Effectivenes of desiccation in densifying a series of sand-clay mixtures
by Howard F Donley

A THESIS Submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University

Abstract:
The purpose of this investigation was to determine the effectiveness of desiccation compaction in densifying a series of sand-clay mixtures. Densities obtained by natural shrinkage were compared with densities obtained by mechanical consolidation and with the standard AASHO density. Also, calculations were made to see how well the maximum AASHO density and optimum moisture content could be predicted with the aid of certain published prediction equations.

Fluid soil samples were placed in cylindrical plastic cups about 76 cc in volume. One type cup had a stem attachment which connected the sample to a water manometer, As the sample shrank, capillary tensions were observed simultaneously with volume determinations. The other type cup had no stem and could be weighed to determine water loss and shrinkage simultaneously.

For clay mixtures, mechanical consolidation pressures were approximately 2/3 as efficient, in compaction effect, as capillary pressures of the same magnitudes, based on the loose unit weight as the zero compaction level. Extrapolation of the pressure head curves indicated that consolidation pressures approximately 4 to 10 times greater than capillary pressures were required to compact the clay mixtures to an equivalent oven-dry volume.

Compaction by desiccation was found to be increasingly effective with increasing clay content when compared to the AASHO compaction. Effective compaction increased linearly from 85% of maximum AASHO density for sand to 100% for clay.

Rowan's and Graham's original equations for predicting maximum AASHO density and moisture content gave slightly better results than Davidson's and Gardner's modifications.

The current concept of the shrinkage limit appears to be in error. The results of this investigation indicated that shrinkage continues even as the soil sample approaches the oven-dry state.

EFFECTIVENESS OF DESICCATION IN DENSIFYING A SERIES OF SAND-CLAY MIXTURES

by

HOWARD F. DONLEY

A THESIS

Submitted to the Graduate Faculty

in

partial fulfillment of the requirements

for the degree of

Master of Science in Civil Engineering

at

Montana State College

Approved:

Head, Major Department

Chairman, Examining Committee

Dean, Graduate Division

Bozeman, Montana
August, 1961

ACKNOWLEDGMENT

The writer wishes to thank Professors T. T. Williams and O. I. Jackson of the Civil Engineering Department for their work in reading the manuscript and their many fine suggestions. Thanks are extended to the major advisor, Professor Alfred Scheer, for the technical advice and guidance which made this report possible.

The credit for the work in preparing this manuscript for final publication goes to Mrs. Vivian Douglas and Mrs. Lilah Duncan, secretaries for the International Cooperation Center.

Finally, the writer wishes to thank his wife, Carole, who spent many long hours proof-reading and typing the original drafts.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

ABSTRACT

The purpose of this investigation was to determine the effectiveness of desiccation compaction in densifying a series of sand-clay mixtures. Densities obtained by natural shrinkage were compared with densities obtained by mechanical consolidation and with the standard AASHO density. Also, calculations were made to see how well the maximum AASHO density and optimum moisture content could be predicted with the aid of certain published prediction equations.

Fluid soil samples were placed in cylindrical plastic cups about 76 cc in volume. One type cup had a stem attachment which connected the sample to a water manometer. As the sample shrank, capillary tensions were observed simultaneously with volume determinations. The other type cup had no stem and could be weighed to determine water loss and shrinkage simultaneously.

For clay mixtures, mechanical consolidation pressures were approximately 2/3 as efficient, in compaction effect, as capillary pressures of the same magnitudes, based on the loose unit weight as the zero compaction level. Extrapolation of the pressure head curves indicated that consolidation pressures approximately 4 to 10 times greater than capillary pressures were required to compact the clay mixtures to an equivalent oven-dry volume.

Compaction by desiccation was found to be increasingly effective with increasing clay content when compared to the AASHO compaction. Effective compaction increased linearly from 85% of maximum AASHO density for sand to 100% for clay.

Rowan's and Graham's original equations for predicting maximum AASHO density and moisture content gave slightly better results than Davidson's and Gardner's modifications.

The current concept of the shrinkage limit appears to be in error. The results of this investigation indicated that shrinkage continues even as the soil sample approaches the oven-dry state.

INTRODUCTION

> "....when a clayey soil dries from a saturated condition, it attains a high density; no amount of compaction force in the laboratory can cause that much compaction." . . . Palit and Joshi

Desiccation compaction is that portion of physical science which deals with soil shrinkage by drying alone. To date, this phenomenon has been attributed to capillary action, or capillarity, which manifests itself in the pore water of soil. Actually, it links two larger, and largely separate, areas of physical phenomena: capillary water and soils compaction.

Capillary water was first extensively investigated by agriculturists. Later, with the advent of surfaced roads, and subsequent breakup during periods of freezing and thawing, civil engineers became concerned with water rise by capillary action. However, the role of capillary action in soil shrinkage has remained an academic curiosity since Karl Terzaghi reported on this phenomenon in 1925.

At that time Terzaghi measured the pressure required to consolidate two highly plastic clays to the same moisture contents that existed at their shrinkage limits. The pressures were about 170 and 340 tons per square foot. Since then, no extensive work has been done in terms of further investigating the relationship between capillary pressures and skrinkage.

The effectiveness of desiccation compaction has also received very little consideration in engineering literature. Nevertheless, any soils laboratory which runs the Atterburg shrinkage limit would normally obtain data for each soil sample tested, from which could be computed the shrinkage ratio which is numerically equal to the maximum unit dry weight (in gm/cc) to which the soil is compacted by capillary forces (presumably) during shrinkage.

Some investigators, recognizing the role of desiccation shrinkage in soil densification, have attempted to correlate the shrinkage limit and shrinkage ratio with impact compaction. Equations were originally formulated by Rowan and Graham, and later modified by Davidson and Gardner, for predicting both the maximum American Association of State Highway Officials (AASHO) density and the optimum moisture content. Since the original articles, very little research appears to have been directed toward checking these equations.

The objective of this investigation is to provide specific information concerning the densification characteristics of capillary action on a series of sand-clay mixtures, anticipating that this information may ultimately have practical application, particularly with respect to effecting economies in certain foundation and backfill situations.

The Problem

The problem to be investigated in this thesis is stated as follows: Is desiccation effective in increasing the densities of a series of sand-clay mixtures? The problem is subsequently divided into three phases:

1. To determine the effectiveness of one-dimensional mechanical

consolidation compared to shrinkage by capillary action.

2. To determine the effectiveness of compaction by capillary action as compared to the standard AASHO compaction.

3. To compare the actual standard AASHO density with that predicted by equations which have been previously formulated to predict the maximum AASHO density and optimum moisture content by using standard American Society for Testing Materials (ASTM) shrinkage data.

The investigation was limited to a medium concrete sand, a lean clay acquired locally (see pages 29 and 30), and several mixtures of the two. The major portion of this investigation was carried out in the Civil Engineering Laboratories of Montana State College during the winter and spring of 1960-61.

To determine the effectiveness of mechanical consolidation compared to shrinkage by capillary action, and to determine the effectiveness of compaction by capillary action as compared to standard AASHO compaction, a series of six soil mixtures was prepared with several samples for each mixture. The following measurements and tests were made:

a. Capillary forces acting on each sample during the shrinkage process.

b. Volume changes on each sample during the process of shrinking.

c. Mechanical consolidation tests on each mixture.

d. A series of standard AASHO compaction tests on each mixture.

e. Loose unit weights, the "no compaction condition," on each mixture.

f. Atterberg limits on each mixture.

g. Shrinkage characteristics on each sample.

In addition, two additional soil mixtures, with two samples for each mixture, were prepared for check purposes. Only items b and g were performed on each of these samples.

The third phase of the problem (equations predicting AASHO densities and moisture contents) required no independent investigation, but was an effort to maximize the use of the data collected for the first two phases.

LITERATURE REVIEW

The first recorded effort to study compaction induced by capillary pressures was made by Karl Terzaghi (11)* in 1925. Terzaghi measured the mechanical pressure required to consolidate a given soil to its shrinkage limit. As mentioned in the Introduction, the pressures on two clays were 170 and 340 tons per square foot.

Initially, Terzaghi used a glass cylinder partially filled with a fluid mixture of clay. The bottom of the cylinder was covered with a sheet of thin filter paper, and on this rested a bronze ring completely surrounded by and immersed in the clay solution. The surface of the mixture was covered with a layer of filter paper, and on top of the paper was placed a four-centimeter filter composed of quartz sand. After initial consolidation under the filter load, a brass cap loaded with shot served as additional load. Pressures up to 1.2 tons per square foot were obtained in this way. Higher pressures were obtained in a testing machine. For this purpose the clay was forced from the glass piston, and the ring, which contained a one-centimeter-thick layer of clay, was cut out. This ring and its contents were placed on top of filter paper in the bottom of a square vessel. It was then covered by filter paper and a one centimeter sand filter. A bronze plate and steel ball served to transmit the mechanical pressure to the filter and soil sample. The sample was submerged at all times.

---

* Number in parentheses (and all subsequent numbers in parentheses) refers to the literature item cited, page 76.

After studying Terzaghi's apparatus and analysis, it is apparent that he assumed that mechanical one-dimensional pressure was the densifying equivalent of a capillary pressure of equal magnitude. Terzaghi apparently ignored side friction along the sand filter. Further, there was nothing shown to indicate that one-dimensional consolidation was as efficient in decreasing the soil volume as the three-dimensional consolidation which takes place during capillary shrinkage.

One of the first investigators to measure capillary pressure directly was L. A. Richards (7). He devised a porous cup, called a tensiometer, in which water, but not air, could pass through the walls of the cup. The cup was filled with water and embedded in the soil. In order to measure pressure differentials, the cup was connected to a mercury manometer. As the soil dried out, water was drawn from the porous cup, thereby causing the mercury column to rise. When the mercury column reached a constant height, the moisture content of the surrounding soil was determined. Thus, Richards was able to show for the first time the relationship between the equilibrium moisture content and corresponding capillary pressure. This relationship is shown in Figure 1 and is termed a desorption curve. Note that the curve becomes almost vertical at some minimum moisture content.

Richards discovered another phenomenon using the tensiometer. If the soil was subjected to an external source of water and became moist, a second curve, termed an absorption curve was obtained. This fell to the left of the desorption curve as shown in Figure 1. The difference between the two was called the hysteresis effect. It is principally this effect which makes it necessary to call attention to the fact that the present investigation is on the desorption side of the graph.

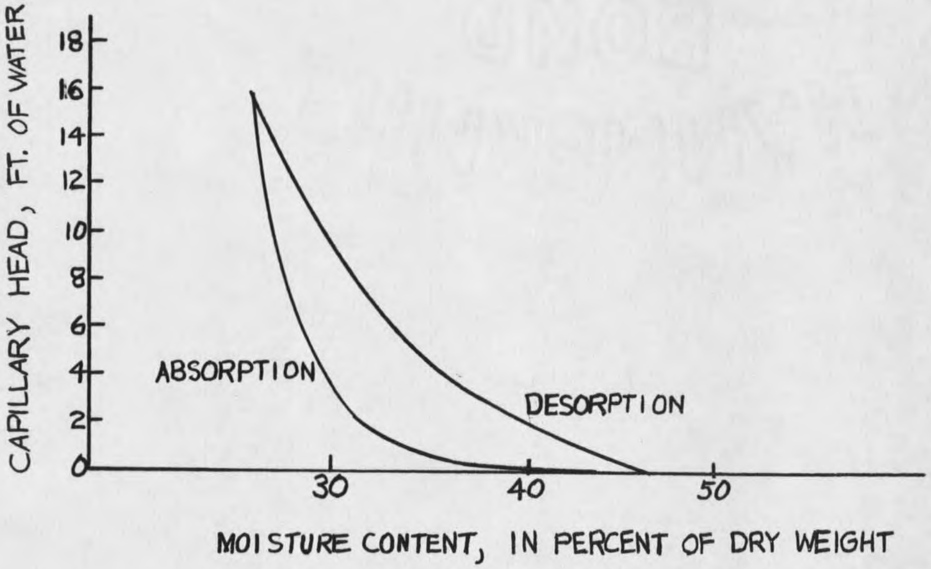

FIG. 1 Soil Sorption Curves Showing Hysteresis Loop (Richards)

J. C. Calhoun (1) duplicated Richards' results using an apparatus (not shown) which tested soil samples of comparable size and shape to those used in this investigation. One advantage of Calhoun's apparatus over that used by Richards was that pressure equilibrium in the pore water could be obtained in a shorter period of time. However, Calhoun's apparatus was considerably more complex than Richards'.

A parallel study of capillary pressures was made by T. W. Lambe (5) in which he presented his results in the form of a graph showing percent saturation as a function of capillary pressure heads. Figure 2 shows both the absorption and desorption curves for a fine sand used in his research. The sand had the following characteristics: $D_{60} = 0.19$ mm, $D_{10} = 0.08$ mm, which corresponds approximately to the 20 percent clay mixture of this thesis. Lambe recommends that four pressure heads be defined from the curves as follows:

h_{cx} = highest head for which there is a continuous channel of water from the free water surface below
h_{cs} = highest capillary head at 100% saturation
h_{cr} = largest rise of water face
h_{cn} = largest rise at maximum percent saturation

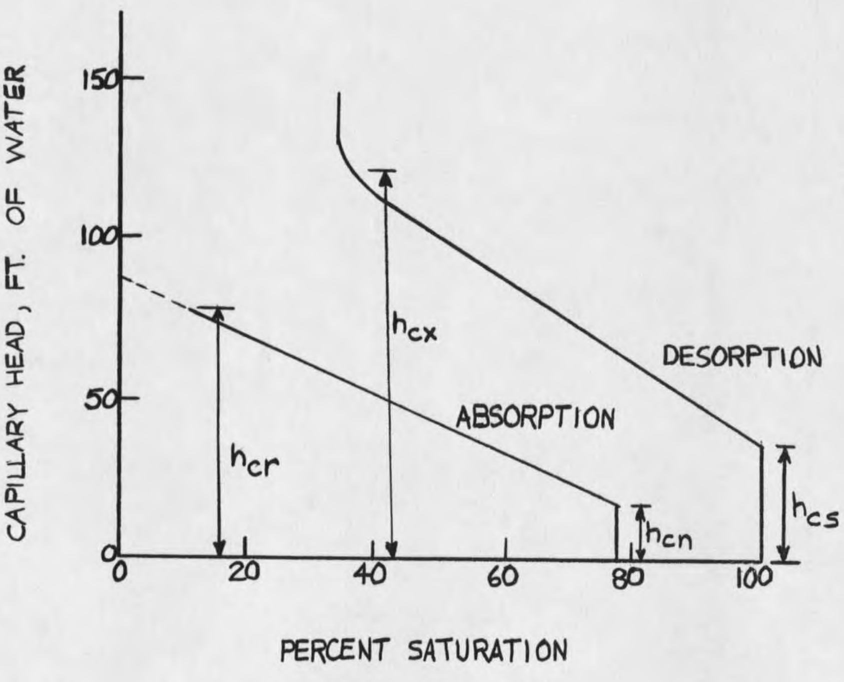

FIG. 2 Capillary Pressure Head vs. % Saturation for a Fine Sand (Lambe)

The pressure heads h_{cx} and h_{cs} are relevant to this investigation. An idealized view of a saturated soil mass would indicate that the soil remains almost saturated until shrinking ceases. Actual measurements of soil samples in this investigation indicated otherwise. However, nothing was found in the literature which would indicate that either of Lambe's pressure heads corresponded per se to the point at which the soil mass reached a constant volume.

It will later be shown (page 18) that capillary pressure can be expressed in terms of an equivalent radius of curvature, R'. A closely related analysis found in the literature was presented by G. P. Tschebotarioff (12). Tschebotarioff used an equation which assumed square openings or pores in the soil and took the following form:

$$p' = \frac{0.306}{b} \tag{1}$$

where p' = maximum capillary pressure and soil compression pressure, in gm/cm^2

b = length of side of capillary opening, cm, assuming the openings to be squares.

This equation applies also to circular openings where b is the equivalent diameter in centimeters. Under the assumption that the size of opening is equal to the particle size, Tschebotarioff developed Table I.

TABLE I: THEORETICAL EFFECTS OF CAPILLARITY (Tschebotarioff)

	Size of Particles and of openings, mm	H_{max}		p'	
		cm	inches	Kg/cm², Tsf	psi
Sand, Coarse	2.00 -0.25	1.5-12	5/8-5	.0015- .012	.021-.171
Fine	0.25 - .05	12-61	5-24	.012- .061	.171-.87
Silt	0.05 - .005	61-610	24-240	.061 - .610	.87 -8.7
Clay	.005- .001	610-3050	240-1200	.610 -3.05	8.7-43.5
Colloids	.001 and finer	3050-	1200-	3.05 —	43.5-

Given a soil of a particular grain size, H_{max} is defined by Tschebotarioff as the maximum height of capillary rise which could occur in that soil. Table I is of value for qualitative comparisons only, as the assumptions entailed in its preparation render it unfit for quantitative purposes.

As illustrated by the preceding articles, measured capillary pressures have principally been defined in terms of moisture percentage only. However, R. M. Palit and S. S. Joshi (4) attempted, in 1958, to investigate shrinkage and capillary pressures simultaneously. A sketch of their apparatus is shown in Figure 3. They had considerable difficulty in obtaining data as the soil samples approached constant volumes because cracking of the soil mass around the rubber membrane relieved the external pressure.

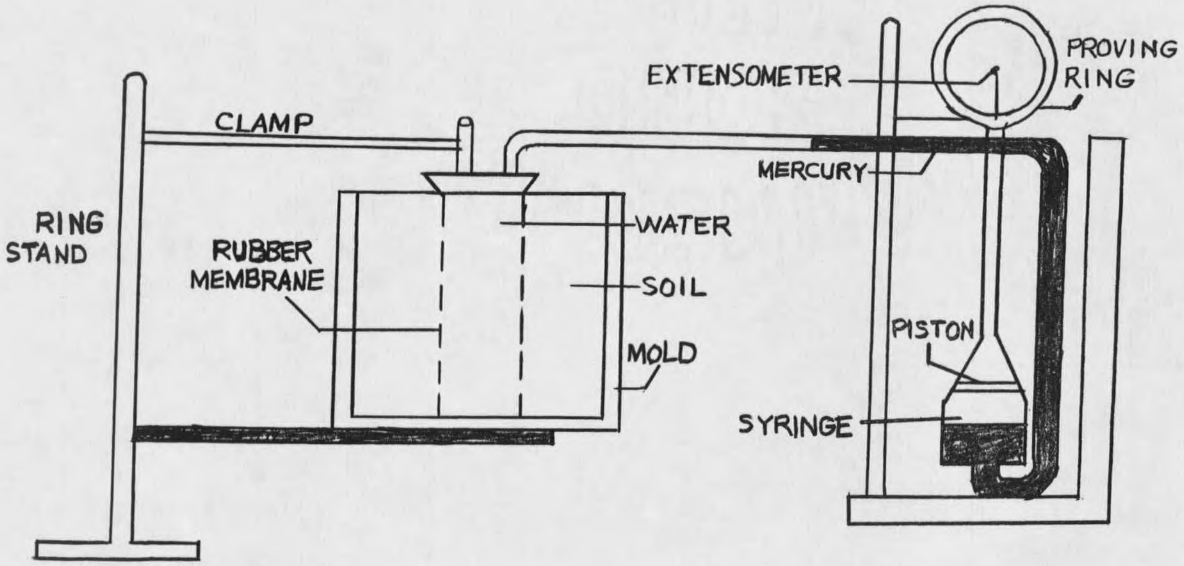

FIG. 3 Shrinkage Apparatus (after Palit and Joshi)

One of the soils they were able to test until shrinkage ceased was very similar to the clay used in this investigation. The clay tested by them had the following characteristics:

Maximum Shrinkage Pressure, (tons per square foot)	0.4
Liquid Limit (LL)	36.9
Plastic Limit (PL)	19.1
Plasticity Index (PI)	17.8
Maximum AASHO Density, (pounds per cubic foot)	123.0
Shrinkage Limit (SL)	12.9
Shrinkage Ratio (SR)	1.99

In their article, Palit and Joshi accepted Terzaghi's equivalent capillary consolidation pressure head as fact, and concluded that most of the capillary pressure was dissipating itself in some fashion with only a minor portion available as internal consolidating pressure.

Very little was found in the literature pertaining to soil compaction by desiccation. Some investigators reported inundating a soil, but if subsequent drying were not permitted, it would not reflect the influence of capillary action. In sand, drainage could take place rapidly enough to permit capillary pressures to develop. Under this assumption, R. L. Greenman's report on granular backfill materials is mentioned, (3). He reported volume changes in coarse sands of 19% without pre-consolidation.

In 1917, H. A. Tempany (10) investigated soil shrinkage on five "loam" soils. His shrinkage apparatus consisted of a wire gauze cage, 8 x 2½ x 2½ cm. The soil samples were made in a rectangular mold, and after shaping, were inserted into the gauze cages to shrink. Volume and weight determinations were made periodically. Each of his soil samples initially plotted as straight lines. However, as the samples approached an air dry condition, they all indicated marked curvatures indicating that the volume decrease was less than the accompanying moisture loss.

It is interesting to note that the ASTM shrinkage limit as defined by the following equation assumes a linear relationship between the volume change and moisture content:

$$\text{Shrinkage limit, SL} = \left(\frac{W_w - W_o}{W_o} - \frac{V_w - V_o}{W_o}\right) 100 \qquad (2)$$

where W_w and V_w are the weight in grams and volume in cubic centimeters respectively, of the wet sample, and W_o and V_o are the weight in grams and volume in cubic centimeters after oven drying.