ABSTRACT OF THESIS

PRACTICAL EFFECT OF THE SMALL
PARTICLES IN A SOIL
ON ITS COMPACTED STRENGTH

Submitted by
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In partial fulfillment of the requirements
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Abstract

PRACTICAL EFFECT OF THE SMALL PARTICLES IN A SOIL
ON ITS COMPACTED STRENGTH

Although in the past century there has been ex-
tensive research and development in the fields of soil
mechanics and soil physics, the engineer who uses soil as
a building material today, still relies on data and tests
which were in use years ago. For the most part, these
tests are expensive and time consuming, because they
are based on the principle that only the combined effect
of all the variable factors must be considered.
Scientists in certain related fields, however, have
studied their own problems with more of an analytical
approach, and their contribution to the general study of
soil may be a valuable one. While the engineer has been
mainly concerned with the physical properties of the soil,
the soil scientist has investigated the chemical, thermal,
and electrical properties of that material. Many
practical soil problems might be solved by weaving to-
gether the work of the engineer and the soil scientist.
It is possible that out of this attempted solution will

come new data and tests that will benefit civil engineers seeking the answer to problems of irrigation, flood control, and highway construction.

The particular problem considered in this study was: How do the physico-chemical properties of a soil mass affect its overall strength.

A solution of the major problem was assumed to depend upon answers to the following:

1. What is the effective size and surface area of certain artificially mixed combinations of different size soil particles?

2. What are the physical properties and strength of each of the articially prepared soils when mixed with water in the usual manner?

3. How can the effect of the physico-chemical properties in each soil be nullified?

4. What is the strength of each of the artificially prepared soils when the effect of the physico-chemical properties in each soil has been nullified?

5. What does the difference in test results indicate concerning the effect of the very small particles in the soil?

To carry out this investigation, eight soil systems were prepared by mixing in different proportions the particle size fractions of one selected sample of disintegrated granite. The compacted strength of each

soil system was determined in the usual manner by two
separate laboratory testing methods. After these were
completed, each of the eight soil systems were treated,
in a previously investigated manner, to repress the
physico-chemical activity of the small soil particles.
The strength tests were then rerun on each of the treated
soil systems to observe the effect when only particle
size was a variable.

The results of the tests indicated that when
the physico-chemical variables were in effect, the
strength of the soil decreased rapidly as the percentage
of small particles increased. When this reaction of the
small particles was effectively nullified, an increase in
the number of small particles in the soil systems resulted
in a slight decrease in strength. The strength of soils
composed almost entirely of small particles was well with-
in the range of values generally observed for excellent,
coarse-grain soils. The physico-chemical activity of the
small particles appeared to contribute much more to the
loss of this soil's bearing strength and stability than
did the actual decrease in particle size.

This study indicated that a simple equation
might be developed to express the strength of this one
particular soil as a function of its effective particle
size or its specific surface area. In the course of this
investigation it was also apparent that studies similar

to this one would have to be made on many other different
types of soil if the results were to really be of
practical value.

T H E S I S

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COLORADO AGRICULTURAL AND MECHANICAL COLLEGE

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR

SUPERVISION BY ......BURRELL BENTON GERHARDT..............................

ENTITLED...PRACTICAL EFFECT OF THE SMALL PARTICLES IN A....

SOIL ON ITS COMPACTED STRENGTH...............................

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE.

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TABLE OF CONTENTS

TABLE OF CONTENTS--Continued

TABLE OF CONTENTS--Continued

LIST OF TABLES

LIST OF FIGURES

Chapter I
INTRODUCTION

For centuries men using soil as a building
material have realized that there are a great number of
factors which determine how strong this extremely hetero-
geneous mass will be after it has been disturbed from its
natural position and manipulated to suit their desires.
Arts and sciences relating to the constituents of the
earth's mantle have developed to the point where the ef-
fect of some of these variable factors are quite clear;
in fact, enough is known to have materially facilitated
the accomplishment of innumerable feats of engineering
and architecture.

Terzaghi and Peck (22), 1948, contend that for
most practical problems in soil mechanics only the com-
bined effects of the variable factors need be considered,
and indeed, this practice has had almost universal fol-
lowing. The result is a deluge of practical soil tests
necessarily applied to every type of soil with which the
engineer comes in contact. Although in soil laboratories
many simplifications and organized procedures have been
developed, the present day soil analysis is quite expen-
sive and time consuming. An analytical and systematic

approach in the study of soil may be lacking. It is possible that an approach similar to that recently undertaken in hydraulics may be applicable.

The problem involved in this study is only one of the many problems that must eventually be undertaken to determine some systematic method for accurately evaluating soil strength by the use of simple and rapid field tests.

The problem

How do the physico-chemical properties of a soil mass affect its overall strength?

Problem analysis.--1. What is the effective size and surface area of certain artificially mixed combinations of different size soil particles?

2. What are the physical properties and strength of each of the artificially prepared soils when mixed with water in the usual manner?

3. How can the effect of the physico-chemical properties in each soil be nullified?

4. What is the strength of each of the artificially prepared soils when the effect of the physico-chemical properties in each soil has been nullified?

5. What does the difference in test results indicate concerning the physico-chemical effect of the very small particles in the soil?

Delimitation.--This investigation is limited to a uniform type of soil found in the vicinity of the continental divide near Loveland Pass in Colorado. The experiments were performed in the Colorado State Highway Soil Testing Laboratory in Denver.

The term soil was taken to include all of the mineral and organic constituents of the earth's mantle in aggregations up to a diameter of three quarters of an inch in size.

Strength of the soil was determined by the California Bearing Ratio Test and the Hveem Stabilometer. To simulate field rolling, the compaction procedure used was the modified method prescribed by the American Association of State Highway Officials. Other auxiliary tests were performed in accordance with the American Association of State Highway Officials and the American Society for Testing Materials standards.

Chapter II
REVIEW OF LITERATURE

Since soil is made up of both coarse and fine
particles it is not surprising to find that it has been
studied from several different points of view. On the
one hand, the coarser fractions are inert and lend them-
selves well to physical analysis. The review of litera-
ture along this line will be taken up under the heading
of soil mechanics in engineering, chemical aspects of
soil studies, and geotechnics.

The very small soil particles, on the other
hand, differ from the coarser fractions in that they have
physico-chemical properties. As a result of special
studies made by members of Chemical and Ceramic Societies,
many theoretical explanations for the behavior of colloids
and soluble salts are available. Following the presenta-
tion of these publications is a review of the work of the
newly termed "geotechnician" who attempts to apply all
of these principles of mechanics, physical chemistry,
and mineralogy to the problems of soil engineering.
These generalizations provide a summary of the studies
made in the first two fields of soil investigation.

Soil mechanics in
engineering

As the result of the projects undertaken by
many engineering agencies in working out problems in
irrigation, flood control, road building, and military
fortifications, considerable information regarding the
physical character and compacted strength of soil has
been published. Before the turn of the last century,
Whitney (24), 1892, concluded that physical properties
are better for indicating the performance of soils than
are chemical properties. Although today's soil scientist
might request that this statement be qualified in that it
holds true for only some soils, the fact remains that man
can and has pushed back a vast curtain of unknowns in the
behavior of soil, by theoretical and experimental investi-
gations.

One of the first serious engineering studies
of soil serving as a foundation for soil mechanics today,
is that applied to fortifications in France in 1773.
According to Krynine (16), 1947, it was there that
Coulomb published a discussion of earth pressure in which
he dealt with particles of soil as "idealized fragmental
masses," and presented the general equation,

$$s = c + p \tan \emptyset$$

in which s is the shearing resistance of the soil, p is
the normal stress on the surface of sliding, c is the
constant of cohesion, and $\emptyset$ is the angle of internal

friction. In accordance with this formula, the shearing strength of a fragmental mass consists of a variable part p tan $\emptyset$ and a constant part c, although it was not specified in what proportion this value is taken separately by friction and by cohesion. Furthermore, there was no indication of the way in which small particles develop this cohesion.

Rankine (18), 1898, also presented an idealized picture of soil and considered that it was made up of grains of different sizes like sand. He developed a theory of equilibrium of earth masses and used it to solve problems involving shear and bearing strength of soil, but he worked with the variables of friction rather than particle size and grading.

Hazen (10), 1920, was one of the first to realize the need for a systematic method of indicating the size of particles which constitute a particular soil. He used the term "effective size" which is the particle size D_{10} such that 10% of all the other particles that make up the soil are smaller. This size is readily determined from the particle size accumulation curve.

As the result of experiments in concrete engineering, Talbot (20), 1923, devised the formula

$$p = (d/D)^n$$

to determine ideal grading for maximum density. In this formula p is the proportion of weight passing a given

screen or sieve opening, d is the size of opening, D is the maximum particle size, and n is an exponent varying from 0.24 to 1.20. When n = 1.0, the curve becomes a straight line, and when n = 0.5 the curve becomes a parabola. This equation was used to design a series of particle size curves from which mixtures of different size particles were combined by weight to give different graded aggregates for use in tests on concrete. Each curve on the particle size graph and each mixture was identified by the value of the exponent n in his equation.

Hogentogler (12), 1937, experimented with a well graded sand and a red clay, mixing them together in such a controlled fashion that their particle size analysis was represented by seven different, though similar shaped, grain size accumulation curves. The soil corresponding to each curve was compacted in a standard laboratory manner to determine the optimum dry density and moisture content. The sample composed entirely of red clay developed the lowest optimum density and the highest optimum moisture content. Soils prepared from the curves showing increasing amounts of sand had correspondingly higher densities and lower moistures at optimum conditions. A soil sample prepared from the sand alone, without its own minus 0.005 millimeter fraction, showed a density of 5.7 lb. per cubic foot less than that of the well graded sand. The optimum moisture was also lower.

No tests were reported for shear or bearing strength for these soil specimens.

Whittaker (25), 1939, studied the properties of clay on the basis of variable grading, and used his determined value of the specific surface area of the different gradings of clay to identify each particle size curve. The physical properties of the clay which he investigated were the plasticity, absorbed film thickness, shrinkage, and dry strength. He found that in general the dry strength increases with decreasing particle size until a maximum is reached; then dry strength decreases. He also came to certain conclusions on the physico-chemical aspects of small clay particles which will be mentioned later in this chapter.

Turnbull (23), 1948, not only developed a method by which optimum moisture content can be determined by the use of the particle size distribution curve, but he also investigated and compared the shear strength of three soils on the basis of their particle size distribution curves. In general, the value of the angle of internal friction, mentioned under the reference to Coulomb, decreased with greater percentages of fine particles. Since there was the chance that different types of clay might be present in each sample in the last mentioned tests, the results could not be compared directly. His work, however, serves as an illustration of an attempt

to analyze soil properties on the basis of particle sizes and grading.

Taylor (21), 1948, summarized previous findings on the correlation between density and soil strength by a statement to the effect that for a saturated clay there is a linear relationship between the logarithm of the compressive strength and the void ratio. With no structural disturbance this relationship appears to be independent of all other variables.

Evidently the idea of analyzing soil on the basis of particle size and grading is not new. However, several different ways of measuring or expressing the size and grading have been used with the result that it is difficult to compare results of the authorities. Terzaghi and Peck (22), 1948, reviewed the work of Allen Hazen with comments to the effect that the character of fine-grain soils depends chiefly on the finest 20 percent, and that it might be preferable to select D_{20} as the significant quantity.

The chemical aspects of soil studies

The engineer usually deals with soil properties as a system. Seldom does he break down the soil into fractions of similar properties to consider each variable separately. He is chiefly concerned with size and gradation. On the other hand, the soil scientist is more

apt to break down his problem and analyze the different parts.

In addition to the physical properties of the soil, there are an infinite number of variable factors which are due in one way or another to the physico-chemical activity of very small particles with liquids. These variables come into greater prominence as the soil is composed of larger amounts of small particles. That these variables should not be overlooked, has been illustrated in an account by Winterkorn (28), 1948. He told of a million dollar airport concrete pavement that is disintegrating at the present time for the sole reason that the engineer in charge neglected to utilize available information concerning the high sodium and magnesium content of the underlying soil.

Most of the early chemical studies of soil were carried on in the interests of agriculture. Hilgard (11), 1911, studied soil ingredients soluble both in water and acids. He found that although the initial leaching of virgin soil extracted a measureable quantity of material, subsequent leachings extracted little if any. When the soil is dried, not only are the soluble materials again drawn to the surface, but heating a soil even to 100° C renders additional amounts of soil ingredients soluble in water and in acids. Even the very common phenomenon of heat from the sun after a rain is effective in bringing

certain salts into activity which formerly behaved as
inert particles. The effect of these salts was shown by
Johnson and Norton (15), 1941, in their experiments on
deflocculation. They showed that the type of soluble salt
present makes considerable difference as to what chemical
agent should be used in treating soils to develop their
best properties.

Moore, Fry, and Middleton (17), 1921, undertook
a series of experiments to determine the active absorbing
component of the soil. They also showed that heating had
a very definite action in destroying this absorptive
power. After heating to 844° C the particles showed very
little power to absorb water and the same material after
being heated to 1130° C showed practically no power to
absorb water. One of the methods of determining the
absorption was to note the presence of colloidal particles
in suspension after weeks of settling in water.

Hogentogler (12), 1937, found a slight decrease
in plasticity of soil when heated to 300° C, a still
greater reduction when the temperature was raised to
400° C, and plastic properties were entirely destroyed
when a temperature of 500° C was reached. He also de-
scribed a method used in Australia for actually heating
soil in place and converting it into a brick-like material.

Berkelhamer (3), 1934, described a method of
classifying clays by the use of heat in dehydration and

rehydration of the particles. His experiments showed
that a dehydration loss of 8.3 - 13.0% from 300° C to
600° C and a rehydration gain of 0.1 - 7.6% from 300° C
to 65° C indicated a clay of the kaolinite type. A loss
of about 4.4% and a gain of about 14.2% in the same de-
hydration and rehydration temperature ranges indicated an
illite type of clay, and a loss of 2.6 - 5.5% and a gain
of 9.3 - 7.2% on dehydration and rehydration in these
temperature ranges indicated a montmorillonite type of
clay.

In regard to the heat of wetting, Hogentogler
(12), 1937, presented a formula for its determination at
that date and expressed the opinion of other authors that
its value might be the heat of absorption of vapors at
their saturation pressure.

Certain scientists have undertaken the study
of variables other than heat. Barker and Truog (1), 1938,
for instance, investigated absorbed moisture and compres-
sive strength on the basis of the pH value of the clay.
They showed that by the control of the pH of the clay,
certain physical properties of the clay can be improved.
They also brought into consideration the factors of solu-
bility of salts and base exchange capacity of the clays
which they investigated.

Grim (7), 1939, was particularly interested
in the base exchange properties of clays. Through his

efforts the reason for the breakup of certain clay parti-
cles into extremely minute flakes was determined. He
concluded that due to the high base exchange capacity of
montmorillonite clays its mechanical analysis is little
more than a measure of the degree of disaggregation.
According to Grim, there may be no relation between the
size distribution determined and the size distribution of
the natural clay.

Harman and Fraulini (8), 1940, showed that the
base exchange capacity of like materials is proportional
to surface area only. For kaolinite, shrinkage and heat
of wetting are linear functions of the base exchange
capacity.

According to the studies made by Whittaker (25),
1939, the plasticity of a soil is increased when hydrogen
is the absorbed cation. Also, in the case of kaolinite,
the removal of exchangeable bases increases the water
required to form a plastic mix of kaolinite.

Baver (2), 1940, observed that the sorption of
non-polar liquids by soil is very limited, and that it
increases with the dielectric constant of the liquid. He
assumed that such non-polar liquids as benzene and carbon
tetrachloride do not cause significant swelling and, con-
sequently may be used to measure the pore space of the
system. A non-polar liquid would only fill the pore
space whereas a polar liquid not only fills the pore

spaces but it also is oriented on the surface of the
particles to produce the phenomenon of swelling. The
difference between the sorption of the water and the non-
polar liquid, therefore, represents the amount of water
that is taken up in the swelling process, but it does not
exactly represent the total volume increase of the clay
because of certain contraction effects. These studies
are especially helpful in understanding the effect of
small particles on the strength of soil, for sorption
characteristics appear to be quite different for large
and small particles.

Hauser (9), 1941, reaffirmed the often suggested
belief that sorption is a necessary prelude to reactions
of small particles with liquids.

Another variable factor controlling the behavior
of small particles and therefore the effect of these small
particles on a soil system is the electrical charge which
not only surrounds small particles but which is also
capable of moving these small particles under certain
conditions. Coughanour and Utter (4), 1944, applied
formulas developed earlier for migration speed, elec-
tronic charge, and charge density to experimental results
in showing that the rate of migration, which is directly
proportional to the zeta potential, decreases with in-
creasing particle size. Other scientists have obtained
similar results.

Winterkorn (26), 1947, gave evidence which indicated that there is a special form of electrical-osmosis known as thermo-osmosis. Although the complete function of this newly introduced variable is not yet understood, the fact that it is a variable factor and that it is a consequence of film water on fine grains of soil is reason to present it at this time.

Eustis and Shockley (5), 1948, reported the laboratory and field tests made on solids treated with certain commercial, resinous water repellents. The experiments showed that by the use of from 0.5% to 2.0% repellent by dry weight of the soil, sand-clays, sand-clay gravels, and similar base course soils having relatively high plasticity indexes can be treated to develop better strength and stability.

Geotechnical summary

Much of the valuable knowledge uncovered in the fields of pure soil mechanics and scientific research is scattered throughout technical perodicals and classical publications. Krynine (16), 1947, stated that a study of American engineering literature for the last half century shows that about all of the outstanding achievements in soil science were actually known years ago. It was necessary to put together and apply the information on shear resistance, particle size, and other factors involving strength of compacted soil. For the most part

this has been accomplished since 1920.

Out of the scientific studies and discoveries concerning the role of soluble salts has come a general understanding of cementation. The engineer is prone to deal with a multitude of variables under this one heading because of the high degree of correlation that exists between the aggregation of small particles and the amounts of cementing agents present. Dehydrated oxides of iron and alumina, colloidal clay, organic matter, and inorganic salts are cementing agents according to Baver (2), 1940, and are often lumped together as a single variable factor. Winterkorn (27), 1948, cited the setting up of a graded mixture of siliceous aggregate and lateritic clay as one example and the cementation resulting from the mixture of limestone aggregate with podsolic clay as another. Terzaghi and Peck (22), 1948, stated that Coulomb's formula (presented earlier in this chapter) can be used in the case of cementation of sands--the cohesion depending only on the strength of the bond between the sand particles. This cohesion was determined from c in the equation:

$$s = c + p \tan \emptyset$$

They also pointed out that sands with the same void ratio, whether in a cemented or cohesionless state, have approximately the same angle of internal friction.

Although the variable factors governing the

behavior of clays are numerable and of vital significance in certain cases, the geotechnician has been able to simplify their over-all effects, somewhat. Johnson and Davidson (14), 1947, pointed out that until there is enough clay to coat the non-clay particles and exert appreciable bonding strength, factors other than cohesion, such as internal friction and surface tension are most effective. In this case the clay is simply a cementing agent and the formula just mentioned holds true; that is, cohesion because of its relative unimportance can be considered a constant. They also said that if the clay content is increased beyond the amount necessary to coat all non-clay mineral surfaces, the cohesion is not a constant but on the contrary, it increases up to a certain point with consolidation. In this case of high clay content the particles may be so consolidated that only the waterfilms separate the individual flakelike clay particles. It is at this point according to these two authors, that the multitude of physico-chemical variables take effect. If the engineer or geotechnician is aware of this possibility he still may have the choice of several courses of action; he may add coarse particles to the soil system or he may investigate the possibility that although these small particles of clay are present, they are not normally in the dispersed state, but in an aggregated condition. Winterkorn (27), 1948, pointed

out that in most soils the calculated internal surface of
the clay is a potential rather than an actual surface
because clay is normally not in a dispersed but in an
aggregated condition.

It thus becomes apparent that the size of the
particles making up a soil system is not only a physical
factor but a chemical variable as well. To the geotech-
nician it is an extremely significant factor, and a better
understanding of its function in the control of shear and
bearing strength would be of value to the engineer. As
an engineering aid, Terzaghi and Peck (22), 1948, divided
soil index properties into two classes; soil grain prop-
erties and soil aggregate properties. If the soil grain
properties include the variable factors of size, shape,
specific gravity, and gradation, then all of the remain-
ing variables are included under the heading of aggregate
properties.

In making this study of the effect of small
particles on soil strength, the intention is to observe
how the shear strength varies as the soil grain proper-
ties are varied and the soil aggregate properties are
held constant. Since the problem is undertaken on only
one particular type of soil, other types of soil with
different aggregate properties will have to be investi-
gated to obtain a knowledge of the effect of variable
aggregate properties on soil strength. Also in this

initial problem of the study, only the variables of size and gradation within the factor of soil grain properties will be varied.

Chapter III
METHODS AND MATERIALS

The practicality of an attempt to determine
the physico-chemical effects on the strength of a soil
system depends almost entirely on the materials and test-
ing methods employed. This particular study involved
determination of the general soil characteristics,
separation of the soil fractions, preparation of the
soil systems, elimination of the physico-chemical effects,
and the methods of testing for soil strength.

General soil characteristics

About 200 pounds of one particular type of soil
were required to supply the soil particles which composed
the artifically prepared systems.

Origin.--The material selected for use in these
tests was taken from the region where U.S. Highway No. 6
crosses the continental divide at Loveland Pass. Dis-
integrated granite appeared to be the parent material.
Samples of the soil were taken at two to three hundred
foot intervals for about one thousand feet along the
highway from the surface to a depth of about three feet.

Classification tests.--Standard soil classifi-
cation tests of the Colorado State Highway Department

laboratory included a particle size analysis, liquid limit, plastic limit, visual mineral identification, and acid test for carbonates. In general, the material consisted of about 7% clay, 20% silt, 50% sand and gravel, and about 23% of particles larger than the mesh of a No. 4 sieve. The liquid limit was about 29% moisture, and the plastic index was less than 6% moisture. Orthoclase, feldspar, and biotite mica were the predominent minerals, although quartz particles were also present. There was hardly any reaction between the soil and 0.1 normal solution of hydrochloric acid indicating that there was very little carbonate present.

The clay fraction.--Special tests, including a chemical analysis, dehydration--rehydration test, and pH determination were made on the clay fraction (0.005 mm particles and smaller) to identify the clay more thoroughly.

About 50 grams of clay were taken from a representative sample of the minus No. 200 material by a process of dispersion and elutriation. A chemical analysis of this clay showed the following:

Insoluble residue	71.77%
Sulfates	0.52
$Fe_2O_3 + Al_2O_3$	9.94
CaO	1.80
MgO	0.93

Loss on ignition   10.03

Undetermined   5.01

The dehydration--rehydration test presented by Berkelhamer (3), 1943, indicated a mixture of illite and kaolinite. The limits given by Berkelhamer and the results of the test on the clay used in this experiment are shown below. Empty containers were heated at the same time to make corrections for container loss and gain. A sample of fuller's earth tested the same way and at the same time showed true montmorillonite values.

Mineral	% loss on dehydration from 300° C to 600° C after two hours	% gain on rehydration from 300° C to 65° C after two hours
Kaolinite	8.3-13.0%	0.1-7.6%
Illite	about 4.4%	about 14.2%
Montomoril- lonite	2.6-5.5%	9.3-27.2%
Clay tested	5.6%	5.7%

A pH value was also determined on the clay fraction. The clay was mixed with distilled water having a pH of 7.0 in the amount equal to about 16% solids by weight. The pH value indicated by the Beckman Glass Electrode meter was 7.3.

Separation of soil
fractions

After classification tests were run on the virgin soil, its particles were separated into certain

size groups by the use of sieves. A particle size analysis by the hydrometer method was also made in order to determine the percentages of different size particles smaller than the No. 200 sieve (0.074 mm.).

Separation of particles by sieving.--The soil was first mixed and washed with water over a No. 200 sieve. Special attention was given to see that all aggregations of clay particles were broken down enough to pass that sieve. Particles washed through the sieve either settled or were suspended in the wash water. All of this water was evaporated at temperatures not exceeding 140 F. To break up the crusts and aggregations of this dried minus No. 200 material, it was worked through smaller and smaller sieves until it finally passed the No. 200 sieve in the dry condition. Coarse material that was retained on the No. 200 sieve was also dried at 140 F and, by the use of sieves, divided into fractions. The following sieves were used: 3/4 inch, No. 4(0.187 in.), No. 10(2 mm.), No. 40().420 mm.), and No. 200(0.074 mm.).

Size analysis by hydrometer method.--A representative sample of the minus No. 200 material was analyzed for particle size by the hydrometer method. In so doing, the deflocculation agent (20 ml of a 3 degree Baume solution of sodium silicate made from meta silicate crystals) was added to 50 grams of the dry material. About 1/2 pint water was added to this mixture and the

suspension dispersed for one minute by the use of a malt mixer. The analysis was made according to the standards of the American Association of State Highway Officials. A copy of the worksheet is included in Appendix B.

Preparation of the soil systems

The fractions obtained from the original soil were mixed in different proportions to form eight soil systems each weighing 10 pounds. The proportions used in mixing each system were determined from particle size curves. Classification tests and void data were determined for each soil system to serve as an aid in identification.

Selecting the particle size curves.--The eight particle size curves chosen are shown in Figure 1. They were chosen arbitrarily as curves typical of well-graded soils found in Colorado. The spacing between curves was judged to cover the interval from the curve for a well-graded coarse-grain soil to a curve for a very fine-grain soil. Spacing of the curves was originally planned for seven soil systems, but test data indicated that another soil system was needed.

In order to extend the particle size curves beyond the size limit of the No. 200 sieve, the information obtained from the particle size analysis of the minus No. 200 material was used. Percentages of particles

Fig. 1.--Particle size graph
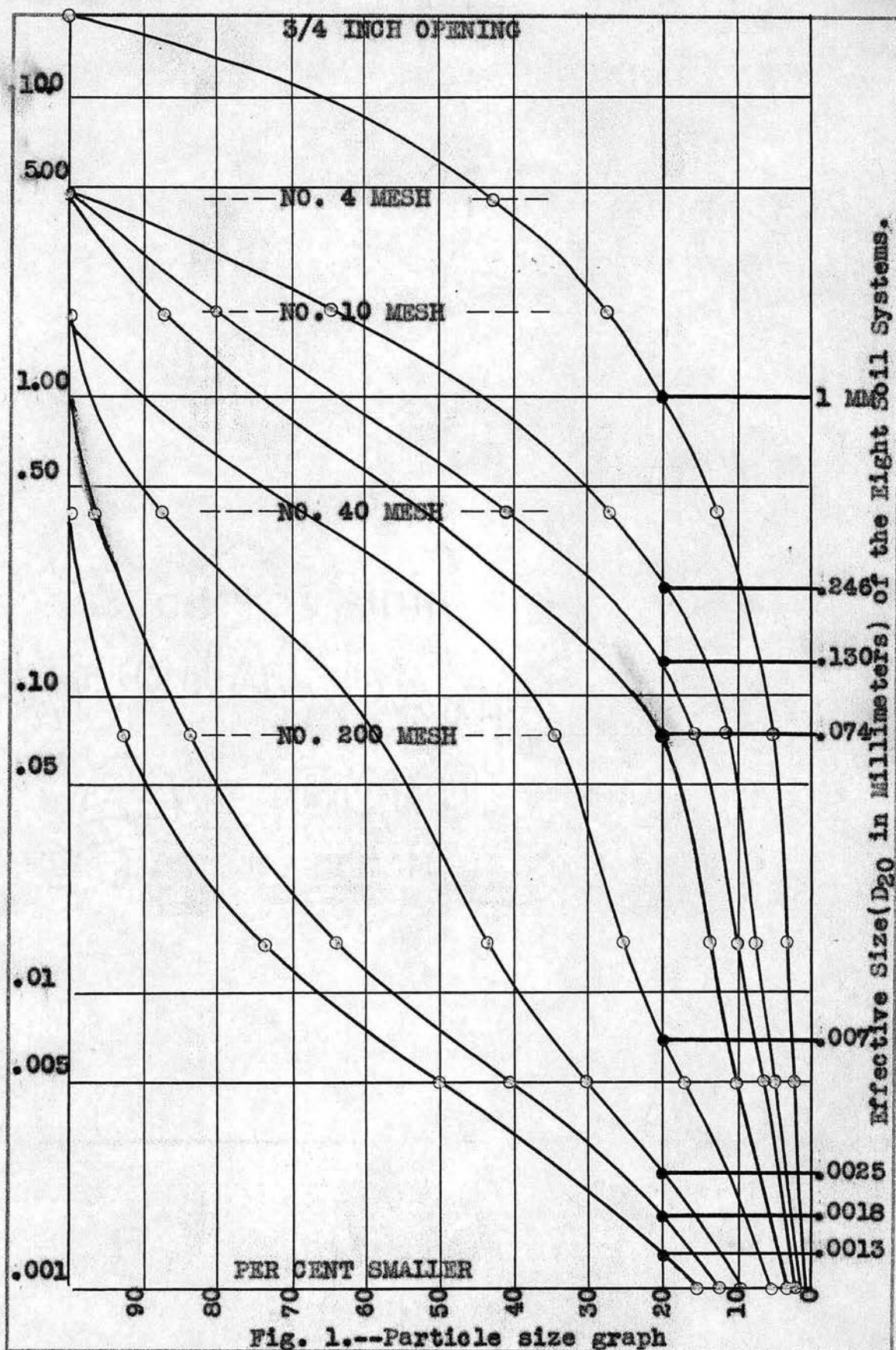
smaller than this sieve were calculated from the percentage of minus No. 200 material mixed in each soil system and the results plotted on the particle size curve.

The soil fraction larger than the 3/4-inch square sieve was discarded since laboratory tests for shear and bearing strength are not ordinarily run on material this large. In so doing, the particle size curve for the soil system with the largest amount of coarse material necessarily showed 100% of the particles passing the 3/4-inch sieve.

Classification tests.--To aid in identifying each soil system, classification tests were run and void data calculated for each soil system. The tests run were the liquid limit, plastic limit, specific gravity, and the compaction test for optimum density and moisture. All tests were made according to the standards of the American Association of State Highway Officials except the compaction test which was a modified type. AASHO standards were followed in this particular test except that the compactive effort was increased in order to match more closely the compaction of very heavy sheepsfoot rollers which have recently come into use. The laboratory compaction was by the use of a 10 pound rammer dropping a distance of 18 inches, 25 times on each of five layers of soil in a 4-inch diameter mold having a volume of 1/30 th cubic foot.

From the classification tests it was possible
to determine theoretical void data for each system and
thus obtain another means of classifying the artificially
prepared soils. The percentage of air voids by volume
was based on 100% compaction at optimum moisture. The
void ratio and the moisture at saturation, however, were
based on 95% of the optimum dry density since soil is
usually compacted with sheepsfoot rollers in field work
to only that degree. Table 1 shows the results of the
classification tests and the calculated void data.

Formulas used were:

$$\% \text{ air voids} = 100\left(1 - \frac{D}{D_0}\right)$$

$$D_0 = \frac{62.4G}{1 + \frac{GW}{100}}$$

$$\text{moisture at saturation} = 100\left(\frac{62.4}{0.95D} - \frac{1}{G}\right)$$

$$\text{void ratio} = \frac{100 - \%S}{\%S}$$

$$\%S = \frac{0.95D}{62.4G}$$

where G = Specific Gravity of the soil system
    W = Optimum moisture content
    D = Optimum dry density
    D_0 = Dry density with zero air voids
    $\%S$ = Percent solid material

The eight soil systems prepared and classified
as just described were identified by the point where
their particle size curve crossed the ordinate at 20%--
commonly designated as D_{20}. The particle size in

Table 1. -- Summary of identification tests & void data.

D$_{20}$ & Surface Area in cm^2/gm	Atterberg Limits			Compaction Results		Specific gravity	% air voids by volume	At 95% compaction	
	LL	PL	PI	Opt. moisture. Percent by dry weight	Opt. dry density lb./cubic foot			Theoretical Sat. Moisture % of dry weight	Void ratio
1 mm. (262)	25.8	20.8	5.0	4.3	139.0	2.66	4.0	9.6	.271
0.246 (455)	25.6	21.6	4.0	7.3	136.5	2.69	2.6	10.9	.294
0.130 (608)				7.7	133.7	2.69	3.9	11.9	.321
0.074 (832)	33.1	24.8	8.3	8.3	132.2	2.70	3.8	12.7	.342
0.007 (1402)	34.0	24.8	9.2	9.0	130.9	2.71	3.5	13.2	.359
0.0025 (2414)	35.5	24.9	10.6	10.9	125.0	2.72	4.5	15.7	.428
0.0018 (3410)	43.7	30.1	13.6	13.7	118.1	2.73	4.7	18.9	.517
0.0013 (3836)	46.4	31.5	14.9	16.1	113.6	2.73	4.0	21.2	.575

millimeters indicated by this point was called the effective size following the suggested revision of the Allen Hazen method by Terzaghi and Peck (22) 1948.

Elimination of physico-chemical effects

In the analysis of the main problem a statement was made that the effect of small particles on the strength of the soil could be observed best if a comparison was shown between the strength of the soil when the effect of the small particles was nullified and the strength of the soil when the small particles exhibited their usual physico-chemical activity with water. An attempt, therefore, was made to treat each of the soil systems in such a manner that physico-chemical reactions would be at least repressed and perhaps nullified. A review of literature indicated that the methods most suitable for use were those employing a non-polar liquid as the wetting agent, the use of heat, and the use of waterproofing agents.

Use of a non-polar liquid.--Baver (2), 1940, pointed out that non-polar liquids, particularly those with low dielectric constants, showed practically no reaction with small particles. Kerosene appeared to be the most suitable liquid for this experiment since other common non-polar liquids such as benzene and carbon tetrachloride evaporate so rapidly that it would be hard to

control the amount mixed with the soil.

After strength tests were run on three of the
artificially prepared soil systems, the material was
dried and mixed with kerosene. As an indication of how
little activity between the soil and the kerosene took
place it should be stated that puddles of kerosene in the
soil were not discolored to any extent and the soil ap-
peared to have no plasticity.

Use of heat.--According to Hauser (9), 1941,
another method of preventing the reaction of clay parti-
cles with water is to prevent the sorption processes.
In the review of literature, were listed authors who
found that heating soils was an effective way of prevent-
ing sorption. Three of the soil systems were heated.

One soil system was heated for eight hours to
approximately 400° C, cooled and again mixed with the
previously determined optimum moisture. Another of the
artificially prepared soil systems was heated to 1000° C
for one hour. Certain aggregations in this system were
observed to have fused, giving them a brick-like appear-
ance, and the percentage of material passing the No. 200
sieve was reduced from 82% to 52.3% for that soil system
as a result of the prolonged heat treatment. To prevent
fusion of the particles, the minus No. 200 fraction of
the last soil system was given the heat treatment to
1000° C for only 20 minutes. Little if any fusion took

place in this case as was evidenced by the particle size analysis recorded in Appendix A.

Use of a waterproofing agent.--Another method of preventing sorption was attempted by the use of a waterproofing agent, aluminum stearate. This compound has been used in the paint industry and its action was reported by Gardner (6) 1937. It is soluble in only a few liquids and then to a limited extent. The method employed in this experiment was to add aluminum stearate powder to mineral spirits in such quantities that no more would dissolve and the solution became milky. Xylol was then added to the solution and stirred until the resulting mixture of liquids just became clear. At this point it was assumed that the liquid had dissolved all of the aluminum stearate possible. This solution was then very thoroughly mixed with the dry soil to be treated. The mineral spirits and xylol were evaporated from the soil at a temperature of 140° F and optimum moisture was added in the amount determined previously when the regular compaction test was run.

Methods of testing for soil strength

California Bearing Ratio Test.--Before and after treatment the California Bearing Ratio Test and the stabilometer test were performed on each soil system. The California Bearing Ratio Test has been extensively

used by highway departments in California and other states,
as well as by irrigation and flood control agencies, to
test the relative bearing value of base, sub-base, and
sub-grade material. When used as a design test CBR values
can be used with moisture, frost, and load indices to in-
dicate the amount of ballast necessary to support the
pavement or surfacing. Since CBR values are only compa-
rable when tests are performed in an identical manner,
the method used in this experiment will be described
briefly.

The amount of soil and water necessary to com-
pact the soil specimen in a 6-inch diameter cylinder to
a height of 4.73 inches at 95% of the optimum density was
first calculated. Since the test is quite sensitive to
moisture content, hygroscopic moisture in the soil was
considered. Regular Denver tap water was mixed with the
soil. The soil was compacted in the 6-inch cylinder by
static loading at the rate of 0.05 inches per minute, and
a record was kept of the load necessary to secure the
proper compaction. A 6-inch diameter filter paper was
then placed over each end of the soil specimen in the
cylinder. The base plate, the 12 1/2 lb. surcharge, and
the tripod containing Ames dial were set in place to
measure the swell. The cylinder was set to soak in a
water tank with the level of the water approximately
4 1/2 inches above the top of the sample. After soaking

four days, the swell was read to the nearest thousandth
of an inch and the cylinder containing the soil specimen
was removed from the water. The tripod and surcharge
were removed and water was poured out of the cylinder.
The soil specimen was then left in the cylinder to drain
in the air for 15 minutes after which the test was begun.

Surcharge weight during penetration was 12 1/2
pounds. The standard penetration piston (three square
inches in area) was forced into the specimen at the rate
of 0.05 inches per minute for a distance of 0.5 inches.
The stress was recorded at the end of every 0.1 inch of
penetration, and a bearing ratio based on the accepted
standard resistance of crushed rock was determined. The
average of all bearing values except the first 0.1 inch
penetration was taken as the CBR values for the particular
soil. A typical work sheet for the test is in Appendix B.

Stabilometer test.--The stabilometer is a
device for determining the intermediate or minor principal
stresses when the major principal stress is known. A
resistance value was determined by dividing the horizon-
tal pressure indicated on the gage of the stabilometer by
the applied vertical pressure and then subtracting this
quotient from unity. This expression is directly pro-
portional to the ratio of the maximum shearing stress to
the major principal stress, and has been found by corre-
lation of field data and experimental data to be a

function of the thickness of cover required over the soil according to Hveem and Carmany (13) 1949.

The resistance value is also affected by the moisture content. After running the CBR test, the specimen was removed from the cylinder and the soil recompacted in a 4-inch cylinder using the same compactive effort as was used in the compaction test. The 4-inch diameter specimen was then cut off and trimmed to a 2 1/2 inch height, wrapped in a thin sheet of paper, and placed in the stabilometer. In so doing, however, it was probable that the soil was neither exactly at optimum or saturation moisture content during the test because of the effect of permeability of the soil specimen during the 4-day soaking period. An initial horizontal pressure of five pounds per square inch was set on the specimen to insure close fitting of the rubber diaphragm. Loading was at the rate of 0.05 inches per minute and readings were taken at 40, 80, 120, and 160 psi vertical load. The readings used to determine the resistance value correspond to a vertical load of 120 pounds per square inch. A sample worksheet for the stabilometer test and the CBR test is listed in Appendix B.

Chapter IV

ANALYSIS OF DATA

In this attempt to determine how the physico-
chemical properties of a soil mass affect its overall
strength, data were obtained by calculating the specific
surface area of each of the soil systems, and by making
strength tests on each of the soil systems both before
and after the treatment to nullify the physico-chemical
properties. The data, analyzed in this chapter under
headings similar to those used when the problem was
analyzed, are presented as: determination of surface
area, strength of the untreated soil systems, strength of
the treated soil systems, and comparative strength.

Surface area

An arbitrarily determined value of the surface
area was calculated for each soil system based on per-
centages of the different-sized particles which composed
that soil. The percentages of each different-sized
particle group, the size limits for each particle group,
and the contribution to the total specific surface area
by each group is shown in Table 2.

Composition of the soil.--The percentages of
each group of different-sized particles for each soil

Table 2.—Method of calculating the specific surface area.

D20 in mm. — Figure in parenthesis below is the contribution to total surface area in square centimeters per gram.

D20 in mm.	%Gravel:	%Coarse sand:	%Fine sand:	%Silt:	%LargeClayParticle:	%Colloids	TOTAL SURFACE AREA
1 mm.	71.5 (1.5)	18.4 (3.7)	4.0 (6.1)	3.0 (25.2)	2.1 (58.4)	1.0 (167)	262
.246	37.4 (0.7)	44.0 (8.9)	9.0 (13.8)	4.0 (25.2)	3.8 (105.5)	1.8 (300.5)	455
.130	22.9 (0.5)	49.0 (9.9)	14.0 (21.4)	7.0 (58.8)	4.8 (133)	2.3 (384)	608
.074	11.3 (0.2)	50.0 (10.2)	20.0 (30.6)	9.0 (129)	6.5 (314)	3.2 (919)	832
.007	-----	47.8 (9.7)	20.0 (30.6)	15.4 (129)	11.3 (314)	5.5 (919)	1402
.0025	-----	23.4 (4.7)	21.0 (32.2)	26.0 (218)	20.0 (556)	9.6 (1603)	2414
.0018	-----	6.2 (1.2)	12.0 (18.4)	40.0 (336)	28.2 (784)	13.6 (2270)	3410
.0013	-----	2.0 (0.4)	8.0 (12.2)	42.3 (556)	32.3 (897)	15.4 (2570)	3836

Soil Constituent	Size in mm.	Average Size cm.	Shape	Sp.Surface in cm/gm	Reference
Gravel	Above 1.981	1.050	Sphere	2.16	Robinson(19)1932
Coarse sand	1.981-0.246	.1113	Sphere	20.3	
Fine Sand	0.246-0.05	.0148	Sphere	153.0	
Silt	0.05-0.005	.0027	Sphere	840	
Clay(lg.part)	0.005-0.001	.0003	Disc.	2780	
Colloids	below 0.001	.00005	Disc.	16700	Baver(2)1940

system were obtained from the particle size curves of Figure 1. They show that coarse grain soils contain high percentages of large size particles and that fine grain soils contain large percentages of very small particles. Coarse grain soils are indicated by the high effective sizes; D_{20} = 1 mm corresponds to the coarsest grained soil system, and the four finest grained soils contain no gravel since all of the particles which compose them passed the No. 10 (1.981 mm.) sieve.

Calculation of the specific surface area.--The specific area was calculated on the theoretical assumption that all particles larger than 0.005 mm are spheres and all particles smaller than that size are disc-shaped. The formula used to determine the surface area of a unit weight of uniform spheres was:

Surface area = $\dfrac{D^2}{\dfrac{D^3}{6}} \times \dfrac{1}{G} = \dfrac{6}{DG}$

where D = diameter of the particle and G = specific gravity.

The formula used to determine the surface area of a unit weight of uniform discs was:

Specific surface = $\left(\dfrac{2}{h} + 2\sqrt{\pi h} \right) \dfrac{1}{G}$

where h = diameter and G = specific gravity.

Table 2 shows the composition of the soil and the method of calculating the specific surface area.

Strength of untreated
soil systems

The results of the California Bearing Ratio
Test and the Stabilometer test for each soil system are
listed in Table 3. In Figure 2, these values were also
plotted using strength values on an arithmetic scale as
the ordinate and specific surface area values on an arith-
metic scale as the abscissa.

The general trend to be noted is that the
strength of the coarsest grained, well graded soil is
highest, and, when the soil systems are arranged in the
order of increasing amounts of small particles they are
also arranged in the order of decreasing soil strength.
Also to be noted is the fact that the strength values
indicated by both the California Bearing Ratio test and
the Stabilometer (R) test decrease at about the same rate.
Stabilometer tests were not made on the coarsest soil
system because of the damage which coarse, angular
particles do to the rubber walls of the stabilometer.

From Table 3 it is also evident that the per-
centage of swell and the percentage of moisture in the
soil system at the end of a four day soaking period in-
creases when the soil systems are arranged in the order
of increasing percentages of small particles.

From Table 3, it should also be noted that, in
general, the static load necessary to compact the soil

Table 3. - Strength test data.

D_{20} (Sp.Surface Area)	% Swell (Before Tr)(After Tr.)	% Moist.by dry wt. (Before Treatment) (After Treatment)		Static Load (Before Tr) (After Tr)	CBR value (Before Tr) (After Tr)	"R" (Before) (After)	Kind of After Treatment given the soil system......
		Top of Specimen	Bottom of Specimen				
1 mm. 262	0.01% 0.4 %	7.06 ----	5.71 ----	56,040 56,040	153.0 164.0	-------- --------	Kerosene used instead of water for mixing and soaking.
.246 455	0.3% 0.0%	9.17 9.51	9.17 11.36	22,550 31,700	42.2 55.0	59.0 73.8	Waterproofed with Aluminum stearate.
0.130 608	0.5% 0.3%	10.86 11.86	9.17 10.83	13.600 56,040	21.6 92.1	45.0 82.5	- No.200 fraction heated at 1000 C for 20 minutes.
.074 832	0.9% 0.9%	13.12 13.12	10.61 10.86	9,450 20,000	15.1 24.8	39.0 52.5	Total soil system heated at 400 C for 8 hours.
.007 1402	1.1% 0.4%	14.42 ------	12.11 ------	9,700 56,040	11.4 93.6	29.0 90.0	Kerosene used instead of water for mixing and soaking.
.0025 2414	2.3% 1.1%	17.65 14.14	14.94 12.11	10,850 16,400	7.4 21.1	25.0 48.8	Waterproofed with Aluminum Stearate.
.0018 3410	3.5% 1.0%	21.95 22.88	17.65 20.77	9,600 56,040	5.2 114.2	21.2 86.8	Total soil system heated at 1000 C.
.0013 3836	3.4% 0.4%	25.00 ------	21.07 ------	6,650 56,040	4.8 94.3	21.0 88.1	Kerosene used instead of water for mixing and soaking.

47
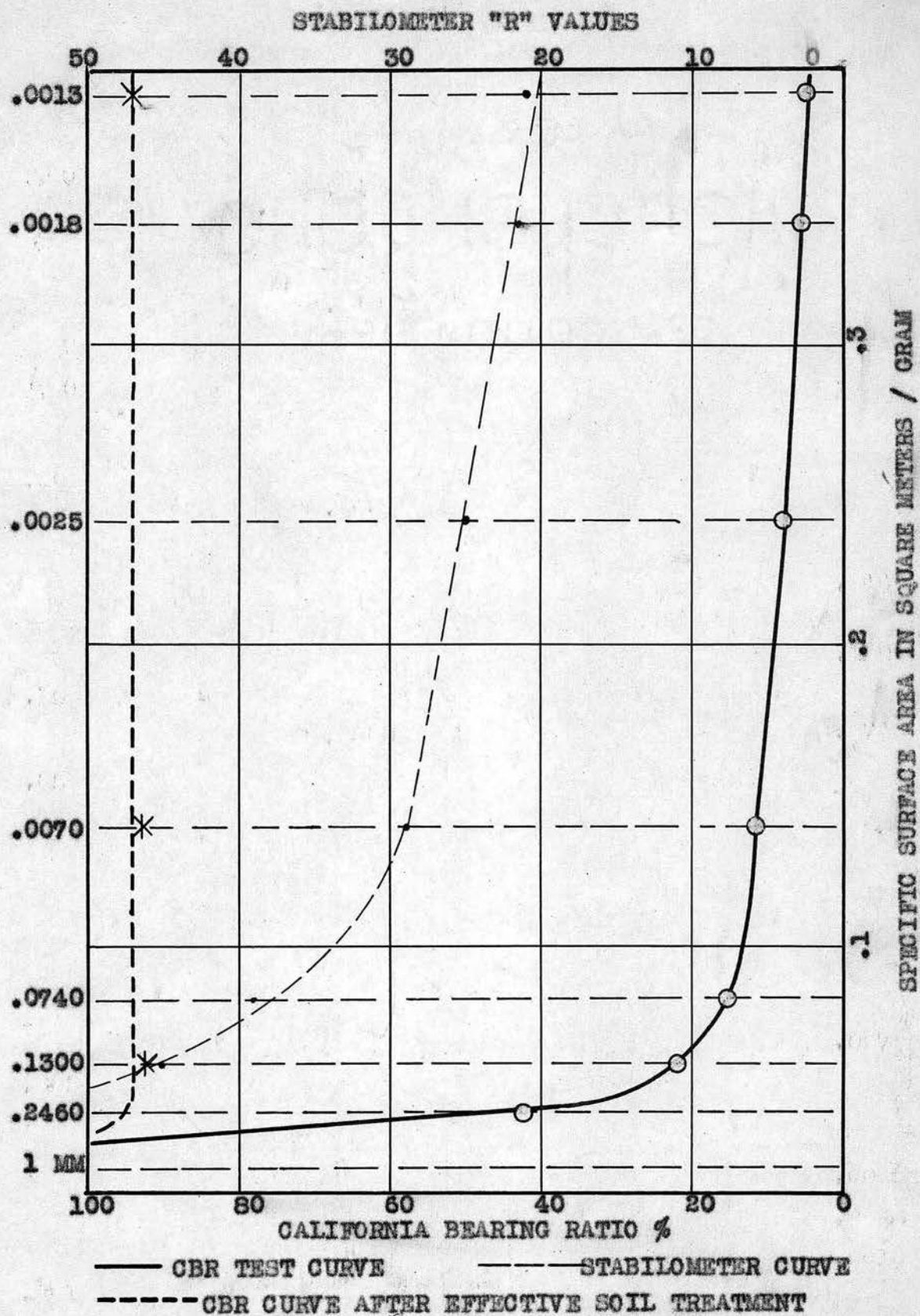
Fig. 2.--Graph of strength test data

is less for soil systems with large amounts of small particles than it is for soil systems with small amounts.

Strength of the treated
soil systems

Results of the two different types of strength tests on the treated soil systems are given in Table 3 directly under the entries for the results of the tests on the untreated soil. Certain CBR values are also plotted in Figure 2. To be noted are the high strength values of certain very fine grain soils which have been treated. The strength values of the soil systems having effective sizes of 0.130 mm, 0.007 mm, and 0.0013 mm, for example, have nearly the same high value.

It should also be noted that treated soils showed very little swell, but in general the percent of moisture in the soil after soaking was greater for fine-grain soils than for coarse-grained soils.

The static load necessary for compaction of the soil was very high for all except three soil systems. A total load of 56,040 pounds corresponds to approximately 2,000 pounds per square inch.

Comparative strength

A comparison of the strength data of treated soils with that of the untreated soils shows that in every case the treatment to nullify the physico-chemical

effects resulted in increased strength of the soil system.
The amount which the strength was increased is different
for different types of treatment, and in general the soil
systems showing greatest increase in strength are the
soils which were treated with kerosene and those which
were heated to 1000° C. In almost every case, the soil
system swelled less and required a greater static load
for compaction after it was treated.

In the case of every soil system investigated,
the treatment appeared to have made little or no change
in the percentage of moisture in the soil after the four
day soaking period.

Chapter V
DISCUSSION

The data presented in Chapter IV indicate that
as the percentage of small particles increases in the
untreated soil-water system, the compacted strength de-
creases. In the treated systems, however, the small
particles caused no appreciable reduction in strength.
In discussing the problem undertaken in this study certain
other results of the tests come to light regarding the
effect of small particles on the strength of soil. These
results will be discussed under the same general headings
and in the order that was used when the problem was
analyzed in the introduction of this study.

Effective size and surface area

The effective size and the surface area were
values determined to assist in identification, since
each soil system could have only one effective size and
one arbitrarily calculated specific surface area.

Effective size.--The effective size was chosen
as D_{20}, instead of D_{10}, as was used by Hazen (10), 1921,
and others. The particle size curves on Figure 1 make
it possible to obtain the D_{10} value for each soil

system if desired.

Surface area.--Soil systems that were prepared according to effective particle sizes ranging from 1 mm to 0.0013 mm were found to have specific surface areas varying from about 250 square centimeters per gram to 4000 square centimeters per gram. From the review of literature, it was observed that many investigators have used a theoretical means of determining surface area. The values used in this study correspond reasonably well with those of the same size particles previously reported in the literature.

Characteristics of the untreated soil systems

Figure 2 illustrates the characteristics and the variations in strength of the untreated soil systems.

Variation of strength with effective size.-- The curves representing the strength values obtained for each type of strength test indicated a fairly continuous function in the range of soil systems up to an effective size of approximately 0.074 mm. At this point the curves, representing the strength of the soil for both the stabilometer and the CBR tests, rose rapidly and became nearly vertical in the vicinity of the 1 mm effective size. In the light of what was reviewed in literature regarding the behavior of the soil system when it is predominantly composed of small particles, it may be

said that the break in the curve at the upper end of this almost horizontal, straight line, indicates the approximate composition of a soil system where small particles are present to such an extent that their effect is greater than just that of cementing the large particles. Below this point the coarse particles are so few that the internal friction no longer controls the strength of the system.

Indication of D_{20} value for safe sub-base.--
According to design procedures in use by the highway departments of Colorado, California, and other states, a soil with a CBR value over 25 requires no ballast to protect the oil mat from the underlying compacted soil. If it may be assumed that soils with strength above this value are excellent bases for highways, for irrigation and flood control structures, it might also be said that for the particular type of soil investigated in this study, the effective size D_{20} of a safe sub-base should be 0.170 mm or higher.

Nullifying the effect of
very small particles
in the soil

Methods for making small soil particles inactive in the soil system were indicated in the review of literature. Of the methods reviewed, it appeared that three of them would be satisfactory for use in this investigation. These methods were described in Chapter III.

Strength of the treated
soil systems

Figure 2 illustrates the characteristics of
the treated soil systems as indicated by the CBR strength
tests. The results of both strength tests on each
treated soil system are listed in Table 3.

Kerosene treated soils.--Soil systems idenfi-
fied by a D_{20} of 1 mm, 0.007 mm, and 0.0013 mm were
mixed with a volume of kerosene equal to the volume of
water previously used in the standard strength tests.
It appeared that when the small particles were unable to
react as they do with a polar liquid, the strength of a
soil system, even though composed only of very small
particles, was comparable to that of a very coarse, well-
graded soil. The physico-chemical effect of the small
particles appeared to have been responsible for reducing
the CBR value from 94.3% to 4.8% in the case of the
finest soil system investigated. Because the CBR value
of about 94% was obtained for both the 0.007 mm and the
0.0013 mm kerosene treated soil systems, it appears that
the CBR values become independent of the particle size
and distribution. As a matter of fact the materials
making up these two soil systems behaved similarly dur-
ing the CBR test. Both specimens resisted penetration
strongly for the first 0.1 inch. Then the top surface
of both gave way very gradually and "fluffed" while re-
sisting the penetration for the last 0.4 inch. It is a

common tendency for non-plastic materials, such as blow sand and silt, to behave in this manner. It is evident from the above discussion, therefore, that kerosene is effective in nullifying the physico-chemical effects.

Soils heat treated at 400° C.--The soil system heated at about 400° C for eight hours showed a CBR value of only 24.8% despite the relatively coarse size of particles of which it was composed. Evidently that temperature was not high enough to render the small particles totally inactive. This result might have been predicted as a result of the dehydration test performed on the clay before the strength tests were run. In the temperature range between 300° C and 600° C the specimen lost about 5.6% moisture to indicate that it took temperatures considerably above 300° C to drive off the water of crystallization. This observation is supported by Berkelhamer (3), 1934, who stated that a temperature of 500° C is necessary to release the crystal water from kaolinite.

Soils heat treated at 1000° C.--The soil systems identified by D_{20} = 0.130 mm and D_{20} = 0.0018 mm were heated to 1000° C. The effectiveness of this attempt to nullify the physico-chemical properties of the small particles was readily observed when the specimen "fluffed" during the strength tests. Furthermore, the CBR values obtained were nearly the same as the CBR

values obtained on strength tests of kerosene-treated soil systems. The exceptionally high CBR value shown by the $D_{20} = 0.0018$ mm soil system was no doubt partly due to fusion of the particles, as this was the soil system which was described in Chapter III as having been subjected to the 1000° C temperature for one hour during treatment.

Soils treated by waterproofing.--The soil systems identified by $D_{20} = 0.246$ mm and $D_{20} = 0.0025$ mm were treated with aluminum stearate. An indication of the ineffectiveness of this method was apparent from the small increase in strength shown after treatment. Other evidence of how ineffectively the treatment nullified the physico-chemical activity of the small particles was shown in the retention of plastic properties by the soil and the low static load necessary to compact it. Furthermore, there was no "fluffing" action at the surface of the specimen during penetration.

Effect of the physico-chemical properties upon strength

The strength of the soil systems treated to effectively repress the physico-chemical reactions of small particles appeared to be well above the critical CBR value of 25%. In fact, the CBR values around 93% appear to be in line with the well-graded, coarse-grained soil systems having effective sizes of 1 mm and 0.246 mm.

The evidence seems to indicate that if it were not for the physico-chemical activity of the small particles, even the soil systems composed entirely of the very small particles would have high strength. If a practical way were devised for effectively repressing these small-particle reactions, use might be made of all soils as good foundation bases.

Tests made with this one particular type of soil, however, give evidence that when an increasing number of small particles are mixed with larger particles, the untreated soil system loses strength rapidly to a point where the effective size is approximately 0.074 mm. Thereafter, the system continues to lose strength but at a decreasing rate.

Chapter VI
SUMMARY

This attempt to determine how the physico-chemical properties of a soil mass affect its overall strength resulted from the realization that soil tests in use at the present time are quite expensive and time consuming. Furthermore, greater use might be made of information from hundreds of thousands of tests previously made on all types of soils if better methods of analyzing the results were developed.

This study was performed on one particular type of soil for the purpose of investigating the relation between strength and particle size when other variables influencing soil behavior were held constant.

The method used was one of redistributing the particles of the original soil into eight systems varying from a coarse-grained soil to a very fine-grained soil. Each soil system was tested by two separate types of strength tests before and after treating them to nullify their physico-chemical properties. A comparison of the strength before and after treatment indicated the effect of their physico-chemical properties and supplied information as to how the strength varied with variations

of particle-size composition. Both the effective size D_{20} and the specific surface area were used to identify the artificially prepared systems.

The information given may be summarized as follows:

1. The specific surface area of the artificially prepared soil systems increases rapidly with increasing amounts of small particles in the soil system, since the surface area contributed by the particles of size 0.005 mm and less is very large.

2. When the attempt was made to nullify the physico-chemical effects of small particles, the non-polar liquid treatment and the heat treatment at 1000° C seemed equally effective in repressing the activity of small particles.

3. When the small particles did not engage in physico-chemical activity the strength of the soil remained very high even when the soil system was entirely composed of small particles.

4. For the particular soil investigated, a comparison of the strength of the treated soil systems, with the untreated systems, showed that the physico-chemical activity was responsible for almost all of the loss of strength.

APPENDIX

APPENDIX TABLE OF CONTENTS

Appendix A.--HYDROMETER MECHANICAL

ANALYSIS OF TREATED SAMPLE

Hydrometer Mechanical Analysis on a 50 gram sample of the soil fraction smaller than the No.200 sieve before heating to 1000 C. Figures in parenthesis are for the same soil after heating for 20 minutes.

Period of Sedimentation Hrs.: Min.		Hyd. Reading	Temp. Degree Fht.	Corrections Temp.		Sp.Gr. 2.74	Corrected Hyd. Reading	% in suspension.	Particle size MM	Corrections for		Corr. Particle size
				-	-					Depth	Sp.Gr.	
0	2/3	48.0 (48.0)	67	-	-	.98	47.0 (47.0)	94.0 (94.0)	0.1	.46	.97	.0446 (.0446)
0	1	47.5 (47.5)	67	-	-	.98	46.6 (46.6)	93.2 (93.2)	0.078	.46	.97	.0348 (.0348)
0	2	44.5 (--)	67	-	-	.98	43.6 (--)	87.2 (--)	0.055	.46	.97	.0245 (--)
0	5	41.0 (49.0)	67	-	-	.98	40.2 (38.2)	80.4 (76.4)	0.035	.47	.97	.0156 (.0159)
	15	(32.0)	67	-	-	.98	(31.4)	(62.8)	0.020	.48	.97	(.0093)
1	00	26.0 (25.0)	67	-	-	.98	25.5 (24.5)	51.0 (49.0)	0.010	.50	.97	.0049 (.0049)
24	00	8.5 (8.0)	67	-	-	.98	8.3 (7.8)	16.6 (15.6)	0.002	.54	.97	.0010 (.0010)

63

Appendix B.--WORK SHEET FOR SOIL

STRENGTH TESTS

Work Sheet for Soil Strength Tests showing Calculations.

$D_{20} = \underline{0.0018}$ Optimum Moisture-13.7%, Opt.Density-118.1
                Specific Gravity=2.73, Hygro Moist-1.843%

CALCULATIONS for CBR TEST
.0736 X 118.1=8.6922,   8.6922 X 1.01843=8.8521 lbs.of soil
8.6922 X .137 = 1.1908, 1.1908-.1602 = 1.0306 lbs.of H_2O
453.6 X 1.0306 = 467.48 cc H_2O This mixture of soil and
water compacted to a height of 4.73 inches in a 6 inch dia.
cylinder is the specimen compacted at 95% of optimum.

Static load of 9,600 lbs. necessary to compact.

CBR SAMPLE COMPACTED AND SOAKED					SWELL
Pene-tration Inches	Total Load Lbs.	Lbs. Sq.In.	Std. Lbs. Sq.In.	Bear-ing Ratio	
.100	130	43	1000	4.3	Swell of 0.170 for original height of 4.73 inches is 3.59%.
.200	234	78	1500	5.2	
.300	280	93	1900	4.9	FINAL % MOISTURE
.400	360	120	2300	5.2	
.500	420	140	2600	5.4	Top of specimen-21.95% Bot of specimen-17.65%

CBR (Avg.0.2-0.5" Penetration)= 5.2%

STABILOMETER TEST
5 lb specimen compacted in 4 inch dia. mold with 10 lb.
rammer by 25 drops from 18 inch height on each of 5 layers
of soaked soil from CBR cylinder. Specimen then trimmed to
2.5 inch height and placed in Hveem Stabilometer.

Vertical Load Lbs.	Vertical Pressure lbs/in^2	Indicated Horizontal psi pressure	P_h/P_v	$100(1-P_h/P_v)$
500	40	28	.70	30%
1000	80	56	.70	30
1500	120	90	.75	25
2000	160	126	.788	21.2
2500	200	162	.81	19

Stability "R" value(At P_v=160) = 21.2%

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