SHRINKAGE AND STRENGTH OF COMPACTED SAND-CLAY MIXTURES

by

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ABSTRACT

The shrinkage and strength behavior of prepared sand-clay mixtures were studied and explained. Different proportions of Ottawa sand and kaolinite were compacted and dried. The resulting volume changes were determined. In addition, the compressive strengths of oven-dried samples compacted at optimum water content were determined.

Samples molded at optimum water content and containing 30% sand had the highest strength but not the lowest shrinkage; those containing 40% sand had concurrently the lowest shrinkage and highest strength; those containing more than 30% sand experienced decreases in strength.

Except for significant variations, the trend of the results indicated that shrinkage decreased as the sand content of the mixtures increased.

For any one mixture, the higher the water content during molding, the higher the shrinkage that it will undergo upon drying. Volume changes measured for mixtures containing from 0% to 50% sand and compacted at water contents lower than optimum molding water content indicated expansion. Reasons for the expansion phenomenon were given.

As the sand content of the mixtures increased, the optimum molding water content decreased, void ratio decreased, and dry density increased. The influence of grain size distribution was discussed.

The strength and shrinkage phenomena were explained with the aid of previous research on the structure of soils. Recommendations for further research were made in order to extend and substantiate the results of this thesis.
Cambridge,
Massachusetts
August 20, 1956

Professor Leicester F. Hamilton
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Sir:

In partial fulfillment of the requirements for the degree of Master of Science, this thesis, entitled "SHRINKAGE AND STRENGTH OF COMPACTED SAND-CLAY MIXTURES", is hereby submitted.

Respectfully yours,

Signature redacted

Isaac Tiles
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CHAPTER I
INTRODUCTION

A. PURPOSE OF RESEARCH

An attempt is made to explain the observed shrinkage* and strength phenomena of compacted wet sand-clay mixtures undergoing drying.

An additional aim of this research was to determine what proportions of sand and clay, by weight, will concurrently yield a maximum strength and present a minimum volume change when dried from the "as-molded" state.

When compacted soil dries, it tends to develop shrinkage cracks that allow entrance to moisture. Deterioration then ensues. Such a problem exists, for instance, in the construction of rammed earth houses ("Pisé-de-Terre").

Although the author's interest in the use of earth for the construction of small houses, and his awareness of their susceptibility to moisture, initiated this research, the conclusions are applicable wherever compacted earth is used in construction.

* The term "shrinkage", as used in this thesis, will mean the volume change of a compacted sand-clay mixture from its molding water content to zero water content.

See also footnote in Chapter III, Section C.
For, by knowing why, and how, shrinkage and strength gains occur upon drying compacted soil, the engineer will be able to predict its behavior with accuracy. Then, by learning how to control such behavior, the designer will be just as confident of his earth structures as he is of his steel or concrete structures.

B. METHOD OF RESEARCH

Different proportions of sand and clay, by weight, were mixed and then compacted at various water contents by the use of the "Wilson Miniature Apparatus." The molding water content was determined by extruding the sample from the mold and placing it in the oven to dry.

From the above compaction data, the void ratio, optimum dry density and water content for the "as-molded" state were determined.

After oven-drying the compacted samples, patties were prepared from them and their volumes determined by the method of displacing mercury.

From the volume and weight of each patty, the void ratio and dry density of each oven-dried sample were computed.

The volume change was the difference between the void ratio existing at the time of compaction and the void ratio
existing after oven-drying the sample.*

For strength determinations, samples were prepared at the optimum molding water content of each mixture, oven-dried, and then tested to failure in the unconfined compression apparatus.

Finally, the results were plotted and correlated in this thesis.

* Figure I-1 shows how data was obtained from the compaction curves in Appendix B.
FIG. I-1

LEGEND
1. Optimum Dry Density for Oven-dried State.
2. Optimum Dry Density for As Molded State.
3. 98% of 2. "Dry Side" and "Wet Side" of Optimum.
5. Molding Water Content for 2.
7. Maximum Molding Water Content of Compaction Run.
14. Minimum Void Ratio for the As Molded State.
15. Minimum Void Ratio for the Oven-dried State.

TYPICAL SOURCE OF DATA FROM PLOTS OF DRY DENSITY AND VOID RATIO OF PREPARED SAND-CLAY MIXTURES.
A. SHRINKAGE OF SOILS.

The volume change of a wet soil undergoing drying is related to the volume of water being evaporated from the soil (1), (7)*, in the following manner:

1. The change in the volume of voids (shrinkage) of a completely saturated soil undergoing drying is equal to the volume of water evaporated from the soil.

2. When \( w_s \), the shrinkage limit, is reached (i.e. smallest water content at which the soil is still completely saturated), any further water loss allows air to replace the space formerly occupied by water, and the volume change is no longer equal to, but less than, the volume of water being evaporated.

The above is illustrated in Figure II-1.

* Figures in parenthesis refer to items in bibliography.
SHRINKAGE OF SOILS vs WATER CONTENT

FIG. II-1
B. **EFFECT OF COMPACTION ON SHRINKAGE OF SOILS.**

Pacey (6) explained the shrinkage of compacted clays as follows:

1. Compaction of clays at high water contents (i.e. higher than optimum molding water content) arranges the plate-shaped clay particles in a parallel manner.

2. At low molding water contents the clay particles are arranged in a random manner.

3. The higher the compactive effort, for a given water content, the closer the interparticle spacing at low water contents and the greater the ability to arrange the particles in a parallel manner.

4. Parallel oriented systems undergo higher reduction in void ratio (i.e. greater volume change) than random systems.

C. **EFFECT OF SAND CONTENT ON SHRINKAGE OF SOILS**

When the sand content of rammed soils undergoing drying is increased, the total shrinkage decreases (1), (2). One explanation given for this is that since less water is needed to achieve good compaction for sandier soils, less water will evaporate upon drying, and therefore, less shrinkage will occur.
D. **STRENGTH OF SOILS.**

Studies by Lambe (5) on the dry strength of clay indicated that at degrees of saturation less than 100%, capillary pressures were still effective in isolated parts. Further drying removed absorbed water which resulted in the interparticle distances being further reduced. It was shown, by means of potential-distance curves, that a reduction in spacing of clay particles already very close to each other will cause an increase in the strength of clay.

E. **STRENGTH OF COMPACTED SOILS.**

Investigations on rammed earth for the construction of houses (1), (2), have shown that the strength decreased rapidly when the clay and silt content of rammed earth dropped below 30% of the total weight.

Pacey (6) commented on the strength of compacted soils as follows:

1. The structure of compacted soils changed from random, at low molding water contents, to parallel at high molding water contents.
2. The highest strength was associated with the most random structure.

3. Strength decreased as water content and parallel orientation increased.

4. For a given molding water content, the higher the compactive energy, the closer the interparticle spacing at low molding water contents and the greater the ability to produce parallel alignment between particles. This results in higher strengths for the higher compactive effort.
CHAPTER III
EXPERIMENTAL PROCEDURE

A. DESCRIPTION OF MATERIALS.

1. KAOLINITE* Color dry: Yellowish white
   Sp. G. : 2.61
   Source : Bath, South Carolina
   W.e : 58.8
   Wp : 29.3
   P.I. : 29.5

Grain Size Distribution**

2. OTTAWA SAND Color Dry: Brownish white
   Sp. G. : 2.66
   Source : Ottawa, Illinois

Grain Size Distribution**


** See Figure V-6
B. COMPACTION*

The testing program began with the compaction of kaolinite alone. The sand content of subsequent mixtures was increased in steps of 10% of the total weight of the mixture.

Each mixture was prepared for a compaction run by hand-mixing with distilled water (molding water content on the dry side of optimum), and allowed to soak in a humid room for 24 hours.

The compaction procedure was similar to that outlined in reference (8), except for the following modifications:

1. "Wilson Miniature" molds, 1 5/16 inches inside diameter and 2.816 inches long, were used.
2. Effort consisted of 25 tamps, from a pre-stressed 40-pound spring hammer, on each of the ten layers comprising the sample.
3. The surface between layers was scarified to insure bonding.

* See Plate 1, Appendix D, for apparatus used.
4. After trimming a compacted sample, it was weighed in the mold, extruded and allowed to air-dry for 24 hours before placing in the oven for final drying.

5. The molding water content was determined by drying the entire sample in the oven at 105° for 24 hours.

6. The molding water content of the mixture was increased for each subsequent compaction by adding distilled water with a sprayer and then mixing in a mortar with a rubber-tipped pestle.

C. SHRINKAGE DETERMINATION.* (For apparatus used see Plate 2, Appendix D)

Except for the following modifications, the procedure was similar to that outlined in Chapter III of reference (8):

* Although the term "shrinkage" is used, the volume change upon oven-drying the compacted samples indicated expansion in many instances.
1. A patty, approximately \(\frac{3}{4}\) inch high and \(1 \frac{1}{4}\) inches in diameter was cut from the mid-section*** of the oven-dried sample, and filed smooth.

2. The patty was placed in the oven at \(105^\circ\)C, weighed after 24 hours, and then stored in a dessicator.

3. The volume of the patty was determined by the method of displacing mercury.

4. Each patty was immersed in mercury at least twice for checking purposes.

D. STRENGTH DETERMINATION. (For apparatus used see Plate 3, Appendix D)

1. Additional samples were compacted as in B above, at the optimum molding water content of each mixture.

2. The oven-dried samples were then tested in the unconfined compression machine.

** This location on the sample varied slightly in order to choose a section that showed the least signs of cracking.
E. DISCUSSION OF EXPERIMENTAL PROCEDURE.

By limiting the variable elements in the mixtures to sand and clay, the strength and shrinkage phenomena observed could be explained more specifically than if silt had also been present.

Homogeneity of materials was insured for each mixture element, by always drawing out Ottawa sand and kaolinite from the same batches in the laboratory.

Before placing the extruded samples in the oven, they were allowed to dry in the air for 24 hours in order to minimize the expansive effect of entrapped air.

The use of patties, rather than the whole sample, for the shrinkage determinations, permitted the use of less mercury in the testing procedure.
CHAPTER IV
RESULTS

A. GENERAL

The dry density and void ratio data of the prepared sand-clay mixtures are found in Appendix B. The results presented in this chapter were obtained from Appendix B,*

B. DESCRIPTION OF FIGURES

1. Figure IV-1 shows, for each mixture, the void ratio change, from the molded to the oven-dried state, as a function of the molding water content.

Also indicated are the void ratio changes of the oven-dried samples compacted at the following water contents:

a. Optimum molding water content of each mixture.
b. Molding water content at which the minimum void ratio occurred in the oven-dried state.
c. Molding water content at which no volume change occurred in the oven-dried state.

2. Figure IV-2 shows as a function of the sand content

* The reader is referred to Fig. I-1 for explanation of how data was obtained.
in the mixture the shrinkage occurring upon oven-drying samples. The results were as follows:

a. Shrinkage of the Samples Compacted at the Optimum Molding Water Content of Each Mixture.

(1) As the sand content increased from 0% to 30%, the shrinkage was relatively constant.

(2) Shrinkage decreased noticeably at 40% sand content.

(3) Shrinkage increased gradually until the sand content reached 60%.

(4) Shrinkage decreased with further increases in the sand content, reaching a minimum for all the mixtures at 80%.

b. Shrinkage at the Maximum Molding Water Content of Each Mixture.

The trend of this curve indicates that the shrinkage of samples compacted at the maximum molding water content of each compaction run decreased as the sand content of the mixtures increased.

3. Figure IV-3 shows the effect of three molding water contents on the shrinkage of each mixture.
Curve 1 shows the shrinkage that occurred when the water content during compaction was greater than the optimum molding water content, and, arbitrarily, when the as-molded dry density was 98% of the optimum as-molded dry density.

Curve 2 shows the shrinkage of samples compacted at the optimum molding water content. It is similar to the curve plotted in Figure IV-2.

Curve 3 shows the shrinkage of mixtures compacted at water contents lower than optimum molding water content, and with an as-molded dry density equal to 98% of the optimum as-molded dry density of each mixture.

The variations between the curves are shown on the lower plot. The least variation occurred for the mixture containing 30% sand. Practically no variation existed for mixtures containing more than 70% sand.

4. Figure IV-4 shows the minimum void ratio that existed for each mixture when in the as-molded state and when in the oven-dried state. The lowest void ratios were obtained with the mixture containing 70% sand.

5. Figure IV-5 shows the optimum dry density that existed for each mixture when in the as-molded state and
when in the oven-dried state. The maximum dry densities were obtained with the mixture containing 70% sand.

6. Figure IV-6 shows the molding water contents that resulted in a minimum void ratio during the as-molded state and during the oven-dried state.

For mixtures containing more than 60% sand, the minimum void ratio for both states occurred at approximately the same molding water content.

7. Figure IV-7 shows the compressive strengths of oven-dried samples compacted at approximately the optimum molding water content of each mixture.

The dashed curve indicates the maximum values of strength reached. The actual and optimum molding water contents are also indicated.

The results were as follows:

a. The highest strength was obtained with the 30% sand content.

b. Additional sand in the mixture decreased the compressive strength gradually.

c. Although the dashed line indicates a decrease in strength from 0% to 20% sand content, the points plotted indicate that the strengths for the mixtures were fairly constant.
8. Figure IV-8 correlated the results shown on Figures IV-2, IV-6 and IV-7.

9. Figure IV-9 shows as a function of the molding water content:
   a. "As molded" and oven-dried dry densities
   b. Oven-dried compressive strengths
   c. Shrinkage from optimum molding water content to oven-dried state.

C. FIGURES
VOID RATIO CHANGE OF SAND-CLAY MIXTURES FROM MOLDED TO OVEN-DRIED STATE

VS.

MOLDING WATER CONTENT

Shrinkage at Molding Water Content that resulted in a Minimum Void Ratio for Oven-dried Samples.

Shrinkage of Samples Compacted at Optimum Molding Water Content.

Notes: Percentages indicate Sand Content of Samples. Shrinkage is Void Ratio Change of Samples from Molded State to Oven-dried State.

No Volume Change.
FIG. IV-2

SHRINKAGE FROM MOLDED TO OVEN-DRIED STATE
VS.
SAND IN MIXTURE

Δε at Maximum Molding Water Content of Compaction Run.

Δε at Optimum Molding Water Content of Mixture

SHRINKAGE, Δε x 10^-5

SAND IN MIXTURE ~ % BY WEIGHT

SAND IN MIXTURE
EFFECT OF MOLDING WATER CONTENT ON SHRINKAGE

**Shrinkage from As Molded to Oven-dried State**
MINIMUM VOID RATIO vs SAND IN MIXTURE

As Molded Samples

\[ e = \frac{3V_v}{V_d} - 1 \]

Oven-Dried Samples

\[ e = \frac{V_v}{V_d} \]

SAND IN MIXTURE ~ % BY WEIGHT

FIG. IV-4
OPTIMUM DRY DENSITY vs. SAND IN MIXTURE

Oven-dried Samples

\[ \gamma_d = \frac{W_{\text{dry}}}{V_{\text{dry}}} \]

As-Molded Samples

\[ \gamma_d = \frac{W}{V(1+w)} \]

FIG. IV-5

SAND IN MIXTURE ~ % BY WEIGHT
MOLDING WATER CONTENT AT MINIMUM VOID RATIO

SAND IN MIXTURE

WATER CONTENT IN %

SAND IN MIXTURE – % BY WEIGHT

Oven-Dried Samples

As-Molded Samples
COMPRESSIVE STRENGTH vs. SAND IN MIXTURE

NOTE: Samples were oven-dried at 105°C.
Figures at points indicate molding water contents.
Figures in parentheses indicate optimum molding water contents of mixtures.

COMPRESSIVE STRENGTH, lbs/sq. ft.

SAND IN MIXTURE ~ % BY WEIGHT
Correlation of Test Results: Sand-Clay Mixtures

Maximum Compressive Strength of Oven-dried Samples Compacted at Optimum Molding Water Content.

Molding Water Content for Minimum Void Ratio after Oven-drying Sample.

Max. Shrinkage at Max. Molding Water Content of Run.

Shrinkage of Oven-dried Samples Molded at Opt. Molding Water Content.

Compressive Strength, lbs per sq in.

Sand in Mixture - % by Weight
SHRINKAGE & STRENGTH OF SAND-CLAY MIXTURES
VS.
MOLDING WATER CONTENT

Notes:
- Percentages indicate sand content of mixture.
- Compaction Data: 10 layers
  - 25 stamps per layer
  - 40 lbs. tamping weight
  - Samples oven-dried at 105°C

Maximum Compressive Strength of oven-dried samples compacted at optimum molding water content.

From optimum molding water content to oven-dried state

FIG. IV-9
A. VOLUME CHANGE: EXPANSION

It was observed that expansion, instead of shrinkage, occurred upon oven-drying mixtures with low sand content (See Figure IV-1). Expansion always occurred at molding water contents lower than the optimum molding water contents of the mixtures.

The expansion phenomenon may be explained with the aid of Figure V-1 below:

![Diagram](image)
During compaction under wet conditions, air was entrapped within the sample. The compactive effort compressed the volume of the entrapped air. The confining action of the mold maintained the entrapped air under pressure. The void ratio for this condition was computed from the compaction data, and is represented by point O above.

When the sample was extruded from the mold, the compressed air expanded. This, consequently, increased the interparticle distances. The resulting void ratio is represented by point E.

On drying the sample, the capillary forces of the water within the voids reduced the interparticle distances. The resulting void ratio was computed from the shrinkage determination data, and is represented by point D.

Since the volume change was computed as the difference between the void ratios at point O and D, this case will indicate expansion. The expansion computed ($OE$) was less than the actual expansion by an amount equal to the volume of water lost during drying ($ED$).

B. **VOLUME CHANGE: SHRINKAGE**

Figure V-2 will be used to explain why most samples showed shrinkage when oven-dried, in spite of the expansion phenomenon occurring upon the removal of the mold.
As explained in A above, on extrusion of the sample from the mold, the void ratio increased to point B. For this case, the molding water content was assumed higher than in A above.

When the sample was dried, the capillary forces of the water within the voids were sufficient to decrease the interparticle distances until the void ratio at D was less than that computed at point O. The difference between the void ratios indicated shrinkage for this case. Figure V-2 shows that the shrinkage computed (OD) was less than the actual shrinkage by an amount equal to the volume increase due to expansion.
C. SHRINKAGE AT OPTIMUM MOLDING WATER CONTENT

With the aid of Figure V-3, the results presented in Figure IV-2 may be explained.*

1. Upon drying an all-clay sample from optimum "as molded" state, the shrinkage was high due to:
   a. High molding water content causing a large volume change upon drying.
   b. Parallel alignment of clay particles permitted efficient packing upon drying.

2. Shrinkage remained high as the sand content increased to 30%, in spite of the fact that the molding water content decreased (See Figure IV-6). This was due to a more complete parallel alignment of the clay particles than in 1 above. This had resulted from the "hammering" effect of the individual sand grains (See Section F below).

3. Shrinkage decreased suddenly at 40% sand content due to:
   a. Sand grains, pushed into contact, extruded some parallel-oriented clay particles, and

* The reader should also refer to Chapter II, Theoretical and Experimental Background.
thus reduced the total packing efficiency of the clay mass.

b. Voids formed by the sand grains enclosed random-oriented clay particles.

c. The decrease in Optimum molding water content was not offset by any other phenomena.
SAND-CLAY MIXTURES IN AS-MOLDED STATE

- **Large Inter-particle Distances**
  - Entrapped Air
  - Clay in Parallel Orientation
  - All Clay

- **Entrapped Air**
  - Clay in Parallel Orientation
  - 10% to 20% Sand

- **Clay in Void is Oriented Parallel**
  - Entrapped Air
  - Clay in Parallel Orientation
  - Close together
  - 30% Sand

- **Clay in Void is Oriented Randomly**
  - Entrapped Air
  - Clay in Parallel Orientation
  - 40% Sand

- **Small Amount of Clay bet. Sand Grains**
  - Little Clay in Void
  - 50% to 60% Sand

- **Very Little Clay bet. Sand Grains**
  - Very Little Clay in Void
  - Over 70% Sand

**FIGURE V-3**
4. Shrinkage increased when the sand content increased from 40% to 70%, due to:
   a. Less random-oriented clay occupied the void spaces formed by the sand grains.
   b. The water replacing the clay in the voids increased the capillary forces upon drying.

5. Shrinkage decreased when the sand content was higher than 70% due to:
   a. Shrinkage was controlled mainly by the capillary forces of the water in the voids.
   b. Optimum molding water content decreased with an increase in sand content. The volume change was, therefore, smaller.

D. SHRINKAGE AT MOLDING WATER CONTENTS ABOVE AND BELOW OPTIMUM

The larger the amount of water present during compaction, the larger the volume change that occurred upon drying the mixtures. This is shown in Figure IV-2.

* It should be noted that at 90% sand content, difficulty in compacting due to the rolling effect of the sand grains prevented the results from being useful. Thusly, poor compaction for this mixture, resulted in lower dry densities and higher void ratios than expected.
Compacting at a molding water content higher than optimum increased the ability of the clay particles to align themselves in a parallel manner. Thus the particles, upon drying, were "packed" more efficiently than when compacted at lower molding water contents, and then dried. This is the reason why the minimum void ratio for the oven-dried state, of mixtures containing up to about 40% clay, occurred at molding water contents higher than optimum molding water content (See Figure V-4).

Figure IV-3 was plotted in order to show how shrinkage varied when the molding water content was above and below the optimum molding water content of the mixture. The significance of the plot is that at 30% sand content, compacting the mixture on the wet side or dry side of optimum caused little variation on shrinkage. This may prove the assumptions made for explaining shrinkage in C, and strength in F. For, if the "hammering" effect of the sand grains already had arranged the clay particles in a highly parallel orientation, and decreased their inter-particle distances, the addition or reduction of water will have little effect on shrinkage from the optimum "as molded" condition.
MINIMUM VOID RATIO AND WATER CONTENT VS. SAND IN MIXTURE

LEGEND
- Molding Water Content for Minimum Void Ratio, As-Molded Sample
- Molding Water Content for Minimum Void Ratio, Oven-Dried Sample
- Minimum Void Ratio, As-Molded Sample
- Minimum Void Ratio, Oven-Dried Sample

FIG. V-4
E. MOLDING WATER CONTENTS CAUSING EXPANSION.

Curve 2 in Figure V-5 shows the molding water content for each mixture that resulted in shrinkage, upon drying, equal to expansion, upon extrusion from the mold (See A above). Thusly, at these molding water contents the volume changes measured were zero.

For any mixture, a molding water content below curve 2 would result in a void ratio for the oven-dried state greater than for the "as molded" state. The volume change measurements would then indicate expansion.

For mixtures containing more than 50% sand, the above effect did not seem to exist. Any molding water content would then always indicate shrinkage upon drying the prepared samples.

F. STRENGTH OF MIXTURES PREPARED AT OPTIMUM WATER CONTENT

The following hypothesis is presented to explain the strength variations of the oven-dried samples:

1. The energy from the spring hammer was transmitted to the clay particles through sand grains acting as "hammers."
2. Since the orientation of clay particles, and their interparticle distances is dependent on the energy applied (6), the clay particles between any two sand-grain "hammers" were highly "packed" in a parallel manner (See Figure V-3).

3. The binding effect of these closely "packed" clay particles was greatest for mixtures containing 30% sand, as indicated by strength determinations (See Figure IV-7).

4. As the sand content increased, less highly "packed" clay was present between any two sand-grain "hammers". This reduced the binding effect of the clay, and the strength decreased.
MOLDING WATER CONTENT vs SAND IN MIXTURE

Water Content for Opt. Molded Dry Density

Water Content for No Change in Void Ratio upon Oven-drying Molded Sample
G. GRAIN SIZE DISTRIBUTION

The grain size distribution curves for the mixtures (See Figure V-6), showed that a "gap" gradation existed.

The horizontal portion of the curves indicate particle sizes absent from the mixtures. As the clay content decreased, the sand portion of the curve approached the familiar shape representing a well-graded soil.

This better gradation partly accounts for the increase in the value of optimum dry density (See Figure IV-5 and V-5) as the sand content of the mixtures increased.

Shrinkage decreased with the better graded mixtures, as explained in H, below.

H. DRY DENSITY AND VOID RATIO

As seen in Figures IV-4 and IV-5, the dry density and void ratio, increased and decreased, respectively, as the sand content of the mixtures increased. The reason for this is that the better grain size distribution, as explained in G, allowed more efficient compaction of particles.

The variation of the dry density and void ratio from the "as molded" to the oven-dried state resulted from volume changes occurring upon drying.
GRAIN SIZE DISTRIBUTION
SAND-CLAY MIXTURES

<table>
<thead>
<tr>
<th>MIT CLASSIFICATION</th>
<th>SAND</th>
<th>SILT</th>
<th>CLAY</th>
</tr>
</thead>
<tbody>
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<td>COARSE</td>
<td>MEDIUM</td>
<td>FINE</td>
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<tr>
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</table>

DIA. - V. G.

PERCENT FINER BY WEIGHT

DIAMETER IN MM
I. DRY DENSITY OF CLAY WITHIN THE MIXTURES.

In order to determine whether the dry density of the clay within the mixture containing 30% sand was higher than the dry density of the all-clay mixture, Figure V-7 was plotted. The solid curve shows the dry density of the clay within the mixture as a function of the sand content.

Since the dry density of the clay was computed on the basis of the optimum dry density of the oven-dried sample (i.e. the specific volume of the sand was subtracted from the bulk volume of the oven-dried sample, and the known weight of the clay was assumed to occupy the remaining volume), the plot indicates average dry density. The dry density of the clay between any two sand grains could not be determined in this manner.

Nevertheless, the curve is significant, since it shows that the dry density of the clay within the mixture decreases rapidly with sand contents greater than 50%.

J. VOID RATIO OF THE CLAY WITHIN MIXTURES.

Using the total voids of the sample and volume of the clay alone, a modified void ratio was computed for the clay within the mixtures. The computations were
based on data of samples in the oven-dried state.

The dashed curve in Figure V-7 shows that the void ratio increased very slightly up to about 50% sand content. The void ratio increased very rapidly for higher sand contents.

The increase in void ratio indicates that the sand was no longer suspended in the clay mass, but began to form a structure of its own, containing voids. This checks with the assumptions made to explain the shrinkage and strength phenomena of the mixtures.
Density & Void Ratio of Clay

VS
Sand in Mixture

Average Dry Density of Clay
at the Optimum Density of
Oven-dried Sample

Void Ratio of Clay at
Optimum Density of
Oven-dried Sample

Fig. V-7
CHAPTER VI
CONCLUSIONS

In the following conclusions the term "shrinkage" will mean the decrease in volume of the "as molded" sample when oven-dried. Strength is that of oven-dried samples compacted at optimum molding water content of each mixture.

1. Increase in the sand content of mixtures from 0%:
   a. Increased the dry density
   b. Decreased the void ratio
   c. Decreased the shrinkage
   d. Decreased the optimum molding water content

2. The higher the molding water content for a mixture, the higher the shrinkage.

3. Volume change measurements of mixtures containing up to 50% sand indicated expansion at low molding water contents.

4. There were indications that molding water contents higher than optimum molding water content arranged the clay particles in a parallel manner and "packed" them more efficiently when oven-dried.

5. The mixture containing 40% sand had, concurrently, the lowest shrinkage, and the highest strength.
6. The mixture containing 30% sand had the highest strength.

7. Increase in sand content from 30%, decreased the strength gradually.

8. Strength was dependent on:
   a. Particle orientation, interparticle distances and quantity of clay among the sand grains.
   b. Grain size distribution of the mixtures.
CHAPTER VII
RECOMMENDATIONS

Future research should be conducted to verify or disprove the reasons presented for the shrinkage and strength phenomena. The author suggests the following testing, which time limitations did not permit running:

1. Optical studies of thin sections.
2. Measurement of expansion upon extrusion from mold.
3. Introduction of another variable, silt, in the mixtures.
4. Effect of additives on strength and shrinkage.
5. Durability and weather-resistivity tests.
6. Strength of oven-dried samples compacted at molding water contents other than optimum molding water content.
APPENDIX A

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BIBLIOGRAPHY

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   International Housing Activities Staff, Office of the Administrator, Housing and Home Finance Agency, Washington, D.C.


APPENDIX B

DRY DENSITY AND VOID RATIO DATA
DRY DENSITY & VOID RATIO vs. WATER CONTENT

Arrows Indicate Optimum Dry Density and Minimum Void Ratio

LEGEND:
○ DRY DENSITY AS COMPACTED
● DRY DENSITY AFTER DRYING
◆ VOID RATIO AS COMPACTED
◆ VOID RATIO AFTER DRYING

30% SAND 70% CLAY
Dry Density & Void Ratio vs. Water Content

40% Sand
60% Clay

Arrows Indicate
Optimum Dry Density
and Minimum Void Ratio

Legend:
- DRY DENSITY AS COMPACTED
- DRY DENSITY AFTER DRYING
- VOID RATIO AS COMPACTED
- VOID RATIO AFTER DRYING
DRY DENSITY / VOID RATIO vs WATER CONTENT

Arrows Indicate
Optimum Dry Density
and Minimum Void Ratio

60% SAND
40% CLAY

LEGEND:
- DRY DENSITY AS COMPACTED
- DRY DENSITY AFTER DRYING
- VOID RATIO AS COMPACTED
- VOID RATIO AFTER DRYING
Dry Density § Void Ratio vs Water Content

Arrows Indicate
Optimum Dry Density
and Minimum Void Ratio

Legend
○ Dry Density as compacted
● Void Ratio as compacted
○ Dry Density after drying
● Void Ratio after drying

Molding Water Content - %

90% Sand
10% Clay
APPENDIX C

TABLES
<table>
<thead>
<tr>
<th>SAND in MIXTURE</th>
<th>AS MOLDED STATE</th>
<th></th>
<th></th>
<th>OVEN-DRIED STATE</th>
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<th></th>
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<td>(E_{\text{min}})</td>
<td>(W_{\text{e min}})</td>
<td>(\gamma_d) opt.</td>
<td>(E_{\text{min}})</td>
<td>(W_{\text{e min}})</td>
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<td>0.364</td>
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**LEGEND**


\(E_{\text{min}}\) Minimum Void Ratio for State Indicated

\(W_{\text{e min}}\) Molding Water Content at Minimum Void Ratio for State Indicated, in %.

\(W_{\text{opt}}\) Molding Water Content for Opt. Molded Dry Density, in %.

\(S_{\text{max}}\) Max. Molding Water Content of Compaction Run, in %.

\(\Delta E\) Max. Compressive Strength in lbs./sq.ft. of Oven-dried Samples Prepared at \(W_{\text{opt}}\).

**TABLE I**

**NOTES:**

\(W_{\text{opt}} = W_{\text{e min}}\) for As Molded State.

Very Poor Compaction Existed for Mixture Containing 90% Sand by Weight.
## Tabulation of Void Ratio Changes for Sand-Clay Mixtures

<table>
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<tr>
<th></th>
<th>ALL CLAY</th>
<th>10% SAND</th>
<th>20% SAND</th>
<th>30% SAND</th>
<th>40% SAND</th>
<th>50% SAND</th>
<th>60% SAND</th>
<th>70% SAND</th>
<th>80% SAND</th>
<th>90% SAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \omega )</td>
<td>( \Delta e )</td>
<td>( \omega )</td>
<td>( \Delta e )</td>
<td>( \omega )</td>
<td>( \Delta e )</td>
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<td>( \omega )</td>
</tr>
<tr>
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<td>0.076</td>
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<td>0.084</td>
<td>22.5</td>
<td>0.101</td>
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<td>0.074</td>
<td>17.0</td>
<td>0.060</td>
<td>15.5</td>
<td>0.072</td>
<td>14.0</td>
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<td>23.5</td>
<td>0.077</td>
<td>22.0</td>
<td>0.090</td>
<td>19.5</td>
<td>0.066</td>
<td>16.5</td>
<td>0.055</td>
<td>15.0</td>
<td>0.058</td>
<td>13.0</td>
</tr>
<tr>
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<td>0.066</td>
<td>21.0</td>
<td>0.060</td>
<td>19.0</td>
<td>0.050</td>
<td>16.0</td>
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</tr>
<tr>
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<td>0.056</td>
<td>20.0</td>
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<td>0.020</td>
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<td>13.0</td>
<td>0.018</td>
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<td>0.000</td>
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<td>0.014</td>
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<td>0.011</td>
<td>7.8</td>
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<td>10.0</td>
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<td>0.002</td>
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</tr>
<tr>
<td>14.0</td>
<td>0.012</td>
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<td></td>
<td>6.0</td>
<td>0.003</td>
<td></td>
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</tbody>
</table>

**Legend**

- \( \omega \): Molding Water Content, in %
- \( \Delta e \): Void Ratio Change from As-Molded State to Oven-dried State;
  Underlined Figured Represent Expansion.

**Table II**
**D Y R  D E N S I T Y & V O I D  R A T I O  O F  C L A Y  I N  M I X T U R E**

<table>
<thead>
<tr>
<th>SAND in MIX.</th>
<th>$\gamma_d$ Opt.</th>
<th>$\gamma'_d$ Clay</th>
<th>$e'$ Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>105.3</td>
<td>105.3</td>
<td>0.548</td>
</tr>
<tr>
<td>10%</td>
<td>108.0</td>
<td>104.0</td>
<td>0.569</td>
</tr>
<tr>
<td>20%</td>
<td>112.1</td>
<td>103.8</td>
<td>0.570</td>
</tr>
<tr>
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</tr>
<tr>
<td>40%</td>
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<td>101.7</td>
<td>0.603</td>
</tr>
<tr>
<td>50%</td>
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</tr>
<tr>
<td>60%</td>
<td>129.5</td>
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<td>0.676</td>
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<tr>
<td>70%</td>
<td>132.8</td>
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<tr>
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<td>121.9</td>
<td>35.2</td>
<td>3.64</td>
</tr>
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</table>

**TABLE III**

**LEGEND**

$\gamma_d$ Opt.  Max. Dry Density for Oven-dried State, in lbs./cu. ft.

$\gamma'_d$ Clay  Average Dry Density of Clay in Mixture @ $\gamma_d$ Opt., in lbs./cu. ft.

$e'$ Clay  Void Ratio of Clay in Mixture @ $\gamma_d$ Opt.

* See Appendix for Sample Computations.
Results of Unconfined Comp. Tests

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sand in Mixture, %</th>
<th>Mold Water Content, %</th>
<th>Compressive Strength, p.s.f.</th>
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<td>22.3 (22.5)</td>
<td>20700</td>
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<td>13</td>
<td>0</td>
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<td>80</td>
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</table>

Notes:

Compressive Strength = \( P/A \), where \( P \) = Load at Initial Failure and \( A \) = Area of Sample.
Sample Size*: 1.500 in. diam., 2.816 in. long.
Rate of Strain Approx. 1% per Minute.
Samples Oven-dried for 24 hours Before Testing.
* The Variation of Size due to Shrinkage was Neglected in Computations.
Figs. in Parenthesis Indicate Opt. Molding Water Contents of Mixtures.

Table IV
APPENDIX D

PHOTOGRAPHS OF APPARATUS
COMPACTION APPARATUS

PLATE I
UNCONFINED COMPRESSION APPARATUS

PLATE III