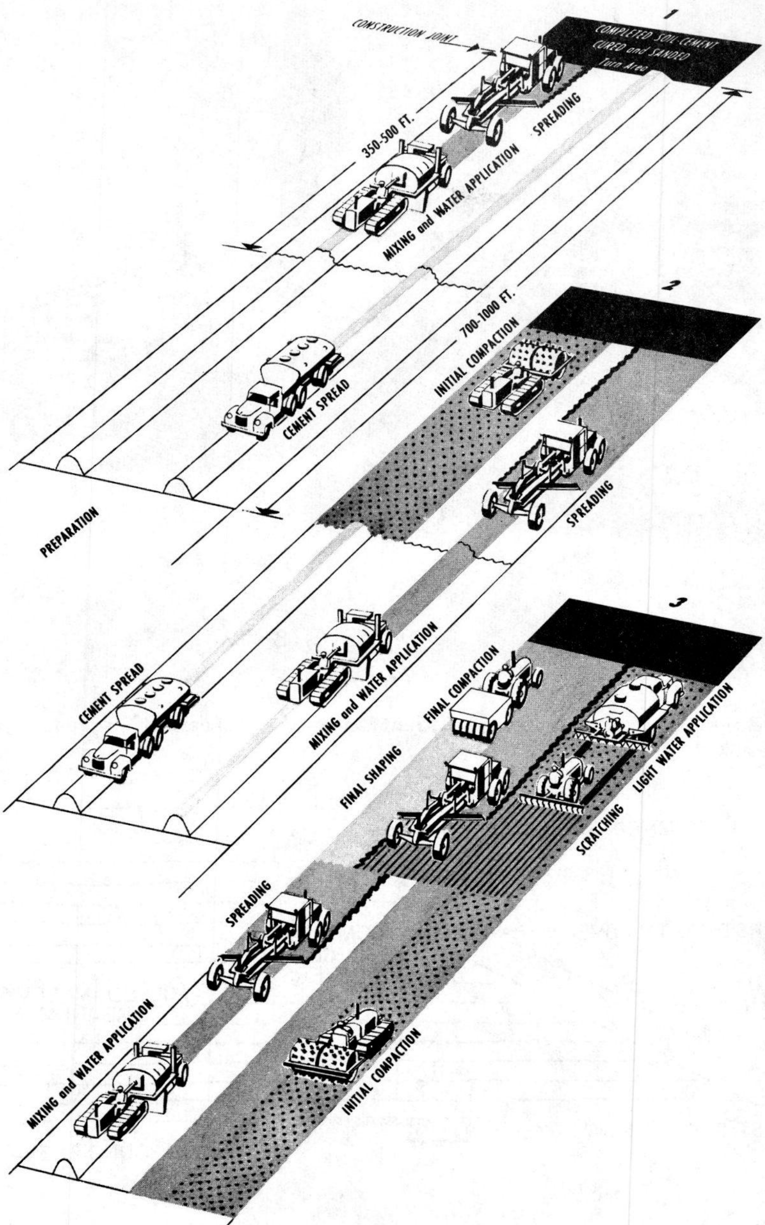


Figure 98A. Diagrammatic sketch of soil-cement processing operations with a windrow-type traveling mixing machine.

CONSTRUCTION PROCEDURES FOR PLASTIC SOIL-CEMENT (95, 97, 98, 114, 185)

Pugmill mixers should be used, except for the very coarse materials having very little silt and clay, which can be mixed with concrete mixers. Mortar-type mixers are also suitable for soil with small amounts of silt and clay. Where plastic soil-cement is used to line irrigation or drainage channels, it may be placed by means of slip-

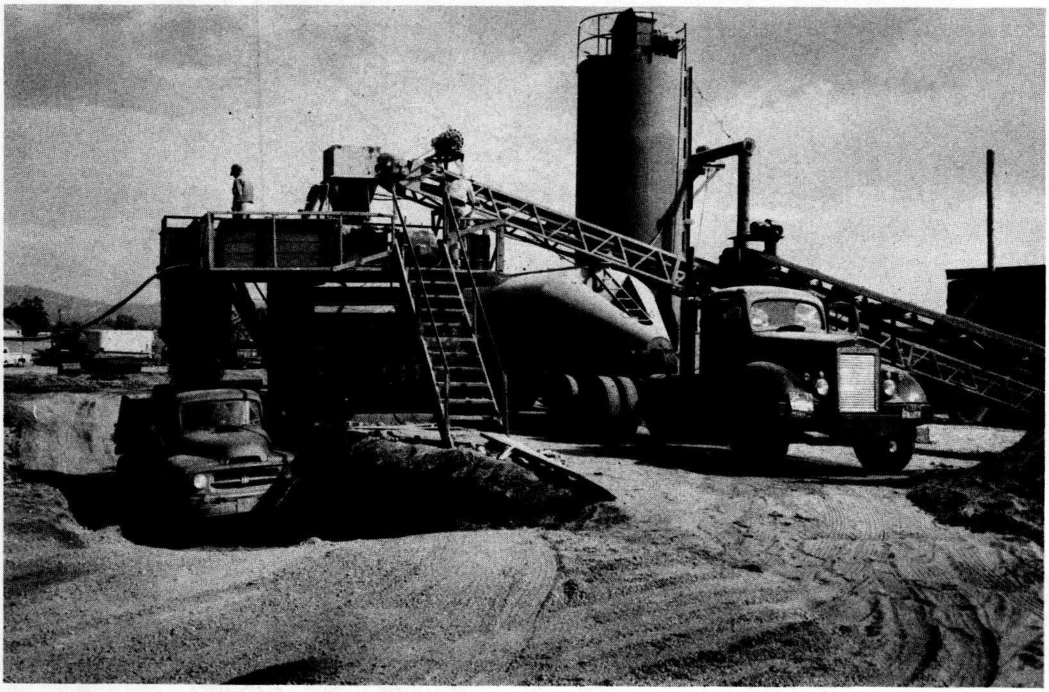


Figure 99. A stationary mixing plant used in soil-cement processing.

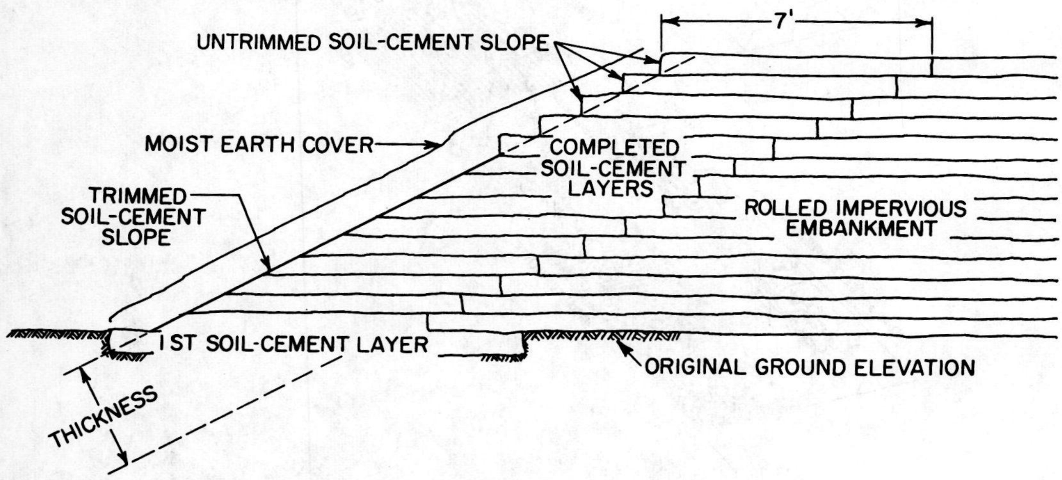


Figure 100. Some details of multiple-lift thick facings for embankments subject to inundation and wave action (95, 185).

forms or may be placed and finished by hand with trowels and wooden lutes. Curing is usually by application of bituminous or other membrane-type materials, although moist earth can be used.

Engineering Control of Construction

The purpose of engineering inspection and control is to assure the quality of construction prescribed and intended by the project plans and specifications. The overall quality of the construction is assessed in terms of the quality of the soil-cement which affects both durability and structural capacity, and by the dimensions that influence structural capacity. The control of quality of the soil-cement lies first in the control of the quality of the individual materials—the soil, cement and water; second, in the proportions of each used; and third, in the mixing, compacting, finishing and curing. Preliminary identification of soil type, testing the materials for quality and testing for mix design to determine the construction control factors have been covered previously.

The principal factors that govern quality of construction and that are controlled in construction by observations, tests and measurements are:

1. The condition of the subgrade on which the soil-cement is to be compacted.
2. Pulverization.
3. Cement content—controlled by observations of quantities used and method of application.
4. Moisture content at the time of compaction, and throughout the curing period.
5. Mixing—the uniformity of dispersion of the cement and moisture.
6. Compaction.
7. Finishing.
8. Final compacted depth.
9. Curing (see moisture content above).

The tests essential to proper inspection and control of construction are listed in Table 38, which also includes post-construction tests and observations that are of interest in studies of the behavior of soil-cement and the continued improvement of soil-cement mixtures.

DETERMINATION OF THE CONDITION OF THE SUBGRADE

The moisture content and the density of the subgrade soil on which the soil-cement is to be built determine whether or not it will be possible to adequately compact the mixture. Soft, moist areas, or areas of low density (that may soften after construction) should be removed and replaced with properly constructed subgrade.

PULVERIZATION

The pulverization test consists of sieving a representative sample over the No. 4 sieve and computing the percentage of soil that passes.

$$\text{Percent pulverization} = \frac{A}{B} \times 100$$

in which

A = the dry weight of the soil-cement mixture passing the No. 4 sieve; and
B = the dry weight of the total sample exclusive of gravel retained on the No. 4 sieve.

The test is usually performed at the moisture content existing at the time of pulverization or immediately prior to compaction, depending on the specification requirements. On the heavier, more clayey soils, where after some effort pulverization has not been attained, pulverization may be accomplished by (a) adding water to about one-half of optimum, (b) obtaining maximum pulverization, and (c) adding cement, mixing, and bringing the mix to "working optimum." The slaking effect of the water and the cement aid pulverization.

CEMENT CONTENT

The cement content of the mixture may be specified in terms of percent of dry weight for a given dry density of the mixture, or as it is more commonly done, in terms of percent by volume of the planned compacted thickness. Percent by volume may be converted to percent by weight for various densities, and vice versa by means of the nomograph in Figure 80. Cement spread in terms of pounds per square yard or bags per square yard may be determined directly from Table 39 or from Figure 101. Pounds of cement required per lineal foot for various widths and depths may be determined from Figure 102. Cement requirements in terms of pounds per lineal foot of windrow for specified cement contents by weight may be determined from Figure 103.

TABLE 38

CONSTRUCTION AND POST-CONSTRUCTION TESTS

Method of Observation or Test	Reference	Purpose of Method
A. Construction Tests		
1. In-place moisture content and density of roadway.	1. AASHO T 147, ASTM "Procedures for Testing Soils."	1. When roadway soils are used, provides basis for determining depth of mixing and water requirements.
2. Pulverization.	2. Screening over No. 4 sieve.	2. To determine compliance with specifications.
3. Moisture-density relations of soil-cement mixtures.	3. AASHO T 134, ASTM D 558.	3. To form basis for specification requirements.
4. In-place moisture content and density of soil-cement.	4. Same as 1 above.	4. To determine compliance with specifications.
5. Cement content of mixture.[1]	5. AASHO T 144, ASTM D 806.	5. To check cement application and uniformity of mixing.
6. Degree of mixing (or mixing efficiency).[1]	6 Compressive strength test, ASTM "Procedures for Testing Soils."	6. To determine the effectiveness of mixing by comparison of compressive strengths of specimens made from field mixing and laboratory mixing (see "Degree of Mixing").
B. Post-Construction Tests[1]		
1. Cement content of soil-cement.	1. AASHO T 144, ASTM D 806.	1. Same as 5 above.
2. Moisture content.	2. Dry to constant weight at temperature of 110 C (230 F).	2. To determine moisture loss during curing.
3. Compressive strength of cores.	3, 4, and 5. Same as A-4, b, c, and d in Table 19.	3, 4, and 5. To check on effectiveness of field proportioning of water and cement, and on mixing, compacting and curing procedures.
4. Wetting and drying test on cores.		
5. Freezing-and-thawing test on cores.		
6. Measurement of crack interval and opening.	6. Visual measurements.	6. To provide data on cracking characteristics for further improvement in mix design.

[1]Not routine tests, see text.

When cement is spread ahead of flat-or rotary-type mixers, the accuracy of the spread can be determined by placing a 1-sq yd canvas or plate on the ground to receive the spread cement. When cement is placed in a windrow of materials, the accuracy of distribution can be measured by pushing two metal plates 1 ft apart into the windrow and removing the cement. The accuracy of the cement spread and the uniformity of mixing may also be checked after construction (see "Post-Construction Tests for Appraisal of Controls").

The Washington Department of Highways has developed a rapid conductimetric method of determining the cement content of plastic cement-treated base (187). The test procedure takes about 20 min to perform and is based on the resultant change in conductivity of water after the addition of cement. Suitable calibration curves are first obtained by batching small test mixtures of cement-treated base aggregate containing

TABLE 39

CEMENT SPREAD REQUIREMENTS PER SQUARE YARD

Percent Cement by Volume	Compacted Depth (in.)							
	5		6		7		8	
	(lb)	(bag)	(lb)	(bag)	(lb)	(bag)	(lb)	(bag)
4	14.1	0.15	16.9	0.18	19.75	0.211	22.55	0.24
5	17.6	0.188	21.2	0.225	24.8	0.263	28.2	0.30
6	21.4	0.225	25.4	0.27	29.7	0.315	33.9	0.36
7	24.7	0.263	29.6	0.315	34.6	0.368	39.5	0.42
8	28.2	0.30	33.8	0.36	39.5	0.421	45.1	0.48
9	31.8	0.338	38.1	0.405	44.6	0.474	50.8	0.54
10	35.2	0.375	42.3	0.45	49.5	0.527	56.4	0.60
11	38.8	0.413	46.5	0.495	54.4	0.579	62.0	0.66
12	42.3	0.45	50.8	0.54	59.4	0.632	67.7	0.72
13	46.8	0.488	55.0	0.585	64.4	0.684	73.3	0.78
14	49.4	0.525	59.2	0.63	69.3	0.737	78.9	0.84
15	53.0	0.563	63.5	0.675	74.3	0.79	84.6	0.90
16	56.4	0.60	67.7	0.72	79.2	0.842	90.2	0.96

known quantities of cement, diluting the mixture with a large quantity of water, and measuring the conductance of the diluted mixture with a conductivity meter. To determine cement contents of field-mixed cement-treated base, representative samples are subjected to the same dilution procedure and the conductivity similarly determined. Reference to the calibration curve gives the amount of cement in the sample.

The California Division of Highways has also developed a test method to determine the percentage of cement in freshly mixed cement-treated base (188). The determinations are based on chemicaltitration methods which relate the cement concentrations. Two different titration procedures are given; first, an acid-base titration method and second, a constant neutralization method. Naturally the first method is used when the aggregates do not react to hydrochloric acid. The second method must be used when the aggregates react to hydrochloric acid. One to four samples can be run simultaneously in about 60 to 90 min.

The British Road Research Laboratory had developed three analytical methods for accurately determining the cement content of soil-cement mixtures (189, 190). In each method the cement content of the mixture is calculated from the calcium oxide contents of the mixture, the cement, and the soil. The three methods of analysis give comparable accuracy, but for control work during soil-cement road construction, when

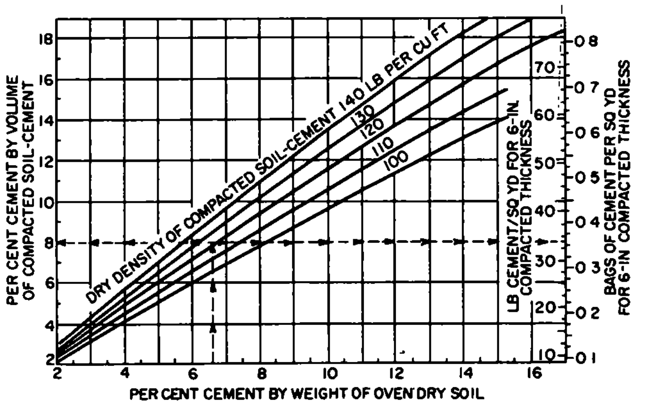


Figure 101. Cement factor conversion chart. Percent cement by volume of compacted soil-cement vs percent cement by weight of oven-dry soil vs quantity of cement per sq yd for a 6-in. compacted thickness for known dry densities of soil-cement (20).

large numbers of samples have to be analyzed, the flame photometer method is probably quickest. By this method it is possible to carry out the complet analysis of eight samples (including the drying and preparation of the samples) in 6½ hours; the purely analytical work on the eight samples takes only 1½ hours (215).

The ASTM Standard Method of Test for Cement Content of Soil-Cement Mixtures (ASTM Designation: D 806-57) (12) is similar to the British Normal Method, which requires about 8 hours to perform.

MOISTURE CONTENT AND WATER REQUIREMENTS

The optimum moisture content from the laboratory moisture-density relations test is used as a basis for the initial determination of water requirements for compaction at optimum moisture content. A moisture-density relations test is made on the job at the end of moist mixing operations to determine the optimum moisture content and density for use in field control. This is done to insure against improper identification of soil type and against changes in optimum moisture content and maximum density resulting from a lengthy mixing period or from delay

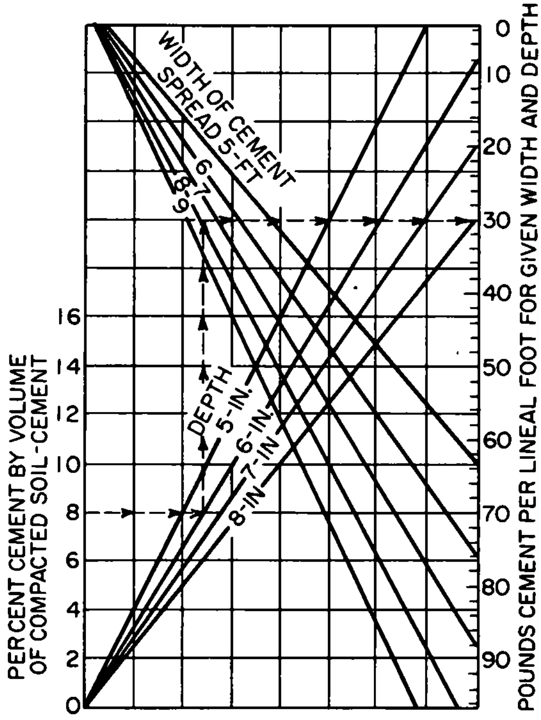


Figure 102. Pounds of cement needed per lineal foot for various widths and depths for specified cement contents by volume (20).

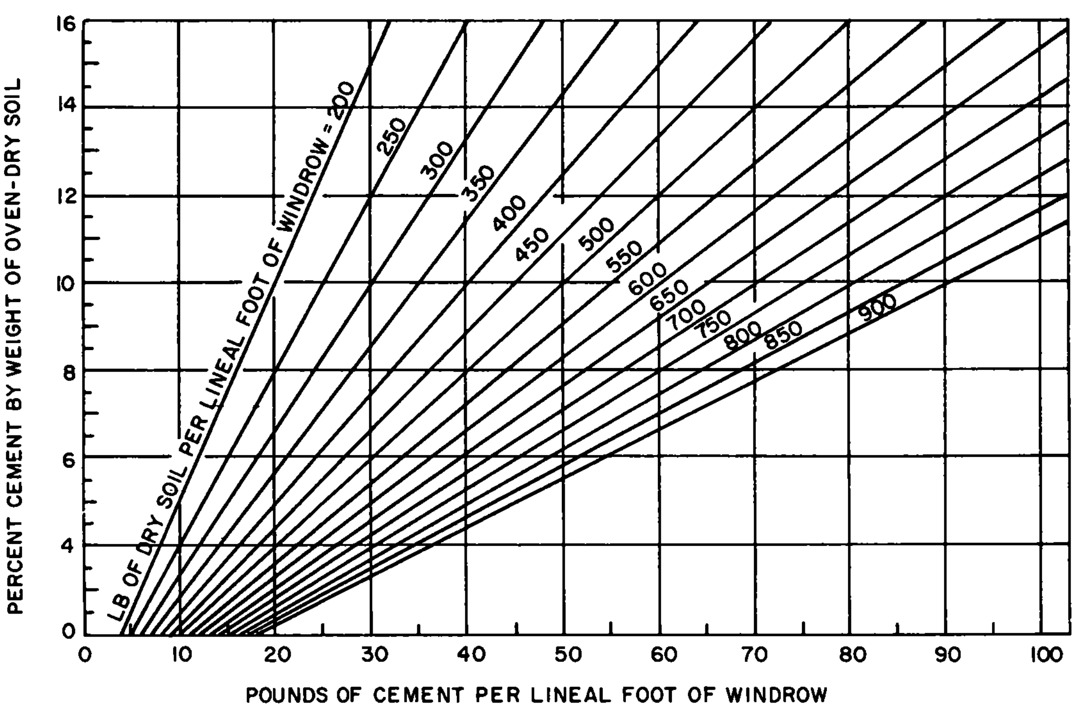


Figure 103. Pounds of cement required per lineal foot of windrow for specified cement contents by weight (20).

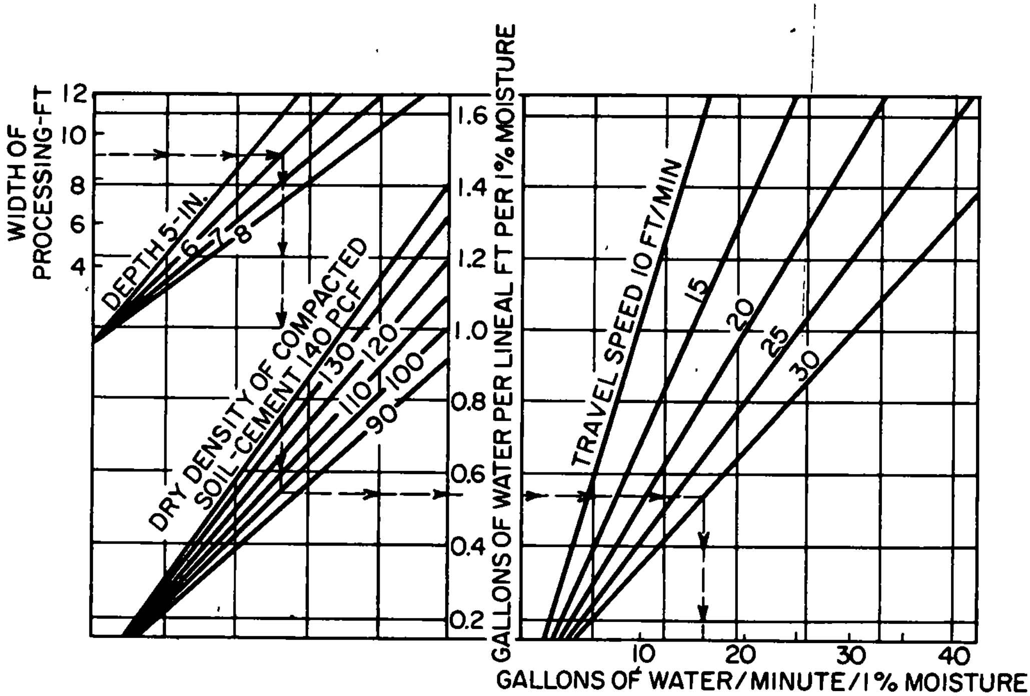


Figure 104. Water required to raise the moisture content one percentage unit (20).

during mixing. The moisture-density test is performed in accordance with the standard AASHO-ASTM Method (AASHO T 134, ASTM D 558). Field moisture-density relations testing is unnecessary if the soil is identical with that used in the preliminary laboratory tests and if mixing is completed in less than 30 min. The moisture content at the time of compaction is one of the most significant of the controls and should be determined frequently either by inspection by trained personnel or by actual test. The approximate percentage of water required is equal to the difference between the optimum moisture content and the moisture content of the raw soil plus cement or the dry soil-cement mix. Approximately 2 percent additional water is needed to compensate for dry cement added to the soil if the moisture content is made on the raw soil prior to the addition of the cement. Required moisture contents in percent can be converted into gallons of water by the use of Figure 104.

MIXING

The uniformity of mixing of cement, soil and water is determined by visual inspection to the full depth of mixing. The mixture should have a uniform color throughout the full depth and width. Thorough inspection can be made only by trenching to full depth across the processed material or through the windrow.

COMPACTION

Specifications usually require compaction to the maximum density obtained in the moisture-density relations test on the soil-cement mixture at the completion of mixing, or to some slightly lesser value. Field in-place density tests are needed to determine compliance with specifications. A careful and systematic inspection procedure is useful in determining compliance as to uniformity of construction. Standard test procedures indicated in Table 38 are available for performing the tests necessary to determine compliance with specification density requirements.

FINISHING OPERATIONS

The nature of the finishing operations in large measure controls the nature of the riding surface and may have marked influence on other performance characteristics of soil-cement bases. The best procedure depends on the equipment and the soil characteristics. Several presently used methods are described in Table 37. Inspection should be aimed at obtaining a smooth, dense, moist surface that is free of cracks, ridges and compaction planes.

COMPACTED THICKNESS

Final compacted thickness is usually determined while making the in-place density determinations. However, if sufficient material to markedly affect depth is removed by scalping during final finishing operations a final check on compacted thickness after finishing operations is in order.

CURING

If the curing method used appears not completely satisfactory, periodic moisture content determinations can be made during the 7- day curing period to determine if the curing procedure is effective in preventing excess moisture loss. Moisture tests are usually made in the top inch and in increments with depth for purposes of determining moisture change with depth.

POST-CONSTRUCTION TESTS FOR APPRAISAL OF CONTROLS

These post-construction tests are not run as a routine. However, when it is desirable to appraise the effectiveness of construction controls, further tests and observations can be made, usually after some standard period of 28 days, 60 days or one year or more after construction. Such testing may concern the quality of the soil-cement, but it may also include evaluation of the structural load-carrying capacity of the pavement-subgrade combination. The tests which can be used to appraise the quality of the soil-cement pavement are indicated in Table 38. Further evaluation may include plate bearing tests, Benkelman beam tests, or accelerated traffic tests.

MAINTENANCE USE OF SOIL-CEMENT

Soil-cement may be used for strengthening of a base, subbase or subgrade in the maintenance of both flexible and rigid types of pavement. For flexible-type pavements, if the failure is in the base and is due to inferior material, it can be repaired by replacing the inferior material with suitable aggregates or by the use of soil-cement. If the failure is due to excessive subgrade deformation because of inadequate pavement thickness, the subgrade can be excavated and replaced with better material and the pavement thickness thus increased. The same end may be accomplished by replacing a portion of the depth of the failed area with soil-cement, unless the underlying material is too soft to permit adequate compaction of the soil-cement.

A small patch under a failed area of a rigid-type pavement may fail due to concentration of pressure and result in a permanent depression of the patched area. It is seldom advisable to prepare a patch smaller than 4 ft in its smallest dimension for the thinner rigid pavements and larger patches may be needed for the thicker pavements. It is well to undercut the remaining slab so the edge of the concrete patch will not coincide with the edge of the soil-cement subgrade or subbase replacement. Undercutting should be 4 to 6 in.

A patching gang can be divided into three groups, one group excavating and removing old pavement, another preparing the soil-cement mixture, and a third placing, compacting and finishing the mixture. Soil-cement at optimum moisture content should be placed in compacted layers not to exceed 3 to 4 in. in thickness when compacted by tamping. Compaction should be to a density of not less than 95 percent of standard AASHO density (Method T 134).

Materials requirements are the same as for soil-cement mixtures. The soil may be any material that reacts favorably with cement and may well be the base material removed from failed areas. Unless a pugmill mixer is used, the soil should be friable and thus preferably granular. Sands with fines, stone screenings, sand-clays, etc., are desirable when a concrete mixer is used. Normal (Type I) portland cement is usually used, although high-early-strength cement may be desirable if time is a factor. Minimum cement requirements may be determined by shortcut methods.

The soil-cement, if it is to be effective, must be protected so it will harden adequately. For subgrade strengthening for rigid-type pavements it should be allowed to harden for 2 to 3 days without loss of moisture before concreting. However, it is better to place concrete directly on the freshly placed soil-cement and permit future hardening as the concrete hardens than to permit the patch to dry prematurely. For flexible-type pavement patching, the soil-cement should be allowed to harden sufficiently so it will not fracture during the replacement of the bituminous surface nor immediately on reopening of the area to normal traffic.

Field Performance of Soil-Cement Base Courses

Numerous reports giving factual information on the in-service behavior of soil-cement base courses are available in published engineering literature. Those reports provide detailed data obtained from condition surveys (39, 55, 61, 64, 107, 109, 164, 199, 200, 201, 202, 204, 205, 206, 207), and field weathering evaluations (30), and field test sections (34, 55, 208, 209).

CONDITION SURVEYS

A committee of the Highway Research Board sponsored condition surveys on 64 projects in 23 states on a total of approximately 200 miles of early soil-cement roads averaging about 2⅔ years in age. The summary report made in 1940 (200) showed 44 of the projects rated excellent, 17 good and 3 fair. None was rated poor. A second report was made in 1941 (201) that reviewed the construction history of the early projects, discussed defects encountered, and gave reasons for the occurrence for the defects. The most frequently occurring defect on the early projects, which were processed largely with agricultural equipment, was scaling of the wearing surfaces that occurred in some degree on 43.5 percent of the projects. Areas of actual structural failure of the soil-cement base were few in number and small in area. Different causes of failure reported were low cement content, inadequate subgrade drainage and support, unsatisfactory compaction due both to inadequate moisture control and poor subgrade support, and excessive mixing time after application of cement and water.

The 1940 and 1941 reports were followed by a 1948 report (204) that summarized two surveys, one made in 1945-1946 and a second made in 1946-1947. The 1945-46 survey covered 18 projects ranging in age from 5½ to 9 years. Fifteen of those projects showed no base maintenance costs. Three projects showed maintenance costs of $10, $24, and $81 per mile. Twelve projects were rated excellent, four were rated good and one average. The 1946-47 survey showed data from 19 states on 59 projects totaling 273 miles of road. Forty-eight of those projects were 6 in. thick. Others ranged from 5 to 10¼ in. thick. Cement contents ranged from 6 to 14 percent, the greater proportion being built with 10 percent cement by volume. Soils had liquid limits up to 72 and plasticity indices up to 35. Age of projects ranged from 2 to 10 years.

On 32 of the projects no base failure had occurred. Some failures had occurred on 27 projects. Only six projects exhibited failures sufficient in extent to warrant analysis. For those six, data were not available for two projects. The remaining four showed excessive breakage for the following reasons:

1. Twenty percent failure. Soil-cement was dry and dusty and not knit together, indicating inadequate construction control.
2. Fifteen percent failure. These were judged due to insufficient thickness (5 in.), low cement content for soil type, and poor construction practices.
3. Ten percent failure, thought due to insufficient thickness (5 in.) on very poor subgrade soils.
4. Thirty-three percent breakage as a result of frost heave on silty soil having a high water table..

Failed areas represented 59 and 10 percent of the total areas of the other two projects.

Blowups have been reported on only one project (199), built in the winter of 1936 with 8 to 10 percent cement. A 4-mi section of this project was primed with tar in March 1937. Soon afterwards blowups occurred in 23 places. They were characterized in a few cases by cracking and shattering of the base for the full depth for about 2 lin ft, but in most cases only the top 2 in. were affected.

A report was made in 1948 on 10 individual projects (28.38 miles) of soil-cement built in Virginia (202) since 1938. Most of the roads were built in the coastal plains and eastern Piedmont areas, but soils ranged from silty sands and sand-clays to silty clays. Projects were largely built by mixed-in-place methods using farm machinery, although a "modern" machine was used on one project. The report concluded that the severe climatic conditions in the areas where the roads are located had not caused any apparent distress in the soil-cement.

The Corps of Engineers (55) obtained pertinent pavement, soil-cement base, subgrade, traffic, and performance data for 35 airfields on which soil-cement was used. Those data were obtained from airfield evaluation reports, most of which are dated 1944 and gave data to that date. With only few exceptions, the quality of the soil-cement was not evaluated but rather arbitrarily assigned a CBR of 50 or 80 based on service behavior.

The materials stabilized and the subgrades on which they were built ranged from lean clays through gravels. A 6-in. thickness was used in most instances. Cement contents averaged 10 percent. Surfacing varied from none to 4 in. of asphaltic concrete. Points of interest drawn from the studies are:

1. Shrinkage cracks are common to many of the bases but definitely did not indicate failure.
2. Unsurface soil-cement is not capable of withstanding the abrasive action of traffic.
3. There were no subgrade failures (except for fill settlement) in those cases where actual soil-cement pavement thickness was greater than that required for flexible pavement design considerations.

In 1958 the Corps of Engineers reported (34) on the service behavior of seven airfields where soil-cement had been used in construction. The airfields were located at Albany, Ga., Valdosta, Ga., West Palm Beach, Fla., Hot Springs, Ark., Little Rock, Ark., Clovis, N.M., and Muroc, Calif. Visual inspections were made on all seven fields and field and laboratory tests were made on the first four. The findings are:

1. Cracking. It appeared that cracking was caused by shrinkage of the soil-cement and was not connected with overload. Age at time of paving ranged from a few months to 8 years but in each case cracks appeared a few months after surfacing. Accelerated traffic showed that soil-cement along construction joints did not afford the same protection to underlying layers as that of interior lanes. No evidence of lack of protection at joints was noted at any of the fields. All but one of the fields were capable of carrying heavier planes than those in use as is shown in the following analysis.

Using CBR value of 15 for subgrade and 8-in. thickness above subgrade, the Albany, Ga., pavement would be adequate for unlimited use by planes with assembly loads of 12,000 lb and single wheels of either high pressure, HP, or low pressure, LP, tires. Based on CBR of 15 and thickness of 15 in., the Valdosta pavement was adequate for use by planes with 19,000-lb load on single wheel with LP tires or 16,000-lb load on single wheels with HP tires, and would probably carry wheel loads up to 25,000 lb for one to two years. Good bond was found on all fields tested in this study.

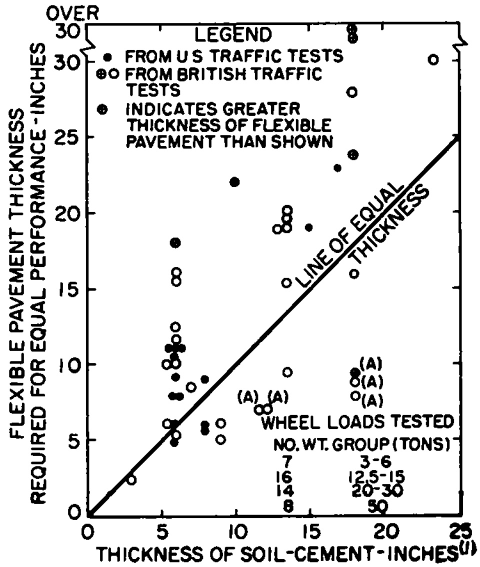
2. Wet-dry and freeze-thaw tests. Cores from two fields were tested (Albany and West Palm Beach) and showed freeze-thaw losses of 36 and 25 compared to allowable losses of 14, but field behavior was good.
3. Reduction in plasticity. Materials having plastic binders at the time of construction were non-plastic when tested 1 to 10 years later (Fig. 35).
4. Healing of cracks. Examination of samples of soil-cement from Valdosta and West Palm Beach airfields showed that numerous cracks in the material had been filled by a deposit of calcareous material. The specimens showed no tendency to break along these cracks; on the contrary, they usually broke in uncracked portions.
5. Further summary statements in regard to cracking were that:
   a. Cracking did not vary noticeably from field to field and was not related to type of material stabilized.
   b. Cracking was not a function of loading. The only reasonable explanation is that cracking is caused by shrinkage of the soil-cement.
   c. The presence of cracks appeared to have no effect on the ability of the soil-

cement to carry the imposed loads or on the durability of the soil-cement mixture.

d. No method was found to evaluate the effects of healing of cracks by deposition of a calcareous material.

FIELD TEST SECTIONS

In 1956 the Corps of Engineers (55) reported on the performance of four United States and five British traffic tests on soil-cement that involved wide ranges in some of the factors that govern behavior. The variables included cement content (range was from 4 to 26 percent), thickness of soil-cement (3½ to 23½ in.), material stabilized (crushed rock to clay), subgrade (sand to clay having a CBR range from 37 to 1), wheel load (2.5 to 50 kips), and tire inflation pressure (40 to 160 psi). The traffic tests were made on unsurfaced soil-cement. A major objective of the tests was to determine the comparable load-carrying capacities of soil-cement and flexible-type pavements having granular base courses without admixtures.



(1) NO SURFACING ON SOIL-CEMENT DURING TRAFFIC TESTING

(A) CBR VALUES DETERMINED FROM CONE PENETROMETER (55 CONE INDEX = 1 CBR). RESULTS APPEAR INCONSISTENT DUE TO USE OF EXTRAPOLATED VALUES.

Figure 105. Results of field traffic tests evaluated in terms of thickness of flexible pavement for equal performance (55).

The thicknesses of flexible pavement construction required to give a performance equal to that of the soil-cement test sections are indicated in graphical form in Figure 105. The flexible pavement thicknesses were determined from plots prepared from CBR design curves in use by the Corps of Engineers at that time (September 1956). Those plots permitted determination of the required pavement thickness for any specified number of coverages.

Figure 105 shows some equivalent thicknesses of flexible pavement approximately one-half of the thickness of the soil-cement tested (below the diagonal line of equal thickness). An explanation given is that values indicated by the notation (a) in Figure 105, the CBR values of the subgrade, were converted from data obtained by the cone penetrometer and converted to CBR's using a cone index of 55 as equal to a CBR of 1. This was believed to be a conservative estimate of CBR. Also there was some evidence that failure occurred in the sand-cement pavement itself that accounts for its poor showing in the graph. Otherwise, generally, the ratio of thickness of flexible pavement required compared to that of soil-cement was of the order of about 2:1 to 4:3 depending on the quality of soil-cement and the nature of the subgrade.

The Corps of Engineers and British studies are also reported in an ASCE paper (210). Pertinent comments of this paper are given in later proceedings of the ASCE (211).

WEATHERING EVALUATIONS

Field studies (30) made after 17 years' experience with soil-cement construction showed that areas giving faulty performance were built in violation of the three fundamental control requirements of: (1) specified moisture content, (2) specified density, and (3) specified cement content.

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RN/3665/DM.BAB.GW. Cement stabilization of granular road base materials.
RN/3705/-. A survey of the results from three full-scale pavement design experiments.
RN/3789/FJG. An analysis of the control tests carried out during the construction of the lean concrete base on the London-Birmingham Motorway.
RN/3798/PTS.GAS. A study of the factors affecting the strength of a cement stabilized lateritic gravel.
RN/3836/BAB. A full-scale specification trial of a cement bound granular base on A. 11 at High Road, Salway Hill, Woodford, Essex.
RN/3837/PTS. The measurement of the pH of soil-cement pastes as a diagnostic test for the presence of deleterious soil organic matter.
RN/3855/DN. A laboratory investigation of thirty sands from Nigeria and British Guiana.

A copy of each of these research notes is available in the Library of the United Kingdom Scientific Mission located at 1907 K Street, N.W., Washington 6, D.C., and can be obtained on loan on request. These research notes are duplicated copies only and are not available for purchase.

Appendix

REPORT ON SOIL-PORTLAND CEMENT STABILIZATION PRACTICES

Prepared for the Committee on
Soil-Portland Cement Stabilization

by

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The Highway Research Board Committee on Soil-Portland Cement Stabilization, desirous of learning the present status of the use of soil-portland cement stabilization in highway construction and in the development of information concerning present research studies that concern soil-portland cement stabilization, prepared and submitted a questionnaire to obtain the desired information.

The questionnaire was submitted to all 50 states and to 25 foreign countries late in 1959. A tabulation of replies received was prepared and submitted to the Committee on Soil-Portland Cement Stabilization at the Thirty-Ninth Annual Meeting of the Highway Research Board on January 11-15, 1960, in Washington, D.C. Since that time, additional replies have been received, the data have been tabulated and a summary report is presented.

GENERAL

In this report "soil-cement" is considered to be a hardened material formed by curing a mechanically compacted intimate mixture of pulverized soil, portland cement and water. Durability and/or compressive strength are the common criteria for hardness. The standard for hardness varies. The term "soil," in addition to its usual connotation, may include mineral aggregate materials produced from quarries, gravel pits and industrial plants, or mixtures of soil and aggregate.

Replies to the questionnaire were received from 49 of the 50 states and from 9 of the foreign countries solicited. Detailed replies were to be submitted from India and from the States of Australia; however, these replies have not been received. The Portland Cement Association of Australia did complete those parts of the questionnaire on which they had some useful information and experience, and these data have been incorporated in the tabulation and in this report.

Of the 58 replies received, 50 have used soil-cement stabilization to some degree. The earliest use reported was in 1936; 27 were using by 1941, and at the present time there are several who have not used soil-cement stabilization but have plans to undertake this type of construction. The extent and type of soil-cement stabilization used varies from short experimental sections of roadway to very extensive use with undeterminable amounts of mileage constructed. Airport use is confined to several southern states in the United States of America and in England, Germany and New Zealand. There are indications that governmental agencies, other than those replying to the questionnaire, have used soil-cement stabilization in airfield construction. All types of geographic locations were reported: valleys, mountains, plains, deserts, coastal areas, tropical and plateau in Brazil. Climatic conditions reported were: rainfall, up to 200 in. in Africa; winter temperature, to -20 F in Utah; summer temperature, to 115 deg in California; and, frost depth, up to 84 in. in Montana.

MIX DESIGN

Gradation limits reported, varied depending on the types of soil stabilized. Atterburg limits were used for control in some instances, and in other instances no limitations were imposed.

Chemical constituents found harmful to soil-cement were organic matter, sulfates and micaceous soils. Organic matter resulted in lower strengths, slowing of hardening and disintegration; suggested methods of combating these harmful effects were to avoid using organic soils, add 2 percent cement for each 1 percent of organic matter, use type V portland cement, and add calcium chloride. The Netherlands suggested using high early strength portland cement for the CaO content to counteract the organic matter; their suggestion was to mix the organic soil with a slurry of cement and water about one day before the actual soil-cement stabilization.

Types I and II portland cement were most commonly used in soil-cement stabilization. Type II was reported to offer greater resistance to the attack of sulfates, alkali or sea water. In England, about 5 percent of their work involved rapid hardening cement, whereas in Africa, rapid hardening cement was not desirable in the tropics because of difficulties in compaction.

Laboratory strength and/or durability tests used were varied. Compressive strength, freeze-thaw and wet-dry, standard PCA Design Manual and Leadabrand Short Test Method, moisture-density relations, punching-shear and unconfined compression test, and the pick-and-click test were reported. In addition, the stabilometer, cohesiometer, cristallization test using Na_2CO_3 (Germany) and the cylinder penetration test (British Std. 1924) were listed.

In evaluating the results of laboratory tests of soil-cement mixtures, the criteria of strength and/or durability used in determining cement requirements were manifold. The wet-dry, freeze-thaw, compressive strength, triaxial shear and cylinder penetration ratio (CPR) tests were given, with specified test criteria being used to determine cement requirements. Some used no specific criteria; the cement content chosen was the most economical one which showed the best comparative results. In addition, cement contents depended on traffic intensity, thickness and type of bituminous surfacing and the texture of the soil.

Among the soil classification systems, or other short-cut procedures, used for determining the cement requirements were the following: PCA short-cut procedure; based on pre-construction laboratory results; with various soil types, use the cement requirement for the most prevalent types, removing the worst soils; complete physical and chemical analysis to approximate the starting point for percent cement to use; rule of thumb—do not start with soils exceeding 30 percent passing the No. 200 sieve or with a PI greater than 10; the Pedological System (see HRB Proceedings, Vol. 19, 1939, p. 522, Table I); trial and error; and, when using sand, appearance, color and granulation as an indication of stability.

The maximum cement content for soil-cement economically competitive with alternate methods of paving construction varied from a low of 2 percent to a high of 20 percent. Length of haul and availability of granular materials, as well as cement, were factors to be considered. In Central Africa, 1 percent cement is equivalent in cost to a 4-mi haul. Also, the use of blending sand, proportioning cement and fly ash into the soil and occasionally adding ½ percent of $CaCl_2$ to the mix were cited as factors affecting the mix design.

THICKNESS DESIGN

Soil-cement thicknesses used ranged from 4 to 18 in. and varied according to use. The methods of thickness design used also varied. Experience, judgment, empirical methods, CBR method, stabilometer R-value, cohesiometer, PCA Manual, Triax Method (HRB Bulletin 8), traffic count and a standard of 6 in. generally limited by ease of processing were listed as methods used.

A variety of reduction factors were given to substantiate the use of thinner construction with soil-cement than with alternate forms of construction.

CONSTRUCTION

Both mix-in-place methods and stationary plant methods were reported used in constructing soil-cement, with a wide variation in the ratio. In preparing soil-cement mixtures with cohesionless soils, discs, plows, harrows, scarifiers, bladers, single- and multiple-pass pulvimixers, stationary and travel plants, windrow mixers, the Howard Train (England) and other makes of equipment were used. For compacting the soil-cement mixture, sheepsfoot, pneumatic, steel-wheel (both pull and self-propelled), vibrating and grid rollers, vibratory pads, Cat tractors and dropping-weight compactor (an integral part of the Howard Train) were used. Finishing operations were accomplished with patrol blades, pneumatic and steel-wheel rollers, finger weeders, Barber-Greene Paver, nail-tooth and broom drags, and a shoulder machine box with strike-off bar.

In preparing, compacting, and for finishing operations on soil-cement mixtures with cohesive soils, many used the aforementioned equipment for use with cohesionless soils. In England, soils with low clay contents can be mixed in paddle-type asphalt mixers and sometimes in pan concrete mixers. For soils with a liquid limit above 40 percent, the Howard single-pass train (England) is reported to be the only machine that gives good mixing.

Many were satisfied with the capabilities of the machines used in soil-cement construction. Needed improvements were better control of cement distribution during mixing and placing. Some felt that there were limitations on the mixing equipment and on plant capacities. Africa reported that the need is always for simple and robust equipment.

Those attempting to pulverize cohesive soils before mixing with cement achieved 60 to 100 percent passing the No. 4 sieve; many did not specify any fineness gradation limitations.

In controlling uniformity of mixing soil and cement, the following were used: visual inspection, titration test (California 338), control of moisture content, uniformity of cement spread, electrical conductivity method for determining cement content (a field test), unconfined compressive strength test, controlling the speed of the single-pass train, maintaining even depth of mix and by designating the number of passes of the pulverizer.

Moisture contents achieved in the soil-cement mixture prior to compaction ranged from optimum (AASHO T-134) to 80 percent of optimum for sandy soils and to 120 percent of optimum for silty and clayey soils. Densities specified for the soil-cement varied from standard (AASHO T-99) to 90 percent of standard.

Field tests used to control moisture content and density were the following: feel and squeeze cast, field moisture-density, alcohol drying, Speedy Tester (calcium carbide method), sand volume, balloon volumeter, oil in hole volume method, Washington Densometer, core cutter for density and nucleodensimeters.

The maximum compacted thicknesses of soil-cement that can be constructed in one lift were 6, 7, and 8 in. Many have used double-lift thicknesses of 3, 4, 5, and 6 in. with satisfactory results. Some have used combinations of 4 and 5 in. and 4 and 6 in. Germany reports 9 and 10 in. total has been used. The Netherlands reports good results with 2 layers of cement stabilized sand, each 6 in. thick, with a 2-in. sand layer in between.

Soil textural type does and does not influence thickness of construction in one lift. Dune sand was reported to be difficult to stabilize with cement in one reply to the questionnaire; yet, another replied that dune sand can be stabilized with cement by compacting with a pneumatic roller, a vibrating beam and a 1-wheel vibratory roller. Others reported: the greater the cohesion, the thinner the lift; greater thicknesses can be built in cohesionless soils; and, soil textural type does not influence thickness up to 8 in.

Time intervals permitted between completion of mixing and completion of compaction were quite variable. Some reported continuous operations and uninterrupted finish; others ranged from 30 min after water is added to 6 hr; one reported absolute minimum to 30 min; and, those using the Howard Train reported no problem with a time interval of from 1 to 5 hr.

Among the major precautions to be observed in soil-cement construction are these: adequate mixing and pulverizing; uniformity of mixing depth; proper moisture content, cement distribution, compaction and finishing; obtain design density; stable subgrade; eliminate questionable soils; don't allow mixture to dry before applying curing material; adequate equipment and maintenance, properly trained personnel, supervision and inspection; elimination of compaction planes; avoid excessive final trimming or recompacting trimmed material; and, as one respondent succinctly reported "too many."

Construction seasons for soil-cement covered all months of the year. Most agreed that winter weather conditions and rain should be avoided, and the majority reported that soil-cement should be constructed when the minimum temperature is 40 F and rising.

The typical unit cost (dollars per sq yd of 6-in. compacted thickness) of soil-cement varied greatly, ranging from $0.38 to $2.00. As many stated in their replies, the cost depends on the type and availability of material, length of haul, depth and method of processing and the amount of cement used.

CURING

All methods have been used for curing soil-cement: wet earth, wet straw, sprinkling with water (varying from a light fog spray till curing seal is applied to specified amounts for specified periods), paper and plastic. All kinds of bituminous seals were reported ranging generally in amount from 0.10 to 0.20 gal per sq yd. A majority wet soil-cement before applying bituminous material. The amount used ranged from a light fog coat to saturation to fill all voids. Many cover bituminous material with aggregate, using sand, quarry fines, cover coat, crushed stone or gravel with gradation limitations and control. Other curing methods reported were from Australia where petroleum tar is used where available, as unsatisfactory results were experienced with light coal tars. France reported that some curing compounds were used on concrete.

The period of curing soil-cement before applying final-type wearing surface and before opening to traffic was also extremely variable. The minimum time interval specified for curing was 3 days with immediate opening to traffic; the maximum time interval for curing was 6 months, with variations in between the minimum and the maximum. The Netherlands reports that they prefer to apply a binder course or surface dressing on completing the soil-cement construction, whereas the final-type wearing surface is applied after a period of about 6 months or more (by preference including a winter season).

Additional remarks on curing were: protect from freezing, have adequate water distributing equipment, and curing and priming in one operation.

SURFACING

Surfacing requirements for soil-cement paving on primary roads varied in the same manner that thickness design varied. Types of surfacing ranged from bituminous binder and seal coat to plant mix asphaltic concrete. Thicknesses ranged from ½ in. to 6 in. Surfacing requirements on secondary roads were similar to those on primary, except that thicknesses ranged only to 4 in. maximum. Urban roads were similar to both primary and secondary. Minor applications of prime and seal, single or double surface dressing and thicknesses to 3 in. were reported for airports, parking lots and shoulders.

The soil type stabilized did and did not influence the wearing surface requirements. On cohesive soils a single surface treatment was used before applying plant mix. The soil type only influences the type of primer and rate of application. Concrete pavement thickness can be reduced from 9 to 8 in. when soil-cement is used. The soil type does not influence the wearing surface requirements when the determining factors are traffic density and type or when concerned with only one soil type.

PERFORMANCE

In general, soil-cement is a satisfactory paving material. A few qualifications reported were: not satisfied with cracking; where there is limited traffic; major condition is presence of a subsoil with a satisfactory bearing capacity; on shoulders soil-cement is good if subdrainage is provided; on airports soil-cement is good for light aircraft up to DC-3. Other suggested uses for soil-cement were: suitable for factory floors, playgrounds, footpaths, cycle paths, tennis courts, erosion control of coarse sand along the beach of a large river, ditch linings and dam and levee faces.

Cracks that have developed in soil-cement pavements vary with soil type. They are shrinkage, transverse (varying distances apart), block or irregular, large and well-spaced with more than 5 percent cement, longitudinal, rectangular, ladder and alligator; old bases are honeycombed, new bases are hairline. They occur from 1 day to 5 years after construction, and their occurrence varies with temperature, first cold weather and first winter. Transverse cracks occur soon after construction and are due to shrinkage from hydration of cement. Ladder and longitudinal occur following prolonged periods of cold weather. Single longitudinal cracks must be caused by insufficient resistance of the unstabilized shoulders or settlements of the subsoil.

Crack patterns appear to be related to the soil textural types stabilized. In gravels they are fine, and not regular in sands they are of the regular block type. Cohesive soils develop more honeycomb, and crack patterns occur more in clayey than granular soils. The finer the texture, the closer the crack pattern. Such patterns may be caused by shrinkage in drying. Compaction seems to affect the crack pattern.

Those who have found that cracking of soil-cement is deterimental to structural integrity state that cracks let water into the soil-cement and the subgrade; closely-spaced cracks lead to early failure; block pattern cracks permit movement which is transmitted to the wearing surface, causing the mat to be broken up; they cause pumping; longitudinal, ladder and alligator cracks are unsightly. Those who have found that cracking of soil-cement is not detrimental to structural integrity state that widely-spaced cracks do not affect strength; cracking denotes adequate rigidity; they do not penetrate all the way through the base; cracking indicates good curing; soil-cement acts as a semi-rigid base, not as a slab; the cracks observed were caused by a spongy subgrade.

Various ways of eliminating or minimizing crack formation are: reduce the amount of cement used to below 3 percent and use a mixture of cement and fly ash; keep cement contents low; control moisture content; delay placement of mat and use drag treatment; use good curing methods; don't construct in hot weather; high penetration asphalts minimize cracking; use sufficient cement; central plant mix jobs look better; compact at or slightly below optimum moisture content; compact on the dry side of optimum; multiple surface treatment helps; early traffic makes cracking less apparent; use well-graded aggregates and obtain higher densities.

Delayed placement of the final bituminous wearing surface minimizes "reflection" cracks and may help delay the occurrence of such cracks, but does not eliminate them. Such cracks occur on bituminous overlays on old concrete pavements. Possibly a 4-in. layer of crushed gravel between the soil-cement and the bituminous surfacing will eliminate such cracking.

The Netherlands reports that, by placing the bituminous wearing surface ½ to 1 year after placement of the binder course or a single surface dressing, the cracks, due to shrinkage, temperature influences, traffic loads and settlements, will occur and their detrimental effects, if any, will be passed when placing the final surface.

The major maintenance operations required for soil-cement pavements are: routine surface treatments, bituminous re-sealing, crack filling, leveling, positive drainage through the shoulders where needed, and are generally due to thin original surfacing.

Maintenance costs for soil-cement pavements ranged from very low, $60.37 per mile, to medium, $398 annually and $650 per mile average per year for 4 years, to high, $153 per mile. One report stated $4,000 per mile every 4 to 6 years.

RESEARCH

Soil-cement research and development programs that are in progress or in the planning stage are the following: attempted correlation of strength tests with brush tests; relationship of cracking and lineal shrinkage of natural material used, placement of cement-treated base directly on subgrade with a layer of untreated surfacing between the cement-treated base and the wearing course to minimize reflection cracking; continuing study of performance; cement in sulfate soils; use of additives $CaCl_2$ and $Ca(OH)_2$; test results of materials used in soil-cement construction over the years are being analyzed for comparison with the short-cut method of testing and to determine whether cement content could be predicted on the basis of gradation in granular materials; in an area where sand clay topping material is scarce, treated top 6 in. of embankment soil (A-6-7) with hydrated lime, then added portland cement to form a 6-in. compacted layer used as the subbase, obtaining better than 65 percent pulverization (passing No. 4); continued evaluation of electrical conductivity method of determining cement content; performance studies on existing soil-cement bases, relating performance to subgrade, gradation, percent cement and wearing courses; investigation of durability of soil-cement and methods of assessing durability by laboratory tests; measurement of mechanical and elastic properties of soil-cement covering a range of soils; simplification of testing methods and procedures; influence of water content, compaction and cement content to durability and compressive strength of soil-cement; influence of prolonged mixing; frost resistance of soil-cement made of cohesive soil which is modified with lime before mixing with cement; investigations on additives to soil-cement; competititve tests using different types of cement, including Pectacrete Cement(hydrophobic); the question "flexible or rigid?"; the construction of joints; the problem of organic matter, the nature of the harmful effects, and how to counterattack them; and, the question of shrinkage due to hydration and temperature influences.

Some of the needed areas of soil-cement research and development are: elimination and prevention of detrimental cracking and surface slippage; control of random cracking; means of pulverizing soils; improvement on freeze-thaw test; better and more practical laboratory tests; service records, a rational design method similar to portland cement concrete and faster methods for determining cement contents; pavement thickness design or performance ratio to other types of base courses; construction methods and/or equipment which will eliminate the need for final trimming; investigation of inter-relationship of molding water content, density and compressive strength; and, the influence of drainage to durability of soil-cement roads.

QUESTIONNAIRE ON SOIL-CEMENT STABILIZATION

Note 1: In this questionnaire soil-cement is considered to be a hardened material formed by curing a mechanically compacted intimate mixture of pulverized soil, portland cement and water. Durability and/or compressive strength are the common criteria for hardness. The standard for hardness varies.

Note 2: The term soil, in addition to its usual connotation, may include mineral aggregate materials produced from quarries, gravel pits and industrial plants, or mixtures of soil and aggregate.

1. GENERAL
   a. Have you used soil-cement?____ Date of first usage:________
   b. How many miles (or square yards) of soil-cement paving have you built?
      (1) Primay roads: Base____, Subbase____, Shoulder*____
      (2) Secondary roads: Base____, Subbase____, Shoulder*____
      (3) Urban roads: Base____, Subbase____
      (4) Subdivision streets: Base____, Subbase____
      (5) Airports:
         (a) Runways: Base____, Subbase____, Shoulder*____
         (b) Taxiways: Base____, Subbase____, Shoulder*____
         (c) Aprons: Surface____, Base____, Subbase____
         (d) What classes of airports?________
      (6) Parking lots: Surface____, Base____, Subbase____
   c. What are the general geographical locations of your soil-cement jobs?________
      (1) In this region the average annual rainfall is:____inches, average winter temperature:____°F, average summer temperature:____°F, average frost penetration:____inches.
      (2) Other pertinent climatic information:________

* It will be assumed that soil-cement shoulders were surfaced unless otherwise indicated.

2. MIX DESIGN
   a. What gradation limits include all the soils used in your soil-cement jobs?

Sieve Analysis		Hydrometer Analysis	
Sieve size	% passing	Particles Smaller than	%
2-inch	____to____	0.074 mm	____to____
1½-inch	____to____	0.005 mm	____to____
¾-inch	____to____	0.001 mm	____to____
⅜-inch	____to____		
No. 4 (4.76 mm)	____to____		
No. 10 (2.00 mm)	____to____		
No. 40 (0.42 mm)	____to____		
No. 100 (0.149 mm)	____to____		
No. 200 (0.074 mm)	____to____		

   b. What ranges in Atterburg limits include all the soils used in your soil-cement jobs?
      (1) Liquid limit:____to____
      (2) Plastic limit:____to____
      (3) Plasticity index:____to____
      (4) Shrinkage limit:____to____
   c. What chemical constituents of soils have you found harmful to soil-cement?
      (1) Organic matter: more than____%. Kinds:________
      (2) Sulfates (SO_3): more than____%. Kinds:________
      (3) Other:________
      (4) What was the nature of the harmful effects?________

(5) Have you developed successful methods of combating the harmful effects? ______________________

d. What other physical or chemical properties of soils do you use to determine suitability of soils for soil-cement (For example—pH)? ______________
e. What types of portland cement were used in your soil-cement? ____________
(1) In your experience which type(s) is most satisfactory? ____________ Why? ______________________
f. What laboratory strength and/or durability tests were used in the mix design of your soil-cement? (If tests are not standard methods please attach a detailed description of the preparation, curing, and testing of test specimens.) ______________________

g. In evaluating the results of laboratory tests of soil-cement mixtures, what criteria of strength and/or durability were used in determining cement requirements? ______________________

h. Did you use soil classification systems or other short cut procedures for determining the cement requirements for your soil-cement? (If you have established cement requirements for classification units, please attach a table showing the correlation.) ______________________

i. In your geographical area, what is the maximum cement content for soil-cement to be economically competitive with alternate methods of paving construction? (Express cement content as percentage of dry soil's weight.) ____

j. Additional remarks on mix design: ______________________

3. THICKNESS DESIGN
a. What soil-cement thicknesses were used in your jobs? (Please tie in with answers to question 1b.) ______________________

b. What method(s) of thickness design did you use for soil-cement? (Please attach detailed description of your method(s) or give references to publications.) ______________________

c. Do you use thinner construction with soil-cement than with alternate forms of construction such as macadam (rolled stone), soil-aggregate or soil-bituminous? ________. If answer is yes, please explain: ______________________

d. Additional remarks: ______________________

4. CONSTRUCTION
a. What proportion of your soil-cement was constructed by mix-in-place methods? ______%. By stationary plant methods? ______%.
b. What kinds of machines did you use for soil-cement construction?
(1) With cohesionless soils
(a) For preparing the soil-cement mixture: ______________________
(b) For compacting the soil-cement mixture: ______________________
(c) For finishing operations: ______________________
(2) With cohesive soils
(a) For preparing the soil-cement mixture: ______________________

(b) For compacting the soil-cement mixture: ____________

(c) For finishing operations: ____________

c. Are you satisfied with the capabilities of the machines used in your soil-cement construction?
(1) With cohesionless soils: ____________
(2) With cohesive soils: ____________
(3) Additional remarks on limitations and needed improvements: ____________

d. How finely did you attempt to pulverize cohesive soils before mixing with cement? ____________
e. How did you control uniformity of mixing soil and cement? ____________

f. What moisture content did you attempt to achieve in the soil-cement mixture prior to compaction? ____________
g. What density did you specify for the soil-cement? ____________
h. What field tests did you use to control moisture content and density? ____________

i. In your experience, what is the maximum compacted thickness of soil-cement that can be constructed in one lift? ____________
(1) Have you used double-lift construction? ____________
(2) If so, how thick and with what results? ____________
(3) Does soil textural type influence thickness of construction in one lift? ____________

j. What maximum time interval do you permit between completion of mixing and completion of compaction? ____________
k. Based on your experience, what are the major precautions to be observed in soil-cement construction? ____________

l. What is your construction season for soil-cement? ____________
m. What is a typical unit cost (dollars per sq. yd. of 6 inches compacted thickness) of soil-cement in your area? ____________

5. CURING
a. What methods of curing soil-cement did you use?
(1) Wet earth: ____________
(2) Wet straw: ____________
(3) Sprinkling with water: ________ Amount per application ____________
Number of applications per day ____________
(4) Paper: ____________
(5) Plastic: ____________
(6) Bituminous seal
(a) Kind(s): ____________
(b) Amount: ____________
(c) Do you wet soil-cement before applying bituminous material? ____________
If so, how much water? ____________
(d) Do you cover bituminous material with aggregate? ____________
If so, what kind(s), gradation and amount? ____________

(7) Other curing methods: ____________
b. How long did you cure soil-cement, before applying final-type wearing surface? ____________
Before opening to traffic? ____________
c. Additional remarks on curing: ____________

6. SURFACING
   a. What are your surfacing requirements for soil-cement paving? (Please give type of bituminous mix or treatment, kind and grade of bituminous material, if surface treatment or seal coat, amount of bituminous material and cover aggregate, approximate thickness of bituminous wearing surface.)
      (1) On primary roads:________________
      (2) On secondary roads:________________
      (3) On urban roads:________________
      (4) On subdivision streets:________________
      (5) On airports
         (a) Runways:________________
         (b) Taxiways:________________
         (c) Aprons:________________
      (6) On parking lots:________________
      (7) On shoulders:________________
   b. Did soil type stabilized influence the wearing surface requirements?_______
      Explain:________________

7. PERFORMANCE AND MAINTENANCE (Please attach copies of any formal reports, performance records, core strengths, in-place strengths, etc. that you may have and can release)
   a. Based on your performance and maintenance records is soil-cement a satisfactory paving material?
      (1) For primary roads
         (a) Base:_____, Subbase:_____, Shoulder:_____
      (2) For secondary roads
         (a) Base:_____, Subbase:_____, Shoulder:_____
      (3) For subdivision streets
         (a) Base:_____, Subbase:_____
      (4) For what classes of airports?________________
      (5) For airport runways
         (a) Base:_____, Subbase:_____, Shoulder:_____
      (6) For airport taxiways
         (a) Base:_____, Subbase:_____, Shoulder:_____
      (7) For airport aprons
         (a) Surface:_____, Base:_____, Subbase:_____
      (8) For parking lots
         (a) Surface:_____, Base:_____, Subbase:_____
      (9) For other use:________________
   b. Have cracks developed in your soil-cement pavements:________________
      (1) If so, what is the crack pattern?________________
      (2) How soon after construction did the cracks appear?________________
      (3) Does the crack pattern appear to be related to soil textural type stabilized?
      ____
      (4) If so, in what way?________________
      (5) Have you found that the cracking of soil-cement is detrimental to structural integrity?_____Explain:________________
      (6) Do you know of a way of eliminating or minimizing crack formation?____
      ____
      (7) Does delayed placement of the final bituminous wearing surface eliminate "reflection" cracks?________________
   c. What are the major maintenance operations required for your soil-cement pavements?________________
      ____
   d. Are your maintenance costs for soil-cement pavements very low_____, low _____, medium_____, or high_____. If possible, give typical cost per mile:
      ____

8. RESEARCH
   a. Please outline soil-cement research and development programs that you have in progress or in the planning stage.
   b. Please indicate what you consider to be needed areas of soil-cement research and development and list any available publications which deal with the properties or hardening mechanism of soil-cement.

RESPONDENTS TO QUESTIONNAIRE

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	1 a		1 b	1 b (1) Base	1 b (1) Subbase	1 b (1) Shoulder	1 b (2) Base	1 b (2) Subbase	1 b (2) Shoulder	1 b (3) Base	1 b (3) Subbase	1 b (4) Base	1 b (4) Subbase
Alabama	Yes	1940	Statistics not available	x	x	x	x	-	-	x	-	-	-
Alaska	-[31]	-	-	-	-	-	-	-	-	-	-	-	-
Arizona	Yes	Summer 1957	-	-[32]	-	Slopes ½	2.2	-	-	-	2.3	-	-
Arkansas	Yes	1938	-	26	-	-	70	-	-	3	-	-	-
California	Yes	1937	-	-[61]	-	-	-	-	-	-	-	-	-
Colorado	Yes	1953	-[97]	-[98]	-	Not for hardened base	-[99]	-	Not for hardened base	-	-	-	-
Connecticut	-[124]	-	-	-	-	-	-	-	-	-	-	-	-
Delaware	Yes	1941	30	-	-	x	x	-	-	-	-	-	-
Florida	Yes	1938	15	x	-	-	x	-	-	-	-	-	-
Georgia	Yes	Summer 1938	-	-[146]	-	-[147]	284	-	-	18	-	390	-
Hawaii	No	-	-	-	-	-	-	-	-	-	-	-	-
Idaho	Yes	1954	-	18	-	9	13	-	13	-	-	-	-
Illinois	Yes	1939	-	12.3	None	None	282	-[196]	None	791,000 sq yd	None	Inf. not avail.	-
Indiana	Yes	1941	-	-	4,700 ft	700 ft (exp)	25	-	-	-[230]	-	-[230]	-
Iowa	Yes	1937	-	65	-	-	4	-	-	-	-	-	-
Kansas	Yes	1938	-[274]	82	-	-	5	-	-	-	-	-	-
Kentucky	Yes	1938	-	-	-	-	139.7	-	-	-	-	35,125 sq yd	-
Louisiana	Yes	1939	-	33	107	36	1,234	None	4	29	None	Not applicable	-
Maine	Yes	1940	-	-	-	2,000 sq yd	7.5	-	-	-	-	-	-
Maryland	Yes	1938	-	-	-	-	12.42	-	-	-	-	-	-
Massachusetts	-[378]	-	-	-	-	-	-	-	-	-	-	-	-
Michigan	-[379]	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	Yes	1941	-	26	-	-	116.3	-	-	-	-	-	-
Mississippi	Yes	1939[414]	-	-	-[415]	-[415]	-[415]	-	-	-	-	-	-
Missouri	Yes	1936	-	85.7	-	-	7.2	-	-	-	-	-	-
Montana	Yes	July 1957	-	42.4-1¾ in.	None	Unsurfaced	6.0-2 in.	None	Unsurfaced	48.4	None	None	-
Nebraska	Yes	1939	-	77	-	-[493]	-	-	-	-	-	-	-
Nevada	Yes	1949	-[510]	6½	-	6½	2	-	2	-	-	-	-
New Hampshire	Yes	Sept. 1958	-	-	-	14 mi (19,663 sq yd)	-	-	-	-	-	-	-
New Jersey	Yes	Oct. [illegible]	-	x	x	122,011 sq yd	51,877 sq yd	x	x	x	x	x	x

New Mexico	Yes	1957	-	349 (4,915,000 sq yd)	261,000 sq yd	-	185,000 sq yd	-	-	203,000 sq yd	77,000 sq yd	-	-
New York	Yes	1946	-	3	-	-	-	-	-	-	-	-	-
North Carolina	Yes	1937	-	-	-	-	800+	-	-	-	-	-	-
North Dakota	Yes	July 6, 1955	-	20.02	-	-[618]	1.2	-	-[618]	-	-	-	-
Ohio	Yes	1939	-	-	3/4	-	116 26	-	-	-	-	-	-
Oklahoma	Yes	About 1940	-	74	None	13	14	None	None	42	None	Inf. not avail.	-
Oregon	No	-	-	-	-	-	-	-	-	-	-	-	-
Pennsylvania	Yes	1937	-	-	-	73	176	-	-	-	-	-	-
Rhode Island	No	-	-	-	-	-	-	-	-	-	-	-	-
South Carolina	Yes	Dec. 1933	-	61.9	7,8	8.6[709]	19.4	-	-[709]	2.4	-	-	-
South Dakota	No[731]	-	-	-	-	-	-	-	-	-	-	-	-
Tennessee	Yes	1938	-	125	-	3	160	-	-	-	-	-	-
Texas	Yes	(Approx.) 1938	-[754]	754	Int. Sys. 222	-	-	-	-	422	-	-	-
Utah	Yes	1940	-	119	-	8.5	x	-	40	x	x	-	-
Vermont	Yes	1953	-	-	-	-	11	-	-	-	-	1	-
Virginia	Yes	1938	-	56	22	12	260	-	-	25	-	20	-
Washington	Yes	(Experimental) 1938	-	397[636]	1[636]	-	37[636]	x[636]	8.8[636]	-	-	-	-
West Virginia	Yes	1946	-	0	0	0	85	-	-	-	-	-	-
Wisconsin	Yes	1936	-	38	-	-	-	-	-	-	-	-	-
Wyoming	Yes	1952	-[909]	269	-	-	13	-	-	16,400 sq yd	-	-	98
Australia	-[932]	-	-	-	-	-	-	-	-	-	-	-	-
Brazil	Yes	1955	-	600	-	No	-	-	Not surfaced	-	-	-	-
England	Yes	Before 1939	-	142	750,000 sq yd	-	28	No	-	71 (see B4)	No	-	No
France	Yes	1940	-	-[1036]	-[1037]	0	37.2[1038]	0[1038]	0[1038]	0	0	0	0
Germany	Yes	1936	-	Autobahn	100	-	-	-	-	10	-	500	-
The Netherlands	Yes	Apr. 1956	-	-[1094]	-	-[1095]	-	-	-	75,000 sq yd	-	No special application	-
New Zealand	-[1144]	-	-	-	-	-	-	-	-	-	-	-	-
Puerto Rico	Yes	July 1957	-	-	-	-	Municipal 1.1	-	-	-	-	-	-
West Africa	Yes	1955	-[1162]	-	-	-	-[1164]	-[1164]	-[1164]	-	-	-	-
Central Africa	Yes	1955 or earlier	-[1162]	-[1163]	-	-	-[1164]	-[1164]	-[1164]	-	-	-	-
East Africa	Yes	1959	Probably 100	-	-	-	-[1164]	-[1164]	-[1164]	-	-	-	-

For footnotes see page 186.

	1b (5)(a)			1b (5)(b)			1b (5)(c)			1b	1b (6)			1c
	Base	Subbase	Shoulder	Base	Subbase	Shoulder	Surface	Base	Subbase		Surface	Base	Subbase	
Alabama	-	-	-	-	-	-	-	-	-	-	-	-	-	-[1]
Alaska	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Arizona	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Arkansas	-	-	-	-	-	-	-	-	-	-	-	-	-	South and East.
California	-	-	-	-	-	-	-	-	-	-	-	-	-	-[62]
Colorado	-	-	-	-	-	-	-	-	-	-	-	-	-	East. ½-plains ar.
Connecticut	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Delaware	-	-	-	-	-	-	-	-	-	-	-	-	-	-[128]
Florida	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Georgia	57	-	30	35	-	-	-	177	-	Military and commercial	-	108	-	All over state
Hawaii	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Idaho	-	-	-	-	-	-	-	-	-	-	-	-	-	S.W. and S.E.
Illinois	Inf. not avail.	-	-	-	-	-	-	-	-	-	Inf. not available	-	-	Throughout the state
Indiana	-[230]	-	-	-	-	-	-	-	-	-	-	-	-	-
Iowa	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Kansas	-	-	-	-	-	-	-	-	-	-	-	-	-	Central and N.E.
Kentucky	91,250 sq yd	-	-	-	-	-	-	-	-	Secondary	-	124,300 sq yd	-	-[305]
Louisiana	Not applicable	-	-	-	-	-	-	-	-	-	-	2	-	Statewide
Maine	-	-	-	-	-	-	-	-	-	-	-	-	-	Coastal
Maryland	-	-	-	-	-	-	-	-	-	-	-	-	-	Coastal and Piedmont
Massachusetts	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Michigan	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	-	-	-	-	-	-	-	-	-	-	-	-	-	North West and South Central
Mississippi	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Missouri	-	-	-	-	-	-	-	-	-	-	-	-	-	-[447]
Montana	None	-	-	-	-	-	-	-	-	-	None	-	-	North-Central and Eastern
Nebraska	-	-	-	-	-	-	-	-	-	-	-	-	-	-[494]
Nevada	-	-	-	-	-	-	-	-	-	-	-	-	-	-
New Hampshire	-	-	-	-	-	-	-	-	-	-	-	-	-	N.E.
New Jersey	x	x	x	x	x	x	x	x	x	x	x	x	x	-[534]

New Mexico	-	-	-	-	-	-	-	-	-	-	-	-	-	Arid to mountainous
New York	-	-	-	-	-	-	-	-	-	-	-	-	-	-[878]
North Carolina	-	-	-	-	-	-	-	-	-	-	-	-	-	-[903]
North Dakota	-	-	-	-	-	-	-	-	-	-	-	-	-	South Eastern
Ohio	-	-	-	-	-	-	-	-	-	-	-	-	-	Scattered
Oklahoma	Do not participate	-	-	-	-	-	-	-	-	-	-	-	-	Western
Oregon	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pennsylvania	-	-	-	-	-	-	-	-	-	-	-	-	-	N.W.
Rhode Island	-	-	-	-	-	-	-	-	-	-	-	-	-	-
South Carolina	-	-	-[709]	-	-	-[709]	-	-	-	-	-	-	-	-[710]
South Dakota	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tennessee	25,000 sq yd	-	-	4,000 sq yd	-	-	-	6,000 sq yd	-	-	-	-	-	West.
Texas	214	-	-[753]	-	-	-	-	-	-	-	-	-	-	Statewide
Utah	-	-	-	-	-	-	-	-	-	-	-	-	-	Valleys of Wasatch Mts.
Vermont	-[758]	-[759]	-	-	-	-	-	-	-	-	-	-	-	Statewide
Virginia	11	-	-	-	-	-	-	-	-	Secondary	100,000 sq yd	-	-	Tidewater and Piedmont
Washington	-	-	-	-	-	-	-	-	-	-	-	-	-	Specific Northwest
West Virginia	-	-	-	-	-	-	-	-	-	-	-	-	-	-[878]
Wisconsin	-	-	-	-	-	-	-	-	-	-	-	-	-	Central and W. Central
Wyoming	Int. 171	-	-[910]	-	-	-	-	-	-	-	-	-	-	N. E. and S. W.
Australia	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Brazil	-	-	-	-	-	-	-	-	-	-	-	-	-	Tableland (plateau)
England	75,000 sq yd	7	-	14	No	-	50,000 sq yd	No	-	-[992]	No	50,000 sq yd	No	-[993]
France	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Germany	x[1073]	-	-	-	-	-	-	-	-	Military	-	-	-	-
The Netherlands	No application	-	-	-	-	-	-	-	-	-	-[1096]	-	-	-
New Zealand	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Puerto Rico	-	-	-	-	-	-	-	-	-	-	-	-	-	-[1143]
West Africa	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Central Africa	-	-	-	-	-	-	-	-	-	-	-	-	-	-
East Africa	-	-	-	-	-	-	-	-	-	-	-	-	-	-

For footnotes see page 186.

	1c (1)				1c (2)	2a							
	Ann. Rainfall (in.)	Winter Temp. (°F)	Sum. Temp. (°F)	Frost Pen. (in.)			2 in.	1½ in	¾ in.	⅜ in.	No. 4	No. 10	No. 40
Alabama	52	50	80	0-3	-	-	-	-	-	-	-	-	-
Alaska	-	-	-	-	-	-	-	-	-	-	-	-	-
Arizona	-	-	-	-	-	-	-	-	To 100	-	-	To 75 max	-
Arkansas	50	44	80	0-3	-	-	100	-	-	-	60-100	-	-
California	2-104	0-40	70-110	None in 95% of hghys.	Temp. extremes -20° - 115°F	-	100	90-100	50-85	-	25-45	-	No. 30 10-25
Colorado	15	32	68	22	-	-	-	-	-	-	To 100	85-100	40-90
Connecticut	-	-	-	-	-	-	-	-	-	-	-	-	-
Delaware	-	-	-	-	-	See 2B	Max size 3 in.	-	-	-	-	-	-
Florida	52	59	81	1-2	-	-	-	-	-	-	-	-	-
Georgia	50	48	80	0-6	Moderate	Class A1-A7	100	95	-	-	-	100-70	-
Hawaii	-	-	-	-	-	-	-	-	-	-	-	-	-
Idaho	13	15	80	24	-	-	-	100	-	-	50-100	50-100	-
Illinois	40	26	76	25	-	-	-	-	100-96	-	100-77	100-59	99-25
Indiana	33-45	30	75	6-40	Range from -20°F-100°F	-	To 100	To 100	94-100	(⅜) 83-100	60-100	43-100	26-99
Iowa	(Ames) 31.4	(Ames) 23	(Ames) 73	(Ames) 30 (40 max)	-[349]	-	-	-	-	-	-	-	-
Kansas	29 (range is 23 - 36 in.)	32	76	No information	-	-[275]	-	-	-	-	-	-	-
Kentucky	39	-	-	-	-	-	-	-	-	-	-	-	-
Louisiana	56.5	54.5	81.4	None	No frost action	-[314]	-[314]	-[314]	-[314]	-[314]	-[314]	-[314]	-[314]
Maine	40	20	67	12-20	-	-	-	-	-	-	50-100	-	5-50
Maryland	44.3	37.3	75.6	20	Frequent freeze-thaw cycles	-	-	-	-	-	To 100	75-100	65-90
Massachusetts	-	-	-	-	-	-	-	-	-	-	-	-	-
Michigan	-	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	33	20	70	40 in South-72 in N. W.	-	-	Represents 10 projects	-	To 100	90-100	73-100	68-100	28-100
Mississippi	50 (over 54-yr period)	39	81	-[416]	-	-	-	-	-	-	-	44-100	63-100
Missouri	40	35	77	20 except S. E.	-	-	95-100	90-100	78-100	73-100	65-100	50-100	35-100
Montana	11.67-13.90	20.5	64.3	84	-	-[473]	-	-	-	-	-	-	-
Nebraska	25-28	20-25	75-80	25-35	-	-	-	-	-	-	-	0-6	32-43
Nevada	9	20	60	0	-	-	4-8	7-16	10-22	-	35-55	40-65	12-20
New Hampshire	40	22	70	36-48	Avg snowfall = 60 in.	-	-	To 100	-	-	45-50	-	-
New Jersey	40-45	30	80	0-12	Temp. range	-	-	-	70-100	x-x	30-80	x-x	10-40

New Mexico	8-15	20-50	80-100	5-15	7°F-92°F -	-	-	100 to	80-100	-	30-60	20-45	
New York	40	20	74	40	-	-	100	-	-	-	65-100	-	-
North Carolina	50	36-48	68-80	-	Low temps. are for mountains	-	-	-	-	-	-	To 100	95-92
North Dakota	18.75	16.4	67	78	-[619]	-	-[620]	-	-	-	100 to	95-100	92-100
Ohio	38	31	72	20	-	-	86-100	81-100	60-100	-	34-100	25-100	20-100
Oklahoma	8-25	37	82	14-22	-[660]	-	-	-	-	-	-	-	95-100
Oregon	-	-	-	-	-	-	-	-	-	-	-	-	-
Pennsylvania	(N.W.) 41	26	70	25	-[680]	3 in. 100-100	-	-	-	-	91-49	83-40	61-21
Rhode Island	-	-	-	-	-	-	-	-	-	-	-	-	-
South Carolina	48	48	80	0	-	-	-	-	90-100	85-100	-	65-100	-
South Dakota	-	-	-	-	-	-	-	-	-	-	-	-	-
Tennessee	-	47	76	3-4	-	-	-	-	-	-	35-100	-	-
Texas	10-55	33-60	77-84	0-1	Relative avg humidity, 44-76	-[786]	-	-	-	-	-	-	-
Utah	14	-20-+40	60-102	18	Rapid temp. changes	-[786]	-	-	-	-	-	-	-
Vermont	-	-	-	-	-	-	100	-	-	-	55-100	-	-
Virginia	43	37	72	12	-	All soils used	-	-	-	-	-	-	-
Washington	E. 10, W. 60[837]	E. 33 W. 41[837]	E. 70 W. 62[837]	E. 32 W. 20[837]	-[838]	-[839]	-	To 100	90-100	65-90	40-75	30-60	13-36
West Virginia	56	30-38	68-76	9	-	-	67.1-100.0	59.6-100.0	35.5-99.9	18.5-99.6	9.5-99.9	4.8-99.9	1.8-96.8
Wisconsin	30	22	70	48	-	-	-	-	-	-	100	77-100	26-85
Wyoming	15	27	85	36	Subject to quick changes	-	-	(1-inch) to 100	To 94	-	100-41	99-30	71-18
Australia	-	-	-	-	-	-	-	-	-	-	-	-	-
Brazil	55	62	72	0	-[970]	-	-	-	-	-	To 100	80-100	60-90
England	25-35	43 (Nov.-Apr.)	55 (May-Oct.)	-	-	Coarse-grained soils only	35-100	80-100	65-100	55-100	40[994]	30[994]	15[994]
France	29.5	32	68	19.7	-	-[1039]	-	-	-	-	-	-	-
Germany	30	31	62	0-50	-	-	0-20	0-30	0-40	0-50	0-60	0-75	0-85
The Netherlands	30 (760 mm)	36	62	27	-[1097]	-[1098]	-[1099]	-[1099]	-[1099]	-[1099]	-[1099]	-[1099]	-[1099]
New Zealand	-	-	-	-	-	-	-	-	-	-	-	-	-
Puerto Rico	74	70	77	-	Tropical region	Grain size analysis: 81% fine gravel and sand, 19% silt-clay; AASHO Classification A-1-b (0)							
West Africa	-[1165]	Also vary	Also vary	-	-[1166]	-[1167]	100[1167]	90-100[1167]	70-100[1167]	55-100[1167]	40-95[1167]	30-90[1167]	15-80[1167]
Central Africa	-[1165]	Also vary	Also vary	-	-[1166]	-[1167]	100[1167]	90-100[1167]	70-100[1167]	55-100[1167]	40-95[1167]	30-90[1167]	15-80[1167]
East Africa	-[1165]	Also vary	Also vary	-	-[1166]	-[1167]	100[1167]	90-100[1167]	70-100[1167]	55-100[1167]	40-95[1167]	30-90[1167]	15-80[1167]

For footnotes see page 186.

	2a (continued)					2b	2b (1)	2b (2)	2b (3)	2b (4)	2c	2c (1)		2c (2)		2c (3)	2c (4)	2c (5)
	No. 100	No. 200	0.074 mm	0.005 mm	0.001 mm							%	Kinds	%	Kinds			
Alabama	-	-	-	-	-	A-2-A-4 soils	-	-	-	-	-	-	-	-	-	-[2]	-[3]	-[4]
Alaska	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Arizona	-	3-20	-	-	-	-	To 35	-	To 15	-	-	-	-	-	-	-	-	-
Arkansas	-	10-90	-	-	-	-	35 to NP	-	10 to NP	-	-	-	-	-	-	-	-	-
California	-	2-9	-	-	-	-	Not used for control	-	-	-	-	Unknown	-	0.2	-[63]	-	-[64]	-[65]
Colorado	20-40	10-30	-	-	-	-	None to 35	NP to 18	NP to 8	Not determined	-	-	-	-	-	-[100]	-	-
Connecticut	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Delaware	-	To 95	-	-	-	-[126]	-[126]	-[126]	-[126]	-[126]	-	-	-	-	-	-	-[127]	-
Florida	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Georgia	-	Chert 70, Reg. 45	Don't use	-	-	-	To 40	-	To 20 (normal = 12)	-	-	12-20	Acid	-	None	-	-[148]	-[149]
Hawaii	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Idaho	-	5-15	Unknown	-	-	-	20 to 40	-	0 to 5	-	-	Unknown	-	-	-	-	-	-
Illinois	98-2	96-1	Not avail.	-	-	-	NP to 54	NP to 29	NP to 25	-	-	-	None	-	None	-	-	No[197]
Indiana	-	5-97	5-97	1-72	0-23	-	14 to 43	14 to 26	NP to 22	10 to 21	-[231]	-	-	-	-	-	-	-
Iowa	-	-	-	-	-	-	-	-	-	-	-[230]	-	-	-	-	-	-	-[231]
Kansas	-	-	-	-	-	-	15 to 50	15 to 25	0 to 30	Not determined	No information	-	-	-	-	-	-	-
Kentucky	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Louisiana	-[314]	-[314]	Approx. to 100	To 35	To 25	-	0 to 40	0 to 30	0 to 20	Not used	-	App 8	Rotted veget.	-	-	-	-[315]	No
Maine	-	1-5	-	-	-	-	-	-	-	-	-	3	-	-	-	-	Non-hardening	-
Maryland	-	15-50	16-20	10-15	3-9	-	13 to 25	13 to 20	0 to 5	14 to 28	-	None	-	-	-	-	-	-[336]
Massachusetts	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Michigan	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	9-99	6-96	8-72[330]	2-19[330]	-	-	21 to 49	18 to 25	0 to 25	20 to 23[331]	-	-	-	-	-	-	-	-
Mississippi	12-95	8-90	8-90	3-35	0-7	-	18 to 35	14 to 20	0 to 15	-	-	-	-	-	-	-	-	-
Missouri	25-100	18-96	18-96	11-26	3-15	-	14 to 42	NP to 21	NP to 23	12 to 20	-	-	No data	-	No data	-	-	-
Montana	-	-	-	-	-	-	20 to 35	-	3 to 10	x to x	-	-	-	0.25	Na_2SO_4	-[474]	Loss in durability	No[475]
Nebraska	54-80	62-90	33-77	30-11	16-5	-	17 to 34	12 to 24	5 to 10	-	-	No data	-	-	-	-	-	-
Nevada	-	4-12	-	-	-	-	16 to 40	-	0 to 12	-	-	None found	-	-	-	-	-	-
New Hampshire	-	3-5	-	-	-	-	-	-	NP	-	-	-	-	-	-	-	-[519]	-[520]
New Jersey	x-x	4 5-12	Not used x	x	x	Not used	x	x	x	x	-	None	-	None	-	None	None	-
New Mexico	-	4-12	-	-	-	-	25 or	-	6 or less	-	-	-	-	-	-	-	-	-

New York	-	Max 20	-	-	-	-	less 0 to 30	NP to 20	0 to 10	-	-	400PPM	-	-	-	-[576]	-[576]	-[577]
North Carolina	-	45-72	-	-	-	-	35 to 65	-	13 to 31	12 to 20	-	Quan not determ	-	-	-	-	Retarded hardening	No
North Dakota	-[621]	34-36	34-36	6-13	5-8	-	19 to 22	-	NP	-	-	-	-	-	-	-	-	-
Ohio	-	10-100	-	-	-	-	48 to non-plastic	22 to non-plastic	26 to non-plastic	-	-	-	-	-	-	-	-	-
Oklahoma	-[661]	-	-	-	-	-	19 to 28	-	0 to 10	-	-[662]	-	-	-	-	-	-	-
Oregon	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pennsylvania	-	33-8	(0.05)-28-4	14-2	-	-	20 to 30	-	0 to 10	-	-	-	-	-	-	-	-[681]	No[682]
Rhode Island	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
South Carolina	-	17-80	-	-	-		17 to 45	8 to 30	9 to 33	10 to 30	-	-	-	-	-	-[711]	-[712]	-[713]
South Dakota	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tennessee	-	3-80	-	-	-	-	25 to 40	20 to 30	0 to 20	-	-	-	-	-	-	-	-	-
Texas	-	-	-	-	-	-	20 to 40	15 to 18	2 to 25	15 to 18	-	None	-	-	-	-	-	-
Utah	-	-	-	-	-	-	-	-	-	-	-	Not studied	-	-	-	-	-[767]	-
Vermont	-	0-35	0-35	-	-	-	To 40	-	0 to 10	-	-	-[790]	-[790]	-[790]	-[790]	-[790]	-[791]	Yes[792]
Virginia	-	-	-	-	-	-	14 to 60	NP to 45	NP to 30	-	-	-	Not measured	-	Not measured	-	-[813]	-[814]
Washington	-	3-15	Not determined	-	-	-	To 30	To 25	0 to 10	-	-	250PPM	Not determined	?	?	-	-[840]	-[841]
West Virginia	1.1-75 4	0 8-71.2	0 8-71 2	1 4-22 3	1 4-10 5	-	2 4 to 40.7	15 2 to 24 8	1 6 to 20.5	14 8 to 17 6	-	-	All	-	-	-[876]	Weak bonding	-[877]
Wisconsin	14-60	9-45	9-45	1-15	0-5	-	12 to 25	-	NP	-	-	Pl 4 (ASTM C40)	-	-	-	-	-[896]	-[897]
Wyoming	-	12-10	-	-	-	-	25 to 20	NB to 18	NP to 7	-	-	None	None yet	None	None yet	-	-	-
Australia	-	-	-	-	-	-	-	-	-	-	-	-	-	-	$CaSO_3$	-	-[933]	No[934]
Brazil	-	20-50	-	-	-	-	15 to 30	-	0 to 12	-	-	-	Not determined	-	-	-	-[971]	-[972]
England	-	-	-[995]	-	-	-	0 to 45	0 to 22	-	Not perf as std. test	-	1 0	-[996]	0.2	-[997]	None	-[998]	-[999]
France	-	-	-	-	-	-	-	-	Less than 10	-	-	None	-	-	-	-	-	-
Germany	0-90	0-100	0-100	-	-	-	0 to 50	0 to 30	0 to 20	-	-	1-2	Humic acid, peat	Not found in soils used	-	-	-[1074]	$CaCl_2$ used (2(c)1)
The Netherlands	-[1099]	-[1099]	-[1100]	-[1100]	-[1100]	-	-[1101]	-[1101]	-[1101]	-[1101]	-[1102]	-[1102]	-[1102]	-[1102]	-[1102]	-[1102]	-[1102]	-[1102]
New Zealand	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Peuto Rico						-	-	-	6 max	-	-	-	-	-	-	-	-	-
West Africa	10-65[1167]	8-55[1167]	7-50[1167]	5-35[1167]	-	-	NP to 55	NP to 25	NP to 30	?	-	-	-	-	-	Micaceous soils	-[1168]	-[1169]
Central Africa	10-65[1167]	8-55[1167]	7-50[1167]	5-35[1167]	-	-	NP to 55	NP to 25	NP to 30	?	-	-	-	-	-	Micaceous soils	-[1168]	-[1169]
East Africa	10-65[1167]	8-55[1167]	7-50[1167]	5-35[1167]	-	-	NP to 55	NP to 25	NP to 30	?	-	-	-	-	-	Micaceous soils	-[1168]	-[1169]

For footnotes see page 186.

	2 d	2 e	(1)	Why?	2 f	2 g	2 h	2 i	2 j	3 a	3 b	3 c	3 d	4a	
Alabama	-[5]	I	I	-[6]	-[7]	-[8]	-[9]	-[10]	-	-[11]	-[12]	-[13]	-	100	-
Alaska	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Arizona	-	I and II	No diff. apparent	-	-[33]	-[34]	No	-	-	6 in	-[35]	No	-	90±	-
Arkansas	-	I	-	-	-[46]	-[47]	No	14%	-	-[48]	-	No	-	100	-
California	Sand equiv. test	-[66]	II	-[67]	-[68]	-[69]	No	-[70]	-	-[71]	-[72]	Yes[73]	-	Est. 75[74]	Est 25
Colorado	-	I	Not investigated	-	400 psi at 7 days	400 psi at 7 days	-[101]	7%	-	6 in. on all proj.	-[102]	Yes[103]	-	100	-[97]
Connecticut	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Delaware	-	-	-	-	-[128]	See 3b	No	7-10%	-	-[129]	-[130]	-[131]	-	100	-
Florida	-	I	-	-	-[147]	-[148]	No	Approx 14%	-	-[149]	-	-	-	90	10
Georgia	None	Normal	Normal-availability	Economics	-[150]	-[151]	No	10-12%	-	-[152]	Experience	No	-	80	20
Hawaii	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Idaho	-[173]	I	I	-	-[174]	-[175]	No[176]	-[177]	-	-[178]	R values	No[179]	-	5	2
Illinois	None	I and IA	No preference	-	-[198]	-[199]	Yes[200]	-[201]	-	-[202]	-[203]	No	-	100	1 job
Indiana	No problem	Normal Type I	-[232]	-	-[233]	-[234]	No short cuts	Probably 12%	-	-[235]	-[236]	Yes[237]	-	All	-
Iowa	None	I	Have only used Type I	-	Standard	-[252]	-[253]	-[254]	-	4-7 in.[255]	-[256]	No	-	100	None
Kansas	None	I	-	-	-[276]	-[277]	-[278]	No information	-	-[279]	-[280]	Yes[281]	-	100	-
Kentucky	-	-	-	-	Freezing and thawing	-[306]	-	-[307]	-	6 in.	-	-	-	100	-
Louisiana	None	I reg.	I	-[316]	-[317]	-[318]	-[319]	-[320]	-[321]	-[322]	-[323]	No	-	(All) 100	0
Maine	None	II and II-A	Unable to answer	-	-[342]	PCA tests and compression	Only those in PCA	-[343]	-[344]	-[345]	-[346]	No	-	100	-
Maryland	-[357]	I	-	-	-[358]	AASHO and PCA Stds	No	11 5%	-	6-in compacted base	PCA recommodations	-[359]	-	100	0
Massachusetts	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Michigan	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	None	I	-	-	-[382]	-[383]	No	-[384]	-	-[385]	-[386]	Yes[387]	-	83	17
Mississippi	-	I	-	-	-[417]	500 lb psi at 7-day age	-[418]	-[419]	-[420]	-[421]	-	-[422]	-	100	-
Missouri	-	-[448]	-	-	-[449]	-[450]	No	12%	-	6 in on all jobs	-[451]	-[452]	-	100	-
Montana	-	I	I	It is cheaper	-[476]	-[477]	No	6%	-	-[478]	-[479]	Yes-approx. 3-5	-	12	88
Nebraska	No data available	I	-	Exper with only one type	-[495]	-[496]	No	Not avail	-	-[497]	-[498]	Yes[499]	-	100	0
Nevada	-	I	-	-	-[511]	-[512]	No	3½%	-	6 and 8 in	-[513]	No	-[514]	100	-
New Hampshire	-	I and II	No choice	-	-[521]	-[522]	No	Not determined	-	-[523]	-[524]	No	-	0	100
New Jersey	None	I and II	Either	-	-[535]	See 2f	See 2f	14%	None	All at 6 in.	PCA's	No[536]	None	100	0
New Mexico	-[549]	I	-	-	-[550]	-[551]	No	-[552]	-	-[553]	-[554]	Yes[555]	-	95	5

New York	-[578]	II also IS	II[579]	-	-[580]	-[581]	-[582]	12%	-[583]	Std 6 in	Experience	No	-[584]	100	-
North Carolina	Durability tests only	I and II	Either	-	-[604]	-[605]	-[606]	About 12% by vol.	-	6-8 in mostly 6 in	-[607]	See 3(b)	-	100	-
North Dakota	-	I and IA	No noticeable diff	-	-[622]	-[623]	No[624]	Less than 8%	-	6 in compacted	PCA recommendations	Yes[625]	-	100	-
Ohio	-	-[642]	No diff found in lab spec	No field evaluation	-[643]	-[644]	-[645]	-[646]	-	-[647]	-[648]	-	-	100	0
Oklahoma	-	I	Type I exclusively	-	-[663]	-[664]	No correlation made presently	9% by weight	-	-[665]	-[666]	No	-	100	-
Oregon	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Pennsylvania	-[683]	-[684]	-	-	-[685]	-[686]	-[687]	12%	-	-[688]	-	Yes[689]	-	100	-
Rhode Island	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
South Carolina	-	-[714]	-	-	-[715]	-[716]	No	Unknown	-	-[717]	-	No	-	100	-
South Dakota	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tennessee	None	I	Only type used	-	Std AASHO test	-[732]	No	12-13%	-[733]	-[734]	-[734]	Yes[735]	-	98	2
Texas	None	Normal only	-	-	-[757]	Unconfined compression	No	Variable	-	5-8 in	-[758]	-[759]	-[760]	75	25
Utah	-	I	I	Gives required strength	Std AASHO methods	-[768]	No	2-6%	-	-[769]	-[769]	-[769]	-	80	20
Vermont	None at present	I, II, IIA	It does not matter	-	-[793]	-[794]	No	-[795]	-	6-in depth	None	No[796]	-	100	0
Virginia	None	I and II	No diff experienced	-	-[815]	Same as f	No	14% by vol	-	-[816]	-[817]	No	-	100	None
Washington	None	I, II (occasionally III)	No diff in performance	-	-[842]	-[843]	No	5-7%	Blending sand	-[844]	6 in (standard)	Yes[845]	-[846]	55 see (3)(d)	45 see (3)(d)
West Virginia	pH meter	I	Only type used	-	-[878]	-[879]	-[880]	About 8%	-	1b(2) base 6 in	-[881]	Yes[882]	-	100	0
Wisconsin	None	I	-	-	-[898]	-[899]	No	-[900]	-	5 and 6 in	Judgment	Not to date	-	-	-
Wyoming	-[911]	I	I	-[912]	-[913]	-[914]	-	Varies 6-12%	-	-[915]	-[916]	-[917]	-	7	93
Australia	-[935]	Normal	Normal	-[936]	-[937]	-[938]	-[939]	Less than 10%	-[940]	-[941]	-[942]	Yes[943]	-	100	Negligible
Brazil	-	Low-alkali	-	-	-[973]	-[974]	No	12%	-	-[975]	-[976]	-[977]	-	100	0
England	-[1000]	-[1001]	-[1002]	-[1002]	-[1003]	-[1004]	-[1005]	10-15% by wt dry soil	-	-[1006]	-[1007]	No	-	60	40
France	-	-[1040]	-[1040]	-[1040]	-[1041]	-[1042]	No	-[1043]	-[1044]	-[1045]	-[1046]	-[1047]	-[1048]	100	0
Germany	-[1075]	-[1076]	Z275, organic matter	Slag cement less expensive	-[1077]	-[1078]	-[1079]	7-20%	-	-[1080]	Experience	-	-	95	5
The Netherlands	-[1102]	-[1102, 1103]	-[1102, 1103]	-	-[1104]	-[1104]	-[1105]	-[1106]	-[1107]	-[1108]	-[1109]	-[1110]	-[1111]	-[1112]	-[1112]
New Zealand	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Puerto Rico	Moist -Den relationship	I	-	-	-[1146]	-[1147]	-[1148]	8% by vol	-[1149]	-[1150]	-[1151]	Yes[1152]	None	100	-
West Africa	-[1170]	-[1171]	Normal portland	-[1172]	-[1173]	-[1174]	-[1175]	-[1176]	-	-[1177]	-[1178]	No	-	-[1179]	-
Central Africa	-[1170]	-[1171]	Normal portland	-[1172]	-[1173]	-[1174]	-[1175]	-[1176]	-	-[1177]	-[1178]	No	-	-[1179]	-
East Africa	-[1170]	-[1171]	Normal portland	-[1172]	-[1173]	-[1174]	-[1175]	-[1176]	-	-[1177]	-[1178]	No	-	-[1179]	-

For footnotes see page 186.

	4b						4c			4d	4e	4f
	(1)(a)	(1)(b)	(1)(c)	(2)(a)	(2)(b)	(2)(c)	(1)	(2)	(3)			
Alabama	Rotary mixers	-[14]	Clipped by patrol blade	Not included	-	-	Yes	-	-	-	-[15]	-[16]
Alaska	-	-	-	-	-	-	-	-	-	-	-	-
Arizona	-[36]	-[37]	Motor grader	Same as (1)(a)	-[38]	Motor grader	No	No	-[39]	Not specified	Not specified	Optimum moisture
Arkansas	-[49]	-[50]	-[51]	Same as (1)(a)	Same as (1)(b)	Same as (1)(c)	Yes	-[52]	-	-[53]	Visual inspection	Optimum of mixture
California	-[75]	-[76]	-[77]	-[78]	-	-	-[79]	See 4b(2)	-[80]	See 4b(2)	-[81]	-[82]
Colorado	-[104]	-[105]	-[106]	Woods roadmixer	-[107]	-[108]	No	No	-[109]	-[110]	-[111]	-[112]
Connecticut	-	-	-	-	-	-	-	-	-	-	-	-
Delaware	Pettibone wood	Pneumatic tired	Grader steel wheel roller	-	-	-	Yes	-	-	-	-[132]	Within 10% of opt.
Florida	-[140]	-[141]	Motor graders and rollers	-[140]	-[141]	Motor graders and rollers	-	-	-	-[142]	-	-[143]
Georgia	-[153]	-[154]	-[155]	-[156]	Sheepsfoot	-[155]	Yes	Yes	-[157]	80% pass. No. 4	Visual inspection	Optimum ±10%
Hawaii	-	-	-	-	-	-	-	-	-	-	-	-
Idaho	-[180]	-[181]	-[182]	-[183]	-	-	-[184]	-	-	-	-[185]	-[186]
Illinois	-[204]	-[205]	-[206]	-[207]	-[208]	-[208]	Yes	Yes	-[209]	-[210]	-[211]	-[212]
Indiana	-[238]	-[239]	-[240]	Same as (1)(a)	-[241]	Same as (1)(c)	Reasonably	Reasonably	-	-[242]	Visual inspection	Optimum
Iowa	-[257]	-[258]	-[259]	-[260]	-[261]	Same as (1)(c)	Yes	Yes	-	100%-1 in 80%-No. 4	-[262]	-[263]
Kansas	-[282]	-[283]	-[284]	-[285]	-[286]	-[284]	Yes	Yes	-	-[287]	-[288]	-[289]
Kentucky	-[308]	-[309]	-[310]	-	-	-	-	-	-	-	-	Std. proctor opt.
Louisiana	-[323]	-[324]	Blade and rubber tired rollers	Same as (1)(a)	Same as (1)(b)	Same as (1)(c)	Yes	Yes	-[325]	-[326]	-[327]	Opt. or 1-2% higher
Maine	-[347]	-[348]	Smooth wheel	-[347]	-	-	Yes	-	-	-[349]	-[350]	Opt. of AASHO std.
Maryland	-[360]	-[361]	-[362]	Same as (1)(a)	Same as (1)(b)	Same as (1)(c)	Yes	Yes	-	-[363]	-[364]	Opt. or slightly above
Massachusetts	-	-	-	-	-	-	-	-	-	-	-	-
Michigan	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	-[388]	-[389]	-[390]	-[391]	-	-	-[392]	Generally satisfied	-[393]	-[394]	-[395]	-[396]
Mississippi	-[423]	-[424]	-[425]	-[426]	-[427]	-[428]	Yes	-[429]	-[430]	-[431]	-[432]	1/10 above or below opt.
Missouri	-[453]	-[454]	-[455]	-[456]	Sheepsfoot rollers	-[457]	-[458]	-[459]	-	80% pass No. 4 sieve	-[460]	About 1% above opt.
Montana	-[480]	-[481]	-[482]	Same as (1)(a)	Same as (1)(b)	Same as (1)(c)	Yes	Yes	-	-[483]	Mixing time and appearance	Optimum
Nebraska	-[500]	-[501]	-[502]	-[503]	-[504]	-[502]	No	-	-	75% to pass No 4 sieve	Not available	-[505]
Nevada	-[515]	-[516]	Blader	Blader preparizer	-[517]	Blader	Yes	Yes	-	Wood preparizer	Windrows	Optimum
New Hampshire	-[525]	-[526]	-[527]	-	-	-	Not fully	-	-[528]	-	-[529]	Opt. was 9.8%
New Jersey	-[537]	-[538]	-[539]	Same	Same	Same	-	Yes	None	95% to pass No 4 sieve	-[540]	-[541]
New Mexico	-[556]	-[557]	Blading and	-[558]	-[559]	Blading and	Yes	-[560]	-	-[561]	-[562]	Bet. opt. and

			pneumatic rolling			pneumatic rolling						3% below
New York	Seaman pulvimixer	-[585]	-[586]	Seaman pulvimixer	-[587]	-[586]	Yes	Yes	-[588]	-[589]	-[590]	±2% of opt.
North Carolina	-[608]	-[609]	-[610]	P and H mixers	-[609]	-[610]	Yes	Yes	-	80% passing No. 4 sieve	Visual	Opt or slightly above
North Dakota	-[626]	Sheepsfoot roller	-[627]	-	-	-	Yes	No experience	-[628]	-[629]	-[630]	-[631]
Ohio	-[649]	Tamping and pneu. roll.	-[650]	Same as (1)(a)	Same as (1)(b)	Same as (1)(c)	-[651]	Same as 4 c (1)	-[652]	80% passing No. 4 sieve	Visual observation	Opt. Moisture
Oklahoma	-[657]	-[658]	-[659]	These soils not used	-	-	Yes	Not used	-	80% passing No. 4 sieve	-	±2% of opt.
Oregon	-	-	-	-	-	-	-	-	-	-	-	-
Pennsylvania	-[690]	-[691]	-[692]	-[693]	-	-	No	-	-[694]	-	-[695]	-[696]
Rhode Island	-	-	-	-	-	-	-	-	-	-	-	-
South Carolina	-[718]	-[718]	-[718]	-[719]	-[720]	Road machine	-	-[721]	-	-[722]	-[723]	-[724]
South Dakota	-	-	-	-	-	-	-	-	-	-	-	-
Tennessee	-[736]	-[737]	-[738]	P and H stabilizer	Sheepsfoot roller	-[739]	Yes	Yes	-	-[740]	-[741]	-[742]
Texas	Various mixers	-[751]	Rubber-tired rollers	Same as (1)(a)	Same as (1)(b)	Same as (1)(c)	Yes	Yes	-	-	-	Optimum
Utah	-[770]	-[771]	-[772]	Same as (1)(c)	-	-	-[773]	-[773]	-	-[774]	-[775]	-[776]
Vermont	Seaman mixer	-[797]	Power grader	-	-	-	Yes	-	-[798]	-	-[799]	Optimum
Virginia	-[818]	All types of rollers	-[819]	Same as (1)(a)	-[820]	Same as (1)(c)	Yes	-[821]	-	-[822]	Visual inspection	± 1% of opt.
Washington	-[847]	-[848]	-[849]	-[850]	Steel wheel rollers	-[851]	-[852]	No use since 1947	-	(attempt) Pass. No. 4 sieve	-[853]	-[854]
West Virginia	-[883]	-[884]	-[885]	Same as 4b(1)	Same as 4b(1)	Same as 4b(1)	Yes	Yes	-	No. 10 sieve	-[886]	Optimum
Wisconsin	-[901]	-[902]	Blades and rollers	-	-	-	-	-	-	-	-	Opt. to opt. + 2%
Wyoming	-[918]	-[919]	Patrol, pneu and steel	-[920]	-	-	Yes	-	-[921]	-	-[922]	Optimum
Australia	-[944]	-[945]	-[946]	-[947]	-[948]	-[949]	Yes	-[950]	-	-[951]	-[952]	Not less than opt.
Brazil	-[978]	-[979]	-[980]	-	-	-	No	-	-[981]	-[982]	By the color (visual)	Std. proctor +1%
England	-[1008]	-[1009]	-[1010]	-[1011]	-[1012]	-[1010]	-[1013]	-[1013]	-[1014]	-[1015]	-[1016]	-[1017]
France	-[1049]	-[1050]	Pneumatic compactors	Not used	-	-	-[1051]	Not used	-	-[1052]	-	-[1053]
Germany	-[1081]	Normal comp equip.	Motor gradar	-[1081]	-	-	Yes	Yes	-	100% smaller ¾ in.	Compres. strength	-[1082]
The Netherlands	-[1112]	-[1112]	-[1112]	-[1113]	-[1113]	-[1113]	-[1114]	-[1114]	-[1114]	No experience	-[1115]	-[1116]
New Zealand	-	-	-	-	-	-	-	-	-	-	-	-
Puerto Rico	-[1153]	-[1154]	-[1155]	Not applicable	-	-	Yes	-	-	Thoroughly pulverized	By eye	From 2 to 3% above opt.
West Africa	-[1180]	-[1181]	-[1182]	-[1183]	-[1181]	-[1181]	No comment	No comment	-[1184]	-	Visual inspection	-[1185]
Central Africa	-[1180]	-[1181]	-[1182]	-[1183]	-[1181]	-[1181]	No comment	No comment	-[1184]	-	Visual inspection	-[1185]
East Africa	-[1180]	-[1181]	-[1182]	-[1183]	-[1181]	-[1181]	No comment	No comment	-[1184]	-	Visual inspection	-[1185]

For footnotes see page 186.

	4g	4h	4i				4j	4k	4l	4m
				(1)	(2)	(3)				
Alabama	Standard AASHO	Field moisture density tests	-[17]	Not for soil cement	-	Yes	6 hr	-[18]	-[19]	-[20]
Alaska	-	-	-	-	-	-	-	-	-	-
Arizona	95%	AASHO Method T-99	6	No	-	-[40]	2 hr	-	-[41]	-[42]
Arkansas	95%	AASHO T-99	-	No	-	-	2 hr	-[64]	Apr 1-Sept 30	0.80-0.90/sq yd
California	95% of lab. spec.	-[63]	6 in. (sometimes 8 in.)	Yes	Two 4-in. layers, satisfactory	Perhaps[64]	2 hr	-[65]	-[66]	-[67]
Colorado	96% of max den.	-[113]	-[114]	No	-	No experience	2 hr	-[115]	-[116]	0.71
Connecticut	-	-	-	-	-	-	-	-	-	-
Delaware	95%	Field moist. and sand cone	7	No	-	Possibly	2 hr	-[133]	Open to conditions	0.26
Florida	95% of standard	-[144]	-	-	-	-	-	-[145]	Year round	-
Georgia	100% T 99	-[158]	6 in. cohesive 8 in. cohesionless	Yes	2 at 4 in., good	Yes	Uninterrupted finish	-[159]	All year	-[160]
Hawaii	-	-	-	-	-	-	-	-	-	-
Idaho	96% min.	Washington Densometer	6	No	-	Don't know	4 hr	-[187]	-[188]	-[189]
Illinois	94% max.	-[213]	8	Yes	-[214]	Not up to 8 in.	-[215]	-[216]	-[217]	1.10-1.50
Indiana	95% of std. max dry den	-[243]	Exp. limited to 6 in.	No	-	Not enough exp. to answer	2 hr	-[244]	-[245]	Present, 1.00/sq yd
Iowa	90% std proctor	-[264]	7	-[265]	-[266]	No	-[267]	-[268]	Mid Apr - mid Oct.	-
Kansas	95% of std.	-[290]	6	Yes	-[291]	No	-[292]	-	-[293]	-[294]
Kentucky	98%	Rubber balloon and sand density	8	No	-	-	2 hr	-[311]	Apr 1-Nov 15	-
Louisiana	100% std. proctor	-[328]	-[329]	Once	-[330]	Yes [331]	-[332]	-[333]	-[334]	-[335]
Maine	95% max of AASHO std.	-[361]	Only tried 6 in.	-	-	-	6 hr	-[362]	Apr-Sept	-[363]
Maryland	100% of std.	-[365]	-[366]	No	-	No	2 hr	-[367]	Apr-Oct	-[368]
Massachusetts	-	-	-	-	-	-	-	-	-	-
Michigan	-	-	-	-	-	-	-	-	-	-
Minnesota	-[397]	-[398]	-[399]	Yes	-[400]	Does not	-[401]	-[402]	about May 15 to Oct 15	0.93 /sq yd
Mississippi	Within 5 lb. of T-99 den.	-[433]	6	No	-	Yes	2 hr	-[434]	40 F in shade and rising	1.30 (Approx) on late jobs
Missouri	-[461]	ASTM D558-57	6	No	-	Think so, no exp.	2 hr	-[463]	Apr 1-Nov 1	0.80 ± /sq yd
Montana	96% of AASHO T 134	Washington Densometer	0.70 ft	No	-	-	-[484]	-	-[486]	-
Nebraska	AASHO T 99—max	Moist. and den. tests	6	No	-	-	4⅘ hr	-[506]	May-Nov	1.50-1.70
Nevada	-	Usual as compaction	6	Yes	8 in.—good	Yes	1⅘ hr	Too many	Summer	-
New Hampshire	125 lb cu ft dry wt	AASHO T 99	6	-	-	Yes	30 min	-[530]	Apr-Oct	1.90 /sq yd
New Jersey	95% proctor	Visual and ASTM	6	No	None	Yes	-[542]	-[543]	Apr 1-Dec 1	-[544]
New Mexico	At least	Proctor, Washington	6	Yes	-[563]	Yes	2 hr	-[564]	-[564]	-[564]

New York	95% of max Min. of 95% of std. AASHO	Densometer -[591]	6	No	-	Not with us	2 hr	-[592]	Apr 15-Oct 15	-[593]
North Carolina	AASHO T-99	-[611]	8	Yes	6 in. layers successful	No	6 hr	-[612]	-[613]	-[614]
North Dakota	-[632]	AASHO Method T-134	6 in., no other exp.	No	-	-	2 hr	-[633]	-[634]	-[635]
Ohio	-[653]	-[654]	6	No	-	-	6 hr	-[655]	May 1-Oct 15	-[656]
Oklahoma	Std. proctor	-[670]	8	No	-	-	30 min after water is added	-	All year	0.77/sq yd at 8% by vol
Oregon	-	-	-	-	-	-	-	-	-	-
Pennsylvania	-[697]	AASHO Method T-147	-[698]	Yes	-[699]	-	2 hr	-[700]	May- end Oct	-[701]
Rhode Island	-	-	-	-	-	-	-	-	-	-
South Carolina	Maximum compaction	-[725]	6	Yes	11 in. — poor results	-	About 8 hr	-[726]	May-Oct	-
South Dakota	-	-	-	-	-	-	-	-	-	-
Tennessee	98% of lab. den.	-[743]	8	Yes	4 and 5 in. each lift	Yes[744]	4 hr	-[745]	-[746]	1.00/sq yd approx
Texas	95% AASHO	-[762]	8	No	-	Yes	2 hr	-[763]	All year	0.75
Utah	95% of T-99	Std. procedures T-147	8	No	-	Yes	-[777]	-[777]	June 1-Oct 30	-[778]
Vermont	-[800]	-[801]	6	No	-	No	2 hr	-[802]	-[803]	-[804]
Virginia	100% of proctor den.	-[833]	-[834]	Yes	Two, 6 in. layers, good	Yes	2 hr	-[835]	Approx Apr 1 thru Dec 1	0.90
Washington	-[855]	-[856]	8 in. experiment	Yes	-[857]	Not known	2 hr	-[858]	Apr-Oct	-[859]
West Virginia	95% of max	-[867]	6	No	-	-	-[868]	-[869]	Apr 15-Oct 15	0.60
Wisconsin	95% of AASHO T-99	-[903]	-	-	-	-	-	-[904]	-[905]	-
Wyoming	95% of std. AASHO	-[923]	8	No	-	Yes	2 hr	-[924]	May-Oct 1	-[925]
Australia	100% of std. AASHO	-[953]	6	Yes	8-12 in. satisfactory	Not observed	-[954]	-[955]	-[956]	-[957]
Brazil	Std. proctor	-[983]	6	No	-	-[984]	6 hr	-[985]	No special	-[986]
England	95% -[1018]	-[1019]	8	Yes	-[1020]	Not greatly	-[1021]	-[1022]	-[1023]	0.85
France	-[1054]	-[1055]	-[1056]	Rarely	-[1057]	Yes	½ hr	-[1058]	-[1059]	-[1060]
Germany	98% std. proctor	-[1063]	(6 in. Seaman) 8 in.	Sometimes	9-10 in. good	Yes	-[1064]	-[1065]	Apr-Nov	0.80-1.20
The Netherlands	-[1117]	-[1118]	-[1119]	-[1120]	-[1120]	-[1121]	-[1122]	-[1123]	-[1124]	-[1125]
New Zealand	-	-	-	-	-	-	-	-	-	-
Puerto Rico	95% max den or more	Std. moist. den. tests	6	No	-	I don't think so	-[1156]	-[1157]	The year round	2.00/sq yd
West Africa	Varies	-[1186]	NA	1 example pre-mix	2 x 6 in., OK	?	-[1187]	-[1188]	-[1189]	-[1190]
Central Africa	Varies	-[1186]	NA	1 example pre-mix	2 x 6 in., OK	?	-[1187]	-[1188]	-[1189]	-[1190]
East Africa	Varies	-[1186]	NA	1 example pre-mix	2 x 6 in., OK	?	-[1187]	-[1188]	-[1189]	-[1190]

For footnotes see page 186.

	5a				5a		5a		5a		5a	
	(1)	(2)	(3)	Amount per Application	(4)	(5)	(6)(a)	(6)(b)	(6)(c)		(6)(d)	
Alabama	-	-	x	-		-	Plant mix sand asphalt seal	21	Yes	Very light sprinkle	-	-
Alaska	-	-	-	-	-	-	-	-	-	-	-	-
Arizona	-	-	Yes	Fog spray	-	-	MC-2	0.15-0.20 gal /sq yd	Yes	Fog spray	No	-
Arkansas	Yes	Yes	Yes	-	-	-	Emulsified asphalt	0.10-0.20 gal /sq yd	-[55]	-[55]	Yes	-[56]
California	No	No	No	-	No	No	MC-2 pen. and mix emul.	0.15-0.25 gal /sq yd	Yes	Variable	Sometimes	-[58]
Colorado	-	-	-	-	-	-	RC-2 cutback asphalt	0.20 gal /sq yd	Yes	Suf. to fill surf. voids	No	-
Connecticut	-	-	-	-	-	-	-	-	-	-	-	-
Delaware	-	-	Yes	Moist	-	-	RC-3	0.2 gal per sq yd	Yes	-[134]	Sometimes	Sand, if open to traffic
Florida	Yes	-	-	-	-	-		-	-	-	-	-
Georgia	No	No	No	-	No	No	Cutback, e-mulsion	0 1-0.2 gal	Yes	Fog	Sometimes	-[161]
Hawaii	-	-	-	-	-	-	-	-	-	-	-	-
Idaho	No	No	Yes	Keep sur-face damp	No	No	RC-1 or RS-1	0.30 gal per sq yd	Yes	Damp sur-face	Yes	-[190]
Illinois	-	-	-	-	-	-	RS-2 or RC-2	0.20 gal/ sq yd	Yes	-[218]	Occasionally	-[219]
Indiana	No	Yes	No	-	No	No	Not used	-	No	-	-	-
Iowa	No	Yes	Yes	-[269]	No	No	RCO-MCO-emulsion	±0.20 per sq yd	Yes—if directed	Damp	No	-
Kansas	-	Yes—also prairie hay	Yes	-[295]	-	-	-[296]	-[297]	Yes	To wet sur-face	No	-
Kentucky	-	Yes	Yes	-[312]	-	-	Tar and MC	-[313]	Yes	Moist but not free	No	-
Louisiana	-	-	-	-	-	-	EA-4	0 3 gal/sq yd	Yes	Heavy sprink-ling	No	-
Maine	-	-	-	-	-	-	RC-T	0.2 gal/ sq yd	Yes	Enough to keep damp	Yes-¼ in. 70-100% pass.	-[354]
Maryland	Yes	No	Yes	Suf to keep conc. moist	No	No	No	-	Yes	To keep moist	Yes[369]	See 6a[373]
Massachusetts	-	-	-	-	-	-	-	-	-	-	-	-
Michigan	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	-	-	-	-	-	-	SS-1 and RC-2	0.2 gal/ sq yd, max	Yes	To fill surface voids	Yes[403]	-[404]
Mississippi	No	One job	-	-	-	-	-[435]	0.2-0 25 gal / sq yd	Maintain moist. con.	Not free water	At times	-[436]
Missouri	-	x	-	-	-	-	MC-1 emul-sion	0.15-0 25 gal / sq yd	Yes	Fog shot	-[463]	-[463]
Montana	-	-	Yes	-	-	-	RC-2 cutback asphalt	0.20 gal/sq yd	Yes	To fill all surface voids	Yes	-[466]
Nebraska	-	x	x	-	-	-	MC-1 prime	0.15 gal/sq yd	No	-	No	-
Nevada	-	-	-	-	-	-	Ample emul-sion	0 2 gal/sq yd	Yes	Dampness	No	-
New Hampshire	-	-	Yes	Surface kept moist	-	-	RC-1	0.25 gal/sq yd	-	Moist	Yes	-[531]
New Jersey		Yes	Yes[63]	-[545]	No	No	RC-3	0.25 gal/sq yd	No	None	Yes	-[546]

New Mexico	[illegible]	No	Ye	-	No	No	RC-2	0.20 gal/sq yd	Yes	Moist surface	Yes	-[563]
New York	-	x	-	-	-	-	Emul. asp or RC-2	0.2-0.3 gal/sq yd	No	-	Yes	-[594]
North Carolina	-	-	Yes	Variable	-	-	-	-	-	-	-	-
North Dakota	-	-	-	-	-	-	RC-2 and RS-2	0.15-0.20 gal/sq yd	Yes	Fog coat	Yes	-[636]
Ohio	2 in.	4 lb/sq yd	7 days	Saturated	-	-	RC-1, RS-1 or MS-2	0.15 gal/sq yd	Yes	Kept damp	No	-
Oklahoma	-	-	-	-	-	-	-[671]	0.15-0.30 gal/sq yd	Yes	-[672]	No	-
Oregon	-	-	-	-	-	-	-	-	-	-	-	-
Pennsylvania	x	x	x	-	-	-	Asp cutbacks or tar cutbacks	0.2-0.3 gal/sq yd	Yes	Fill surface voids	Yes	-[702]
Rhode Island	-	-	-	-	-	-	-	-	-	-	-	-
South Carolina	-	Yes	Yes	-	-	-	-	-	-	-	-	-
South Dakota	-	-	-	-	-	-	-	-	-	-	-	-
Tennessee	-	-	-	-	-	-	-[747]	0.2 gal/sq yd of the mixture	Yes	Wet surface, fill voids	No	-
Texas	x	x	x	-	X	X	RC-2 and MC-2	0.2 gal/sq yd	Some	Until damp	Yes	-[764]
Utah	-	-	-	-	-	-	-[779]	0.15 gal/sq yd	Yes	Light sprinkling	No	-[780]
Vermont	No	No	Yes	0.2 gal/sq yd	No	No	MC-3, RC-3 (50-50) blend	0.25 gal/sq yd	Yes	0.2 gal/sq yd	Yes	-[805]
Virginia	-[826]	No	Yes	Enough to keep damp	-	-	-[827]	0.2-0.30 gal/sq yd	Yes	Dampen	Yes	-[828]
Washington	-	-	-	-	-	-	SS-1	0.15-0.25 gal/sq yd	Yes	Fog coat or more as needed	Occasionally[850]	-[851]
West Virginia	-	-	x	-	-	-	RC asphalt (4-5)	0.15-0.25 gal/sq yd	Yes	Just moist	Yes	Crushed stone size 12
Wisconsin	-	-	x	-	-	-	Emulsified asphalt	0.25 gal/sq yd	No	-	No	-
Wyoming	-	-	Until bitum. seal is placed	Fog spray	-	-	RC-2	1.2 lb/sq yd	Yes	Fog spray	-[925]	-[926]
Australia	-	-	Yes	Kept damp	-	-	Bituminous emulsion	0.20 gal/sq yd	Yes	Quite damp	Yes	-[958]
Brazil	-	x yes	-	-	-	-	-[987]	-[988]	Yes	Not specified	No	-[989]
England	Yes—multi layer work only	No	Yes	-[1024]	Occasionally	Occasion-ally	-[1025]	6-10 sq yd/gal	-[1026]	-	-[1027]	-
France	No	No	Rarely	-	No	No	-[1051]	Less than 1kg/m^2	No	-	-[1052]	-[1053]
Germany	No	No	Sometimes	-	No	No	Asphaltic e-mulsion	0.15-0.20 gal/sq yd	Yes	-	No	-
The Netherlands	-[1126]	-[1126]	-[1126]	-[1126]	-[1126]	-[1126]	Bitumen emul-sion	-[1127]	-	-	-	-[1127]
New Zealand	-	-	-	-	-	-	-	-	-	-	-	-
Puerto Rico	-	x	x	-	-	-	No	No	-	-	-	-
West Africa	Yes	-	Yes	-	-	-	-[1191]	-[1192]	Yes	-[1193]	Not usually	-[1194]
Central Africa	Yes	-	Yes	-	-	-	-[1191]	-[1192]	Yes	-[1193]	Not usually	-[1194]
East Africa	Yes	-	Yes	-	-	-	-[1191]	-[1192]	Yes	-[1193]	Not usually	-[1194]

For footnotes see page 186.

	5a (7)	5b	5b	5c	6a (1)	6a (1)	6a (2)	6a (3)	6a (4)	6a (5)(a)	6a (5)(b)	6a (5)(c)
Alabama	-	-[22]	-[23]	-	-	-[24]	-[25]	-	-	-	-	-
Alaska	-	-	-	-	-	-	-	-	-	-	-	-
Arizona	-	7 days	7 days	-	-	3-4 in. A.C.	2-3 in. A.C.	2-4 in. A.C.	-	-	-	-
Arkansas	-	14 days	7 days	-	-	-[57]	-[58]	-[59]	-	-	-	-
California	-	3 days	-[89]	-[90]	-	-[91]	-[92]	3 in. A. C.	-	-	-	-
Colorado	None	No time specified	No time spec.	-	-	-[117]	-[118]	-	-	-	-	-
Connecticut	-	-	-	-	-	-	-	-	-	-	-	-
Delaware	-	7 days	Open	-[125]	-	-	-[126]	-	2 in. hot mix	-	-	-
Florida	-	About 30 days	30 days	-	-	-	-	-	-	-	-	-
Georgia	-	5-7 day min	5-7 day min.	-	-	2-6 in.	-[152]	1-6 in.	-[153]	1-4 in.	1-4 in.	1-4 in.
Hawaii	-	-	-	-	-	-	-	-	-	-	-	-
Idaho	None tried	-[191]	24 hr	-	-	0.3 ft plant mix	0.2 ft plant mix	0.3 ft plant mix	-	-	-	-
Illinois	None	Min of 7 days	-[220]	None	-	-[221]	-[222]	Same as (2)	-	-	-	-
Indiana	-	7 days	7 days	-	-	-	-[240]	No experience	No experience	-	-	-
Iowa	-	7 days	-[270]	-	-	-[271]	-	-	-	-	-	-
Kansas	-	7 days	-[298]	-	-	-[299]	Same as primary ½-1½ in.	-	-	-	-	-
Kentucky	-	7 days	7 days for local traffic	-	-	-		-	-	-	-	-
Louisiana	None	7 days	7 days	-[336]	-	-[337]	-[337]	2-4 in. hot mix asphalt	Not applicable	Not applicable	-	-
Maine	-	No spec. time req.	No spec. time req.	-	-	-[355]	2-in. bit. gravel mix	-	-	-	-	-
Maryland	-	3-7 days	-[370]	-[371]	-	-[372]	-[373]	-	-	-	-	-
Massachusetts	-	-	-	-	-	-	-	-	-	-	-	-
Michigan	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	-	Min. 7 days	-	-	-	-[405]	-	-	-	-	-	-
Mississippi	-	Min. 7 days	Min. 8 days	-[437]	-	-[438]	-[439]	-	-	-	-	-
Missouri	-	At least 7 days	At least 7 days	-	-[464]	-[464]	-[464]	-	-	-	-	-
Montana	-	21 days for plant mix	Not less than 7 days	-	-	-[487]	-[488]	-[487]	Same as urban	-	-	-
Nebraska	-	10 days min.	Not known	-	-	-[507]	-[508]	-	-	-	-	-
Nevada	-	7-14 days	-	-	-	2½ in. plant mix	2 in. road mix	-	-	-	-	-
New Hampshire	-	6 months	-[532]	-	-	-[533]	Pea stone seal	-	-	-	-	-
New Jersey	None	7-30 days	Not closed	None	-	None	-[547]	X	X	X	X	X
New Mexico	-	7 days	7 days	-[566]	-	-[567]	-[568]	-[567]	-	-	-	-

New York	-	7 days	- [595]	-	-	- [596]	Same as primary	-	-	-	-	-
North Carolina	-	7 days	7 days	-	-	- [615]	Same as primary	-	-	-	-	-
North Dakota	-	Min. 7 days	7 days	-	B. P. R. class G	- [637]	Same as primary	-	-	-	-	-
Ohio	-	7 days	7 days	-	-	-	- [657]	-	-	-	-	-
Oklahoma	-	7 days	- [673]	-	-	4½-in. as-pltc. conct.	- [674]	Same as 6(a)2	-	- [675]	- [675]	- [675]
Oregon	-	-	-	-	-	-	-	-	-	-	-	-
Pennsylvania	-	7 days	- [703]	-	-	-	- [704]	-	-	-	-	-
Rhode Island	-	-	-	-	-	-	-	-	-	-	-	-
South Carolina	-	Up to several months	'After a few days (see c)	- [727]	-	- [728]	- [729]	-	-	-	-	-
South Dakota	-	-	-	-	-	-	-	-	-	-	-	-
Tennessee	-	7 days	7 days	-	-	- [748]	-	-	-	- [749]	-	-
Texas	-	7 days	7 days	-	-	2-in. hot mix	1½-in. hot mix	2-in. hot mix	-	None	-	-
Utah	-	Min. 3 days (72 hr)	7 days	-	-	- [781]	- [782]	Same as primary	-	-	-	-
Vermont	None	7 days approx.	Light traffic immed.	- [805]	-	None	- [807]	-	-	-	-	-
Virginia	None	3 days	Built under traffic	-	-	- [829]	Prime and double treat.	Same as 6(a)2	- [830]	Same as 6(a)4	-	-
Washington	-	Min. 4 days	Variable	-	-	- [862]	- [863]	Same as 6(a) 1 and 2	Not applicable	Not applicable	Not applicable	-
West Virginia	-	7-10 days	Open immediately	-	-	-	- [890]	-	-	-	-	-
Wisconsin	-	-	-	-	- [905]	-	-	-	-	-	-	-
Wyoming	-	Varies min. 14 days	- [927]	- [928]	Base (not used in surf.)	-	-	-	-	-	-	-
Australia	- [959]	7 days min.	As little as 12 hr	- [960]	-	- [961]	- [962]	-	-	- [963]	-	-
Brazil	-	No special spec.	Sometimes	-	-	- [990]	-	-	-	-	-	-
England	None	- [1028]	7 days	-	- [1029]	-	-	-	-	-	-	-
France	Used on concrete	- [1033]	1 month	-	- [1034]	-	-	Not used	Not used	-	-	-
Germany	-	More than 1 week	More than 2 weeks	- [1086]	-	- [1087]	-	¾-in. asp. concrete	- [1088]	-	-	-
The Netherlands	-	At least 1 week	- [1128]	- [1129]	-	- [1130]	- [1131]	- [1132b]	No spec. applications	No spec. applications	No spec. applications	No spec. applications
New Zealand	-	-	-	-	-	-	-	-	-	-	-	-
Puerto Rico	-	Not less than 7 days	Not less than 4 days	None	-	-	- [1158]	-	-	-	-	-
West Africa	-	Varies about 7 days	Not less than 14 days	- [1195]	-	- [1196]	- [1197]	- [1198]	- [1199]	- [1200]	- [1200]	Not normally used
Central Africa	-	Varies about 7 days	Not less than 14 days	- [1195]	-	- [1196]	- [1197]	- [1198]	- [1199]	- [1200]	- [1200]	Not normally used
East Africa	-	Varies about 7 days	Not less than 14 days	- [1195]	-	- [1196]	- [1197]	- [1198]	- [1199]	- [1200]	- [1200]	Not normally used

For footnotes see page 186.

	6a (6)	6a (7)	6b	7a	7a (1) Base	7a (1) Subbase	7a (1) Shoulder	7a (2) Base	7a (2) Subbase	Shoulder	7a (3) Base	7a (3) Subbase
Alabama	-	-	-	-	Yes	-	Yes	Yes	-	-	-	-
Alaska	-	-	-	-	-	-	-	-	-	-	-	-
Arizona	-	-	No	-	Yes	-	Yes	Yes	-	Yes	Yes	-
Arkansas	-	-	-	-	Yes	-	-	Yes	-	-	-	-
California	-	2-3 in. A. C.	-	-	Yes	Normally not economical	Yes	Yes	Normally not economical	Yes	-	-
Colorado	-	-	No, traf. vol basic criterion	-	-	-[97]	-[97]	-	-	-	-	-
Connecticut	-	-	-	-	-	-	-	-	-	-	-	-
Delaware	-	-	No	-	-	-	-	Yes	-	-	Yes	Yes
Florida	-	-	-	-	-	-	-	-	-	-	-	-
Georgia	-[194]	-[195]	Yes[196]	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hawaii	-	-	-	-	-	-	-	-	-	-	-	-
Idaho	-	Same as travelway	No	-	Yes	-	Yes	Yes	-	Yes	-	-
Illinois	-	-	No	-	Insufficient experience	-	-	Yes	-	-	-	-
Indiana	-	-	No	-	-	Yes	Yes	Yes	-	-	No experience	-
Iowa	-	-	No	-	Yes	-	-	-	-	-	-	-
Kansas	-	-	No[300]	-	-	-	-	-	-	-	-	-
Kentucky	-	-	-	-	-	-	-	Yes	-	-	-	-
Louisiana	-	-	No	-	Yes	Yes	Yes	Yes	None	Yes	Not applicable	-
Maine	-	-	No	-	-	-	Yes	Yes	-	-	-	-
Maryland	-	-	No	-	Not used for primary roads	-	-	Yes	-	-	-	-
Massachusetts	-	-	-	-	-	-	-	-	-	-	-	-
Michigan	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	-	-	No	-[406]	-[407]	Yes	Yes	Yes	Yes	Yes	-	-
Mississippi	-	Same as 6a(1)	No[440]	-	-	x	x	x	x	x	-	-
Missouri	-	-[465]	No	-	Yes	Yes	Yes	Yes	Yes	Yes	-	-
Montana	-	-	No	-	-	-	-	-	-	-	-	-
Nebraska	-	-	No-traffic was cont. factor	-	x	-	-	x	-	-	-	-
Nevada	-	-	No	-	Yes	-	Yes	Yes	-	-	-	-
New Hampshire	-	-	No	-	-	-	O. K.	-	-	-	-	-
New Jersey	X	-[548]	No-X	-	x	x	Yes	Yes	x	Yes	x	x

New Mexico	-	-	No	-	Yes	Yes	-	Yes	Yes	-	-	-
New York	Same as 6a(1)	-[697]	Not nec.[698]	-	Yes	Never used by us	Yes	Yes	-	Yes	-	-
North Carolina	-	-	No	-	Yes	-	-	Yes	-	-	-	-
North Dakota	-	-	No	-	Yes	Yes	Yes	Yes	Yes	Yes	No experience	No experience
Ohio	-	-	-	-	-	No	-	Yes	-	-	-	-
Oklahoma	-	-	-	-	-	-	-	-	-	-	-	-
Oregon	-	-	-	-	-	-	-	-	-	-	-	-
Pennsylvania	-	-[705]	No[706]	-	-	-	Yes	Yes	-	-	-	-
Rhode Island	-	-	-	-	-	-	-	-	-	-	-	-
South Carolina	-	-	-	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-
South Dakota	-	-	-	-	-	-	-	-	-	-	-	-
Tennessee	-	-	No	-	Yes	-	-	Yes	-	-	-	-
Texas	-	-	No	-	Yes	Yes	Yes	Yes	Yes	Yes	-	-
Utah	-	-	No[783]	-[784]	-	-	-	-	-	-	-	-
Vermont	-	-	No[808]	-	-	-	-	Yes	-	-	Yes	-
Virginia	1⅛-in. bit. conc.	-[831]	No	-	Fair	Good	Good	Good	Not used	Not used	Good	Not used
Washington	-	-	No data[864]	-	Yes	Yes	Possibly, if sub-drainage provided	Yes	Yes	Same as 7a(1)	Yes	Yes
West Virginia	-	-	Understudy	-	No	Yes	No	Yes	Yes	Not tried	No experience	
Wisconsin	-	-	-	-	Yes	-	-	-	-	-	-	-
Wyoming	-	-	-	-[929]	-	-	-	-	-	-	-	-
Australia	-	-	No-not observed	-	Yes	Yes	Yes	Yes	-	-	Yes	-
Brazil	-	-	No	-	Yes	Yes	-	-	-	-	-	-
England	-	-	Yes-to some extent[1030]	-	Yes	Yes	No experience	Yes	Yes	No experience	Yes	Yes
France	-	-	Yes[1065]	-[1066]	-	-	-	-	-	-	-	-
Germany	-	-	No	-	-	Yes	Yes	Yes	-	-	Yes	-
The Netherlands	-[1132]	-[1133]	-[1134]	-[1135]	-[1135]	-[1135]	-[1135]	-[1135]	-[1135]	-[1135]	-[1135]	-[1135]
New Zealand	-	-	-	-	-	-	-	-	-	-	-	-
Puerto Rico	-	-	No	-	-	-	-	-[1189]	-	-	-	-
West Africa	Prime and seal	Prime and seal	-[1201]	-	Yes[1202]	-	-	Yes	-	-	-	-
Central Africa	Prime and seal	Prime and seal	-[1201]	-	Yes[1202]	-	-	Yes	-	-	-	-
East Africa	Prime and seal	Prime and seal	-[1201]	-	Yes[1202]	-	-	Yes	-	-	-	-

For footnotes see page 186.

	7a (4)	7a (5) Base	7a (5) Subbase	7a (5) Shoulder	7a (6)			7a (7)			7a (8)		
Alabama	-	-	-	-	-	-	-	-	-	-	-	-	-
Alaska	-	-	-	-	-	-	-	-	-	-	-	-	-
Arizona	-	-	-	-	-	-	-	-	-	-	-	-	-
Arkansas	-	-	-	-	-	-	-	-	-	-	-	-	-
California	-	-	-	-	-	-	-	-	-	-	-	-	-
Colorado	-	-	-	-	-	-	-	-	-	-	-	-	-
Connecticut	-	-	-	-	-	-	-	-	-	-	-	-	-
Delaware	-	-	-	-	-	-	-	-	-	-	-	-	-
Florida	-	-	-	-	-	-	-	-	-	-	-	-	-
Georgia	-	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Hawaii	-	-	-	-	-	-	-	-	-	-	-	-	-
Idaho	-	-	-	-	-	-	-	-	-	-	-	-	-
Illinois	No Inf avail.	No Inf. avail.	-	-	No information avail.	-	-	No information avail.	-	-	No	Yes	-
Indiana	-	No experience	-	-	-	-	-	-	-	-	-	-	-
Iowa	-	-	-	-	-	-	-	-	-	-	-	-	-
Kansas	-	-	-	-	-	-	-	-	-	-	-	-	-
Kentucky	-	-	-	-	-	-	-	-	-	-	-	-	-
Louisiana	Not applicable	-	-	-	Not applicable	-	-	Not applicable	-	-	-	Yes	-
Maine	-	-	-	-	-	-	-	-	-	-	-	-	-
Maryland	-	-	-	-	-	-	-	-	-	-	-	-	-
Massachusetts	-	-	-	-	-	-	-	-	-	-	-	-	-
Michigan	-	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	-	-	-	-	-	-	-	-	-	-	-	-	-
Mississippi	-	-	-	-	-	-	-	-	-	-	-	-	-
Missouri	-	-	-	-	-	-	-	-	-	-	-	-	-
Montana	-	-	-	-	-	-	-	-	-	-	-	-	-
Nebraska	-	-	-	-	-	-	-	-	-	-	-	-	-
Nevada	-	-	-	-	-	-	-	-	-	-	-	-	-
New Hampshire	-	-	-	-	-	-	-	-	-	-	-	-	-
New Jersey	X	X	X	X	X	X	X	X	X	X	X	X	X

New Mexico	-	-	-	-	-	-	-	-	-	-	-	-	-
New York	-	-	-	-	-	-	-	-	-	-	-	-	-
North Carolina	-	-	-	-	-	-	-	-	-	-	-	-	-
North Dakota	-	-	-	-	-	-	-	-	-	-	-	-	-
Ohio	-	-	-	-	-	-	-	-	-	-	-	-	-
Oklahoma	-	-	-	-	-	-	-	-	-	-	-	-	-
Oregon	-	-	-	-	-	-	-	-	-	-	-	-	-
Pennsylvania	-	-	-	-	-	-	-	-	-	-	-	-	-
Rhode Island	-	-	-	-	-	-	-	-	-	-	-	-	-
South Carolina	-	-	-	-	-	-	-	-	-	-	-	-	-
South Dakota	-	-	-	-	-	-	-	-	-	-	-	-	-
Tennessee	-	Yes	-	-	Yes	-	-	-	Yes	-	-	-	-
Texas	-	-	-	-	-	-	-	-	-	-	-	-	-
Utah	-	-	-	-	-	-	-	-	-	-	-	-	-
Vermont	Light aircraft	-	-	-	-	-	-	-	-	-	-	-	-
Virginia	Secondary	Good	Not used	Not used	Good	Not used	Not used	Not used	Good	Not used	Not used	Good	Not used
Washington	No experience not applicable	Same as 7a(4)	Same as 7a(4)	-	-	-	-	-	-	-	-	-	-
West Virginia	-	-	-	-	-	-	-	-	-	-	-	-	-
Wisconsin	-	-	-	-	-	-	-	-	-	-	-	-	-
Wyoming	-	-	-	-	-	-	-	-	-	-	-	-	-
Australia	Low class up to D/C3	-	-	-	-	-	-	-	-	-	-	-	-
Brazil	-	-	-	-	-	-	-	-	-	-	-	-	-
England	Military and civil	Yes	Yes	-	Yes	Yes	-	No experience	-	-	No experience	Yes	No experience
France	-	-	-	-	-	-	-	-	-	-	-	-	-
Germany	-	-	-	-	-	-	-	-	-	-	-	Yes	-
The Netherlands	- [1135]	- [1135]	- [1135]	- [1135]	- [1135]	- [1135]	- [1135]	- [1135]	- [1135]	- [1135]	- [1135]	- [1135]	- [1135]
New Zealand	-	-	-	-	-	-	-	-	-	-	-	-	-
Puerto Rico	-	-	-	-	-	-	-	-	-	-	-	-	-
West Africa	- [1203]	Yes	Yes	-	Yes	Yes	-	-	Yes	Yes	-	Yes	-
Central Africa	- [1203]	Yes	Yes	-	Yes	Yes	-	-	Yes	Yes	-	Yes	-
East Africa	- [1203]	Yes	Yes	-	Yes	Yes	-	-	Yes	Yes	-	Yes	-

For footnotes see page 186.

	7a (9)	7b	7b (1)	7b (2)	7b (3)	7b (4)	7b (5)	7b (6)	7b (7)	7c	7d	
Alabama	-	-	-	-	-	-	-[26]	-[27]	-[28]	-[29]	Medium	-[30]
Alaska	-	-	-	-	-	-	-	-	-	-	-	-
Arizona	-	Yes	-[43]	Sev mo. to few weeks	No	-	Only in extreme cases	-[44]	-	-[45]	Medium	Not available
Arkansas	-	Yes	Mostly transverse	-	Yes	-[60]	No, but not desireable	No	No	Sealing operations	Medium	-
California	-	Yes	-[93]	Variable	No	-	-[94]	-[95]	No	-[96]	Low	Unknown
Colorado	-	Yes	-[119]	1 day to 2 months	Yes	-[120]	-[121]	-[122]	No experience	-[123]	-	Not known
Connecticut	-	-	-	-	-	-	-	-	-	-	-	-
Delaware	-	-	-	-	-	-	-	No	-	-	-	-
Florida	-	-	-	-	-	-	-	-	-	-	-	-
Georgia	-[167]	-	6 in. to 14 ft	1-30 days	Yes	-[168]	No[169]	-[170]	No	-[171]	Very low	Not available
Hawaii	-	-	-	-	-	-	-	-	-	-	-	-
Idaho	-	Yes	Transverse 15-400 ft	1 mo. to 5 yr	Not certain	-[192]	No[193]	-[194]	Believe it does	-[195]	Low	Unknown
Illinois	-	Yes	Rectangular and lateral	-[224]	Yes[225]	-[226]	No	-[227]	-[228]	-[229]	Low	Not available
Indiana	-	Yes	Var. depend. on soil types	Less than 7 days	Yes	-[247]	No	No concern	No experience	-[248]	-	Not available
Iowa	-	Yes	About 25 ft slab length	Soon	No	-	No[272]	No	-[273]	-	Medium	-
Kansas	-	Yes	-[301]	Varies	-	-	Yes[302]	No	No[303]	-[304]	-	-
Kentucky	-	Some	Fine check crack	36-72 hr	No	-	No	-	-	Resurfacing	-	-
Louisiana	None	Yes	Transv. and longitudinal	2 weeks-1 yr	Yes	More in finer text. soil	No-mostly shrink. cracks	-[338]	No	-[339]	Very low	Unknown
Maine	-	Yes	50-80 ft transverse	Couple of months	No	-	No	-	-	To keep the surf. sealed	Low	No data available now
Maryland	-	Yes	8-10 ft	1-2 weeks	No	-	No[374]	No	-[375]	-[376]	Very low	Not available
Massachusetts	-	-	-	-	-	-	-	-	-	-	-	-
Michigan	-	-	-	-	-	-	-	-	-	-	-	-
Minnesota	-	-[408]	-[409]	3-6 months	No	-	-[410]	-[411]	-[412]	-[413]	High	61-153 dollars
Mississippi	-	Yes	Varies with type of soil	About 2 weeks	Yes[441]	-	Yes[442]	-[443]	-[444]	-[445]	Medium	-
Missouri	-	Yes[465]	-[466]	-[467]	Yes-definately	-[468]	-[469]	No[470]	Not sure but don't think so	-[471]	Medium	-[472]
Montana	-	Yes	Varies from 10-15 ft	4-6 months	No	-	No[489]	No	No	-[490]	-[491]	-[492]
Nebraska	-	Yes	Shrinkage cracks	1-2 years	No information	-	No	No	Do not know	-[509]	Medium	-
Nevada	-	Yes	Transverse and longitudinal	First cold	No	-	No-cracks very narrow	-[518]	Do not know	Same as other paved roads	Low	-
New Hampshire	-	-	-	-	-	-	-	-	-	-	-	-
New Jersey	x	Yes	Continuation of transv. joint	0-6 months	No	None	No-X	No	No	Surface treat. 3-6 yr	Low	Not available
New Mexico	-	Yes	-[569]	Varies	Yes[570]	-[570]	-[571]	-[572]	Not yet	Not yet de-	-	-

New York	-	Very little	-[599]	1 year	No	-	No[600]	-[601]	Don't know	-[602]	Low	-
North Carolina	-	Yes	Transverse and longitudinal	A few months	Yes[616]	-	No	Thicker wearing surface	Some	-[617]	Very low	Not available
North Dakota	-	Yes	-[638]	-[639]	No experience	-	No	No experience	-[640]	Crack sealing	Medium	-[641]
Ohio	-	Slight amount	Longi. - random.	After 1st winter in service	No	-	No[658]	-[659]	-	Resealing or resurf.	Medium	-
Oklahoma	-	Yes	Primarily transverse	1-6 months	-[676]	-	No[677]	No	-[678]	-[679]	-	Ins. data to date
Oregon	-	-	-	-	-	-	-	-	-	-	-	-
Pennsylvania	-	Yes	Transverse	2-3 days	-	-	No[707]	-[708]	?	Surface treatm.	Low	-
Rhode Island	-	-	-	-	-	-	-	-	-	-	-	-
South Carolina	-	Yes	Alligator	1 day	Yes	-[729]	No[730]	-	-	Chiefly surf. patching	Low	-
South Dakota	-	-	-	-	-	-	-	-	-	-	-	-
Tennessee	-	Yes	Varies with soil type	Varies	Yes	-[750]	No[751]	-[752]	No-but reduces to min.	-[753]	Very low	Not known
Texas	-	Yes	Frequent transverse	Variable	No	-	Yes[765]	No good way	No	Sealing cracks	Medium	Unknown
Utah	-	-[785]	-[785]	-	Not conclusive	-	No[786]	Yes[787]	Not studied	Crack filling	Not available	-
Vermont	-	Yes	Transverse	I'm not sure	No	-	No[809]	No	I believe it does	-[810]	Low	-[811]
Virginia	-[832]	Yes	Variable	Soon	Yes	More in clay than granular	Yes[833]	-[834]	To some deg	-[835]	Low	Not available
Washington	-	Yes	-[865]	-[866]	-[867]	-	Yes and no [868]	-[869]	-[870]	-[871]	Very low	$60.37/mile[872]
West Virginia	-	Yes	-[891]	-[892]	Yes	-[893]	Yes [894]	No	Unknown	Surface patching	Medium	-
Wisconsin	-	Yes	-[907]	± 1 year	Not known	-	No[908]	No	Not known	Sealing cracks	Low	-
Wyoming	-	Yes	Transverse and longitudinal	Approx. 7 days	Yes	-	No	-[930]	Not entirely but it helps	-[931]	Very low	-
Australia	-	Yes	-[964]	Sometimes 24 hr	Yes[965]	-[965]	No[966]	Yes[967]	-[968]	-[969]	Very low	-
Brazil	-	Yes occasionally	Transversal lines	-	-	-	-	-	-	-	-	Very variable
England	-[1031]	Yes	-[1032]	Within a few days	Yes	-[1032]	No	-[1033]	-[1034]	Normal resurfacing	No records yet available	-
France	-	Yes[1067]	-	-[1068]	Only in thin gravels	When made of thin concrete	Yes[1069]	-[1070]	No	-[1071]	-	-
Germany	-	Yes	Transversal	Winter	-[1089]	-	No	-[1090]	-	-[1091]	Low	-
The Netherlands	-[1135]	Yes	-[1136]	-[1137]	-[1137]	-[1137]	-[1138]	-[1139]	-[1140]	-[1141]	-[1142]	-
New Zealand	-	-	-	-	-	-	-	-	-	-	-	-
Puerto Rico	-	Yes	Longitudinal cracks	8 days	I don't know	-	No[1160]	No	No	-[1161]	Very low	I don't have the figures
West Africa	-	Yes	-[1204]	Varies	Yes	-[1205]	-[1206]	-[1207]	No	-[1208]	-[1209]	-
Central Africa	-	Yes	-[1204]	Varies	Yes	-[1205]	-[1206]	-[1207]	No	-[1208]	-[1209]	-
East Africa	-	Yes	-[1204]	Varies	Yes	-[1205]	-[1206]	-[1207]	No	-[1208]	-[1209]	-

For footnotes see page 186.

	8a	8b
Alabama	-	-
Alaska	-	-
Arizona	-	-
Arkansas	-	-
California	-	-
Colorado	None	Elimination of detrimental cracking and surface slippage
Connecticut	-	-
Delaware	-	-
Florida	-	-
Georgia	-[173]	Means of pulverization of soils
Hawaii	-	-
Idaho	-	-[223]
Illinois	-	-
Indiana	None at present	-
Iowa	-	-[223]
Kansas	None in progress or planned	-
Kentucky	-	-
Louisiana	-[340]	-[341]
Maine	None going on	-
Maryland	None	-[223]
Massachusetts	-[379]	-
Michigan	-	-
Minnesota	-	Need for thickness design methods and criteria
Mississippi	-[446]	-
Missouri	-	Shorter reliable test methods to determine cement content to use in construction
Montana	-	-
Nebraska	-	-
Nevada	None	-
New Hampshire	-	-
New Jersey	None	None

New Mexico	-[873]	-[874]
New York	-	-[223]
North Carolina	None	-
North Dakota	None	Control of random cracking
Ohio	-	Shorter method of determining optimum cement content
Oklahoma	-	-
Oregon	-	-
Pennsylvania	-	Improvements on freeze-thaw tests
Rhode Island	-	-
South Carolina	-	-
South Dakota	-	-
Tennessee	-	-[223]
Texas	Continuing study of performance	Prevention of cracking
Utah	Cement in sulfate soils	Service records[223]
Vermont	-[812]	Thickness design or performance ratio to other types of base courses
Virginia	None	Design criteria
Washington	-[873]	-[223, 874]
West Virginia	-[895]	-
Wisconsin	None	Way to eliminate transverse cracking
Wyoming	-	-
Australia	-	-
Brazil	-[991]	-
England	-[1035]	-[223]
France	-[1078]	Improvement of machinery for mixing gravelly soils
Germany	-[1093]	-[1093, 223]
The Netherlands	-[1143]	-[1143, 223]
New Zealand	-	-
Puerto Rico	-	-
West Africa	-[1310]	-[1310]
Central Africa	-[1310]	-[1310]
East Africa	-[1310]	-[1310]

For footnotes see page 186.

FOOTNOTES

[1]North and central sections of state. [2]Highly colloidal clays and enough acid to show a pH of less than 5. [3]SO3 forms acid destructive to cement. Many organics also form acids, esp. tannic acid. Too much organic matter of certain types prevents thorough mixing and compaction. [4]Only by hauling in suitable soils. [5]Most soils treated to date average pH of 7.0. [6]Readily available and less expensive than Type III. [7]For soil-cement base minimum strength 600 psi on field cylinders 7 days. Durability tests based on ASTM freeze-thaw method. [8]Strength is the main requirement since the durability tests are based primarily on freezing and thawing which are not a problem in this state. [9]Most soil-cement requirements were based primarily on preconstruction laboratory results. [10]Approximately 8% (if economical at all). [11]Soil-cement base—8 in. on primary roads. County type projects—5 in. or 6 in. [12]Base and CBR design values for crushed stone base. For primary 18,000-lb wheel load requiring 10-in. crushed stone base, we assume 8-in. soil-cement base to be equivalent. [13]Yes, soil-cement bases on primary roads based on 8-in. compacted depth. Crushed stone and gravel on comparative roadway 10 in. [14]Usually sheepsfoot and rubber-tired rollers. [15]By analyzing successive samples of soil for cement content. [16]Optimum moisture (Standard Proctor). [17]Depends on soil—average approximately 6 in. [18]Proper mixing and adequate compaction. Also no loss of time between mixing and compaction. [19]Most ideal from March thru October, however we use year around construction. [20]0.70/sq yd for 6-in. compacted average. [21]Voids according to type of roadway. [22]Can be applied after 7 days curing. [23]As soon as bituminous paving is completed. [24]2½-in. bituminous binder and 1½-in. seal. [25]Double bituminous surface treatment and later sealed with 1-in. plant mix seal. [26]Yes, lets water into soil-cement and subgrade. [27]Only by using sandy friable soil and this only minimizes cracking. [28]It may in some instances however, the answer would better include (minimizes the crack). [29]Most of our soil-cement roads are comparatively new and have required only minor maintenance. [30]Pavements too new for reliable estimate. [31]Since this department has not designed or constructed any such projects, we were unable to complete the questionnaire. It was our understanding that other agencies in Alaska had used a soil-cement design for airport subgrades. We made inquiries to determine if this was the case but did not receive any answers. [32]29 mi on Interstate 23, single lane. [33]Compressive strength at 7 days. Plasticity index. [34]Class A—300-500 psi at 7 days, Class B—non-plastic within 7 days. [35]Assigned value equivalent to crushed sand and gravel. [36]Single pass or multiple pass traveling continuous mixing machine, batch pugmill or continuous type mixer. [37]Pneumatic and steel-wheel rollers. [38]Same as 1b except sheepsfoot may also be used. [39]Resulting smoothness is poor. [40]6-in. dune sand difficult to compact. [41]Northern part (April 15-Dec 1), Southern part (all year). [42]0.38/sq yd including aggregate. [43]Initially transverse shrinkage, to random or block. [44]Are experimenting with aggregate cushion course. [45]Usually crack-patching or resealing. [46]Standard wet-dry and freeze-thaw durability. Compressive strength. [47]Loss in wet-dry or freeze-thaw tests. Soil groups A-1, A-2-4, A-2-5, and A-3—max 14%. Soil groups A-2-6, A-2-7, A-4 and A-5—max 10%. [48]All 6 in. except one small urban job 7 in. [49]Discs, plows, graders, Seaman pulverizers and P and H mixers. [50]Sheepsfoot rollers and rubber-tired rollers. [51]Rubber-tired rollers and smooth-wheel steel rollers. [52]Not entirely. Should get better pulverization and mixing. [53]At least 80% passing No. 4 sieve. [54]Be sure subgrade is stable. [55]Yes, if surface gets dry enough to dampen. [56]Sandy soil if constructed under traffic. [57]2 in. of dense graded asphalt mixture or double surface treatment with emulsified asphalt, RC cutback or asphalt cement 150 pen. Total asphalt 0.5 to 0.7 gal/sq yd. Cover material 60 to 70 lb/sq yd. [58]Single or double surface treatment. [59]2- 4-in. dense graded hot asphalt mixture. [60]More cracks in fine grained soils. [61]Not available. Cement treated base has been used extensively. [62]State wide—valleys, mountains, deserts and coastal areas. [63]Magnesium or sodium sulfate. [64]Organics—lowering of compressive strength sulfates, disintegration. [65]For sulfates—provide good drainage in subsoil. Import mineral aggregate for cement treatment. Use Type V cement. [66]Formerly Type I; now all Type II low alkali. [67]Greater resistance to attack of sulfates, alkali or sea water. [68]Compressive strength, wetting and drying, freezing and thawing

(for colder areas). [69]Enough cement to develop: for heavy traffic—750 psi at 7 days; for medium traffic—400 psi at 7 days; for light traffic—80 min R-value. [70]8 in. of Class A Cement Treated Base using about 5% cement can compete in price and structurally with 12-in. untreated base. [71]Heaviest traveled roads, 10 in.; heavy traveled roads, 8 in.; medium traveled roads, 6 in. min; light traveled roads, 5 in. min. [72]California Test Method No. 301 of Materials Manual of Testing and Control Procedures and in Division of Highways Planning Manual. [73]8 in. Class A Cement Treated Base (750 psi) = 14 in. untreated base; 8 in. Class B Cement Treated Base (400 psi) = 12 in. untreated base; 8 in. Class C Cement Treated Base (80 R-Value) = 8 in. untreated base. [74]Actual values unknown since road-mixing has been optional on most projects in the past. [75]Road mixers and stationary plant mixers both batch and continuous. [76]3-wheel, 12-ton steel-tired rollers. [77]Motor graders and pneumatic-tired rollers. [78]We do not cement treat cohesive soils such as heavy clays, shales, etc. [79]Not entirely. Our new 1960 standard specifications have more rigid controls. [80]Better control of cement distribution during mixing and placing needed. [81]Titration Test, Test Method No. California 338, for checking cement content during construction. [82]Optimum as determined by Test No. California 312. [83]Moisture by drying density by sand volume. [84]However, we generally use only granular aggregates and therefore do not make any allowances for soil texture. [85]Careful control of cement distribution, moisture content and compaction. [86]All year in most of state. Temperature must be above 35F. [87]Class A cement treated base using 5% cement 1.18. Class B cement treated base using 3½% cement 1.07. [88]Sometimes. Used only to prevent pick-up by traffic. Sand 90-100% pass No. 4, 0-5% pass No. 200. [89]3 day min preferred, sometimes road immediately opened to traffic if no detours available. [90]Curing seal shall be placed as soon as possible but not later than 8 hours after completion of final rolling. The surface shall be kept moist until the seal is applied. [91]4 to 6 in. AC, using 85 to 300 pen. range of paving asphalts. [92]3 to 4 in. AC, using 85 to 300 pen. range of paving asphalts. [93]Transverse longitudinal and/or block. [94]No, widely spaced cracks do not affect strength. Closely spaced cracks lead to early failure. [95]Use well graded aggregates and only moderate amount of cement will minimize shrinkage cracking. Nonresilient subbase and adequate structural section to minimize pavement deflections under wheel loads. We have found that a C.T.B. consisting of a mixture of the existing bituminous surfacing and the underlying base material, produces very few shrinkage cracks. [96]No maintenance unless failures develop. [97]2% cement by weight has been used extensively since 1955 to improve substandard (sand-size) base course materials for flexible pavements and subbases for P.C. Concrete Pavement. Cement treatment includes shoulders on both types of pavements. No reduction in design thickness is made for this type of cement-treatment. Usual thickness for cement-treated bases and subbases is four (4) inches. Generally, cement and water have been mixed with aggregates in stationary mixing plants, spread by Jersey spreaders, and compacted by vibratory and pneumatic-tired rollers. No curing methods are employed but bituminous prime coat may be of some benefit. Total tonnage of cement-treated subbase and base course used to date is 1,366,280 tons including 27,980 tons of portland cement (2.1%). [98]7 (cement-hardened base course). [99]43(cement-hardened base course). [100]Not determined, usually clean sands are selected. [101]Portland Cement Association short-cut procedures for sandy soils is the usual methods. [102]6 in. considered minimum (see 3c) Ref: PCA Soil-Cement Construction Handbook. [103]Total thickness of base and subbase reduced on basis of "gravel equivalent" for soil-cement according to Hveem's cohesiometer values. Reference: "Factors Underlying the Rational Design of Pavements" by F.N. Hveem, Proceedings, Highway Research Board, 1948 (Vol. 28), pp. 101-136. [104]Woods Roadmixer and Seaman Pulvimixer. [105]Sheepsfoot rollers and pneumatic-tired rollers. [106]Finger-weeder, pneumatic-tired roller and flat-wheel roller. [107]Sheepsfoot roller and pneumatic-tired roller. [108]Finger-weeder, pneumatic-tired roller and steel-wheel roller. [109]Mixing in stationary plant and spreading with Jersey spreader is decided improvement. [110]Specs. required 80% to pass No. 4 sieve; 100% passing No. 4 was achieved. [111]Field lab tests supplemented by squeeze test and visual observation. [112]Standard optimum moisture—AASHO T-134. [113]Oven and open-pan drying for moisture. Sand density method for density control. [114]Our experience limited to 6-in. maximum thickness. [115]Use of proper finishing procedures to obtain a smooth, dense, moist surface that is free of cracks, ridges, and compaction planes. [116]May-Oct. specs. require only that temperature be 40F and rising. [117]3-in. plant-mix asphalt surface—85-100 pen. AC. [118]1½-in. road-mix (RC-2 or MC-3); 2-in. plant-mix (85-100 or 100-120 pen. AC); double bituminous surface treatment RC-3 or RC-4, ¾-in. max. size aggregate. [119]Transverse and longitudinal usually intersecting at right angles. [120]Plastic soils show more tendency to develop cracks. [121]Yes, in areas having highly plastic subgrade soils. Cracks permit entry of water. [122]Non-plastic granular materials have less tendency to develop cracks. [123]Repair of areas of surface slippage and sealing cracks. [124]Soil-cement stabilization is new in Connecticut. This fall (1959) was the first time it was used and only on two very small sections of road. We plan to do further experimental work during the coming year (1960). [125]Kent County—1941; Sussex County—1957. [126]Gradation and Atterburg limits are open. [127]This requirement has not been analyzed. [128]Standard PCA Design manual to determine percent cement content. [129]Secondary Roads—4 in. to 6 in. have been used with surface treatment. Suburban Development—5 in. to 7 in. have been designed with 2 in. hot mix. This depends upon question 3b. [130]PCA Manual—7-day moist cure 4 hr. immersion. [131]Secondary roads use 4-6-in. asphalt stabilization. Suburban development use 6-in. select borrow, 5-in. water bound and 2-in. hot mix for 11-in. base subbase. [132]Moisture shall be within 10% of optimum and by blend and texture. [133]Proper moisture to end result. [134]Sufficient to prevent penetration of RC-3. [135]Stabilize only at temperature of 40 F and rising. Also protect against freezing. [136]Initial treatment—½ gal/sq yd. RC-1, 40 lb/sq yd slag chips; two (2) treatments—¼ gal/sq yd. RC-3, 20-lb stone chips each application. [137]Wetting and drying and freezing and thawing tests. [138]We used a maximum loss of 14% for both wetting and drying and freezing and thawing. [139]Majority were 6 in.; however, in some cases it was increased to 8 in. when used in widening strips. [140]Pulvimixers, harrows, motor graders, etc. [141]Steel wheel and pneumatic-tired traffic rollers. [142]To approximately 90% passing the No. 4 sieve. [143]2.0% above optimum moisture. [144]By determining the percent moisture and density in place. [145]Do not mix more than can be compacted and finished before the mixture takes its initial set. [146]234, on 1A Interstate 10. [147]7, on 1A Interstate 45. [148]Organic coating slows up hardening. [149]Waste and replace with neutral soil. [150]ASTM until experience record of most soils showed compression tests were adequate. [151]300-lb triaxial shear, 20-lb lateral pressure, 28 days. [152]6 in. on Secondary Base, 8 in. on Primary Base, 8 in. on Interstate Shoulders, 5 in. some Subdivision Streets. [153]Rotary mixer, traveling plants and central plants. [154]Vibrating steel wheel and rubber tired compactors. [155]Motor patrol, rubber tired roller. [156]Rotary mixer, traveling plant (not pug or paddle) central plant. [157]Capacity of paddle type traveling plants is not powerful enough. [158]Dry sample use sand cone. [159]Homogeneous mix, moisture control, compaction finish. [160]0.25/sq yd processing, 0.50/sq yd cement (no top). [161]Sand or quarry fines (10 lb) so that traffic can use. [162]Double surface treatment single surface treatment with ± 100 lb plant mix seal. [163]Double surface treatment to 2 in. plant mix. [164]Double surface treatment, 1 in., 2 in. [165]Single and double surface treatment, 1 and 2 in. plant mix. [166]Single surface treatment on cohesive soils before applying plant mix. [167]Ditch linings, dam and levee faces. [168]Heavier the clay the closer the cracks. [169]"V" in Cross Section and full of bitumen, no leak to subgrade. No definite plane of Cleavage between hardened base and subgrade; therefore, no rocking or pumping. [170]No double or multiple surface treatments hide cracks. [171]None other than replacement of worn thin bituminous tops. [172]Joint research program, Tech. and Highway. [173]Strength tests, wet and dry tests. [174]Class A aggregates 650 psi, 7 day. Class B aggregates 400 psi, 7 day. Actual amount used set by strength and wet and dry tests. [175]We set cement content at amount when wet and dry test has little effect. Freeze and thaw tests will be used in future but have not been in past. Limits to be used are unknown as yet. [176]Used as guide to setting cement content for tests. [177]Not more than 5%. Most instances used only where shipping aggregates long distances, otherwise necessary. [178]0.4 or 0.5 ft on top of other base or subbase material. [179]Did reduce thickness on one job as experiment. [180]Seaman pulvimixer, Woods mixer, stationary pugmill. [181]Sheepsfoot, pneumatic-tired rollers, steel wheel rollers, Buffalo Springfield Compactor. [182]Blades and Barber Greene Paver. [183]Have not used strictly adhesive soils. [184]Pugmill is best. Travel mixing leaves some doubt of completeness. [185]Control cement spread and depth of mixing on road. Pugmill-conductivity of cement soil water mixture. [186]± 1% of Standard Proctor Optimum. [187]Timing operations to complete mixing and compaction before cement sets. [188]Temperature over 50F before apply cement. [189]0.90/sq yd or $2.80 per ton of aggregate treated with cement. [190]Cover coat or surfacing material. [191]Not specified, generally 2 weeks. [192]Fine gradations may crack quicker than coarse. Compaction affects crack pattern. [193]Deflections at crack are higher than elsewhere. [194]Early traffic over surface makes cracking less apparent—higher densities. [195]Similar other roads—recommend sealing cracks. [196]None other than limited areas of weak subsoils found during construction. [197]Possibly harmful chemical constituents affect cement requirements as determined by physical durability tests. [198]Unconfined compression tests: wetting-drying tests; freezing-thawing tests. [199]Criteria have varied since first construction. Now permit soil-cement loss in freeze-thaw or wet-dry of not over 14% for A-1, A-2-4, A-2-5, and A-3; not over 10% for A-2-6, A-2-7, A-4 and A-5; not over 7% for A-6 and A-7. Compressive strength should increase both with age and cement content. [200]Portland Cement Association short-cut method for sandy soils. [201]Economic competition will vary with location of competitive stone and gravel deposits. [202]b1—6 and 10 in.; b2—6, 6.5 and 7 in.; b3—6, 6.5, 7 and 8 in. [203]Empirical method. [204]Rotary speed mixer; 1-pass stabilizer; traveling pugmill; and stationary plant. [205]Pneumatic roller, vibratory roller and vibratory pads, steel wheel roller. [206]Motor grader, nail drag, pneumatic tire roller, steel wheel roller. [207]Rotary speed mixer: 1-pass stabilizer. [208]Tamping roller, pneumatic tire roller, steel wheel roller. [209]Better cement spreading equipment needed; equipment capable of stabilizing thicker lifts is desirable. [210]100% to pass 1-in. sieve, 80% to pass No. 4 sieve, exclusive or gravel or stone. [211]Mixing shall be continued until the resulting mixture is homogeneous and uniform in appearance. [212]80-100% of optimum for sandy soils, 100-120% of optimum for silty and clayey soils. [213]Moisture controlled by feet, density checked by sand method. [214]2-5 in. lifts, to early to tell. [215]2½ hr for compacting, 2 hr for finishing. [216]Proper pulverization; suitable moisture for compaction; adequate subgrade support; uniformity of cement spreading; uniformity of mixing depth; obtain design density. [217]Not limited by season. Temperature in shade must be not less than 40 F and rising. [218]Sufficient to fill the surface voids. [219]Sufficient sand is applied to prevent pick-up. [220]May be opened to local traffic immediately, to all traffic after 7 days. [221]Dense-graded hot plant mix, PA-6, PA-3, 3 in. thickness. [222]Same as primary for hot mix. For surface treatment first and second cover and seal: 0.2 to 0.3 gal/sq yd usually MC-5; 15 to 25 lb aggregate per sq yd total thickness ½ to ¾ in. [223]See special list of publications on page 212. [224]Initial usually within 7 days. [225]Cohesive soils crack more severely than non-cohesive. [226]May be tied in to higher cement requirements. [227]Obtain highest possible density at a not excessive moisture content; construct during season of moderate temperatures. [228]Does not eliminate but reduces. [229]Pouring large cracks; renewing seal coat over surface treatments. [230]Soil Cement Projects constructed in Indiana in 1959: State Highway Department does not have any detailed information. [231]Any questionable soils were avoided. [232]Either normal or air-entraining. [233]Standard Freeze-Thaw and Wet-Dry Test. [234]PCA standards of allowable losses by brushing the freeze-thaw and wet-dry specimens. [235]Base 6 in., subbase 3 and 5 in., shoulder 6 in. [236]Standard thickness of 6 in.—generally limited by ease of processing. [237]Not enough experience to develop proper design for soil-cement. [238]Flinn, plows and harrows, P and H single pass, Seaman pulvimixers. [239]10-12 ton—3-wheel rollers and pneumatic rollers. [240]3-wheel roller and/or pneumatic. [241]Sheepsfoot, 10-12 ton 3-wheel roller, pneumatic rollers. [242]Some scarifying and preliminary pulverization. [243]Determined maximum density and optimum moisture of mixture. Made moisture tests after mixing. Made in-place density tests after compaction. [244]Proper spread of cement, thorough dry mixing, proper moisture content and proper compaction. [245]General limited from April-November because of freezing. [246]Minimum of 2-in. thickness of plant mix or equivalent. [247]Closer pattern on cohesive soils. [248]Bituminous surface, generally due to thin initial application. [249]Northwest corner -3 F, Southeast corner +3 F from average reported. [250]Requires about 2% additional cement for each 1% of organic matter as determined by our method for hardening. [251]Only by the use of additional cement. [252]As recommended by PCA—using the next highest whole percentage of cement. [253]Only as a guide for estimating purposes when the standard laboratory tests cannot be completed in time. [254]12%—governed by availability of other granular materials. [255]On page 211 see special table showing projects by county, route and city, year built, length miles, width feet, depth inches and square yards; and, shows 1950 surveys, distressed areas. [256]Traffic count, max depth that can be constructed from existing road bed material (usually 7 in.). [257]Farming, Seaman, P and H Woods Traveling Plant. [258]Sheepsfoot—pneumatic pull and self propelled, smooth-steel tired cat and grid roller. [259]Pneumatic, smooth steel tired, patrol and scratchers. [260]Farming, Seaman, P and H. [261]Sheepsfoot—pneumatic, smooth steel tired. [262]To the satisfaction of the engineer. [263]An amount evenly distributed that will enable the contractor to obtain the specified density. [264]Plate dry for moisture-density by oil method. [265]Only to strengthen subgrade conditions. [266]Satisfactory, same as surface course. [267]All operations, except curing, must be completed during daylight hours. [268]Immediate compaction after water is added. [269]Thoroughly wetted first 5 daylight hours after compaction, then primed while damp. [270]As soon as wearing course is applied. [271]Asphalt mat—3 in., 2 layers. [272]Not any more than cracks in other types of base. [273]May help delay cracking, but does not eliminate. [274]Tabulation of projects and map showing location submitted with questionnaire return. [275]One project (3.5 mi) constructed by stabilizing A-4 and A-6-7 subgrade soils with from 10 to 14% cement by volume. Remaining projects used more friable materials ranging from fine sandy loams to sand-gravel with soil binder. The major portion of these materials had 100% passing the No. 4 sieve. [276]ASTM, D558-44, D 559-44, D560-44 since they were approved and essentially similar procedures prior to ASTM adoption of these methods (note exception under 2h). [277]Allowable losses for 12 cycles of wet-dry or freeze-thaw tests range from 7% for heavier textured soils to 14% for sandy soils in accordance with PCA recommendations. (For sandy soils the durability tests may be omitted, see 2h). [278]For sandy soils having combined silt and clay contents within the range of 15 to 35% the short-cut test procedures for sandy soils (Chapter 6 PCA Soil-Cement Laboratory Handbook—1956) are generally used. [279]Thicknesses range from 5 to 9 in. not including wearing surface. Thickness is not influenced by the material in the cement treated base itself, but is governed by traffic and rainfall factors and the characteristics of the subgrade under the base. [280]Triaxial method (HRB—Bulletin 8). [281]Since soil-cement is not a truly flexible type of base it cannot be evaluated in the same manner as macadam or bituminous types for our design method. The adjusted values assigned to soil-cement generally result in slightly less thickness compared to macadam or bituminous on the same subgrade. [282]Seaman tiller, Woods mixer, Barber Greene, Flynn mixer, motor grader, disc, spring-tooth harrow. [283]Sheepsfoot roller followed by pneumatic roller. [284]Patrol blade and pneumatic roller. [285]Scarifier, disc, plow, spike and spring-tooth harrow, Flynn mixer. [286]Sheepsfoot roller followed by pneumatic roller. [287]80% pass No. 4 sieve required on several projects. Current spec. requires 75% pass No. 4. [288]By spotting sacks at the proper interval or by the use of a cement spreader set to deliver the required amount. (Majority of projects used bulk cement and cement spreader). [289]Optimum to optimum + 3%. [290]Moisture samples evaporated to dryness. Sand method density test. [291]Two 4 in. lifts, results good. [292]Rolling must begin within 30 min and be completed within 2 hr. [293]Apr-Oct (approx.). Spec. require temperature be not less than 40 F and rising. [294]No information, cost vary due to difference in materials, length of haul, manipulation and other factors. [295]Sufficient to wet surface, no free water. [296]Mostly RC-2, -3 or -4 asphalt. MC used on two projects and SC on one. [297]Varies depending on nature of base material. [298]Min 7 days—length of time usually depends on time required to construct wearing surface. [299]Road mix bituminous mat with approximately 4% MC-4 cutback—2 in. thick. [300]Wearing surface of bituminous mat is necessary to secure satisfactory riding surface. [301]Start as transverse cracks at fairly regular intervals. [302]In some cases the transverse cracking is followed by longitudinal cracks so that the base may be broken into a block pattern. This permits some movement which is transmitted to the wearing surface and causes the mat to be broken up and whipped out by traffic. [303]Our experience limited to two projects. [304]Periodic sealing of wearing surface. [305]State wide, except central blue grass area. [306]AASHO T-135-45 and 136-45. [307]We have used 10% by volume of all our soil-cement. [308]P and H Machine, Flynn Machine, Seaman Mixers. [309]Sheepsfoot roller, pneumatic roller, and 3-wheel flat rollers. [310]Grader, nail tooth drag, small amount of additional water and a pneumatic roller. [311]Good pulverization, good mixture of cement, optimum moisture and good density. [312]Keep well moist until curing applies. [313]Keep well covered 0.2-0.5 gal. [314]Primary criterion is the friability of the soil and its Atterburg Limits. [315]Failure to set up with corresponding low strength and failure on wet-dry and brush tests. [316]Setting time remains almost constant. [317]Strength test requirements are not less than 300 psi unconfined and passing the standard wet-dry and brush tests (AASHO T 135-57). [318]Minimum unconfined strength of 300 psi and losses of not over 14% for soil groups A-1, A-2-4, A-2-5 and A-3; not over 10% for soil groups A-2-6, A-2-7, A-4 and A-5; and, not over 7% for A-6 and A-7 soil groups. [319]Where various soil types are found on one subgrade survey, the general practice is to use the cement requirement of the most prevalent types and recommend removal of the worst soils. [320]Up to 15% depending on the availability of granular materials. [321]Each soil type is run on every major project. For minor projects, only the questionable soils are run. Cement contents for tests are set by experience. [322]Original designs call for 6 in. but present practice is to use 8 in. About 50% of our present yardage is 6 in. Normally a 6 in. or 8 in. soil-cement thickness with wearing course thicknesses and subbase thicknesses adjusted according to Texas Triax. Method. [323]P and H, Flynn, Andwall-Seaman pulvimixers. [324]Sheepsfoot, wobble wheel and rubber-tired rollers. Contractor may use vibratory or steel wheel if he desires providing 100% compaction is secure. [325]Need better cleaning devices for sheepsfoot rollers. [326]100% passing 3/4 in. sieve and 60% passing No. 4 sieve (may be done while mixing cement). [327]Stringline with tailgate spreaders and uniform truck loading plus frequent checks on depth of cut. All subgrades are placed to grade and section, then resampled prior to mixing with cement. [328]Balloon volumeter or sand displacement density tests and moisture tests after mixing and before and after rolling. [329]Depends on equipment used—8 in. normally. [330]Two 6 in. lifts, results good. [331]Greater the cohesion the thinner the lift. [332]Depends on weather—4 to 6 hours. [333]Proper proportioning of soil water and cement-rapid mixing and compacting and proper compaction. [334]Whenever weather is 40 F and rising—normally all year long. [335]From 0.70-1.25/sq yd for 8-in. compacted thickness depending on cement content and location. [336]Highly satisfactory—local traffic allowed immediately after compaction. [337]Primary Roads: 1½ to 4 in. hot mixed hot laid asphalt; also, 3 course treatment on frontage roads and shoulders. Secondary Roads: 1½-in. hot mix hot laid asphalt or 3 course treatment. [338]Keep cement content to minimum requirements. [339]Periodic resealing of surface. [340]Attempted correlation of soil types with cement contents and attempts to correlate strength tests with brush test. [341]Rational design method similar to portland cement concrete and faster methods for determination of cement contents. [342]Standard tests as outlined by PCA. [343]Use of soil-cement has been when material for base (gravel) has been non-existent = 10 mi overhaul. [344]We find ± 8% satisfactory with our soils. [345]6 in. to replace 12 in. of crushed gravel base. [346]Checked by Kansas highway commission design method. [347](Cohesionless = silty sand), Seamans. [348]Sheepsfoot, wobblewheel and smooth wheel. [349]Non-cohesive soils did not lump up. [350]Field test and predominately the color. [351]Field, density by sand cone, water content by drying with alcohol. [352]Uniformity of materials including cement. [353]About 0.90. Sand 0.11, processing 0.25, cement 0.45, seal 0.09. [354]No. 100—0-20%, No. 200—0-5%. [355]On shoulders only—bituminous concrete 1.5 in. [356]We have not ventured in areas where tannic conditions might be encountered. [357]Prefer sands or friable silts, Would not consider heavy clay. [358]AASHO and PCA standards for test. [359]Would be based on economic consideration for a particular project. [360]Farm machinery such as disc harrows, cultivators on initial project. Later projects used multiple pass stabilizers and blade graders. [361]Sheepsfoot, steel wheel and pneumatic rollers, spike tooth harrow for removing compaction planes. [362]Steel wheel and pneumatic rollers, blade graders, broom drag. [363]80% passing No. 4 and 100% passing 1 in., exclusive of gravel or stone. [364]Moisture and pulverization tests and field inspection for uniform mix. [365]AASHO—standard in-place density. [366]Our experience has been only with 6 in. bases. [367]Elimination of questionable soils prior to processing, moisture control, uniform mixing, proper compaction and curing. [368]0.75-1.00 per 6 in. depth per sq yd. [369]As surface treatment not specifically for curing. [370]1 day—with soil curing cover. [371]Adequate moisture should be provided to keep surface continuously moist. Important to have adequate water distribution equipment. [372]No experience. Would depend on traffic and subgrade conditions per standard design practice. [373]Prime—0.1-0.5 gal/sq yd. MC-0, MC-1, RT-2, IE-1. 1st seal—0.25-0.5 gal/sq yd. RC-2, RC-3, RT-5, RT-6 (rate varies per project AE-5, AE-6 (25-50 lb S. P. No. 6 top size 1 in.) and subject to engineer). 2nd seal—0.2-0.35 gal/sq yd. RC-2, RC-3, RT-5, RT-6, AE-5, AE-6 (20-35 No. S. P. 78) (Top size ¾ in.). [374]Cracking is inherent to this type of construction. An established crack pattern denotes adequate rigidity. [375]No experience. Have used this surface treatment on soil-cement bases. [376]Resealing as warranted by traffic abrasion and spalling at cracks. [377]Pavement thickness design. Better and more practical lab tests than freeze-thaw and wire brush. [378]The only construction of this type by this department was on one urban street during 1939, but there are no records now available concerning the work done. Research on Soil-Portland Cement Stabilization is now in process by this division as of 2/5/60. [379]The Michigan State Highway Department has had little direct experience with soil-cement stabilization. The results of that limited experience were not too satisfactory. Some of the counties in Michigan are using soil-cement stabilization quite extensively with varying degrees of success. The Michigan State Highway Department has determined by tests that the use of a well graded base course containing an appreciable amount of crushed material provides adequate load bearing capacity. Consequently, we do not anticipate any soil-cement stabilization in the near future. [380]Includes tests from only 3 projects. [381]Only tests for 2 jobs. [382]Freeze-thaw and wet-dry durability tests. (Standard Methods). [383]Soil Groups: (1) A-1, A-2, A-2-5 and A-3—14% loss max. (2) A-2-6, A-2-7, A-4 and A-5—10% loss max. (3) A-6 and A-7—7% loss max. [384]In general, if cement requirement exceeds about 12%, it is not likely to be economically justified. [385]6 in. on all except 1 project. 1 secondary project was constructed of cement treated base (4% cement) with 8 in. and 10 in. sections. [386]Empirical. It is estimated that 6 in. soil-cement base will sustain spring axle loads of 6-7 tons. [387]With aggregate base, would use approximately 100% more thickness of granular material than soil-cement. [388]In-place mixing: P and H Stabilizer; Wood Mixer; Bros. Preparator; Seaman Mixer with water trucks. Prior to 1951 farming methods used on 3 projects. [389]Central mixing plant. Sheepsfoot rollers, crawler type tractors, pneumatic rollers, pad type vibrating compactors and vibrating rollers. [390]Nail drag, broom, motor grader, pneumatic-tired rollers and steel rollers. [391]Same equipment as used with cohesionless soils. [392]Sheepsfoot roller not satisfactory for granular aggregates. [393]The cement spreaders used have not been satisfactory. Mix-in place machines should be required to accomplish 1 cycle of dry mixing of cement and soil before water is introduced. Uniform application of water is difficult to control with most machines. [394]100% pass 1 in. sieve and 80% (by moist weight) pass No. 4, exclusive of stones or fragments of old bituminous surfacing. [395]Before introducing water, sufficient mixing to prevent formation of cement balls. Cement spread on road is checked on a 1-sq yd area. On central plant a calibrated metering device measures cement and aggregate belt is calibrated. [396]100-120% of opt. moist. Base shall not be unstable for compacting and finishing. [397]Not less than max density minus 5 lb. [398]AASHO T 134-57 and T 147-54 moisture. [399]The thickest lift we have used is 6 in. [400]8 in. base—two 4 in. lifts; 10 in. base—6 in. and 4 in. lifts. [401]5 hr from the start of mixing to the completion of compaction. [402](1) Uniform cement spread, (2) sufficient mixing of soil and cement before addition of water, (3) uniform application of water, (4) compaction control, (5) finishing to prevent shear plains, (6) excessive moisture when using vibratory compactors, (7) joint construction. [403]Sand passing No. 4—100%, passing No. 40—0-40%, passing No. 100—0-5%, No. 200—0-2%. [404]15 No. 1 sq yd max. [405]1-in. temporary road mix; 1- to 2-in. plant mix in following year. [406]Not satisfied with cracking. [407]Yes, limited traffic—perhaps 2,000 vpd. [408]Yes—transverse: 5 to 30 ft interval. [409]Longitudinal: very irregular, sometimes as many as

3 or 4 in pavement width. [410]No, excavation of very few cores at cracks indicates that cracks penetrate the base only about 2-3 in., do not extend all the way through the base. [411]Not positively. Central plant mixed jobs look better. [412]Indications on young jobs are that it may help. [413]Crack filling and faulted joints. [414]A 23.776-mi project was constructed in 1939 using 9% cement by volume; later covered with approximately 2½ in. of hot mix sand asphalt. Still in use. Present traffic—1,740 ADT. [415]Approximately 2,308,016 sq yd. Soil-cement base completed. Eight (8) projects (approximately 884,500 sq yd) now under contract. One project cement treated material being used as subbase and 9 ft cement-treated shoulders. This project is on the primary system. [416]Ranges from trace to approximately 6 in. in North Mississippi. [417]Freezing and thawing, wetting and drying, and compressive strength in early jobs. Now—compressive strength only, unless retrogression in strength at older age is indicated. [418]Complete physical and mechanical analyses to approximate starting point for cement percentages to use in tests. [419]Alternate bids are received using mechanically stabilized base of 8 in. compacted thickness vs 6 in soil-cement base in areas where the two types of base are competitive. From 6-12% approximately depending on location of project. [420]Mississippi being a sedimentary deposit primarily has over 100 major geologic soil combinations on the surface. Some areas do not have any sand gravel deposits. Extensive areas of heavy clays are encountered in other areas. Except for soft limestone, crushed stone is not available in Mississippi. [421]6-in. compacted thickness on all jobs. [422]Arbitrarily used 6-in. compacted soil-cement equivalent to 8-in. clay gravel base. [423]P and H and scarifier (when necessary) and Seaman Mixers. [424]Sheepsfoot and self-propelled pneumatic-tired rollers and self-propelled tandem (present practice) vibratory roller used on several late jobs. [425]Motor patrol, harrow, pneumatic-tired roller, smooth-wheel roller. [426]Scarifier, disc, harrow, P and H, Seaman Mixers. [427]Sheepsfoot and pneumatic-tired rollers. [428]Motor patrol, pneumatic and tandem rollers. [429]A-4 plastic (PI 10) (nothing retained on No. 10 sieve). About worst soil mixed with cement to date. [430]More thorough pulverization on plastic, fine-grained soils. [431]90% pass No. 4 (exclusive of material-gravel—retained on No. 4). [432]Field laboratory on each job made gradation, density, thickness and cement yield tests. [433]Tests for total water and the sand method. [434](1) Thorough pulverization, (2) Start mixing soon after cement spread, (3) Compact to maximum density at optimum or slightly below, (4) Do not allow to dry before application of curing material. [435]Emulsified asphalt (Miss. EA-4) diluted with 100% water and applied. [436]Use concrete or coarse sand with some retained on No. 40. Some projects where local traffic must enter, 6 in. selected material for turn-around areas and crossovers to protect cement-treated base. [437]Heavy equipment or loads not permitted on soil-cement base during protection and cover period (7-day minimum). [438]9 ft cement surface treated shoulders, 1 course 150-200 pen. A.C. at application 0.30-0.40 sq yd, followed immediately by 0.50 cu ft 1¼ in. max size aggregate (can be slag, stone or gravel); second application of 150-200 pen. A.C. at 0.27 to 0.35 gal sq yd immediately covered with 0.25 cu ft ½ in. max size aggregate (can be slag, stone or crushed gravel). [439]On secondary roads: few jobs received approximately 2½ in. sand asphalt hot mix. Most projects received double bituminous surface treatment described under 6a(1) for shoulder surfacing. [440]Traffic density and type determined kind of surface. [441]Heavy delta gumbo A-6-7 embankment tends to have some longitudinal cracking near edges. [442]When placed on heavy clay soils and not supported by layer of granular material, at least 6 in. compacted thickness; but where embankment is low volume change material, cracking does not seem to be too detrimental to structural integrity but is unsightly. [443]Compacting mixture at or slightly below optimum seems to reduce cracking and severity of cracks. [444]Helpful but some reflection cracks eventually come through thin bituminous mats. [445]Seal about every 6th year using approximately 0.28 gal of 150-200 pen. asphalt cement /sq yd and 0.23 cu ft ½ in. down crushed aggregate (stone, slag or gravel) /sq yd. [446]Project recently completed in Delta area where sand clay topping material is scarce. Treated top 6 in. of embankment soil (A-6-7) with hydrated lime, then added portland cement. This 6-in. compacted layer used as the subbase. Better than 65% pulverization obtained (passing No. 4). [447]Missouri river area, north central edge of Ozarks, extreme Southeast Missouri. [448]I conforming with ASTM C 150.

[449]ASTM D559-57 and D560-57. [450]Soil-cement losses during twelve cycles of either wet-dry or freeze-thaw shall conform to the following limits: Soil Groups A-1, A-2-4, A-2-5 and A-3 not over 14%; Soil Groups A-2-6, A-2-7, A-4 and A-5 not over 10%; Soil Groups A-6 and A-7 not over 7%. [451]Built before we adopted a thickness design method. [452]We haven't since none has been constructed since adoption of a thickness design method. [453]Woods mixer, P and H 1-pass stabilizer, Flynn Machine. [454]Pneumatic and flat steel-wheel rollers. [455]Motor grader, broom drag, pneumatic and flat steel-wheel rollers. [456]Woods Mixer supplemented with tiller, P and H 1-pass stabilizer, Flynn Machine, plows, disc harrows, cultivators and rotary tillers. [457]Motor grader, nail drags, spike tooth harrows, pneumatic and flat steel-wheel rollers. [458]Yes, except with mixer that elevates material from windrow. This machine is inefficient if overloaded. [459]Traveling plants that elevate material from windrow cannot be overloaded and must be supplemented with other equipment. [460]By observing the mixture for the full depth of treatment from time to time. [461]Not more than 5 lb below max density. [462]Adequate mixing and water distribution. [463]Only where it is used by traffic during curing period. Any approved sand, 12 lb/sq yd. [464]3-4 in. of asphaltic concrete (hot-mix) depending on the traffic. 2-in. bituminous mat (cut-back asphalt and aggregate). [465]Seal coat of penetration asphalt (1st appl.), RC-1 (2nd appl. for color differential), and cover materials; makes about ¾ in. [466]As illustrated by Hveem, Figure 31, HRB Bul 187. [467]Varies considerably with temperature—7-14 days. [468]The finer the texture, the closer the crack pattern. [469]Not shrinkage cracks. We have made a practice of pouring these cracks which eliminate the main danger of surface abrasion. [470]But understand PCA advises they can be minimized by compacting slightly on the dry side of optimum moisture. [471]We have had to resurface several jobs that had only a seal coat or light bituminous surface originally. [472]$398.00 annually (based on 1950 figures). [473]Crush to ¾ in. max with 25% of minus No. 4 pass No. 200 mesh from designated sources. [474]Sulfate concentration based on optimum moisture (0.25% of optimum by weight). [475]Except to avoid using highly alkaline soils. [476]Minimum of 350 psi in 7 days Freeze-Thaw Test (Standard). [477]Freeze-thaw and 7 and 28 day compressive strength. [478]1-6 (1) Primary 0.60 ft and 0.50 ft. 1-6 (2) Secondary 0.50 ft. [479]HRB Soils Classification, Vol. 4-5 with Montana Revision 12/15/55. [480]Seaman Rotary Mixers and Central Mixing Plants. [481]Self-propelled pneumatic and steel-wheel rollers and vibropack. [482]Motor patrol blade and steel-wheel rollers. [483]Till a minimum of 80% of soil passes No. 4 sieve exclusive of gravel retained on No. 4 sieve. [484]Not more than 6 hr after cement is added until completely processed. [485]Not during season of probable freezing and temperatures above 40 F and rising. [486]Minus ¾ in. soil-cement aggregate. [487]0.25 ft comp. in two 0.125 ft courses of two bin plant mix. [488]0.20 ft comp. depth—1 course—1 bin plant mix. [489]Except for freezing and thawing prior to plant mix (surfacing). [490]Filling pavement cracks with bituminous material. [491]Very low—yes, low-x. [492]Not available as all projects are less than 2 years old. [493]The last soil-cement base course constructed by this department was in 1947, and we therefore cannot provide information on any projects which were built under more recent methods of construction. [494]All but two projects in eastern ⅓ of state. [495]Moisture-density relations, wetting and drying test and freezing and thawing test. ASTM D-558, D-559 and D-560. [496]Wetting and drying, freezing and thawing and unconfined compression test results. [497]5 in.—30 mi., 5-8 in.—4 mi, 6 in.—43 mi, total 77 mi. [498]Followed general recommendations of PCA. [499]Considered higher strength material and to have better load distribution. [500]Flynn roadbuilder, disc harrow and pike tooth harrow. [501]Sheepsfoot rollers, pneumatic-tired rollers, 6½ ton tandem roller. [502]Blades and pneumatic-tired rollers. [503]Flynn roadbuilder, Jaeger traveling plant mixer and Barber-Greene Mixer. [504]Sheepsfoot rollers, pneumatic-tired rollers, and tandem steel-wheel rollers.' [505]Optimum—determined by laboratory tests. [506]Uniform mixing, time of laying, moisture content and compaction. [507]Minimum of 3 in. of asphaltic concrete. [508]Double Armor Coat would be minimum RC-2 or 3. Cover aggregate-gravel, 20-30 lb/sq yd. [509]Some patching and seal coating. [510]1 job, 2 mi using dune sand and 6% cement—1949 6 in. thick. 1 job, 6½ mi using in-place base and surfacing 8 in. thick put through preparizer. 3½% cement—layed in two 4 in. courses, 1955. [511]Comprehensive (compressive-?) strength, freeze, thaw. [512]Comprehensive strength

(compressive-?). [513]Based on required thickness crushed gravel. [514]Both jobs soil-cement used on account of scarcity of gravel. [515]Harrows, gang plows and blader. [516]Sheepsfoot and steel rollers. [517]Blader, pneumatic roller and steel roller. [518]Decreasing quantity of cement helps. [519]Any appreciable amount of top soil will prevent hardening of the soil-cement. [520]The addition of calcium chloride (up to 1% by weight of soil) will overcome this condition usually. [521]Cubes for compressive strength, cylinders for compressive strength. Density tests. [522]Min 250 psi in 7 days, 400 psi desirable. [523]Project consisted of widening the existing roadway. Shoulders were widened 5 ft on each side 9 in. deep. [524]Soil-cement was constructed to same thickness as original 9-6-9 pavement. [525]Hetherington-Bemer set up as stationary plant, having water tank and belt with strike-off bar. [526]Two Jackson vibrators, grader and 3-wheel steel roller. [527]Shoulder machine, box with adjustable strike-off bar, and grader. [528]Need more accurate control over materials and water. [529]By using Hetherington-Bemer mixing machine. [530]Proper preparation of materials and due regard for weather. [531]Bank run sand, 10 lb/sq yd. [532]Not closed except during construction period. [533]Either asphaltic concrete or ⅝ in. pea stone seal. [534]Central and south New Jersey—Hunterdon, Burlington, Monmouth, Ocean, Cape May, Salem. [535]Leadabrand short test method. [536]Soil-cement at 6 in. [537]Road graders to scarify. Pulvimixers to pulverize. [538]Sheepsfoot, rubber tire and steel wheel (both tandem and 3 wheel). [539]Road grader, rubber-tire and steel-wheel rollers (tandem and 3 wheel) broom drag. [540]Visual sampling and inspection during dry and wet mixing. [541]Optimum ± 2% depending on season of year. [542]No stated time interval, all construction operations are continuous. [543]Adequate equipment and maintenance, properly trained operating personnel, supervision and inspection. [544]$1.225 with 11% cement by contract (1959). [545]½ to 1 gal per day or as required. [546]⅜-in. crushed stone or gravel at 15 lb/sq yd. [547]First application: RT 1 or 2 at 0.25 gal/sq yd and 15 lb ⅜-in. crushed stone or gravel; second and third application: RT 7 or 8 at 0.30 gal/sq yd and 30 lb ⅜-in. crushed stone or gravel. [548]First application: MC^0 at 0.20 gal/sq yd or RC 3 at 0.25 gal/sq yd plus 15# ⅜-in. crushed stone or gravel. Second application: MC 2 at 0.40 gal/sq yd or RC 3 at 0.25 gal/sq yd plus 25# ⅜-in. crushed stone or gravel. [549]Standard specification for hardness, soundness, etc. [550]Standard AASHO methods: Class A—min 650 psi at 7 days and Class B—min 300 psi at 7 days. [551]Class A—650 psi min at 7 days and Class B—300 psi min at 7 days. [552]This study has not been made. However, it would depend on length of haul of materials suitable for construction without treatment. [553]Primary (including Interstate) 6 in. basically, under concrete pavement 4 in.; secondary 6 in.; urban 4 to 8 in. [554]Hveem "R" Value Method has been used to determine total thickness of base. However, depth and type of cement treatment is based on other factors such as traffic, locality, existing moisture conditions, etc. [555]1 in. Class B cement-treated base equivalent to 1½ in. untreated gravel. Class A treatment equivalent to 1¾ in. untreated gravel. [556]Woods Windrow Mixer, Plant Mixed and P and H Traveling Mixer. [557]Pneumatic and steel-tired rollers. [558]Woods Windrow Mixer, P and H Traveling and Seamans. [559]Pneumatic and steel-tired rollers, vibrators (plate type). [560]Yes, except Seaman Mixers required at least 4 passes for proper mixing. [561]Materials used have been sands or standard base course aggregates. [562]Visual inspection. No problem here due to types of material used. See 4d. [563]8 in. total in 4 in. lifts—good. [564]Proper moisture content. Finishing details for a smooth surface especially at joints. Limited to temperature min 40 F or when temperature may fall to 40 F within 24 hr. 0.75 to 0.80 /sq yd based on material at $1.20 per ton and cement + processing at 0.35 to 0.40/sq yd. [565]In some cases it is covered with sand for blotting purposes. [566]Water curing is used on cement treatment under concrete slabs to allow fine grading prior to slab placement. [567]Plant mix 3-4 in., 85-100 pen. asphalt. [568]Plant mix 2-3 in., 120-150 pen. asphalt. 2-course surface treatment 120-150 pen. asphalt and MC-5. [569]Transverse—varies with percent cement and material types. [570]Cracking varies with lineal shrinkage of natural material used. This study is not complete nor conclusive. [571]Reflective cracking through the wearing course but does not seem detrimental as yet. [572]Our experience shows min water content to obtain proper density minimizes cracking. [573](1) Relationship of cracking and lineal shrinkage of natural material used. (2) Placement of cement-treated base directly on subgrade with a layer of untreated surfacing between the cement-treated base and the wearing course. This should eliminate or at least minimize reflective cracking. [574]Our only problem seems to be the cracking, although it does not yet seem to be structurally detrimental. [575]Suffolk County, Long Island and Onondaga County in central New York. [576]Organic residue from coniferous trees (pine, hemlock, spruce) would not allow cement-treated soils to harden. [577]By use of 1% calcium chloride. [578]pH, gradation, specific gravity, Atterberg limits. [579]II—Most generally used in the state and specification can be most general. [580]Unconfined compression, freeze-thaw and wet-dry losses after 12 cycles. [581]Min 300 psi unconfined compressive strength and max 10% loss on 12 cycles of freeze-thaw or wet-dry testing. [582]Rule of thumb method wherein we do not start with soils exceeding 30% pass No. 200 sieve or PI greater than 10. [583]We occasionally require ½% calcium chloride to be added to mix. [584]PCA does not recommend less than 6 in. thickness for rigid pavement of soil-cement. [585]Sheepsfoot rollers and/or pneumatic-tired multiple rollers 1 ton capacity with 1,000 to 2,500 lb/tire pressure. [586]10-ton steel-wheel tandem rollers. [587]Sheepsfoot rollers having feet of minimum 7-in. lengths and 5 sq in. flat surface and pneumatic-tired rollers of 10 ton capacity having 1,000 to 2,500 lb/tire pressure. [588]Need of more thorough uniform incorporation of cement throughout the mixture. [589]Most of our so-called cohesive soils are predominately of silt size and therefore are not really lumpy or clod like at beginning of operations. [590]By designating a minimum number of passes at pulverizer initially, with additional passes as required in opinion of engineer. [591]Sand cone method for density control with field drying by gas stove of moisture samples. [592]Uniform incorporation of cement througout mix, proper moisture content, specified compaction requirement. [593]Between $1.15 and $1.30; this includes bituminous seal coat. [594]20-30 lb of No. 1A stone (½ to ¼ in.). This is for stabilized shoulder area. On base course construction we do not place stone chip seal. [595]After wearing surface had been applied. [596]2½ in. AC top (1¾ in. of binder and ¾ in. wear surface). Binder is NYS coarse mix—approximately 4.8% asphalt cement; top coarse is fine mix—approximately 6.5% asphalt cement. [597]Only single shot seal with stone chips. [598]We use single surface seal chip on shoulder and 2½ in. treatment on regular traveled sections of pavement. [599]Shrinkage on expansion but not due to settlement of base. [600]Our stabilized bases have had sufficient structural rigidity. [601]Suggest sufficient cement be used; also, proper compaction and moisture control and curing. [602]Periodic single surface treatments with bituminous material and chips. [603]Coastal plain, piedmont, and mountains. [604]Wet-dry durability tests—AASHO T-135, freeze-thaw durability test—AASHO T-136. [605]Max. loss (%) durability test for indicated soils: A-1, A-2, A-3—14%; A-4, A-5—10%; A-6, A-7—8%. [606]We use the pedological system. See Proc. HRB, Vol. 19 (1939), p. 522, Table 1. Cement for the Iredell "B" horizon has since been established at 16% cement. [607]1 in. of soil-cement = 1⅓ in. of aggregate base course. Factor established by experience. For pavement thickness design, see HRB Research Report 16-B, pp. 73-77. [608]Seaman, Wood and P and H Mixers. [609]Sheepsfoot and pneumatic rollers. [610]Pneumatic and steel-wheel rollers. [611]Moisture by visual inspection; density by in-place density tests. [612]Correct amounts of cement and water, thorough mixing and adequate compaction. [613]Generally April-November, lowest temperature is 40 F. [614]$1.06 for 12% by volume based on $6.00 per barrel for cement and $0.35/sq yd for processing. [615]BST 0.2 gal MCO prime, 0.4 gal APO, 42 lb stone, 0.3 gal RC-2, 25 lb seal stone. [616]Heavy clay soils crack more. [617]Replacing thin wearing surfaces that permit water to penetrate and freeze. [618]Soil-cement base was constructed from shoulder to shoulder of the road bed, but narrower on secondary. [619]Extreme temperatures during summer may reach 100 + F and also lows of -40 F during winter. [620]Textural Class. Fine sandy loam BPR soils group A-2-4 (0). [621]No. 140 (0.105 mm) 45 to 49. [622]Total specimen weight loss by ASTM. Wet-dry and freeze-thaw tests. [623]% of weight of specimen lost in accordance with ASTM specifications. [624]Used ASTM specifications in accordance with PCA recommendations. [625]Soil-aggregate—9 in. base thickness. Soil-bituminous—6 in. base thickness. [626]Pettibone-Wood Traveling Mixer. [627]Self-propelled pneumatic-tired roller. [628]There was tendency to operate beyond the capacity of the machine so the pug-mill would become choked. This, however, is no fault of the machine. It appears to operate satisfactorily when loaded properly. [629]Our soil was 100% imported and it was cohesionless but the specifications required 80% of the soil by dry weight exclusive of gravel or stone has to pass a No. 4 sieve for cohesive soils. [630]The soil was placed in windrows of known cross section by use of a spreader box. Then bulk cement was charged into the windrow at a predetermined rate directly from the cement bulker. [631]Not more than 2%—age points above optimum moisture content. [632]The average density of the base constructed on any one day shall not be less than the max. density as obtained by AASHO T-134 minus 5 pounds. No individual test shall have a density less than the max. minus 10 lb. [633]Eliminating or avoiding compaction planes and the method of making construction joints. It requires good procedure in the finishing operations to obtain a smooth riding surface. [634]June 1-Oct 1. Varies from year to year because of temperature differences in fall of year. [635]1st job let in 1955 cost $0.98/sq yd. 2nd job let in 1956 cost $1.23/sq yd. [636]Sand at 20 lb/sq yd, 100% pass ⅝ in. sieve, 90-100% pass ¼ in. sieve and 0-20% pass No. 100 sieve. [637]2-in. asphalt concrete wearing course 150-200 pen. asphalt. [638]Both random longitudinal and transverse. [639]Some minor cracking developed during construction but most of it during 1st winter. [640]No experience, but it is believed delayed placement would not eliminate "reflection" cracking. Bituminous overlays on old concrete pavements bear this out. [641]$650. per mile average per year for the first 4 years of its life. [642]Portland cement and air-entraining portland cement. [643]AASHO T-135-57 (ASTM D-559-57). AASHO T-136-57 (ASTM D-560-57). [644]No strength criteria. Allowable loss of durability criteria: A-1-a, A-1-b, A-2-4, A-2-5, A-3—14%; A-2-6, A-2-7—None; A-4, A-5—10%; A-6, A-7-5, A-7-6—7%. [645]Use minimum amount of cement that results in meeting "Durability requirements[644]." [646]Soil-cement projects have not included alternate methods of construction. [647]Primary roads—subbase, 3 and 5 in. Secondary roads—base, 6 in. [648]Based on experience with general construction of this type. [649]Farm tools, P and H and Seaman Traveling Rotary Type Mixing Machines. [650]Smooth wheeled tandem roller. [651]P and H and Seaman Mixers gave good results. [652]Farm tools not generally satisfactory. [653]Not less than 5 lb below wet weight specified by the engineer based on field density tests. [654]AASHO T-99-57T (ASTM D 698-58T) and actual field drying of moisture samples. [655]Uniform mixing of cement with soil. [656]$0.99/sq yd (latest available information). [657]Bituminous surface treatment or bituminous road mix surface course. [658]Spongy subgrade responsible for cracks observed. [659]Eliminate or avoid spongy subgrade. [660]Rapid and severe weather changes and variations. [661]% combined silt and clay 10-45. [662]We have used only clean sands and silty sands. The top soil has been excluded. [663]Short-cut method proposed by PCA for soils containing less than 55% combined silt and clay, and less than 20% clay. [664]Compressive strength is used on PCA curves. [665]8 in. on primary roads, 6 in. on rural roads. [666]We use same thickness design as that determined for soil-aggregate base course. [667]Disc, harrow, motor patrol, grader, water truck equipped with spray bar, mechanical spreader, traveling plant (single pass type). [668]Sheepsfoot, pneumatic-tired and steel-wheeled rollers. [669]Motor patrol grader, water truck with spray bar steel-wheeled roller. [670]Density by rubber balloon volume meter. Moisture content by drying a sample. [671]Asphalt emulsion prime coat applied immediately after finishing. [672]Saturate surface to prevent absorption of bitumen. [673]At engineer's discretion after 7 days curing. [674]Double bituminous surface treatment. Total 200-250 pen. asphalt = 0.55 gal/sq yd. Total No. 1 cover = 1 C.Y./60 S.Y. Total No. 2 cover = 2 C.Y./140 S.Y. [675]Do not participate in airfield construction. [676]Shrinkage cracks develop with curing and drying of soil-cement course. [677]Cracks in surface are usually too narrow for raveling to develop heavily traveled lanes sealed during warm weather. Seal can be effected with light treatment of emulsion or road oil. [678]Does not eliminate but helps. [679]Bituminous seal coats over secondary surfaces. None to date on asphaltic concrete. [680]Average annual mean temperature 48F. Average annual freeze-thaw cycles 60 F. [681]Failure to harden properly in curing. [682]In several cases a $CaCl_2$ additive failed to give desirable hardening. [683]Color—avoid gray or black soils (organic). [684]Air-entraining portland cement—normal strength. [685]Seven day unconfined compressive strength test. Freeze-thaw test (12 cycles). [686]300 psi min 7-day unconfined compressive strength 12 cycle freeze, thaw, losses max. A-1, A-2-4, A-2-5, A-3—14%. A-2-6, A-2-7, A-4, A-5—10%. A-6, A-7—7%. [687]For A-1-a, A-1-b, A-2-4 soils the "short-cut test procedures for sandy soils" (modified) has been recently adopted. [688]6 in. base on secondary roads, 4 and 5 in. shoulders on existing primary roads. [689]A 6-in. soil-cement base was used in place of an 8-, 9- or 10-in. crushed aggregate base course. [690]Motor grader, multiple-pass rotary mixers, traveling plant (formerly used farm type equipment such as harrows, etc.). [691]3-wheel steel rollers and pneumatic-tired rollers. [692]Motor grader, broom, steel wheel and pneumatic-tired rollers. [693]We have not used cohesive soils in any quantity. [694]There is a need for more use of single pass traveling plants. [695]Uniform spreading of cement, having soil in a uniform loose condition at time of cement application, control of moisture content, color. [696]Various tolerances based on optimum moisture content AASHO T-134. [697]100% of max with a 5-lb tolerance. [698]Observations of other construction indicate 8 in. [699]Two 3 in. layers—too thin with our max. size aggregate. [700]Obtain thorough pulverization of soil, equal distribution of mixing of cement with soil and water, highest possible density, careful curing. [701]With department forces $1.01/sq yd using 50% borrow and 50% site soil. Contract project $1.20/sq yd, 40% borrow, 60% site soil. [702]Sand percent pass: No. 200 (0-6), No. 100 (5-30), No. 50 (40-75), No. 30 (65-90), No. 16 (85-98), No. 8 (100). [703]After placement of wearing surface. [704]P.D.H. specs: CP-2, 2 in. road mix surface; AT-1, 1 in. road mix surface. [705]Existing primary roads (surface treatment—0.3 gal bituminous per 25 lb chips). New construction primary roads (P.D.H. spec.—ID-2 binder course). [706]Most construction was performed by department maintenance forces. They used a surface treatment with which they have had experience. [707]Any failures investigated appear to have no relation to the common transverse cracking. [708]Careful curing appears to reduce the size of cracks and spread them over a larger area. [709]It will be assumed that soil-cement shoulders were surfaced unless otherwise indicated. [710]Coastal, central and upstate. [711]Clay in excess of 40%. [712]Poor stability and considerable cracking of the base. [713]Increased cement content helps. [714]Type I (1 job—Type III). [715]Durability tests: wetting-drying and freezing-thawing. These tests were run on samples compacted to optimum moisture content as determined by Proctor density curves. Wetting-drying cycle consisted of 8 hr wetting at 70 F, followed by 16 hr drying at 400 F. Freezing-thawing cycle consisted of 8 hr wetting at 70 F, 16 hr freezing at 0 F, 8 hr thawing at 70 F, and 16 hr drying at 400 F. [716]Wetting-drying and freezing-thawing tests on samples compacted to optimum moisture content and containing various amounts of cement. [717]Primary—base: 6 in. - 46.8 mi, 5 in. - 15.1 mi; subbase: 5 in. - 5.1 mi, 4 in. - 2.7 mi; shoulders: 6 in. - 7.5 mi, 5 in. - 1.1 mi. Secondary—base: 5 in. - 13.0 mi, 4 in. - 6.4 mi. Urban—base: 6 in. - 0.7 mi, 5 in. - 1.7 mi. [718]This process is generally not used with cohesionless soils. [719]Scarifier, disc harrow, road machine, cement spreader, turn plow and water spreader. [720]Sheepsfoot roller, road machine (smoothing), pneumatic-tired roller. [721]The compaction of the top layer of soil, so that it is smooth, is difficult. The final compaction of the soil-cement has been done in some instances with a tandem roller. However, the top portion of the soil-cement was not properly bonded to the base, and scaling sometimes resulted. [722]Max lump size 1 in. in diameter. [723]By color in some cases. Laboratory analysis has shown the method to produce uniform mixing. [724]The moisture content which was desired was the optimum moisture content determined in the laboratory by the Proctor density method. Soil samples were tested every 500 ft, or more often if the soil type changed. [725]Samples were compacted in a Proctor mold and weighed. Then the samples were dried on a hot plate, and dry densities were determined. The moisture content and dry density were then compared to the Proctor curve to see if the section was ready to be compacted. [726]When constructing the soil-cement in sections, as was our usual practice, the "turn-arounds" gave trouble. There was danger that the heavy equipment might break the previously compacted section or that excess soil might be mixed with the soil-cement at these places. Rain can cause a section of uncompacted soil-cement to become too wet. In that event, if the section had not dried to near optimum water saturation within the specified 8 hr compaction period, the section might be ruined. Priming was necessary in order to achieve a good bond between the bituminous wearing surface and the soil-cement base. The surfacing might ravel at the edges if the surfacing was not terminated some 6 in. short of the edge of the soil-cement. [727]The surface was primed within a few days with tar or cut-back asphalt. Sand was placed on the prime to form a temporary wearing surface. [728]Surfacing requirements: 0.4 gal/sq yd of 150-200 pen. asphalt (over prime), 32# of aggregate, RC-2 asphalt seal with 22# of fine stone. The thickness of the wearing surface is approximately ½ in. [729]Heavy clay soils produce the most cracking. [730]Nearly all soil-cement cracks, but the jobs generally are satisfactory. [731]A few very small unstable areas in some roadbeds have been treated. [732]No specific criteria. The cement content chosen is the most economical one which shows the best comparative results. Standard AASHO. [733]4 to 13% by weight depending on type of material. [734]6 and 8 in. on all primary roads. 4 and 6 in. on secondary or county roads. 6 in. has proved adequate for secondary traffic, 8 in. for heavier traffic. [735]In cases where alternates have been taken with clay gravel, 8 in. of soil-cement was considered equal to 12 in. clay gravel. [736]Seaman mixer, P and H stabilizer. [737]Sheepsfoot roller, pneumatic roller and vibrating roller. [738]Motor patrol, spike tooth harrow. [739]Motor patrol, spike tooth harrow and pneumatic roller. [740]Mixing is done at the same time as pulverization—80% passing No. 4. [741]By uniformity of spreading cement and visual inspection of mix. [742]From 1 to 2% above optimum according to soil type and weather. [743]Sand density cones and field determination of moisture. [744]Greater thicknesses can be built in cohesionless soils. [745]Eliminate unstable subgrade uniformity of cement spread and mixing. [746]No seasonal limitation—40 F and rising. [747]Emulsified asphalt, SS-1 cut with 50% water. [748]Plant mix—½ in. down limestone with 40% natural sand. AC 85-100 pen. seal—½ in. down limestone 8-12 lb/sq yd tar, cutback or AC 200-300, 0.2-0.3 sq yd. Surface treatment—¾ in. down min aggregate 12 lb min sq yd tar, cutback emulsion, 25-50 gal sq yd. [749]Bituminous double surface treatment (see footnote 748). [750]Heavier soils have close pattern. [751]Pavements under traffic 18 yr have no structural failures. [752]High penetration asphalts minimize cracking. [753]Very low maintenance—reseal from 4 to 8 yr. [754]Quantities furnished by PCA. [755]These figures not broken down by base, subbase or shoulders. [756]We have treated soils of all kinds of gradations. [757]Punching-shear and unconfined compression. Methods will be printed in New Design and Testing Manuals. [758]Most old job designs were based on judgment. Hope to use triaxial and cohesiometer methods in the future. [759]Sometimes. Real thick bases are reduced on the bases of cohesiometer values. [760]Methods will be in New Design and Testing Manuals. [761]Sheepsfoot, vibratory and rubber-tired rollers. [762]The usual, plus squeeze casts in the hands. [763]Avoid poor design, mixing, compacting and curing. Prevent raveling under traffic. [764]Aggregate number 10, 1 cu yd/100 sq yd. [765]Causing pumping and freeze-thaw damage. [766]No soil poorer than A-2-4 used. Every project varies in grading analysis. A-2-4 to A-1-a soils used—we remove all + 3 in. material. [767]Study underway by Utah State University at Logan, Utah in cooperation PCA. [768]Strength P.S.I. at 7 and 28 days. [769]Thicknesses vary considerably, depends on local conditions (from 3½ to 8 in.). We use what we term a cement treated base course (soil-cement) 2% by weight, not for strength but to upgrade our crushed gravel base course. We find that we do, however, obtain slight beam strength not used in design. (See PCA Cement Content vs Thickness.) [770]When satisfactory materials are in place on the roadway or shoulder and grade lines are not to be altered, we use road mixing equipment. All projects where we import or transport for cement-aggregate or soil-cement, we require plant mixing for better control. Practically all interstate projects will have a 6 in. ± cement treated base 2% ± by weight, plant mixing. Road mixing and plant mixing machines. [771]Tamping, steel wheel and pneumatic. [772]Standard motor graders, laying machines and sprinklers. [773]Yes, with right and rigid controls. [774]Types of soils A-2-4 to A-1-a pulverize very easily, not difficult to obtain complete pulverization. [775]By thorough spreading of cement, water and mixing. [776]Optimum as required for mixture. [777]Must be laid and in place 4 hr after addition of water. Correct distribution of cement, thorough mixing, compacting and other rigid construction controls. [778]Varies according to location and quantity of cement specified. Including all materials and complete in place with 4% cement 0.50/sq yd. [779]RC-1 liquid asphalt or RS-2 emulsified. [780]Sand or friable fine material at traffic crossings. [781]3 in. min hot plant mix using 85-100 or 120-150 pen. asphalt. [782]Road mix using MC-3 liquid asphalt and plant mix using same as primary. [783]Used for same as any other granular base for asphalts. [784]Not as a surface, only used in base. [785]30-90 days in mixtures of 5-10% cement by weight. [786]Not if cracks are properly filled and maintained in climates of freezing and thawing actions. [787]Reduction in cement lean mixtures, 2-4% show less cracking. Rich mixes like PC concrete, we have arrested crack reflection by placing a 4 in. thickness of dense crushed gravel (non-plastic) between cement base and bituminous surfacing. [788]2,000 ft by 40 ft by 6 in. runway (proposed for 1960 construction). [789]7 mi times 20 ft times 6 in. (E. Haven Access Road) (proposed for 1960 construction). [790]We are not sure at the present. Additon of 1% $CaCl_2$ on one isolated project seemed to work. However, in the future we will try to analyze the soil chemistry. [791]Non-hardening of the soil-cement mixture. [792]Addition of 1% $CaCl_2$ by weight of dry soil. [793]Contract project—freeze-thaw. Maintenance and force account—Pick and Click and/or compression strength. [794]Contract project—soil-cement loss (%). Maintenance and force account (Pick and Click) hardness and sound at 7 days. Compressive strength at least 300 psi at 7 days. [795]It is my opinion that 16% is the max. [796]Normally we use 15-24 in. of gravel base course for our secondary roads. We use 12 in. of selected borrow with the top 6 in. soil-cement. [797]3-wheel, 10 ton roller (steel) rubber-tired rollers, capacity unknown. [798]We have trouble with rutting when rolled with heavy rubber-tired rollers. [799]Visually checking for uniform color of soil and cement. [800]Not less than 5% below max density. [801]Moisture content by alcohol drying. In-place density by sand cone method. [802](1) Premixing, (2) Mixing of soil and cement, (3) Max of 0.5 gal/sq yd of water per shot during wet mixing, (4) Seal as soon as possible. [803]May 1-Nov 1 (temperature min 40 F). [804]0.81 to 1.04/sq yd (not including wearing surface). [805]Sand cover, ⅝ in. to 100%; No. 4, 85-100%; No. 100, 0-8%. [806]We sealed as soon as compaction operations were completed. [807]Blade mix using ¾ in. max stone MC-3, RC-3 blend with sand seal. [808]We've used a blade mix over most of our soil-cement projects. [809]It is considered to act as a semi-rigid base and not as a slab. [810]Only retreatment of wearing surface every 3 or 4 years. [811]$4,000/mi every 4-6 yr. [812]Soil-cement is rather new to us and we haven't considered any research programs yet. [813]The soil-cement mixture does not harden. [814]Cap the sections which contain organic material with select borrow and stabilize the borrow material or add $CaCl_2$ (0.6% by weight of cement) to soil and cement. [815]Designed strength of 500 psi and ASTM methods. [816]From 6-8 in. one primary project with 12 in. base (8 mi) 8 in. to 15 mi. All other 6 in. [817]Arbitrary 6 in. depth for secondary roads, CBR method for primary roads. [818]One pass or multipass pulvimixers. [819]Motor graders, brooms, harrows and rubber-tire and steel-wheel roller. [820]Sheepsfoot and rubber-tire rollers. [821]Need better pulverizers for heavy clays to prevent large clay balls. [822]Until 80% of soil mixture passes the No. 4 sieve. [823]Take moisture samples and run in-place density tests. [824]8 in. (with longer feet on roller). [825]Proper and uniform amount of cement, thorough pulverization, proper compaction at optimum moisture and good finishing and curing. [826]Some in the pass, none since 1954. [827]RC-2-AEM-1 or 2 and MC-1 or 2. [828]¾ in. down or coarse sand. [829]Prime, 80 lb drag and seal 1½ to 3 in. of bituminous concrete. (Plant Mix). [830]Double surface treatment or 1½ in. of bituminous concrete. [831]Interstate—3 in. plant mix. Primary—prime and seal. [832]Erosion control of coarse sand along the beach of a large river. [833]Cracks the surface but does not appear to weaken the base. [834]We can minimize the cracks by delayed placement of the surface or by using a drag treatment. [835]Patching occasional weak spots in the base soon after construction and sealing the surface after 2 or 3 yr. [836]These figures are miles of equivalent 2-lane roadway. Also built are 55 mi of widening, ramps, frontage roads and truck lanes. [837]Rainfall extremes: East—7½ in. - 25 in., West—15 in. - 135 in. Temperature extremes: East—-20 F - 110 F, West—+10 F to 100 F. Max frost pen.: East—54 in., West—25 in. [838]Weather conditions differ on either side of Cascade Mountains. [839]The limits shown include practically all soils used. [840]Lack of compressive strength in treated material. [841]None, other than rejection of material which fails to develop sufficient compressive strength in laboratory tests. [842]Compressive strength tests (7 day) on test cylinders fabricated in laboratory by methods similar to attachment No. 1 in Footnote 223. [843]850 psi compressive strength at 7 days. [844]6 in. (occasionally 5 in. thickness used where subgrade conditions are unusually good). One short trial section of 8 in. thickness. [845]Total cover depth over subgrade is modified by reducing base thickness in the ratio of 1 in. CTB = 1.5 to 1.75 in. of untreated base (within total cover depth of 15-30 in. resp.). See attachment No. 3 in Footnote 223. [846]Future construction will be limited to stationary plant methods except for unusual construction conditions. [847]Road Mix: Seaman Mixers; Central Plant Mix; Barber-Greene, Pioneer and Cedar Rapids. [848]Jackson and Lima vibratory compactors, steel-wheel tandems and 3-leggers, rubber-tired rollers. [849]"Tight blade" and compaction with steel-wheel rollers. Sealed with SS-1 emulsion. (See Footnote 850). [850]Disc, plows and harrows (1938) Barber-Greene Travel Plant in 1947. [851]Blade finished, sealed with MC-2. Note: Early experimental jobs only—no treatment of such soils since 1947. [852]Road mix—no; central plant—yes. [853]Formerly by visual inspection and specification. Now, by electrical conductivity method of determining cement content. [854]As high as possible and still allow compaction. [855]95% of standard, determined by "Maximum Density of Coarse Granular Material." (See Footnote 223). [856]Moisture—alcohol burning method; density—by Washington densometer. [857]Two 3-in. lifts (apparently successful). [858]Maintain moisture content; do not attempt compaction on yielding subgrade; avoid excessive final "trimming" or recompacting trimmed material. [859]$1.30 (4.5% cement-mixed in central plant). [860]To accommodate localized traffic and access to driveways, road crossings, etc. where necessary. [861]Generally ⅝ in. or ¼ in. minus cover stone—22 lb/sq yd. [862]Minimum of 3 in. asphalt concrete in 2 lifts (paving grade asphalt 85-100). [863]Min of 3 in. asphalt concrete or plant mix. [864]Experience confined generally to one soil type. [865]Transverse, longitudinal ladder and alligator. [866]Note: Transverse appear soon after construction—1-2 months. Longitudinal and ladder generally appear following a prolonged period of cold weather. [867]Experience confined to one soil type. [868]Transverse, no. Longitudinal, ladder and alligator, yes. [869]Not in cement-treated material. [870]Some possible evidence that it does. [871](1) Timely sealing of all reflection cracks. (2) Provision of positive drainage through shoulders where needed. [872]$60.37. Based on 30.17 mi of 2-lane roadway over a 5-yr period (1953-1958). Average age of pavements in 1958 = 6 yr. Includes sections with extremely heavy logging traffic. [873]Continued evaluation of electrical conductivity method of determining cement content. [874](1) Construction methods and/or equipment which will eliminate need for final trimming. (2) Investigation of inter-relationship of molding water content, density and compressive strength. (See Footnote 223). [875]Southern, southwestern, central and western. [876]High acid sands—pH 4 or less. [877]Eliminate their use as much as possible. [878]Stabilometer, cohesiometer, unconfined compression, freeze-thaw durability. [879]At least 300 psi compressive strength at the end of 7-day cure. [880]PCA guide, percent by weight of material between No. 10 and 100 sieve. [881]Cohesiometer and stabilometer. [882]Soil-cement or cement stabilized base is considered to have a gravel equivalent of 1.6 (6 in. of soil-cement = 9.6 in. gravel). [883](1) Pettibone-Wood Preparizer (for pulverizing soil), (2) Adjustable cement spreaders, (3) Water trucks, (4) Seaman Mixers. [884]3-wheel, 10-ton roller. [885](1) Greater (for shaping), (2) Drag broom (for removing loose aggregate). [886]By maintaining even spread from spreader box and maintaining even depth of mix. [887]Field density and moisture tests (densometer). [888]Compaction accomplished as quickly as possible after completion of mixing. [889](1) Proper gradation of particles (keep aggregate under 2 in. and enough fines for mortar). (2) Proper moisture content, compaction and curing. [890]Penetration seal 25 lb/sq yd on some and 1 in. hot-laid asphaltic concrete on some. [891]Old bases—honey combed, new bases—hair line. [892]New—12-24 hr, old—1-2 yr. [893]Cohesive soils, honey comb more. [894]Permits surface water to penetrate subgrade. [895]Performance studies on existing soil-cement bases relating performance to subgrade, gradation, percent cement and wearing courses. [896]Slow hardening of soil-cement mixture. [897]Tests indicate that $CaCl_2$ in amounts up to ¾% by weight of aggregate may counteract effects of high organic content. [898]Freezing and thawing—(ASTM D 560), wetting and drying—(ASTM D 559) unconfined compression. [899]Those suggested by PCA in their Soil-Cement Laboratory Handbook. [900]Soil-cement considered for base course only. About 10% cement would be considered max to be competitive. [901]On early projects—discs, harrows, blades. On more recent work—pulverizer-mixer type machine. [902]Cat-tractor, pneumatic and steel-wheel roller. [903]Proctor compaction and sand-cone density tests. [904]Uniform dispersion of cement in soil-aggregate moisture control, compaction, curing. [905]Apr-Oct (Inclusive) require 40 F + temperature. [906]Not standardized. On past experimental pavements used

2-in. hot-mix (120-150 pen.) and 3-in. road-mix (SC-3) mats. [907]Closely-spaced (4-10 ft interval) transverse cracks. [908]Not detrimental on projects to date. However, create problem of sealing narrow openings, and are unsightly. [909]Base treatment extends across roadway, thereby forming the shoulders. [910]There have been city projects and airport work in Wyoming but another agency would have to be contacted. [911]Had occasion to use no other methods other than physical. [912]Unless high sulfate condition exists. [913]First method used was the standard durability test. After experience had been obtained laboratory strength tests are now used. [914]First method—standard wet-dry, freeze-thaw durability test. Loss of weight from brushing determined cement requirements as specified in standard methods for soil type. Now the strength criteria is used and set at 300 psi (gravels and sands only). [915]6 in. is used as a standard and subbase soils are varied. [916]Modified CBR and Hveem Stabilometer. [917]Interstate construction—no. Primary roads have had the sections reduced in 3 cases using soil-cement construction due to the better bearing value and slab action. [918]Woods Machine (travel plant), Barber-Greene, Cedar Rapids and Boardman Plants. [919]Sheepsfoot, steel pneumatic, D-6 Cat and vibratory steel rollers. [920]No soils considered very cohesive in construction as yet. [921]Need: (1) More accurate cement metering device on plants and (2) A fast method of field check for cement content. [922]Visual, calculations and cylinders made in the field to check strength. [923]Squeeze test, visual, compaction tests and density tests. [924](1) Keeping proper moisture content. (2) Curing. (3) Keeping finishing operations in order with hardening time. [925]Approximately 0.66/sq yd with 4% by weight cement (without haul). [926]Where traffic immediately uses road 40 lb/sq yd 3/8 and 1/2 max chips with MC-3 at 3.2 lb/sq yd (Inv. pen.). [927]Where necessary open it as soon as cover material is placed. [928]Curing seal should be maintained at all times. [929]With the exception of northeast Wyoming the soil-cement projects have been constructed within the last 3 years and have required no maintenance. Northeast Wyoming would be an erroneous cost since we do not attribute the failures to the soil-cement. [930]It has been noted that delayed mat placement minimizes crack formation; however, it does not eliminate it entirely. [931]In the northeast area, any road failure was not attributed to the CTB, but to subbase failure. We assume that in 7 years maintenance has been negligible. [932]Detailed statistical information is not available to this Association (PCA). The total yardage of soil-cement in Australia is approaching 6,000,000 sq yd. Note: Additional questionnaires were sent to the PCA to be sent out to all agencies in Australia who have carried out soil-cement work. The Australia PCA has completed those parts of the questionnaire on which they have some useful information and experience. [933]Typical sulfate attack—swelling and disintegration of test cylinders. [934]Avoid use of soils containing sulfates or organic acids. $CaCl_2$ has been tried but not always with success. [935]pH test sometimes done to check failure of test cylinders. [936]Experience only with normal portland cement. [937]Under normal circumstances a compressive strength test only is used. Cylinders are moulded in standard Proctor moulds at standard AASHO compaction. They are extracted from the moulds, cured 7 days, soaked 4 hours and then crushed. [938]For hardened soil-cement an unconfined compressive strength of 250 psi is specified. For cement modified soils the reduction in plasticity is measured and this should be less than 6 in a typical case. [939]When PRA classification is known reference is made to PCA "Soil-Cement Laboratory Handbook," otherwise purely trial and error. [940]There is a marked tendency to the use of cement-modified soil with cement factors of less than 4%. [941]Generally 6 in. but sometimes 5 in. for roads. In airfields up to 12 in. [942]Based on flexible pavement design—different methods are used in each state but most are based on CBR curves. N.S.W. has unique system but leads to similar results. [943]Assumed that 6 in. soil-cement with unconfined compressive strength of 250 psi at 7 days (4 hr soak) equals 8 in. flexible pavement determined by design methods mentioned in Footnote 942. [944]Seaman Pulvimixer, P and H Single Pass Stabilizer, "Rotomobile" (Australian designed machine). [945]Pneumatic-tired rollers, vibratory rollers. [946]Smooth-wheeled rollers, power graders. [947]P and H single pass stabilizer, "Rotomobile," pulvimixer. [948]Sheepsfoot rollers (not commonly), pneumatic-tired and smooth-wheeled rollers. [949]Pneumatic-tired smooth-wheeled rollers and power graders. [950]Not entirely—difficulties occur in pulverizing heavy clay soil with the new "Rotomobile," a high-speed rotor coupled to a 100 horsepower motor appears to improve pulverization of all types of soil. [951]So that at least 80% will pass $^3/_{16}$ in. sieve. [952]Sampling material as mixed at various depths and locations and testing for unconfined compressive strength. [953]In situ density test using sand displacement, then drying and weighing. [954]Absolute minimum but usually up to half an hour. [955]Proper mixing and thorough compaction—sometimes difficult because of poorly compacted subgrades. [956]All year round except in Tasmania—construction restricted in winter. [957]6-in. compacted soil-cement includes cost of cement, between $0.40 and $0.90. Average $0.55/sq yd. [958]Quarry dust or sand. [959]Where available petroleum tar sometimes used; unsatisfactory results experienced with light coal tars. [960]In hot arid areas of south Australia curing is a problem—necessary to apply curing medium as soon as possible after compaction—the same day or next morning. [961]2 in. dense graded bituminous macadam. [962]Single flush seal 80-100 pen. asphalt 0.30 gal/sq yd, $^3/_4$ in. aggregate at 1 cu yd to 75 sq yd. [963]1 in. premixed bituminous macadam. [964]Varies but normally rectangular. [965]Soils of low shrinkage limit appear to crack more than granular soils—they have cracked prior to mixing with cement. [966]Many engineers will not accept soil-cement because of this cracking. [967]By reducing the cement factor. [968]Probably, but no definite information—cracks have been reflected irrespective of delay in sealing. [969]Bituminous resealing. Very little maintenance has been required otherwise. [970]CB'r and BB'w (Thornthwaite classification). [971]Slow curing and low compressive strength. [972]The use of $CaCl_2$ in laboratory tests (not applied till now on the field). [973]Short-cut test procedures for sandy soils, PCA, supplemented in some cases by durability test (only wet and dry). [974]20 Kg/cm^2—280 psi for strength (7 days curing) and the criteria of the PCA for durability (wet and dry). [975]6 in. in all our jobs till now, except 1 with 8 in. in single lift (20 mi). [976]6 in. when CBR of subgrade was $\geq$ 12% (by indication of the PCA of Brazil) (Sao Paulo, Brazil). [977]Because in the soil-cement we consider the cohesion. [978](A-2-4 and A-4) pulvimixer or rotating tiller or PH single-pass (in few jobs). [979]Sheepsfoot on the beginning and pneumatic for finishing. Some contractors beginning to use vibratory roller (smooth wheel). [980]Pneumatic roller and smooth-steel roller. [981]Compaction equipment must be improved. Equipment available in our market is poor. [982](A-2-4 and A-4) according with the requirements of the method referred in 2f. [983]Speedy or fry pan and sand method for density. [984]We do not know because our soils are texturally similar. [985]Good finishing and good priming. [986]USA $1.25 (free change rate $1.00 equals 200 cruzeiros. [987]RC-1 and 2, MC-1 and 2, emulsions. [988] 1-1, 5 l/m^2 (=0.221 to 0.3315 gal/sq yd). [989]Sometimes we put sand when the job traffic goes over the priming. [990]Thickness (1 in. to 1.5 in.) surface treatment or bituminous mix (hot or cold laid). [991]Use of additives ($CaCl_2$, $CaOH_2$). Minimum compressive strength. [992]1 military airfield (subbase), 3 commercial airports, 2 airfields for aircraft manufacturers. [993]Fairly widespread throughout England but little in Scotland or Wales. In England especially in Warwickshire, Worcestershire, Kent, Hertfordshire, Dorset, Hampshire, Norfolk, Surrey, Yorkshire. [994]Upper limit governed by plastic properties of the fine fraction. [995]This is not performed as a standard test for deciding on suitability of a soil for cement stabilization. [996]In the case of alkaline soils (pH 7.0) 2.0% organic matter can be taken as the limiting value. Certain acidic soils having organic contents below 1.0% can still have low strengths. [997]Rarely encountered except in clay soils, usually present as gypsum. [998]Organic matter prevents cement from hydrating and low strengths are obtained. Sulfates cause swelling and cracking of soil-cement when it is immersed in water. [999]No remedy for effect of sulfates. Effect of organic matter can sometimes be overcome by addition of $CaCl_2$. [1000]Determination of pH. Alkaline soils usually harden satisfactorily when stabilized with cement. Acidic soils with organic contents below 1.0% are also usually satisfactory but there are important exceptions. [1001]Ordinary—complying with B.S. 12 for about 95% of the work. Ordinary containing $CaCl_2$ (super rapid hardening) for the remainder. [1002]Ordinary except with organic soils when super rapid hardening is preferable. Cheapest and most readily available. [1003]As described in B.S. 1924: 1957 which includes a compressive strength test and a test for resistance to freeze-thaw. [1004]The strength requirements for soil-cement bases depend on the traffic intensity, the thickness and type of bituminous surfacing and the texture of the soil to be stabilized. For many years in the design of lightly trafficked roads a minimum cylinder compressive strength of 250 lb/sq in. for specimens of soil-cement prepared in accordance with B.S. 1924 and cured at 25 C for 7 days has been used to decide on the cement content required. However, for heavily-trafficked roads there is evidence that higher strengths of the order of 400 lb/sq in. at 7 days are required for the soil-cement base although for use as a subbase the lower strength is still considered adequate. The two durability tests have only recently been developed, and therefore our experience of them is limited but resistances to damage by either freezing or immersion of at least 80% are considered desirable. [1005]The pedological class. has been used to determine depth in a soil profile at which soils suitable for stabilization with cement are likely to be found. [1006]Extremely variable, minimum thickness 6 in., maximum thickness 18 in. [1007]CBR method using curves given in Road Research Road Note No. 20 and curves as yet unpublished for motorway and very heavy traffic categories. [1008]Single pass and multi-pass mix-in-place machines. Pan-type concrete mixers or asphalt paddle mixes for stationary plant work. [1009]Vibrating or rubber-tired rollers together with an 8-10 ton smooth-wheeled roller or the dropping weight compactor—an integral part on Howard single pass train. [1010]Grader used during rolling operations, a light smooth-wheeled roller if dropping weight compactor used. [1011]Mix-in-place equipment as for cohesionless soils but soils with low clay contents can be mixed in paddle-type asphalt mixers and sometimes in pan concrete mixers. For cohesive soils with liquid limits above 40% the Howard single pass train is the only machine that gives good mixing. [1012]Pneumatic-tired and smooth-wheeled rollers or the dropping weight compactor of the single-pass train. [1013]Not entirely—most mix-in-place machines too limited in depth of processing. [1014]Stationary plant mixes require development for dealing with cohesive soils and to give improved output. [1015]80% of the soil excluding stones should pass 3/16 in. sieve. [1016]Visually and by making and testing compressive strength cylinders, also by supervising the mixing time (stationary plant work) and the number of mixing passes (multi-pass work) or the forward speed of the single-pass train. Cement content is sometimes measured on a large job but not often. [1017]Pulverization and mixing of cohesive soil are usually undertaken when the soil is at the plastic limit or one or two percent below this value. With granular soils the moisture content at which pulverization and mixing are undertaken is not particularly critical except to note that the soil should not be saturated. When compacting soil-cement mixes the moisture content should usually be such that the soil-cement is just saturated when fully compacted by the compaction plant available. [1018]The dry density is selected either from a consideration of existing information on the state of compaction of soils that can be obtained with different machines. (Road Research Technical Papers No. 17 and 33) or by special field trials in which the available machines are used. The maximum dry density given by the B.S. compaction test is used as a rough guide to the value of dry density required. [1019]Speedy tester (calcium carbide method) for fine-grained soils or a heating method which is applicable to all soils. [1020]Three 6-in. layers mixed in place. Satisfactory. [1021]About 1½ hr. It is usually specified as 2 hr from the start of mixing at any vertical section to the completion of compaction at this section. It has been found to be more critical to observe this time limit with the cohesive soils than with the granular soils. [1022]Adequate sampling and testing prior to construction—then intimate mixing and most important good construction. [1023]March-October, although some years may be extended throughout the year. [1024]Varying amounts, not more than 3 times a day. [1025]Bituminous emulsion, cut-back bitumen, hot bitumen, hot tar. [1026]Some authorities apply a small amount of water, if spraying with emulsions. [1027]If construction or other traffic is to use the base the bitumen is often blinded with sand, ¼ in. or ⅜ in. single-size stone. In many instances two such treatments are given prior to allowing traffic to use the base. [1028]Usually 3-7 days but on occasion the day after laying. [1029]This section can only be answered generally because a wide variety of surfacing materials has been used. On primary and secondary and urban roads the surfacing varies from 2-4 in. usually consisting of a base course coated macadam 1½ in. - 2½ in. thick and then a dense wearing course such as rolled asphalt. On housing estate roads surface dressings have been used for the first few years, then followed by premixed bituminous surfacing. On one commercial airport a 2½ in. rolled asphalt has been used as the wearing course, with no base course. However, 4 in. of surfacing is more usual. [1030]Yes, to some extent. For example on stabilized cohesive soils a simple surface dressing is not sufficient whereas such a dressing is quite sufficient on stabilized gravel or sand soils provided the traffic is not too heavy. [1031]Suitable for factory floors, playgrounds, footpaths and tennis courts. [1032]On cohesive soils transverse and longitudinal cracks have developed at about 6 in. to 6 ft intervals probably due to shrinkage in drying as a result of an inadequate curing coat. On granular soils the cracks are farther apart. [1033]Avoiding excessively high strengths and insuring good curing methods. [1034]Reflection cracks have not often occurred with the low strengths aimed at in this country. [1035]By Cement and Concrete Association: (1) Investigation of durability of soil-cement and methods of assessing durability by laboratory tests. (2) Measurement of mechanical and elastic properties of soil-cement covering a range of soils. (3) Simplification of testing methods and procedures. [1036]About 6.2 mi subcoat of heavy bituminous during the war. [1037]37.5 mi sublayer of highway in concrete. [1038]Rural roads—279 mi, approximate length. [1039]No gradation limits are imposed. [1040]All types—cinder cement and fly ash cement and mixtures of portland cement and fly ash. All types of cement have been satisfactory. Mixtures of portland cement and fly ash have been economical close to steam generating plants. [1041]We have until now used in France the English standards for soil-cement. [1042]Compressive strength at 7 days of between 12.5 and 25 Kg/cm^2 and also as close as possible to 17.5 Kg/cm^2; after freeze-thaw cycles the strength should not be less than 70% of specimens of the same age not submitted to freeze-thaw cycle. [1043]This is extremely variable depending on the region. Except in the northern region France is abundantly supplied with stone quarries and gravel beds. In the north, fine sand is stabilized with cement (6-10% cement); otherwise gravel is stabilized slightly flexible (about 3% cement). [1044]The most economical mixtures are ¼ to ⅓ portland cement to ¾ to ⅔ fly ash to the soil to be stabilized. [1045]10 cm in sublayers under concrete pavements, 15 cm on other roads. [1046]The 15 cm thickness is the max possible for the actual mixing machines on the market. [1047]It is granted that soil-cement layers are better by ⅓; thus a 15 cm layer is equivalent to 20 cm in figuring thickness of the roadway. The rigidity of soil-cement accounts for this. [1048]Rational design methods are used. [1049]Pulvimixer, Howard train, Wood machine. [1050]Generally pneumatic compactors for fine soils and vibrating compactors, then pneumatic compactors on gravelly soils. [1051]The improvement of the machines themselves appears to be necessary. [1052]Many jobs have been followed up, with experimental tests, by a special crew from the Central Laboratory of Bridges and Roads. Special methods of control were devised and perfected. [1053]About the optimum percentage of water of the modified Proctor test. [1054]95% of the max of modified Proctor for fine soils. [1055]Membrane densitymeters, nucleodensimeters, etc. [1056]At least 50 cm for vibrated gravelly soils; at most 15 cm for fine soils. [1057]30 cm—bad bonding between layers. [1058]Numerous precautions (see French technical literature on this subject, especially Cycled Etudes, Dec. 1959). [1059]At all times of the year except in freezing weather. [1060]\$0.50 to \$0.75/sq yd for gravel. \$1.00 to \$1.50/sq yd for fine sand. [1061]Connecting layers with tar or cut-back. [1062]Sometimes sand or fine gravel but generally nothing. [1063]As soon as the soil-cement is hard enough to support the passage of construction equipment. [1064](1) The soil-cement is covered with a semi-thick layer (5-10 cm) of dense material. (2) Coat of ordinary fine gravel, either a single layer but preferably a double layer. [1065]See French technical literature on this subject. [1066]Until now soil-cement has been used only in a minor way and too recent to be able to derive any valuable experience. [1067]Notably shrinkage cracks in the gravels treated with cement. [1068]From a few hours to a few days. Transverse cracks regularly spaced about 10 meters apart. [1069]These cracks are transmitted to the surface layer which then is no longer impervious. [1070]These cracks vanished by reducing the amount of cement below 3% or by using mixtures of cement and fly ash. [1071]Reinforcement of the hydrocarbon layer of the surface. [1072]Important research is in progress to determine the optimum amount of cement, also on experimental jobs to improve machines and methods. [1073]During World War II only. More than 150 airports unsurfaced. [1074]Retardation of cement hydration (see question 2c(1)). [1075]NaOH—test for detection of organic matter. [1076]Z275, Z375 (equivalent to ASTM Type I) slag cement also used. [1077]Compressive strength crystallization test using Na_2CO_3 freeze-thaw test (ASTM). [1078]1135 psi—28 day strength is sometimes used for subbase on the Autobahn 7, 10 respectively, 14% weight-loss. [1079]PCA short-cut procedure to a limited extent. [1080]6-8 in. (see Question 1b(1)); 5-6 in. (see Question 1b(4)). [1081]Vögle, Linhoff, Seaman, Harnischfeger, Skoda, Ringhoffer, Howard. [1082]Sandy soils—0-2% below optimum cohesive soils—0-2% above optimum. [1083]C-M-Gerät (similar speedy moisture tester), air-pyknometer. [1084]Sandy soils 4 hr, cohesive soils 3 hr. [1085](1) Organic matter. (2) Stability of subsoil. (3) Thickness of construction. (4) Compaction. (5) Water content. (6) Shape and grade of surface. [1086]Curing is only done if warm weather prevails. [1087]Autobahn: 9-in. concrete or 9-in. asphalt. [1088]¾-in. asphalt concrete, on forest roads granular stabilized soil (1-2 in.). [1089]Only in granular soil observed. [1090]If possible construction not during very hot time, thicker surface. [1091]Maintenance of surface seal of cracks. [1092](1) Influence of water content, compaction and cement content to durability and compressive strength of soil-cement. (2) Influence of prolonged mixing. (3) Frost resistance of soil-cement made of cohesive soil, which is modified with lime, before mixing with cement. (4) Investigations on additives to soil-cement. (5) Competitive tests using different types of cement, including Pectacrete cement (hydrophobic). (6) Field research on soil-cement roads using clay soils and very low cement content (5-8% by weight). (7) Field research on modification of soils with lime prior to stabilization with cement. [1093](1) Cause and prevention of cracks. (2) Thickness design of soil-cement roads using soils having granular skeleton, cohesive soils and dune sands. (3) Influence of drainage to durability of soil-cement roads. [1094]About 540,000 sq yd—under concrete pavements (national roads) and as shoulders. Shoulders sprayed with bitumen emulsion and gritted with chippings. [1095]About 1,000,000 sq yd—so-called agricultural roads. [1096]About 85,000 sq yd, including "Typical Dutch" cycle tracks. [1097]The Dutch climate is a so-called temperate maritime climate (temperated by the Gulf-stream). [1098]The soils used in the Dutch soil-cement jobs range from very fine dune sand to well-graded gravel-sand-clay mixtures (old gravel roads), inclusive river sand and gravelous sand. [1099]Dutch sieves generally used, and percent passing, are as follows:

U.S. Sieve	Dutch Sieve	% Passing
2-in.	-	100
1½-in.	-	100
¾-in.	23 mm	100
⅜-in.	11.2 mm	84-100
No. 4 (4.76 mm)	5.6 mm	70-100
No. 10 (2.00 mm)	2.8 mm	56-100
No. 20 (4.00 mm)	1.4 mm	40-100
No. 40 (0.42 mm)	0.60 mm	30-95
No. 100 (0.149 mm)	0.150 mm	6-40
No. 200 (0.074 mm)	0.075 mm	1-5

[1100]Generally not done. [1101]Since only sands (cohesionless soils) have been used, Atterberg limits not determined. [1102]The Dutch procedure for preparing soil-cement is as follows: If a so-called suitability test (with 10% cement by weight) or an examination of the color of the sand (by an experienced road engineer) shows that harmful reactions of chemical constituents or possible, the soil in situ (or in the sandpit) is not to be used but another more suitable sand will be sought, usually in sandpits, at a larger depth. Therefore it is not a general rule to determine the presence of chemical constituents or their chemical and physical properties. The only strength-reducing constituent in the Dutch sands seems to be organic matter. Although we get round "the problem of organic matter" by taking another more suitable sand, sometimes the organic soils have been rendered more suitable by the admixture of about 0.25% $CaCl_2$ (by weight of the dry soil), but mostly it proved to be better to take another soil free of organic matter. As much of all the sands used in Dutch soil-cement jobs have been imported from sandpits and because the amount of organic materials is decreasing with increasing depth of the sandpit, the extra charges are not so much. Nevertheless we are trying to determine the nature of the harmful effects of organic matter in order to develop simple and cheap methods of counter-attack, which will be important for the cement-stabilizations of Dutch soils in situ. One successful method seems to be the application of portland cement (especially high early strength portland cement) instead of slightly cheaper blast furnace slag portland cement, which has been used up to now in all the Dutch soil-cement jobs. The higher CaO content of the portland cement seems to have a similar (or a better) effect as the admixture of calcium chloride. Another successful method may be the preparation of the organic soil by mixing it with a cement-and-water slurry about one day before the actual stabilization. The extra addition of calcium ions seems to have a similar (or a better) effect as calcium chloride, but will be cheaper. Both methods are under investigation, in the laboratory and in the field. [1103]In much of all soil-cement jobs: ordinary blast furnace slag portland cement (content of blast furnace slag about 35%; compressive strength after 28 days, cubes, side 7.07 cm, mix 1:3, conform to the specifications in the Dutch Standard N484: about 7,800 psi = 550 Kg/cm^2). [1104]Laboratory strength after 7 days: 354-429 psi (25-30 Kg/cm^2); the cylinders are made in a so-called Proctor mould and compacted conform to the British Standard Compaction (or Proctor) Test B.S. 1377:1948. It has been determined that a compressive strength of 300 psi (21 Kg/cm^2) obtained with such cylinders is in accordance with the minimum compressive strength of 250psi(17.5 Kg/cm^2) obtained with the normal cylinders (ratio height/diameter = 2), used in the British soil-cement practice. In order to avoid the formation of harmful cracking and especially to prevent the so-called "blow ups" (due to high temperatures) the upper limit of the compressive strength has been fixed at about 430 psi (30 Kg/cm^2). [1105]Soil classification systems are not used, mainly because we have stabilized exclusive sands (and sometimes gravel-sand-clay mixtures as in old gravel roads). However, an experienced road engineer may be able to use the color of the sand as a criterion for its suitability for stabilization with cement. The appearance (color, granulation a.s.o.) of the sand gives an indication of its suitability, and in a certain sense this procedure is a simple sort of soil classification. [1106]Maximum cement content 15% (by weight of the dry soil). [1107]None, except those in preceding answers. [1108]6 in. (15cm) thick subbase under 8 in. (20 cm) thick concrete pavements; two 6 in. (15 cm) thick layers, with 2 in. (5 cm) thick sand between them, as a 14 in. (35 cm) thick shoulder (sprayed with bitumen emulsion and gritted with chippings) along the concrete pavements mentioned above; mostly 6 in. (15 cm) thick bases in so-called agricultural roads (sometimes thicknesses of 5 in. (12.5 cm) and 7 in. (17.5 cm); 6 in. (15 cm) and 8 in. (20 cm) thick bases in urban roads; 4 in. (10cm) thick soil-cement layers in parking lots, cycle tracks, a.s.o. [1109]The much applied 6 in. (15 cm) thickness has been based upon British experiences and practices and the experience obtained with lean concrete bases in the Netherlands. In accordance to the expected traffic loads this thickness is reduced or increased. Sometimes the so-called C.B.R.-method (California Bearing Ratio) for the design of flexible bases, as published by the British Road Research Laboratory in Road Research Paper No. 15, has been used, taking into account that soil-cement has some load distributing capacities, which permit a reduction of 15% and more. [1110]The Dutch soil-cement bases have sometimes the same thickness as the traditional granular bases; in several cases the first have been constructed thinner than the latter and with success. With a soil-cement subbase of 6 in. (15 cm) thickness the concrete pavement could be constructed with a thickness of 8 in. (20 cm) instead of 9 in. (23 cm), like the normal Dutch concrete pavements on a subbase of compacted sand. In secondary roads the thickness of bituminous top layers has been reduced as compared with those in traditional road constructions. [1111]A simple method for the design of soil-cement roads and the relationship between the load bearing capacities of flexible bases and those of soil-cement bases are problems, which are under investigation now. [1112]Mix-in-place (mainly single-pass) about 84%; stationary plant (pre-mix) about 15%; traveling plant about 1%. Preparing and compacting with the so-called Howard-Train (Rotary Hoes Limited, England) by a single-pass mix-in-place method; finishing (and curing) during the same pass by means of a grader, a vibrating beam and a bitumen emulsion spreader, all three attached to the mentioned train. In other cases preparing by means of a so-called paddle-mixer (pre-mix) a Barber-Greene "Travel Plant," agricultural equipment (rotavator, rotary hoe) and sometimes with the help of rakes; compacting with a single-wheel vibrating roller (without and with vibration); finishing—after regulation—with the same roller; on very stable material (gravel-sand-clay) also a vibrating roller with two wheels in use. [1113]Except the mentioned gravel-sand-clay mixtures (old gravel roads, which have been stabilized by means of stationary plants and by multi-pass mix-in-place methods) there is no experience with cohesive soils. [1114]Yes, especially with the so-called Howard trains, which in The Netherlands have been supplied—according to the original ideas of the owner, The Netherlands Land Development and Reclamation Society—with a grader in front and with a grading and vibrating beam and a bitumen emulsion spreader behind the train. Note: In much of all the jobs the Howard train stabilized sand, which has been imported from sandpits. [1115]At first by an examination of the color (has to be uniform); secondly, by comparing the compressive strength of a soil-cement sample, taken from the mixer (or from the uncompacted stabilized road) and compacted conform to the Proctor-test, with the compressive strength of a similar soil-cement sample, which has been re-mixed in a laboratory-mixer and then compacted conform to the Proctor test. The last compressive strength is considered to have uniformity of mixing of 100%. [1116]Mostly the so-called optimum moisture content (conform to the Proctor test). [1117]At least 95% of the so-called maximum dry density (conform to the Proctor test or a little bit lower). [1118]Control of moisture content by means of the C. M. -moisture tester (German made; containing calcium carbide). Control of density by means of a core cutter (the dry density is calculated after weighing the soil and determining the moisture content). If the stabilized soil contains gravel it may be necessary to dig a hole, after which the dry density is calculated after weighing the dried soil and estimating the volume by means of oil. [1119]In 1 lift: compacted thickness about 7-8 in. (17.5—20 cm) at the most. [1120]Yes, the shoulders along the new parts of National Road 4A (concrete pavement with soil-cement base) consist of 2 layers cement-stabilized sand, each 6 in. thick with 2 in. sand between them. Up to now with good results. [1121]The compaction of fine-graded sand (dune sand) needs the use of a pneumatic roller, a vibrating beam or a one-wheel vibrating roller; the use of a smooth-wheel roller or a two-wheeled vibrating roller leads to the occurrence of "cracks" and a not closed surface. The latter two rollers can be used with success for the compaction of sandy gravel. [1122]1-5 hr (using the single-pass mix-in-place method by means of the Howard Train—the problem of the time interval does not raise). [1123]At first the necessity of a subsoil without settlements or with only uniform settlements. Before and after mixing and compaction shaping up and regulating the surface. Note: The two Dutch Howard Trains have been supplied at the front with an equipment which insures the final grading of the soil, and at the rear with a grading and vibrating beam which insures the final grading of the compacted soil-cement. [1124]All the year, except the days with low temperature (below freezing point) and with heavy rains. [1125]Depends on thickness and cement content: premix—$0.60-$1.10/sq yd; traveling mix—$0.50-$0.90/sq yd; mix-in-place—$0.50-$0.75/sq yd, transport of sand not included. [1126]Curing—mostly bituminous material, without wetting the soil-cement before the application. [1127]0.5 Kg/sq meter (about 1 lb/sq yd). After the application of the emulsion the surface is gritted with sand (sometimes with chippings). [1128]After 1 week light traffic (with pneumatic tires) is tolerated (bicycles at an earlier time). [1129]Sometimes the final-type wearing surface is applied after the 7-days curing, but mostly it seems to be more preferable to apply at that time only a binder course on surface dressing, while the final-type wearing surface is applied after a period of about 6 months or more (by preference inclusive a winter-time). [1130]8-in. thick concrete pavement; 5½-in. asphalt for approaches. [1131]On secondary roads (so-called agricultural roads): (a) Asphalt construction (cold process) 50-60 Kg/sq meter (85-110 lb/sq yd); aggregate size 1-12 mm. (b) Binder course of cold asphalt macadam 18-25 mm size (emulsion process and after ½-1 yr a wearing course and/or a sealing coat). [1132]On parking lots and cycle tracks—a single or double surface dressing of a wearing course. [1133]A single surface dressing (sprayed with bitumen emulsion and gritted with chippings). [1134]The thickness of the concrete pavement with a soil-cement subbase has been reduced from 9 to 8 in. [1135]In our opinion, soil-cement is a satisfactory material for all the mentioned purposes (already constructed in our country or not yet). In The Netherlands the major condition seems to be the presence of a subsoil with a satisfactory bearing capacity (without settlement "or with only uniform settlement)." [1136]Transverse cracks at distances of 20-40 ft; sometimes longitudinal cracks. [1137]About 1-2 days after the construction (in our opinion they are produced by the shrinkage due to the hydration of the cement). The single longitudinal cracks must be caused by insufficient resistance of the not-stabilized shoulders or settlements of the subsoil. Note: Remarkably are the so-called "blow-ups", narrow elevations of the soil-cement surface (or of the bituminous wearing surface) in transverse direction and at irregular distances. They occurred during seasons with high temperatures, in soil-cement with rather high compressive strengths and without or with a thin bituminous top layer. Therefore, in the last two years we have limited the 7-days compressive strength to about 430 psi (30 Kg/cm^2) and in several cases "trough-shaped" joints (with at the top a width of 8 in. and at the bottom of 4 in.; afterwards filled with a mixture of sand, 2% cement and 10% bitumen emulsion—both by weight of the dry soil) have been applied successfully. In our opinion such joints, at distances of about 150 ft, are also reducing the number of transverse cracks, which are produced by the shrinkage due to the hydration of the cement and by temperature influences. Another remarkable phenomenon is the fact that in cement-stabilized old gravel (gravel-sand-clay) roads (and to a less extent in cement-stabilized articially composed gravel-sand-clay mixtures) practically not one transverse crack nor "blow-ups" have been detected. In our opinion the present amount of clay is reducing the rigidity of the soil-cement, thus producing a more flexible material and decreasing the compressive strength. Since the cement contents in such stabilization jobs are rather low (about ¾% by weight of the dry soil), we are thinking that the material produced in this way is bearing a resemblance to the so-called cement-modified soils, also because the mentioned gravel-sand-clay mixtures have already a good natural stability under normal conditions. [1138]We do not think that the cracking is detrimental to structural integrity, on account that their width is not too large and that water penetration is prevented. [1139]Limiting the cement content as far as possible, applying the mentioned "trough-shaped" joints and perhaps additioning small amounts of clay, bitumen emulsion, etc. These methods are under investigation now. [1140]Yes, indeed. Therefore, the bituminous wearing surface is, when possible, placed mostly ½-1 yr after the placement of the binder course or (sometimes) of a single surface dressing. In this period the cracks, due to shrinkage, temperature influences, traffic loads and settlements, will occur and their detrimental effects, if any, will be passed when placing the final surface. [1141]Only "leveling" the mentioned "blow-ups." [1142]Up to now very low, but the oldest soil-cement roads in The Netherlands are only 4 yr old. [1143]In our country we have a working party on "Lean Concrete and Soil-Cement", belonging to the Dutch Foundation for Research in Road Construction (Stichting Studie-Centrum Wegenbouw). This working party, started in 1956, is making researches in soil-cement test roads, particularly with regard to: thickness (for developing a simple method of design), minimum and maximum cement content, whether flexible or rigid, the construction of joints, a.s.o. The test results will be published in so-called "S.C.W.-Mededelingen" (of the mentioned Foundation). In 1960 a new committee on "Soil-Cement Problems" has been installed, not as a committee belonging to the Dutch Organization for Concrete Research (Commissie voor Uitvoering van Research), but as a subcommittee of our working party "Lean Concrete and Soil-Cement." The activities of this committee will comprise among other things: "the problem of the organic matter" (the nature of the harmful effects and how to counterattack them) and "the question of shrinkage" (due to the hydration, temperature influences a.s.o.). We have started with a study of the problem "Is it possible to determine the suitability of soils for cement stabilization by means of a (revised) system of pedological soil-classification"; we decided to make similar tests as have been made by Mr. Sherwood of the Road Research Laboratory in England (see Research Note No. RN/3284, "A study of the pedological classification of soils in relation to soil-cement stabilization," August 1958). At the same time we started the study of the problem "Is it possible to stabilize some organic soils and in what way?" [1144]The only soil-cement stabilization that has been carried out to date was a section of the runway at Wanganui Airport measuring 1,100 ft long times 150 ft wide times 6 in. deep. This was done some years ago and the equipment and methods used were fairly primitive. Nevertheless the pavement has lasted very well and is still giving good service. A much greater interest in soil-cement stabilization has become evident in recent months. A contract for this class of work has now been let by Tauranga County and it is anticipated that construction will be carried out in the months of Feb. and March, 1960. The contract comprises the stabilization of 6 sections of secondary road, each approximately 1 mi long and totaling 54,800 sq yd in all. The soil types vary but include a large percentage of pumice. The specification is based on standard Australian practice and calls for a compressive strength of 250 lb/sq in. at 7 days. At Wanganui Airport it is likely that a further section of the runway will be stabilized with cement during 1960. [1145]Our first and only soil-cement job is located at the central part of the island—mountainous region. [1146](1) Compressive strength tests. (2) Wetting and drying tests. [1147](1) Durability equals not more than 14% loss. (2) Volume change equals not more than 2%. (3) Compressive strength equals more than 290 psi. [1148]Short-cut procedures as described on "Short-Cut Soil-Cement Testing Procedure for Sandy Soils"—PCA. [1149]8% cement by volume—11% water by weight. [1150]6-in. compacted depth, ¾-in. plant mix asphaltic concrete wearing surface. [1151]CBR Method and Soil-Cement Construction Handbook from PCA. [1152]It is assumed that 6-in. soil-cement is equivalent to 8 in. water-bound macadam. [1153]Discs, harrows, spike tooth harrows, plows. [1154]D-6 tractors and 3-wheel rollers. [1155]Grader and tire rollers (smooth-wheeled). [1156]Compaction operations are started as soon as mixing operations are through. [1157]Adequate distribution of cement, thorough mixing, uniform compaction. [1158]¾-in. bituminous concrete surface course. [1159]The performance of the job after 2½ yr of service has been very satisfactory. [1160]Cracking is indicative of good curing—hardened cement-soil. [1161]Ceiling of cracks due to settlement of fills. [1162]Now in the region of several hundred miles. [1163]A much greater amount of work has been done with lime stabilization, particularly in Northern Rhodesia. [1164]Soil stabilization has found its main use on main roads. These may carry up to and in some cases slightly more than 2,000 vehicles per day. [1165]A great variation—between 200 in. and 10 in. per annum. [1166]The 3 main climatic groups are: tropical rain forest, tropical savannah, and sub-tropical savannah. [1167]For lateritic gravels; values for quartzitic gravels, respectively, 90-100, 85-100, 75-100, 60-95, 50-85, 45-70, 25-50, 15-45, 10-40, 7-35, and 5-10. [1168]Difficult in handling and compacting—low strength when compacted. [1169]By avoiding soils contaminated with mica. [1170]Some authorities use CBR tests. [1171]Normal portland, sometimes so finely ground that it verges on rapid hardening. [1172]Rapid hardening cements not desirable in the tropics as they bring difficulties in compaction. [1173]Initially unconfined compression tests but now more usually cylinder penetration tests—both to British Standard 1924. [1174]Originally 250 lb/sq in. at 7 days on the unconfined compression test. Now generally 100-160% of CBR at 7 days on specimens compacted to densities equivalent to those obtained in the field. [1175]It is becoming apparent that cement contents in the region of 4% are generally adequate for lateritic and quartzitic gravels used in road bases in the tropics. [1176]Varies with price of cement. In Central Africa it is said that 1% of cement is equivalent in cost to a 4 mi haul. [1177]Generally mix-in-place construction with 6 in. of stabilized soil overlying the same material unstabilized. Base and subbase gravels imported from nearby borrow pits. Thickness of subbase varies according to strength of subgrade. [1178]General experience combined with CBR design. [1179]All known work mix-in-place except for one recent example in West Africa. [1180]Disc harrows, blade graders, are more rarely single pass and multi-pass mixers. [1181]Generally rubber-tired rollers with flat steel rollers to finish. Sheepsfoot rollers are used but are getting deservedly less popular. [1182]Blade graders used for trimming surface—smooth rollers. [1183]With the few examples known, in situ multipass and/or in one case premix with double paddle mixers. [1184]Need is always for simple and robust equipment. [1185]± 2% of optimum for compaction plant. [1186]Visual inspection, various methods for moisture content, sand bottle for density. [1187]Varies. General need in hot climates to compact quickly. [1188]Control of moisture content and of compaction. [1189]Generally in the dry season, or at the beginning and end of the rains. [1190]Varies enormously with price of cement. [1191]Emulsion and fluid cutbacks, the latter preferred. [1192]Generally 0.10-0.20 gal of bitumen/sq yd. [1193]To surface damp condition. [1194]Generally sand, if the bituminous application is so heavy that aggregate is needed. [1195]Curing and priming are frequently combined in one operation. [1196]Prime and single- or double-surface dressing. [1197]Prime and single- surface dressing. [1198]Prime and single-course asphalt. [1199]Prime and surface dressing. [1200]Prime and single- or double-course of asphalt. [1201]Only influences type of primer and the rate of application. [1202]Carrying up to 2,000 vehicles per day. [1203]Where it is the most economic of alternatives, can find use on all airfields. [1204]Block or irregular. With over 5% cement, cracks tend to be large and well spaced. [1205]Gravels—fine, not very regular pattern. Sands—regular block pattern. [1206]Not yet long enough experience but we are worried about the block cracking with some non-cohesive sands. [1207]Careful control over moisture content and curing helps. Keep cement contents as low as practicable. [1208]Routine surface treatments. [1209]Probably lower than with other methods of base construction. [1210]Much of the soil stabilization in the tropics is with gravels which are nearly but not quite adequate as base materials when they are dug. With these materials the main emphasis on present research is in learning more about constructional problems and the way these problems affect design. How, for instance, does the weather affect moisture conditions and how do these in turn affect the standards of compaction which can be achieved? What standards of control over constructional thickness and finished profile can be obtained with different methods of mixing and compaction? This is one of the fields where research and development are most required. A further aim is to pursue the possibilities of stabilizing the more plastic soils which occur in the tropics.

SOIL-CEMENT ROADS IN IOWA

County	Rt. and City	Year Built	Length (mi)	Width (ft)	Depth (in.)	Square Yards	1950 Surveys—Distressed Areas: Square Yards	1950 Surveys—Distressed Areas: Percentage
Wayne	40 - Allerton, North	1937	1.64	26	4	25,016	4	0.02[1]
Cass	83 - near Marne	1938	2.50	26	5	38,113	6,084	16.00[2]
Wapello	15 - Ottumwa N.W.	1940	4.07	24	7	57,476	1,018	1.8[3]
Muscatine	22 - near Muscatine	1946	10.89	24	6	153,289	240	0.16
Monona	37 - Soldier to Turin	1946	9.05	24	6	126,800	2,025	1.6[4]
Fremont	184 - Imogene west	1947	6.8	24	6	96,500	254	0.26
Johnson-Washington	22 - Lone Tree to Rt. 218	1947	6.07	24	6	86,224	300	0.35
		Total	41.02		Total	583,418	9,925	1.7%
Iowa		1954	12.79	24	7	-	-	-
Jasper	117 - Colfax to 64	1957	11.26	22	7	-	-	-
Webster	County experimental	1959	1.00	24	8			
	County experimental	1959	3.00		6 and 8	Soil-cement-lime		

[1]Road in excellent condition at time of inspection. Some repairs have been made in previous years.
[2]Most of this distress is located in a cut area containing excessively wet subgrade and subject to frost action.
[3]Concentrated heavy truck traffic using this road—600 trucks and buses/day during 1949.
[4]No extensive maintenance required to date. Vertical drains have been placed through the base into the subgrade—water seep area

PUBLICATIONS DEALING WITH PROPERTIES OR HARDENING MECHANISM OF SOIL-CEMENT

Respondent	Publication
Idaho	Performance of Cement-Treated Base on Projects ST-3271(504) Smiths Ferry South and F-3271(1) Round Valley - Cascade
	Cement Stabilized Soil Experiment F-3112(1) Strawberry - New Meadows
	Soil-Cement Stabilization, by John K. Stowe, presented at Materials Clinic, March 1954
Iowa	Construction Report, Soil-Cement Base with Asphalt Wearing Surface, from a Point 2,280 Ft. North of Benton - Iowa County Line (End of Conc Paving) to Marengo, Also 6 Blocks of A/C Resurfacing in Marengo
	Jasper County - Summarized Construction Report Flexible Base Course and Type B Asphaltic Concrete Surfacing - Road No. 117, Project F-772(7), 11.257 Miles, Colfax Northerly to Iowa No. 64
Maryland	Reference HRB 1939 "Construction in the Hills of Maryland."
New York	Copy of Specification for Soil-Cement Construction
Tennessee	Copy of Special Provision Regarding Section 45, Gravel or Chert - Cement Base
Utah	Report on Cement Stabilization vs Gravel Base (Not Published Material) by D.F. Larsen
	Research - Cement-Treated Granular Base and Soils, A Report of April 25, 1958 by D.F. Larsen
Washington	Instructions for Sampling Cement-Treated Material (Revised 4-23-57)
	Reprint from Washington 1957 Standard Specifications, Sec. 31 - Cement-Treated Base
	Standard Design Chart for Flexible Pavements, Plate K-4 of Design Standards
	A Method for Controlling Compaction of Granular Materials, by Herbert W. Humphres
	The Effect of Compacted Density on Compressive Strength of Cement-Treated Base, Laboratory Report No. 88, October 1956
	A Discussion of 145 Miles of Cement-Treated Base Constructed Between 1950 and 1958
England	A Tabulation of Road Bases and Subbases - Objective, Present Position and Proposed Future Work and Remarks. (Note: India— "The use of Soil-Cement for Road Construction in India," from Transport Communications Monthly Review, March 1959.
Germany	In English: Reinhold "Elastic Behavior of Soil-Cement Mixtures," HRB Bul. 108, Washington, 1955. Clare and Foulkes: "Soil Stabilisation in Germany." Engineering, Aug. 27, London, 1954.
The Netherlands	Part A of a literature review of soil-cement concerning its general aspects. The Cembureau - organization in Malmö, Sweden has proposed an English translation.

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