5-1972

The Use of Soil-Cement as a Highway Material

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THE USE OF SOIL-CEMENT AS A HIGHWAY MATERIAL

by

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A report submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil Engineering

Plan B

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UTAH STATE UNIVERSITY
Logan, Utah

1972

ACKNOWLEDGMENTS

I wish to express my sincere appreciation to my major professor, William A. Cordon; to my committee members, Professor Derle J. Thorpe and Professor Fred W. Kiefer, for their help in completing this paper.

I also wish to express my appreciation to Mr. Sondhi Limthongkul and Miss Linda Warren who corrected and typed the first draft for me.

My deepest thanks go to my parents and especially to Miss Puang-kaew Sovitayasakul who have given me constant support and encouragement throughout my studies in the United States.

Acknowledgment is also made to the Civil Service Commission of Thailand for their financial support of my education.

Vongchai Jarernswan

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INTRODUCTION

Soil-cement is not a new material; its low cost but high quality make it well-known and the use of this material for highway, dam, and airfield purposes increases every year. The origin of the idea of mixing soil and cement to produce a structural material has not been definitely established; informal records show that mixing soil and cement was tried in Iowa, Ohio, Texas and probably in other places by 1920 (1). Since the first controlled soil-cement construction was carried out near Johnsonville, South Carolina in 1935 (2), soil-cement has been considered a valuable engineering material. It is now an accepted practice to denote the result of adding cement to soil as a soil-cement mixture (3), or in other words, soil-cement is the stabilization of soil with portland cement. This mixture is a simple, highly compacted mixture of soil, portland cement, and water. As the cement hydrates, the mixture becomes a hard, durable paving material (4).

Soil-cement has been much developed during the last two decades; many research and laboratory experiments are continuing efforts to improve its properties and usage. The works of the Portland Cement Association contain many useful sources of information concerned with design and construction methods which are widely used today.

Many engineering institutes developed their own methods which are more sufficient, suitable, and advantageous for use in their specific area yet may be unsuitable for use in other places with different climatic conditions.

The properties of soil-cement have been developed in many countries, and hundreds of research publications are issued on this subject each year; but we need more research in this area because there are many problems that should be solved, for example, the problem of cracking of soil-cement in tropical climates which seriously weakens protection against rainwater penetration.

Soil-cement is now used for many highway purposes, such as the sub-base for rigid pavement, road widening, reconstruction of failing granular bases, etc. These can be built by using the methods to mix, place, compact, cure, similar to those which are used for base courses. Highway ditch linings and slopes may also be paved by using plastic soil-cement.

The purpose of this paper is to introduce the general information concerned with soil-cement where it is used in highway construction. Design for the base of asphalt pavement, which is a primary use of soil-cement today, will be introduced. Because the engineering properties of soil-cement are influenced by many factors, only a few important factors will be introduced. The methods of laboratory tests, design and construction which are shown in this paper were summarized from those that are widely used for general conditions.

MATERIALS FOR PRODUCING SOIL-CEMENT MIXTURES

According to the Soil-Cement Construction Handbood (5), soil and cement mixtures can be separated into three general types.

1. Compacted soil-cement. This mixture contains sufficient cement to withstand laboratory freeze-thaw and wet-dry tests and meet weight loss criteria, and contains enough moisture for maximum compaction. Compacted soil-cement will be referred to simply as "soil-cement", and will be discussed in this paper since it is by far the most commonly used type of soil and cement mixture.

2. Cement-modified soil. It is an unhardened or semi-hardened mixture of soil and cement, only enough cement is used to change the physical properties of the soil to the desired degree; less cement than is required to produce a hard soil-cement. In highway construction modification of silt-clay materials is used to improve unsuitable subgrade and fill materials; modification of granular soils is used to increase the bearing values and reduce or eliminate plasticity of base and sub-base materials.

3. Plastic soil-cement. It is also a hardened mixture of soil and cement that contains, at the time of placing, sufficient water to produce a consistency similar to that of plastering mortar. Plastic soil-cement is used to line or pave steep, irregular or confined areas where it is difficult to use road-building equipment.

Only three basic materials are needed for soil-cement: soil, portland cement, and water (4). In some cases chemical additives such as calcium chloride and sodium chloride, may be used to improve the quality of soil-cement (2). The quantities of portland cement and water to be added and the density to which the mixture must be compacted is determined by standardized tests. Soil-cement obtains its stability primarily from the hydration of cement and not by cohesion and internal friction of materials (5). The materials should be clean and free of organic matters that have lower molecular weights such as nucleic acid and dextrose. The properties as well as purity of these three basic materials affect the quality of soil-cement.

Portland Cement

Any type of portland cement that complies with the requirements of the latest ASTM, AASHO, CSA, or federal specifications may be used. In the United States, Types I and IA (normal and air entraining, respectively) portland cements are generally used (5). In Great Britain considerable work has been done using "417" super-rapid-hardening cement and alumina cement as well as normal portland cement (6). Super-rapid-hardening cement is similar to the U.S. Type III, high early-strength cement; the only difference being that about two percent calcium chloride has been added. The rapid-setting cements are sometimes effective in soils where normal cement is unsatisfactory, since the rapid-hardening cements contain greater amounts of calcium (2).

Water

The water used in soil-cement should be relatively clean and free from harmful amounts of alkalies and acids. Water fit to drink is satisfactory (5). Where fresh water is not available, sea water may serve as a satisfactory substitute. The water serves two purposes (5):

1. It helps to obtain maximum compaction (density) by lubricating the soil grains.

2. It is necessary for cement hydration, which hardens and binds the soil into a solid mass.

Properly designed soil-cement contains enough water for both purposes.

Soil

About 90 percent of the materials needed to build a soil-cement are obtained directly from the site, or from a nearby source in the form of soil. The soil includes a wide range of materials besides surface dirt or earth. Existing material in an old granular base or bituminous-surfaced road frequently may be utilized. Scoria, caliches, limerocks, shell, slag, cinders, shale, windblown, glacial, and beach sands have all been used successfully (7).

Good gradation from course to fine is not needed (7); but experience has shown that soils meeting the following conditions can be hardened effectively through the addition of reasonable amounts of cement (2):

Percent finer than 0.002 mm - less than 35

Percent passing No. 4 sieve (4.76 mm) - greater than 55

Maximum size - 3 in.

Liquid limit less than 50 percent

Plasticity index less than 25 percent.

Classification of soils will follow the AASHO Classification System as shown in Table 1 (18).

Table 1. Portion of AASHO Classification System Divided for Soil-Cement Design Procedure (18).

General classification	Granular materials (35 percent or less passing No. 200)							Silt-clay materials (more than 35 percent passing No. 200)			
Group classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				A-7-5, A-7-6
Sieve analysis, percent passing:											
No. 10	50 max.										
No. 40	30 max.	50 max.	51 min.								
No. 200	15 max.	25 max.	10 max.	35 max.	35 max.	35 max.	35 max.	36 min.	36 min.	36 min.	36 min.
Characteristics of fraction passing No. 40:											
Liquid limit				40 max.	41 min.	40 max.	41 min.	40 max.	41 min.	40 max.	41 min.
Plasticity index	6 max.		NP	10 max.	10 max.	11 min.	11 min.	10 max.	10 max.	11 min.	11 min.
Textural type for soil-cement thickness design procedure	Granular soils					Fine-grained soils					

Additives

The quality of soil-cement has been improved in many cases through the addition of suitable additives. Research at the Massachusetts Institute of Technology Soil Stabilization Laboratory has been conducted to improve the properties of soil-cement by the use of chemical additives. The test results of Lambe, Michaels, and Moh (8) indicate that a very large increase in the strength of soil-cement can be obtained with low-level chemical treatment. Both a considerable financial saving and a successful stabilization of soils which normally cannot be economically stabilized can result from the use of additives with soil-cement. A further advantage of the use of additives is that considerable construction and cure time can be saved because a number of the chemicals accelerate the rate of strength development of soil-cement. The durability tests by Norling and Pachard (9) indicate that the effects of the additives on durability, as measured by the standard freeze-thaw and wet-dry tests, were similar to the effects on compressive strength. The summary of test results from references (8) and (10) will give some idea of the kind of additives for use in some cases.

1. Calcium and magnesium sulfates, in addition to sodium sulfate, are found to be very effective in increasing the strength of organic sand-cement.

2. The silicates of high soda content are very effective in improving strength.

3. Sodium additives considerably increase the resistance of all types of soil-cement to sulfate attack.

4. Sulfate compounds are uniquely effective in improving the strength of cement-stabilized sandy soils containing organic matter.

5. The effectiveness of sodium hydroxide in caly-cement can be materially improved by pretreating the heavy clays with secondary additives.

6. Pretreatment of silty soils with caustic soda diminished the beneficial effects obtained by the incroporation of this additive simultaneously with the cement.

7. Hydroxides or weak-acid salts of any alkali metal or cation which yields soluble silicates (or aluminates) are beneficial to soil-cement.

8. Sodium metasilicate was the most effective on the clean sandy soils.

9. The effectiveness of sodium compounds decreased with increasing plasticity and/or organic matter of the soil.

10. Soil containing free sodium chloride was much less responsive to cement-stabilization than was the same soil after salt removal.

11. The 28-day strength of additive treated soil-cement was virtually independent of additive concentration when the latter was above a certain minimum (0.5 to 1.0 normal).

12. The strength increase of soil-cement due to addition of alkaline sodium compounds appeared to be permanent.

13. With silty soils, the strength improvement produced by sodium additives became smaller at higher cement contents.

14. The magnitude of strength increase obtained by addition of alkaline sodium compounds appeared to increase with the amount of reactive silica (or silicates) present in a soil.

From the study of Arman and Dantin (11) to investigate the effect of dispersant additives on the physical characteristics of soil-cement mixes and layered pavement systems, the tests show that there is a definite increase produced in the shear strength of the layered system by developing a bond between adjacent layers of a soil-cement stabilized system with the addition of calcium lignosulfonate and hydroxylated carboxylic acid for soils of low plasticity with the exception of pure silts. The study of George (12) in search for treatments to reduce shrinkage led to several promising additives; lime and fly ash proved to be the best. Sulfates of magnesium, sodium, and calcium and expansive cement, by virtue of their ability to expand and compensate for the shrinkage, are the second best additives. Pozzolith 8, although less effective than fly ash, improves the workability and therefore enables better compaction, which, in turn, reduces shrinkage. Calcium chloride provides improvement in poorly reacting uniformly graded sands. The tests of O'Flaherty, Mateos, and Davidson (13) found that fly ash can be used either as an additive to, or as a replacement for, cement in friable soil-cement mixtures; the addition of fly ash tends to retard the setting-up of soil-cement mixtures, thus allowing more time for mixing and compacting; also, sodium carbonate can be detrimental over a long period of time to soil-cement and soil-cement-fly ash mixtures containing low cement content. The usefulness of fly ash and/or sodium carbonate as an additive to, or as a replacement for, cement in soil cement is dependent on the available curing time in which the design strength is to be attained and on the availability and cost of the materials at the site.

PROPERTIES OF SOIL-CEMENT

Soil-cement is a tightly compacted mixture of pulverized soil, portland cement and water; during construction it is compacted to a high density. As the cement hydrates, the mixture hardens in this dense state to produce a durable structural slab-like material. It does not consolidate further under traffic nor does it rut or shove during spring thaws. Soil-cement can bridge over local weak subgrade areas. It is little affected by water or freezing and thawing. The cement in soil-cement continues to hydrate for a long time even under traffic, so it has a reserve of strength to accommodate increases in volume and weight of traffic. Because of soil-cement's slab-like character it has high load-carrying capacity which can support up to three times greater loads than other low-cost base material of the same thickness (5).

Soil-cement relations are a complex of physico-chemical properties of soils, of the chemistry of cement and the physico-chemical properties of soil-cement mixtures before, during and after cement hydration. The addition of portland cement to soil to produce a different, improved and unique structural material for engineering purposes is a commonplace practice internationally (3).

Structural Properties

The structural properties of soil-cement depend on many factors and when more research on this field has been done, more information on the factors effecting its properties will be obtained.

Compressive Strength

The physical property to which reference is made most frequently is compressive strength. Although this may not be the most important characteristic of soil cement, many of the factors which influence compressive strength also influence other properties such as durability, flexural strength, shear strength and modulus of elasticity (14). Most tests and experiments have determined the quality and strength of soil-cement by measuring its dry or wet compressive strength. The important factors that effect the strength of soil-cement are:

Soil Type. The type of soil is the most important single factor affecting the quality of soil-cement. In Table 2, typical compressive strength values are given for various soil types stabilized with about ten percent cement by weight (2).

Table 2. Illustrative Values of the Elastic and Strength Properties of Soil-Cement Mixture (2).

Soil	Cement Content Per Cent		Values at 28 days, Moist Cure, psi			
	By Weight	By Volume	Comp. Str.	Mod. of Rupture	Mod. of Elast. Dynamic	Mod. of Elast. Static
Sand	3.8	5	450	110	2.05×10^6	
	6.0	8	800	180	2.75	
	8.5	11	1225	260	3.30	
Sandy loam	3.8	5	300	80	1.40	0.90×10^6
	6.1	8	650	145	2.00	1.25
	8.6	11	1025	215	2.60	1.65
Clayey Sand	5.7	7	475	105	1.30	
	8.3	10	625	150	1.50	
	11.0	13	800	195	1.75	
Silt Loam	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

Quantity of Cement. For any type of soil, strength of soil-cement will increase proportionally as the amount of cement increases. The test result by Vaughan and Redus, of samples of soil in Table 3 is shown in Figure 1 (15).

Table 3. Characteristics of Samples of Materials Available in Borrow Area (15).

Sample No.	Sample	Percent Passing			LL	PI	Max. Dens.	Opt. Moist.
		No. 40	No. 60	No. 200				
1	Clayey sand	100	99	27	30	4	118.0	12.6
2	Clayey sand	97	52	18	25	3	122.7	10.6
3	Sandy silt	99	90	53	29	7	123.6	11.6
4	Silty sand	98	83	13	NP	NP	116.7	11.2

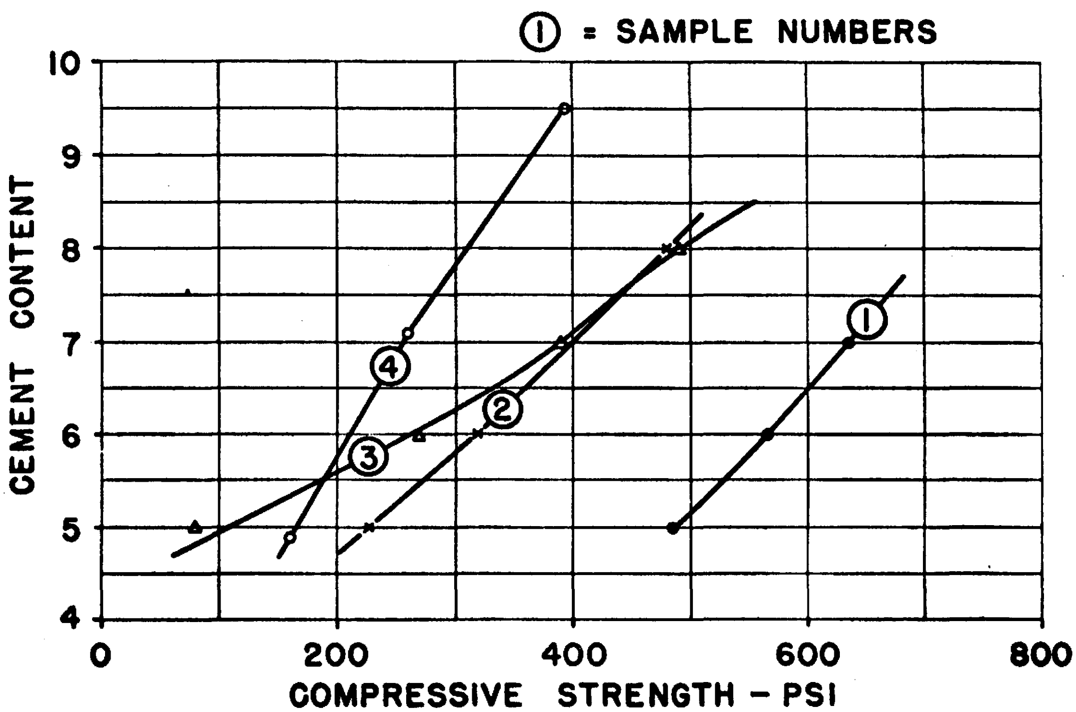

Figure 1. Compressive Strength Versus Cement Content (15).

Water Content and Compaction. The water content at which the test specimens are molded influence compressive strength; the data in Table 4 show that the compressive strength of both the sandy and silty soil-cement is greatest when the material is compacted at a moisture content slightly dryer than optimum (14).

Table 4. Effect of Moisture Content on Compressive Strength (14).

Moisture Content Variation, %*	28- day Comp. Str. psi
Sandy Soil No. 2a-3 + 8 % Cement by Volume D 558 Opt. M.C. is 10.5 %	
-4	600
-2	870
0	770
+2	540
A-Horizon Silty Soil No. 4b-3 + 14 % Cement by Volume. D 558 Opt. M.C. is 22 %	
-4	290
-2	300
0	290
+2	230
+4	200

* Percentage points variation in molding-moisture content below or above ASTM D 558 optimum moisture content. All specimens molded at D 558 Max. density.

Compaction is usually considered in terms of density. The relationship between the density and moisture content of soil-cement, using Yazoo clay in Mississippi, for example, is shown in Figure 2 (15). The maximum density to which a soil cement mixture can be compacted is controlled by the water and air content. In Table 5 the greatest density achieved at ASTM D 558-57 (23) optimum moisture content was about 5 lbs. per cu. ft. above D 558 maximum density. An increase in strength results when additional compactive effort is used to attain still greater densities at reduced water content (14).

Table 5. Effect of Density on Compressive Strength (14).

Density Variation pcf*	28-day Comp. Str. psi
Sandy Soil No. 2a-3 + 8% Cement by Volume D 558 Max. Den. is 122 pcf	
-10	500
- 5	580
0	690
+ 5	780
A-Horizon Silty Soil No. 4b-3 + 14 % Cement by Volume D 558 Max. Den. is 97 pcf	
-10	210
- 5	240
0	300
+ 5	400

* Lb per cu ft. Variation density below or above ASTM D 558 maximum density. All specimens molded at D 558 optimum moisture.

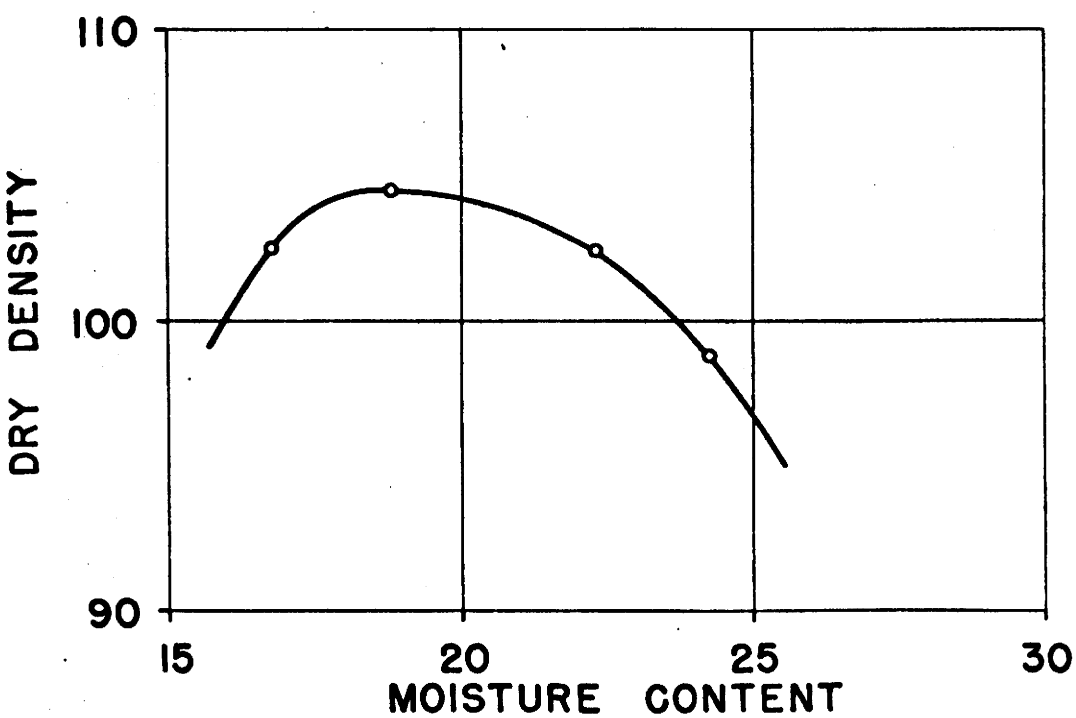

Figure 2. Moisture-density Curve (15).

<u>Curing.</u> Soil-cement was observed to increase in compressive strength with time of curing with a better than random correlation in both a semi-logarithmic and logarithmic manner. From the test of various types of soils representing ages up to five years, indications are that for granular soil-cement (A-1, A-2, and A-3 soil) the best relationship is semi-logarithmic. This is similar to the relationship observed in concrete whose constituents are similar to granular soil-cement. Silty or clayey soil-cement (A-4, A-5, A-6 and A-7 soils) on the other hand, exhibits the closest relationship logarithmically. The data of test are shown in Figure 3 (16).

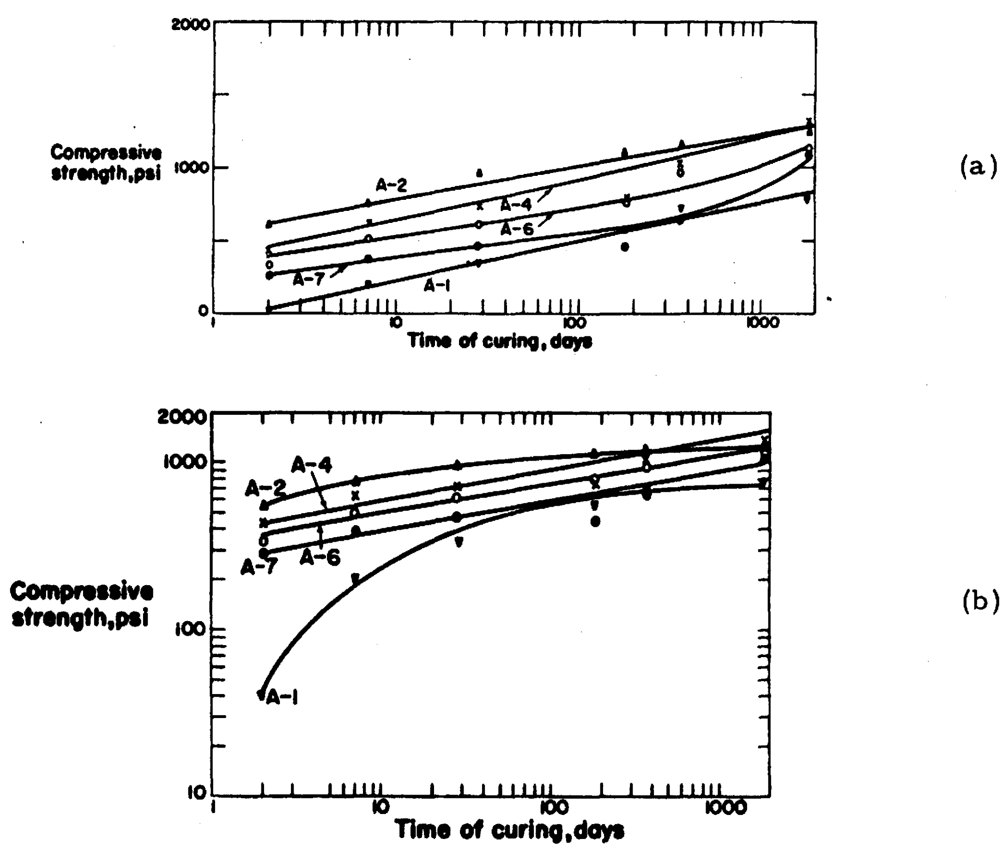

Figure 3. Effect of Curing Time on Unconfined Compressive Strength of Soil-cement Mixtures (16).

Another curing condition that influences the strength of soil-cement mixtures is the curing temperature. The study in this field (17) shows that soil-cement will harden in cold weather provided that the temperature is not below $0^{o}C$. The seven-day strength of soil-cement changes by 2.0 - 2.5 percent with each degree centigrade change in the curing temperature when the latter is near $25^{o}C$; with the cohesive soils, the seven-day strength at $25^{o}C$ was approximately obtained in one day when the curing temperature was raised to $45^{o}C$ but only after 28 days when it was reduced to $0^{o}C$. The nature of the strength/age relationships obtained with the cohesive soils suggests that at temperatures up to $45^{o}C$, one mechanism of hardening is involved and that this is accelerated by increased temperature. At $60^{o}C$ and $100^{o}C$ variable results were obtained with silty clay, consistent with more than one type of mechanism of hardening. The test results of silty clay and clay stabilized with 10 percent of ordinary portland cement are shown in Figure 4 and Figure 5, respectively (17).

Age. Over the design life of a soil-cement pavement the average strength will be considerably greater than the 28-day values, since the cement in soil-cement continues to hydrate for a long time. Figure 6 shows 5-year laboratory strength gain on four projects for various time periods. Cores taken from roads after 15 or 20 years of use show appreciably greater strength than samples tested when the road was built, as shown in Figure 7 (18).

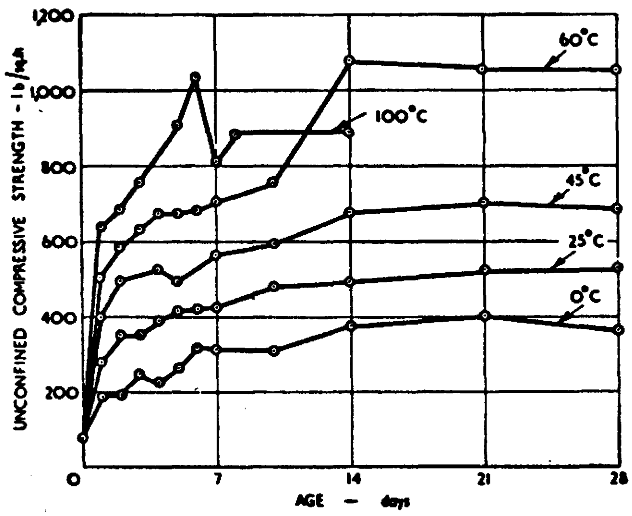

Figure 4. The Relationships Between Unconfined Compressive Strength and Age at Different Temperatures for Specimens of a Silty Clay Stabilized with 10 Percent of Ordinary Portland Cement (17).

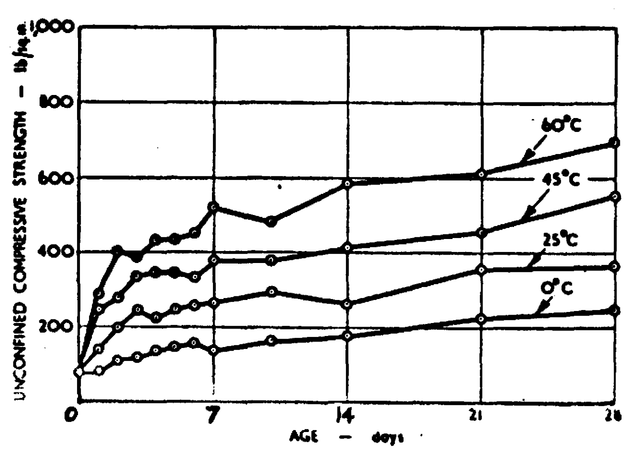

Figure 5. The Relationships Between Unconfined Compressive Strength and Age at Different Temperatures for Specimens of a Clay Stabilized with 10 Percent of Ordinary Portland Cement (17).

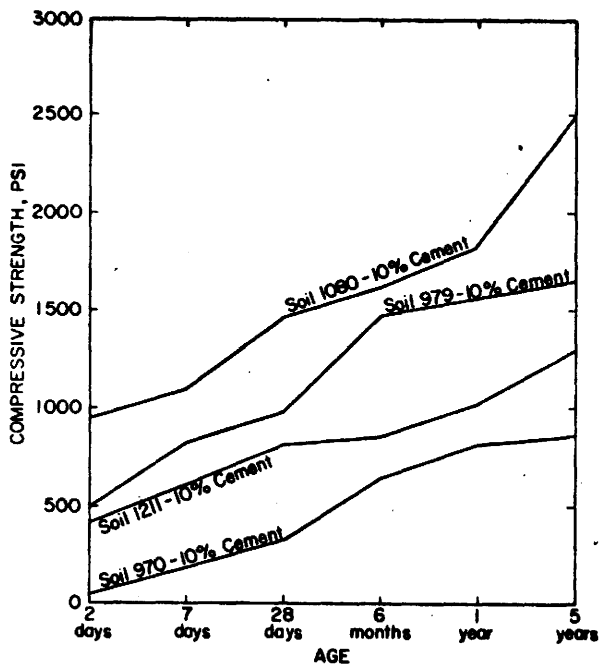

Figure 6. Strength Gain with Age Laboratory Specimens (18).

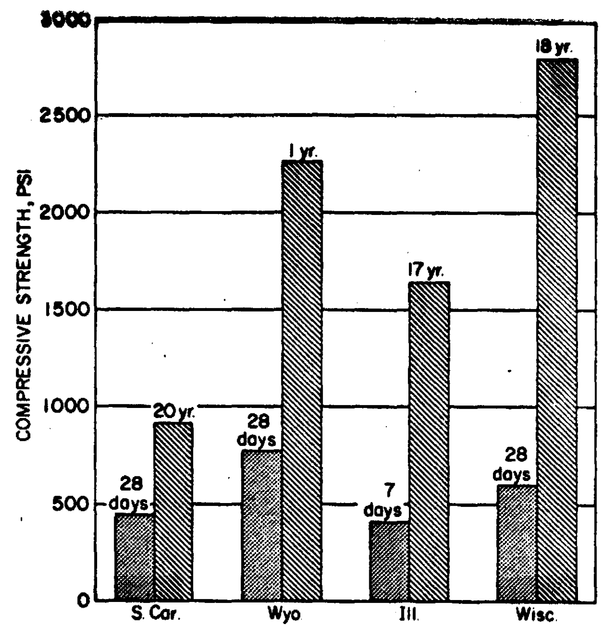

Figure 7. Strength Gain with Age Projects in Service (18).

Modulus of Elasticity

The modulus of elasticity of soil-cement is influenced by all the factors which affect compressive strength. Data in Figure 8 show that the modulus of elasticity of wet tested specimens is greater than and may be even double, the modulus of dry-tested specimens. This trend is in agreement with similar data for concrete; however, the modulus of dry-tested concrete appears to be about 70 to 90 percent of that of wet-tested concrete. It is reasonable to assume that the greater modulus of the wet specimens is due to the low compressibility and confinement of the water in the voids (14).

Test data have been obtained which show that the static modulus of elasticity in flexure is equal to the dynamic modulus computed from

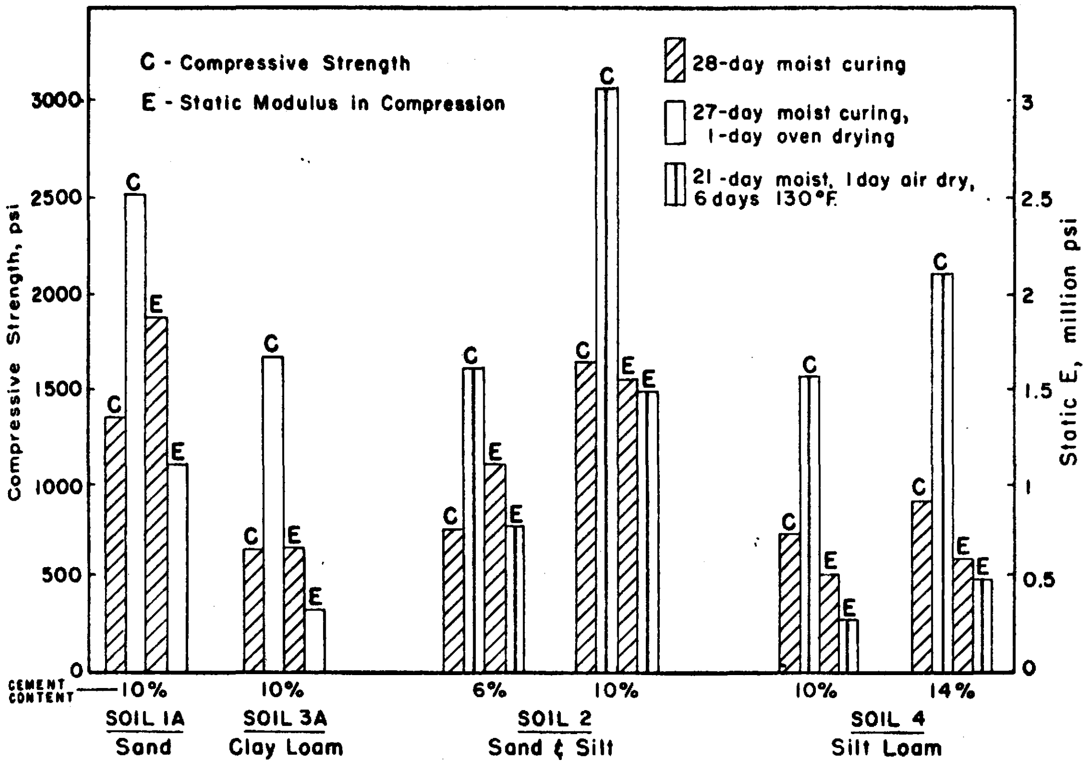

Figure 8. Compressive Strength and Static Modulus of Elasticity (14).

the fundamental transverse frequency, weight and dimensions of the test specimen. Other data show that the static modulus in flexure is a third or more greater than the static modulus of elasticity in compression, as shown in Figure 9 (14).

Representative data in Figure 10 show that the dynamic modulus of elasticity is greater for sandy soil-cement than for silty soil-cement and that with both soil types the modulus increases with cement content and age (14).

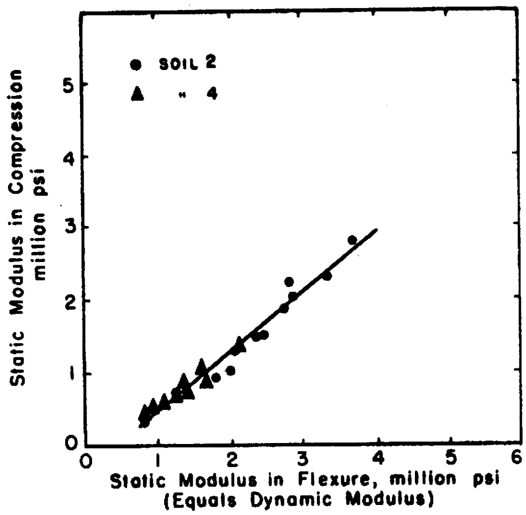

Figure 9. Relation Between Static Modulus in Flexure and in Compression (14).

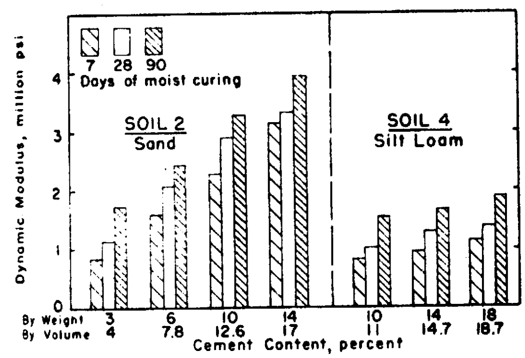

Figure 10. Dynamic Modulus of Elasticity, Soil Type, Cement Content and Age (14).

Modulus of Rupture

Again, the same factors that influence compressive strength affect the modulus of rupture (flexural strength). The strengths as in Figure 11 increase in an orderly manner with cement content made of sandy soil No. 2 are much greater than those of soil-cement made of silty soil No. 4. Data in Figure 12 show that the modulus of rupture of soil-cement is about 20 percent of the compressive strength (14).

Shearing Stress

The shearing strength is usually expressed by the formula:

$$\zeta = C + \sigma_n \tan \phi \tag{1}$$

where

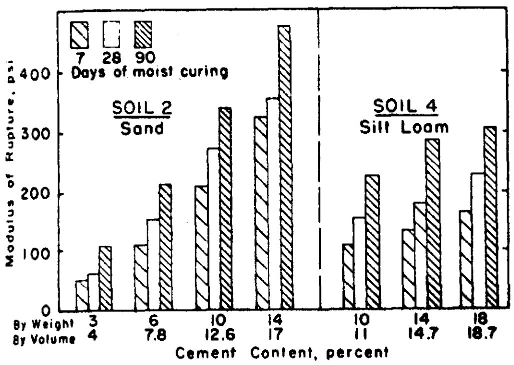

Figure 11. Modulus of Rupture, Soil Type, Cement Content and Age (14).

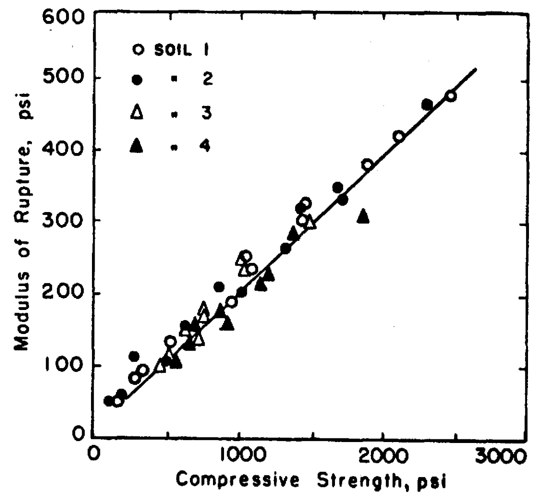

Figure 12. Relation Between Modulus of Rupture and Compressive Strength (14).

ζ = shearing stress at failure

C = cohesive strength

σ_n = normal stress at failure

tan ϕ = coefficient of internal friction.

Some typical shear strength values are presented in Table 6. It appears that the shearing strength of soil-cement is sufficiently high to preclude initial failure of road and airfield pavements in shear (14).

Table 6. Triaxial Test Results on Typical Soil-Cement 28-Day Values (14).

Cement Content, %		Soil No. and	Shearing Strength*		Stress Relationship*	
By Wt.	By Vol.	Type	C, psi	Tan Ø	a, psi	b
6	7.8	No. 6 Sandy Loam	150	1.04	749	6.20
6	7.7	No. 1A Sand	202	0.84	867	4.60
12	12.9	No. 4 Silt Loam	177	0.89	785	4.93
14	14.6	No. 8 Silty Clay Loam	198	0.74	784	3.92

* Least square values of the parameters of the equation, $\tau = C + \sigma n \tan \phi$, and the corresponding principal stress equation, $\sigma_1 = a + b\,\sigma_3$ where σ_1 = major principal stress (axial), psi; a = unconfined compressive strength, psi; b = slope of principal stress equation; and σ_3 = minor principal stress (lateral), psi.

Durability

Standard ASTM tests D 559-57 (24) and D 560-57 (25) investigate the resistance of soil-cement to wetting and drying and to freezing and thawing. They are designed to evaluate the effectiveness of the cement reaction with a soil and shed insight on the durability of the soil-cement (14).

As with other physical properties, the resistance to wetting and drying and freezing and thawing is dependent upon soil type, cement content, molding water content, density, length of mixing time, and age. Information showing that best resistance to freezing and thawing is obtained when specimens are molded at a high density and at optimum moisture content has been presented in Tables 7 and 8 (14).

Table 7. Effect of Density on Resistance to Freezing and Thawing (14).

Density Variation pcf*	Freeze-Thaw Loss, %
Sandy Soil No. 2a-3 + 8 % Cement by Volume D 558 Max. Den. is 122 pcf	
-10	25
- 5	15
0	11
+ 5	7
A-Horizon Silty Soil No. 4b-3 + 14 % Cement by Volume. D 558 Max. Den. is 97 pcf	
-10	39
- 5	37
0	20
+ 5	6

* Lb per cu ft. Variation density below or above ASTM D 558 maximum density. All specimens molded at D 558 optimum moisture.

Load-deflection Characteristics

The load-deflection research (19) on soil-cement pavements shows that the variables of thickness, size of bearing plate, strength of subgrade, soil type and cement content all effect the load-deflection characteristics of soil-cement base construction. Each variable is examined in terms of load capacity with the remaining variables held constant.

Table 8. Effect of Moisture Content on Resistance Freezing and Thawing (14).

Moisture Content Variation, %*	Freeze-Thaw Loss, %
Sandy Soil No. 2a-3 + 8 % Cement by Volume D 558 Opt. M.C. is 10.5 %	
-2	7
0	7
+2	9
+4	9
A-Horizon Silty Soil No. 4b-3 + 14 % Cement by Volume. D 558 Opt. M.C. is 22 %	
-4	40
-2	35
0	15
+2	14
+4	15

* Percentage point variation in molded-moisture content below or above ASTM D 558 optimum moisture content. All specimens molded at D 558 Max. density.

Effect of Thickness on Load Capacity

Load capacity increased with increasing thickness. The trend of this property, illustrated by Figure 13, shows that for a constant deflection the load capacity increased exponentially with increased thickness of soil-cement (19).

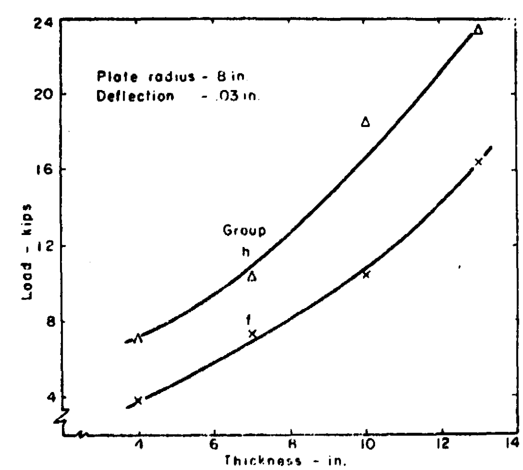

Figure 13. Curvilinear Relationship Between Thickness and Load Capacity (19).

Effect of Plate Size and Shape on Load Capacity

It is significant that soil-cement bases are more sensitive to plate size than are the more rigid concrete pavement. However, the effect of increasing plate size was reduced for increased thickness of soil-cement. An example of the data for the 7-inch thick slab is shown in Figure 14.

The oval steel bearing plates, arranged to simulate the bearing area of dual truck tires (201 sq. in.) were tested. A comparison is made in Figure 15 between deflections measured at the center of the dual plates and those measured at the periphery of a 16-inch diameter circular plate. Deflections of the oval and circular plates were in good agreement (19).

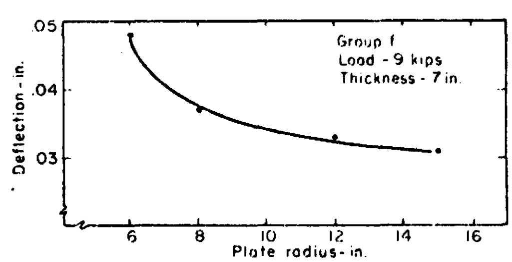

Figure 14. Effect of Plate Size on Deflection (19).

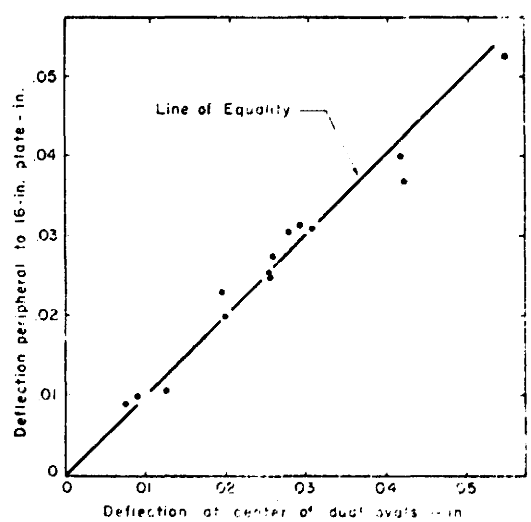

Figure 15. Comparison of Deflections for Circular and Oval Plates (19).

Effect of Subgrade Strength on Load Capacity

Data in Figure 16 show that load capacity of the soil-cement increased with increasing subgrade strength. The data show considerable scatter, but indicate that a linear relationship is acceptable (19).

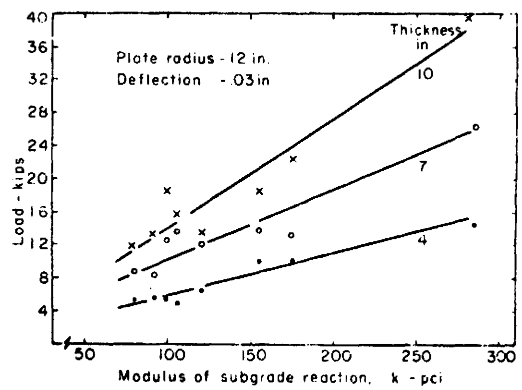

Figure 16. Effect of Subgrade Strength on Load Capacity (19).

Influence of Soil Type and Cement Content on Load Capacity

The results of tests show that the wide variations of soil type and cement content were of minor significance in influencing the load deflection response of soil-cement bases (19).

Effect of Higher or Lower Cement-content on Load Capacity

Data in Figure 17 show that for the same soil component, deflections decreased significantly as the cement content was increased in the range of cement-modified soils. For the range of cement contents greater than the minimum requirements for soil-cement, the rate of decrease of deflection was smaller (19).

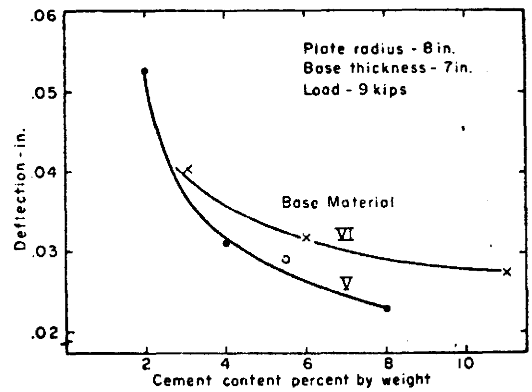

Figure 17. Effect of Cement Content on Deflection for Cement-treated Soils (19).

Analysis of Load-deflection Test Results

An analysis of the load-deflection test results was made to develop an equation evaluation the influence of the significant variables on load capacity for soil-cement base (19). A non-dimensional logarithmic plot of the test data, in Figure 18, is the result of equation (2A).

$$\frac{wk}{p} = \alpha \left(\frac{a}{h}\right)^{\beta} \tag{2A}$$

where

w = deflection, in.

k = modulus of subgrade reaction, pci

p = intensity of applied load, psi

h = soil-cement thickness, in.

a = bearing area radius, in.

α = the ordinate at a point on the best-fit line corresponding to an abscissa of a/h=1

β = the slope of the regression line.

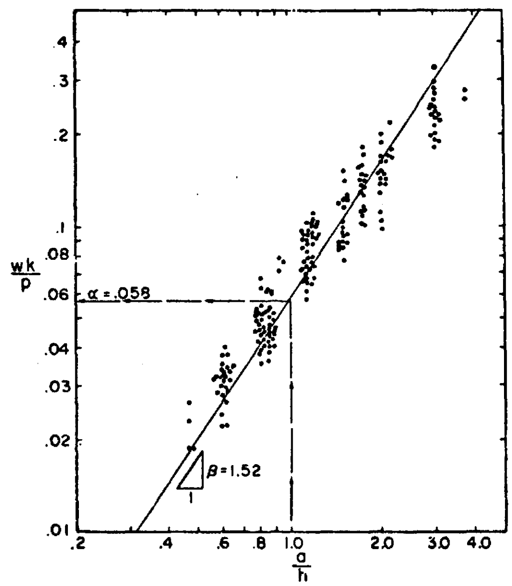

Figure 18. Best Fit Line for Soil-cement Bases (19).

It is seen that $\alpha = 0.058$ and $\beta = 1.52$. Thus, the specific expression describing the load response of soil-cement is:

$$\frac{wk}{p} = 0.058 \left(\frac{a}{h}\right)^{1.52} \tag{2B}$$

The best-fit equation may be solved explicitly for thickness of soil-cement, h, to yield:

$$h = a \left(\frac{0.058p}{wk}\right)^{1/1.58} \tag{2C}$$

and may be restated in terms of the total applied load, P, to read:

$$h = a \left(\frac{0.072}{0.32}\right) \left(\frac{P}{wk}\right)^{0.658} \tag{2D}$$

Equation (2D) defines the load response characteristics for soil-cement produced from a wide range of soil types stabilized with the cement content required from ASTM tests and PCA weight-loss criteria.

Fatigue Properties

The fatigue studies (20) indicated that failure of slabs of soil-cement due to interior loads began with radial cracking in the bottom surface. Circumferential cracks at the top were observed after a longer number of load applications. As a consequence the fatigue beams were considered to have failed when the first flexural crack became visible. This failure criterion did not exclude the possibility of the formation of microcracks prior to the visible crack. This was considered realistic because pavements continue to be serviceable after bottom surface cracking.

Radius of curvature (Appendix A) rather than deflection was selected as the principle measurement of the fatigue program. In a static test the radius of curvature decreased with increasing load and developed a minimum value at the location where the specimen eventually failed. The minimum radius of curvature at failure when loaded statically was defined as the critical radius of curvature, Rc. Specimens made from a given soil type had a characteristic value of critical radius of curvature (20).

Main Fatigue Test Programs

Fatigue curves were established in plots of fatigue ratio, Rc/R versus number of load repetitions to produce failure, N. The data as illustrated in Figure 19 produced curves simple to the usual curves of strength versus number of cycles for most materials. As Rc/R

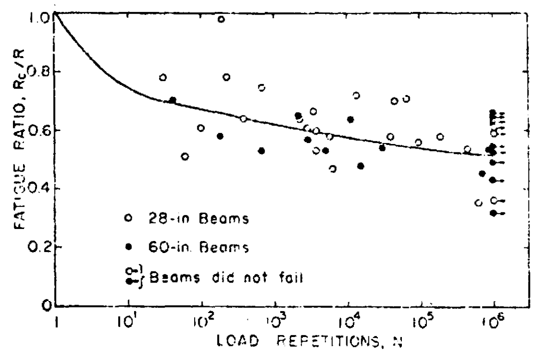

Figure 19. Effect of Beam Length. A-1-b Soil (20).

decreased, N became larger. Analysis of results was based on the portion of the curve for N greater than 10 and less than 1 million.

Regression analysis of the data in this area by electronic computation resulted in equations of the form

$$Rc/R = aN^{-b} \quad (3A)$$

Coefficient "a" and exponent "b" are called the fatigue characteristics.

Effect of Soil Type

As shown in Figure 20, slopes at corresponding N-values between ten and one million repetitions were steeper for the plastic A-4 soil

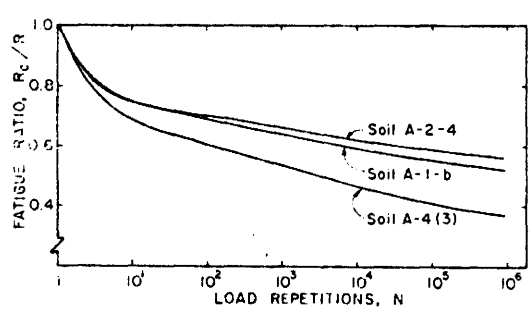

Figure 20. Influence of Soil Type on Fatigue (20).

than for the A-1-b and A-2-4 materials. The exponent, "b", of Equation (3A) is the slope of the best fit straight line in logarithmic coordinates through the fatigue data over the range of N larger than 10 and less than 1 million and indicated the rate of change in the fatigue ratio with load repetitions. Therefore "b" is a function of soil type (20).

Influence of Thickness

The fatigue curves presented in Figure 21 for the four beam thicknesses are approximately parallel curves. It is seen that the fatigue ratio for any given number of load repetitions is decreased for thicker beams. Hence, it is concluded that the thickness influences the coefficient "a", while the exponent, "b", is independent of thickness, h.

The relationship between the coefficient, a, and thickness, h, is demonstrated in Figure 22 where "a" is plotted versus "h" and can be expressed by the equation (20):

$$a = 1.05 - 0.042\,h \tag{3B}$$

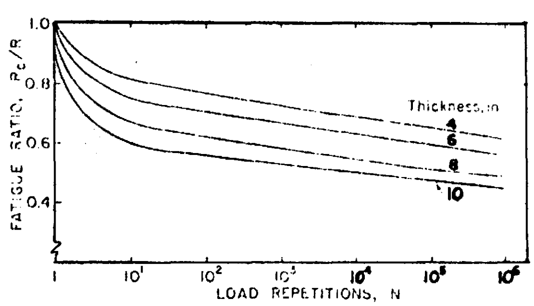

Figure 21. Influence of Thickness on Fatigue (20).

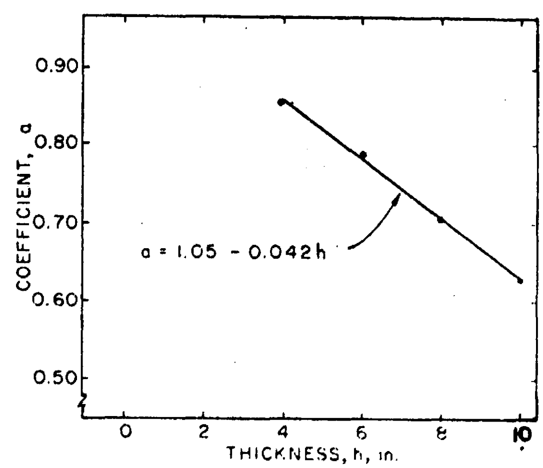

Figure 22. Influence of Thickness on Coefficient, a (20).

It is seen that depth of beam is an important consideration in fatigue life and pavement performance. The thin sections allowed repetitive loads to produce more bending than the deep sections but as a consequence would produce higher subgrade pressures. The thicker sections with longer limiting radii would distribute the load over greater areas and reduce subgrade deflections and pressures (20).

<u>Subgrade Effect</u>

Tests with different subgrade strength, k-values as measured by the volume displacement, showed that the plot of Rc/R versus N for this test did not produce curves that were essentially different. It was concluded that the effect of subgrade reaction modulus was insignificant.

From these tests it has been shown that the coefficient, a, is dependent on the thickness of the specimen. Substituting this value of the coefficient as written in Equation (3B) into Equation (3A), the following expression is obtained:

$$Rc/R = (1.05 - 0.042h)\, N^{-b} \qquad (3C)$$

Solving for the allowable radius of curvature, R, Equation (3C) is transposed to read:

$$R = \frac{RcN^{b}}{1.05 - 0.042h} \qquad (3D)$$

In using Equation (3D) it is necessary to recall that the exponent, b, is dependent on the soil type used in producing the soil-cement (20).

For basic structural properties, typical ranges for a wide variety of soil cement at their respective cement content required for durability are (18):

Property	28-day Values
Compressive strength, saturated	300 - 800 psi
Modulus of elasticity (static modulus of flexure)	$6 \times 10^5 - 2 \times 10^6$ psi
Modulus of rupture	70 - 150 psi
Poisson's ratio*	0.12 - 0.14
Critical radius of curvature on 6 x 6 30-inch beam	4,000 - 7,500 in.

Shrinkage Characteristics

The investigations (21) indicate that shrinkage forces set up by the tension in capillary water account for the volume change at fairly high humidities. The liquid-absorption phenomenon discussed in that report indicates shrinkage is swelling to the interaction between soil grains and water. The information on factors affecting shrinkage (21, 22) of soil-cement were observed and discussed as follows.

Shrinkage and Time

Shrinkage-versus-time graphs are shown in Figure 23; the clay soil-cement specimens with no moist curing began to shrink almost immediately

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*Poisson's ratio can be quite variable, depending on method of test and other conditions. Values shown are based on triaxial test-results.

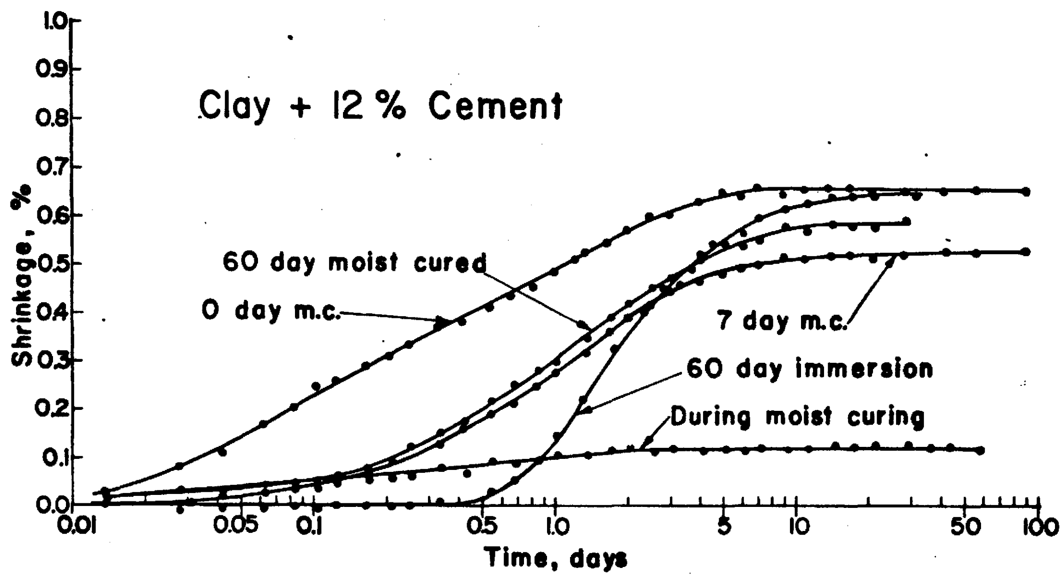

Figure 23. Shrinkage Data for Typical Mix Under Different Curing Conditions (22).

on air drying. With the clay soil-cement after moist or immersion curing, shrinkage was delayed for periods ranging from several hours to one day. Presumably the time delay was necessary for shrinkage tension to build up and overcome internal restraints in the hydrated cement gel (22).

Shrinkage and Cement Content

Shrinkage of soil-cement beams first decreased with the proportion of cement, then attained a minimum and thereafter increased slightly with cement-content, as shown in Figure 24.

We may theorize that in a simplified system, shrinkage should be varied with the amount of evaporation and drying rate. Shrinkage

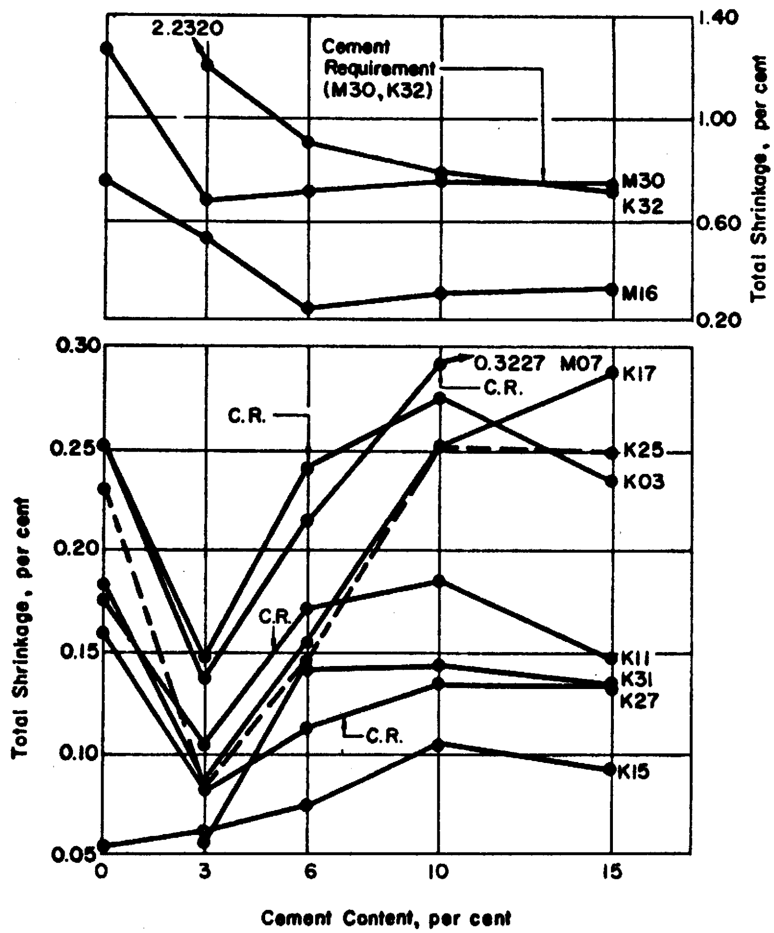

Figure 24. Effect of Cement Content on Shrinkage of Soil-cement Mixes (21).

then will be a function of time that can be expressed by (22):

$$S = ct^{\beta} \tag{4A}$$

where

S = shrinkage

t = drying time

c and β = constants.

Shrinkage and Curing

Table 9 indicates that shrinkage increased slightly if it took place after 28 days of moist curing instead of immediately after molding; however, the tendency to shrink decreases with moist curing. The increased shrinkage from prolonged curing may be attributed to the higher proportion of gel and the fact that less restraint is offered from unhydrated cement particles (21).

Table 9. Shrinkage and Moist Curing (21).

Soil No.	-2 μ Content (%)	Shrinkage After Curing in 100 percent RH As Indicated (%)			
		0 day	1 day	7 days	28 days
K15-06[a]	4	0.0613	0.0631	0.0742	—
K25-06	8	—	0.1346	0.1431	0.1849
M07-06	9	0.2196	0.2275	0.2147	0.2311
K27-06	11	0.1289	0.1236	0.1124	0.1244
K11-06	12	0.1654	0.1431	0.1714	—
M16-06	13	—	0.2800	0.2578	—
K03-06	16	0.2436	0.2302	0.2407	0.1831
M30-10	23	0.8213	0.7742	0.7506	0.6205
K32-10	35	1.2115	—	0.7899	0.7155

[a]Cement content, percent dry weight of soil.

Increase in shrinkage with cement content in soil-cement could be the result of several factors; the cement hydration may be robbing clay of water. Since the loss of moisture is the primary reason for shrinkage, cement hydration causes a kind of self-desiccation and shrinkage (21).

Shrinkage and Clay Content

The data pertaining to shrinkage and clay content are shown in Figure 25. As the clay content increases, the shrinkage appears to

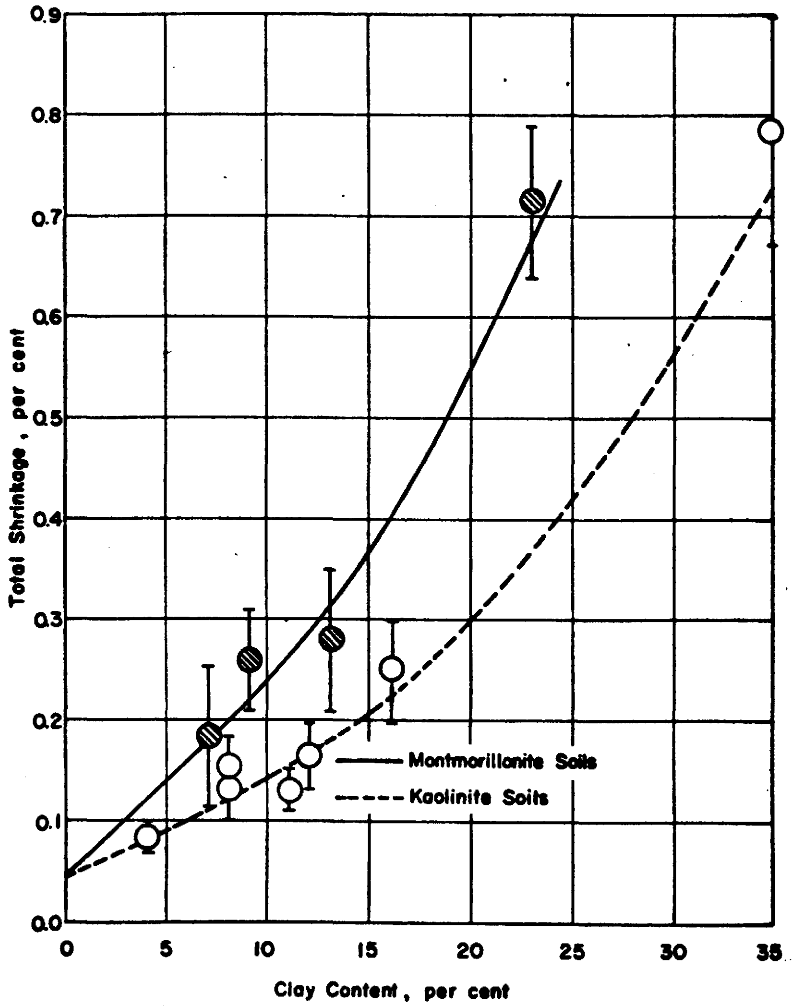

Figure 25. Effect of Two Clays on Shrinkage (21).

increase at a faster rate, indicated by the steeper slope of the shrinkage-clay content relationship. This would be expected, since aggregates serve to reduce shrinkage, theoretically, by acting as rigid inclusions in the shrinkage matrix. This would tend to put shrinkage in proportion to some power function of clay content. This equation for soil-cement is (21):

$$S = S_o (1 - g)^{\alpha} \tag{4B}$$

where

S and S_o = unit linear shrinkages of soil-cement and cement-clay pastes, respectively

g = volume fraction of the aggregate (+2μ particles)

α = a constant, depending on the elastic proportions of the paste and aggregate.

Shrinkage and Moisture Content

Figure 26 shows the relationship between shrinkage and molding moisture content for three different soils. The shrinkage in soil-cement is not a linear function of moisture content but increases in proportion to some power function of moisture content (21).

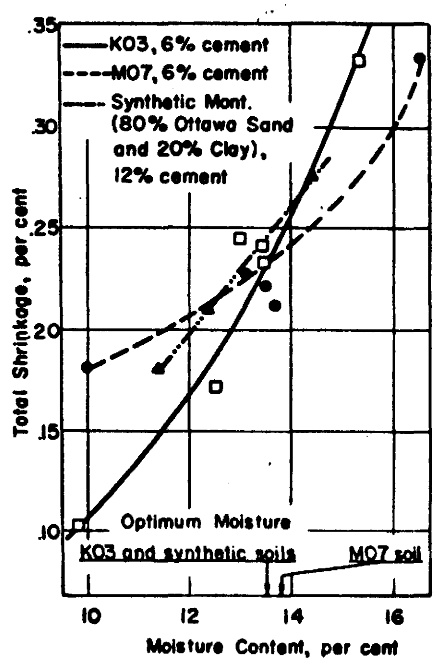

Figure 26. Effect of Moisture on Shrinkage (21).

Shrinkage and Density

Curve 4 and 5 of Figure 27 show that shrinkage can be improved by the compaction. Curve 3 and 4 show that it is not desirable to attempt to compact soil-cement to higher density wihtout a corresponding decrease in the moisture content.

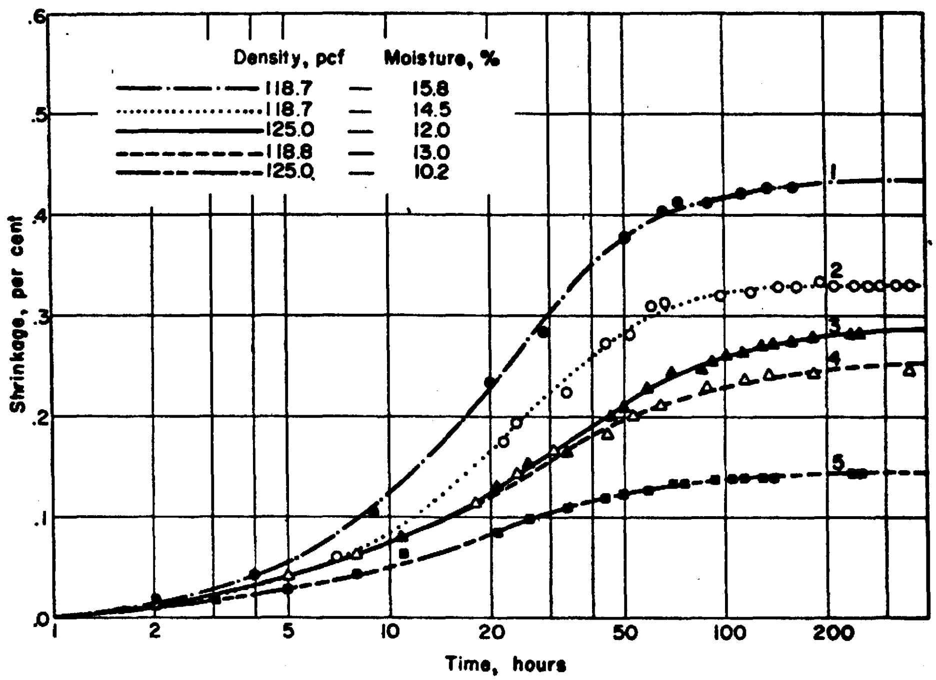

Figure 27. Effect of Density and Moisture on Shrinkage (21).

Shrinkage and Temperature

For general discussion the results of data in Figure 28 indicate that the shrinkage increases as the temperature increased. One of the reasons for this increased shrinkage could be that the setting time of cement is reduced by the increased temperature. Related to early set, a poor structural matrix decreased workability and then decreased

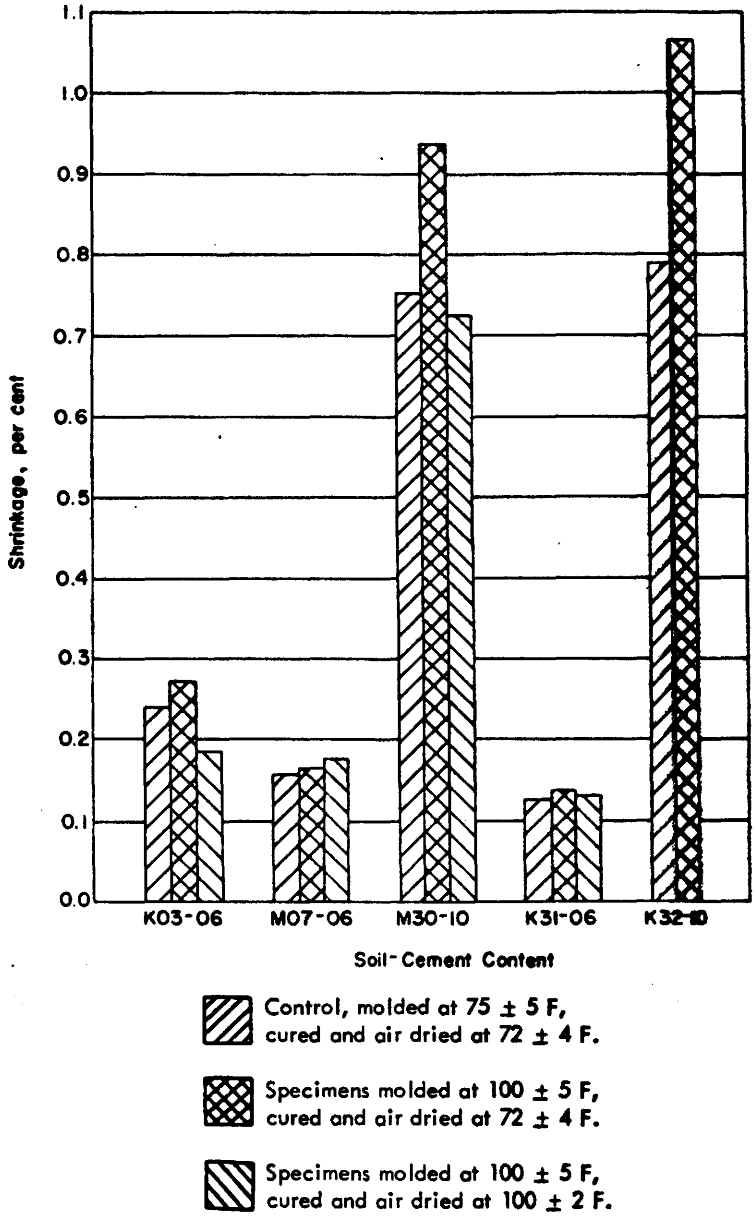

Figure 28. Comparison of Shrinkages of Soil-cement Mixtures Processed at Various Temperatures (21).

the compacted density. Another investigation (21) shows that the shrinkage of specimens, cured and dried at 100°F is slightly less than that of identical specimens which were cured at 72°F (Figure 28). The treatment at high temperature could be considered accelerated curing, which would result in greater development of a network of cementitious particles, which, in turn, tends to retard shrinkage.

Cracking Characteristics

A soil-cement problem which is probably more damaging to public relations than to the pavement is shrinkage cracking. Soil-cement commonly contracts slightly following construction; the resulting cracks may be as much as 1/8-inch across, although they are usually much less. At worst the cracks have about the same effect as joints on the load-carrying capacity, permitting water to infiltrate and weaken the subgrade (22).

The study of variables influencing of cement-treated bases analytical expressions for both cracking spacing and crack width were derived.

Crack Spacing

As a result of linear shrinkage, tension stresses can be set up in cement-treated base slabs. When friction exists between the slab and subgrade, restraint results from the friction forces. Balancing total forces (12),

$$\sigma_c bh = \mu\gamma bhL/2 \qquad (5A)$$

where

σ_c = tensile stress at center of slab, psf

b = breadth of pavement, ft

h = depth of pavement, ft

μ = coefficient of sliding friction

γ = unit weight of material, pcf

L = length of slab, ft.

The slab length (L_{max}) at which tensile stress will become critical is as follows:

$$L_{max} = \frac{2\sigma u}{\mu\gamma} \tag{5B}$$

where

σ_u = ultimate tensile strength, psf.

Crack Width

The crack width is influenced by two opposing factors: the tendency of soil-cement to shrink, compensated to some extent by the extensibility of the material. Accordingly, the width of crack will be the difference between the contraction due to chrinkage of the slab assuming no friction, and the elongation of the same section off the slab due to frictional resistance (12).

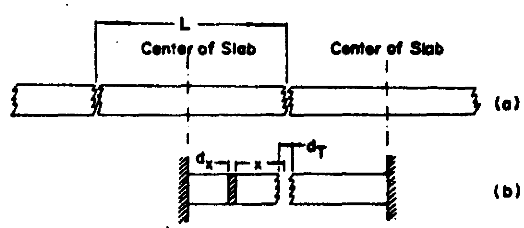

Figure 29. Transverse Cracking in Pavement Base; (a) Cracked Base and (b) Section Considered for Crack Width Calculation (12).

To make the derivation more general, it is assumed that at the time of cracking the material has not attained its maximum chrinkage. Then:

$$\delta_1 = \varepsilon_{cr} L$$

$$\delta_2 = 2 \int_o^{L/2} \frac{\delta x}{E_t} \, dx \quad = 2 \int_o^{L/2} \frac{\mu \gamma x}{E_t} \, dx$$

$$= \frac{\mu \gamma L^2}{4 E_t}$$

and

$$\delta'_{cr} = \delta_1 - \delta_2$$

$$= \varepsilon_{cr} L - \frac{\mu \gamma L^2}{4 E_t} \qquad (5C)$$

where

δ_1 = the contraction due to shrinkage of the slab, assuming no friction, ft.

δ_2 = the elongation of slab due to frictional resistance, ft.

δ'_{cr} = the crack width immediately after cracking, ft.

ε_{cr} = shrinkage at cracking, in. /in.

E_t = modulus of elasticity of cement-treated soil in tension, psf

$$\delta''_{cr} = (\varepsilon_c - \varepsilon_{cr}) \, L \qquad (5D)$$

where

δ''_{cr} = the subsequent widening of the crack, ft.

ε_c = total shrinkage, in. /in.

In Equation (5D) it is tacitly assumed that the coefficient of sliding friction remains unchanged from that before cracking; hence, the narrowing of the cracking due to the extensibility of the slab becomes zero.

Total width of crack, therefore, will be obtained by combining Equations (5C) and (5D), thus:

$$\delta_T = \varepsilon_c L - \frac{\mu \gamma L^2}{4 E_t} \tag{5E}$$

where

δ_T = total cracking width, ft.

LABORATORY TESTS

A key to successful application of soil-cement to the paving field is careful predetermination of engineering control factors in the laboratory and their application throughout construction. The primary requisite for producing soil-cement with satisfactory characteristics and serviceability is that an adequate quantity of portland cement be incorporated with the pulverized soil. Secondary requisites are that the proper amount of water be mixed uniformly with the soil-cement mixture and that the moistened soil-cement mixture be compacted to proper density before cement hydration (27). Before construction starts the soil that will be treated with cement should be identified and representative samples of each soil type forwarded to a laboratory for testing. The purposes of these tests are:

1. To find the optimum moisture content that can produce the soil-cement mixture at maximum density.

2. To find the minimum amount of portland cement that will produce the soil-cement mixture which can stay hard on alternate freezing and thawing and moisture changes.

The amount of laboratory testing required for a given project depends on the requirements of the constructing agency, the number of soil types encountered, the size of the job, and similar factors (27). Three general procedures are in existence (28).

On major projects, when time is available for testing, and with all soils, a detailed procedure to establish the satisfactory minimum cement content is recommended.

Short-cut test procedures have been evolved to determine adequate cement content for sandy soils. This procedure is designed for use on smaller projects, particularly those where testing facilities and man-power are limited; it results in safe but not necessarily minimum cement content for these soils. The only tests required are grain size analysis moisture-density tests and compressive strength tests.

For emergency construction and for very small projects where laboratory testing facilities are not available or detailed testing is not feasible or practical, a rapid method has been used successfully. It provides a safe cement factor but one that may be appreciably higher than the minimum for adequate hardness.

Selection of Cement-content for Tests

In order to obtain the maximum amount of information from the wet-day and freeze-thaw tests, it is important that the laboratory engineer design the soil-cement specimens properly. For instance, if specimens are designed with very high cement contents, they will all pass the wet-dry and freeze-thaw tests and a minimum cement factor will not have been determined. On the other hand, if the specimens are designed with inadequate cement contents, they will all fail in the tests (27).

As a general rule, it will be found that the cement requirement of soils increases as the silt and clay contents increase, gravelly and sandy soils requiring less cement for adequate hardness than silt and clay soils. The one exception to this rule is that poorly graded, one-size sand materials that are devoid of silt and clay require more cement than do sandy soils containing some silt and clay. Table 10 gives the usual range in cement requirements for subsurface soils of the various AASHO soil groups.

Table 10. Cement Requirements of AASHO Soil Groups (27).

AASHO soil group	Usual range in cement requirement		Estimated cement content and that used in moisture-density test, percent by wt.	Cement contents for wet-dry and freeze-thaw tests, percent by wt.
	percent by vol.	percent by wt.		
A-1-a	5– 7	3– 5	5	3– 4– 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	11–13–15

Determining Moisture-density Relations of Soil-cement Mixtures

Before determining the moisture-density relations of soil-cement mixtures, it is necessary to select the cement contents by weight from Table 10. Since the maximum density of a soil-cement mixture varies only slightly as the percentage of cement varies, a moisture-density test at the median cement content will suffice (27).

There are many procedures used to determine the optimum moisture content and maximum density. But generally the ASTM-AASHO method and the procedures developed by the Portland Cement Association are used.

Test procedure: The detail of test procedures following the ASTM Designation D558-57 (23) is given in Appendix D. There are two methods for determining moisture-density relations of soil-cement mixtures.

Method A, using soil material passing a No. 4 (4.76-mm) sieve. This method shall be used when 100 percent of the soil sample passes the No. 4 (4.76-mm) sieve.

Method B, using soil material passing a 3/4 in. (19.05-mm) sieve. This method shall be used when part of the soil sample is retained on the No. 4 (4.76-mm) sieve.

The soil sample used in the test specimens has the same percentage of material retained on the No. 4 sieve as the original soil material. The maximum size used is 3/4 in. material. Should there be material larger than 3/4 in. in the original soil, it is replaced with an equivalent weight of No. 4 to 3/4 in. material.

Calculations: After finishing the laboratory tests, calculate the moisture content and dry unit weight, γ_d, in pounds per cubic foot (grams per cubic centimeter) of the compacted soil-cement mixture for each trial as follows:

$$w = \frac{A - B}{B - C} \times 100$$

$$\gamma_d = \frac{\gamma_m}{w + 100} \times 100$$

where

w = percentage of moisture in the specimen

A = weight of moisture can and wet soil-cement

B = weight of moisture can and oven-dry soil-cement

C = weight of moisture can

γ_d = dry unit weight in pounds per cubic foot (grams per cubic centimeter) of compacted soil-cement

γ_m = wet unit weight in pounds per cubic foot (grams per cubic centimeter) of compacted soil-cement.

Moisture-density relationship: After calculating the moisture content and corresponding dry-unit weight (density) of the compacted soil-cement for each trial made on the mixture, the densities are plotted as ordinates and the corresponding moisture contents as abscissas. By connecting the plotted points with a smooth line, a curve is produced as in Figure 30. The moisture content at which maximum density is obtained is called the "optimum moisture content" of the soil-cement mixture. The dry unit weight of the mixture at optimum moisture content is called the "maximum density". These maximum density and optimum moisture content are used for design of wet-dry and freeze-thaw test speciments.

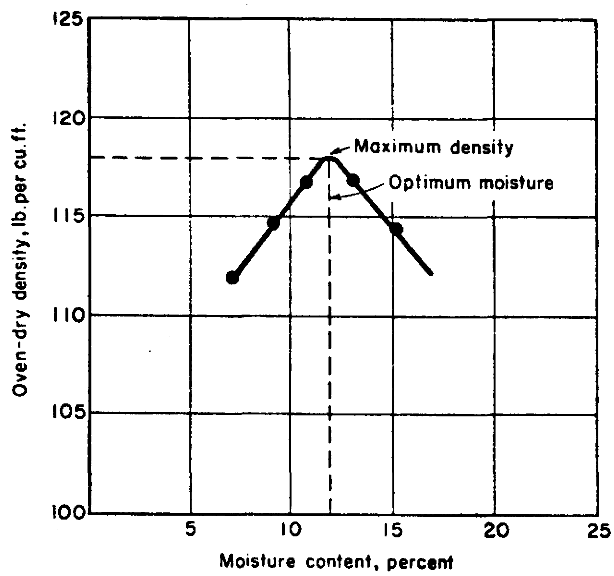

Figure 30. Typical Moisture-density Curve (27).

Determining Cement Content of Soil-cement Mixtures

The purpose of these tests is to find the minimum amount of cement that will produce a soil-cement mixture with adequate resistance to exposure. That is, the hardened soil-cement mixture can withstand the wetting and drying and the freezing and thawing cycles of nature and still maintain at least the stability inherent in the mass at the time the roadway was opened to traffic. Since it takes many days to complete these cycles of tests, research for developing test methods and decreasing time periods are desirable. Some local experiences have shown that the period of testing time can be reduced and still be suitable for use in a specific area. A rapid method for soil-cement design (Louisiana Slope Value Method) (29) has been used successfully in areas where the temperature is not too cold, since this method does not consider the effect from freezing and thawing. For general areas, the ASTM-AASHO method and also the procedures that were developed by the Portland Cement Association are recommended.

Standard Test Procedure

Limiting test values, for ensuring that the soil-cement mixture has adequate cement content to withstand exposure to the elements, the following limiting test values are suggested to produce soil-cement of satisfactory strength and durability (30):

1. Soil-cement losses during 12 cycles of either wet-dry or freeze-thaw tests shall be within the following limits:

Soil Groups A-1-a, A-1-b, A-3, A-2-4, and A-2-5, not over 14 percent.

Soil Groups A-2-6, A-2-7, A-4 and A-5, not over 10 percent.

Soil Groups A-6, A-7-5 and A-7-6, not over 7 percent.

2. Maximum volume change during either wet-dry or freeze-thaw tests shall not exceed the volume at the time of molding by more than 2 percent.

3. Maximum moisture content during either wet-dry or freeze-thaw tests shall not exceed that quantity which 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.

Test procedure: The methods for wet-dry and freeze-thaw tests given here will follow the ASTM-AASHO standard methods. There are also two methods for each test of soil-cement mixtures.

Method A, using soil material passing a No. 4 (4.76-mm) sieve. This method shall be used when 100 percent of the soil sample passes the No. 4 (4.76-mm) sieve.

Method B, using soil material passing a 3/4 in. (19.05-mm) sieve. This method shall be used when part of the soil sample is retained on the No. 4 (4.76-mm) sieve. The detail of wet-dry tests (24) and freeze-thaw tests (25) are given in Appendix E and Appendix F, respectively. The calculated minimum cement content in soil-cement mixture which is within limit of losses from both wet-dry and freeze-thaw tests will be obtained. This value of cement content shall be used as mix design for soils of that type on the project.

Short-cut Test Procedures for Sandy Soils

The short-cut test procedures for sandy soils were developed by the Portland Cement Association. The procedures can be used only with soils containing less than 50 percent material smaller than 0.05 mm (silt and clay), less than 20 percent material smaller than 0.005 mm (clay) and less than 45 percent material retained on the No. 4 sieve. These were the gradation limits for the soils that were included in the correlation used to develop the original charts. Dark grey to black soils with appreciable amounts of organic impurities were not included in the correlation and therefore cannot be tested by these procedures. This is also true of miscellaneous granular materials such as cinders, caliche, chert, marl, red dog, scoria, shale, slag, etc. Moreover, the short-cut procedures cannot be used with granular soils containing material retained on the No. 4 sieve if that material has a bulk specific gravity less than 2.45 (27). Two procedures are used:

Method A for soils not containing material retained on the No. 4 sieve.

Method B for soils containing material retained on the No. 4 sieve.

Before applying the short-cut test procedures it is necessary to (1) determine the gradation of the soil, and (2) determine the bulk specific gravity of the material retained on the No. 4 sieve.

Method A:

1. Determine by test the maximum density and optimum moisture content for a mixture of the soil and portland cement (23).

2. Use the maximum density obtained by test in 1 to determine from Figure 31 the indicated cement requirement.

3. Use the indicated cement factor obtained in 2 to mold compressive-strength test specimens (31) in triplicate at maximum density and optimum moisture content.

4. Determine the average compressive strength of the specimens after 7 days' moist-curing.

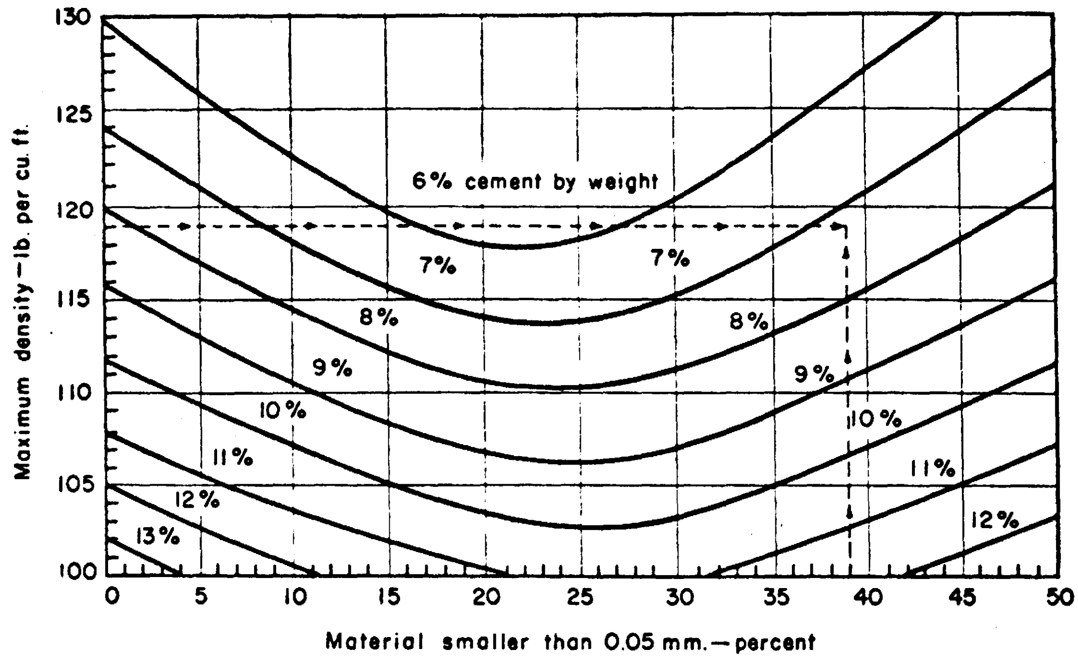

Figure 31. Indicated Cement Contents of Soil-cement Contents of Soil-cement Mixtures not Containing Material Retained on No. 4 Sieve (27).

5. On Figure 32, plot the average compressive-strength value obtained in 4. If this value plots above the curve, the indicated cement factor by weight, determined in 2, is adequate.

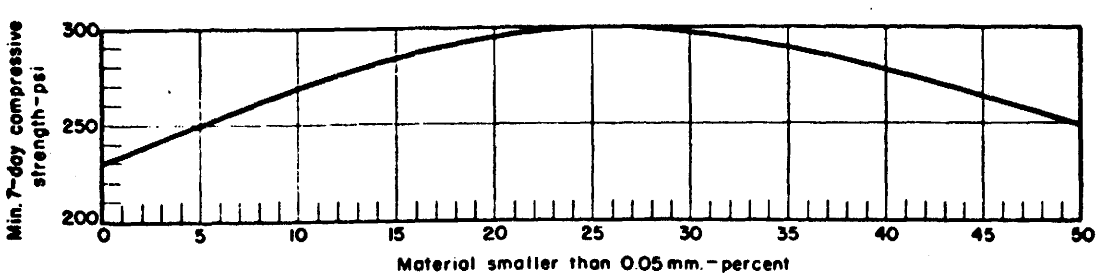

Figure 32. Minimum 7-Day Compressive Strengths Required for Soil-cement Mixtures not Containing Material Retained on the No. 4 Sieve (27).

Method B:

1. Determine by test the maximum density and optimum moisture content for a mixture of the soil and portland cement (23).

2. Use the maximum density obtained by test in 1 to determine from Figure 33 the indicated cement requirement.

3. Use total material as described in 1 and the indicated cement factor obtained in 2 to mold compressive-strength test specimens (31).

4. Determine the average compressive strength of the specimens after 7 days' moist-curing.

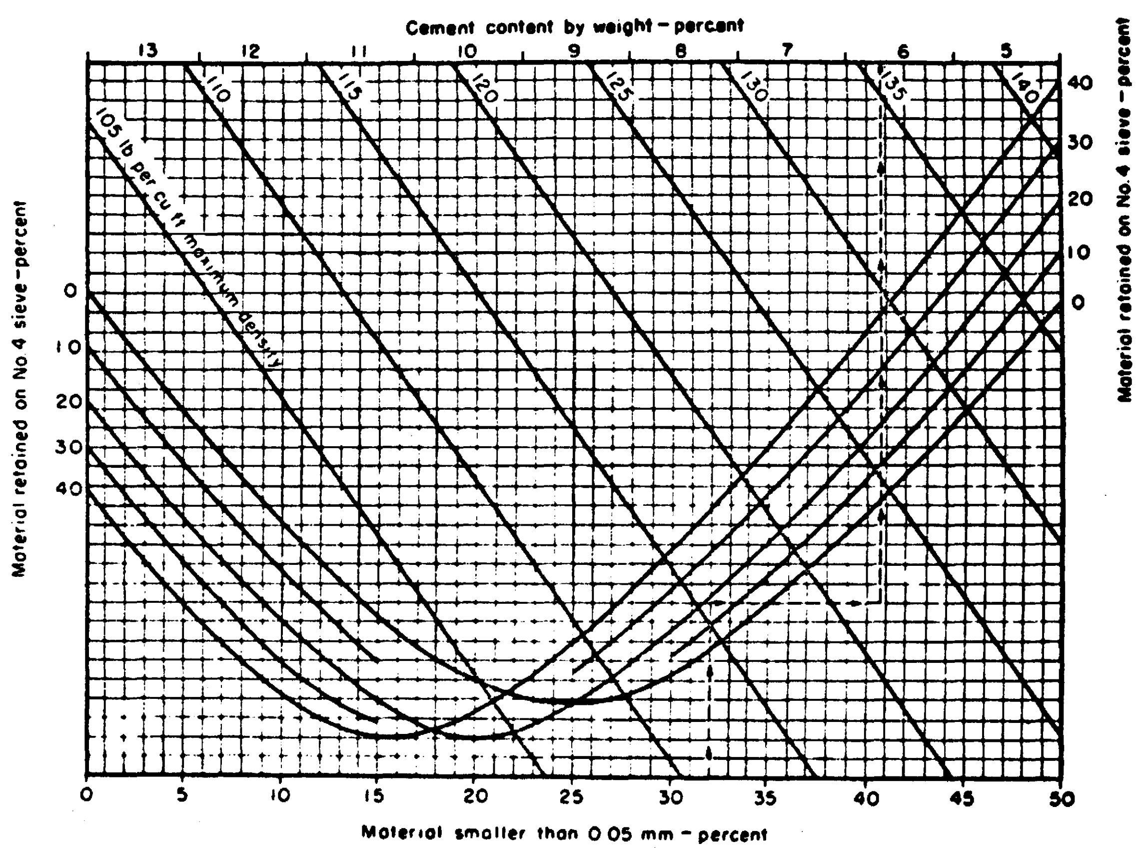

Figure 33. Indicated Cement Contents of Soil-cement Mixtures Containing Material Retained on the No. 4 Sieve (27).

5. Determine from Figure 34 the minimum allowable compressive strength for the soil cement mixture. If the average compressive strength obtained in 4 equals or exceeds the minimum allowable strength, the indicated cement factor by weight obtained in 2 is adequate.

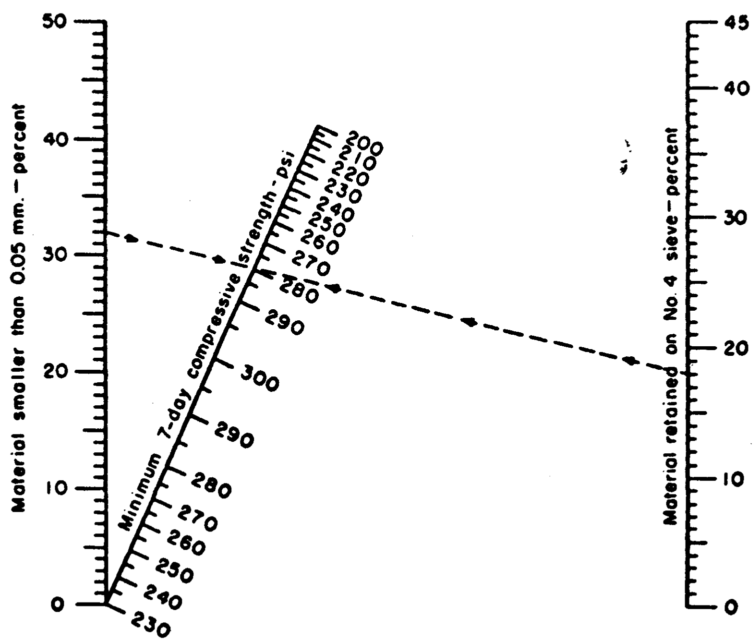

Figure 34. Minimum 7-Day Compressive Strengths Required for Soil-cement Mixtures Containing Material Retained on the No. 4 Sieve (27).

Rapid Test Procedures

A rapid method of testing soil-cement has been used successfully for emergency construction and for very small projects. The following steps are suggested (27):

1. Determine the maximum density and optimum moisture content for the soil-cement mixture (23). They can be determined at 10 percent cement by weight. With experience the optimum moisture can be

determined quite closely by "feel". When squeezed, soil-cement at optimum moisture will form a cast that will stick together when it is handled.

2. Mold specimens for inspection of hardness. These specimens are molded by the same procedure described in Appendix F. They generally contain 6, 10 and 14 percent by weight.

3. Inspect specimens using "pick" and "click" procedures:

a. Pick Test - The specimen is held in one hand and a relatively sharp-pointed instrument, such as a dull ice pick, is slightly jabbed into the specimen from a distance of two or three inches. If the specimen resists this ligh picking, the force of impact is increased until the pick is striking the specimen with considerable force. To pass the pick test, a specimen that is not over 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 one-eighth to one-quarter inch.

b. Click Test - The specimens that pass the pick test are held perpendicular to each other and about four inches apart, one in each hand. They are then slightly 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.

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

THICKNESS DESIGN

The method of thickness design for soil-cement basecourse in this paper will follow the procedure developed by the Portland Cement Association, which is described in Thickness Design for Soil-cement Pavements (18). In this method the proper design thickness is based on the following factors (32):

1. Subgrade strength.
2. Pavement design period.
3. Traffic, including volume and axle weight distribution.
4. Soil-cement base course thickness.
5. Bituminous surface thickness.

Following the research of this association, resulting design procedure in terms of the five elements that are essential parts of the design equation was obtained.

Subgrade Support

The support is a major element of the thickness design procedure. It is measured in terms of Westergaard's modulus of subgrade reaction, k, and is determined by plate bearing tests on that subgrade. If time and equipment do not allow these tests to be performed, the approximate relationships listed in Table 11 may be used as a guide (18). Very soft subgrades that have strength values less than the strength values

Table 11. Relationship Between Soil Types and Bearing Values (18).

Type of soil	Subgrade strength	CBR* range, percent	*R*-value** range	*k*-value range, pci
Fine-grained soils in which silt and clay size particles predominate	Low	3 to 6	20 to 30	100-150
Poorly graded sands and soils that are predominantly sandy with moderate amounts of silt and clay	Medium	7 to 10	30 to 45	150-220
Gravelly soils, well-graded sands, and sand-gravel mixtures relatively free of plastic fines	High	More than 10	45 or more	220 or more

*California Bearing Ratio.
**Resistance value determined by stabilometer.

shown in Table 11 have to be improved, because they will not be able to support the compaction equipment necessary for achieving adequate compaction for soil-cement.

Design Period

A design period of 20 years has been selected for use with this procedure. This should not be confused with service life which can easily exceed 35 years. The design period is an arbitrary selection and the designer may select a different value and then proportion the total volume of traffic accordingly (32).

Traffic

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

1. Determining average daily traffic in both directions (ADT) and the percentage of trucks, as shown in Table 12 (18). These figures can be obtained directly from traffic surveys or from the state highway departments annual traffic loado-meter surveys (32).

2. Projecting the traffic to a future design period. Traffic growth and projection factors are used to estimate design ADT and the number of trucks that will use the pavement during the design period (32).

Table 12. Highway Capacity Guide (18).

	Capacity—average daily volume of automobiles and trucks (two directions)		
Commercial vehicles, percent	Two-lane rural highways	Four-lane rural highways	Four-lane urban highways
0	5,750	19,250	37,500
10	5,200	17,500	34,000
20	4,800	16,050	31,000

As an example, Table 13 shows relationships between yearly rates of growth and 20-year projection factors. Annual traffic growth varies from about 2 to 6 percent, with the lower values more applicable to the types of roads and streets where soil-cement is commonly used. The higher growth rates are for intercity and urban highways (18).

3. Determining the probably axle-load distribution. This information, on truck traffic, is needed to compare the numbers of single and tandem axles of various weights expected during the design period (32). These data are then used to compute the Fatigue Factor.

Table 13. Yearly Rates of Traffic Growth and Corresponding Projection Factors (18).

Yearly rate of traffic growth, percent	Projection factor for 20-year design period
1	1.1
1½	1.1
2	1.2
2½	1.3
3	1.4
3½	1.5
4	1.5
4½	1.6
5	1.7
5½	1.8
6	1.9

4. A single value that expresses the total fatigue consumption effects of the volumes and weight of single and tandem axle loadings for a given design problem is called the "Fatigue Factor". There are two methods of completing the design in this procedure depending on whether or not loado-meter data (from W-4 table), Table 14 (18) for example, are available.

In many cases, axle-load distribution data will not be available. This will be especially so on secondary roads and residential streets where the traffic is relatively light. In the absence of these data, values from Table 15 (18) may be used to represent fatigue requirements (32).

Fatigue Factor is based on coefficients showing the relative fatigue consumption of different axle-load magnitudes, the "Fatigue Consumption Coefficients", which are listed in Table 16. For use of this table, the two borad types are differentiated by AASHO soil classifications:

Table 14. Axle-load Data (Table W-4) for Local Station in a Mid-western State (18).

Axle loads in pounds	Single-unit trucks: Panel and pickup under 1 ton	Other 2-axle, 4-tired	Other 2-axle, 6-tired	3-axle or more	Single-unit trucks, probable no.	Tractor semi-trailer units: 3-axle	4-axle	5-axle or more	Tractor-trailer units, probable no.	Truck & trailer units: 4-axle	5-axle	All truck-trailer units probable	Axles per 1,000 vehicles
Single axles													
Under- 3,000	200	39	17	–	1,967	–	–	–	–	11		103	1,014.2
3,000- 6,999	48	29	130	6	1,088	–	4	3	42	12		109	607.1
7,000- 7,999	–	1	21	5	123	–	–	–	–				60.3
8,000-11,999	1	1	40	12	256	1	2	7	66				157.8
12,000-15,999	–		18	5	109	2	1		41				73.5
16,000-17,999	–		5		22		–		–				10.8
18,000-18,500	1		2		18		–		–				8.8
18,501-19,999			2		9		–		–				4.4
20,000-21,999			3		13		1		7				9.8
22,000-23,999													
24,000-25,999													
26,000-29,999													
Total single axles weighed	250	70	238	28	–	3	8	10	–	23		–	–
Total single axles counted	2,314	70	1,064	157	3,605	51	54	51	156	2,121		212	–
Tandem axles													
Under- 6,000				–	–		–	–	–				–
6,000-11,999				2	11		–	4	21				15.7
12,000-17,999				8	45		2	6	44				43.6
18,000-23,999				5	28		1	3	22				24.5
24,000-29,999				3	17		–	2	10				13.2
30,000-31,999				1	5		–	1	5				4.9
32,000-32,500				–	–		–	1	5				2.4
32,501-33,999				3	17		–	1	5				10.7
34,000-35,999				2	11		–	1	5				7.8
36,000-37,999				3	17		–	–	–				8.3
38,000-39,999				1	6		–	–	–				2.9
40,000-41,999							1	1	12				5.9
42,000-43,999													
44,000-45,999													
46,000-49,999													
Total tandem axles weighed				28	–		4	20	–				–
Total tandem axles counted				157	157		27	102	129				–
Total vehicles counted†	1,157	35	532	157	1,881	17	27	51	95	66		66	

Table 15. Representative Fatigue Factors for Light-traffic Pavements (18).

Facility	*ADT*	Total trucks,* percent (approx.)	Heavy trucks,** percent (approx.)	Fatigue Factor†
Purely residential streets	300 to 700	8	3	5 to 12
Residential collector streets	700 to 4,000	8	3	12 to 20
Secondary roads	Up to 2,000+	14 to 20	5 to 8	12 to 30

*All commercial vehicles, including two-axle, four-tire vehicles.

**Excludes panels, pickups, and other two-axle, four-tire vehicles that are seldom heavy enough to affect design thickness.

†These particular ranges of values for the Fatigue Factor are based on the following characteristics of street and secondary road traffic: (1) one-half the indicated number of heavy axle loads, one direction; (2) axle-load distributions varying from 12,000 to 20,000 lb. on individual axles; (3) weighted averages of axle loads varying between 13,000 and 16,000 lb. on individual axles.

Table 16. Fatigue Consumption Coefficients (18).

Axle load, kips	Granular soil-cement	Fine-grained soil-cement
Single axles		
30	12,500,000.	3,530.
28	1,270,000.	1,130.
26	113,000.	337.
24	8,650.	93.
22	544.	23.3
20	27.	5.2
18	1.0000	1.0000
16	0.0250	0.1600
14	0.0004	0.0200
12	–	0.0018
Tandem axles		
50	12,500,000.	3,530.
48	3,210,000.	1,790.
46	792,000.	890.
44	186,000.	431.
42	41,400.	203.
40	8,650.	93.
38	1,690.	41.1
36	305.	17.5
34	50.4	7.1
32	7.5	2.74
30	1.0000	1.0000
28	0.1200	0.3410
26	0.0120	0.1070
24	0.0010	0.0310
22	–	0.0081
20	–	0.0018

Granular Soils: A-1, A-3, A-2-4 and A-2-5.

Fine-grained Soils: A-2-6, A-2-7, A-4, A-5, A-6 and A-7.

The Fatigue Consumption Coefficients are multiplied by the numbers (in thousands) of axles in each weight group and then summed to give a single-value Fatigue Factor (18).

Soil-cement Thickness

The thickness of the soil-cement base course is determined by the use of Figure 35 for granular soil-cement or Figure 36 for fine-grained soil-cement. The thickness is read to the nearest 1/10 in. by using the computed Fatigue Factor and design k-value.

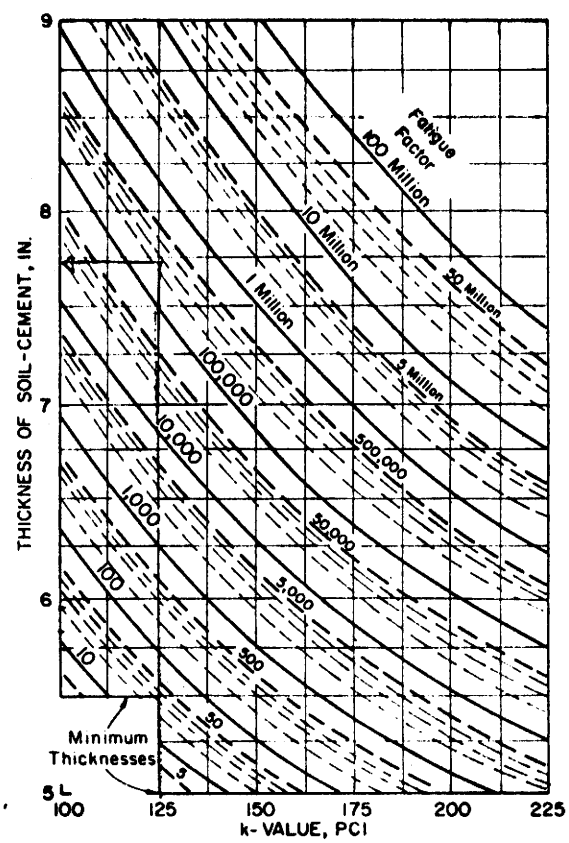

Figure 35. Thickness Design Chart for Granular Soil-cement (18).

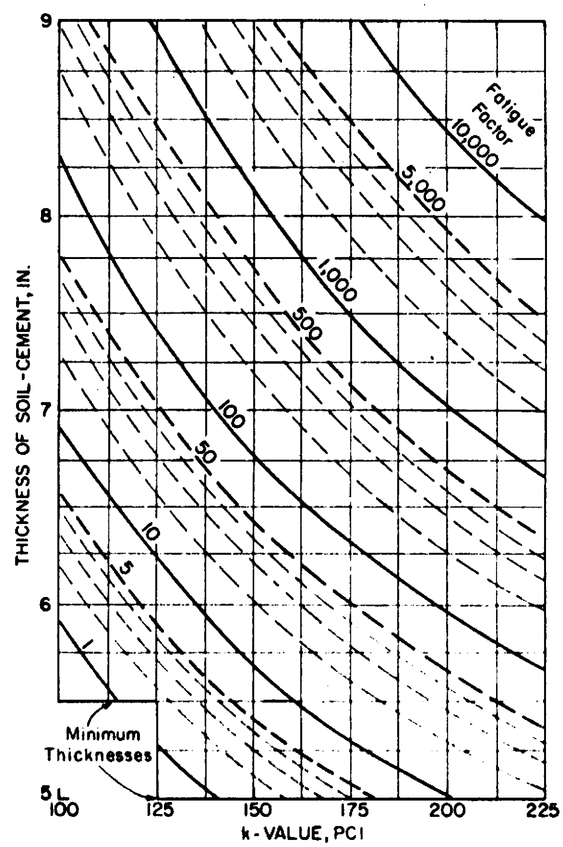

Figure 36. Thickness Design Chart for Fine-grained Soil-cement (18).

Bituminous Surface Thickness

The thickness of the bituminous surface depends on many factors: the type of surfacing, the volume and composition of traffic, climatic conditions, availability of materials and local practices. Table 17 is based on experience covering a wide range of these variables and shows the surface thicknesses recommended as good design practice (18).

Table 17. Bituminous Surface Thickness (18).

Soil-cement thickness, in.	Recommended bituminous surface thickness, in.	Minimum bituminous surface thickness, in.	
		Non-frost area	Frost area
5-6	¾-1½	SBST*	DBST*
7	1½-2	DBST	1**
8	1½-2½	1	1½
9	2 -3	2	2

*SBST, single bituminous surface treatment; DBST, double bituminous surface treatment
**Where snowplows are used, a minimum of 1½ in. is recommended.

CONSTRUCTION METHOD

The objective of soil-cement construction is to mix pulverized soil and cement thoroughly in correct proportions with sufficient moisture to permit maximum compaction (4). When determined cement factors and thickness requirements have been calculated, the soil-cement project enters its construction phase. There are two steps following a definite procedure.

Preparation

The site for processing has to be prepared. It consists of placing guide stakes and blading the road or street site to crown and grade. Heavy soils are usually scarified as an aid to the mixing operation (32), all soft subgrade areas, springs, and frost-heavy areas should be located and corrected, and stumps and other debris removed (5).

Moist soil-cement is built from soils that required little or no preliminary pulverizing. If pulverization is required, it is usually done the day before actual processing (5).

Processing

Processing operations are continuous and are completed in the same working day. For maximum efficiency and to meet specification time limits, the day's work should be broken down into several sections rather than building one or two long sections. This procedure will result in maximum daily production and will prevent a long stretch of road from being "rained Out" in case of sudden severe rainstorm. Steps in processing should be as follows.

Handling and Spreading Cement

The spreading of the portland cement may be accomplished in a variety of ways. Bags of cement may be spotted and spread but this is quite inefficient and should be limited to exceptionally small jobs. Spreader boxes which attach to either 10-wheel dump trucks or specially constructed auger-type bulk delivery trucks are the most widely used implements. If the mixing is to be accomplished in a windrow operation, a windrow spreader is used (32).

Table 18 can be used to determine quantities of cement per square yard of pavement (5).

Table 18. Cement Spread Requirements, Pounds per Square Yard (5).

Percent cement by volume	Compacted depth, inches			
	5	6	7	8
4	14.1	16.92	19.74	22.56
5	17.625	21.15	24.675	28.2
6	21.15	25.38	29.61	33.84
7	24.675	29.61	34.545	39.48
8	28.2	33.84	39.48	45.12
9	31.725	38.07	44.415	50.76
10	35.25	42.3	49.35	56.4
11	38.775	46.53	54.285	62.04
12	42.3	50.76	59.22	67.68
13	45.825	54.99	64.155	73.32
14	49.35	59.22	69.09	78.96
15	52.875	63.45	74.025	84.6
16	56.4	67.68	78.96	90.24

Soils that are too wet will not mix readily; sandy soils may be mixed with cement even if the moisture content is 2 percent above optimum. On the other hand, clayey soils generally will not readily mix with cement if the moisture content is greater than about optimum (4).

Mixing and Application of Water

Mixing can be done with traveling mixing machines or in stationary, central-mix plants. The traveling mixers can be the multiple-pass rotary mixers, single-pass stabilizers, or the windrow type (32).

Enough water should be applied to bring the mixture to optimum moisture content or slightly above. Water is added by means of pressure distributors in amounts as large as the equipment and soil will permit. After the last amount of water has been applied, mixing continues until all of the mixture is free of wet-and-dry streaks and is uniform in color and texture from top to bottom indicate a satisfactory mix. Proper width and depth of mixing are important in this step (5).

Compaction

Compaction is a very important part of soil-cement. For best results compaction should begin immediately after mixing is completed. Usually not more than 30 to 60 minutes elapse between the start of moist-mixing and the start of compaction of the mixture. Less water will be last and densities will be obtained more easily. Water lost by evaporation during compaction should be replaced in light applications of water (4).

The principles governing compaction of soil-cement are the same as those for compacting the same soils without cement treatment. Tamping rollers are generally used for initial compaction on all but the most granular soils (5). Pneumatic-tire rollers are used to compact very sandy soils with little or no binder material, also sand and gravel of low plasticity (4). Vibratory compactors, self-propelled pneumatic rollers, and tandem steel-wheel rollers are also used.

Minimum density requirements for soil-cement range from 95 to 100 percent of the maximum density as determined on a representative field sample taken from the moist mix (ASTM D 558 or AASHO T 134). Excess densities are beneficial (5).

Finishing

When compaction is about completed, a motor grader is used to bring the roadway to crown and grade. Smooth spots left by compaction equipment should be scratched out. This may be done with a weeder, nail drag or spike-tooth harrow (4). There are several acceptable methods of finishing soil-cement. The exact procedure depends on the equipment, job conditions and soil characteristics. The surface should be smooth, dense and free of ruts, ridges, or cracks (5) and also should be kept quite moist (4).

Curing

Finished soil-cement contains enough moisture for adequate cement hydration. A protective cover is immediately placed over the completed base to retain this moisture. Most soil-cement is covered with a bituminous material but other materials such as waterproof paper or moist straw are entirely satisfactory (4).

Soon after completion, the base shrinks and transverse shrinkage cracks form. This is a natural characteristic of soil-cement; it does not affect performance of the base. Rather, cracking indicates that cement hydration is producing a hardened material. Most cracks appear during the first few days, although additional cracks may appear later (4).

Surfacing

A bituminous surface should be placed on the soil-cement base as soon as practicable. The type and thickness of surface will depend on traffic, available materials, cost, and local practices. Local experience and practice will dictate the specific details of construction. Good construction practices, such as thorough cleaning of the base course, should always be followed when the surfacing is placed (5).

Special Construction Problems

Joint Construction

At the end of each day's construction a transverse vertical construction joint is formed by cutting back into the completed soil-cement to the proper crown and grade. This is done usually the last thing at night or the first thing the following morning, using the toe of the motor grader blade or hand axes. After the next day's mixing has been completed at the joint, it is cleaned of all dry and unmixed material and retrimmed if necessary.

A longitudinal joint adjacent to partially hardened soil-cement can be constructed with most mixing equipment by merely cutting back a few inches with the mixer into the previously constructed area. The amount of overlap is determined by digging back into the completed work until solid material and proper crown and grade are reached (5).

Multiple-layer Construction

If the specified thickness of soil-cement is more than 8 in., it cannot be thoroughly mixed, moistened, compacted and finished in one layer. Multiple layers have to be constructed with no layer less than 4 in. thick. The lower layer can be cured with moist soil that is subsequently used to build the top layer, which may be built immediately the following day or sometime later. The lower layer does not have to be finished to exact crown and grade, nor do surface compaction planes have to be removed since they are too far from the final surface to be harmful (5).

Soft Subgrade

If the subgrade is soft and cannot properly support the compaction equipment, adequate density will not be obtained. Therefore, soft areas such as springs, seepage areas and differential forst-heave areas should be located and corrected before processing begins. These areas can usually be stabilized by aerating and recompacting the soil. When deep unstable areas are encountered, it is usually necessary to remove the underlying wet soil and replace it with stable material but the area may be subprocessed with soil-cement or cement-modified soil (5).

Rainfall

Wet weather need not be a serious construction hazard, but any loose or pulverized soil should be crowned so it will shed water, and low places in the grade where water may accumulate should be trenched so that they will drain freely. Usually construction requires the addition of water equivalent to 1 to 1 and 1/2 in. of rain.

A light drizzle causes no harm. If rain falls during cement spreading operations, spreading is stopped and the cement already spread is quickly mixed into the soil mass. However, a heavy rainfall that occurs after most of the water has already been added may be serious. Generally, the best procedure is to obtain rapid compaction by using every available piece of equipment so that the section will be compacted and shaped before too much damage results from the rain. After the mixture has been compacted and finished, rain will do no harm (5).

Cold Weather

Cement hydration practically ceases when temperatures are near or below freezing, therefore, soil-cement should not be placed when the temperature is $40^{o}F$ or below. Moreover, it should be protected to prevent its freezing for a period of 7 days after placement and until it has hardened by a suitable covering of hay, straw or other protective material (5).

INSPECTION AND FIELD CONTROL

The role of the inspection in soil-cement is a very essential one. There are three basic and fundamental factors that must be controlled to assure quality soil-cement. These are the proper cement content, optimum moisture content and the proper degree of compaction (32). If these three essentials can be controlled, a quality soil-cement project will then become reality.

Determination of Cement Content

There are many methods used for determining the cement content. These methods are: Public Roads method (33), ASTM method (34), the California method (35) and many others. For this paper the EDTA (ethylenedinitrilotetraacetic acid) method (36) is introduced, because the required testing time can be decreased by using this method. The detail of this method is as follows:*

Principle

A 10 percent ammonium chloride solution is used as the solvent system for the calcium compounds present in cement-treated base materials. The solution is titrated with the disodium salt of EDTA after adjustment of pH, using hydroxynaphthol blue as indicator. Cement content is determined from a standard graph after subtracting the aggregate blank.

Reagents

1. EDTA, 0.1 M-weight 116.88 g. of EDTA, A.C.S. reagent

*The detail of this method is quoted from Reference No. 36.

grade, into a 3-ℓ beaker. Add approximately 1.5ℓ of distilled water and place on stirrer. Add sodium hydroxide pellet by pellet until the acid is completely dissolved. Make up to exactly 4ℓ and transfer to a 1-gal polyethylene bottle. This solution must be stored in plastic.

2. Ammonium chloride solution, 10 percent-transfer 1,893 g. of U.S.P. granular ammonium chloride to a 5-gal plastic bottle. Make up to 5 gallons with distilled water, mixing thoroughly.

3. Sodium Hydroxide, 50 percent. Dissolve 500 g. of sodium hydroxide pellets in distilled water and dilute to 1ℓ. Use caution; store in plastic when cool. Dilute 1:1 with distilled water for use.

4. Triethanolamine, 20 percent. Dilute 100 ml of triethanolamine to 500 ml with distilled water.

5. Hydroxynaphthol blue. Obtain from Headquarters.

Procedure

Preparation of Curve. Prepare three duplicate samples as follows:

Set 1: Transfer two 300-gm samples of aggregate at the planned moisture content for the job to separate plastic containers. (The water used in bringing up the moisture to the correct amount should be that used at the job site.)

Set 2: Prepare two samples containing 2.5 percent cement of the type to be used on the job.

Set 3: Prepare two samples containing 5.0 percent cement.

Proceed with each sample as with production samples. Construct a graph showing milliliters of EDTA versus percent cement, [as in Figure 37], using the average figures from Sets 1, 2 and 3. This should yield a straight line. Set 1 corresponds to the blank for the aggregate being used.

Production Samples. Weigh into a 2 qt. plastic container exactly 300 g of soil-cement mixtures. Add 600 ml ammonium chloride solution and stir exactly 2 minutes with a stainless steel stirring rod. Allow mixture to settle exactly 4 minutes and then pipette a 10-ml aliguot of the supernatant solution into a 250 ml

Erlenmeyer flask. Add approximately 75 ml distilled water and with thorough mixing add the diluted NaOH dropwise until a pH between 13.0 and 13.5 is obtained using the pH indicator paper. Add 4 drops of 20 percent triethanolamine solution and then add hydroxynaphthol blue indicator. Titrate with EDTA to a pure blue endpoint. Determine cement content from the previously prepared graph [Figure 37].

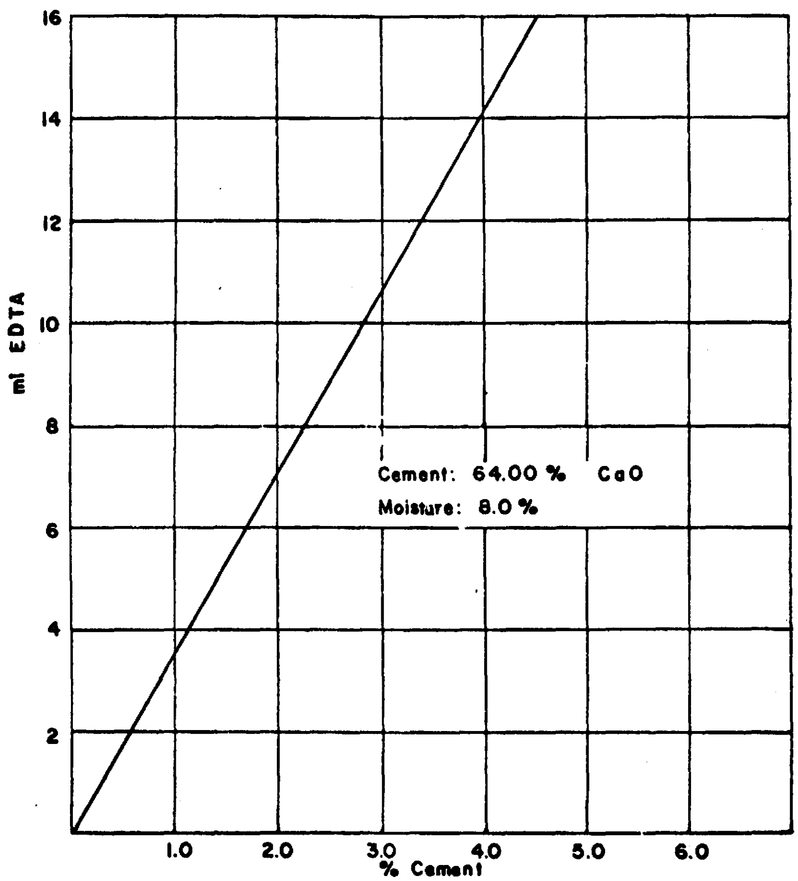

Figure 37. EDTA and Percentage Relationship (36).

Moisture Content Check

At the conclusion of moist-mixing, a moisture-density test (23) is made on a representative sample of the mixture taken from the roadway. This determines the optimum moisture and maximum density to be used for field control of the section under construction. These results may differ from laboratory values due to minor variations in the soil or due to the effects of partial hydration of the cement during the mixing period (27). To determine the amount of water to add, first calculate the percentage of water in a sample of the raw soil or dry soil-cement mixture, as follows:

$$\text{Percentage of moisture} = \frac{\text{wet weight - dry weight}}{\text{dry weight}} \times 100$$

The amount of water to be added during processing will be the difference between the required moisture content and the moisture content of the dry soil-cement mixture, as determined above (4).

Short Cuts Test

Many engineers have devised short cuts in making field moisture-density tests. For instance, the field sample, which is near optimum moisture, is split in three parts and one portion is used to establish a point near the peak of the moisture-density curve. A second portion of material is then used with the addition of a small increment of water to establish a point on the wet side of the curve. The third part of the original field sample which has dried slightly in the interim, is used to establish a dry point on the curve, as shown in Figure 38.

After a little experience, an operator can accurately judge when a soil or soil-cement mixture is at optimum moisture by its feel and by the way it packs into the mold. Such short cuts decrease the time

Moisture-density data			
Trial	Wet density, lb. per cu. ft.	Moisture content, per cent	Dry density, lb. per cu. ft.
1	130.4	10.0	118.5
2	130.4	11.5	117.0
3	128.1	9.0	117.5

Maximum dry density: 118.5 lb. per cu. ft.
Optimum moisture: 10.3 per cent

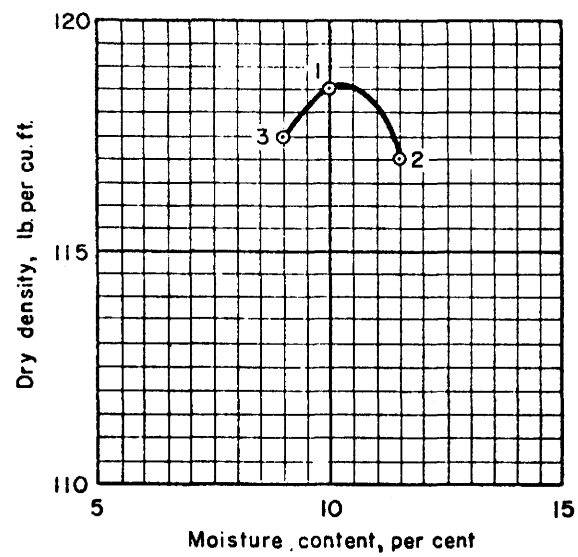

Figure 38. A Field Moisture-density Curve (26).

required to make a moisture-density test and produce reliable results when tests are performed by an experienced operator (26).

Hand-squeeze Test

With a little experience, the moisture content of a soil-cement mixture can be estimated closely by observation and feel. A mixture near or at optimum moisture content is just moist enough to dampen the hands when it is packed in a tight cast. Mixtures above optimum will leave excess water on the hands, whereas mixtures below optimum will tend to crumble easily. If the mixture is near optimum, it is possible to break the cast into two pieces with little or no crumbling.

The hand-squeeze test is not a replacement for the standard moisture-content test, but it does reduce the number of these tests required during construction. The moisture-determination test validates what has been determined by visual inspection and the hand-squeeze test.

Degree of Compaction Check

Density should be determined at several locations on the first few sections completed; the tests are made immediately after final rolling. Comparison of these densities with the results of the field moisture-density test indicates any adjustments in compaction procedures that may be required to ensure compliance with job specifications. Specifications generally require that the density obtained shall be not less than standard maximum minus 5 lb. (some agencies specify not less than 95 percent of the maximum density) as determined by the field moisture-density test. After compaction procedures have been adjusted, only routine daily density checks are required (26).

A density test is made by augering or digging a 5-inch diameter hole almost the full depth of processing. All material removed is carefully salvaged and the wet weight is measured; moisture content and oven-dry weight of this material are determined as follows:

$$\text{Percent moisture of representative sample} = \frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}} \times 100$$

$$\text{Dry weight of material from test hole} = \frac{\text{wet weight}}{(100 + \text{percent moisture}) \div 100}$$

The excavated hole is then filled with a material of known density; the hole's volume is calculated by:

$$\text{Volume, cu. ft.} = \frac{\text{weight of material used to fill the hole, lb.}}{\text{unit weight of that material, lb. per cu. ft.}}$$

And then the density is determined as follows:

$$\text{Density} = \frac{\text{dry weight of material removed from hole, lb.}}{\text{volume of hole, cu. ft.}}$$

The most common methods used for the volume determination of the density hole are (26).

1. Sand-cone method.
2. Balloon method.
3. Oil method.
4. Nuclear method.

Curing

Soil-cement at optimum moisture contains sufficient moisture for adequate cement hydration. After final compaction, a moisture-retaining cover is placed over the soil-cement to permit the cement to hydrate. Bituminous material is usually used, although waterproof paper, moist straw, or dirt is satisfactory for small areas. The bituminous materials most commonly used are RC-2, MC-2 and emulsified asphalt.

The rate of application varies from 0.15 to 0.30 gal. per square yard. Before the bituminous material is applied, the surface of the soil-cement should be free of dry, loose material and in a moist condition. In most cases a light application of water precedes the bituminous cure.

When the air temperature may be expected to reach the freezing point, sufficient protection from freezing should be given the soil-cement for 7 days after its construction and until it has hardened (26).

CONCLUSION

1. Soil-cement is a low cost highway material that can be constructed with only three basic raw materials: water, portland cement and soil. The water should be clean and free from harmful amounts of alkalies and acid; many types of portland cement conforming to ASTM Specifications can be used; and most of the soils at site or nearby source are acceptable. In some conditions the additives may be added to improve the properties or an economical standpoint.

2. Compressive strength is most frequently referred to as the important characteristic of soil-cement. The important factors that effect this strength are: soil type, quantity of cement, water content and compaction, curing condition, and age of soil-cement. Other properties that should be considered are the durability, load-deflection characteristics, fatigue properties, shrinkage characteristics and cracking.

3. Mix designs of soil-cement are to find the optimum moisture content that produce the soil-cement mixture at maximum density, which can be found by using ASTM Designation D 558-57; and to estimate the minimum amount of cement that will produce the soil-cement mixture for staying hard on alternate freezing-and-thawing and moisture changes, using ASTM Designation D 559-57 and D 560-57. Other methods may be used to fit the local experience.

4. Thickness design for soil-cement base course is developed on the basis of the following factors: subgrade strength, pavement design period, traffic-volume and axle weight distribution, and the relationship between the thickness of soil-cement base course and bituminous surface.

5. There are two steps in constructing the soil-cement at the roadsite:

a. Preparation of the site to proper crown and grade, scarifying and pulverizing may be required in this step.

b. Processing operations should be as follows: handling and spreading cement, mixing and application of water, compaction, finishing, curing and surfacing.

6. During construction the inspection in the field is essential and required for every step. The soil-cement mixtures will be satisfactory when they have the proper cement of compaction and curing materials.

The use of soil-cement in highway and airfield is on the increase every year because of its excellence properties and comparative economy over other materials. The research in this area has been continuing to improve the properties of soil-cement and to make soil-cement a more economical and more suitable material for engineering purposes.

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APPENDICES

Appendix A

Determination of Radius of Curvature*

There are essentially two methods for determining the radius of curvature of a deflected structure:

1. From physical property values, assuming that flexural theory is applicable, and

2. From the geometry of the deflection profile.

Assuming flexural conditions, the following expressions apply:

$$R_f = \frac{EI}{M} \tag{A-1}$$

where

R_f = radius of curvature by flexural theory, in.

E = modulus of elasticity, psi

I = moment of inertia, $in.^4$

M = bending moment, lb. /in.

and

$$R_f = \frac{h}{2\varepsilon} \tag{A-2}$$

where

h = depth of beam, in.

ε = fiber strain, in. /in.

By geometrical approach the radius of curvature is (for all practical purposes) expressed by the equation:

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*Appendix A is quoted from Reference No. 20.

$$R_g = \frac{1}{d^2 w/dx^2} \tag{A-3}$$

where

R_g = radius of curvature from geometrical consideration, in.

w = deflection of displacement, in.

x = distance along horizontal axis of beam, in.

To solve Equation (A-3) the numerical value of the second derivative is required. The formulas for derivatives are found by determining the equation for a polynomial passing through the given points and then evaluating the derivatives of the polynomial. For five given points the second derivative at the center point, x_2, is:

$$\frac{d^2w}{dx^2} = \frac{1}{12C}(-1W_0 + 16W_1 - 30W_2 + 16W_3 - 1W_4) \tag{A-4}$$

where C is the distance between equally spaced points and the subscripts refer to the five respective points. Formulas similar to Equation (A-4) can be developed for each point so that second derivatives of end points and penultimate points can be determined.

It is noted that the two methods, values of R_f in Equation (A-1) or (A-2) and R_g in Equation (A-3) and (A-4) are in good agreement. By both methods the R-values can be expressed in terms of EI/PL:

$$R = A\frac{EI}{PL} \tag{A-5}$$

where

P = the total load

L = the span length

A = the value from Table A1.

Table A1. Comparison of Geometrical and Flexural Determination of R

Distance from Center Line, in.	Value of A in Eq. (A5)									
	28-in. Beam					60-in. Beam				
	0	3	6	9	12	0	3	6	9	12
Eq. (A1)	0.222	0.222	0.250	0.400	1.000	0.080	0.080	0.083	0.095	0.111
Eq. (A3)	0.222	0.220	0.250	0.389	0.349	0.080	0.079	0.084	0.095	0.117
R_f/R_g	1.00	1.01	1.00	1.03	2.87	1.00	1.01	0.99	1.00	0.95

Appendix B

Capacity Design*

For high-traffic-volume project it is sometimes necessary to base the traffic volume on practical capacity, i.e., the maximum number of vehicles per lane per hour that can pass a given point under prevailing road and traffic conditions without unusual delay or restricted freedom to maneuver. Prevailing conditions include: composition of traffic, vehicle speeds, weather, alignment, profile, number and width of lanes, and type of area.

The term "practical capacity" is commonly used in reference to existing highways and the term "design capacity" is used for design purposes. Where traffic flow is uninterrupted, or nearly so, practical capacity and design capacity are numerically equal and have essentially the same meaning. The term "design capacity" is used in this paper in accordance with AASHO usage, and design capacities for various kinds of multilane highways are summarized in Table B1.

Capacity of Multilane Highways

For thickness design it is necessary to convert the passenger cars per hour in Table B1 to average daily traffic in both directions, ADT. For fultilane highways with uninterrupted flow, the following formula

*Appendix B is quoted from Reference No. 18.

Table B1. Design Capacities for Multilane Highways

Type of highway	Design capacity—passenger cars* per 12-ft. lane per hour
Urban freeways with full access control (30 to 35 mph)	1,500
Suburban freeways with full access control (35 to 40 mph)	1,200
Rural freeways with full or partial access control	1,000
Rural major highways with moderate cross traffic and roadside interference	700-900
Rural major highways with considerable cross traffic and roadside interference	500-700

*Also includes panels, pickups, and other four-tire commercial vehicles that function as passenger cars in terms of traffic capacity. Values are taken from two AASHO publications, *A Policy on Geometric Design of Rural Highways* and *A Policy on Arterial Highways in Urban Areas.*

is used:

$$ADT = \frac{100\,P}{100 + T_{ph}\,(j - 1)} \cdot \frac{5,000\,N}{KD}$$

where

P = passenger cars per lane per hour (from Table B1).

N number of lanes - total both directions

T_{ph} = trucks, percent, during peak hours

j = number of passenger cars that occupy the same space as one truck, i.e., four in rolling terrain and two in level terrain

K = design hour volume, DHV, expressed as a percentage of ADT; 15 percent is commonly used for rural freeways and 12 percent for urban freeways

D = traffic, percent, in direction of heaviest travel during peak hours - about 50 to 75 percent; 67 percent is commonly used for rural freeways and 60 percent for urban freeways.

Detailed discussions of this formula will be found in the AASHO publications, A Policy on Geometric Design of Rural Highways (1964) and A Policy of Arterial Highways in Urban Areas (1957).

Capacity of Two-lane Highways

Important factors in the design capacity of two-lane highways are:

1. The percent of total project length where sight distance is less than 1,500 ft.

2. Lane widths of less than 12 ft.

The design capacity in vehicles per hour for uninterrupted flow on two-lane highways is shown in Table B2.

It is good practice to use both traffic projection factors and design capacity for thickness design of specific projects. Design capacity should not be used where it shows a greater ADT than shown by traffic projection.

Table B2. Design Capacities for Uninterrupted Flow on Two-lane Highways*

Terrain	Alignment, percent of total project length with sight distance of less than 1,500 ft.	Design capacity, both directions, in vehicles per hour** where: L = lane width, feet; T_{ph} = trucks, percent, in peak hour†								
		L = 12			L = 11			L = 10		
		T_{ph} =			T_{ph} =			T_{ph} =		
		0	10	20	0	10	20	0	10	20
Level	0	900	780	690	770	670	600	690	600	530
	20	860	750	660	740	640	570	660	580	510
	40	800	700	620	690	600	530	620	540	480
Rolling	0	900	640	500	770	550	430	690	500	390
	40	800	570	450	690	490	380	620	440	340
	60	720	510	400	620	440	340	550	400	310
	80	620	440	350	530	380	300	480	340	270

*Source: AASHO's *A Policy on Geometric Design of Rural Highways*, Table II-10, page 88.

**Tabular values apply where lateral clearance is not restricted. Where clearance is less than 6 ft., apply values given in Table II-11 of the above-cited publication, page 89.

†Does not include four-tire vehicles.

Appendix C

Basis of Design Charts and Fatigue Factor*

The design procedure given in this paper is based on the formulations described in PCA Development Department Bulletin D142. The procedure has been developed further so that the same result is obtained in a more direct manner. The purpose of this appendix is to explain how the original formulations are applied in the design procedure.

Equations 25 and 25a in the research report give the allowable number of load repetitions in the form

$$N = \left[\frac{(1.77k_g)^{A_1}}{C/f(h)} \right]^{A_2} \left(\frac{\sqrt{a}}{P} \right)^{A_2}$$

where

N = allowable number of load repetitions

k_g = Westergaard's modulus of subgrade reaction, pounds per cubic inch

A_1 = an exponent : 0.3 for granular soil-cements and 0.315 for fine-grained soil-cements

A_2 = an exponent : 40.0 for granular soil-cements and 20.0 for fine-grained soil-cements

C = a constant : 10.4 for granular soil-cements

$$f(h) = \frac{(2.1h - 1)^2}{h^{1.5}}$$ where h is thickness, in.

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*Appendix C is quoted from Reference No. 18.

a = radius of load contact area, in.

P = wheel load, kips.

The total fatigue consumption of the expected number of axle loads, n_i, of various magnitudes, P_i, can be expressed as:

$$\text{fatigue consumption} = \Sigma \frac{n_i}{N_i}$$

Substituting for N, the equation becomes:

$$\text{fatigue consumption} = \Sigma \frac{n_i}{\left[\frac{(1.77k_g)^{A_1}}{C/f(h)}\right]^{A_2} \left(\frac{\sqrt{a_i}}{P_i}\right)^{A_2}}$$

$$= \left[\frac{C}{f(h)\ (1.77k_g)^{A_1}}\right]^{A_2} \cdot \Sigma \left(\frac{P_i}{\sqrt{a_i}}\right)^{A_2} \cdot n_i$$

In the summation, dividing by an arbitrarily selected $(P_9/\sqrt{a_9})^{A_2}$ (in this case for an 18-kip single-axle load or a 9-kip dual-wheel load) and multiplying this term outside the summation,

fatigue consumption =

$$= \left[\frac{C}{f(h)\ (1.77k_h)^{A_1}}\right]^{A_2} \left(\frac{P_9}{\sqrt{a_9}}\right)^{A_2} \cdot \Sigma \left(\frac{P_i}{\sqrt{a_i}} / \frac{P_9}{\sqrt{a_9}}\right)^{A_2} \cdot n_i$$

In Table 16 the Fatigue Consumption Coefficients, F_i, represent the values of:

$$F_i = \left(\frac{P_i}{a_i} \Big/ \frac{P_9}{\sqrt{a_9}} \right)^{A_2}$$

The Fatigue Factor, T, represents the summation, i.e.,

$$T = \Sigma \; F_i n_i$$

Setting fatigue consumption equal to 100 percent, the fatigue consumption computation procedure can be expressed as:

$$\left(\frac{C}{f(h)\;(1.77k_g)^{A_1}} \cdot \frac{P_9}{\sqrt{a_9}} \right)^{A_2} \cdot \; T = 1$$

From this equation the design curves in Figures 35 and 36 were constructed. The result is that the designer may read the thickness, h, directly from the curves for a given k_g and T, avoiding the selection of trial thickness that gives fractional fatigue consumption.

Because the values of A_1, A_2 and C are different for granular and fine-grained soil-cements, separate design charts and Fatigue Consumption Coefficients are required.

Appendix D

Methods of Test for Moisture-density Relations of Soil-cement Mixtures*

Method A. Using Soil Material Passing a No. 4 Sieve

Sample.

1. Prepare the sample for testing by breaking up the soil aggregations to pass the No. 4 sieve in such a manner as to avoid reducing the natural size of the individual particles. When necessary, first dry the sample until it is friable under a trowel. Drying may be accomplished by air drying or by the use of drying apparatus such that the temperature of the sample does not exceed 140°F.

2. Select a representative sample, weighing approximately 6 lbs. or more, of the prepared soil.

Procedure.

1. Add to the soil the required amount of portland cement. Mix the cement and soil thoroughly to a uniform color.

2. When needed, add sufficient potable water to dampen the mixture to approximately four to six percentage points below the estimated optimum moisture content and mix thoroughly. At this moisture content, plastic soils, tightly squeezed in the palm of the hand, will form a cast that will fracture with only slight pressure applied by the thumb and fingertips; nonplastic soils will bulk noticeably.

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*Appendix D is quoted from Reference No. 23.

3. When the soil is a heavy-textured clayey material, compact the mixture of soil, cement, and water in the container to a depth of about 2 in. using the rammer or similar hand tamper. Cover, and allow to stand for not less than 5 minutes but not more than 10 minutes to aid dispersion of the moisture and to permit more complete absorption by the soil-cement.

4. After the absorption period thoroughly break up the mixture, without reducing the natural size of individual particles, until it will pass a No. 4 sieve and then remix.

5. Form a specimen by compacting the prepared soil-cement mixture in the mold, with the collar attached, in three equal layers so as to give a total compacted depth of about 5 in. Compact each layer by 25 blows from the rammer dropping free from a height of 12 in. above the elevation of the soil-cement when a sleeve-type rammer is used, or from 12 in. above the approximate elevation of each finally compacted layer when a stationary-mounted type rammer is used. The blows shall be uniformly distributed over the surface of the layer being compacted. During compaction, the mold shall rest on a uniform, rigid foundation such as provided by a cylinder or a cube of concrete weighing not less than 200 lbs.

6. Following compaction, remove the extensive collar, carefully trim the compacted mixture even with the top of the mold by means of the knife and straightedge, and weigh.

7. Multiply the weight of the compacted specimen and mold, minus the weight of the mold, by 30; record the result as the wet unit weight, γw, in lb. /ft.^{3} of the compacted soil-cement mixture.

8. Remove the material from the mold and slice vertically through the center. Take a representative sample of the material, weighing not less than 100 gm, from the full height of one of the cut faces, weigh immediately and dry in an oven at $230 \pm 9^{\circ}F$ for at least 12 hours or to constant weight.

9. Calculate the moisture content of the sample. Record the result as the moisture content, w, of the compacted soil-cement mixture.

10. Thoroughly break up the remainder of the material as before until it will pass a No. 4 sieve, as judged by eye, and add all other material remaining after obtaining the moisture sample.

11. Add water in sufficient amounts to increase the moisture content of the soil-cement mixture by one or two percentage points, mix, and repeat the procedure given in 5 to 10 for each increment of water added.

12. Continue this series of determinations until there is either a decrease or no change in the wet unit weight, γm, in lb. /ft.^{3} of the compacted soil cement mixture.

Method B. Using Material Passing a 3/4 in. Sieve

Sample.

1. Prepare the sample for testing by segregating the aggregate retained on a No. 4 sieve and breaking up the remaining soil aggregations to pass the No. 4 sieve in such a manner as to avoid reducing the natural size of individual particles. When necessary, first dry the sample until it is friable under a trowel. Drying may be accomplished by air drying or by the use of drying apparatus such that the temperature of the sample does not exceed 140°F.

2. Sieve the prepared soil over the 3-in., 3/4 in. sieve and No. 4 sieves. Discard the material retained on the 3-in. sieve. Determine the percentage of material, by oven-dry weight, retained on the 3/4-in. and No. 4 sieves.

3. Saturate the aggregate passing the 3/4 in. sieve and retained on the No. 4 sieve by soaking in potable water; surface-dry the material as required for later testing.

4. Select and maintain separate representative samples of soil passing the No. 4 sieve and of saturated, surface-dry aggregate passing the 3/4-in. sieve and retained on the No. 4 sieve so that the total sample will weigh approximately 11 lb. or more. The percentage, by oven-dry weight, of aggregate passing the 3/4-in. sieve and retained on the No. 4 sieve shall be the same as the percentage passing the 3-in. sieve and retained on the No. 4 sieve in the original sample.

Procedure.

1. Add to the portion of the soil sample passing the No. 4 sieve, the amount of cement required for the total sample. Mix the cement and soil thoroughly to a uniform color.

2. When needed, add water to this soil-cement mixture and facilitate moisture dispersion as described for Method A in 2 to 4. After this preparation, add the saturated, surface-dry aggregate to the soil-cement mixture passing the No. 4 sieve and mix thoroughly.

3. Form a specimen by compacting the prepared soil-cement mixture in the mold (with the collar attached) and trim and weigh the compacted specimen as described for Method A in 5 and 6. During the trimming operation remove all particles that extend above the top level of the mold. Correct all irregularities in the surface by hand-tamping fine material into these irregularities and leveling the specimen again with the straightedge.

5. Remove the material from the mold and take a sample for determining the moisture content as described for Method A in 8 and 9 except that the moisture sample shall weigh not less than 500 gm. Record the result as the moisture content, w, of the compacted soil-cement mixture.

6. Thoroughly break up the remainder of the material as before until it will pass a 3/4-in. sieve and at least 90 percent of the soil particles smaller than a No. 4 sieve will pass a No. 4 sieve, as

jodged by eye, and add all other material remaining after obtaining the moisture sample.

7. Add sufficient water to increase the moisture content of the soil-cement mixture by one or two percentage points, mix, and repeat the procedure described in 3 to 6 for each increment of water added. Continue this series of determinations until there is either a decrease or no change in the wet unit weight, γ w, in lb. /ft.^{3} of the compacted soil-cement mixture.

Appendix E

Wetting-and-Drying Tests of Compacted Soil-cement Mixtures*

Method A. Using Soil Material Passing a No. 4 Sieve

Preparation of Material for Molding Specimens.

1. Prepare the soil sample in accordance with the procedure described in Appendix D.

2. Select a sufficient quantity of the soil prepared in 1 to provide two** compacted specimens and required moisture samples.

3. Add to the soil the required amount of cement. Mix the cement and soil thoroughly to a uniform color.

4. Add sufficient potable water to raise the soil-cement mixture to optimum moisture content at the time of compaction and mix thoroughly. When the soil used is a heavy textured clayey material, compact the mixture of soil, cement, and water in the container to a depth of about 2 in. using the rammer or a similar hand tamper, cover, and allow to stand for not less than 5 minutes but not more than 10 minutes to aid dispersion of the moisture and to permit more complete absorption by the soil-cement.

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*Appendix E is quoted from Reference No. 24.

**Usually only one specimen (identified as No. 2) is required for routine testing. The other specimen (identified as No. 1) is made for research work and for testing unusual soils.

5. After the absorption period, thoroughly break up the mixture, without the natural size of individual particles, until it will pass a No. 4 sieve, as judged by eye, and then remix.

Molding Specimens.

1. Form a specimen by immediately compacting the soil-cement mixture in the mold (with the collar attached) and later trimming the specimen in accordance with Method A in Appendix D, and in addition scarify the tops of the first and second layers to remove smooth compaction planes before placing and compacting the succeeding layers. This scarification shall form grooves at right angles to each other, approximately 1/8 in. in depth and approximately 1/2 in. apart.

2. During compaction, take from the batch a representative sample of the soil-cement mixture, weighing not less than 100 gm, weigh immediately, and dry in an oven at $230 \pm 9^{\circ}F$ for at least 12 hours or to constant weight. Calculate the percentage of moisture as prescribed in Appendix D to check against design moisture content.

3. Weigh the compacted specimen and mold, remove the specimen from the mold, and calculate the oven-dry weight of each specimen in lb. $/ft.^3$ to check against design density.

4. Identify the specimen on a metal tag as No. 1 (see Note of the previous page) together with other needed identification marks and use to obtain data on moisture and volume changes during the test.

5. Form a second specimen as rapidly as possible and determine the percentage of moisture and oven-dry weight as described in 1 to 3. Identify this specimen as No. 2, together with other needed identification marks and use to obtain data on soil-cement losses during the test.

6. Determine the average diameter and height of the No. 1 specimen and calculate its volume.

7. Place the specimens on suitable carriers in the moist room and protect them from free water for a period of seven days.

8. Weigh and measure the No. 1 specimen at the end of the seve-day storage period to provide data for calculating its moisture content and volume.

Procedure.

1. At the end of the storage in the moist room, submerge the specimens in potable water at room temperature for a period of 5 hours and remove. Weigh and measure the No. 1 specimen (volume and moisture change specimen).

2. Place both specimens in an oven at 160°F for 42 hours and remove. Weigh and measure the No. 1 specimen.

3. Give specimen No. 2 (soil-cement loss specimen) two firm strokes on all areas with the wire scratch brush. The brush shall be held with the long axis of the brush parallel to the longitudinal axis of the specimen. Apply these strokes to the full height and width of the specimen with a stroke corresponding to approximately 3 lbs. of force.

Eighteen to twenty vertical brush strokes are required to cover the sides of the specimen twice and four strokes are required on each end.

4. The procedures described in 1 to 3 constitute one cycle (48-hour) of wetting and drying. Again submerge the specimens in water and continue the procedure for 12 cycles.

5. After 12 cycles of testing, dry the specimens to constant weight at 250°F and weigh to determine the oven-dry weight of the specimens.

6. The data collected will permit calculations of volume and moisture changes of specimen No. 1 and the soil-cement losses of the specimen No. 2 after the prescribed 12 cycles of test.

Method B. Using Material Passing a 3/4 in. Sieve

Preparation of Material for Molding Specimens.

1. Prepare the soil sample in accordance with Method B of Appendix D.

2. Select and maintain separate representative samples of soil passing the No. 4 sieve and of saturated, surface-dry aggregate passing the 3/4-in. sieve and retained on the No. 4 sieve so that the total sample will be enough to provide two compacted specimens and required moisture samples. The percentage, by oven-dry weight, of aggregate passing the 3/4-in. sieve and retained on the No. 4 sieve shall be the same as the percentage passing the 3-in. sieve and retained on the No. 4 sieve in the original sample.

3. Add to the sample passing the No. 4 sieve, the amount of cement required for the total sample specified in 2. Mix the cement and soil thoroughly to a uniform color.

4. Add to the sample passing the No. 4 sieve, sufficient water to raise the total soil-cement mixture prescribed in 2 to optimum moisture content at time of compaction and facilitate moisture dispersion as described for Method A in 4 to 6.

5. After preparation of the mixture as described in 1 to 4, add the saturated, surface-dry aggregate to the mixture and mix thoroughly.

Molding Specimens.

1. Form a specimen by immediately compacting the soil-cement mixture in the mold (with the collar attached) and later trimming the specimen in accordance with Method B of Appendix D, and in addition as the mixture for each layer is placed in the mold, spade along the inside of the mold with a butcher knife before compaction to obtain uniform distribution of the material retained on the No. 4 sieve and scarify the tops of the first and second layers as described for Method A of this method.

2. During compaction, take from the batch a representative sample of the soil-cement mixture weighing not less than 500 gm, weigh immediately, and dry in an oven at $230 \pm 9^{\circ}F$ for at least 12 hours or to constant weight to determine the moisture content to check against design moisture content.

3. Form a second specimen as rapidly as possible in the same manner.

4. Weigh each compacted specimen to check against design density, identify, measure the No. 1 specimen, place in the moist room, and measure the No. 1 specimen again at the end of the seven-day storage period as described for Method A in 3 to 8.

Procedure. Proceed as directed in Method A.

Calculations. Calculate the volume and moisture changes and the soil-cement losses of the specimens as follows:

1. Calculate the difference between the volume of specimen No. 1 at the time of molding and subsequent volumes as a percentage of the original volume.

2. Calculate the moisture content of specimen No. 1 at the time of molding and subsequent moisture contents as a percentage of the original oven-dry weight of the specimen.

3. Correct the oven-dry weight of specimen No. 2 for water that has reacted with the cement and soil during the test and is retained in the specimen at 230°F, as follows:

$$\text{Corrected oven-dry weight} = \frac{A}{B} \times 100$$

where

A = oven-dry weight after drying at 230°F

B = percentage of water retained in specimen plus 100.

The percentage of water retained in specimen No. 2 after drying at $230^{\circ}F$ for use in the above formula can be assumed to be equal to the water retained in specimen No. 1. When No. 1 specimens are not molded, the foregoing data are not available and the average values prescribed in Table E1 are used.

Table E1. Average Values

AASHO Soil Classification	Average Water Retained After Drying at 230 F (110 C), per cent
A-1, A-3	1.5
A-2	2.5
A-4, A-5	2.0
A-6, A-7	3.5

4. Calculate the soil-cement loss of specimen No. 2 as a percentage of the original oven-dry weight of the specimen as follows:

$$\text{Soil-cement loss, percent} = \frac{A}{B} \times 100$$

where

A = original calculated oven-dry weight minus final corrected oven-dry weight

B = original calculated oven-dry weight.

Appendix F

Freezing-and-Thawing Tests of Compacted Soil-cement Mixtures*

Method A. Using Soil Material Passing a No. 4 Sieve

The method of preparation of material for molding specimens and molding specimens are the same as given in Method A in Appendix E.

Procedure.

1. At the end of the storage in the moist room, place water-saturated felt pads about 1/2 in. thick, blotters, or similar absorbant material between the specimens and the carriers, and place the assembly in a freezing cabinet having a constant temperature not warmer than -10°F for 24 hours and remove. Weigh and measure the No. 1 specimen (volume and moisture change specimen).

2. Place the assembly in the moist room or suitable covered container having a temperature of 70°F and a relative humidity of 100 percent for 23 hours and remove. Free potable water shall be made available to the absorbant pads under the specimens to permit the specimens to absorb water by capillary action during the thawing period. Weigh and measure the No. 1 specimen.

3. Give specimen No. 2 (soil-cement loss specimen) two firm strokes on all areas with the wire scratch brush. The brush shall be held with the long axis of the brush parallel to the longitudinal axis of

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*Appendix F is quoted from Reference No. 25.

the specimen or parallel to the ends as required to cover all areas of the specimen. Apply these strokes to the full height and wid of the specimen with a firm stroke corresponding to approximately 3-lb. force. Eighteen to twenty vertical brush strokes are required to cover the sides of the specimen twice and four strokes are required on each end.

4. After being brushed, the specimens shall be turned over end for end before they are placed on the water-saturated pads.

5. The procedures described in 1 to 4 continue one cycle (48 hour) of freezing and thawing. Again place the specimens in the freezing cainet and continue the procedure for 12 cycles.

6. After 12 cycles of test, dry the specimens to constant weight at 230^{o}F and weigh to determine the oven-dry weight of the specimens.

7. The data collected will permit calculations of volume and moisture changes of specimen No. 1 and the soil-cement losses of specimen No. 2 after the prescribed 12 cycles of test.

Method B. Using Material Passing a 3/4 in. Sieve

The method of preparation of material for molding specimens and molding specimens is the same as given in Method B in Appendix E.

Procedure. Proceed as directed in Method A.

Calculations. The formula used to calculate the percent of soil-cement loss is the same as that used in Appendix E.