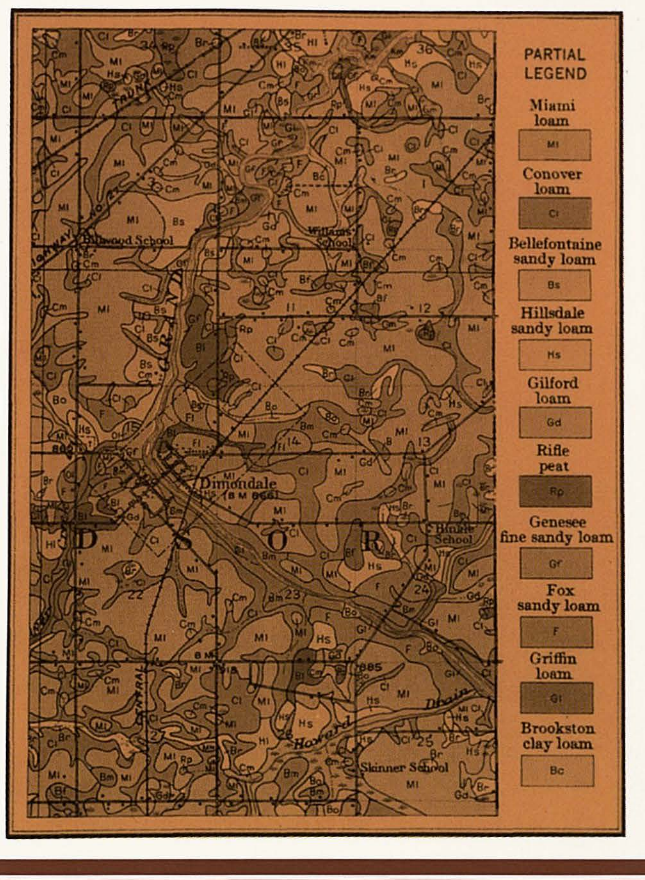
PORTLAND CEMENT ASSOCIATION

Soil-Cement Laboratory Handbook



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FOREWORD

For many years engineers have worked to develop a practical method of combining common soils with portland cement to produce a hardened, durable paving material at low cost. The first recorded road projects in which a mixture of soil and cement was used were built in South Dakota, Iowa, Ohio, California, and Texas. In 1933, 1934, and 1935, the South Carolina State Highway Department built several sections of road base with a soil-cement mixture. This work was notable because it proved beyond doubt that soil and cement could be mixed together to produce a construction material suitable for paving roads.

In 1935, the Development Department of the Portland Cement Association began extensive research to determine whether scientific control methods could be developed to produce uniformly satisfactory mixtures of portland cement and various soils. This investigation established scientific soil-cement testing and construction procedures that ensure dependable results. As part of this initial work, the moisture-density test, the wet-dry test, and the freeze-thaw test for soil-cement mixtures were developed. These tests were adopted as standards by the American Society for Testing Materials in 1944, and by the American Association of State Highway Officials in 1945. After 13 years of successful use, the test methods were revised by ASTM and by AASHTO in 1957 to incorporate the information and experience gained during that period. Subsequent revisions and reapprovals have been made over the years with current issue dates of 1989 and 1990. The revisions have greatly reduced the time, manpower, and material required to run the laboratory tests.

In the United States and Canada, as well as in other countries, there has been rapid growth in soil-cement paving construction. The outstanding performance record of the millions of square yards of soil-cement proves that the testing and construction principles are sound. These principles have transformed low-cost paving construction from a "cut-and-try" process into a sound engineering procedure.

This *Soil-Cement Laboratory Handbook* and the related publications, *Soil-Cement Construction Handbook* and *Soil-Cement Inspector's Manual*, present in practical form the complete procedure for testing and constructing soil-cement paving.

CAUTION: Contact with wet (unhardened) concrete, mortar, cement, or cement mixtures can cause SKIN IRRITATION, SEVERE CHEMICAL BURNS, or SERIOUS EYE DAMAGE. Wear waterproof gloves, a long-sleeved shirt, full-length trousers, and proper eye protection when working with these materials. If you have to stand in wet concrete, use waterproof boots that are high enough to keep concrete from flowing into them. Wash wet concrete, mortar, cement, or cement mixtures from your skin immediately. Flush eyes with clean water immediately after contact. Indirect contact through clothing can be as serious as direct contact, so promptly rinse out wet concrete, mortar, cement, or cement mixtures from clothing. Seek immediate medical attention if you have persistent or severe discomfort.

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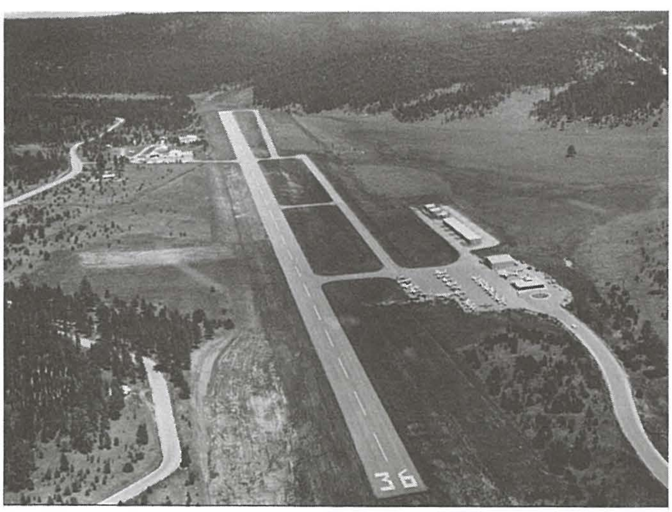

Soil-cement runway and taxiways, Ruidoso, New Mexico

A soil-cement parking lot in Texas

Constructed in 1935, the first scientifically controlled soil-cement project, SC 41 near Johnsonville, South Carolina, after 30 years of service (1965 photo).

INTRODUCTION

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 (1) that the proper amount of water be mixed uniformly with the soil-cement mixture and (2) that the moistened soil-cement mixture be compacted to proper density before cement hydration. These fundamental factors can be determined for any soil by laboratory tests and can be accurately and simply controlled in construction.

This handbook is devoted principally to the methods of making laboratory tests for determining the above control factors.

Since soil constitutes a very large portion of a soil-cement mixture, proper soil identification, classification, and sampling are also recognized as fundamental. The term "soil" as used in soil-cement testing and construction refers to any combination of the soil separates: gravel, sand, silt and clay, crushed materials, and materials such as cinders, slag, shale, caliche, chert, scoria, etc. Any mineral material that will pass the soil-cement tests is suitable for use in soil-cement. For practical reasons the soil should not have more than about 45 percent material retained on a No. 4 sieve or any material greater than 2 in. in diameter. Crushed stone and gravel base course materials that have more than 45 percent retained on the No. 4 sieve are being used successfully. However, because of their coarse gradation, these materials may require higher cement contents than less coarsely graded materials. When coarse-graded aggregates are used for soil-cement, it is important, as with all soil-cement materials, that the mix design be based on the ASTM and AASHTO standard freeze-thaw and wet-dry tests.

CHAPTER 1

METHODS OF TESTING SOIL-CEMENT

Laboratory and field experience during more than 57 years has shown conclusively that soils can be hardened adequately by the addition of relatively small quantities of portland cement to produce a strong, durable material suitable for low-cost paving. 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. Adherence to this principle has accounted for the uniformly high quality of thousands of miles of soil-cement pavement.

The composition of soils varies considerably and this affects the degree to which they react when combined with portland cement and water. The way a given soil reacts with cement is determined by simple laboratory tests made on mixtures of cement with the soil. The amount of laboratory testing required for a given project depends on the requirements of the constructing agency, the number of soil types encountered, and the size of the job.

On major projects, for example, detailed tests are generally required and the minimum cement content that can be used safely is determined for each significant soil type on the job. State highway department laboratories and many others are well equipped to run complete, detailed tests. The cost of laboratory tests for major projects is quite small in comparison with the total cost of the project.

On smaller projects, particularly where testing facilities and manpower are limited, it is sometimes considered advantageous to conduct only enough laboratory tests to determine a safe, but not necessarily minimum, cement factor that can be used for construction.

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

The various test methods are shown graphically in Fig. 1.

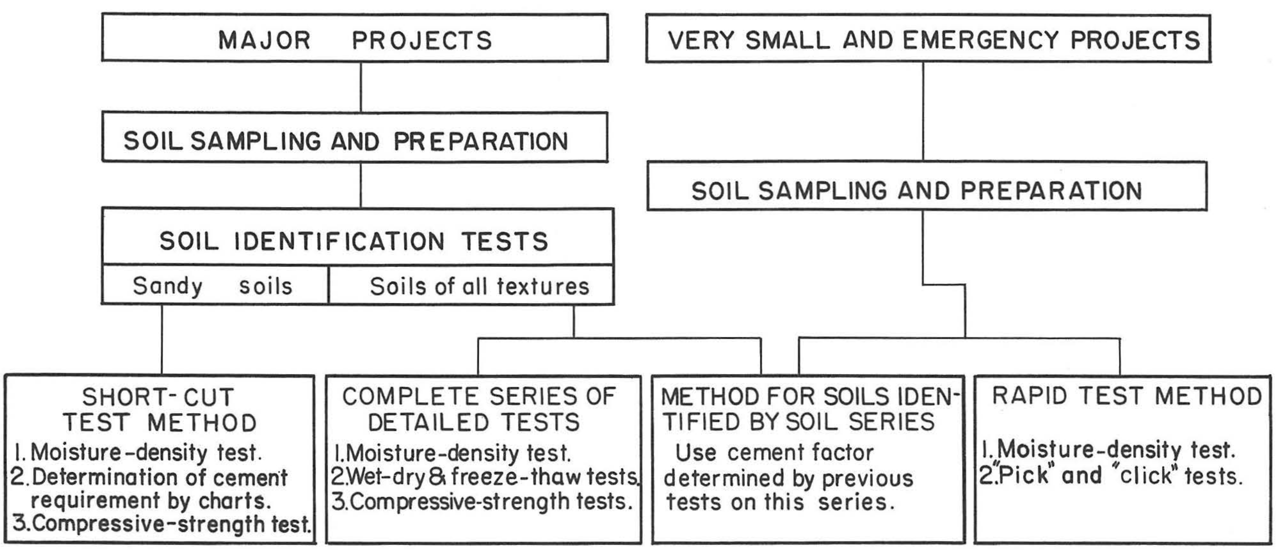

Fig. 1. Soil-cement laboratory testing methods.

In some areas, special test methods and criteria have been developed specifically for local conditions. For the particular soils and climate involved, these locally developed test methods also have proved satisfactory.

In all cases the tests are performed to determine three fundamental requirements for soil-cement:

1. How much portland cement is needed to harden the soil adequately?
2. How much water should be added?
3. To what density must the soil-cement be compacted?

Detailed test methods for determining these control factors are described in:

Methods of Test for Moisture-Density Relations of Soil-Cement Mixtures, ASTM Designation: D558; AASHTO Designation: T134.

Methods of Wetting and Drying Test of Compacted Soil-Cement Mixtures, ASTM Designation: D559; AASHTO Designation: T135.

Methods of Freezing and Thawing Test of Compacted Soil-Cement Mixtures, ASTM Designation D560; AASHTO Designation: T136.

The dependability of these test methods has been proved by the outstanding service record of soil-cement paving for roads and streets, as well as for many airports, parking areas, and similar projects that were built using control factors obtained by these test methods. But, invaluable as they are, they require considerable time to obtain the factors needed for construction. In a continuing effort to reduce the time and manpower needed for laboratory testing, the Portland Cement Association has developed a special short-cut test procedure for determining cement factors for sandy soils.

The following paragraphs give a general discussion of the ASTM-AASHTO test methods. This is followed by a general discussion of the special short-cut test procedures for sandy soils, and then by a discussion of test methods used for emergency construction and for very small projects. The value of identifying the soils occurring on a project by soil series name, as identified by the U.S. Department of Agriculture, is stressed as an additional means of reducing testing requirements.

A detailed discussion of the ASTM-AASHTO test procedures for routine testing is given in Chapter 3; the short-cut test procedure for sandy soils is described in Chapter 6; and the rapid test procedure for emergency projects is given in Chapter 7.

ASTM-AASHTO Test Methods

MOISTURE-DENSITY TEST

The moisture-density test is used to determine the proper moisture content and density (termed the optimum moisture content and maximum density) for molding laboratory test specimens. It is also used in the field during construction to determine the quantity of water to be added and the density to which the mixture should be compacted.

The moisture-density test for a soil-cement mixture determines the relationship between the moisture content of the soil-cement mixture and the resulting density when the mixture is compacted before cement hydration with a standard compactive force. A typical moisture-density curve is shown in Fig. 2.

While soil, cement and water are being mixed, a distinct change is taking place in the mixture. Apparently there is a base exchange phenomenon occurring. The soil becomes more or less coagulated, which causes an increase in internal friction.

Therefore, moisture-density relations of a soil-cement mixture will vary slightly as a result of this chemical phenomenon and of the partial cement hydration that has taken place during damp-mixing. These effects will be noted as an increase in the optimum moisture content and a decrease in the maximum density of the soil-cement mixture as the damp-mixing time increases. For this reason, moisture-density tests in the laboratory are made on the soil-cement mixture as rapidly as possible. This is necessary because test specimens, which are designed from these test data, are molded after a few minutes of mixing soil, cement, and water, and before cement hydration.

Specifications for soil-cement construction require that moisture-density relations be established in the field toward the end of the damp-mixing procedure, with the use of soil-cement taken directly from the area being constructed. If need be, laboratory soil-cement moisture-density test that simulate the time elements of field mixing operations may be run. Results will closely approximate the actual field optimum moisture and maximum density.

During construction, estimates of water requirements are based on moisture-density tests made in the laboratory until the mixture is close to the optimum moisture and until the optimum moisture prevailing in the moist soil-cement at time of compaction has been determined.

Details of performing the moisture-density test are given in Chapter 3.

FREEZE-THAW AND WET-DRY TESTS

The freeze-thaw and wet-dry tests were designed to determine whether the soil-cement would stay hard or whether expansion and contraction on alternate freezing-and-thawing and moisture changes would cause the soil-cement to soften.

It has been amply demonstrated that cement contents that produce low soil-cement weight losses in the freeze-thaw and wet-dry tests (described in detail in Chapter 3) resist volume changes or hydraulic pressures that could gradually break down bonds of cementation.

The severity of the freeze-thaw test depends largely on the moisture conditions prevailing in the specimens. Since the moisture content of road bases is usually less than saturation, the test condition used in the standard freeze-thaw test seems rational since it produces a moisture content that is determined by the capillarity and permeability properties of the soil-cement.

In the development of the standard testing procedures, the possibility of an accelerated strength gain due to the high

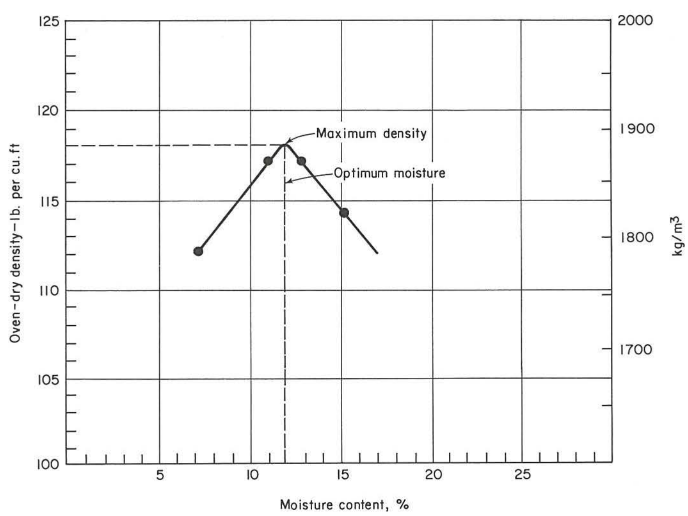

Fig. 2. Typical moisture-density curve.

temperature of the wet-dry test was recognized. This is one reason that the two procedures, freeze-thaw and wet-dry tests, were selected to be used together to measure the properties of soil-cement mixtures.

The wire brush used in these tests produces some abrasion on sandy soil-cement specimens, thus removing some material in addition to that loosened by the alternate freezing-and-thawing and wetting-and-drying. This abrasion is considered when cement recommendations are selected. For instance, greater soil-cement losses are permitted for satisfactorily hardened sandy soil-cement mixtures than for satisfactorily hardened silt and clay soil-cement mixtures.

Short-Cut Test Procedures for Sandy Soils

Short-cut test procedures have been evolved to determine adequate cement contents for sandy soils.* These procedures do not involve new tests or additional equipment. Instead, data and charts developed from previous tests of similar soils are utilized to eliminate some tests and greatly reduce the amount of work required. The only laboratory tests required are a grain-size analysis, a moisture-density test, and compressive-strength tests. Relatively small soil samples are needed, and all tests except the 7-day compressive-strength tests can be completed in one day.

While these procedures do not always give the minimum cement factor that can be used, they provide a safe cement factor generally close to that indicated by standard ASTM-AASHTO wet-dry and freeze-thaw tests. The procedures are finding wide application by engineers and builders and may largely replace the standard tests as experience in their use is gained and the relationships are checked. Possibly the charts and procedures may be modified to conform to local conditions if needed.

The short-cut test procedures for sandy soils are discussed in detail in Chapter 6.

*J. A. Leadabrand and L. T. Norling, "Soil-Cement Test Data Correlation in Determining Cement Factors for Sandy Soils," *Highway Research Board Bulletin 69*, 1953, pages 24-46. J. A. Leadabrand and L. T. Norling, "Simplified Methods of Testing Soil-Cement Mixtures," *Highway Research Board Bulletin 122*, 1956, pages 35-47. L. T. Norling and R. G. Packard, "Expanded, Short-Cut Test Method for Determining Cement Factors for Sandy Soils," *Highway Research Board Bulletin 198*, 1958, pages 20-31.

Rapid Test Procedure

A rapid method of testing soil-cement has been used successfully for emergency construction and for very small projects where more complete testing is not feasible or practical. It involves molding and visually inspecting several specimens that cover a wide range of cement contents—for example, 10, 14 and 18 percent. After at least a day or two of hardening, the specimens are inspected by "picking" with a relatively sharp-pointed instrument and by sharp "clicking" of each specimen against a hardened object such as concrete to determine the relative hardness. If a specimen cannot be penetrated more than 1/8 to 1/4 in. by picking and if it produces a clear or solid tone upon clicking, an adequate cement factor is indicated.

Even an inexperienced person can soon differentiate between satisfactorily and unsatisfactorily hardened specimens and will be able to select a safe cement content to harden the soil.

The rapid test procedure is discussed in more detail in Chapter 7.

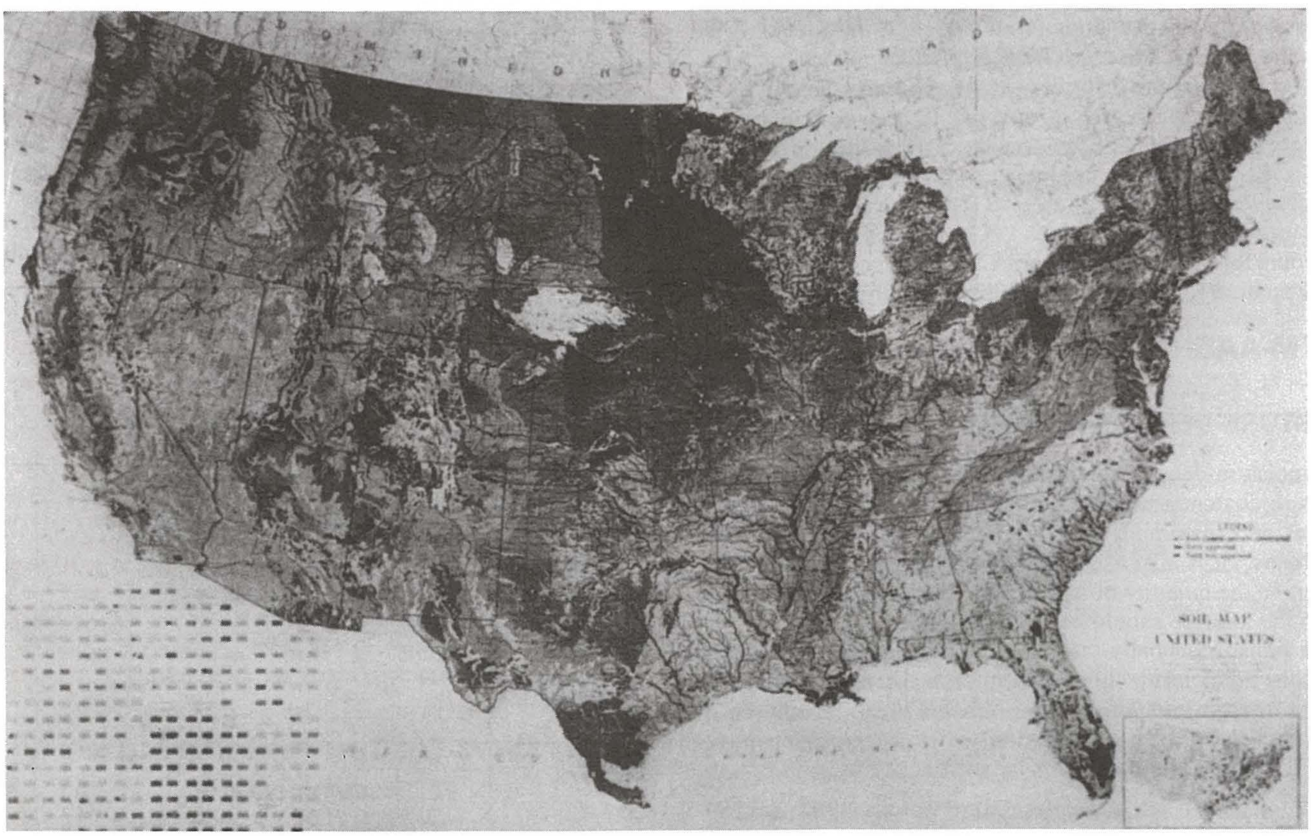

Fig. 3. Major soil series in the United States. (From "Soils of the United States," *Part III, Atlas of American Agriculture,* U.S. Department of Agriculture.)

Tests on Soils Identified by Soil Series

A very helpful tool for the engineer in reducing soil-cement test work is the identification of soils by the Department of Agriculture soil classification system.* In this classification system, soils are subdivided into groups called soil series. Soils of a certain soil series have similar characteristics of subsoil (B horizon), parent material (C horizon), climate vegetation, and age. Large areas may be covered by soils of the same series (See Fig. 3).

Identifying soils by series name is important in soil-cement work because it has been found that soils of the same soil series and horizon require the same amount of cement for adequate hardening. Once the cement requirement of a given soil series and horizon has been determined by laboratory tests, another complete series of soil-cement tests is not needed for this particular soil series when it is again encountered.

Thus, by identifying soils by soil series, the need for conducting soil-cement tests can be sharply reduced or eliminated for large areas. An increasing number of engineers are making use of this system of classification to reduce their soil-cement testing work. Soil surveys have been made over a large portion of the United States and maps have been prepared by the Department of Agriculture. County maps are available to the public and can be viewed or obtained from the U.S. Department of Agriculture, county extension agents, colleges, universities, libraries, or from other sources.

A tabulation of the counties in the United States for which maps have been published as of February 1991 is given in *List of Published Soil Surverys*, 1990, U.S. Department of Agriculture, Soil Conservation Service, revised February 1991. This publication may be obtained from Public Information Division, Soil Conservation Survey, P.O. Box 2890, Room 0054-S,Washington, D.C. 20013.

Grain-size and physical-test-constant tests are also helpful in the identification and classification of soils, and the data can be used to good advantage in conjunction with the soil series identification system. These tests also provide additional information to permit the construction engineer to identify on the project the various soil types that were tested in the laboratory.

*The Department of Agriculture soil classification system is described in *PCA Soil Primer* published by Portland Cement Association.

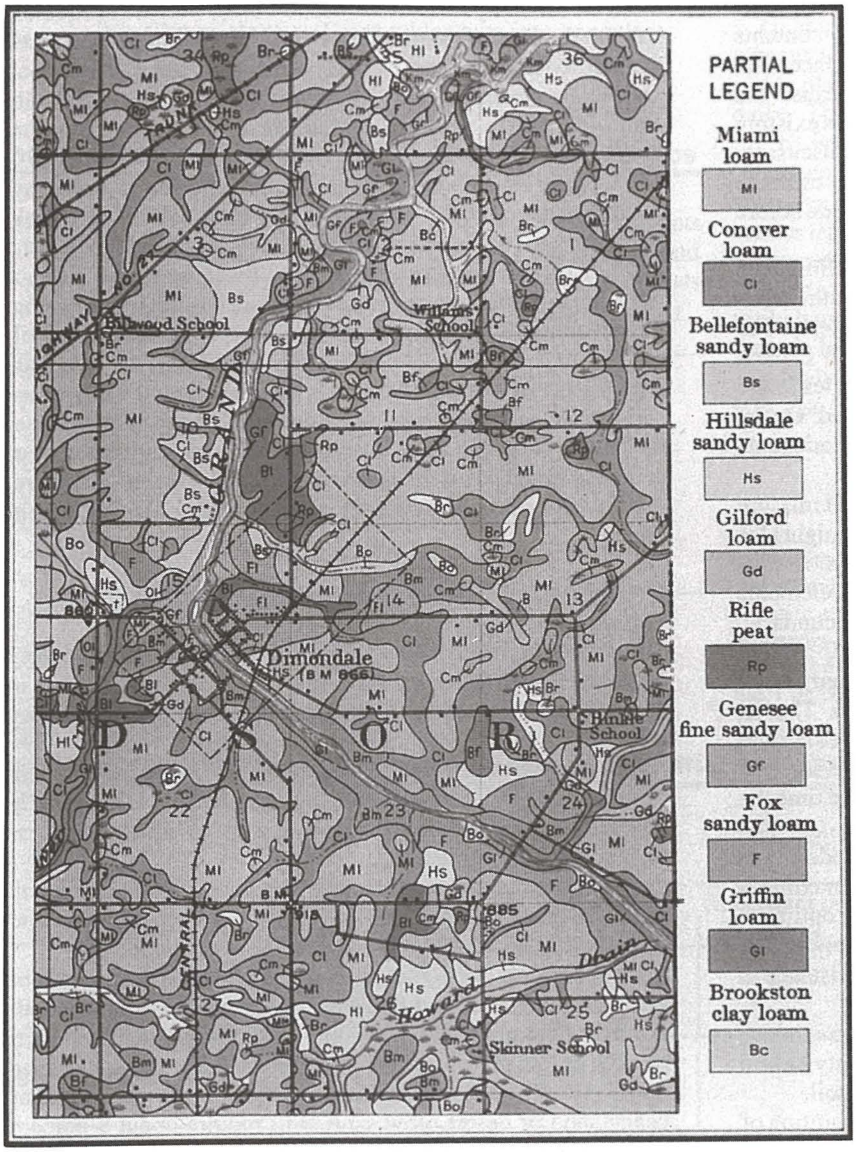

Fig. 4. Reprint of a small section of a typical detailed soil map (Eaton County, Mich.). From "Development and Significance of the Great Soil Groups of the United States," *Miscellaneous Publication No. 229*, U.S. Department of Agriculture.

CHAPTER 2

SELECTION OF CEMENT CONTENTS FOR TESTS

This chapter will be of major interest to the laboratory engineer because it will assist him in determining what cement contents to investigate in the soil-cement tests. The filed engineer and administrative engineer will also be interested because the properties of soil-cement mixtures and the relationships existing among these properties and various test values are discussed. Information is presented that will enable engineers to estimate probable cement factors so that job estimates can be made before any tests are made.

In order to obtain the maximum amount of information from the wet-dry 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.

The principal requirement of a hardened soil-cement mixture is that it withstand exposure to the elements. Strength might also be considered a principal requirement; however, since most soil-cement mixtures that possess adequate resistance to the elements also possess adequate strength, this requirement is secondary.

Therefore, in a study to determine when a certain soil-cement mixture has been adequately hardened, the requirement of adequate resistance to exposure is the first considered. That is, will the hardened soil-cement mixture 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?

For instance, consider a hypothetical road subgrade made from a clay loam soil without cement, packed to maximum density at a moisture content slightly less than its optimum moisture content. This mass can withstand relatively heavy loads without failure, although it cannot offer much resistance to abrasive forces.

The same soil mixed with cement and compacted to maximum density at optimum moisture content will have stability before the cement hydrates at least equal to that of the raw soil.

But consider the two cases at a later date under a condition of slow drainage when moisture, by capillary action or in some other manner, has permeated the masses. The voids in the raw soil become filled with water and the soil loses the original inherent physical stability that was built into it by compaction to maximum density. This is not so, however, with the adequately hardened soil-cement mixture, which has continually increased in stability since its construction because of cement hydration and resultant cementation. Its air voids may become filled with water too, but its stability will still be much greater than that built into it originally.

The next important requirement to consider is economy. Available data indicate that about 85 percent of all soils likely to be used for soil-cement can be adequately hardened by the addition of 14 percent cement or less. To determine whether or not a soil falls into this category would not require much testing. However, more than 50 percent of all soils so far tested for soil-cement require only 10 percent cement or less for adequate hardening. To identify these soils requires more testing. Since soil-cement is in the low-cost paving field, the testing engineer on large jobs should determine by test the minimum quantity of cement that can be safely used with each soil. By this procedure, the lowest-cost soil-cement construction possible will be obtained.

Estimating Cement Requirements

The following information will aid the engineer in estimating cement requirements of the soils proposed for use and in determining what cement factors to investigate in the laboratory tests.

As a general rule, it will be found that the cement requirement of soils increases as the silt and clay content increases, 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.

In general, a well-graded mixture of stone fragments or gravel, coarse sand, and fine sand either with or without small amounts of slightly plastic silt and clay material will require 5 percent or less cement by weight. Poorly graded one-size sand materials with a very small amount of nonplastic silt, typical of beach sand or desert blow sand, will require about 9 percent cement by weight. The remaining sandy soils will generally require about 7 percent. The nonplastic or moderately plastic silty soils generally require about 10 percent cement by weight, and plastic clay soils require about 13 percent or more.

Table 1 gives the usual range in cement requirements for subsurface soils of the various AASHTO* soil groups. "A" horizon soils may contain organic or other material detrimental to cement reaction and may require higher cement factors. For most A horizon soils, the cement content in Table 1 should be increased four percentage points if the soil is dark grey to grey and six percentage points if the soil is black. It is usually not necessary to increase the cement factor for a brown or red A horizon soil. Testing of "poorly reacting" sandy surface soils is discussed in detail in Chapter 8. These cement contents can be used as preliminary estimates, which are then verified or modified as additional test data become available.

STEP-BY-STEP PROCEDURE

The following procedure will prove helpful to the testing engineer in setting up cement contents to be investigated:

Step 1: Determine from Table 1 (fourth column) the preliminary estimated cement content by weight based on the AASHTO soil group.

Step 2: Use the preliminary estimated cement content obtained in Step 1 to perform the moisture-density test.

Step 3: Verify the preliminary estimated cement content by referring to Table 2 if the soil is sandy or to Table 3 if it is silty or clayey. These tables take into consideration the maximum dry density and other properties of the soil, which permits a more accurate estimate. In the case of A horizon soils, the indicated cement factor should be increased as discussed above for Table 1.

Sandy soils:

(1) Using the percentage of material smaller than 0.05 mm, the percentage of material retained on the No. 4 sieve, and the maximum density obtained by test in Step 2, determine from Table 2 the estimated cement content.

(2) Mold wet-dry and freeze-thaw test specimens at the estimated cement content by weight obtained in (1) and at cement contents two percentage points above and below that cement factor.**

Silty and clayey soils:

(1) Using the percentage of material between 0.05 mm and 0.005 mm, the AASHTO group index (See Fig. 5, page 12), and the maximum density obtained by test in Step 2, determine from Table 3 the estimated cement content.

(2) Mold wet-dry and freeze-thaw test specimens at the estimated cement content obtained in (1) and at cement contents two percentage points above and below that factor.

To help in determining how well the soil reacts, it is advantageous to save half of the last moisture-density test specimen and to place it in an atmosphere of high humidity for inspection daily. This half specimen, called the "tail-end" specimen (see Fig. 6), is obtained during the usual procedure of cutting the last specimen of the moisture-density test in half vertically (details are given on page 19) so that a representative moisture sample can be taken. The criteria used in the rapid test procedure, as discussed in Chapter 7, can be used to judge the hardness of the tail-end specimen. Generally, tail-end specimens are satisfactorily hardened in two to four days and it is not uncommon for them to be satisfactory a day after molding.

A study of compressive-strength data, as discussed in Chapter 4, is also helpful in checking the estimated cement factor.

Table 1. Cement Requirements of AASHTO Soil Groups

AASHTO soil group	Usual range in cement requirement, percent by vol.	Usual range in cement requirement, percent by wt.	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.
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

*Charts and tables for use in classifying soils by the American Association of State Highway and Transportation Officials Soil Classification System (AASHTO Designation M145) are given in the Appendix.

**If the estimated cement content is 5 percent, it is good practice to use 1 percentage point increments below 5 percent.

Table 2. Average Cement Requirements of B and C Horizon Sandy Soils

Material retained on No. 4 sieve, percent	Material smaller than 0.05 mm, percent	Cement content, percent by wt. — Maximum density, lb per cu ft: 105-109	110-114	115-119	120-124	125-129	130 or more
0-14	0-19	10	9	8	7	6	5
	20-39	9	8	7	7	5	5
	40-50	11	10	9	8	6	5
15-29	0-19	10	9	8	6	5	5
	20-39	9	8	7	6	6	5
	40-50	12	10	9	8	7	6
30-45	0-19	10	8	7	6	5	5
	20-39	11	9	8	7	6	5
	40-50	12	11	10	9	8	6

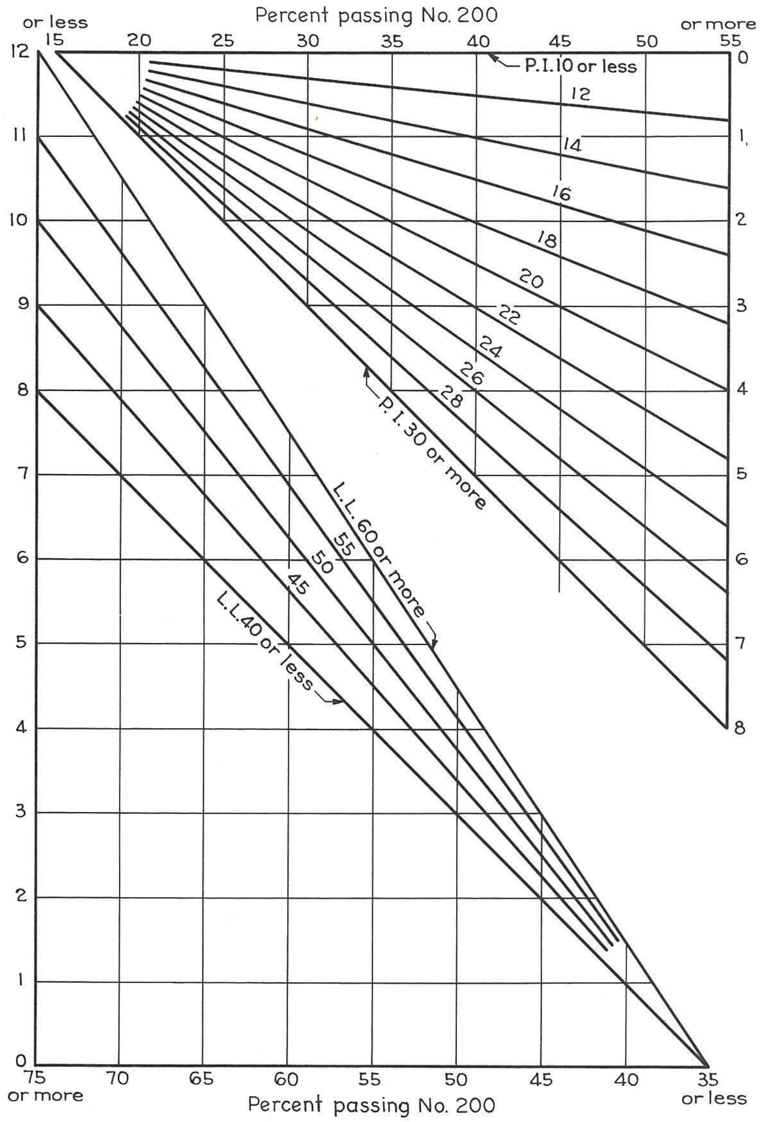

Fig. 5. Charts for calculating group index values for use with Table 3. The group index is the sum of the values obtained by using the liquid limit and the plasticity index. (See footnote, Table 3)

Miscellaneous Soils

A number of miscellaneous materials or special types of soils, such as caliche, chert, cinders, scoria, shale, etc., have been used successfully in soil-cement construction. In some cases, these materials have been found in the roadway or street that was to be paved with soil-cement; in other cases, in order to reduce the cost of the project, they have been used as borrow materials to replace soils that required high cement contents for adequate hardening.

The procedure for testing miscellaneous materials is the same as that used for regular soils. Average cement requirements of a number of miscellaneous materials and cement contents to be investigated in the laboratory test are given in Table 4. As test data are accumulated and experience is gained with local miscellaneous materials, it may be found that future testing can be reduced for similar materials.

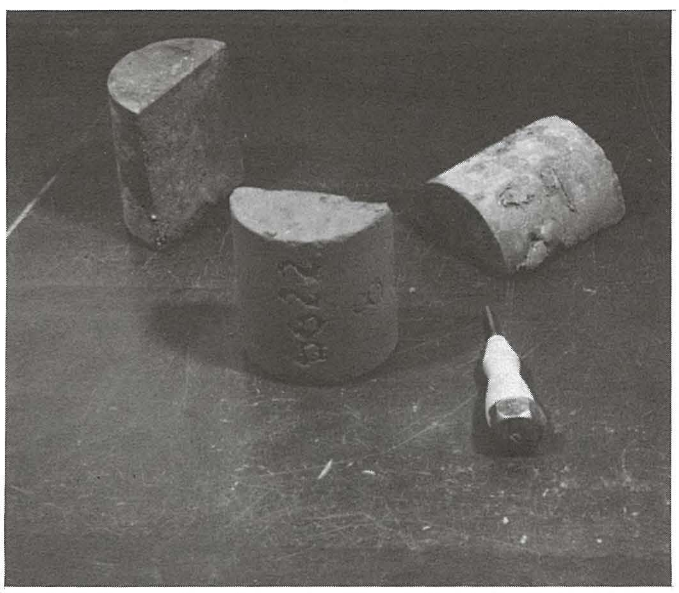

Fig. 6. Soil-cement specimens saved from tail end of moisture-density test procedure. Rate of hardening of the soil-cement mixture is investigated from day to day with a dull-pointed instrument.

Table 3. Average Cement Requirement of B and C Horizon Silty and Clayey Soils

Group Index*	Material between 0.05 mm, and 0.005 mm, percent	Cement content, percent by wt.						
		Maximum density, lb per cu ft						
		90-94	95-99	100-104	105-109	110-114	115-119	120 or more
0-3	0-19	12	11	10	8	8	7	7
	20-39	12	11	10	9	8	8	7
	40-59	13	12	11	9	9	8	8
	60 or more	--	--	--	--	--	--	--
4-7	0-19	13	12	11	9	8	7	7
	20-39	13	12	11	10	9	8	8
	40-59	14	13	12	10	10	9	8
	60 or more	15	14	12	11	10	9	9
8-11	0-19	14	13	11	10	9	8	8
	20-39	15	14	11	10	9	9	9
	40-59	16	14	12	11	10	10	9
	60 or more	17	15	13	11	10	10	10
12-15	0-19	15	14	13	12	11	9	9
	20-39	16	15	13	12	11	10	10
	40-59	17	16	14	12	12	11	10
	60 or more	18	16	14	13	12	11	11
16-20	0-19	17	16	14	13	12	11	10
	20-39	18	17	15	14	13	11	11
	40-59	19	18	15	14	14	12	12
	60 or more	20	19	16	15	14	13	12

*Group index values determined by charts used in AASHTO M 145-49 (see Fig. 5). The newer group index chart developed in 1973 for AASHTO M 145, is given on page 59. This new chart cannot be used to determine group index values for Table 3 since this table is based on AASHTO M 145-49.

Table 4. Average Cement Requirements of Miscellaneous Materials

Type of miscellaneous material	Estimated cement content and that used in moisture-density test		Cement contents for wet-dry and freeze-thaw tests, percent by wt.
	percent by vol.	percent by wt.	
Shell soil	8	7	5- 7- 9
Limestone screenings	7	5	3- 4- 5- 7
Red dog	9	8	6- 8- 10
Shale or disintegrated shale	11	10	8-10-12
Caliche	8	7	5- 7- 9
Cinders	8	8	6-8-10
Chert	9	8	6-8-10
Chat	8	7	5- 7- 9
Marl	11	11	9-11-13
Scoria containing material retained on the No. 4 sieve	12	11	9-11-13
Scoria not containing material retained on the No. 4 sieve	8	7	5- 7- 9
Air-cooled slag	9	7	5- 7- 9
Water-cooled slag	10	12	10-12-14

CHAPTER 3

DETAILS OF SOIL-CEMENT TEST METHODS

This chapter will be of major interest to the laboratory engineer because it discusses details of methods for testing soil-cement mixtures.

The complete series of tests, which are here described in detail, will determine the minimum amount of cement required* to harden the soil adequately. State highway departments and commercial laboratories generally have the necessary equipment to run these tests. On smaller projects, such as some county and city work where testing facilities are at a minimum and where it is not so important to determine the minimum cement content, a complete series of laboratory tests is not always needed. For example, if the soils are sandy, short-cut test procedures, as described in Chapter 6, are run in many cases. For emergency construction and for very small projects where testing facilities are not available, a rapid test procedure, as described in Chapter 7, has been used successfully to indicate safe cement factors.

The test procedures given in this chapter are similar to the ASTM-AASHTO methods specified for routine soil-cement testing. For research work on soil-cement and for tests of unusual soils, some additional testing involving the molding and testing of volume- and moisture-change specimens is specified by ASTM and AASHTO.

Two methods for determining moisture-density relations of soil-cement mixtures and for molding wet-dry and freeze-thaw test specimens are described. The first is to be used with soils containing material retained on the No. 4 sieve, and the second with soils not containing material retained on the No. 4 sieve.

The soil sample used in the moisture-density test and in the wet-dry and freeze-thaw test specimens has the same percentage of material retained on the No. 4 sieve as the original soil material. Three-quarter-in. material is the maximum size used. 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.

Proportioning Cement

In soil-cement testing, cement quantities are proportioned on a weight basis in terms of percent of total oven-dry soil, and all laboratory calculations are made on this basis. At the completion of tests, the recommended cement content by weight may be converted to the equivalent cement content by volume for field construction, because adding cement on a volume basis may simplify construction control depending on the type of construction. Proportioning on a volume basis for field construction is in terms of percentage of a U.S. bag of cement in a compacted cubic foot of soil-cement, assuming that a bag of cement weights 94 lb. Thus 10 percent by volume indicates 9.4 lb of cement per cubic foot of compacted soil-cement. If the roadway is 6 in. thick, 1 sq yd of roadway contains $3 \times 3 \times 1/2 \times 0.10 \times 94$, or 42.3 lb of cement.

The criteria used to determine adequate cement factors for soil-cement were developed as percent cement by volume in terms of a 94-lb U.S. bag of cement. The equivalent cement content by volume, based on a 40 kg (88.2 lb) Canadian bag, can be calculated by multiplying the value based on a 94-lb bag by 1.066. Thus, 10 percent by volume (based on a 94-lb bag of cement) is equivalent to 10×1.066, or 10.66 percent by volume based on an 40 kg bag. The amount of cement per square yard for a 6-in.-thick base is $3 \times 3 \times 1/2 \times 0.1066 \times 88.2$, or 42.3 lb.

Preparing Soil for Testing

Seventy-five to 100 lb of soil is sufficient to run a complete series of soil and soil-cement tests. When necessary, the sample is first dried until it is friable under a trowel. Drying may be accomplished by air-drying or by using drying apparatus that limits the temperature of the sample to 60 deg C (140 deg F). To prepare the soil for testing, it is separated on the 2-in., 3/4-in. and No. 4 sieves. All clods are broken up or pulverized in such a way as to avoid reducing the natural size of individual particles. The pulverized soil passing the No. 4 sieve should be well mixed and then stored in a covered container throughout the duration of the tests. This will prevent any major moisture changes.

The quantity of material larger than 2 in. is not included in calculations of grain-size distribution. The quantity, however, is noted and the material discarded. If the soil contains material retained on the 3/4-in. and No. 4 sieves, the quantities are calculated, recorded, and included in calculations of grain-size distribution in the total sample. A portion of Form Sheet No. 1, page 50, is provided for this purpose.

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* The required cement content shall be based on tests utilizing the specific cement type and soil to be used on the project.

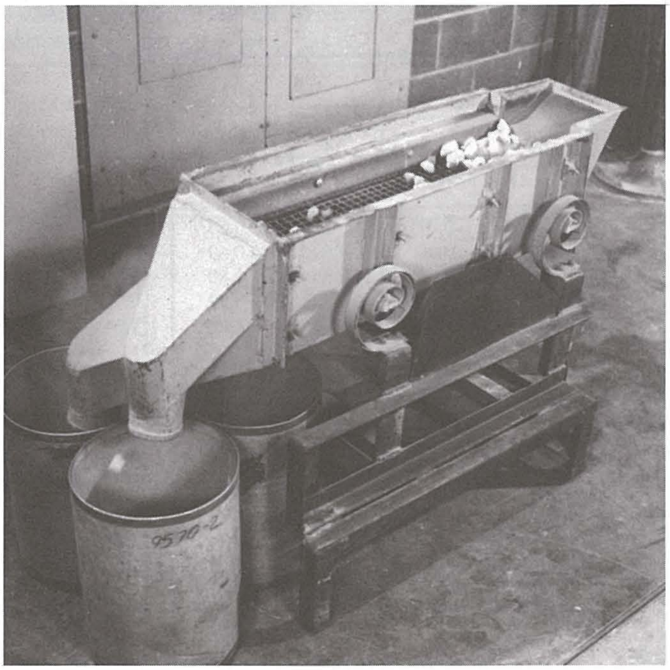

Fig. 7. Screening soil through 3/4-in. and No. 4 sieves

The material larger than 3/4 in. is stored until soil-cement test specimens have been molded, after which it is usually discarded. The material larger than the No. 4 sieve and smaller than 3/4 in. is soaked in water and later added, in a saturated and surface-dry condition, to the soil used for the moisture-density test and in the wet-dry and freeze-thaw test specimens. It is added in such amount, by dry weight, that the percentage of material from the No. 4 sieve size up to 3/4-in. size in an individual soil-cement test specimen equals the percentages of material larger than the No. 4 sieve and smaller than 2 in. in the original total sample.

In many instances, the roadway material used for soil-cement will include the old bituminous surfacing. This offers a practical and economical way of salvaging existing materials. When soil samples contain bituminous surfacing material, the pulverizing effort used should be sufficient to produce the approximate pulverization that will be obtained in the field. Some of the bituminous material or bituminous-coated material will thus be pulverized and included in tests on the portion of the soil passing the No. 10 and No. 40 sieves. It may also be necessary to pulverize an additional amount of bituminous material larger than 3/4 in. so that the specimens made from the fraction smaller than 3/4 in. will contain a representative amount of bituminous material. The bituminous material retained on the No. 4 sieve is handled and included in the test specimens in the same way that other materials retained on the No. 4 sieve are handled.

Determining Moisture-Density Relations of Soil-Cement Mixtures

A. For Soils Containing Material Retained on the No. 4 Sieve

To facilitate understanding of the discussions on the moisture-density test and on molding test specimens, illustrations of actual laboratory problems follow.

In this illustration, assume that a brown, C horizon, A-2-4 (0) soil is to be tested. As shown on the summary sheet, Fig. 32, page 31, the soil contains 18 percent material retained on the No. 4 sieve that has an absorption of 2.0 percent.*

CHOOSING THE CEMENT CONTENT BY WEIGHT

Before determining the moisture-density relations of soil-cement mixtures, it is first necessary to select the cement contents by weight that are to be investigated in the wet-dry and freeze-thaw tests. The cement contents are usually selected in two percentage point increments such as 6, 8, and 10 percent or 8, 10, and 12 percent, depending on the type of soil being tested. The median cement content is the same as the estimated cement requirement for the soil, and this cement content is also used in the moisture-density test. 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. Valuable suggestions for determining the estimated cement requirement of the soil and for choosing the cement contents to be investigated are given in Chapter 2.

In the present illustration using a brown, C horizon, A-2-4 (0) soil, the estimated cement requirement from Table 1, page 11, is 7 percent by weight, since the cement requirements for this

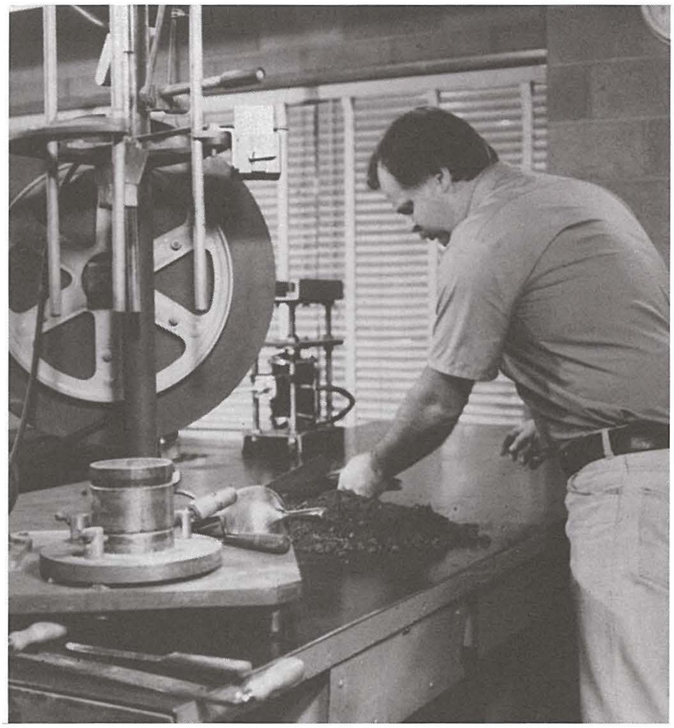

Fig. 8. Mechanical rammer with circular rammer face arrangement to control 12-in. drop. A sector rammer face can be substituted with mechanical rammers if the test report shows that this type of rammer was used. The sector face shall be a sector of a 4.0-in. diameter circle and have an area equal to that of the circular face rammer. The sector face rammer shall not be used to compact wet-dry and freeze-thaw specimens unless previous tests on like soils show strength and resistance to wetting and drying and freezing and thawing of specimens compacted with this rammer to be similar to those of specimens compacted with the circular face rammer.

*As determined in accordance with ASTM Designation C127, using the following formula: Absorption, percent

$$= \frac{\text{saturated surface-dry weight} - \text{oven-dry weight}}{\text{oven-dry weight}} \times 100.$$

Table 5. Quantities of Material Retained on the No. 4 Sieve for 11.0-Lb Batch of Total Soil for Use in Moisture-Density Test

Material retained on No. 4 sieve, percent	Oven-dry material retained on No. 4 sieve, lb	Absorption of material retained on No. 4 sieve, percent									
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
		Saturated, surface-dry material retained on No. 4 sieve, lb.									
5	0.55	0.55	0.56	0.56	0.56	0.56	0.57	0.57	0.57	0.57	0.58
6	0.66	0.66	0.67	0.67	0.67	0.68	0.68	0.68	0.69	0.69	0.69
7	0.77	0.77	0.78	0.78	0.79	0.79	0.79	0.80	0.80	0.80	0.81
8	0.88	0.88	0.89	0.89	0.90	0.90	0.91	0.91	0.92	0.92	0.92
9	0.99	0.99	1.00	1.00	1.01	1.01	1.02	1.02	1.03	1.03	1.04
10	1.10	1.11	1.11	1.12	1.12	1.13	1.13	1.14	1.14	1.15	1.16
11	1.21	1.22	1.22	1.23	1.23	1.24	1.25	1.25	1.26	1.26	1.27
12	1.32	1.33	1.33	1.34	1.35	1.35	1.36	1.37	1.37	1.38	1.39
13	1.43	1.44	1.44	1.45	1.46	1.47	1.47	1.48	1.49	1.49	1.50
14	1.54	1.55	1.56	1.56	1.57	1.58	1.59	1.59	1.60	1.61	1.62
15	1.65	1.66	1.67	1.67	1.68	1.69	1.70	1.71	1.72	1.72	1.73
16	1.76	1.77	1.78	1.79	1.80	1.80	1.81	1.82	1.83	1.84	1.85
17	1.87	1.88	1.89	1.90	1.91	1.92	1.93	1.94	1.94	1.95	1.96
18	1.98	1.99	2.00	2.01	2.02	2.03	2.04	2.05	2.06	2.07	2.08
19	2.09	2.10	2.11	2.12	2.13	2.14	2.15	2.16	2.17	2.18	2.19
20	2.20	2.21	2.22	2.23	2.24	2.26	2.27	2.28	2.29	2.30	2.31
21	2.31	2.32	2.33	2.34	2.36	2.37	2.38	2.39	2.40	2.41	2.43
22	2.42	2.43	2.44	2.46	2.47	2.48	2.49	2.50	2.52	2.53	2.54
23	2.53	2.54	2.56	2.57	2.58	2.59	2.61	2.62	2.63	2.64	2.66
24	2.64	2.65	2.67	2.68	2.69	2.71	2.72	2.73	2.75	2.76	2.77
25	2.75	2.76	2.78	2.79	2.81	2.82	2.83	2.85	2.86	2.87	2.89
26	2.86	2.87	2.89	2.90	2.92	2.93	2.95	2.96	2.97	2.99	3.00
27	2.97	2.98	3.00	3.01	3.03	3.04	3.06	3.07	3.09	3.10	3.12
28	3.08	3.10	3.11	3.13	3.14	3.16	3.17	3.19	3.20	3.22	3.23
29	3.19	3.21	3.22	3.24	3.25	3.27	3.29	3.30	3.32	3.33	3.35
30	3.30	3.32	3.33	3.35	3.37	3.38	3.40	3.42	3.43	3.45	3.47
31	3.41	3.43	3.44	3.46	3.48	3.50	3.51	3.53	3.55	3.56	3.58
32	3.52	3.54	3.56	3.57	3.59	3.61	3.63	3.64	3.66	3.68	3.70
33	3.63	3.65	3.67	3.68	3.70	3.72	3.74	3.76	3.78	3.79	3.81
34	3.74	3.76	3.78	3.80	3.81	3.83	3.85	3.87	3.89	3.91	3.93
35	3.85	3.87	3.89	3.91	3.93	3.95	3.97	3.98	4.00	4.02	4.04
36	3.96	3.98	4.00	4.02	4.04	4.06	4.08	4.10	4.12	4.14	4.16
37	4.07	4.09	4.11	43.13	4.15	4.17	4.19	4.21	4.23	4.25	4.27
38	4.18	4.20	4.22	4.24	4.26	4.28	4.31	4.33	4.35	4.37	4.39
39	4.29	4.31	4.33	4.35	4.38	4.40	4.42	4.44	4.46	4.48	4.50
40	4.40	4.42	4.44	4.47	4.49	4.51	4.53	4.55	4.58	4.60	4.62
41	4.51	4.53	4.56	4.58	4.60	4.62	4.65	4.67	4.69	4.71	4.74
42	4.62	4.64	4.67	4.69	4.71	4.74	4.76	4.78	4.80	4.83	4.85
43	4.73	4.75	4.78	4.80	4.82	4.85	4.87	4.90	4.92	4.94	4.97
44	4.84	4.86	4.89	4.91	4.94	4.96	4.99	5.01	5.03	5.06	5.08
45	4.95	4.97	5.00	5.02	5.05	5.07	5.10	5.12	5.15	5.17	5.20

type of soil generally range from 5 to 9 percent. Seven percent cement by weight will therefore be used in the moisture-density test, and wet-dry and freeze-thaw test specimens will be molded at 5, 7, and 9 percent.

CALCULATING BATCH WEIGHTS OF MATERIALS

The next step is to calculate the batch weights of soil and cement needed for at least four moisture-density test trials, re-using the same batch of material for each trial. The amount of soil needed can be closely calculated by using an estimated maximum density and including sufficient soil for moisture samples. The estimated maximum dry density can be obtained by comparing the gradation of the soil being tested with that of similar soils previously tested.

Assume in this illustration that similar soils previously tested had maximum dry densities in the order of 120 lb per cubic foot. This density will therefore be used as the estimated density for this soil-cement mixture. The cement content to be investigated is 7 percent by weight of oven-dry soil. Therefore, a cubic foot of soil-cement contains 120.0/1.07, or 112.15 lb of soil. The amount of oven-dry soil needed for one moisture-density specimen (1/30 cu ft) is 112.15/30, or 3.74 lb. This amount is increased by 1/10 (0.37 lb) to provide soil for manipulation. (Increasing soil quantities by 1/10 gives sufficient soil to provide a specimen about 5 in. in height before the collar of the mold is removed. The excess soil-cement is then trimmed from the top to give a specimen the exact height of the mold.)

Because four individual moisture-density test trials will be made, four moisture samples, each weighing about 750 g (grams), will need to be taken, totaling 6.61 lb. Thus the total soil required is equal to 3.74 + 0.37 + 6.61, or 10.72 lb. To simplify calculations, 11.0 lb of oven-dry soil is generally used for all soil-cement mixtures that contain material retained on the No. 4 sieve, and this amount will be used in this illustration.

Table 6. Quantities of Air-Dry Soil Passing No. 4 Sieve for 11.0-Lb Batch of Total Oven-Dry Soil for Use in Moisture-Density Test

Material retained on No. 4 sieve, percent	Oven-dry material retained on No. 4 sieve, lb	Hygroscopic moisture content of material passing No. 4 sieve									
		0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
		Air-dry material passing No. 4 sieve, lb.									
5	10.45	10.50	10.55	10.61	10.66	10.71	10.76	10.82	10.87	10.92	10.97
6	10.34	10.39	10.44	10.50	10.55	10.60	10.65	10.70	10.75	10.81	10.86
7	10.23	10.28	10.33	10.38	10.43	10.49	10.54	10.59	10.64	10.69	10.74
8	10.12	10.17	10.22	10.27	10.32	10.37	10.42	10.47	10.52	10.58	10.63
9	10.01	10.06	10.11	10.16	10.21	10.26	10.31	10.36	10.41	10.46	10.51
10	9.90	9.95	10.00	10.05	10.10	10.15	10.20	10.25	10.30	10.35	10.40
11	9.79	9.84	9.89	9.94	9.99	10.03	10.08	10.13	10.18	10.23	10.28
12	9.68	9.73	9.78	9.83	9.87	9.92	9.97	10.02	10.07	10.12	10.16
13	9.57	9.62	9.67	9.71	9.76	9.81	9.86	9.90	9.95	10.00	10.05
14	9.46	9.51	9.55	9.60	9.65	9.70	9.74	9.79	9.84	9.89	9.93
15	9.35	9.40	9.44	9.49	9.54	9.58	9.63	9.68	9.72	9.77	9.82
16	9.24	9.29	9.33	9.38	9.42	9.47	9.52	9.56	9.61	9.66	9.70
17	9.13	9.18	9.22	9.27	9.31	9.36	9.40	9.45	9.50	9.54	9.59
18	9.02	9.07	9.11	9.16	9.20	9.25	9.29	9.34	9.38	9.43	9.47
19	8.91	8.95	9.00	9.04	9.09	9.13	9.18	9.22	9.27	9.31	9.36
20	8.80	8.84	8.89	8.93	8.98	9.02	9.06	9.11	9.15	9.20	9.24
21	8.69	8.73	8.78	8.82	8.86	8.91	8.95	8.99	9.04	9.08	9.12
22	8.58	8.62	8.67	8.71	8.75	8.79	8.84	8.88	8.92	8.97	9.01
23	8.47	8.51	8.55	8.60	8.64	8.68	8.72	8.77	8.81	8.85	8.89
24	8.36	8.40	8.44	8.49	8.53	8.57	8.61	8.65	8.69	8.74	8.78
25	8.25	8.29	8.33	8.37	8.42	8.46	8.50	8.54	8.58	8.62	8.66
26	8.14	8.18	8.22	8.26	8.30	8.34	8.38	8.42	8.47	8.51	8.55
27	8.03	8.07	8.11	8.15	8.19	8.23	8.27	8.31	8.35	8.39	8.43
28	7.92	7.96	8.00	8.04	8.08	8.12	8.16	8.20	8.24	8.28	8.32
29	7.81	7.85	7.89	7.93	7.97	8.02	8.04	8.08	8.12	8.16	8.20
30	7.70	7.74	7.78	7.82	7.85	7.89	7.93	7.97	8.01	8.05	8.09
31	7.59	7.63	7.67	7.70	7.74	7.78	7.82	7.86	7.89	7.93	7.97
32	7.48	7.52	7.55	7.59	7.63	7.67	7.70	7.74	7.78	7.82	7.85
33	7.37	7.41	7.44	7.48	7.52	7.55	7.59	7.63	7.66	7.70	7.74
34	7.26	7.30	7.33	7.37	7.41	7.44	7..48	7.51	7.55	7.59	7.62
35	7.15	7.19	7.22	7.26	7.29	7.33	7.36	7.40	7.44	7.47	7.51
36	7.04	7.08	7.11	7.15	7.18	7.22	7.25	7.29	7.32	7.36	7.39
37	6.93	6.96	7.00	7.03	7.07	7.10	7.14	7.17	7.21	7.24	7.28
38	6.82	6.85	6.89	6.92	6.96	6.99	7.02	7.06	7.09	7.13	7.16
39	6.71	6.74	6.78	6.81	6.84	6.88	6.91	6.94	6.98	7.01	7.05
40	6.60	6.63	6.67	6.70	6.73	6.77	6.80	6.83	6.86	6.90	6.93
41	6.49	6.52	6.55	6.59	6.62	6.65	6.68	6.72	6.75	6.78	6.81
42	6.38	6.41	6.44	6.48	6.51	6.54	6.57	6.60	6.64	6.67	6.70
43	6.27	6.30	6.33	6.36	6.40	6.43	6.46	6.49	6.52	6.55	6.58
44	6.16	6.19	6.22	6.25	6.28	6.31	6.34	6.38	6.41	6.44	6.47
45	6.05	6.08	6.11	6.14	6.17	6.20	6.23	6.26	6.29	6.32	6.35

Since the soil in this illustration contains 18 percent material retained on the No. 4 sieve, 11.0 × 0.18, or 1.98 lb, of oven-dry material is required. It is added in a saturated, surface-dry condition; therefore, 1.98 × 1.02, or 2.02 lb, of saturated, surface-dry coarse material is weighed out. (The material retained on the No. 4 sieve in this example has an absorption of 2.0 percent.) Since the specimen is only 4 in. in diameter, it is necessary to set a maximum size of material that may be used. A maximum size of 3/4 in. has been selected since material up to this size can be handled readily in the laboratory. Should material larger than 3/4 in. occur in the field sample, it is replaced in the specimen with an equivalent dry weight of the No. 4 to 3/4-in. material.

In those isolated cases where material that is retained on the No. 4 sieve and passes the 2-in. sieve is also retained on the 3/4-in. sieve, the material shall be crushed, and that portion then passing the 3/4-in. sieve and retained on the No. 4 sieve is used in the proper dry-weight proportions.

The required amount of oven-dry soil passing the No. 4 sieve is 11.0 - 1.98, or 9.02 lb. The hygroscopic moisture content of this material is 1.2 percent. Thus, 9.02 × 1.012, or 9.13 lb, of air-dry material is weighed out.

The quantity of cement required is 11.0 × 0.07, or 0.77 lb, which is 0.77 × 454, or 350 g.

Quantities of saturated, surface-dry material retained on the No. 4 sieve, of air-dry soil passing the No. 4 sieve, and of cement needed to run a moisture-density test with soils that contain material retained on the No. 4 sieve can be conveniently obtained from Tables 5, 6, and 7.

The details of adding water and making the moisture-density test follow.

Table 7. Quantities of Cement for Running Moisture-Density Test

Cement content, percent by wt.	6.0-lb batch of soil passing No. 4 sieve		11.0-lb batch of total soil	
	Cement, lb	Cement, g	Cement, lb	Cement, g
3	0.18	82	0.33	150
4	0.24	109	0.44	200
5	0.30	136	0.55	250
6	0.36	163	0.66	300
7	0.42	191	0.77	350
8	0.48	218	0.88	400
9	0.54	245	0.99	449
10	0.60	272	1.10	499
11	0.66	300	1.21	549
12	0.72	327	1.32	599
13	0.78	354	1.43	649
14	0.84	381	1.54	699
15	0.90	409	1.65	749
16	0.96	436	1.76	799

Fig. 9. Surface drying material retained on a No. 4 sieve with towel

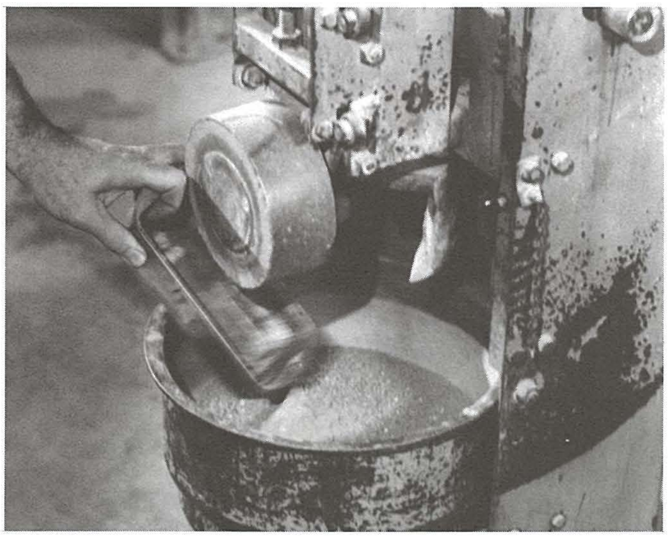

Fig. 10. Mechanical mixer to mix soil, cement, and water. Mixing may also be done by hand on a steel-top table using a trowel.

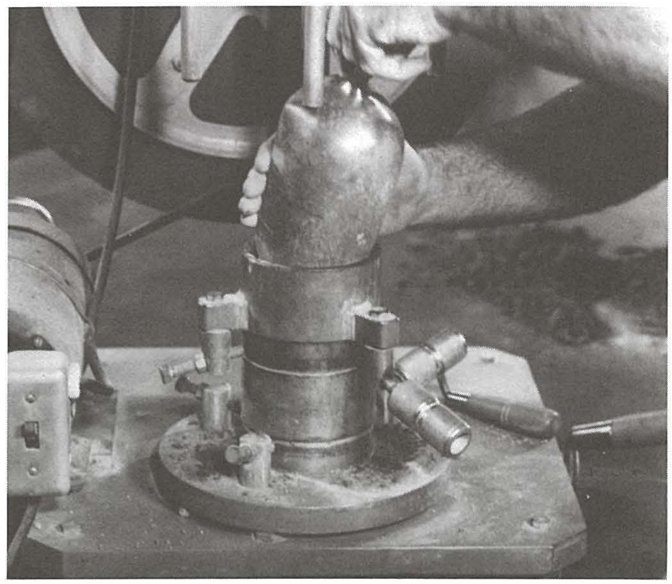

Fig. 11. The quantity of moist soil-cement to place in the mold for each of three equal compacted layers can easily be judged by using a scoop or cardboard container.

Fig. 12. Taking moisture sample from center plane of specimen during moisture-density test.

Fig. 13. Moisture samples are dried to constant weight in a thermostatically controlled oven at 110 deg C.

PERFORMING THE MOISTURE-DENSITY TEST

The moisture density relations of soil-cement mixtures containing material retained on the No. 4 sieve are determined in accordance with ASTM Designation D558 or AASHTO Designation T134.

Form Sheet No. 3, as shown on page 51, is provided to record the data needed for the test. In this test procedure, the air-dry soil is first pulverized to pass a 2-in., 3/4-in., and No. 4 sieve without reducing the particle size. Sufficient air-dry soil passing the No. 4 sieve (9.13 lb in this example) is then weighed out so that with the addition of the required amount of material retained on the No. 4 sieve there will be sufficient material for at least four moisture-density test trials. The required cement (350 g) is added to the pulverized soil and the two are thoroughly mixed to uniform color. A quantity of water sufficient to dampen the mixture to a degree approximately four to six percentage points below the estimated optimum moisture content is then thoroughly incorporated.

When the soil is a heavy-textured, clayey material, the semi-mixture of soil, cement, and water is compacted in a container such as a skillet (Fig. 16, page 22) to facilitate moisture distribution. The mixture is covered, allowed to set for 5 to 10 minutes, then removed and troweled lightly.

The saturated, surface-dry material retained on the No. 4 sieve (2.02 lb in this example) is then added and intimately mixed in. (The material retained on the No. 4 sieve is prepared by being soaked in water overnight and then surface-dried immediately before being added.)

The soil-cement mixture is then immediately compacted in the mold in three layers of approximately equal thickness, to give a total compacted depth of about 5 in. Each layer is compacted by 25 uniformly spaced blows of a 5.5-lb rammer with a 2-in.-diameter circular face or a sector face dropping free from a height of 12 in. During compaction, the mold shall rest on a uniform, rigid foundation that weighs approximately 200 lb or more.

After compaction, the collar on the mold is removed and excess compacted soil-cement is carefully trimmed level with the top of the mold with a knife and straightedge. During this trimming operation, all particles that extend above the top of the mold are removed. This may cause some irregularities in the surface of the specimen, which can be corrected by hand-tamping fine material into these irregularities and leveling the specimen again with a straightedge.

The compacted specimen and mold are then weighed and the tare of the mold is subtracted to give the wet weight of the specimen. The specimen is removed from the mold and sliced vertically through the center. A representative sample of the material is taken from the full height of one of the cut faces, weighed immediately, and placed in an oven to dry at 110 deg C (230 deg F) for at least 12 hours or to constant weight to permit determination of the moisture content. A 750-g moisture sample is taken.

The remaining soil-cement mixture is then broken up to pass a 3/4-in. sieve. All lumps made up of particles smaller than the No. 4 sieve are broken up again to pass a No. 4 sieve. Sufficient water to increase the moisture content of the mixture by approximately two percentage points is added and thoroughly mixed with the soil-cement.* The moistened soil-cement mixture is again compacted in the mold, as previously described, and the procedure is repeated for each increment of water until the wet weight of the compacted soil-cement mixture decreases or until the specimen becomes spongy.

With coarse, sandy soils that contain very few fines, the compacting action may force a portion of the water downward and out of the mold. This loss makes it difficult to obtain a decrease in density. Loss of water can be prevented by sealing the point of contact between the bottom of the mold and the base plate with petroleum jelly or some similar material. With these coarse soils, a more representative moisture sample can be obtained if it is taken from the soil-cement mixture before compaction of the specimen.

Considerable information can be obtained by saving half of the last specimen made near optimum moisture. This "tail-end" specimen is stored in the moist room and inspected daily to determine the rate of hardening.

*When a moisture-density test is being performed on fragile materials that tend to crush or break down under the weight of the rammer, a separate batch of soil-cement is used for each trial.

CALCULATING MOISTURE-DENSITY RELATIONSHIPS

The moisture content and oven-dry weight of the soil-cement mixture as compacted in each trial are calculated as follows:

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

$$W = \frac{W_1}{w + 100} \times 100$$

where

- w = moisture content of specimen, percent by weight;
- A = weight of moisture can and wet soil-cement;
- B = weight of moisture can and dry soil-cement;
- C = weight of moisture can;
- W = dry weight of compacted soil-cement, lb per cubic foot;
- W_1 = wet weight of compacted soil-cement, lb per cubic foot (30 times the wet weight of the specimen).

After calculating the moisture content and corresponding oven-dry weight (density) of the compacted soil-cement for each test made on the mixture, the dry 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 Fig. 2. The moisture content at which maximum density is obtained is called the "optimum moisture content" of the soil-cement mixture. The oven-dry weight per cubic foot of the mixture at optimum moisture content is called the "maximum density." This maximum density and optimum moisture content are used for design of wet-dry and freeze-thaw test specimens.

B. For Soils Not Containing Material Retained on the No. 4 Sieve

The moisture-density relations of soil-cement mixtures for soils that do not contain material retained on the No. 4 sieve are determined in essentially the same manner as that previously described for soils containing this material. However, the handling of the coarse material and calculations relating thereto are not required.

The following illustration covers the calculations required and discusses items in performing the moisture-density test that differ from the procedure for soils containing material retained on the No. 4 sieve.

Assume that a brown, B horizon A-4(5) soil is to be tested that, as shown on the summary sheet, Fig. 33, page 32, does not contain material retained on the No. 4 sieve.

Table 8. Quantities of Air-Dry Soil Passing No. 4 Sieve for 6.0 -Lb Batch of Oven-Dry Soil for Use in Moisture-Density Test

Hygroscopic moisture content, percent	Air-dry soil, lb
0.5	6.03
1.0	6.06
1.5	6.09
2.0	6.12
2.5	6.15
3.0	6.18
3.5	6.21
4.0	6.24
4.5	6.27
5.0	6.30

CHOOSING THE CEMENT CONTENTS BY WEIGHT

From Table 1, page 11, the general range of cement requirements for B horizon, A-4 soils is from 7 to 12 percent by weight, and 10 percent is used as the estimated cement requirement. Ten percent cement by weight will, therefore, be used in the moisture-density test; wet-dry and freeze-thaw test specimens will be molded at 8, 10, and 12 percent.

CALCULATING BATCH WEIGHTS OF MATERIALS

Six pounds of oven-dry soil is adequate for running the moisture-density test. Assume in this example that the hygroscopic moisture content of the soil is 2.2 percent. Thus, the air-dry soil to be weighted out is 6.0 × 1.022, or 6.13 lb. The quantity of cement required is 6.0 × 0.10, or 0.60 lb, which is 0.60 × 454, or 272 g.

Quantities of cement and air-dry soil needed to run a moisture-density test with soils that do not contain material retained on the No. 4 sieve can be conveniently obtained from Tables 7 and 8.

PERFORMING THE MOISTURE-DENSITY TEST

The quantity of air-dry soil required (6.13 lb in this example) is first weighed out. The required cement (272 g) is added to the pulverized soil and the two are thoroughly mixed to uniform color. A quantity of water sufficient to dampen the mixture to a degree approximately four to six percentage points below the indicated optimum moisture is then incorporated. The soil-cement mixture is then immediately compacted in the mold as described on page 19, and the procedure is repeated until there is a decrease in the wet weight of the compacted soil-cement mixture or until the specimen becomes spongy.

A 100-g moisture sample will suffice.

Calculation of moisture content and corresponding oven-dry weight (density) of the compacted soil-cement for each test made on the mixture, and plotting of the moisture-density curve are the same as given on page 19 for soils containing material retained on the No. 4 sieve.

Molding Wet-Dry and Freeze-Thaw Test Specimens

A. For Soils Containing Material Retained on the No. 4 Sieve

After determination of the maximum dry density and optimum moisture content of the soil-cement mixture, the next step is to mold specimens at different cement contents for testing in the wet-dry and freeze-thaw tests. These tests will determine the minimum amount of cement required to harden the soil properly. The test specimens are molded at the optimum moisture content determined from the moisture-density test with the same compaction equipment.* The density of the test specimens will therefore be comparable to the maximum density obtained in the moisture-density test and to the density that will be obtained during construction.

CHOOSING THE CEMENT CONTENTS BY WEIGHT

The cement contents to be investigated in the wet-dry and freeze-thaw tests will depend on the type of soil being tested. Valuable information in establishing these cement factors was given in Chapter 2. As previously discussed, the cement contents are selected in an ascending order of two percentage points difference,** the median cement content being the estimated cement requirement for the soil. As previously described, this is also the cement content at which the moisture-density test is run.

Two specimens are molded at each cement content, one for use in the wet-dry test and one for the freeze-thaw test.

Experience has shown that the freeze-thaw test is generally the critical test except for soil-cement mixtures that contain relatively large amounts of silt and clay. Therefore, time and work can be saved by molding only one wet-dry test specimen—generally at the median cement content—for all soil-cement mixtures except those having high silt and clay contents.

In the example being illustrated for an A-2-4(0) soil that contains material retained on the No. 4 sieve, specimens will be molded at 5, 7, and 9 percent cement by weight. The specific data and calculations are given in detail on Form Sheet No. 6, Fig. 14. The sequence and accuracy of calculations can be determined from Form Sheet No. 6, illustrated in Fig. 15.

CALCULATING BATCH WEIGHTS OF MATERIALS

Assume that the moisture-density relations obtained at 7 percent cement by weight are 121.2 lb per cubic foot maximum density at 11.5 percent optimum moisture. The soil contains 18 percent material retained on the No. 4 sieve that has an absorption of 2.0 percent. The hygroscopic moisture content of the soil passing the No. 4 sieve is 1.2 percent.

The amount of soil required for one specimen is first calculated. When these computations are being made, it is good practice to compute the quantity of soil that is required for molding a specimen having the median cement content; this quantity of soil is then used for molding all specimens. Of course, the cement quantities and water quantities vary for specimens that contain different percentages of cement. In this example, the median cement content is 7 percent, and the following calculations will be those required to mold a test specimen at that cement content.

The maximum density of the soil-cement mixture being illustrated is 121.2 lb per cubic foot, and a cubic foot contains 121.20/1.07, or 113.27 lb of soil. The amount of oven-dry soil needed for one specimen (1/30 cu ft) is113.27/30, or 3.78 lb. This amount is increased by 1/10 (0.38 lb) to provide soil for manipulation and by 1.65 lb (750 g) for a moisture sample. (Increasing soil quantities by 1/10 gives sufficient soil to provide a specimen 5 in. in height before the collar of the mold is removed. The excess soil-cement is then trimmed from the top to give a specimen the exact height of the mold.) Thus the total soil required per specimen is equal to 3.78 + 0.38 + 1.65, or 5.81 lb.

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*See footnote, page 22.

**See second footnote, page 11.

Soil-Cement Laboratory, Form Sheet No. 6

DESIGN AND MOLDING WET-DRY AND FREEZE-THAW TEST SPECIMENS

DATA ON SOIL NO. C

Maximum Density 121.2 lb. per cu. ft.

Optimum Moisture 11.5 %

Material Retained on No. 4 Sieve 18 % Absorption 2.0 %

Material Passing No. 4 Sieve
Hygroscopic Moisture 1.2 %

QUANTITIES FOR MOLDING SPECIMENS

Total Oven-dry Soil 5.81 lb. $\frac{\frac{121.2}{100+7} \times 100}{30} = 3.78$ $+0.38$ $+1.65$ $= 5.81$

Material Retained on No. 4 Sieve
Oven-dry 1.05 lb.
Saturated, Surface Dry 1.07 lb.*

Material Passing No. 4 Sieve
Oven-dry 4.76 lb.
Air-dry 4.82 lb.*

Cement Content by wt. %	Cement Content Batch lb.	Cement Content Batch grams *	Total Oven-dry soil + cement, lb.	Mat'l. pass. No. 4 + cement, lb.	Water for batch: Theo. ml	Abs. mat'l. ret. on No.4, ml	Hygro. moist., mat'l. pass. No. 4, ml	Evaporation %	Evaporation ml	Net ml *
5.0	0.240	132	6.10	5.05	319	10	26	1	23	306
7.0	0.407	185	6.22	5.17	325	10	26	1	23	312
9.0	0.523	237	6.33	5.28	331	10	26	1	24	319

*To be weighed out for molding specimens

DATA FROM MOLDED SPECIMENS

Tare 8.50 Operator A. T. Date

Cement content % by wt.	Wet wt. spec. plus mold, lb.	Wet wt. spec. lb.	Moisture Determination: Can No.	Wet soil + can gr.	Dry soil + can gr.	Wt. can gr.	Moisture loss gr.	Dry wt. soil gr.	Moisture %	Density lb. per cu. ft.
F-5.0	12.94	4.44							11.4	119.6
W-7.0	12.95	4.45							11.4	119.8
F-7.0	12.94	4.44							11.2	119.8
F-9.0	12.92	4.42							11.1	119.4

Fig. 14. Data for molding wet-dry and freeze-thaw test specimens. Soil No. C.

Soil-Cement Laboratory, Form Sheet No. 6

Numbers show degree of accuracy to which calculations are made. Letters show sequence and method of making calculations.

DESIGN AND MOLDING WET-DRY AND FREEZE-THAW TEST SPECIMENS

DATA ON SOIL NO.

Maximum Density 0.1 A lb. per cu. ft.

Optimum Moisture 0.1 B %

Material Retained on No. 4 Sieve 1.0 C % Absorption 0.1 D %

Material Passing No. 4 Sieve
Hygroscopic Moisture 0.1 E %

QUANTITIES FOR MOLDING SPECIMENS

Total Oven-dry Soil 0.01 G lb. $\left[\frac{\left(\frac{A}{100+F}\right)100}{30}\right]\frac{11}{10} + 1.65$

Material Retained on No. 4 Sieve $G\left(\frac{C}{100}\right)$
Oven-dry 0.01 H lb.
Saturated, Surface Dry 0.01 I lb.* $H\left(\frac{100+D}{100}\right)$

Material Passing No. 4 Sieve
Oven-dry 0.01 J lb. $G-H$
Air-dry 0.01 K lb.* $J\left(\frac{100+E}{100}\right)$

Cement Content by wt. %	Cement Content Batch lb.	Cement Content Batch grams *	Total Oven-dry soil + cement, lb.	Mat'l. pass. No. 4 + cement, lb.	Water for batch: Theo. ml	Abs. mat'l. ret. on No.4, ml	Hygro. moist., mat'l. pass. No. 4, ml	Evaporation %	Evaporation ml	Net ml *
0.1	0.001	1.0	0.01	0.01	1.0	1.0	1.0	0.5	1.0	1.0
F	L	M	N	Φ	P	Q	R	S	T	U
	$G\left(\frac{F}{100}\right)$	454L	G+L	J+L		$H\left(454\frac{D}{100}\right)$	$J\left(454\frac{E}{100}\right)$			

*To be weighed out for molding specimens

$N\left(454\frac{B}{100}\right)$ $\phi\left(454\frac{S}{100}\right)$ P-Q-R+T

DATA FROM MOLDED SPECIMENS

Tare 0.01 V Operator Date

Cement content % by wt.	Wet wt. spec. plus mold, lb.	Wet wt. spec. lb.	Moisture Determination: Can No.	Wet soil + can gr.	Dry soil + can gr.	Wt. can gr.	Moisture loss gr.	Dry wt. soil gr.	Moisture %	Density lb. per cu. ft.
0.1	0.01	0.01							0.1	0.1
F	W	X							Y	Z
		W-V								$\frac{30X}{\frac{100+Y}{100}}$

Fig. 15. Sequence and degree of accuracy of calculations for wet-dry and freeze-thaw test specimens for soils containing material retained on the No. 4 sieve.

Since the soil in this illustration contains 18 percent material retained on the No. 4 sieve, 5.81 × 0.18, or 1.05 lb, of this oven-dry material is required for one specimen. It is added in a saturated, surface-dry condition; therefore, 1.05 × 1.020, or 1.07 lb, of saturated, surface-dry material is weighed out. (The material retained on the No. 4 sieve has an absorption factor of 2.0 percent.)

The oven-dry soil passing the No. 4 sieve required for one specimen is 5.81 - 1.05, or 4.76 lb. The hygroscopic moisture content of this soil is 1.2 percent. Thus 4.76 × 1.012, or 4.82 lb, of air-dry soil is weighed out.

These quantities of material retained on and passing the No. 4 sieve will be used for molding each specimen. The quantity of cement required for molding a specimen that contains 7.0 percent cement by weight is 5.81 × 0.07, or 0.407 lb, which is 0.407 × 454, or 185 g.

The water required to bring the soil-cement mixture to its optimum moisture content equals the weight of total oven-dry soil plus the weight of cement multiplied by the optimum moisture content: (5.81 + 0.407) × 0.115 × 454, or 325 ml (one gram of water is equal to one ml); minus the amount of water already in the voids of the saturated, surface-dry material retained on the No. 4 sieve: 1.05 × 0.02 × 454, or 10 ml; minus the hygroscopic moisture in the soil passing the No. 4 sieve: 4.76 × 0.012 × 454, or 26 ml; plus an extra amount for evaporation loss during mixing, which is assumed in this case as 1.0 percent of the weight of soil passing the No. 4 sieve plus cement: (4.76 + 0.407) × 0.01 × 454, or 23 ml. The total quantity of water to add for accurate control equals 325 - 10 - 26 + 23, or 312 ml net water.

The above calculations are tabulated on Form Sheet No. 6, Fig. 14.

MOLDING SPECIMENS

Data for molding and checking molded specimens can also be kept on Form Sheet No. 6, as illustrated in Fig. 14.

The designed quantities of air-dry soil passing the No. 4 sieve (4.82 lb in this example) and cement (185 g) are weighed out and mixed together. The designed quantity of water (312 ml) is added, and mixing is continued until the mixture is of uniform color. Although most soils will mix easily, some heavier-textured soils may require additional treatment.

Moisture distribution in the heavier-textured soils is facilitated by pounding the semi-mixed soil-cement-water into a container such as a skillet. As shown in Fig. 16, a metal hand tamper is used in this operation. The mixture is covered and permitted to set in the semi-compacted condition 5 to 10 minutes; then it is removed and troweled lightly. In some instances it may be well to repeat the above procedure to ensure uniform distribution of moisture.

The designed quantity of saturated, surface-dry material retained on the No. 4 sieve (1.07 lb) is then added and uniformly

Fig. 16. Giving soil-cement-water preliminary compaction to facilitate moisture distribution in heavy-textured soil.

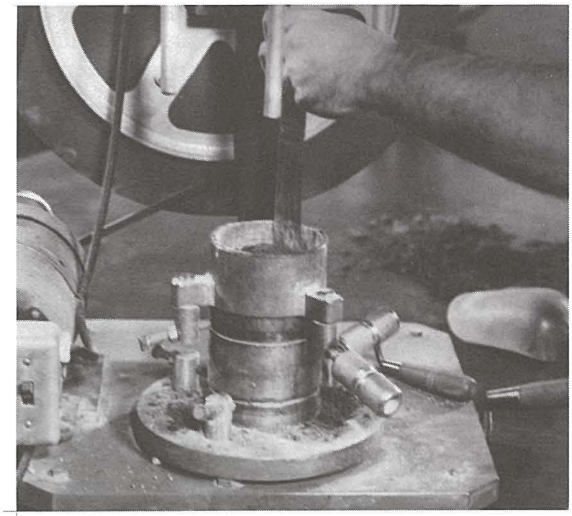

Fig. 17. Spading along inside of mold with knife blade to obtain uniform distribution of material retained on the No. 4 sieve.

mixed with the soil-cement-water mixture. (The material retained on the No. 4 sieve is prepared by being soaked in water overnight and then surface-dried immediately before being added.)

The soil-cement mixture is then compacted with the same compaction equipment* used to make the moisture-density test and in the same manner, except that as the soil-cement mixture for each layer is placed in the mold, a knife blade is used to spade along the inside of the mold before compaction to obtain uniform distribution of the material retained on the No. 4 sieve. The top surfaces of the first and second layers are scarified to remove smooth compaction planes. *Particular attention must be given to this scarifying operation to ensure adequate bond between layers.* At the time the second layer of the specimen is being placed, a 750-g representative sample for moisture determination is taken from the batch.

After the third layer has been compacted, the collar of the mold is removed and the surface of the specimen is leveled with a straightedge. All particles that extend above the top level of the mold are removed. This may cause some irregularities in the surface of the specimen, which can be corrected by hand-tamping fine material into these irregularities and leveling the specimen again with a straightedge. The weight of the molded specimen is then obtained and used in conjunction with the moisture determination to compute the dry weight (density) of the molded specimen.

The test specimen is carefully removed from the mold. Laboratory equipment for this purpose is shown in Fig. 19.

After specimens are molded, they are placed in an atmosphere of high humidity to permit cement hydration for 7 days before wet-dry and freeze-thaw tests are started. If the soil is very sandy and the specimens are fragile at the time of molding, they are placed on suitable specimen carriers (note Fig. 20, page 24) for safe handling.

*Strength and resistance to wetting-and-drying and freezing-and-thawing of specimens compacted with the sector face rammer may differ from those of specimens compacted with the circular face rammer. Therefore the sector face rammer should not be used unless previous tests on like soil-cement mixtures show that similar resistance to wetting-and-drying and freezing-and-thawing is obtained with the two types of rammer faces.

CHECKING MOLDED SPECIMENS

As specimens are molded, data are entered on Form Sheet No. 6, as illustrated in Fig. 14. A portion of the sheet is provided for check calculations of the molded specimens.

As an illustration, assume that the 7 percent specimen previously designed has been molded and the following data has been obtained:

Wet weight of specimen = 4.44 lb

Moisture content of specimen = 11.2 percent

The cement content of the specimen is 7.0 percent by weight as designed and the moisture content is 11.2 percent as determined from the moisture sample. The dry density of the specimen is $\frac{4.44 \times 30}{1.112}$, or 119.78 lb per cubic foot.

The theoretical values were 121.20 lb per cubic foot oven-dry density and 11.5 percent moisture.

TOLERANCES

Obviously, the objective when molding soil-cement test specimens is to obtain specimens with the designed theoretical moisture content and density. However, for practical reasons some variation must be permitted.

The following tolerances are used to determine whether the test specimens are satisfactorily molded or whether they should be remolded.

Moisture content: plus or minus one percentage point. Density: plus or minus 3 lb per cubic foot.

B. For Soils Not Containing Material Retained on the No. 4 Sieve

The procedure for molding wet-dry and freeze-thaw test specimens with soils that do not contain material retained on the No. 4 sieve is essentially the same as that previously described for soils that do contain this material.

The following illustration covers the required calculations. Also discussed are steps required in the process of molding the specimens that differ from the procedure just described for soils containing material retained on the No. 4 sieve.

In the example being illustrated for an A-4(5) soil that does not contain material retained on the No. 4 sieve, specimens will be molded at 8, 10, and 12 percent cement by weight. The data and calculations are given in detail on Form Sheet No. 6, Fig. 21. The sequence and accuracy of calculations can be determined

Fig. 18. Scarifying top of first and second layers to remove smooth compaction planes.

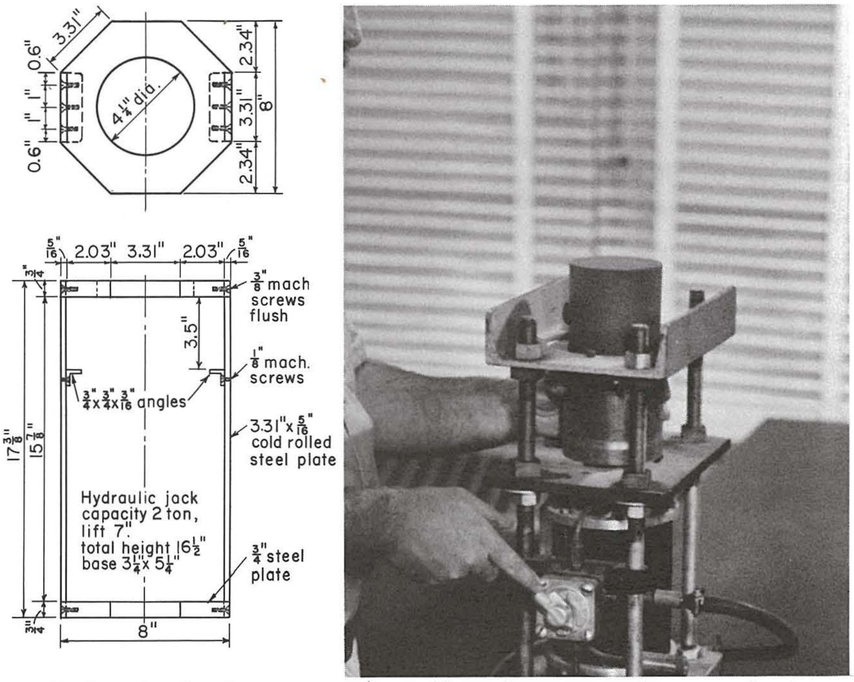

Fig. 19. Drawing showing apparatus for pushing soil-cement specimens out of moisture-density mold. Photograph shows a similar device operated pneumatically.

from Fig. 22. The following calculations will be those required to mold a test specimen at the median cement content.

CALCULATING BATCH WEIGHTS OF MATERIALS

Assume that the maximum density obtained in the moisture-density test is 109.2 lb per cubic foot and the optimum moisture content is 16.0 percent. The hygroscopic moisture content of the soil is 2.2 percent.

The maximum density of the soil-cement mixture being illustrated in 109.2 lb per cubic foot, and a cubic foot contains 109.20/1.10, or 99.27 lb of soil. The amount of oven-dry soil needed for one specimen (1/30 cu ft) is 99.27/30, or 3.31 lb. This amount is increased by 1/10 (0.33 lb) to provide soil for manipulation and by 0.22 lb (100 g) for a moisture sample. Thus the oven-dry soil required for one specimen is equal to 3.31 + 0.33 + 0.22, or 3.86 lb. The hygroscopic moisture content of the soil is 2.2 percent. Thus the air-dry soil to be weighed out is 3.86 × 1.022, or 3.94 lb. This quantity of soil is used for molding specimens at all cement contents.

The quantity of cement required for molding a specimen containing 10.0 percent cement by weight is 3.86 × 0.10, or 0.386 lb, which is 0.386 × 454, or 175 g.

The water required to bring the soil-cement mixture to its optimum moisture content equals the oven-dry weight of soil plus the weight of cement multiplied by the optimum moisture content: (3.86 + 0.386) × 0.16 × 454, or 308 ml; minus the hygroscopic moisture in the soil: 3.86 × 0.022 × 454, or 39 ml; plus an extra amount for evaporation loss (1.0 percent assumed in this example): (3.86 + 0.386) × 0.010 × 454, or 19 ml. The total quantity of water to add for accurate control equals 308 - 39 + 19, or 288 ml net water.

The above calculations are tabulated on Form Sheet No. 6, Fig. 21.

MOLDING SPECIMENS

Data for molding and checking molded specimens can also be recorded on Form Sheet No. 6, as is illustrated in Fig. 21

The designed quantities of air-dry soil (3.94 lb in this example) and cement (175 g) are weighed out and mixed together. The designed quantity of water (288 ml) is added, and mixing is continued until the mixture is of uniform color. The soil-cement mixture is than compacted in the same manner as described on page 21 for soils that contain material retained on the No. 4 sieve, except that spading along the inside of the mold is not necessary. As previously described, the top surfaces of the first and second layers are scarified to remove smooth compaction planes.

A 100-g moisture sample is taken at the time the second layer is being placed. The weight of the molded specimen is obtained, and the specimen is placed in an atmosphere of high humidity for 7 days, as previously described.

CHECKING MOLDED SPECIMENS

As specimens are molded, data are entered on Form Sheet No. 6, as illustrated in Fig. 21. A portion of that form sheet is provided for check calculations of the molded specimens. These check calculations, to determine the actual moisture content and density of the specimens, are the same as those described on page 22 for soils that contain material retained on the No. 4 sieve. The tolerances are also the same as those given on page 22.

In this example, assume that the 10 percent cement specimen previously designed has been molded and the following data have been obtained:

Wet weight of specimen = 4.20 lb
Moisture content of specimen = 15.7 percent

The cement content of the specimen is 10.0 percent by weight as designed and the moisture content is 15.7 percent as determined from the moisture sample. The dry density of the specimen is $\frac{4.20 \times 30}{1.157}$, or 108.9 lb per cubic foot. The theoretical values were 109.2 lb per cubic foot oven-dry density and 16.0 percent moisture.

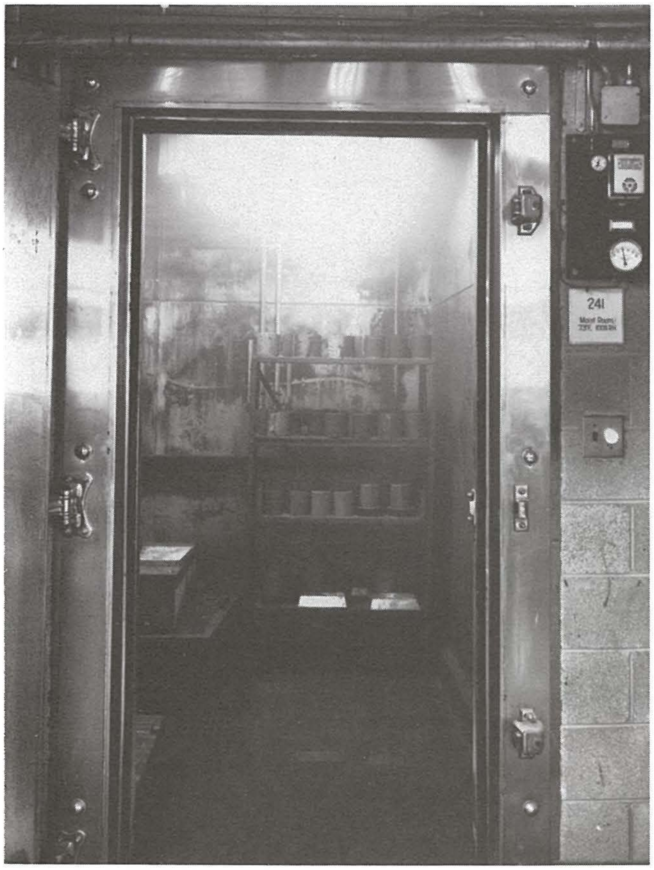

Fig. 20. Wet-dry and freeze-thaw test specimens hydrate in an atmosphere of high humidity for a period of 7 days. Fragile specimens are placed on specimen carriers for safe handling until they have hardened.

Soil-Cement Laboratory, Form Sheet No. 6

DESIGN AND MOLDING WET-DRY AND FREEZE-THAW TEST SPECIMENS

DATA ON SOIL NO. D

Maximum Density 109.2 lb. per cu.ft.

Optimum Moisture 16.0 %

Material Retained on No. 4 Sieve
0 % Absorption -- %

Material Passing No. 4 Sieve
Hygroscopic Moisture 2.2 %

QUANTITIES FOR MOLDING SPECIMENS

Total Oven-dry Soil 3.86 lb.

$$\frac{\frac{109.2}{100+10} \times 100}{30} = 3.31$$
$$+ 0.33$$
$$+ 0.22$$
$$3.86$$

Material Retained on No. 4 Sieve
Oven-dry -- lb.
Saturated, Surface Dry -- lb.*

Material Passing No. 4 Sieve
Oven-dry 3.86 lb.
Air-dry 3.94 lb.*

Cement Content			Total	Mat'l.	Water for batch					
by wt. %	Batch lb.	Batch grams *	Oven-dry soil + cement, lb.	pass. No. 4 + cement, lb.	Theo. ml	Abs. mat'l. ret. on No.4, ml	Hygro. moist., mat'l. pass. No. 4, ml	Evaporation %	Evaporation ml	Net ml *
8.0	0.309	140		4.17	303	—	39	1.0	19	283
10.0	0.386	175		4.25	308	—	39	1.0	19	288
12.0	0.463	210		4.32	314	—	39	1.0	20	295

*To be weighed out for molding specimens

DATA FROM MOLDED SPECIMENS

Tare 8.50 Operator A.T. Date

Cement content % by wt.	Wet wt. spec. plus mold, lb.	Wet wt. spec. lb.	Moisture Determination: Can No.	Wet soil + can gr.	Dry soil + can gr.	Wt. can gr.	Moisture loss gr.	Dry wt. soil gr.	Moisture %	Density lb. per cu. ft.
F-8.0	12.69	4.19							15.9	108.5
W-10.0	12.71	4.21							15.9	109.0
F-10.0	12.70	4.20							15.7	108.9
F-12.0	12.67	4.15							15.6	107.7

Fig. 21. Data for molding wet-dry and freeze-thaw test specimens. Soil No. D.

Conducting Wet-Dry and Freeze-Thaw Tests on Compacted Soil-Cement Specimens

The test procedures given for the wet-dry and freeze-thaw tests are those specified for routine testing in ASTM Designations D559 and D560 or AASHTO Designations T135 and T136.

CONDUCTING WET-DRY TEST

At the end of the 7-day storage period in an atmosphere of high humidity, the specimens are submerged in tap water at room temperature for a period of 5 hours and then removed. The specimens are then placed in an oven at 71 deg C (160 deg F) for 42 hours and removed.

The specimens are then given two firm strokes on all areas with a wire scratch brush to remove all material loosened during the wetting and drying cycles.* (Description of scratch brush is given on page 49.) These strokes are applied to the full height and width of the specimen with a firm stroke corresponding to approximately 3-lb force.** Approximately 18 to 20 vertical brush strokes are required to cover the sides of the specimen twice and 4 strokes are required on each end. During the 12 cycles of the the test, the size of an inadequately hardened specimen will be reduced; in this case the total number of brush strokes should be reduced proportionately.

The procedure described in the preceding paragraphs constitutes one cycle (48 hours) of wetting and drying. The specimens are then submerged in water again and the wetting-drying cycles continued for 12 cycles.

If it is not possible to run the cycles continuously—for example, because of weekends or holidays—the specimens are usually held in the oven during the layover period.

After 12 cycles of tests, the specimens are dried to constant weight at 110 deg C (230 deg F) and weighed to determine their oven-dry weights.

CALCULATIONS

The weight of soil-cement specimens dried out at 110 deg C includes some water used for cement hydration that cannot be driven off at this temperature. The oven-dry weight of the specimen must be corrected for this retained water. The percent

*Other methods of measuring the condition of soil-cement specimens during wet-dry and freeze-thaw tests have been studied. The use of precise length change measurements, which are very sensitive and direct measures of deterioration are particularly promising. See R.G. Packard, "Alternate Methods for Measuring Freeze-Thaw and Wet-Dry Resistance of Soil-Cement Mixtures," in *Highway Research Board Bulletin*, No. 353, 1962, pages 8-41, and R.G. Packard and G.A. Chapman, "Developments in Durability Testing of Soil-Cement Mixtures," in *Highway Research Record*, No. 36, 1963, pages 97-122.

**This force is measured as follows: Clamp a specimen in a vertical position on the edge of a platform scale and set the scale at zero. Apply vertical brushing strokes to the specimen and note the force necessary to register approximately 3 lb.

Soil-Cement Laboratory, Form Sheet No. 6

Numbers show degree of accuracy to which calculations are made. Letters show sequence and method of making calculations.

DESIGN AND MOLDING WET-DRY AND FREEZE-THAW TEST SPECIMENS

DATA ON SOIL NO. ________

Maximum Density 0.1 A lb. per cu.ft.

Optimum Moisture 0.1 B %

Material Retained on No. 4 Sieve
— % Absorption — %

Material Passing No. 4 Sieve
Hygroscopic Moisture 0.1 C %

QUANTITIES FOR MOLDING SPECIMENS

Total Oven-dry Soil 0.01 E lb. $\left[\frac{\left(\frac{A}{100+D}\right)100}{30}\right]\frac{11}{10} + 0.22$

Material Retained on No. 4 Sieve
Oven-dry F — lb.
Saturated, Surface Dry ____ lb.*

Material Passing No. 4 Sieve
Oven-dry 0.01 G lb. E-F
Air-dry 0.01 H lb.* $G\left(\frac{100+C}{100}\right)$

Cement Content by wt. %	Cement Content Batch lb.	Cement Content Batch grams *	Total Oven-dry soil + cement, lb.	Mat'l. pass. No. 4 + cement, lb.	Water for batch: Theo. ml	Water for batch: Abs. mat'l. ret. on No.4, ml	Water for batch: Hygro. moist., mat'l. pass. No. 4, ml	Water for batch: Evaporation %	Water for batch: Evaporation ml	Water for batch: Net ml *
0.1	0.001	1.0		0.01	1.0		1.0	0.5	1.0	1.0
D	I	J		K	L	—	M	N	Φ	P
	$E\left(\frac{D}{100}\right)$	454 I		E + I			$G\left(454\,\frac{C}{100}\right)$			

*To be weighed out for molding specimens

$K\left(454\,\frac{B}{100}\right)$

$(G+I)\left(454\,\frac{N}{100}\right)$

L-M+Φ

DATA FROM MOLDED SPECIMENS

Tare 0.01 Q   Operator ________   Date ________

Cement content % by wt.	Wet wt. spec. plus mold, lb.	Wet wt. spec. lb.	Moisture Determination: Can No.	Wet soil + can gr.	Dry soil + can gr.	Wt. can gr.	Moisture loss gr.	Dry wt. soil gr.	Moisture %	Density lb. per cu. ft.
0.1	0.01	0.01							0.1	0.1
D	R	S							T	U
		R - Q								$\frac{30S}{\frac{100+T}{100}}$

Fig. 22. Sequence and degree of accuracy of calculations for wet-dry and freeze-thaw test specimens for soils not containing material retained on the No. 4 sieve.

water of hydration can be estimated by setting it equal to 1/4 of the percent cement in the specimen.* For example, a specimen containing 8 percent cement by weight retains about 8/4 or 2 percent water. The oven-dry weight of the specimen is corrected for this water of hydration as follows:

Corrected oven-dry weight =

$$\frac{\text{oven-dry weight after drying at 110 deg C}}{\text{percentage of water of hydration retained in specimen} + 100} \times 100.$$

The soil-cement loss of the specimen is then calculated as a percentage of the original oven-dry weight, as follows:

Soil-cement loss, percent =

$$\frac{(\text{original calculated oven-dry weight} - \text{final corrected oven-dry weight})}{\text{original calculated oven-dry weight}} \times 100.$$

* ASTM D559 and D560 base the water of hydration on the AASHTO classification of the soil, as follows:

A-1, A-3 soils	— 1.5 percent
A-2 soils	— 2.5 percent
A-4, A-5 soils	— 3.0 percent
A-6, A-7 soils	— 3.5 percent

In the range of cement contents usually investigated, the soil-cement losses calculated using these figures will be quite similar to the losses calculated using 1/4 of the cement content as described in the text above. However, recent studies indicate that use of 1/4 of the cement content is a more rational and accurate method.

Fig. 23. Wet-dry test specimens are immersed in water for 5 hours each cycle.

Fig. 24. Forty-two hours' drying at 160 deg F completes cycle of wet-dry test.

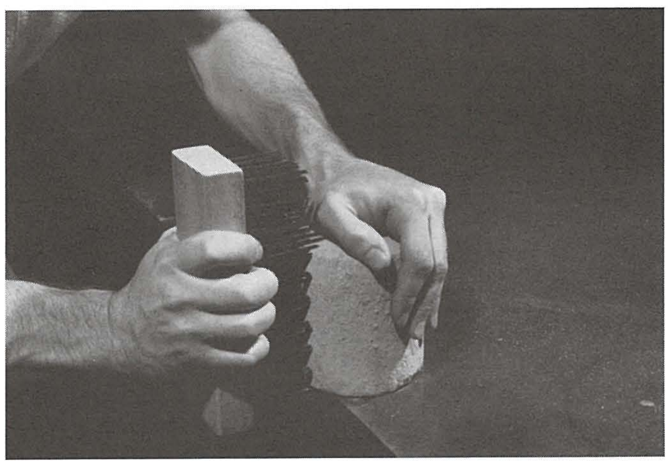

Fig. 25. Soil-cement specimens are given two firm strokes on all areas with a wire scratch brush after each cycle of wetting and drying or freezing and thawing. See Appendix, for specifications for this brush.

Soil-Cement Laboratory, Form Sheet No.7

WETTING-DRYING TEST OF COMPACTED SOIL-CEMENT MIXTURES

Soil No. C   Date Molded________

Cement content, % by wt.		7	
Initial moisture content, %		11.4	
Initial calculated oven-dry wt.,lb.		3.99	
Final oven-dry wt.,lb.*		3.77	
Final corrected oven-dry wt.,lb.**		3.71	
Soil-cement loss, %		7	

*After 12 cycles of testing and after drying to constant wt. at 110° C.
**After correcting for water of hydration. (_____%)

SCHEDULE FOR SPECIMENS DURING TEST

Date	Remove from oven & brush	Cycles com-pleted	Place to soak	Place in oven 160°F.	Remarks
4-13-54	X	start of test	10 AM	3 PM	
4-15	9 AM	1	10 AM	3 PM	
4-17	9 AM	2	10 AM	3 PM	
4-19	✓	3	✓	✓	
4-21	✓	4	✓	✓	
4-23	✓	5	✓	✓	
4-26	✓	6	✓	✓	Held over in oven on Sunday
4-28	✓	7	✓	✓	
4-30	✓	8	✓	✓	
5-3	✓	9	✓	✓	Held over in oven on Sunday
5-5	✓	10	✓	✓	
5-7	✓	11	✓	✓	
5-10	✓	12	X	X	Held over in oven on Sunday

Fig. 26. Data for calculating soil-cement losses and typical schedule for handling wet-dry test specimens during test.

To illustrate the calculation of soil-cement losses, assume that the oven-dry weight of the wet-dry test specimen molded with the A-2-4(0) soil previously illustrated is 3.77 lb after 12 cycles of testing and after drying to constant weight at 110 deg C.

The original calculated oven-dry weight of the specimen was 3.99 lb. The percent of water of hydration for this 7 percent cement specimen is 1.75. The final oven-dry weight of the specimen corrected for retained water is 3.77/1.0175, or 3.71 lb. The soil-cement loss is then [(3.99 - 3.71)/3.99] $\times$ 100, or 7.0 percent. Soil-cement losses are usually reported to the nearest whole number. The above calculations and a typical schedule for handling the wet-dry test specimens during testing are tabulated on Form Sheet No. 7, Fig. 26.

CALCULATION OF APPROXIMATE SOIL-CEMENT LOSS OF WET-DRY TEST SPECIMENS DURING TEST

In certain cases it may be necessary to determine the soil-cement loss of a wet-dry test specimen during testing to permit an accurate estimate of the cement requirement of the soil to be made before tests are completed. This may be done by weighing the specimen after the drying part of the cycle, correcting this weight for the water in the specimen, and calculating the approximate soil-cement loss as a percentage of the original oven-dry weight. The amount of water in the specimen after drying at 71 deg C is slightly larger than the amount given on page 25 for specimens dried at 110 deg C. It is suggested that the percentage given for specimens dried at 110 deg C be increased three percentage points for use with specimens dried at 71 deg C.

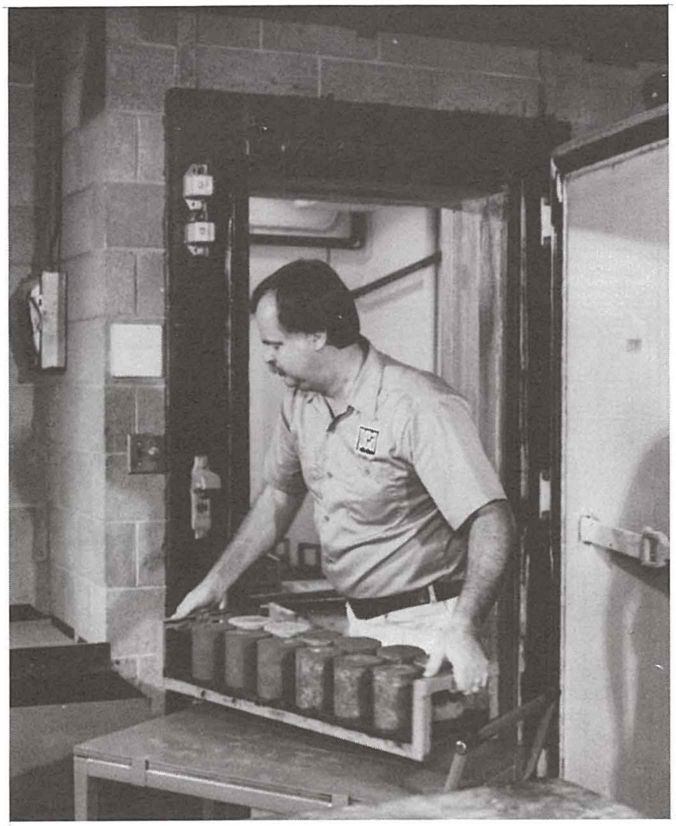

Fig. 27. First portion of freeze-thaw test cycle consists of 24 hours' freezing at a temperature not warmer than - 10 deg F.

CONDUCTING FREEZE-THAW TEST

At the end of the 7-day storage period in an atmosphere of high humidity, water-saturated felt pads about 1/4 to 1/2 in. thick, blotters, or similar absorptive material are placed between the specimens and the specimen carriers, and the assembly is placed in a refrigerator with a constant temperature of not more than −23 deg C (−10 deg F) for 24 hours and then removed.

The assembly is then placed to thaw in the moist room or in suitable covered containers with a temperature of 21 deg C (70 deg F) and a relative humidity of 100 percent for 23 hours and then removed. Free water shall be made available to the absorbent pads to permit the specimens to absorb water by capillary action during the thawing period.

The specimens are then brushed in the same manner as described on page 24.

After being brushed at the end of each thawing period, the specimens are turned over end for end before they are replaced on the water-saturated pads.

Some specimens made of silty and clayey soils tend to scale on sides and ends, particularly after about the sixth cycle of test. This scale should be removed with a sharp-pointed instrument such as an ice pick since the regular brushing may not be effective.

The procedure described in the preceding paragraphs constitutes one cycle (48 hours) of freezing and thawing. The specimens are then replaced in the refrigerator and the freeze-thawing cycles continued for 12 cycles.

If it is not possible to run the cycles continuously—for example, because of weekends or holidays—the specimens should be held in the freezing cabinet during the layover period.

After 12 cycles of test, the specimens are dried to constant weight at 110 deg C (230 deg F) and weighed to determine their oven-dry weights.

Fig. 28. Freeze-thaw test specimens complete thawing portion of cycle in contact with saturated absorbent pads which supply excess quantities of water that specimens absorb by capillary action.

CALCULATIONS

The method of calculating soil-cement losses at the completion of 12 cycles of freeze-thaw testing is the same as that described on pages 24 and 25 for wet-dry test specimens.

An example of the necessary calculations and a typical schedule for handling the freeze-thaw test specimens during the test are tabulated on Form Sheet No. 8, Fig. 29.

CALCULATION OF APPROXIMATE SOIL-CEMENT LOSS OF FREEZE-THAW TEST SPECIMENS DURING TEST

The approximate soil-cement loss of freeze-thaw test specimens can be calculated during the test by determining the approximate oven-dry weight of the test specimen and calculating the soil-cement loss as a percentage of the original oven-dry weight.

In order to calculate the approximate oven-dry weight of the specimen, it is first necessary to make an assumption of its moisture content. This assumption can be made based upon the molded moisture content of the specimen. Test data show that the test specimens usually contain an amount of water slightly more than the moisture content at which they were molded. Average amounts of moisture absorbed in excess of the molded moisture content are given below. The values are obviously not exact but are generally on the safe side.

1. For specimens having an optimum moisture content of less than 10 percent, use the molded moisture content.
2. For specimens having an optimum moisture content between 10 and 15 percent, use the molded moisture content plus one and one-half percentage points of moisture.
3. For specimens having an optimum moisture content between 15 and 20 percent, use the molded moisture content plus two and one-half percentage points of moisture.
4. For specimens having an optimum moisture content of more than 20 percent, use the molded moisture content plus three percentage points of moisture.

The above factors are used to determine the approximate oven-dry weight of the freeze-thaw test specimen during the test, which permits the soil-cement loss to be calculated. For example, assume that the approximate soil-cement loss of a freeze-thaw test specimen is needed after six cycles of testing. Assume also that the molded moisture content was 12.0 percent, that the original oven-dry weight was 4.20 lb, and that the wet weight after six cycles of testing is 4.53 lb. The moisture content of this specimen after six cycles of testing is approximately 12.0 + 1.5, or 13.5 percent. The oven-dry weight after six cycles of testing is 4.53/1.135, or 3.99 lb. The soil-cement loss is then approximately $[(4.20 - 3.99)/4.20] \times 100$, or 5 percent.

INSPECTION OF WET-DRY AND FREEZE-THAW TEST SPECIMENS DURING TEST

Visual inspection of test specimens is generally made every three cycles of the test by subjecting them to "picking" and "clicking" as discussed on page 38. This will furnish information on the condition of the specimens as testing progresses and will permit a check on the estimated cement requirement. It will also determine whether an adequate number of cement contents are being investigated. For instance, if test specimens are molded at 8, 10, and 12 percent cement by weight and if after six cycles of test the 8 percent cement specimens are very hard and have low soil-cement losses, it is advisable to mold specimens containing 6 percent cement by weight in order to determine the most economical cement content that will adequately harden the soil. The other extreme will occur when the 12 percent cement specimens are not adequately hardened. It is then necessary to mold test specimens containing 14 and 16 percent cement by weight to determine a satisfactory cement content.

Soil-Cement Laboratory, Form Sheet No. 8

FREEZING-THAWING TEST OF COMPACTED SOIL-CEMENT MIXTURES

Soil No. C   Date Molded______

Cement content, % by wt.	5	7	9
Initial moisture content, %	11.4	11.2	11.1
Initial calculated oven-dry wt., lb.	3.99	3.99	3.98
Final oven-dry wt., lb.*	3.24	3.72	4.00
Final corrected oven-dry wt., lb.**	3.20	3.66	3.91
Soil-cement loss, %	20	8	2

*After 12 cycles of testing and after drying to constant wt. at 110° C.
**After correcting for water of hydration. (_____%)

SCHEDULE FOR SPECIMENS DURING TEST

Date	Remove from moist room & brush	Cycles completed	Place in refrigerator, -10°F.	Date	Remove from refrig. & place in moist room	Remarks
4-13-54		start of test	10 AM	4-14	10 AM	
4-15	9 AM	1	10 AM	4-16	10 AM	
4-17	9 AM	2	10 AM	4-19	10 AM	Held in refrigeration on Sunday
4-20	✓	3	✓	4-21	✓	
4-22	✓	4	✓	4-23	✓	
4-24	✓	5	✓	4-26	✓	Held in refrigeration on Sunday
4-27	✓	6	✓	4-28	✓	
4-29	✓	7	✓	4-30	✓	
5-1	✓	8	✓	5-3	✓	Held in refrigeration on Sunday
5-4	✓	9	✓	5-5	✓	
5-6	✓	10	✓	5-7	✓	
5-8	✓	11	✓	5-10	✓	Held in refrigeration on Sunday
5-11	✓	12				

Fig. 29. Data for calculating soil-cement losses and typical schedule for handling freeze-thaw test specimens during test.

CHAPTER 4

COMPRESSIVE-STRENGTH AND OTHER SUPPLEMENTARY TESTS

Compressive-strength tests are generally made as supplementary to the regular soil-cement tests. Compressive-strength test specimens are broken in compression at ages of 2, 7, and 28 days. They are stored at room temperature in an atmosphere of approximately 100 percent humidity until the day of testing and are then broken in compression after being soaked in water. A rate of application of load of 20 lb per square inch per second is generally used.

Fixed cement contents by weight are selected for these specimens without regard to the type of soil except when the short-cut test procedure for sandy soils, given in Chapter 6, is being used. Generally, cement contents of 6 and 10 percent are used, although in many instances 14 percent specimens are included and in some instances even higher cement contents are investigated.

When the supply of soil is short, the number of specimens may be reduced, as a minimum, to 7 day breaks at a single cement content indicated in Table 2 or Table 3.

Four-inch-diameter, 4.6-in.-high compressive-strength test specimens are practical because they can be molded in the regular moisture-density test cylinder, which is generally available. Two-inch-diameter, 2-in.-high specimens, described below, are also advantageous because they require a minimum of soil. However, for this smaller mold size, only those soils with particles no larger than a No. 4 size should be used. Specimens of other sizes, such as those 2.8 in. in diameter and 5.6 in. high, may also be practical.* Since compressive-strength test data are not used for design purposes but only to determine the rate of hardening and whether the soil is reacting normally, the size of the specimens is not very important. When comparing strengths of specimens with different height-to-diameter ratios, a correction factor should be used—see ASTM C42, "Obtaining and Testing Drilled Cores and Sawed Beams of Concrete," which has been found applicable to soil-cement.

*Making and Curing Soil-Cement Compression and Flexure Test Specimens in the Laboratory (ASTM D1632) and Compressive Strength of Molded Soil-Cement Cylinders (ASTM D1633).

FOUR-INCH-DIAMETER SPECIMENS

Four-inch-diameter, 4.6-in.-high specimens are generally molded with the same compaction equipment used to make the moisture-density test and to mold wet-dry and freeze-thaw test specimens. They are molded at the optimum moisture content, determined from the moisture-density test, and contain the percent of material retained on the No. 4 sieve that occurs in the soil sample. The calculations required and the procedure for molding are the same as those given in Chapter 3 for wet-dry and freeze-thaw test specimens. These specimens are soaked in water for 4 hours and capped before they are broken. Form Sheet No. 5, page 53, is provided for making calculations and recording test data.

TWO-INCH-DIAMETER SPECIMENS

Specimens 2 in. in diameter and 2 in. in height can be molded in the machine shown in Fig. 30 when the soil does not contain material retained on the No. 4 sieve. These specimens are soaked in water for 1 hour before they are broken. A designed quantity of soil-cement at optimum moisture is weighed out and compacted to an exact height of 2 in. Force of compaction is applied by the double piston method: force is applied to the top piston, but both top and bottom pistons are left free to move during compaction. The quantity of soil-cement weighed out and placed in the machine is such that the specimens have the designed density. Form Sheet No. 4, page 52, is provided for making calculations and recording test data.

These 2-in.-diameter, 2-in.-high specimens can also be molded in a hydraulic testing machine. Molds similar to those shown in Fig. 30 are used. Hydraulic testing machines will cut off automatically when a certain distance is reached between the head and the compression block. This automatic shutoff can be used to control the 2-in. height of the specimen merely by making the base-plate thickness of the mold 2 in. less than the space between the head and the compression block of the machine at the time of shutoff.

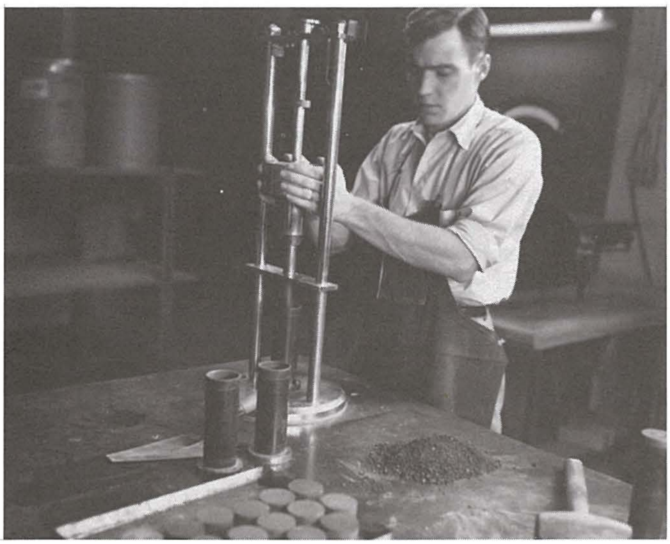

Fig. 30. Molding 2-in. compressive-strength test specimens.

ANALYSIS OF COMPRESSIVE-STRENGTH DATA

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

The 7-day compressive strength of saturated specimens that represents a durable soil-cement base varies with the physical and chemical properties of the soil and will generally be between 300 and 800 psi. Fig. 31 gives data on the relationship between strength and durability. It is apparent from these curves that a compressive strength that would be adequate for all soils would be higher than needed for many of the soils.

The determination of a suitable design compressive strength is simplified when materials within a narrow range of gradations and/or soil types are used. As a result, some agencies have determined and used successfully for a particular type of material a compressive strength requirement generally based on results of previous wet-dry and freeze-thaw tests.

Strength requirements are of secondary importance to results of the standard freeze-thaw and wet-dry tests, which determine for the particular soil material the amount of cement needed to hold the mass together permanently and maintain stability under shrinkage and expansive forces that occur in the field.

Compressive-strength tests are also used to check soils previously tested. When the field data indicate that a soil has the same texture and is from the same soil series and horizon as a previously tested soil, compressive strengths should be about the same.

Grain Size and Physical Test Constants

Grain size and physical test constants are most helpful in identifying and analyzing a soil and in comparing it with other soils. These tests, however, are distinctly secondary to the moisture-density, wet-dry, and freeze-thaw tests.

As discussed in Chapter 5, information on the gradation and physical test constants of the soil is helpful in determining the ease of pulverization in the field and in choosing the type and weight of compaction equipment.

Soil-Cement and Organic Relation

Considerable research data show that there is a definite tendency for the cement requirement of a soil-cement mixture to increase as the colorimetric reading of the soil increases.* However, sufficient data are available for soil with high colorimetric readings and low corresponding cement requirements to show that the colorimetric test is not a direct index of the deleterious material's influence on cement requirements. For this reason the test is not routine.

The area in which the soil develops is of considerable importance in the study of the effect of organic matter. For instance, for northern soils (podzols and podzolic soils) these data indicate that when the colorimetric tests show 2,000 parts per million or more, the organic material may likely influence the action of the cement, as shown by reduced compressive strength. In a number of cases on record, however, soils from these areas have contained much higher organic contents with no apparent ill effects. On the other hand, a number of soils on which organic tests showed 1,000 parts per million have required very high cement contents. (It is not known whether the cause for the high cement requirements in the latter cases was organic matter or some other factor, such as base exchange or the presence of a film on the soil grains that prevented the cement from binding the soil grains together.)

Soils from the Southeast and South (red and yellow soils, not from poorly drained sand areas) and from the Far West may contain considerable organic matter (10,000 to 30,000 parts per million, for instance) and still react well with relatively low cement contents.

To sum up: The colorimetric organic test does not necessarily indicate what the cement reaction will be, although high organic contents may be indicative of a poor reaction. The organic test is of major value when the soil being tested is sand or a sandy soil. In any case, the wet-dry and freeze-thaw tests will reliably show whether the soil-cement is satisfactorily hardened.

Poorly reacting sandy soils that contain a particular type of organic material are discussed in Chapter 8.

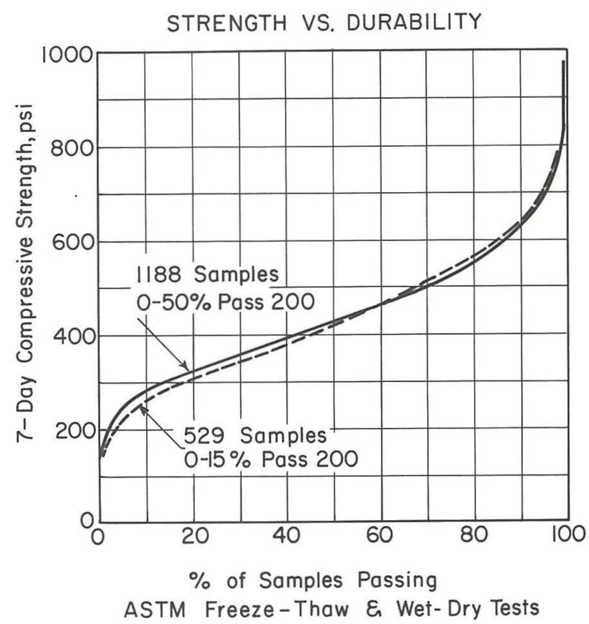

Fig. 31. Relationship between strength and durability.

*As determined by a procedure essentially the same as "Test for Organic Impurities in Fine Aggregates for Concrete," ASTM Designation C40.

CHAPTER 5

ESTABLISHMENT OF CEMENT FACTORS FOR CONSTRUCTION

The principal requirement of a hardened soil-cement mixture is that it withstand exposure to the elements. Thus the primary basis of comparison of soil-cement mixtures is the cement content required to produce a mixture that will withstand the stresses induced by the wet-dry and freeze-thaw tests. The service record of projects in use proves the reliability both of the results based upon these tests and of the criteria given below.

The following criteria are based on considerable laboratory test data, on the performance of many projects in service, and on information obtained from the outdoor exposure of several thousand specimens. The use of these criteria will provide the cement content required to produce hard, durable soil-cement, suitable for base-course construction of the highest quality.

1. Soil-cement losses after 12 cycles of either the wet-dry test or freeze-thaw test shall conform to the following limits:
   Soil Groups A-1, A-2-4, A-2-5, and A-3, 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 and A-7, not over 7 percent.
2. Compressive strengths should increase both with age and with increases in cement content in the ranges of cement content producing results that meet requirement 1.

These criteria should be considered not as irrevocable recommendations but as criteria found to be satisfactory with present knowledge. No allowance is made for variable climatic conditions in different sections of the country. The freeze-thaw test, for example, is run on soils from southern states as well as on soils from northern sections of the country. It is to be expected that experience will effect some variation in these procedures in order to conform to local climatic conditions.

On the Soil-Cement Laboratory Form Sheets No. 13 (Figs. 32 and 33), complete test data are given for the two representative soils illustrated in Chapter 3. Here are listed the gradation of the soil that was tested, the physical test constants of the soil, and other data pertaining to the raw soil. In addition, moisture-density test data, compressive-strength test data, and wet-dry and freeze-thaw test data are given for the soil-cement mixture.

Interpreting Test Data

The gradation and physical test constants data are the principal information needed for determining the ease of pulverization of the soil in the field, the type and weight of rollers needed for compaction, and the quantity of hygroscopic moisture that the soil may have at the time soil-cement construction is started. If the soil contains less than 50 percent material passing the No. 200 sieve, it may be assumed that pulverization problems will not be difficult. This is particularly true since the liquid limit and the plasticity index of these materials are likely to be low; for instance, the liquid limit will probably be 35 or less, and the plasticity index will probably be 15 or less. As an example, the A-2-4(0) soil (Fig. 32) will pulverize readily and no particular attention will be required during the pulverization process. The A-4(5) soil (Fig. 33) contains 68 percent material passing the No. 200 sieve; however, no particular attention should be required during the pulverization process because the liquid limit and plasticity index are low.

In instances where the amount of material passing the No. 200 sieve is more than 50 percent but the clay fraction (material smaller than 0.005 mm) is less than about 20 percent, the pulverization problem will still be rather simple because of the natural friability of the silt material. In cases where the amount of material passing the No. 200 sieve is more than 50 percent and the clay fraction is more than about 30 percent, with a corresponding plasticity index of more than about 20 and a liquid limit of more than about 45, special effort will generally be required to obtain adequate pulverization.

The gradation of the soils will supply the information on which to base the choice and weight of rollers for the project. For instance, soils that contain a small amount of nonplastic binder material passing the No. 200 sieve will be difficult to compact satisfactorily with tamping rollers. For these soils, compaction is obtained with pneumatic-tire rollers, steel-wheel rollers, track-type tractors, and vibratory compactors.

Compressive strengths of soil-cement mixtures should increase both with age and with increase in cement content in the ranges of cement content that produce satisfactory soil-cement.

Soil-cement losses of satisfactorily hardened specimens should meet the criteria for soil-cement loss given on page 30. The magnitude of these losses is applicable only when there have been specimens tested that contain two or more cement contents. This makes it possible to determine the decrease in loss caused by the increase in cement content. This is very important in analyzing the data on soil-cement loss. For instance, assume wet-dry and freeze-thaw test specimens were molded with an A-2-4(0) soil at cement contents of 5, 7, and 9 percent. Assume also that the soil-cement loss for the 5 percent specimen was 21 percent, for the 7 percent specimen 13 percent, and for the 9 percent specimen 6 percent. Seven percent cement would be satisfactory if compressive strengths in this range were satisfactorily increasing with cement content and with age.

If the soil-cement losses for the specimens described above were 70, 14, and 5 percent, 8 percent should be recommended because of the critical reaction of cement contents less than 7 percent. A guide that can be used for soils having a critical reaction is that the soil-cement loss (based on a straight-line plot) at 90 percent of the cement content being recommended should be less than two times the maximum allowable loss.

It is the practice in most laboratories to inspect individual specimens for hardness during the wet-dry and freeze-thaw tests and also at the completion of tests before oven-drying. The specimens are rapped with a hard specimen and picked with an ice pick to determine if they are thoroughly hardened. Recommendations are then made both on the basis of soil-cement-loss data and on the basis of visual inspection. Good soil-cement specimens are hard and stable even when wet.

Soil-Cement Laboratory, Form Sheet No. 13 Date tests completed______

SUMMARY OF TESTS ON SOIL-CEMENT MIXTURES
PORTLAND CEMENT ASSOCIATION

State______ Project______ PCA Soil No. C

County______ Field Project No.______

Sampling location Represents top 6" of old gravel road. Taken at station 50+00

GRADATION

Per cent passing	Soil mortar	Total sample
3-in. sieve		100
¾-in. sieve		95
No. 4 sieve (4.76 mm.)		82
No. 10 sieve (2.00 mm.)	100	66
No. 18 sieve (1.00 mm.)	83	55
No. 35 sieve (0.50 mm.)	68	45
No. 40 sieve (0.42 mm.)	65	43
No. 60 sieve (0.25 mm.)	55	36
No. 140 sieve (0.105mm.)	38	25
No. 200 sieve (0.074mm.)	32	21
Per cent smaller than		
0.05 mm.	26	17
0.005mm.	12	8
0.002mm.	9	6

U.S. DEPT. OF AGRICULTURE
SOIL CLASSIFICATION

Soil series______
Soil horizon______
Textural class Gr. coarse sandy loam
Color of moist soil Brown

PHYSICAL TEST CONSTANTS
L. L. 26
P. I. 8

AASHO SOIL CLASSIFICATION
A-2-4 (O)

COMPRESSIVE STRENGTH, psi*

Cement content, % by wt.	Age when tested, days		
	two	seven	twenty-eight
6	295	540	770
10	340	795	965

*Specimens saturated in water before testing

DATA FROM WET-DRY AND FREEZE-THAW SPECIMENS

Cement content % by wt.	Total soil-cement loss, %	
	Wet-Dry	Freeze-Thaw
5.0	–	20
7.0	7	8
9.0	–	2

MATERIAL RETAINED ON NO. 4 SIEVE
Absorption, % 2.0
Bulk sp. gravity 2.55

RECOMMENDATIONS

Recommended cement content 7.5 % by volume (6.2 % by weight)
which is 5.29 lb. per sq. yd. per inch of compacted thickness.
Laboratory optimum moisture content** 11.5 %
Laboratory maximum density** 121.2 lb. per cu. ft.

Tests made on total sample using ¾ in. maximum size material.
**Moisture-density test made during construction govern field control.

Remarks:______

Fig. 32. Summary of soil and soil-cement tests on soil No. C.

Soil-Cement Laboratory, Form Sheet No. 13

Date tests completed

SUMMARY OF TESTS ON SOIL-CEMENT MIXTURES
PORTLAND CEMENT ASSOCIATION

State ______ Project ______ PCA Soil No. D

County ______ Field Project No. ______

Sampling location ______

GRADATION	Soil mortar	Total sample
Per cent passing		
3-in. sieve		100
¾-in. sieve		100
No. 4 sieve (4.76 mm.)		100
No. 10 sieve (2.00 mm.)	100	100
No. 18 sieve (1.00 mm.)	100	100
No. 35 sieve (0.50 mm.)	99	99
No. 40 sieve (0.42 mm.)	98	98
No. 60 sieve (0.25 mm.)	96	96
No. 140 sieve (0.105mm.)	78	78
No. 200 sieve (0.074mm.)	68	68
Per cent smaller than		
0.05 mm.	57	57
0.005mm.	24	24
0.002mm.	19	19

U.S. DEPT. OF AGRICULTURE SOIL CLASSIFICATION

Soil series Belknob
Soil horizon B
Textural class Loam
Color of moist soil Brown

PHYSICAL TEST CONSTANTS
L. L. 36
P. I. 8

AASHO SOIL CLASSIFICATION
A-4(5)

COMPRESSIVE STRENGTH, psi*			
Cement content, % by wt.	Age when tested, days: two	seven	twenty-eight
6	170	235	280
10	263	395	460

*Specimens saturated in water before testing

DATA FROM WET-DRY AND FREEZE-THAW SPECIMENS		
Cement content % by wt.	Total soil-cement loss, %: Wet-Dry	Freeze-Thaw
8.0	–	23
10.0	7	11
12.0	–	3

MATERIAL RETAINED ON NO. 4 SIEVE
Absorption, % –
Bulk sp. gravity –

RECOMMENDATIONS

Recommended cement content 11.0 % by volume (10.5 % by weight) which is 7.76 lb. per sq. yd. per inch of compacted thickness.

Laboratory optimum moisture content** 16.0 %

Laboratory maximum density** 109.2 lb. per cu. ft.

Tests made on total sample using ¾ in. maximum size material.

**Moisture-density test made during construction govern field control

Remarks:

Fig. 33. Summary of soil and soil-cement tests on soil No. D.

Recommendations for Field-Control Factors

For control during construction, the required cement content by weight can be converted to the equivalent cement content by volume, based on a 94-lb U.S. bag of cement, using the following formula or Fig. 34.

$$\text{Percent cement by volume} = \frac{D - \frac{D}{C}}{94} \times 100, \text{ where}$$

D = oven-dry density of soil-cement in pounds per cubic foot;
C = 100 + percent cement by weight of oven-dry soil, the quantity divided by 100.

The criteria used to determine adequate cement factors for soil-cement construction were developed as percent cement by volume in terms of a 94-lb U.S. bag of cement. The cement content by volume in terms of an 40 kg (88.2 lb) Canadian bag can be determined by multiplying the value obtained from Fig. 34 by 1.066 or by using 88.2 rather than 94 in the denominator of the above formula. In such cases the test report should indicate that the cement content by volume represents the percent of a 40-kg bag of cement in a cubic foot of compacted soil-cement rather than the percent of a 94-lb bag.

In addition to being reported on a volume basis, the required cement content can be expressed as pounds per square yard per inch of compacted thickness for ready use by the construction engineer. Table 9 can be used to make this conversion.

The laboratory moisture-density test data are not, of course, directly applicable to field control. Moisture-density tests on representative samples taken during construction toward the end of the damp-mixing operations show the optimum moisture content of the mixture and the density to which the mix should be compacted. This procedure covers small variations in soil type and variations in optimum moisture and maximum density that result from prolonged damp-mixing operations. However, the laboratory moisture-density test data for the soil-cement mixtures occurring on a project are sufficiently close to the field moisture-density test data that they can be used for estimating equipment needs and for setting up bid items in the contract proposal.

Table 9. Percent Cement by Volume Expressed as Pounds per Square Yard per Inch of Compacted Thickness

Cement content, percent by vol.	Cement, lb per sq yd per in. of compacted thickness	Cement content, percent by vol.	Cement, lb per sq yd per in. of compacted thickness
6.0	4.23	12.0	8.46
6.5	4.58	12.5	8.81
7.0	4.94	13.0	9.17
7.5	5.29	13.5	9.52
8.0	5.64	14.0	9.87
8.5	5.99	14.5	10.22
9.0	6.35	15.0	10.58
9.5	6.70	15.5	10.93
10.0	7.05	16.0	11.28
10.5	7.40	16.5	11.63
11.0	7.76	17.0	11.99
11.5	8.11	17.5	12.34

NOTE: In Table 9, percent cement by volume is based on a 94-lb cement bag. For percent cement by volume based on other cement bag weights, Table 9 cannot be used.

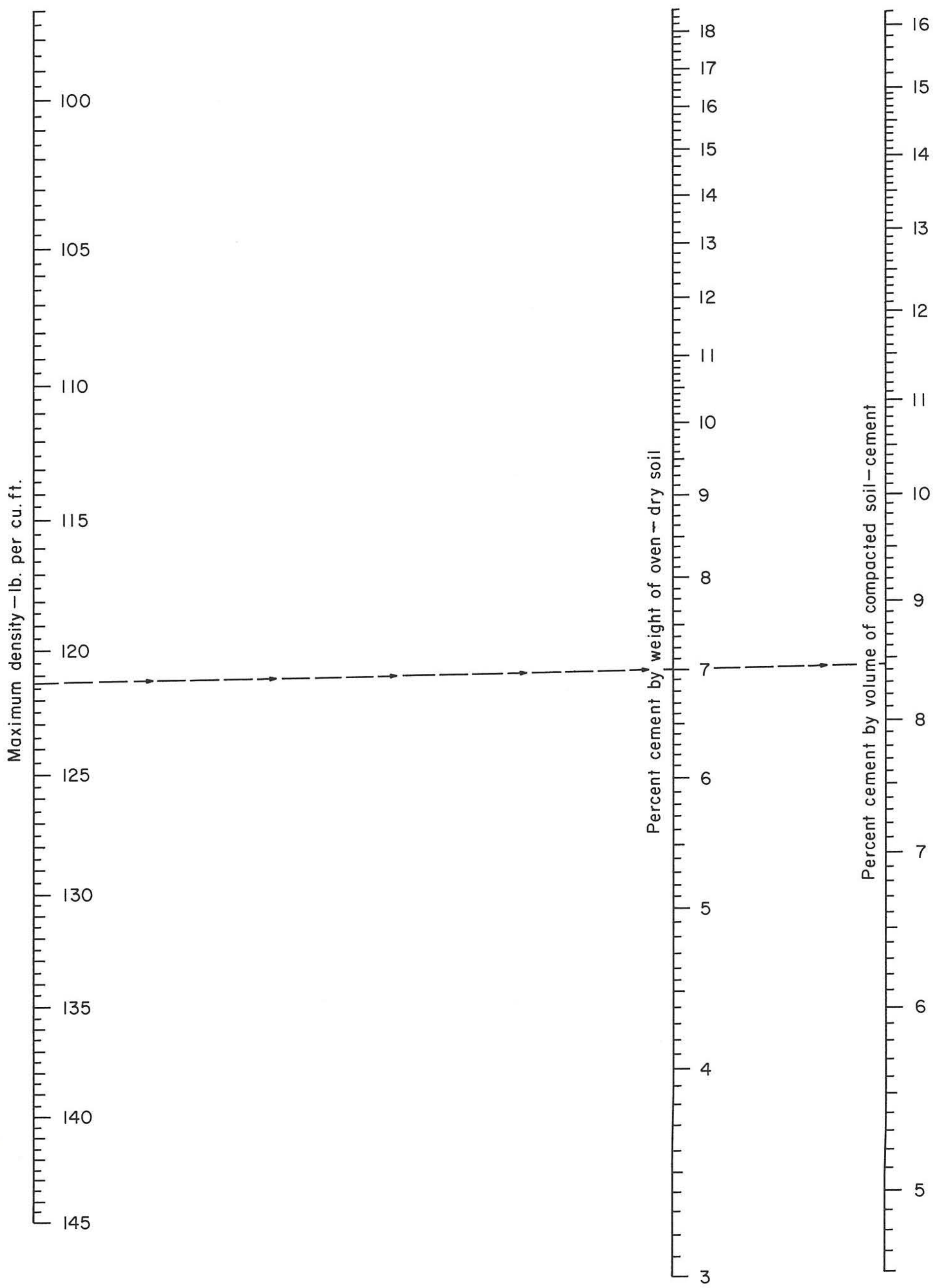

Fig. 34. Relation of cement content by weight of oven-dry soil to cement content by volume of compacted soil-cement mixture.

CHAPTER 6

SHORT-CUT TEST PROCEDURES FOR SANDY SOILS

The following short-cut test procedures for sandy soils were developed in the 1950's as a result of a correlation made by the Portland Cement Association of the data obtained from ASTM-AASHTO tests on 2,438 sandy soils using Type I cement.* Since then, these procedures have been further verified with tests on approximately 2000 additional sandy soils. These procedures do not involve new tests or additional equipment. Instead, some tests can be eliminated by the use of charts developed in previous tests on similar soils. The only tests required are a grain-size analysis, a moisture-density test, and compressive-strength tests. Relatively small samples are needed. All tests, except for the 7-day compressive-strength tests, can be completed in one-day.

Two procedures are used: Method A for soils not containing material retained on the No. 4 sieve and Method B for soils containing material retained on the No. 4 sieve. Method B was developed to permit the use of moisture-density data obtained on the total soil-cement mixture, as specified by the ASTM-AASHTO moisture-density test methods.

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, chat, 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.

The short-cut test procedures do not always indicate the minimum cement factor that can be used with a particular sandy soil. However, they almost always provide a safe cement factor, generally close to that indicated by standard ASTM-AASHTO wet-dry and freeze-thaw tests.

The procedures are being widely applied by engineers and builders and may largely replace the standard tests when experience in their use is gained and the relationships are checked. The charts and procedures may be modified to conform to local climatic and soil conditions if necessary.

Step-by-Step Procedures

Short-cut test procedures involve:

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

PRELIMINARY STEPS

Before applying the short-cut test procedures, it is necessary (1) to determine the gradation of the soil, and (2) to determine the bulk specific gravity of the material retained on the No. 4 sieve. If all the soil passes the No. 4 sieve, Method A should be used. If material is retained on the No. 4 sieve, Method B is used.

METHOD A

Step 1: Determine by test** the maximum dry density and optimum moisture content for a mixture of the soil and portland cement.

> **Note 1: Use Fig. 35 to obtain an estimated maximum density of the soil-cement mixture being tested. This estimated maximum density and the percentage of material smaller than 0.05 mm (No. 270 sieve) can be used with Fig. 36 to determine the cement content by weight to use for the test.**

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*See footnote, page 8.

**Method of Test for Moisture-Density Relations of Soil-Cement Mixtures, ASTM Designation D558; AASHTO Designation T134.

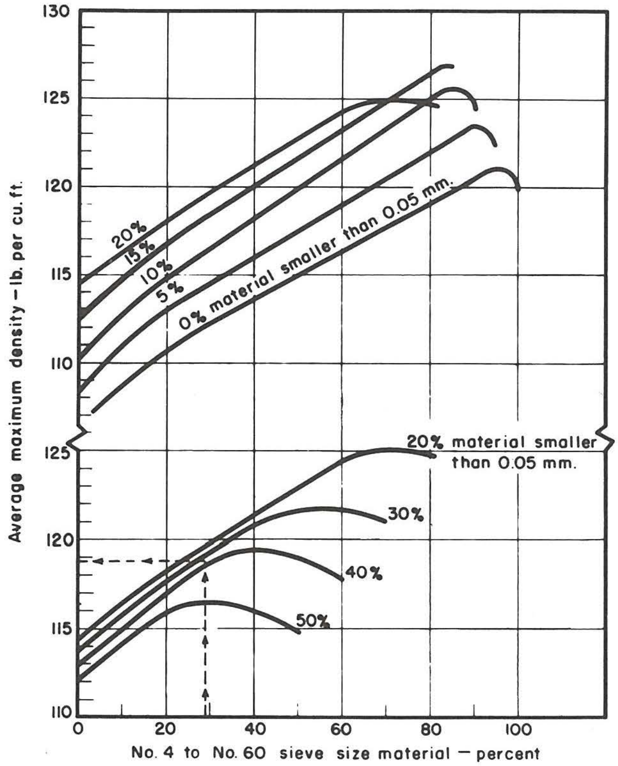


Fig. 35. Average maximum dry densities of soil-cement mixtures not containing material retained on the No. 4 sieve.

Step 2: Use the maximum dry density obtained by test in Step 1 to determine from Fig. 36 the indicated cement requirement.

Step 3: Use the indicated cement factor obtained in Step 2 to mold compressive-strength test specimens* at maximum density and optimum moisture content.

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

Step 5: On Fig. 37, plot the average compressive-strength value obtained in Step 4. If this value plots above the curve, the indicated cement factor by weight, determined in Step 2, is adequate.

If it is desired to convert the recommended cement content by weight to the equivalent cement content by volume for field construction, the conversion can be made by using Fig. 34, page 33.

Note 2: If the average compressive-strength value plots above the curve of Fig. 37, the cement content indicated in Fig. 36 is verified. Strengths at higher or lower cement contents are not determined since these data cannot be used in the procedure. In most cases the strength will be substantially higher than the minimum allowable value. This merely indicates that the soil is reacting normally. When high strengths are obtained, it is not correct to reduce the cement factor so that a strength value close to the curve in Fig. 37 is obtained. Such a reduction invalidates the reliability of the procedure and will usually result in a cement content that is not sufficient to meet ASTM-AASHTO freeze-thaw and wet-dry test criteria. Although a very high compressive strength may indicate that the soil is reacting better than average, any reduction in the cement factor can only be made based on freeze-thaw and wet-dry tests at lower cement contents.

Note 3: If the average compressive-strength value plots below the curve of Fig. 37, the indicated cement factor obtained in Step 2 is probably too low. Additional tests will be needed to establish a cement requirement. These tests generally require the molding of two test specimens, one at the indicated cement factor obtained in Step 2 and one at a cement content two percentage points higher. The specimens are then tested by ASTM-AASHTO freeze-thaw and wet-dry test procedures.

METHOD B

Step 1: Determine by test the maximum dry density and optimum moisture content for a mixture of the soil and portland cement.

Note 4: Use Fig. 38 to determine an estimated maximum density of the soil-cement mixture being tested. This estimated maximum density, the percentage of material smaller than 0.05 mm (No. 270 sieve), and the percentage of material retained on the No. 4 sieve can be used with Fig. 39 to determine the cement content by weight to use in the test.

---

*Specimens of either 2-in. diameter and 2-in. height or 4-in. diameter and 4.6-in. height may be molded. The 2-in. specimens shall be submerged in water for one hour before testing and the 4-in. specimens for four hours. The 4-in. specimens shall be capped before testing. It is recommended that the 2-in. specimens be molded in triplicate. For the 4-in. specimens, a single specimen may be molded if soil supply is short; if the strength exceeds the strength criteria by a substantial margin, this procedure is satisfactory.

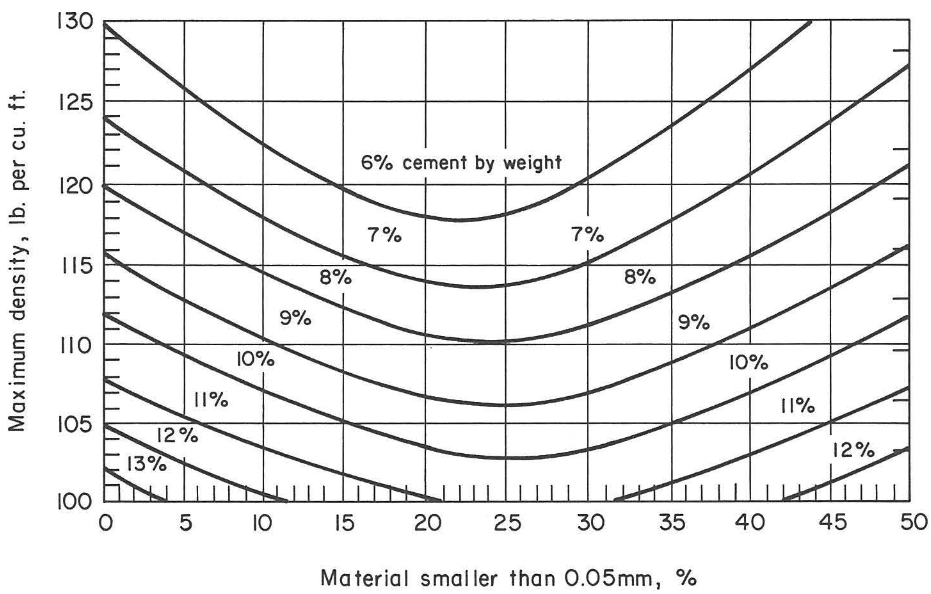


Fig. 36. Indicated cement contents of soil-cement mixtures not containing material retained on the No. 4 sieve.

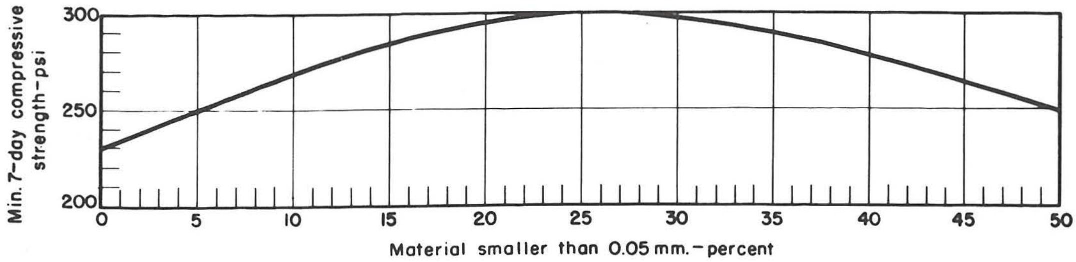


Fig. 37. Minimum 7-day compressive strengths required for soil-cement mixtures not containing material retained on the No. 4 sieve.

The soil sample for the test shall contain the same percentage of material retained on the No. 4 sieve as the original soil sample contains. Three-quarter-inch material is the maximum size used. Should there be material larger than this in the original soil sample, it is replaced in the test sample with an equivalent weight of material passing the 3/4-in. sieve and retained on the No. 4 sieve.

Step 2: Use the maximum dry density obtained by test in Step 1 to determine from Fig. 39 the indicated cement requirement.

Step 3: Use total material as described in Step 1 and the indicated cement factor obtained in Step 2 to mold compressive-strength test specimens* at maximum density and optimum moisture content.

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

Step 5: Determine from Fig. 40 the minimum allowable compressive strength for the soil-cement mixture. If the average compressive strength obtained in Step 4 equals or exceeds the minimum allowable strength, the indicated cement factor by weight obtained in Step 2 is adequate.

If it is desired to convert the recommended cement content by weight to the equivalent cement content by volume for field construction, the conversion can be made by using Fig. 34, page 33.

Note 5: If the average compressive-strength value equals or exceeds the minimum allowable strength obtained in Fig. 40, the cement content indicated in Fig. 39 is verified. Strengths at higher or lower cement contents are not determined since these data cannot be used in the procedure. In most cases the strength will be substantially higher than the minimum allowable value. This merely indicates that the soil is reacting normally. When high strengths are obtained, it is not correct to reduce the cement factor so that a strength value close to the minimum allowable from Fig. 40 is obtained. Such a reduction invalidates the reliability of the procedure and will usually result in a cement content that is not sufficient to meet ASTM-AASHTO freeze-thaw and wet-dry test criteria. Although a very high compressive strength may indicate that the soil is reacting better than average, any reduction in the cement factor can only be made based on freeze-thaw and wet-dry tests at lower cement contents.

Note 6: If the average compressive-strength value is lower than the minimum allowable, the indicated cement factor obtained in Step 2 is probably too low. Additional tests as described in Note 3 are needed.

Example of Use of Short-Cut Test Procedures

Following is an example of the use of the short-cut procedures.

Preliminary tests determine the gradation of the soil and bulk specific gravity of the material, if any, retained on the No. 4 sieve. The data obtained from the tests are tabulated below. In this example, Method B should be used since the soil contains material retained on the No. 4 sieve.

Gradation:
- Passing
  - No. 4 sieve .... 82 percent
  - No. 10 sieve .... 77 percent
  - No. 60 sieve .... 58 percent
  - No. 200 sieve .... 37 percent
- Smaller than
  - 0.05 mm (silt and clay combined) ...... 32 percent
  - 0.005 mm (clay) .... 13 percent

Color: Brown

Bulk specific gravity of material retained on No. 4 sieve: 2.50

Step 1: Fig. 38 indicates that the estimated maximum dry density of the soil-cement mixture is 122 lb per cubic foot since the soil contains 32 percent material smaller than 0.05 mm and 23 percent material retained on the No. 10 sieve.

Fig. 39 is used to determine the cement content by weight to use in the moisture-density test. Since the soil contains 32

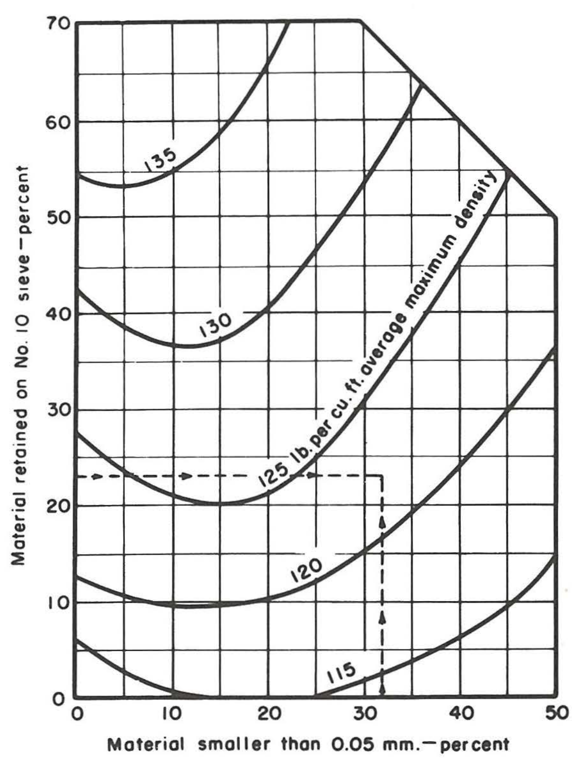


Fig. 38. Average maximum densities of soil-cement mixtures containing material retained on the No. 4 sieve.

*Specimens of 4-in. diameter and 4.6-in. height shall be molded. They shall be submerged in water for four hours and shall be capped before testing. A single specimen may be molded if soil supply is short; if the strength exceeds the strength criteria by a substantial margin, this procedure is satisfactory.

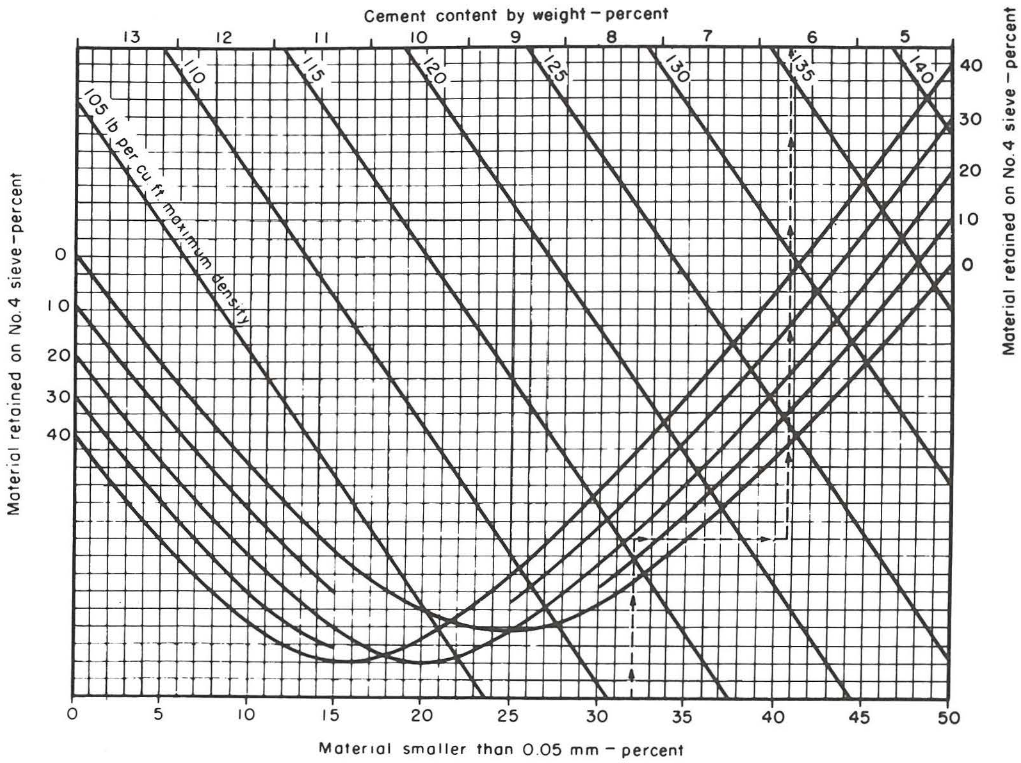


Fig. 39. Indicated cement contents of soil-cement mixtures containing material retained on the No. 4 sieve.

percent material smaller than 0.05 mm and 18 percent material retained on the No. 4 sieve, and since the estimated maximum density is 122 lb per cubic foot, 6 percent cement by weight is indicated.

Perform the moisture-density test.

For this example, assume the maximum dry density obtained by test to be 123.2 lb per cubic foot at 10.2 percent moisture.

Step 2: Fig. 39 indicates a cement factor of 6 percent, using the calculated actual density of 123.2 lb per cubic foot.

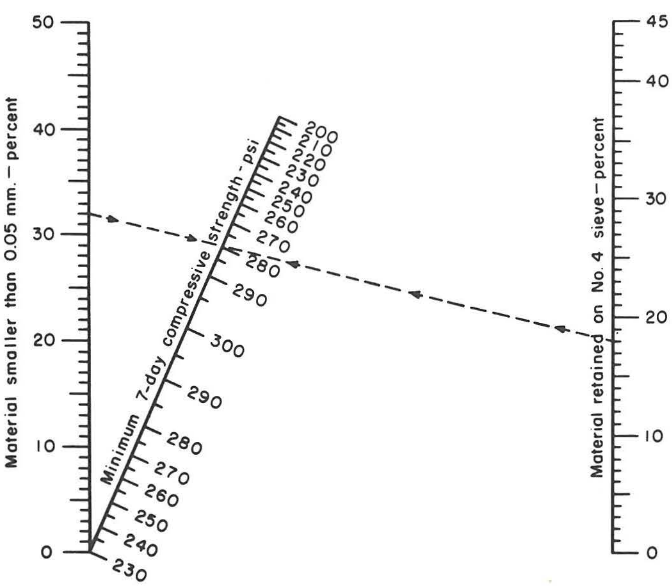


Fig. 40. Minimum 7-day compressive strengths required for soil-cement mixtures containing material retained on the No. 4 sieve.

Step 3: Using total material and 6 percent cement by weight, mold compressive-strength test specimens at maximum density (123.2 lb per cubic foot) and optimum moisture (10.2 percent).

Step 4: Determine the average 7-day compressive strength.

For this example, assume the average compressive strength to be 345 psi.

Step 5: Since the soil contains 32 percent material smaller than 0.05 mm and 18 percent material retained on the No. 4 sieve, the minimum allowable compressive strength for this soil-cement mixture is 280 psi, as shown in Fig. 40. The average compressive strength of the mixture used in this example (345 psi), as obtained in Step 4, is higher than the minimum allowable strength. Therefore, the indicated cement content of 6 percent by weight is adequate.

For field construction, Fig. 34, page 33, shows that 6 percent cement by weight is equivalent to 7.4 percent cement by volume.

If the average compressive strength in Step 4 had been lower than the minimum allowable strength, say 245 psi, 6 percent cement by weight probably would not have been adequate. Additional testing would then have been required to establish the cement requirement for the soil. These tests would involve molding and testing freeze-thaw and wet-dry test specimens according to ASTM-AASHTO procedures. Specimens containing 6 and 8 percent cement by weight would probably be adequate in this instance.

CHAPTER 7

RAPID TEST PROCEDURE

A rapid method of testing soil-cement has been used successfully for emergency construction and for very small projects where more complete testing is not feasible or practical. The engineer applying this procedure should be familiar with the details of the ASTM-AASHTO soil-cement test methods described in Chapter 3 so that he can properly interpret and evaluate the data obtained with this rapid method.

The following steps, which are described in more detail in the following paragraphs, are suggested:

1. Determine the maximum density and optimum moisture content for the soil-cement mixture.
2. Mold specimens for inspection of hardness.
3. Inspect specimens using "pick" and "click" procedures.

Moisture-Density Test

The maximum density and optimum moisture content are determined at 10 percent cement by weight by means of the standard moisture-density test procedure described in Chapter 3.

In instances where the standard mold and rammer are not available, tests can be made by using a 2-in.-diameter filled-in gas pipe of sufficient length to weigh 5.5 lb as the compacting rammer and a No. 2-1/2 tin can as the mold.

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.

Molding Specimens

Specimens for inspection of hardness are molded by the same procedure described in Chapter 3. These specimens generally contain 6, 10, and 14 percent cement by weight. It is best if these specimens can be molded in the standard mold and then removed from the mold and placed in high humidity for hydration.

However, if a standard mold is not available it is possible to mold these specimens in No. 2-1/2 tin cans, using the compacting rammer suggested above. The tin-can mold can be torn or ripped from the hardened soil-cement specimens with pliers after a few days.

Inspecting Specimens

After at least a day or two of hardening, during which they are kept moist, and after a 4-hour soaking, the specimens are inspected by "picking" with a sharp-pointed instrument and by sharply "clicking" each specimen against a hard object such as concrete to determine their relative hardness when wet.

PICK TEST

In the pick test, the specimen is held in one hand and a relatively sharp-pointed instrument, such as a dull ice pick, is lightly jabbed into the specimen (or the end of a specimen molded in a can) from a distance of two or three inches. If the specimen resists this light picking, the force of impact is increased until the pick is striking the specimen with considerable force. Specimens that are hardening satisfactorily will definitely resist the penetration of the pick, whereas specimens that are not hardening properly will resist little. 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.

CLICK TEST

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

Fig. 41. The pick test.

Fig. 42. The click test.

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

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

The above 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.

If equipment is available for making compression tests, these tests will provide further valuable data for study. It is suggested that duplicate specimens be molded and tested in compression at the age of 7 days and after a soaking in water for 4 hours. Analysis of compressive strength data is discussed in Chapter 4.

General Remarks

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

If the 10 and 14 percent specimens are apparently hardening satisfactorily and compression-test data are favorable, the project can be built using 12 percent cement by weight. If the 6 percent cement specimens are satisfactorily hardened, 8 percent cement can be used in construction.

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

In some unusual instances, the 14 percent cement specimen may not harden satisfactorily. The engineer then has two alternatives: (1) the effect of higher cement contents may be investigated; or (2) a borrow soil requiring a relatively low cement factor may be located and hauled to the runway or roadway to "cap" the poor soil. In this case, the latter procedure will generally be the more economical one.

CHAPTER 8

TESTING OF UNUSUAL SANDY SOILS

In glaciated areas in the northern United States and in the eastern and southeastern coastal areas, there are some sandy surface soils that require high cement contents as compared with average sandy soils. These soils are apparently contaminated by certain organic or other deleterious materials and are described as "slow hardening" or "poorly reacting" soils.*

Usually the subsurface soils below these poorly reacting sandy surface soils will react normally and the use of the subsurface soils is an excellent solution to the problem. However, in some cases it may not be economically feasible to use the subsurface soils for blanketing the poorly reacting surface soil or to expose them for use in grading operations. In such cases, it will generally be more economical to improve the poorly reacting surface soils.

Two methods that can be used to improve these poorly reacting sandy soils are:

1. Dilute them with an admixture of normally reacting soil, crushed limerock, limestone screenings, marl, etc.
2. Add a small percentage of calcium chloride ($CaCl_2$).**

In addition, tests may show that adding sodium chloride (NaCl) or seawater may also be effective.†

*Research conducted in the Road Research Laboratory, Great Britain, showed that the compounds of a soil's organic matter that are the most active in retarding the normal reaction of cement are the hydroxyquinone type. This research is reported in "An Investigation of Soil Organic Matter on the Setting of Ordinary Portland Cement—Chemical Studies on the Active Fraction," by V. Arkley, Research Note No. RN/3193/VA, Department of Scientific and Industrial Research, Road Research Laboratory, Hammonds-worth, Middlesex, England, Feb., 1958.

**Detailed information on the effect of soil and $CaCl_2$ admixtures on poorly reacting sandy soils is given in "Effect of Soil and Calcium Chloride Admixtures on Soil-Cement Mixtures," by M.D. Catton and E.J. Felt, *Highway Research Board Proceedings*, 1943.

†Research shows that the addition of certain sodium compounds is also effective. See "Improvement of Soil-Cement with Alkali Metal Compounds," by T.W. Lambe, A.S. Michael, and Za-Chieh Moh, *Highway Research Board Bulletin* 241, 1960.

Soil Admixtures

Generally, the admixture of one-fourth of a relatively normally reacting friable clayey soil to three-fourths of the poorly reacting sandy soil will give a mixture that will react with a normal quantity of cement. If the admixture soil is a lighter textured soil, limestone screenings, crushed lime-rock, etc., a 50-50 mixture of the soil admixture and the poorly reacting sandy soil may be required to obtain a material that will react normally. The percentage of admixture soil required will vary not only with its type and character but with the degree to which the poorly reacting sandy soil reacts with cement. Preliminary compressive-strength data for mixtures of various percentages of admixture are of immense value in determining suitable percentages.

The usual wet-dry and freeze-thaw tests are then conducted on the most economical mixture to determine the cement content that is required.

Calcium Chloride Admixture

The improvement in the cement reaction that results from the addition of small percentages of calcium chloride ($CaCl_2$) to poorly reacting sandy soils is generally outstanding. The optimum amount of $CaCl_2$ is usually from 0.6 percent to 1.0 percent by weight of dry soil.

The $CaCl_2$ may easily be added in the laboratory. Similar test results are obtained whether it is added in solution in the mixing water or added in dry form as the soil and cement are mixed together. After preliminary tests indicate a poorly reacting sand,* compressive-strength test specimens containing 0.6 per-

*A chemical test method has been developed that can be used in the laboratory or in the field to detect poorly reacting sands. This test is described in "Development of a Test for Identifying Poorly Reacting Sandy Soils Encountered in Soil-Cement Construction," by E.G. Robbins and P.E. Mueller, *Highway Research Board Bulletin* 267, 1960.

Proper and careful preparation of the calcium hydroxide solution used in this test is essential. Some revision in the test has been made to reflect experience gained since 1960. Write to the Paving and Transportation Department, Portland Cement Association.

cent calcium chloride by weight of soil and with varying cement contents by weight (usually 6, 10, and 14 percent) are generally molded. Seven-day compressive strengths will permit an estimate to be made of the required cement content of the soil with the addition of calcium chloride. Generally, soil-cement admixtures of this type that have a compressive strength of approximately 250 lb per square inch or more at 7 days will pass the wet-dry and freeze-thaw tests satisfactorily. Wet-dry and freeze-thaw test specimens are then molded at the cement content that gives adequate compressive strength and at cement contents two percentage points higher and lower than this cement content. Results of these tests will determine the cement requirement of the soil with the addition of calcium chloride.

Although the addition of calcium chloride to poorly reacting sandy soil is definitely beneficial, no advantage is obtained in the case of normally reacting soils.

On field work, the calcium chloride can be added (1) in solution as part of the water required to bring the mixture to optimum moisture content; (2) in dry form before cement is spread and then mixed with the soil along with the cement; or (3) in either solution or dry form on the day before construction as part of the prewetting operation.

CHAPTER 9

TESTING OF PLASTIC SOIL-CEMENT

The preceding discussions and explanations of soil-cement testing dealt with the soil-cement mixtures containing the optimum moisture content and compacted to maximum density as determined by the moisture-density test.

When soil-cement mixtures are used for lining irrigation canals, roadside ditches, levee slopes, and erosion-control structures with slopes steeper than about 4 to 1 and in confined areas, it may be advantageous to increase water requirements of the soil-cement mixture to form a plastic mixture so that placement of the soil-cement can be facilitated.

In this discussion, plastic soil-cement is defined as a thorough mixture of soil and portland cement combined with sufficient water to produce, at time of placing, a consistency similar to that of plastering mortar.

The lighter textured or sandy soils are the most satisfactory for plastic soil-cement mixtures. Soils that contain more than about 30 percent material passing the No. 200 sieve are generally not used; they are difficult to pulverize and because of their stickiness they are difficult to mix and place in a plastic condition.

Laboratory Procedures

The laboratory tests to determine construction-control requirements for soil-cement mixtures placed at a plastic consistency are similar to those for soil-cement mixtures placed to maximum density at optimum moisture content, determined by the moisture-density test, with modifications necessitated by the plastic consistency of the mixture.

Following are suggested modifications that have been used successfully.

ESTABLISHING CEMENT FACTORS TO BE INVESTIGATED

Suitable cement contents by weight to be used with plastic mixtures are usually about four percentage points higher than those used with soil-cement compacted with optimum moisture to maximum density. For example, assume that preliminary information indicates that the soil being investigated will require about 9 percent cement by weight for compacted soil-cement. For a soil-cement mixture at optimum moisture using this soil, a moisture-density determination would be made at 9 percent, and 7, 9, and 11 percent cement by weight would be investigated in the wet-dry and freeze-thaw tests. For a plastic soil-cement mixture using this soil, about four percentage points more of cement, or 13 percent, would probably be required to harden it adequately. Thus, the plastic moisture content and density would be determined at 13 percent, and 11, 13, and 15 percent cement by weight would be investigated in the wet-dry and freeze-thaw tests.

DETERMING THE PLASTIC MOISTURE CONTENT AND DENSITY

Quantities of soil and cement required for making the moisture-density determination on a plastic mixture, as well as for making calculations to determine the actual moisture content and density, are determined as outlined in "Determining Moisture-Density Relations of Soil-Cement Mixtures," Chapter 3, page 15, except that an allowance for soil for only one moisture sample will be needed. The density of a plastic soil-cement mixture is about 15 lb per cubic foot less than the maximum density of a compacted soil-cement mixture at the optimum moisture content.

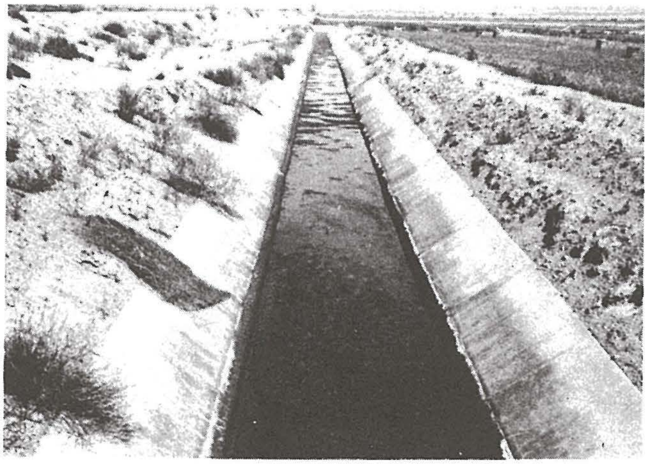


Fig. 43. Plastic soil-cement was used to line this irrigation canal at Yuma Mesa, Ariz.

The moisture content of a plastic soil-cement mixture is determined by mixing increments of water with the soil-cement mixture until the desired plastic consistency is reached. The plastic soil-cement mixture is then placed in three layers in a moisture-density mold. Each layer is compacted by rodding with a 3/4-in. bullet-nosed rod or with the fingers, and the mold containing the mixture is dropped three times on a firm foundation, from a height of 1 ft. This removes large air voids in the mixture.

A moisture sample is obtained from the soil-cement mixture at the time the second layer is being placed. The percentage of moisture and the wet weight of the specimen provide data for determining the plastic moisture content and dry density. Because this one trial furnishes all the data needed for design of the test specimens at the plastic consistency, no moisture-density curve is needed.

MOLDING WET-DRY AND FREEZE-THAW TEST SPECIMENS

Wet-dry and freeze-thaw test specimens are then molded and tested to determine the proper cement content at the plastic moisture content. These specimens are molding using the same procedure as that used in making the plastic moisture-density specimen described in the preceding paragraphs. It is usually necessary to leave the specimens in the mold overnight to permit their removal without distortion. Lubricating the inside surface area of the mold with a thin coating of petroleum jelly or similar material before molding will help in removal of the specimen the next morning.

Both the calculations for determining the quantity of soil, cement, and water needed for each specimen and the calculations for checking molded specimens are the same as those for compacted mixtures described in Chapter 3.

In some instances, a moisture content above or below that which produces the plastic consistency in the laboratory may be required during construction. In order that the cement, moisture, and density requirements of plastic soil-cement mixtures can be determined in such instances for a range of moisture contents for various field conditions, an additional set of test specimens may be molded at a moisture content one-fifth higher and another set at a moisture content one-fifth lower than the plastic moisture content.

CONDUCTING WET-DRY AND FREEZE-THAW TESTS

The plastic soil-cement specimens are subjected to the wet-dry and freeze-thaw tests, as discussed in "Conducting Wet-Dry and Freeze-Thaw Tests on Compacted Soil-Cement Specimens," Chapter 3. Soil-cement losses are calculated by the same procedure as described.

Testing Criteria

The criteria used to determine the required cement content of plastic soil-cement mixtures, using soils that contain less than 30 percent material passing the No. 200 sieve—the most desirable soils—are the same as those used for road paving (given in Chapter 5). To provide a surface more resistant to water erosion, it is recommended that the cement contents required by these criteria be increased by two percentage points. For example, when the soil-cement loss data indicate a 12 percent cement content requirement, the cement content recommended for construction becomes 14 percent.

CHAPTER 10

MODIFICATION OF SOILS WITH PORTLAND CEMENT

The foregoing discussions and explanations of soil-cement testing dealt with the addition of cement to produce a *hardened soil-cement structural material*. Cement may also be used as an admixture with soils to change their undesirable characteristics and *"modify" the soil into a more favorable construction material*. This use of cement to produce a "cement-modified" soil is applied both to silt-clay soils and to granular soils. These two applications will be discussed separately. Modification of silt-clay materials applies to soils that have such high water-holding and volume-change capacities and such low structural values that they are unsuitable for use in subgrades. Modification of granular soils is used in highway construction to increase the bearing values and reduce or eliminate plasticity, thereby providing a greatly improved base or subbase material.*

Cement-Modified Granular Soils

Cement has been used to improve bearing values of granular base and subbase materials, to reduce their plasticity, to prevent consolidation, and to produce a firm working table as a subbase. With the rapid depletion of acceptable granular materials for use as bases and subbases, it becomes even more important to conserve the remaining limited supply of acceptable materials. Submarginal granular materials, cement-modified to improve their bearing values and reduce their plasticity, will meet specifications for acceptable base and subbase materials. Consequently, the limited supply of acceptable materials can be conserved. The resulting product, however, is still primarily a granular base material with all the characteristics of that type construction. A much stronger and more durable base course can be obtained by adding the additional amount of portland cement needed to harden the material into soil-cement.

An increase in cement content of the cement-modified granular material is accompanied by an increase in strength. Any reduction in load-carrying capacity in the field at low cement contents due to weathering cycles will still result in a material having the capacity to support loads significantly greater than those that can be supported by untreated granular material of the same thickness.

Table 10 is a summary of tests run on a cement-modified chert material from Tennessee. Cement-modified soil specimens were subjected to 60 cycles of freeze-thaw testing (ASTM Designation D560, except that the specimens were not brushed) and the plasticity indexes were determined periodically. The data show that 1 percent cement by volume of the total sample reduced the plasticity index from 14 to 5 during the 7-day hydration period. The addition of 5 percent cement resulted in a completely nonplastic material. The plasticity index of the 1 percent mixture increased from 5 to 9 during the 60 cycles of freeze-thaw testing, indicating a tendency to partially revert to the original soil. The reduction in plasticity index obtained by adding 3 and 5 percent cement appears to be permanent.

The permanency of bearing values is illustrated in Table 11 for a granular soil from California. The California Bearing Ratio (hereafter referred to as "CBR") of the granular soil increased from 43 to 255 with the addition of 2 percent cement by weight, and to 485 with the addition of 4 percent cement by weight. After 60 cycles of freeze-thaw testing, the CBR of the 2 percent mixture was about the same as that at 7 days, while the 4 percent mixture increased from 485 to 574.

Cement-Modified Silt-Clay Soils

The construction engineer may at times be confronted with the problem of building pavement on clay soils of low bearing power and high volume-change characteristics. Such soils require greater thicknesses of paving to carry superimposed loads successfully and cause pavement distortion because of their volume-change characteristics brought about by changes in moisture content. Again, these soils may be present for

*Additional data on the modification of both granular and silt-clay soils and permanency of the modification is given in *Properties and Uses of Cement-Modified Soil*, published by Portland Cement Association.

Table 10. Permanency of Plasticity Index Reduction of Cement-Modified Soil*

Test Conditions	Plasticity Index, Cement content, percent by vol. 0	1	3	5
Raw soil	14	-	-	-
Lab mixture, age 7 days	-	5	4	NP
Lab mixture after 30 cycles freezing and thawing	-	8	3	NP
Lab mixture after 60 cycles freezing and thawing	-	9	1	NP

*A-2-6(0) soil from Carroll County, Tenn

Table 11. Permanency of Bearing Values of Cement-Modified Soil*

Test Conditions	California Bearing Ratio
Raw soil	43
Lab mixture, age 7 days, 2 percent cement by wt.	255
Lab mixture after 30 cycles freezing and thawing, 2 percent cement by wt.	258
Lab mixture, age 7 days, 4 percent cement by wt.	485
Lab mixture after 60 cycles of freezing and thawing, 4 percent cement by wt.	574

*A-1-b(0) disintegrated granite material from Riverside County, Calif.

Table 12. Physical Test Constants of Raw Soil and Cement-Modified Soil

	Soil A*					Soil B**							
	Raw Soil	Cement-modified soil				Raw Soil	Cement-modified soil						
Cement added by vol., percent	0	4.0	6.1	8.1	10.1	0	1/2	1	2	3	4	5†	8†
Liquid limit	45.2	42.3	41.0	39.2	38.6	54	51	48	46	45	45	45	41
Plastic limit	21.1	26.2	26.8	28.4	28.3	24	24	24	25	27	28	34	33
Plasticity index	24.1	16.1	14.2	10.8	10.3	30	27	24	21	18	17	11	8
Field moisture equivalent	28.6	31.6	31.2	32.3	33.7	31	31	31	33	32	31	37	34
$\frac{\text{Vol. at S.L.}}{\text{Vol. at F.M.E.}} \times 100$	76.4	83.6	87.4	90.7	89.5	80.2	80.4	83.3	81.8	85.9	95.2	89.6	91.6
Shrinkage limit	12.7	20.3	22.5	25.9	26.2	17	17	20	20	22	28	29	28
Shrinkage ratio	1.95	1.71	1.65	1.59	1.57	1.8	1.8	1.8	1.7	1.6	1.5	1.5	1.5
$\frac{\text{Vol. at S.L.}}{\text{Vol. at L.L.}} \times 100$	61.1	72.6	76.7	82.8	83.4	60.5	62.5	65.8	69.0	73.2	79.2	80.1	83.6

*Data from "Concrete Pavement Subgrade Design, Construction, Control," *Proceedings of 19th Annual Meeting*, Highway Research Board, 1939, page 541.

**Data from "Laboratory Investigations of Soil-Cement Mixtures for Subgrade Treatment in Kansas," *Proceedings of 17th Annual Meeting*, Highway Research Board, Part II, 1937.

†Constants determined on pulverized soil-cement mixture after cement has hydrated for 43 days; all other constants determined after cement has hydrated 7 days.

possible use in high embankments or earth dams, but because of their low strength they will introduce special design construction problems. If such soils and conditions are encountered, the soil engineer immediately surveys the surrounding territory to determine whether soils are readily and economically available that do not present these unfavorable characteristics and that can be imported to the site of the work and used instead of the poor soils.

In some areas where these poor soils are encountered, there are also favorable soils that can be used in their stead. Hence, it may not be economical or necessary to consider ways to make the poor soil better. However, there will be locations where it is cheaper, quicker, and easier to modify or improve the poor soil by adding cement.

Laboratory research and field work show that cement may be used most effectively to reduce the volume-change characteristics and to increase the load-carrying capacity of silt-clay subgrade soils.

The research tests and field work on cement-modified soils show that relatively small quantities of cement flocculate the fine soil grains, perhaps by a combination of base exchange phenomenon and cementing action, to form small conglomerate masses of new soil grains or aggregates. These new soil aggregates will have lower plasticity and volume-change characteristics than the raw soil and greater load-carrying capacity over a wider range in moisture content. The degree of modification of the soil will vary with the amount of cement added, and therefore a cement-modified soil can be produced that will have the characteristics required in volume change and load-bearing capacity for the particular structure under consideration. The effect of the cement on clay soils is best shown by two examples (see Table 12) in which various quantities of cement were added to clay soils and the effect determined by conducting the common physical tests on the cement-modified soil.

According to Table 12, the liquid limit of the Clay Soil B that requires modification is 54, the plasticity index is 30, and the shrinkage limit is 17. Various percentages of cement were added to the soil and allowed to hydrate, and the physical test constants were determined for the cement-modified soil. For the 5 percent cement mixture, the decided change in the soil is seen by the reduction in liquid limit from 54 to 45, the reduction in plasticity index from 30 to 11, and the increase in shrinkage limit from 17 to 29. Thus the soil was changed from a plastic high-volume-change soil to a low-volume-change soil of low plasticity.

Also associated with the reduction in volume change and plasticity is the relative increase in the stability of the cement-treated soil at high moisture contents. As an example, the stability of the cement-modified soil will not start decreasing until its plastic limit of 34 percent is reached.

The effect of cement on an A-7-6(14) silty clay soil from Illinois is shown in Fig. 44. It can be seen that 7 percent cement or more changes the soil from a plastic, high-volume-change soil to a relatively nonplastic, low-volume-change soil.*

Another important benefit obtained in the cement-modified soil mixture is the increase in the shrinkage limit value. The shrinkage limit is defined as the moisture content, expressed as a percentage of the oven-dry weight, at which a further reduction in moisture is not accompanied by reduction in volume. The shrinkage limit for untreated soils is commonly less than the optimum moisture content. This implies that a soil placed at optimum moisture will shrink or swell if allowed to dry or increase in moisture significantly. Extreme changes in moisture content of expansive soils are kept to a minimum by compacting the soil at a moisture content slightly above optimum moisture since the permeability of cohesive soils is at a minimum at this moisture content.

In contrast, the addition of cement generally increases the shrinkage limit to values greater than optimum moisture content. For example, the addition of 5 percent cement of an A-7-6(17) Texas clay* increased shrinkage limit from 10 to 36,. indicating a substantial reduction in potential volume change.

The preceding discussion is based on the assumption that the cement-modified soil will actually function as a soil. In practice, however, the cement-soil mixture is mixed to optimum moisture content and compacted to maximum density during construction; and as the cement hydrates, a semihardened soil-

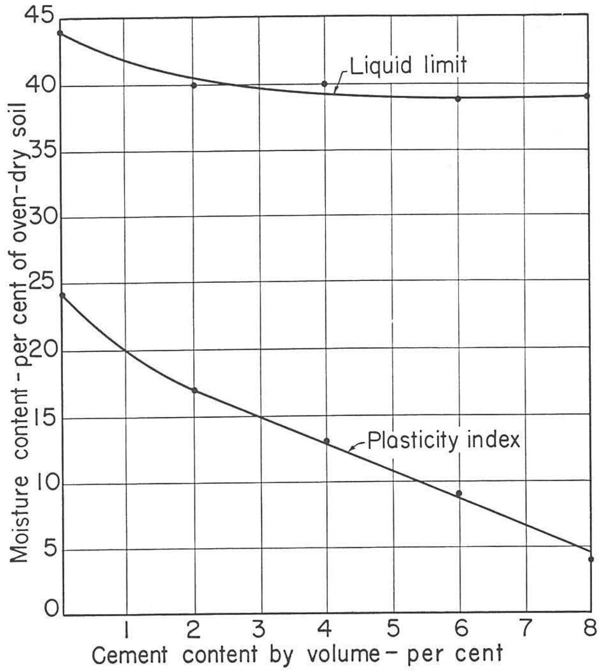


Fig. 44. Change in physical test constants of an A-7-6(14) silty clay soil from Illinois with the addition of cement.

Table 13. Permanency of Cement-Modified Soil*

Test Conditions	Plasticity index
Raw soil	28-1/2
Lab mixture, 7 percent cement by volume	14-1/2
Field mixture after construction, 7 percent cement by vol.	10-1/2
Field mixture after 6 years of service, 7 percent cement by volume	5-11

*An A-7 clay from Comanche County, Okla.

*Additional information on cement-modified silt-clay soils is given in "Cement Modification of Clay Soils," by A.P. Christensen, published by Portland Cement Association. This report contains data showing the improvement of liquid limit, plastic limit, plasticity index, and shrinkage limit properties of 11 clay soils. Data on the improvement in strength as measured by the cohesiometer and by unconfined and triaxial compressive strength tests are also included.

Table 14. Plasticity Index After 1 and 24 Hours

Soil no.	Cement added, percent	Delay period, hr.	Plasticity index
2	3	1	11
	3	24	7
	0	24	19
3	3	1	10
	3	24	7
	0	24	29
6	3	1	11
	3	24	10
	0	24	18
8	3	1	5
	3	24	3
	0	24	18

Table 15. Plasticity Index After 24 and 48 Hours

Soil no.	Cement added, percent	Delay period, hr.	Plasticity index
1	0	24	33
	5	24	24
	5	48	18
5	0	24	32
	5	24	13
	5	48	10
9	0	24	36
	5	24	22
	5	48	14
10	0	24	41
	5	24	33
	5	48	23

cement mixture results. If the cement-modified soil is being used under a pavement to control the volume-change characteristics of the subgrade and prevent pavement distortion, it will be on this semihardened soil-cement that the pavement will be laid. Thus, for an indeterminate time, depending on the severity of weathering agencies, the cement-modified soil will serve as a semihardened soil-cement mixture that has inherent stability much greater than the soil itself. Because the semihardened soil-cement has very low permeability, it will prevent uneven entrance of moisture into the subgrade, and thus pavement distortion by subgrade swell will be controlled. Furthermore, the slow absorption of water by the semihardened soil-cement slab will not be detrimental since the cement-modified soil will possess very low volume-change characteristics.

As the semihardened soil-cement slab weathers and disintegrates into a granular mass, it will start to function as a soil with low-volume-change characteristics and increased load-carrying capacity comparable to subgrade soils that have given satisfactory service. It is at this time that the action of the cement-modified soil will be predicated on the physical test constants as previously discussed.

Laboratory research and field work indicate that the modification obtained with cement is permanent and that the soil does not revert to a material that has the properties of the original soil.

The data in Table 13 are also examples of the permanency of cement modification. These data were obtained on an experimental cement-modified soil subgrade for a concrete pavement project built by the Oklahoma Highway Department in 1938. According to Table 13, the cement-modified soil has a plasticity index of 10-1/2 after construction. Six years later the plasticity index ranged from 5 to 11, based on a number of tests. Thus, after six years the plasticity indexes had either remained about the same or had shown further reduction. Tests were performed again in 1983 and showed the same conclusions after 45 years of service; this is reported in "Performance of Cement-Modified Soils, A Follow-Up Report," by John D. Roberts, *Transportation Research Record 1089*, Transportation Research Board, 1986.

Modification of silt-clay applies to subgrade materials and similar uses only and is not recommended for base construction. Experience has shown that the modified silt-clay material is not satisfactory for bases.

Laboratory Tests

All types of soils can be improved by cement-treatment, the amount of improvement depending upon the amount of cement added. The amount of cement required for construction can be determined by tests that measure increase in strength, reduction in volume change, and plasticity, using criteria based on the standards set for untreated materials.

Increase in strength or bearing can be measured by a number of tests such as unconfined compressive strength, triaxial compressive strength, cohesiometer, stabilometer, CBR, and load-deflection tests. Moisture-density relations are first determined at the median cement content that will be investigated. Specimens for the strength tests to be used are then molded at maximum density and optimum moisture content. The specimens are molded immediately after mixing the cement-soil-water mixture or after a delay period such as 24 hours. During the delay period, the mixture is stored at about 73 deg F and remixed just before molding. Any water lost during the delay period is replaced. All the test specimens are molded at about 73 deg F and placed in a moist room or in polyethylene bags until tested at 7, 28, or 90 days after molding.

Samples for liquid, plastic, and shrinkage-limit tests are prepared by mixing cement with the fraction of soil passing the No. 40 sieve. The cement contents investigated will usually vary by 2 percentage points by dry weight of soil. Sufficient water is added to each sample and mixed to obtain a uniform moisture content slightly greater than the plastic limit. After a delay period of 1, 24, 48 hours or longer, the mixture is washed over a No. 40 sieve. The material passing the sieve is allowed to settle in a pan and the clear water is then siphoned off.

Either of two methods can be used to dry the cement-soil mixtures prior to running the liquid, plastic, and shrinkage-limit tests:

1. Dry the sample at 140 deg F and reduce by a mortar and rubber-covered pestle so that it passes a No. 40 sieve. Water is then added as needed to perform the liquid, plastic, and shrinkage-limit tests. Or,
2. After siphoning off the clear water, place the mixture in a plaster of Paris absorption dish until excess water is absorbed and the liquid, plastic, and shrinkage-limit tests can be run.

Raw soil samples containing no cement for liquid, plastic, and shrinkage-limit tests can be prepared by washing a representative sample over a No. 40 sieve and drying the soil either in the 140 deg F oven or in the absorption dish. The oven-dried soil is pulverized with mortar and rubber-covered pestle to pass the No. 40 sieve.

The liquid, plastic, and shrinkage-limit values obtained from samples dried in the absorption dish may vary from the values obtained from the oven-dried samples. It is believed that the absorption dish method of drying provides data more representative of field conditions.

In many cases, the liquid, plastic, and shrinkage-limit tests are run on cement-modified soil mixtures that have hydrated for 7 days. However, data indicate that much of the improvement in the soil takes place rapidly and time can be saved by running the tests after a shorter delay period such as 1, 24, or 48 hours. Of course, improvement will continue to take place in the field over a longer period of time because of additional cement hydration.

Plasticity index value for four clayey soils after 1- and 24-hour delay periods are given in Table 14.* The addition of 3 percent cement produced a reduction in plasticity index after 1 hour nearly as great as the reduction after 24 hours.

Table 15 compares plasticity index values for 4 soils after 24- and 48-hour delay periods.*

Volume-change characteristics of a soil or cement-modified soil mixture can also be measured by tests such as AASHTO T116, "Determination of Volume Change of Soils." This method covers tests of undisturbed soil at natural moisture content and density and samples molded at one or more moisture contents and densities to satisfy the purposes for which the tests are made.

Summary

Sufficient data are available to prove that cement may be used effectively to reduce the volume-change characteristics and to increase the load-carrying capacity of "poor" soils. Data also show that the modification is permanent under the weathering cycles in the field.

The modification of silt-clay soils will effectively reduce their volume-change characteristics and increase their load-carrying capacity, thereby making them better subgrade materials. The modified silt-clay material, however, is not satisfactory for bases.

The modification of granular soils will effectively improve their bearing values and reduce their plasticity, thus making them acceptable base and subbase materials. However, the use of regular hardened soil-cement, involving only a small additional amount of cement, may be more economical and satisfactory in the long run and its use should also be investigated.

*Data from Christensen, *Cement Modification of Clay Soils*, see footnote on page 46.

APPENDIX

Laboratory Equipment Requirements for Soil and Soil-Cement Tests

This selective list of equipment is intended only as a reasonable guide. Exact prices on the equipment can be obtained from the manufacturers.

The quantities of equipment given are sufficient to keep two laboratory men busy.

As the personnel is increased, the equipment items that are listed as Nos. 1, 4, 5, 6, 7, 14, 16, 17, and 18 will need to be increased to maintain the efficiency of operations.

Most laboratories, such as state highway department laboratories and large private laboratories, will have much of this equipment on hand. Laboratories of this type will also find it to their advantage to purchase more permanent and efficient equipment than that covered by Nos. 14, 15, and 16.

Item No.	Quantity	Description
1	1	Moisture-density mold and sleeved rammer
2	1	Hydraulic jack and piston equipment*(for removing soil-cement specimens from mold. See Fig. 19 .)*
3	1	12-in. steel straightedge
4	1	10-in. butcher knife
5	1	10-in. mason's trowel
6	1	3x4-ft., 8-gage steel sheet *(mixing table)*
7	72	Moisture cans
8	2	500-ml graduates
9	2	250-ml graduates
10	2	100-ml graduates
11	1	Balance with weights, 1,000-g capacity, sensitive to 1/10 g
12	1	Scale with weights, 20-lb capacity, sensitive to 1/100 lb
13	1	Drying oven thermostatically controlled *(for dehydrating moisture samples)*
14	1	Two-burner gas stove, or equivalent, with oven *(for drying molded specimens in wet-dry tests; capacity: 12 standard specimens)*
15	1	Two-burner oven *(extra drying capacity on gas range; capacity: 12 specimens)*
16	1	Two-hole ice cream storage cabinet or deep freeze unit *(for freezing freeze-thaw specimens; capacity: 15 standard specimens)**
17	4	Metal moist-storage boxes, 12x12x48 in with cover *(for 7-day preparation of specimens and thawing freeze thaw specimens)*
18	12	Specimen holders *(for fragile specimens during hydration period, see Fig. 20. Large carriers can be used for handling specimens during test. See Fig. 27)*
19	1	Water tank *(for soaking speciments in wet-dry test)*
20	1	Scarifier *(for removing compaction planes when molding test specimens)*
21	1	Set of sieves: 3/4 in., No. 4, No. 10, No. 40, No. 60, No. 200; cover, pan—8 in. round. Also include No. 4 and 3/4-in. sieves having diameters of about 24 in., for preparing large samples.
22	3	Two thermometers, 0 deg to 250 deg F; and one, 0 deg to 200 deg C
23	1	Liquid-limit device and grooving tool
24	1	High-speed dispersion machine*(for soil dispersion in hydrometer grain-size test)*
25	1	Dispersion cup *(for hydrometer grain-size test)*
26	1	Hydrometer
27	1	Hydrometer jar constant temperature bath *(not thermostatically controlled)*
28	1	Mortar and pestle set
29	6	Hydrometer jars *(sedimentation cylinder, see ASTM D422)*
30	2	Wire brushes for use in wet-dry and freeze thaw test *(Brush consists of 2x1/16-in. flat No. 26 gage wire bristles assembled in 50 groups of 10 bristles each and mounted to form 5 longitudinal rows and 10 transverse rows of bristle groups on a 7-1/2x2-1/2-in. hardwood block. See Fig. 25)*
31		Miscellaneous: shovel, pails, pans, table brush, chemical supplies, etc.

*Size of freezing unit will depend on volume of work.

Soil and Soil-Cement Form Sheets

Form Sheet No.	Field of Use
1	Grain-size analysis of soil
1A	Grain-size curve of soil
2	Physical test constants of soil
3	Moisture-density test of soil-cement mixtures
4	Compressive-strength tests using 2-in.-diameter, 2-in.-high specimens
5	Compressive-strength tests using 4-in.-diameter, 4.6-in.-high specimens
6	Molding wet-dry and freeze-thaw wet specimens
7	Wet-dry test
8	Freeze-thaw test
9	Inspection of wet-dry and freeze-thaw test specimens
13	Summary of soil and soil-cement tests
14	Summary of exploratory tests

Soil-Cement Laboratory, Form Sheet No. 1

GRAIN SIZE ANALYSIS OF SOIL

Date______________ Soil No.__________

TOTAL FIELD SAMPLE ANALYSIS

Air dry wt. sample, lb._____*
Retained on ¾" sieve_____lb.,_____%
Retained on No. 4 sieve_____lb.,_____%

*Includes only material smaller than 3".
Note:_____lb. retained on 3" sieve.
Place No. 4 to ¾", and ¾" plus material in separate containers.

ANALYSIS OF MATERIAL PASSING NO. 4 SIEVE

Wt. retained on No. 10 sieve, gm._________
Wt. passing No. 10 sieve, gm._________
Wt. passing No. 10 sieve, corrected for hygroscopic, gm._________
Total wt. of sample, gm._________
Per cent of total sample passing No. 4 sieve_________
Per cent of total sample passing No. 10 sieve_________

ANALYSIS OF MATERIAL PASSING NO. 10 SIEVE

HYGROSCOPIC MOISTURE DETERMINATION

Wt. air dry soil + can _____gr.
Wt. oven dry soil + can _____gr.
Moisture loss _____gr.
Weight of can No.___ _____gr.
Wt. oven dry soil _____gr.
Hygroscopic moisture _____%
Wt. air-dry soil for analysis, gr.____
Wt. corrected for hygroscopic, gr.____

SIEVE ANALYSIS

Fraction from hydrometer analysis — Sieve sizes	Cumulative total retained on each sieve — gr.	Cumulative total retained on each sieve — %	Per cent passing, soil mortar
10 (2.0 mm.)			
40 (0.42 mm.)			
60 (0.25 mm.)			
200 (0.074 mm.)			

HYDROMETER ANALYSIS

Time interval, minutes	Observed time	Temperature °F	Temperature Correction	Hydrometer Reading	Hydrometer Corrected	Theo. grain size, mm.	Corrected grain size, mm.	Per cent smaller
1						0.078		
2						0.055		
5						0.035		
15						0.020		
30						0.014		
60						0.010		
250						0.005		

GRADATION
Per cent passing

	Total sample	Soil mortar
3" sieve	____	
¾" sieve	____	
No. 4 sieve	____	
No.10 sieve	____	100
No.18 sieve	____	____
No.35 sieve	____	____
No.40 sieve	____	____
No.60 sieve	____	____
No.140 sieve	____	____
NO.200 sieve	____	____
0.05mm.	____	____
0.005mm.	____	____
0.002mm.	____	____

U.S.D.A. SOIL SEPARATES

_____% gravel
_____% very coarse sand
_____% coarse sand
_____% medium sand
_____% fine sand
_____% very fine sand
_____% silt
_____% clay

COLOR
____

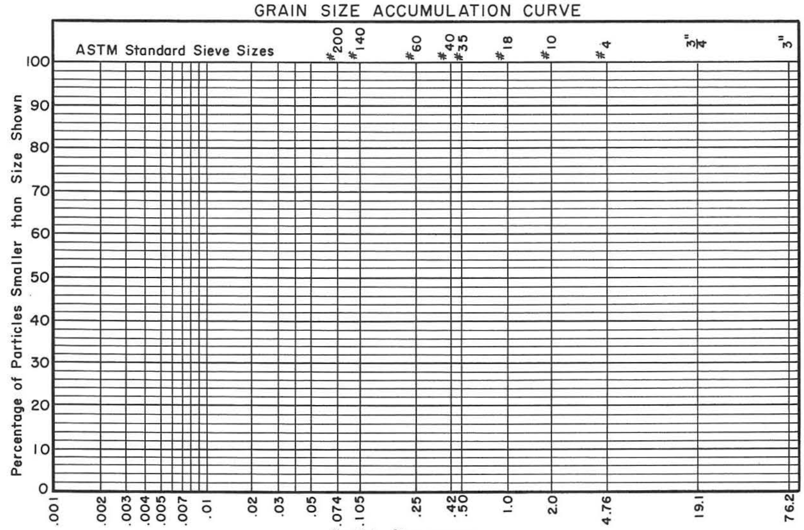
U.S.D.A. TEXTURAL CLASS
____

A.A.S.H.O. SOIL CLASS
A-__________

Form Sheet No. 1. Grain-size analysis of soil.

Soil-Cement Laboratory Form Sheet No. 1A

GRAIN SIZE ACCUMULATION CURVE



U.S. DEPT. OF AGRICULTURE SOIL SEPARATE SIZE LIMITS

Clay	Silt	Sand: Very Fine	Sand: Fine	Sand: Medium	Sand: Coarse	Sand: Very Coarse	Gravel
-.002	.002 – .05	.05-.1	.1-.25	.25-.5	.5-1.0	1.0-2.0	2.0 – 76.2

U.S. Dept. of Agriculture Textural Class __________ PCA Soil No. __________
A.A.S.H.O. Soil Class __________ PCA Project No. __________

Form Sheet No. 1A. Grain-size curve of soil.

Soil-Cement Laboratory, Form Sheet No. 2

Soil No. ______

Operator ______

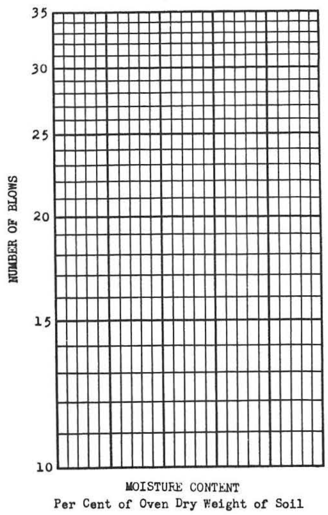
Date ________

PHYSICAL TEST CONSTANTS OF SOILS

LIQUID LIMIT DETERMINATION
with liquid limit machine

Determination No.	1	2	3	4
Can No.				
Wt. of can & wet soil, gr.				
Wt. of can & dry soil, gr.				
Moisture loss, gr.				
Wt. of can, gr.				
Wt. of dry soil, gr.				
Moisture content, %				
No. blows				

LIQUID LIMIT GRAPH



PLASTIC LIMIT DETERMINATION

Determination No.	1	2
Can No.		
Wt. of can & wet soil, gr.		
Wt. of can & dry soil, gr.		
Moisture loss, gr.		
Wt. of can, gr.		
Wt. of dry soil, gr.		
Plastic limit, %		
Av. plastic limit, %		

Color of moist soil ________

SUMMARY OF
PHYSICAL TEST CONSTANTS

Liquid limit, ____________________
Plastic limit, ____________________
Plasticity index, ____________________

Form Sheet No. 2. Physical test constants of soil.

Soil-Cement Laboratory, Form Sheet No. 3

MOISTURE-DENSITY RELATIONS OF SOIL-CEMENT MIXTURES

DATA ON SOIL NO. ________

AASHO Soil Group________

Material Retained on No. 4 Sieve
________% Absorption________%

Material Passing No. 4 Sieve
Hygroscopic Moisture________%

Cement Content to Use________%

QUANTITIES FOR MOISTURE-DENSITY TEST

Total Oven-dry Soil________lb.*

Material Retained on No. 4 Sieve
Oven-dry________lb.
Saturated, Surface Dry________lb.**

Material Passing No. 4 Sieve
Oven-dry________lb.
Air-dry________lb.**

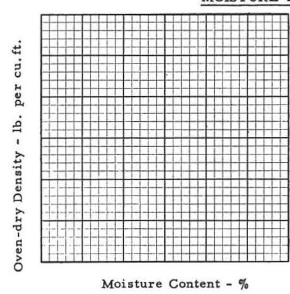
Cement________lb. or ________grams**

DATA FROM MOISTURE-DENSITY TEST

Tare________lb. Operator________ Date________

Trial No.	Wet wt. spec. plus mold, lb.	Wet wt. spec. lb.	Moisture Determination: Can No.	Wet soil + can, gr.	Dry soil + can, gr.	Wt. can, gr.	Moisture loss, gr.	Dry wt. soil, gr.	Moisture, %	Wet wt. lb. per cu. ft.	Dry wt. (density) lb. per cu. ft.
1											
2											
3											
4											
5											

MOISTURE-DENSITY RELATIONS



Maximum Density =________lb. per cu. ft.
Optimum Moisture =________% at
________% cement by wt.

*Use 11.0 lb. when soil contains material retained on No. 4 sieve; use 6.0 lb. when it contains none of this material.
**To be weighed out for running test.

Form Sheet No. 3. Moisture-density test of soil-cement mixtures.

Soil-Cement Laboratory, Form Sheet No. 4

DESIGN AND MOLDING 2" dia., 2" high COMPRESSIVE STRENGTH SPECIMENS

DATA ON SOIL NO. ________

Maximum Density ________ lb. per cu. ft.

Optimum Moisture ________ %

Hygroscopic Moisture Content ________ %

QUANTITIES FOR MOLDING SPECIMENS*

Oven-dry Soil ________ grams.

Air-dry Soil ________ grams.**

Wt. of Soil-Cement at optimum moisture for one spec. ________ grams.**

Cement by wt. %	Cement for batch, grams **	Oven-dry S+C, grams	Water for batch				
			Theo. ml	Hygroscopic moist. in soil, ml	Evaporation		Net ml **
					%	ml	

*Vol. of cylinders is 6.2832 cu.in.; conversion factor to change wt. of cylinders in grams to lb. per cu.ft. is 0.6063.
**To be weighed out for molding specimens.

DATA FROM MOLDED SPECIMENS

Operator ________ Date ________

Cement content, % by wt.	Wet wt. spec. gr.	Moisture Determination							Density, lb. per cu. ft.
		Can No.	Wet Soil + can, gr.	Dry Soil + can, gr.	Wt. can, gr.	Mois-ture loss, gr.	Dry Wt. soil, gr.	Moisture content, %	

← *Front*

Form Sheet No. 4. Compressive-strength tests using 2-in.-diameter, 2-in.-high specimens.

Reverse →

Soil-Cement Laboratory Form Sheet No. 4 (Cont'd.)

DETERMINATION OF COMPRESSIVE STRENGTH

Cement content, % by wt.												
Total load, lb.												
Ave. unit load, psi												
Age, days												

Cylindrical specimens 2" dia., 2" ht. submerged in water 1 hr. before testing

Soil-Cement Laboratory, Form Sheet No. 5

DESIGN AND MOLDING 4" dia., 4.6" high COMPRESSIVE STRENGTH SPECIMENS

DATA ON SOIL NO.________

Maximum Density________lb. per cu. ft.

Optimum Moisture________%

Material Retained on No. 4 Sieve
________% Absorption________%

Material Passing No. 4 Sieve
Hygroscopic Moisture________%

QUANTITIES FOR MOLDING SPECIMENS

Total Oven-dry Soil________lb.

Material Retained on No. 4 Sieve
Oven-dry________lb.
Saturated, Surface Dry________lb.*

Material Passing No. 4 Sieve
Oven-dry________lb.
Air-dry________lb.*

Cement Content			Total	Mat'l.	Water for batch					
by wt. %	Batch lb.	Batch grams *	Oven-dry soil + cement, lb.	pass. No. 4 + cement, lb.	Theo. ml	Abs. mat'l. ret. on No.4, ml	Hygro. moist., mat'l. pass. No. 4, ml	Evaporation %	Evaporation ml	Net ml *

*To be weighed out for molding specimens

DATA FROM MOLDED SPECIMENS

Tare________ Operator________ Date________

Cement Content % by wt.	Wet wt. spec. plus mold, lb.	Wet wt. spec. lb.	Moisture Determination: Can No.	Wet soil + can gr.	Dry soil + can gr.	Wt. can gr.	Moisture loss gr.	Dry wt. soil gr.	Moisture %	Density lb. per cu. ft.

← *Front*

Form Sheet No. 5. Compressive-strength tests using 4-in.diameter, 4.6-in.high specimens.

Reverse →

Soil-Cement Laboratory Form Sheet No. 5 (Cont'd.)

DETERMINATION OF COMPRESSIVE STRENGTH

Cement content, % by wt.												
Total load, lb.												
Ave. unit load, psi												
Age, days												

Cylindrical specimens 4" dia., 4.6" high submerged in water 4 hrs. before testing.

Soil-Cement Laboratory, Form Sheet No. 6

DESIGN AND MOLDING WET-DRY AND FREEZE-THAW TEST SPECIMENS

DATA ON SOIL NO. ________

Maximum Density________lb. per cu. ft.

Optimum Moisture________%

Material Retained on No. 4 Sieve
________% Absorption________%

Material Passing No. 4 Sieve
Hygroscopic Moisture________%

QUANTITIES FOR MOLDING SPECIMENS

Total Oven-dry Soil________lb.

Material Retained on No. 4 Sieve
Oven-dry________lb.
Saturated, Surface Dry________lb. *

Material Passing No. 4 Sieve
Oven-dry________lb.
Air-dry________lb. *

Cement Content			Total	Mat'l.	Water for batch					
by wt. %	Batch lb.	Batch grams *	Oven-dry soil + cement, lb.	pass. No. 4 + cement, lb.	Theo. ml	Abs. mat'l. ret. on No.4, ml	Hygro. moist., mat'l. pass. No. 4, ml	Evaporation %	Evaporation ml	Net ml *

*To be weighed out for molding specimens

DATA FROM MOLDED SPECIMENS

Tare________ Operator________ Date________

Cement content % by wt.	Wet wt. spec. plus mold, lb.	Wet wt. spec. lb.	Moisture Determination							Density lb. per cu. ft.
			Can No.	Wet soil + can gr.	Dry soil + can gr.	Wt. can gr.	Moisture loss gr.	Dry wt. soil gr.	Moisture %	

Form Sheet No. 6. Molding wet-dry and freeze-thaw test specimens.

Soil-Cement Laboratory, Form Sheet No.7

WETTING-DRYING TEST OF COMPACTED SOIL-CEMENT MIXTURES

Soil No. ________ Date Molded________

Cement content, % by wt.			
Initial moisture content, %			
Initial calculated oven-dry wt.,lb.			
Final oven-dry wt.,lb.*			
Final corrected oven-dry wt.,lb.**			
Soil-cement loss, %			

*After 12 cycles of testing and after drying to constant wt. at 110° C.
**After correcting for water of hydration.(______%)

SCHEDULE FOR SPECIMENS DURING TEST

Date	Remove from oven & brush	Cycles completed	Place to soak	Place in oven 160°F.	Remarks
		start of test			
		1			
		2			
		3			
		4			
		5			
		6			
		7			
		8			
		9			
		10			
		11			
		12			

Form Sheet No. 7. Wet-dry test.

Soil-Cement Laboratory, Form Sheet No. 8

FREEZING-THAWING TEST OF COMPACTED SOIL-CEMENT MIXTURES

Soil No. ________ Date Molded______

Cement content, % by wt.			
Initial moisture content, %			
Initial calculated oven-dry wt., lb.			
Final oven-dry wt., lb.*			
Final corrected oven-dry wt., lb.**			
Soil-cement loss, %			

*After 12 cycles of testing and after drying to constant wt. at 110° C.
**After correcting for water of hydration. (_____%)

SCHEDULE FOR SPECIMENS DURING TEST

Date	Remove from moist room & brush	Cycles completed	Place in refrigerator, -10°F.	Date	Remove from refrig. & place in moist room	Remarks
		start of test				
		1				
		2				
		3				
		4				
		5				
		6				
		7				
		8				
		9				
		10				
		11				
		12				

Form Sheet No. 8. Freeze-thaw test.

Soil-Cement Laboratory, Form Sheet No. 9

REPORT OF INSPECTION OF SOIL-CEMENT
FREEZE-THAW AND WET-DRY TEST SPECIMENS AT THE
COMPLETION OF 12 CYCLES OF TEST

Name of Project________________________

Field Project No.______ Soil No.________ Specimen No.__________

CONDITION OF FREEZE-THAW SPECIMENS

Cement Content of Specimens Molded_____, _____, __________

Scaling ________________________

Cracking ________________________

Hardness ________________________

____

Apparent Cement Requirements*________________________

Miscellaneous________________________

CONDITION OF WET-DRY SPECIMENS

Cement Content of Specimens Molded_____, _____, __________

Scaling ________________________

Cracking ________________________

Hardness ________________________

Apparent Cement Requirement*________________________

Miscellaneous________________________

*See Soil-Cement Laboratory Form Sheet No. 13 for final cement recommendations based on test data.

Inspection by__________

Date__________

Form Sheet No. 9. Inspection of wet-dry and freeze-thaw test specimens.

Soil-Cement Laboratory, Form Sheet No. 13 — Date tests completed____________

SUMMARY OF TESTS ON SOIL-CEMENT MIXTURES
PORTLAND CEMENT ASSOCIATION

State____________ Project ____________________ PCA Soil No.____________

County____________ ____________________ Field Project No.____________

Sampling location____________________

GRADATION

Per cent passing	Soil mortar	Total sample
3-in. sieve		______
¾-in. sieve		______
No. 4 sieve (4.76 mm.)		______
No. 10 sieve (2.00 mm.)	100	______
No. 18 sieve (1.00 mm.)	______	______
No. 35 sieve (0.50 mm.)	______	______
No. 40 sieve (0.42 mm.)	______	______
No. 60 sieve (0.25 mm.)	______	______
No. 140 sieve (0.105mm.)	______	______
No. 200 sieve (0.074mm.)	______	______
Per cent smaller than		
0.05 mm.	______	______
0.005mm.	______	______
0.002mm.	______	______

U.S. DEPT. OF AGRICULTURE SOIL CLASSIFICATION

Soil series____________
Soil horizon____________
Textural class____________
Color of moist soil____________

PHYSICAL TEST CONSTANTS

L. L.__________
P. I.__________

AASHO SOIL CLASSIFICATION

A -

COMPRESSIVE STRENGTH, psi*

Cement content, % by wt.	Age when tested, days: two	seven	twenty-eight

*Specimens saturated in water before testing

DATA FROM WET-DRY AND FREEZE-THAW SPECIMENS

Cement content % by wt.	Total soil-cement loss, %: Wet-Dry	Freeze-Thaw

MATERIAL RETAINED ON NO. 4 SIEVE

Absorption, %____________
Bulk sp. gravity____________

RECOMMENDATIONS

Recommended cement content____________% by volume (______% by weight)
which is____________lb. per sq. yd. per inch of compacted thickness.
Laboratory optimum moisture content**____________%
Laboratory maximum density**____________lb. per cu. ft.

Tests made on total sample using ¾ in. maximum size material.

**Moisture-density test made during construction govern field control.

Remarks:____________________

Form Sheet No. 13. Summary of soil and soil-cement tests.

Soil-Cement Laboratory, Form Sheet No. 14 — Date of Tests____________

SUMMARY OF EXPLORATORY TESTS
ON SOIL AND SOIL-CEMENT MIXTURES
PORTLAND CEMENT ASSOCIATION

State____________ Project____________

County____________

P.C.A. Soil No.	GRADATION - Per cent smaller than: 3"	¾"	No. 4	No. 10	No. 18	No. 35	No. 40	No. 60	No. 140	No. 200	.05 mm.	.005 mm.	.002 mm.	TEST CONSTANTS: L.L.	P.I.	AASHO SOIL CLASS	OPTIMUM MOISTURE %	MAXIMUM DENSITY lb/cu.ft.

P.C.A. Soil No.	U.S.D.A. SOIL CLASSIFICATION: Soil Series	Hor-izon	Textural Class	Color of moist soil

COMPRESSIVE STRENGTH - lb./sq. in.: Two	Seven	Twenty-eight
Cement content by weight - %		

P.C.A. Soil No.	Field Soil No.	Sampling Location	Estimated cement requirement, % by vol.

Form Sheet No. 14. Summary of exploratory tests.

Textural Classification System—U.S. Department of Agriculture

Basic textural groups based on particles smaller than 2 mm in diameter, as used in the Department of Agriculture Textural Classification System, are given in Fig. 45. Subdivisions of the sand, loamy sand, and sandy loam basic groups can be determined from Table 16 (page 58). The terminology size limits of the soil separates used are:

Very coarse sand:	2.0 mm to 1.0 mm (No. 10 sieve to No. 18 sieve)
Coarse sand:	1.0 mm to 0.5 mm (No. 18 sieve to No. 35 sieve)
Medium sand:	0.5 mm to 0.25 mm (No. 35 sieve to No. 60 sieve)
Fine sand:	0.25 mm to 0.1 mm (No. 60 sieve to No. 140 sieve)
Very fine sand:	0.1 mm to 0.05 mm (No. 140 sieve to No. 270 sieve)
Silt:	0.05 mm to 0.002 mm
Clay:	0.002 mm to 0.0 mm

The soil group is given a "gravelly" prefix if it contains 20 percent or more gravel (material retained on No. 10 sieve). The basic soil textural class name, however, is based on the size distribution of the material smaller than 2 mm in diameter. Therefore, the percentages of each of the soil separates are met after the gravel material has been excluded.

More detailed information on this testural classification system is given in *PCA Soil Primer*, published by Portland Cement Association.

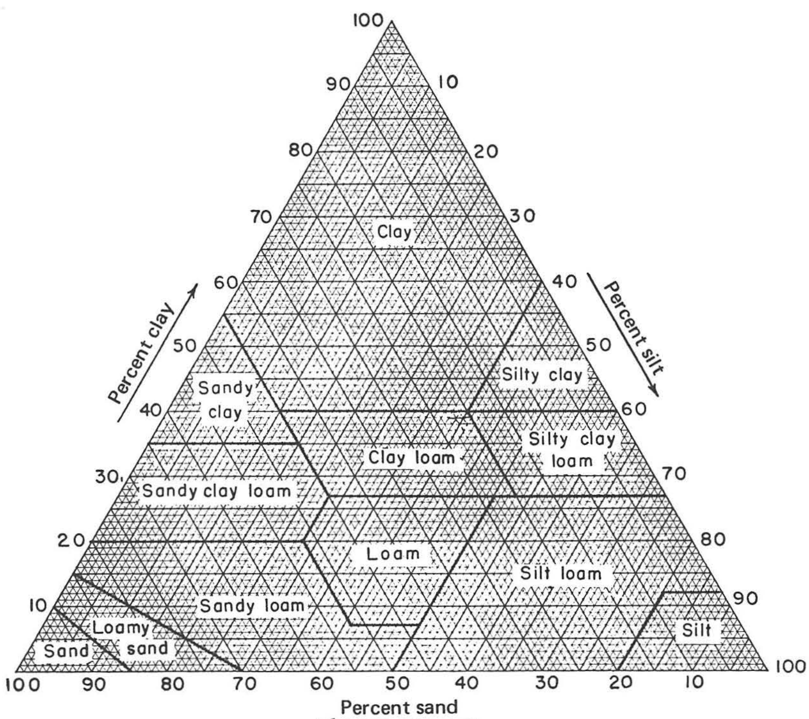


Fig. 45. The U.S. Department of Agriculture Textural Classification Chart (2-micron clay). From Soil Survey Manual, U.S. Department of Agriculture Handbook No. 18, 1951.

Table 16. Percentage of Sand Sizes in Subclasses of Sand, Loamy Sand and Sandy Loam Basic Textural Classes

		Soil separates				
Basic soil class	Subclass	Very coarse sand, 2.0-1.0 mm.	Coarse sand, 1.0-0.5 mm.	Medium sand, 0.5-0.25 mm.	Fine sand, 0.25-0.1 mm.	Very fine sand, 0.1-0.05 mm.
Sands	Coarse sand	25% or more		Less than 50%	Less than 50%	Less than 50%
	Sand	25% or more			Less than 50%	Less than 50%
	Fine sand	Less than 25%		—or—	50% or more	Less than 50%
	Very fine sand					50% or more
Loamy sands	Loamy coarse sand	25% or more		Less than 50%	Less than 50%	Less than 50%
	Loamy sand	25% or more			Less than 50%	Less than 50%
	Loamy fine sand	Less than 25%		—or—	50% or more	Less than 50%
	Loamy very fine sand					50% or more
Sandy loams	Coarse sandy loam	25% or more		Less than 50%	Less than 50%	Less than 50%
	Sandy loam	30% or more; Less than 25%		—and—	Less than 30%	Less than 30%
	Fine sandy loam	—or— Between 15 and 30%			30% or more	Less than 30%
	Very fine sandy loam	Less than 15%		—or—	More than 40%*	30% or more

* One half of fine sand and very fine sand must be very fine sand.

Soil Classification System—American Association of State Highway and Transportaion Officials

These tables and charts are from AASHTO Designation M145, Recommended Practice for the Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes.

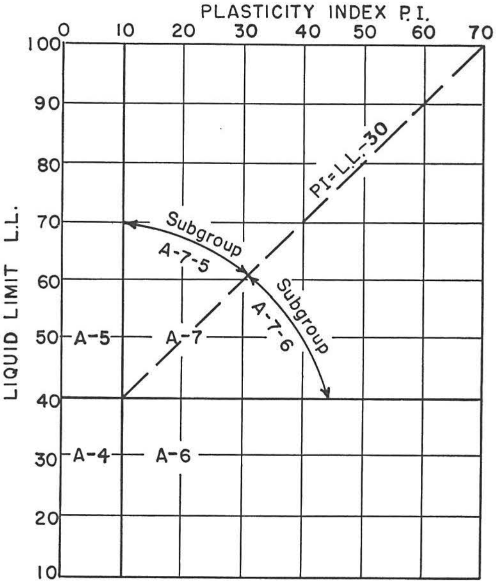


Fig. 46. Liquid-limit and plasticity-index ranges for the A-4, A-5, A-6, and A-7 subgrade groups.

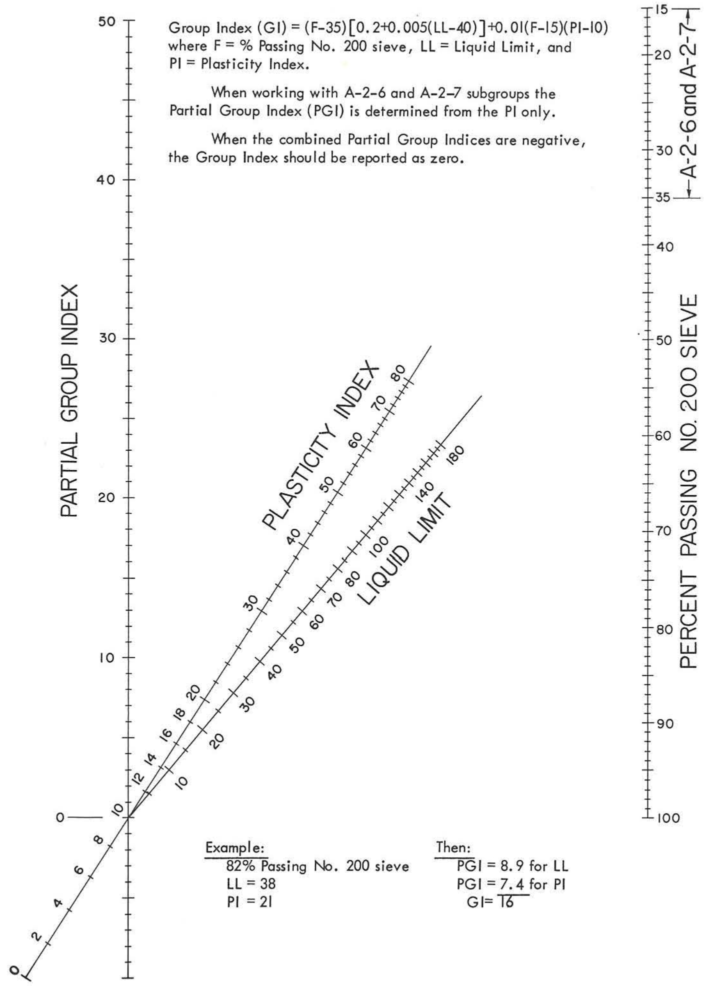


Fig. 47. Group index chart.

Table 17. Classification of Soils and Soil-Aggregate Mixtures

General classification	Granular materials (35% or less passing No. 200)							Silt-clay materials (More than 35% passing No. 200)			
	A-1			A2							A-7
Group classification	A-1-a	A-1-b	A-3	A-2-4	A-2-5	A-2-6	A-2-7	A-4	A-5	A-6	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.
Charateristics 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.	6 max.	N.P.	10 max.	10 max.	11 min.	11 min.	10 max.	10 max.	11 min.	11 min.*
Usual types of significant constituent materials	Stone fragments, gravel and sand		Fine sand	Silty or clayey gravel and sand				Silty soils		Clayey soils	
General rating as subgrade	Excellent to good						Fair to poor				

* Plasticity index of A-7-5 subgroup is equal to or less than L.L. minus 30. Plasticity index of A-7-6 subgroup is greater than L.L. minus 30.

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