CEMENT STABILIZATION
OF
OREGON COASTAL DUNE SANDS

by

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TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

TABLES

FIGURES

CEMENT STABILIZATION
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INTRODUCTION

The prospect of economically stabilizing dune sand as a base material for highways and airfields in coastal areas, removed from aggregate sources, has been an appealing thought for many years. The use of cementitious binders with existing soils in numerous other localities, having a wide variety of soil types, has proven to be expedient, satisfactory in performance, and a monetary saving. Nonetheless, dune sand stabilization has continued in a latent state due to inherent characteristics of the sand.

The purpose of this study was to provide experimental results for analyzation and subsequent determination of the type and amount of additives that are needed to attain the prescribed minimum results for a stabilized base. The binder used was Portland cement with other additives included as supplementary materials. The use of Portland cement with the dune sand categorizes these mixtures in the common area of "soil-cement."

Soil-cements have several advantages which have enhanced their usage. The in situ soils make up the filler or voluminous bulk of the stabilized material although upon occasion, inert filler materials are also added to the in situ soils to act in some predetermined manner.

The inclusion of native soils eliminates to a large degree the transportation of soil or aggregate where no large cuts or fills are to be made. A second factor is the restricted amount of cement needed to adequately bind the mixture together. Most soils can be stabilized by adding from three to fifteen percent cement by weight of dry soil, which is comparable to a one to a four and a half bag mix. Also, the equipment requirements for soil-cement stabilization are usually less than for aggregate base construction.

The Portland Cement Association, in its Soil Cement Laboratory Handbook, anticipates a cement requirement of nine percent for poorly graded dune sands having uniformily sized grains. The current economic picture in Oregon indicates the necessity of restricting the cement content to less than eight percent, even when the haul distance for aggregates exceeds ten miles. Thus, even before experimentation, the expectation for supplementary additives in conjunction with cement was forecast.

Economic matters were not the paramount factors in this study. However, the impact of monetary terms on the practical application of results obtained through this study dictates the need for economic guidelines of thought. Additives were examined first for beneficial contribution and then, if favorable, for economic feasibility.

DEVELOPMENT OF SOIL-CEMENT CRITERIA

Two basic concepts have guided the design of soil-cement bases. One of these concepts is the belief that a soil-cement base is to function on the principle of slab action. The second idea is the belief that a soil-cement base is to act under the description of a semi-rigid material.

The slab action design was propounded by the Germans, particularly for the stabilization programs during the period of World War II. Airfields and roads were constructed in a variety of terrains using soil-cement bases having compressive strengths from fourteen hundred to two thousand pounds per square inch. The base thus acted like a rigid mat, possessing sufficient strength to resist the flexural tensile stresses that developed.

The semi-rigid design for a soil-cement base is adhered to by the majority of designers. Compressive strengths are kept low, from two hundred and fifty to five hundred pounds per square inch, and as a consequence, the modulus of elasticity is low. With the low modulus of elasticity the flexibility increases and the soil-cement base acts as a semi-rigid base flexing under a load without developing large flexural tensile stresses.

The rigid mat design is not favorable for general use for three principal reasons. The cement requirement to develop the strength is high, fifteen to twenty percent; the high strength of the mixture produces large shrinkage cracks; and the required depth of the stabilized base is greater.

The more favorable semi-rigid base usually requires from four to ten percent cement and, though shrinkage cracks occur, they are numerous and are the fine, hairline type that do not spread noticeably. The British give a confirmation of the semi-rigid design method by comparing rigid mat design with semi-rigid pavement performance. Analysis by the Westergaard rigid pavement design method shows that a twenty-four inch thickness of rigid pavement would be needed to support a nine thousand pound wheel load on a base having a subgrade reaction value, K, equal to one-hundred pounds per square inch per inch. Whereas, in actual practice a six inch semi-rigid soil-cement base has been found to suffice.

In view of the predominant acceptance of the semi-rigid base theory and the criteria published by the Portland Cement Association, a compressive strength of two-hundred and fifty pounds per square inch at seven days was established as the lower limit of acceptability for the tests conducted in this study.

BACKGROUND ON DUNE SAND STABILIZATION IN OREGON

The Oregon coast has several long stretches in which dune sand extends inland from the present shoreline for several miles. The coastal highway traversing these dune areas is often many miles from aggregate sources and during construction, the haul distance for base and surface rock has been long and expensive.

A cement treated sand base appeared to warrant investigation in an effort to devise a method for reducing costs. To provide a basis for a determination, Oregon's first and only cement stabilized dune sand base was designed and constructed during the period from 1939 to 1941. The base of a thousand foot section of the coastal highway in a dunes area south of North Bend, Oregon, was stabilized by adding Portland cement and a sandy loam to the inplace dune sand. The base, after compaction and curing, was then covered with an asphaltic wearing surface.

This section proved to be uneconomical primarily because of excess cement requirements, although mixing and compacting difficulties were also contributory toward unfavorable costs. The prohibitive cement requirement was attributed to two principal conditions. One is the dune sand gradation. The uniformity in size of the sand grains has the piled marbles effect of large void ratios. Even after undergoing standard compactive effort, the void ratio of plain dune sand is nearly 0.66, which means the volume of voids is forty percent of the entire volume. The second deterrent is the acidic condition which persists in much of the coastal dune sand. The acid acts as an inhibitor to the chemical reactions that take place during hydration. The Road Research Laboratory of England offers the explanation that the calcium ions freed during hydration are adsorbed by the organic acids, thereby causing a shortage of calcium ions for the curing process of cement.

Renewed interest in the possibilities of cement stabilized bases in dune areas has been brought about by the decline in the availability of aggregate sources and the advancement of techniques and machines for soil-cement stabilization. As the aggregate sources become further depleted and stabilization methods perfected, the economic disadvantage of using cement to stabilize dune sand for a base may reverse itself to become favorable, particularly if adequate study on sand-cement mixtures has been performed to enable an accurate estimate of its performance in field operations.

MATERIALS

The materials used in the soil-cement mixtures are individually described in the following paragraphs. Data obtained from physical and chemical tests on a material are discussed under "Test Results" of this report.

Dune Sand. Samples were procured from various depths and different locations to investigate uniformity and acidity. Only two samples were used in the compression tests as they seemed to exemplify the two prevailing conditions. They were obtained in a dune area north of Seaside, Oregon. The sample pits were several miles from the shoreline and in each case, the surface of the dune was covered with a light growth of vegetation. To provide simplicity in identification, hereafter in this report, these two samples will be referred to as Sample #1 and Sample #2.

1. Sample #1 was obtained by augering down from the top of the dune for a distance of six feet. This sample contains some sandstone grains that are stained with organic matter.
2. Sample #2 was procured from a cut bank that had been recently exposed. The depth of the sample ranged from fifteen to twenty feet below the old, natural surface of the dune. The sand

appeared clean and free of organics.

Portland Cement. The Portland cements used in testing were standard commercial products manufactured by the Oregon Portland Cement Company. The two types used were Type I (standard) and Type III (high early strength) and in each case, were fresh at the start of testing. Chemical analyses of the cements, obtained from the Oregon Portland Cement Company, are shown in Table 1.

Silt. The silt used in the tests was a volcanic ash taken from a borrow area in Union County of eastern Oregon. This material was previously tested by the Oregon State College Civil Engineering Department and test results on silt shown in this report are taken from previous examinations.

Calcium Chloride. The calcium chloride was a commercial product sold under the trade name "Wyandotte" by Great Western Chemical Company. The calcium chloride came in pellet form having approximately 97 percent purity.

Calcium Hydroxide. A purified calcium hydroxide having a minimum amount of foreign compounds was used in these tests.

TABLE I

REPRESENTATIVE CHEMICAL ANALYSES OF OREGON PORTLAND CEMENT

1. Oxide Analyses by Percentage of Weight

	Type I	Type III
Lime, CaO	63.64	65.29
Silica, SiO_2	21.04	22.64
Alumina, Al_2O_3	4.80	3.52
Iron, Fe_2O_3	4.46	3.04
Magnesia, MgO	2.38	1.68
Sulfur trioxide, SO_3	1.61	1.93

2. Principal Compounds Present by Percent

	Type I	Type III
Tricalcium Silicate $3CaO \cdot SiO_2$	56.0	60.1
Dicalcium Silicate $2CaO \cdot SiO_2$	18.1	19.6
Tricalcium Aluminate $3CaO \cdot Al_2O_3$	5.1	4.2
Tetracalcium Aluminoferrite $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	13.7	9.3

TEST APPARATUS

The tests performed in this study of soil-cement mixtures followed established methods wherever possible. Consequently, most of the equipment and apparatus used was of the standard, commercial variety. To assure complete clarity in procedure, each significant item will be described individually.

Moisture-Density Apparatus:

Standard Proctor compaction equipment with one-thirtieth of a cubic foot mold and a 5.5 pound hammer with a one foot drop constituted the moisture-density apparatus.

Curing Room for Soil-Cement Specimen:

The curing room was a fog-type room which maintained a relative humidity of 100 percent and a constant temperature of 70°F.

Compression Test Machine:

Compression molding and crushing was accomplished with a hydraulic Southwark-Emery testing machine having a maximum load capacity of sixty thousand pounds. The machine has a spherical head which was rotated as needed to assure the contact surface was parallel with the top surface of the specimen. Testing of the soil-cement specimens was performed on the low range portion of the indicator to permit the reading of small load changes. Figure 1 illustrates the test machine during a molding operation.

Cylindrical Soil-Cement Molds and Pistons:

Split brass molds having three cylinders, each two inches in diameter, have been used throughout these tests. The molds are four inches high and eight inches in length. Prior to molding operations, the mold was securely clamped to a flat plate to maintain the correct sample size and provide a smooth surface to mold the specimen end. Screw clamps were secured at the quarter point from the bottom of the mold to prevent expansion of the mold during the application of the molding load.

The two pistons used in compacting the specimens were 2.5 inch round bar stock milled at each end to a desired shape. One end on each piston was rounded to give point contact with the compression machine. The other end on the pistons was cut to a two inch diameter for a distance of three inches on one piston and a distance of two inches on the other. The one-fourth inch shoulder thus prevented the pistons from penetrating into the cylinders more than three and two inches respectively. The cylinder being four inches in depth, the soil-cement could then be molded in lifts of one inch. Figure 2 illustrates the apparatus used in molding compression specimens.

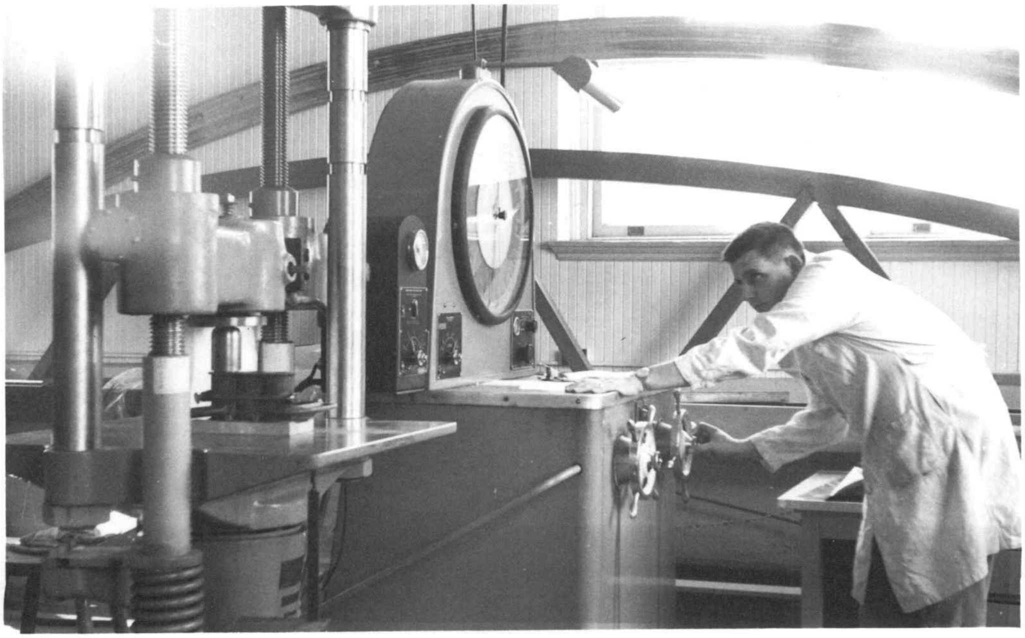


Figure 1. Southwark-Emery universal test machine used for the molding and compressive testing of sand-cement specimen.

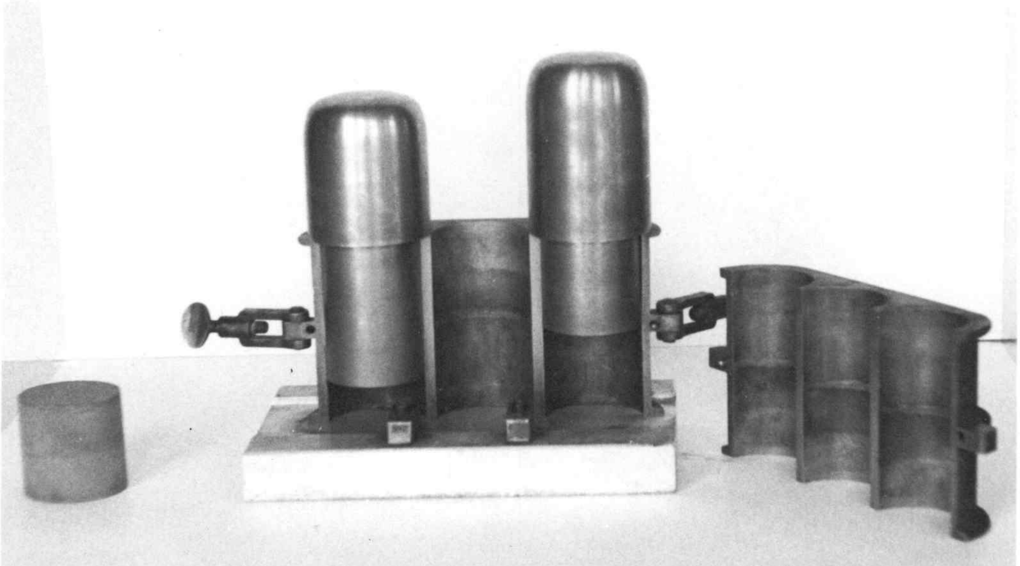


Figure 2. Apparatus for molding cylindrical sand-cement specimens two inches in diameter and two inches in height.

TEST METHODS

Where practicable, standarized methods of testing were used to permit maximum assimilation of acquired data with past and future results of comparable experiments. The materials used in this study were subjected to the tests described in the succeeding paragraphs, generally following the pattern of normal sequence for investigation of materials.

Mechanical Analysis of Soils

1. Sand. Sieve analysis and hygroscopic moisture determinations were obtained by following A.A.S.H.O. Specification T88-57.
2. Silt. Testing of the silt used in this study was previously performed by the Oregon State College Civil Engineering Department with values being taken directly from previous reports. In addition to the hydrometer and sieve analysis for grain size, the Atterberg limits tests were performed.

Specific Gravity Determination

1. Sand. Specific gravity was determined by the method outlined in A.A.S.H.O. Test T84-57.

Loss on Ignition

1. Sand. Material from each sample was subjected to drying at 100°C for a period of twenty-four

hours, after which no additional weight loss was apparent. Weighed material from each of the samples in turn was subjected to a furnace temperature of 1700°F. for a term of twenty minutes. The weight loss during ignition provided an indication of the organic material in the sand.

Acidity-Alkalinity Test

1. Sand and Silt. Following methods prescribed by the manufacturer, pH values were determined by using the Beckman pH meter.

Moisture-Density Relationships of Soils

1. Sand and Sand plus Silt. Testing was conducted by following the methods outlined in A.A.S.H.O. T99-57, using the one-thirtieth cubic foot mold. This test is often termed "standard Proctor compaction." The variable silt content is a percentage of the dry weight of dune sand in the mixture.

Moisture-Density Relationships of Soil-Cement Mixtures

1. Sand plus Cement and Sand plus Silt plus Cement. Testing was performed as prescribed in A.A.S.H.O. T134-57, which is comparable to the above test for soils. In determining the proportionality of the mixtures, it should be understood that silt contents are a percentage of the dry

weight of sand, and cement content is a percentage of the combined dry weights of sand and silt. When silt is not present, the cement content is the percentage proportion of the dry weight of cement to the dry weight of sand.

Soil-Cement Specimens for Compression Testing

The Portland Cement Association in their Soil Cement Laboratory Handbook (12, p. 32-33) describe the use of cylindrical soil-cement compression specimens two inches in diameter and two inches in height. Having selected this specimen size for these tests, the procedures set forth in the Handbook were followed where possible in the molding, curing, and compressive testing of the specimens.

1. Mixing Procedure. Material to mold four cylindrical specimens was batched together, the weight of each ingredient being proportional to its weight in the compaction test and as interpreted from the density curves plotted from the compaction test results. The mixing of material for four specimens, when only three were molded from the mixture, allowed for spillage and losses occurring during mixing. The constituents in any batch were thoroughly integrated to uniformity by hand mixing.

2. Molding. Distilled water was added to the uniform mixture in proportion to the optimum moisture content obtained in the compaction tests, allowance being made for hygroscopic moisture. The moistened material was then compacted into the cylindrical molds in two one-inch lifts, each one-inch lift being carefully weighed. Compaction was accomplished by application of a hydraulic load on a piston placed in the cylinder. Two lifts of one inch were considered advisable to compact the specimen uniformily throughout. Scarification between lifts also helped prevent the existence of a high density surface between the two lifts since the piston tends to create higher densities next to the piston surface. Figure 2 with the split mold demonstrates the action of the pistons in compacting the specimen.

3. Curing. The molds containing the specimens were placed in the curing room for a period of three days, at which time, the specimens were extruded from the molds. Extrusion was necessary as splitting the molds often split the specimen as well. The extruded specimens were then returned to the curing room until the proper curing time had elapsed.

4. Compressive Testing. Prior to unconfined compressive testing, the specimens were soaked one hour. Specimens were then individually stressed to failure in the testing machine. Loading rate was twenty pounds per square inch increase per second as recommended in A.S.T.M. Test D1633-59T (Compressive Strength of Molded Soil-Cement Cylinders) with ultimate load capacities being read to the nearest five pounds.

TEST RESULTS AND INTERPRETATIONS

Having completed the description of the methods used in testing, the results obtained from these tests are presented in the following discussion.

Mechanical Analysis of Soils

1. Sand. The dune sand samples exhibited poor gradation with particles approaching uniformity in size. Sieve analysis results are shown in Figure 3. Further examination of the grains under a microscope revealed rounded shapes resembling those commonly found in the bottom of creeks.
2. Silt. The silt test results, as previously mentioned, were already recorded. The silt grain size test results are shown in Figure 3. The silt, after being thoroughly broken down, was sifted through a #100 screen and all material of size greater than the #100 screen (0.147 mm) was excluded from further use. As can be seen from the comparison of the sand and silt curves of Figure 3, after exclusion of grains larger than the #100 mesh, nearly all the silt is finer than the dune sand grains.

Specific Gravity Determinations

1. Sand. The specific gravity of the tested

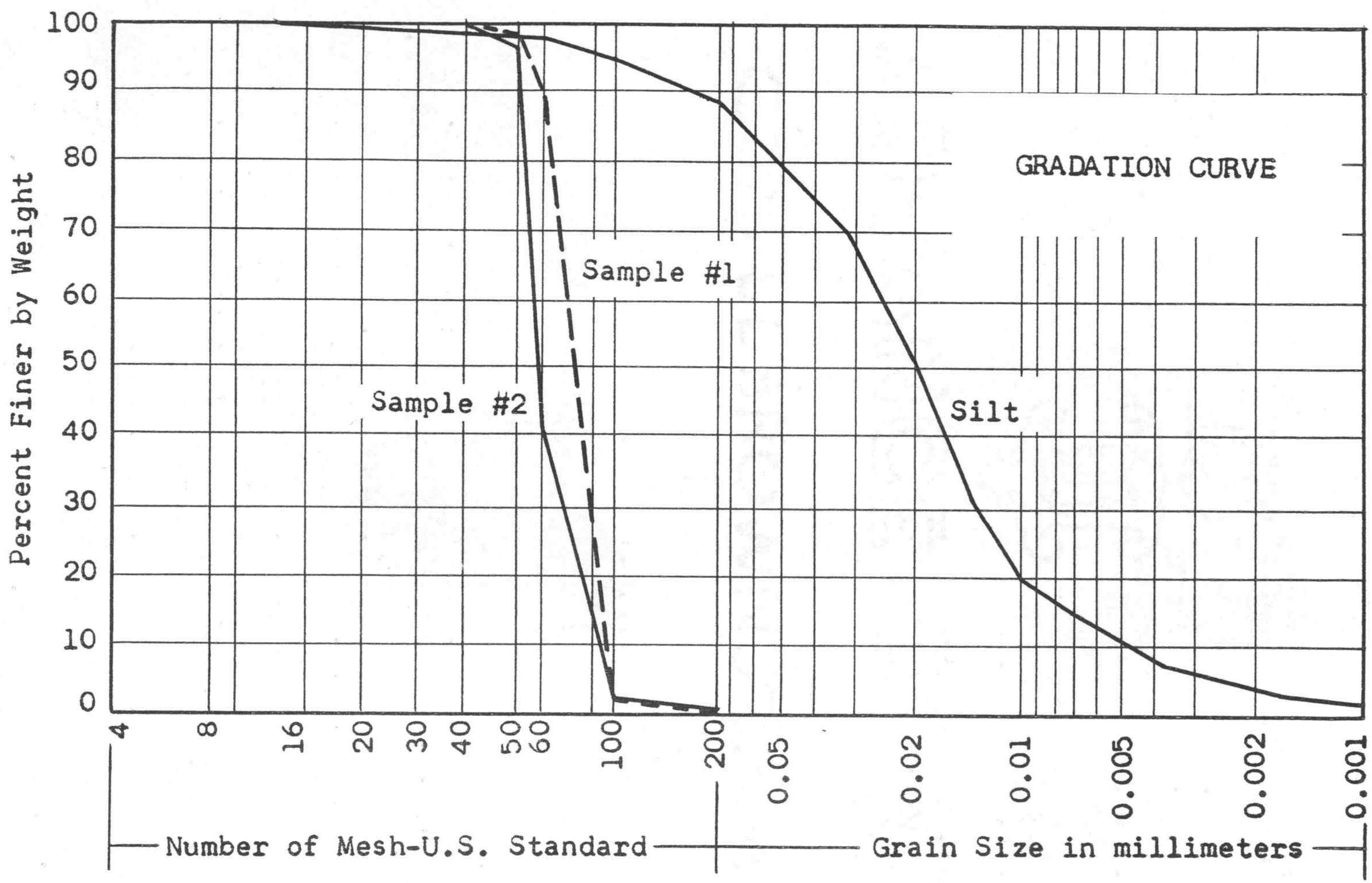

GRADATION CURVE
Sample #1
Sample #2
Silt
Percent Finer by Weight
100
90
80
70
60
50
40
30
20
10
0
4
8
16
20
30
40
50
60
100
200
0.05
0.02
0.01
0.005
0.002
0.001
Number of Mesh-U.S. Standard
Grain Size in millimeters

Figure 3

samples was 2.64.

2. Silt. The specific gravity of the silt used in the tests was 2.5.

3. Cement. The specific gravity of cement was assumed to be 3.14, since the specific gravity test on cement was not run. This is a mean value commonly used when a specific gravity test has not been performed.

Ignition of Organics

1. Sand. Using the entire weight loss of the sand by comparing ignited sample weights before and after placement in the furnace, Sample #1 had an organic content of 9100 ppm and Sample #2 had 9700 ppm. Oxidation of a portion of the soil grains probably occurred; however, this oxidation loss was unavoidably included in these figures. Even so, the organics present in each sample is reasonably accepted to be approximately 9000 ppm. This is deemed to be a reasonable organic content for a coastal sand.

Acidity-Alkalinity Test

1. Sand. Sample #1, the surface sand, had a slight acidic condition with a pH of 6.4. Sample #2, the deeper sample, was at a state of neutrality with a pH reading of 7.0. Ignited

Sample #2 also had a neutral pH of 7.0.

2. Silt. The pH reading for silt was 5.9.

Moisture-Density Relationships of Soils

1. Sand and Sand plus Silt. Moisture-density curves were plotted from compaction tests to complement and corroborate later curves having cement and other additives. The curves were in all cases run with sand from Sample #2, since this sand is considered representative in grain size of the usual coastal dune sand of Oregon.

Considerable difficulty in obtaining consistent moisture samples was encountered when attempting to ascertain the moisture contents of the successive points of the compaction curve. For example, wet density would increase as expected when on the dry side of optimum, but the moisture contents of the dried samples extracted from the molded specimen would often drop or fluctuate radically. Upon reconsideration of procedures, the conclusion was to cut a pie-shaped wedge from the compacted cylindrical specimen, running vertically from top to bottom, thereby drying a sample based upon its proportionate amount of the volume. This conclusion was founded on the concept that the center of the mold was being consolidated to a greater extent than the edges due to overlapping of the falling piston. Radial flow of moisture towards the outside was thus expected. Moisture tests taken thereafter with the wedge-shaped samples were consistent and true to expectations.

The curves in all cases demonstrated a definite sensitivity towards moisture content with the typical curve having a comparable slope before and after the optimum moisture-maximum density point. A typical compaction curve is shown in Figure 4. Optimum moisture for plain sand was 15.8 percent, while for sand with a twenty percent silt additive, the optimum moisture varied from 13.5 to 14.5 percent. The trend was thus a decrease in optimum moisture with the increase in silt content. As shown in Figure 5, increasing silt content produced increased densities of sand-silt mixtures.

Moisture-Density Relationships of Soil-Cement Mixtures

The soil-cement tests were performed in the same manner described in the foregoing tests on sand plus silt. Tests were concluded within the approximate span of an hour to prevent undue

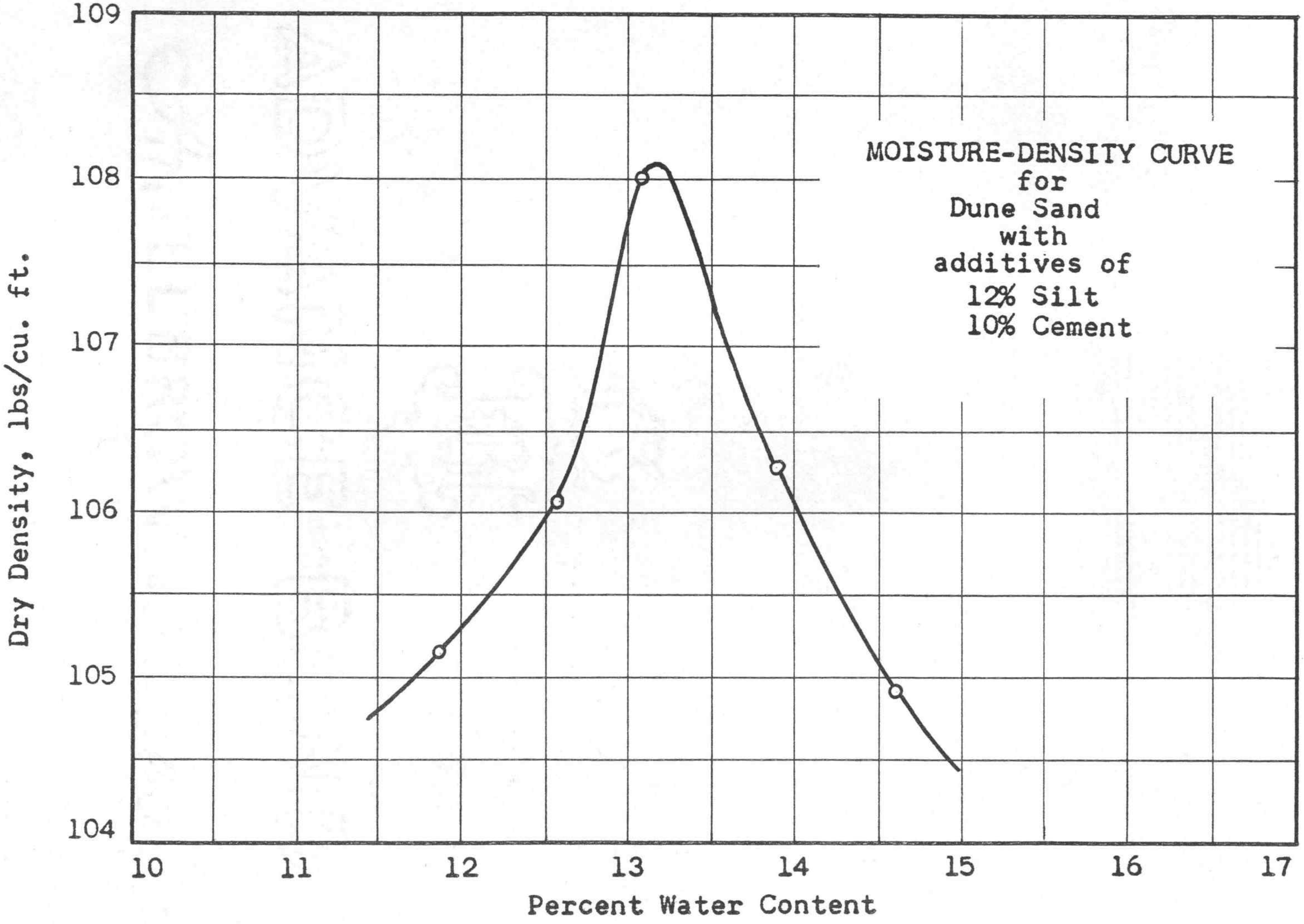
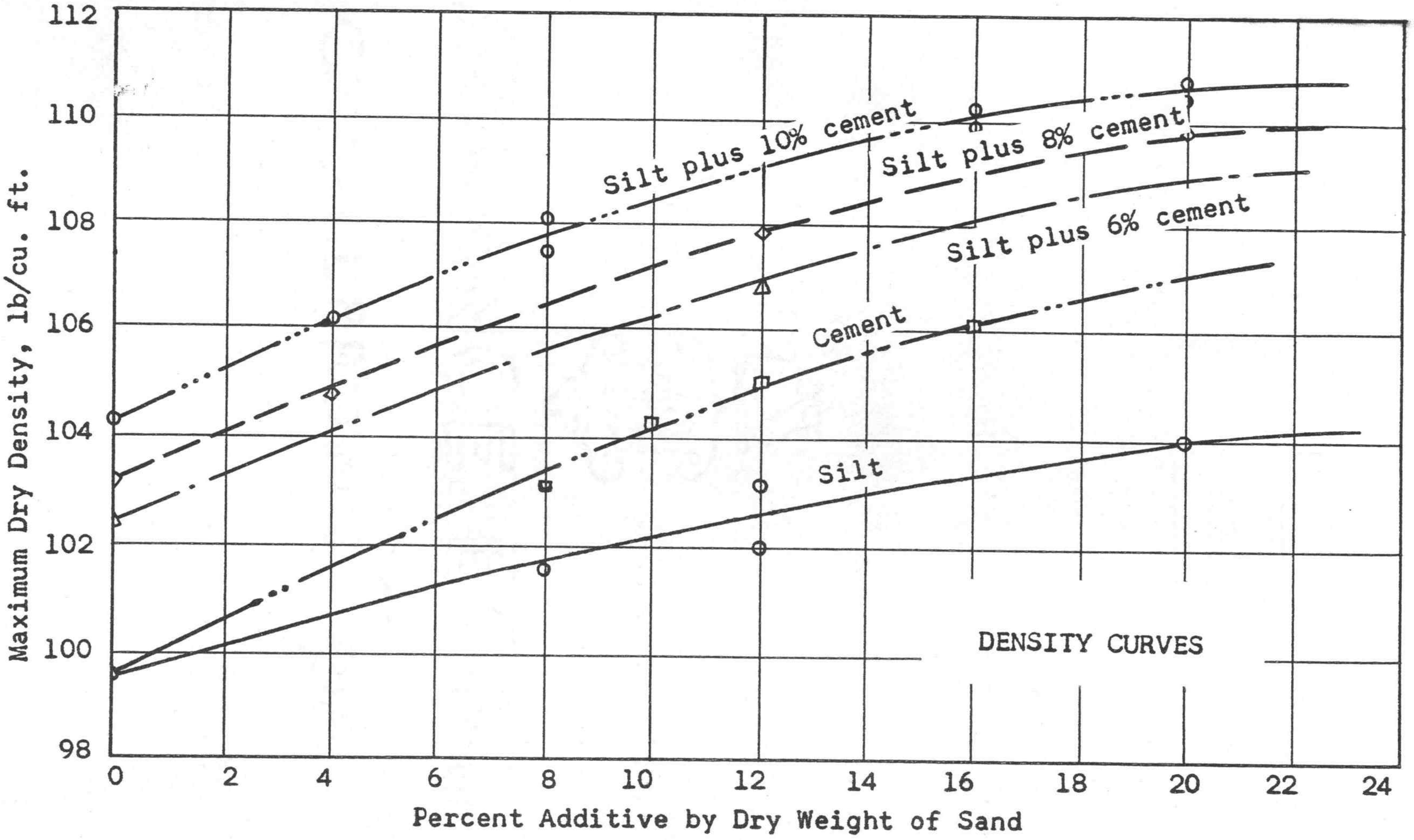

MOISTURE-DENSITY CURVE
for
Dune Sand
with
additives of
12% Silt
10% Cement
Dry Density, lbs/cu. ft.
109
108
107
106
105
104
10
11
12
13
14
15
16
17
Percent Water Content

Figure 4



Silt plus 10% cement
Silt plus 8% cement
Silt plus 6% cement
Cement
Silt
DENSITY CURVES
Maximum Dry Density, lb/cu. ft.
112
110
108
106
104
102
100
98
0
2
4
6
8
10
12
14
16
18
20
22
24
Percent Additive by Dry Weight of Sand

Figure 5

hydration of the cement. There seems to be no apparent correlation of optimum moisture content in the various mixtures of sand and cement. For plain sand, the optimum moisture is 15.8 percent; for sand with ten percent cement additive, 15.8 percent; and for sand with sixteen percent cement, the optimum moisture is 14.4 percent. Since these values are based on single compactions, these moistures are subject to further testing for verification.

Compressive Test Results

1. Sand plus Cement. Since prior research indicates a minimum compressive strength of 250-300 per square inch at seven days is necessary to sustain the normal highway loads, the initial step was to determine the cement content required to develop this strength in the dune sand samples. Varying percentages of Type I Portland cement were mixed with sand from Sample #1, Sample #2, and ignited sand from Sample #2. The plot of the compressive strengths of these combinations, as shown in Figure 6, then allows the selection of a cement content dependent upon desired strength and type of dune sand. The plotted curves also show (1) the effects

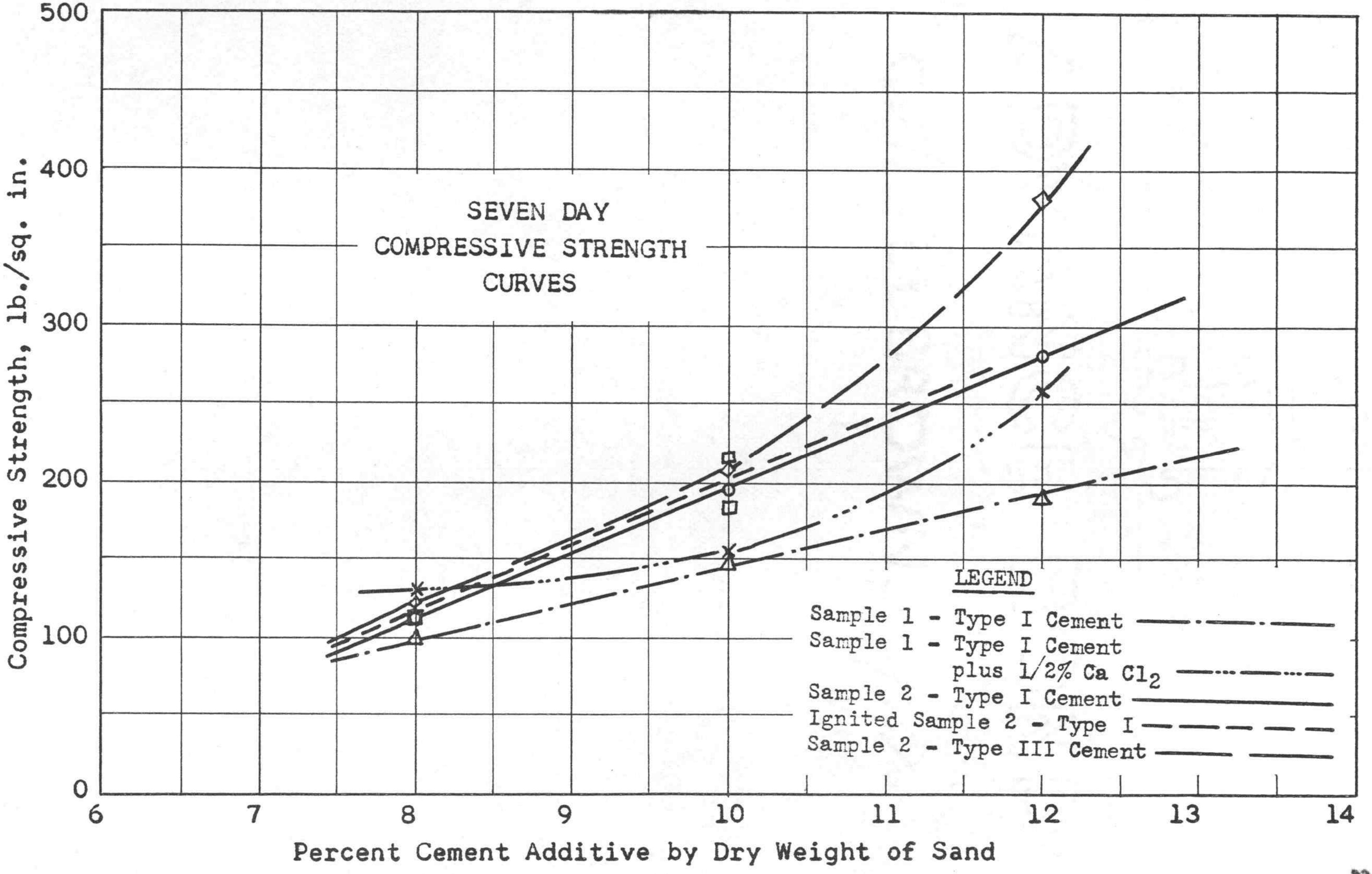

SEVEN DAY
COMPRESSIVE STRENGTH
CURVES
LEGEND
Sample 1 - Type I Cement
Sample 1 - Type I Cement
plus 1/2% Ca Cl2
Sample 2 - Type I Cement
Ignited Sample 2 - Type I
Sample 2 - Type III Cement
Compressive Strength, lb./sq. in.
0
100
200
300
400
500
6
7
8
9
10
11
12
13
14
Percent Cement Additive by Dry Weight of Sand

Figure 6

of the organics by comparison of the strengths of normal state sand from Sample #1 and Sample #2 with the ignited, organic-free sand from Sample #2, and (2) the effect of an acidic condition by comparing the strengths of Sample #1 which is slightly acidic with Sample #2 which is neutral.

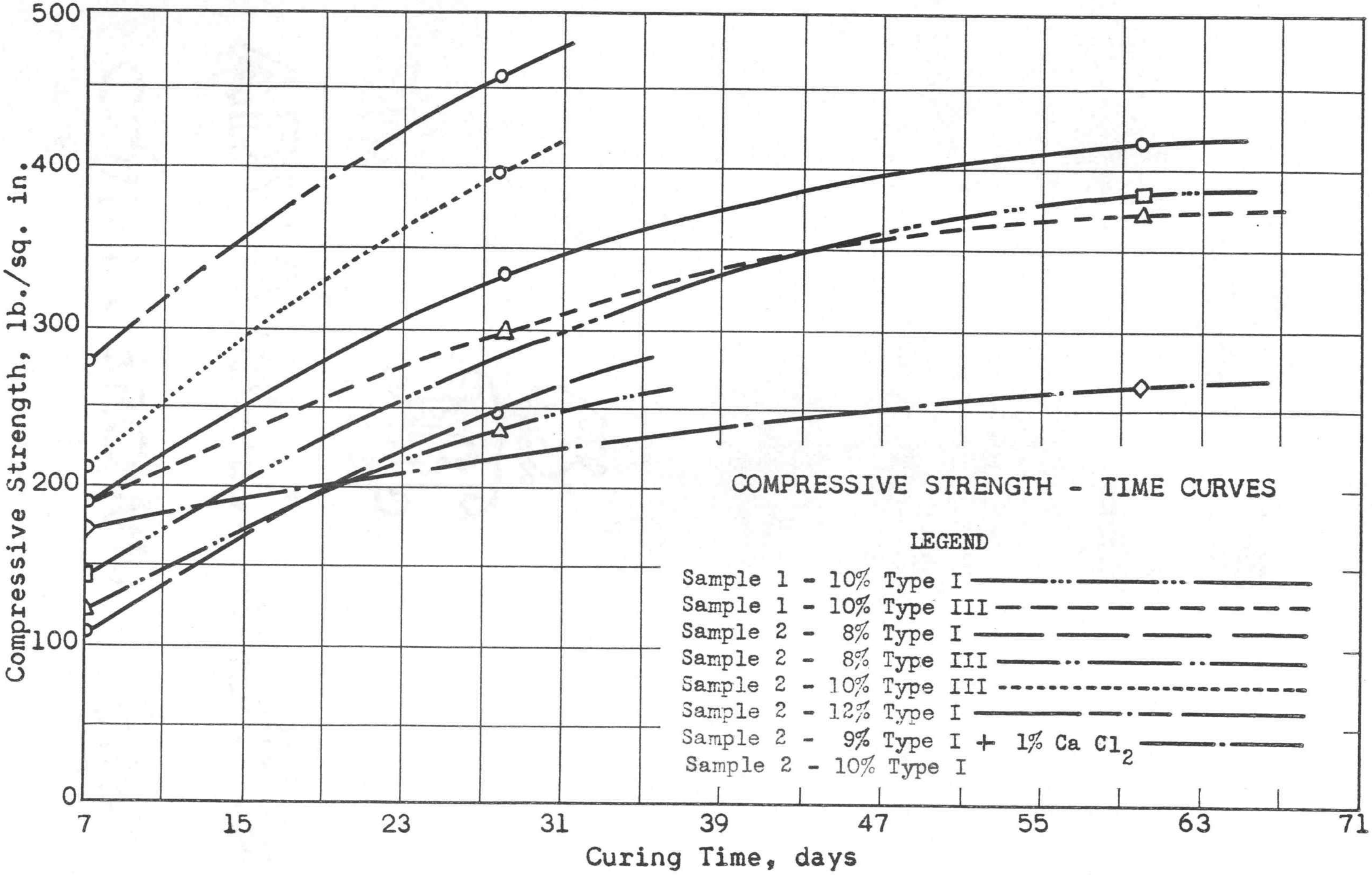
As may be seen from the curves of Figure 6, the cement content required for 250 per square inch strength when using Sample #1 is 14.5 percent upon extrapolation of the curve for Type I cement. For Sample #2, the Type I curve intersects the 250 per square inch strength line at 11 1/4 percent cement. The curves also show that for Type I cement, the Sample #2 and ignited Sample #2 strengths are nearly congruent, whereas the Sample #1 strengths are definitely lower.

Type III cement was substituted for Type I and the series of compression tests repeated. The intent of this substitution was to ascertain if the high early strength characteristic of the Type III cement would be beneficial in the acidic sands. Curing time for some samples was extended to sixty days to compare strength trends with the Type I samples cured for a like period of sixty days. Figure 7 graphically illustrates the strengths attained from the Type I and Type III cements in both Samples #1 and #2. Type III cement, as expected, produces a rapid initial strength that exceeds the Type I cement strength. However, the strength advantage of Type III cement is short lived for within 28 days for eight percent cement content and within sixty days for the ten percent cement content, the Type I strengths exceed the Type III strengths.

Another noticeable development from Figure 7 is the nearly constant strength differential in the ten percent Type I cement curves. The initial strength loss suffered by the cement in the acidic Sample #1 is apparently never recovered.

2. <u>Sand plus Silt plus Cement.</u> With the prevailing high voids ratio, the logical step was the inclusion of a filler. A non-plastic silt was selected for its ease in mixing, practical availability, and low cost.

When early test results indicated that the addition of silt was producing definite increases in strength, a series of curves was



COMPRESSIVE STRENGTH - TIME CURVES
LEGEND
Sample 1 - 10% Type I
Sample 1 - 10% Type III
Sample 2 - 8% Type I
Sample 2 - 8% Type III
Sample 2 - 10% Type III
Sample 2 - 12% Type I
Sample 2 - 9% Type I + 1% Ca Cl2
Sample 2 - 10% Type I
Compressive Strength, lb./sq. in.
Curing Time, days
0
100
200
300
400
500
7
15
23
31
39
47
55
63
71

Figure 7

developed which enables the rapid determination of the cement and silt variables necessary to produce a desired strength. The curves shown in Figure 8 were established by holding cement content constant and varying the silt. From these curves any combination of variables with the resultant strength can be approximated with a satisfactory degree of accuracy. For example, if a compressive strength of 300 pounds per square inch using nine percent cement is desired, by interpolating between the eight and ten percent cement curves, a silt content of eleven percent is found to be required.

3. Sand plus Cement plus Calcium Chloride and Sand plus Cement plus Calcium Hydroxide. In an attempt to counteract the acidic condition, trace amounts of calcium chloride ($Ca\ Cl_2$) and calcium hydroxide or lime ($Ca\ (OH)_2$) were introduced into soil-cement mixtures containing sand from Sample #1. The premise for this action is the argument (3, p. 625-630) that the calcium ions liberated by the calcium silicates and aluminates during the initial stages of hydration are adsorbed by the active organic materials and thus are not available for the compounds

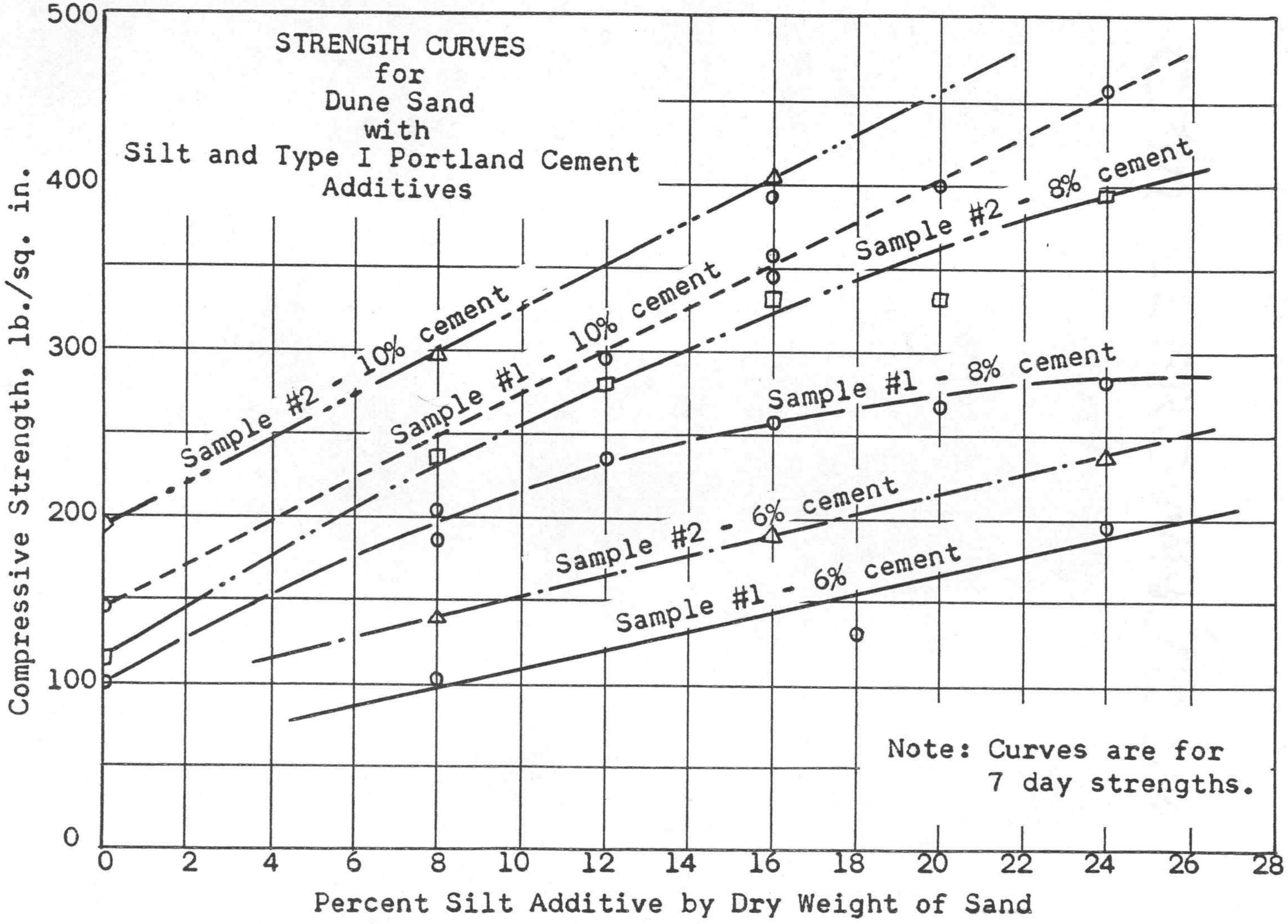

STRENGTH CURVES
for
Dune Sand
with
Silt and Type I Portland Cement
Additives
Sample #2 - 10% cement
Sample #1 - 10% cement
Sample #2 - 8% cement
Sample #1 - 8% cement
Sample #2 - 6% cement
Sample #1 - 6% cement
Note: Curves are for
7 day strengths.
Compressive Strength, lb./sq. in.
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
Percent Silt Additive by Dry Weight of Sand

Figure 8

produced in the hardening process. The inclusion of trace amounts of calcium chloride, 0.5 percent of dry weight of sand, had a varying effect. With a mixture having an eight percent Type I cement content, the trace of calcium chloride increased compressive strengths thirty percent. In ten percent cement mixtures, the calcium chloride raised the strength only two percent, but then with a twelve percent cement content, the strength was improved by thirty-three percent. A note of caution is made on these seven-day values, as three trial specimens containing calcium chloride displayed reduced strengths after sixty days when compared with anticipated strengths of samples without calcium chloride. This sixty-day strength trend is shown in Figure 7 for the curve having additives of nine percent cement plus one percent calcium chloride.

Calcium hydroxide improved the strengths of all of the specimen tested. With trace amounts of calcium hydroxide, 0.5 percent by dry weight of sand, the eight percent cement specimen had an increase in strength of thirty percent, the ten percent cement mixtures averaged sixteen percent higher, and the twelve percent specimen were thirteen percent greater in strength.

CONCLUSIONS

The following conclusions are derived from interpreting experimental results described in the foregoing sections, in conjunction with information presented in other papers on this subject.

1. The inclusion of silt in sand-cement mixtures appears to bring the use of cement stabilized dune sand bases within the limits of economic feasibility. The sand-silt-cement mixtures exhibit nearly a linear increase in strength for either increasing silt or cement content. An optimum value for the two variables can be found by using the curves of Figure 8 in conjunction with the economic considerations of each additive.
2. The compressive strength of sand-cement mixtures increases almost proportionally to the increase in cement content. A sand-cement mixture possessing a compressive strength of two-hundred and fifty pounds per square inch would demand from eleven to fourteen percent cement, depending upon the acidity of the dune sand. This content may not be unfavorable in certain instances where small stabilized areas are involved. Cement requirements may be

estimated by using Figure 6.

3. After the elapse of a sixty day curing period, the strength curves from Sample #1 using ten percent Type I and Type III cements cross. The benefits from Type III cement are of a transient nature and if a slower initial set is permissible, the use of Type I cement is recommended.
4. Trace amounts of calcium chloride can be expected to improve seven-day strengths up to thirty percent. The inclusion of calcium chloride in small quantities as a replacement for cement or as a trace additive is not recommended until further study has been made on its total effect in dune sand-cement mixtures. Its long term effect on trial specimens in this study was definitely detrimental to the development of compressive strength.
5. The increase in strength from the use of trace amounts of calcium hydroxide is encouraging and, therefore, further study in the use of this additive is warranted. Long term effects should be investigated also.
6. The presence of an acidic condition appears to differentiate whether organics are detrimental

to the proper setting of cement. The results from the tests in this study indicate that the mere existence of organics does not affect the compressive strength characteristics, as illustrated by the nearly identical strengths exhibited by the natural Sample #2 and the ignited Sample #2. But with the organic content approximately the same, the acidic Sample #1 consistently demonstrated reduced strengths when compared with the neutral Sample #2.

7. The acidic effect is felt only in the initial hydration period. At seven days, the strength differential is distinct for the acidic and neutral sands with the differential appearing to be nearly constant thereafter, as is demonstrated in the sixty day curves for ten percent cement content in Figure 2. This is felt to be a corroboration of the concept of the adsorption of calcium ions by the acidic organics during the early stages of hydration.

8. From observation of ground conditions and the depth of sample procurement in the dune areas, the surmise which is tacitly assumed is that the acidic condition prevails in the surface layer of dunes supporting vegetation growth

and diminishes with increasing depth, although there is strong possibility of the collection of active organics again at the water table. Thus, if active organics are a factor varying with depth, a mixture of active and neutral elements is to be expected in any dune sand operation.

9. The compressive strengths obtained in this study are from cylinders having a height to diameter ratio of one to one. The desired ratio for a compressive specimen is two to one to permit the development of a shear plane. It is likely that the compressive strengths shown in this report are somewhat higher than the compressive strengths of specimens having the customary height to diameter ratio of two to one.

10. The strengths developed by the laboratory specimens in this study were under ideal conditions for mixing and curing. Whether the minimum strengths and associated required additives presented by the experimental data of this report will suffice in field operations is open to judgment.

11. The moisture content in the laboratory

moisture-density tests is quite critical as is apparent from the steep slopes of the compaction curve. However, in field operations the porosity of the sand base eases this situation considerably and excess moisture is usually rapidly dissipated if an over-optimum condition should develop.

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