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Compaction of Sand-Processed Clay Soil Mixtures


ABSTRACT: The effects of type of processed clay soil, curing period, and mixing procedure on laboratory compaction of sand-attapulgite clay (S-AC), sand-granular bentonite (S-GB), sand-powdery bentonite (S-PB), and sand-attapulgite clay-granular bentonite (S-AC-GB) mixtures are evaluated. Compaction is evaluated for total clay soil contents of 10, 15, and 20%. Different trends in optimum water content, w\text{opt}, and maximum dry unit weight, γ\text{dmax}, versus clay soil content among the S-AC, S-GB, and S-PB mixtures are attributed, in part, to (1) the greater water sorptivity and lower swelling potential of attapulgite clay relative to the bentonites, (2) the larger particle sizes of the granular bentonite in the air-dried condition relative to the powdery bentonite, and (3) the possible correlation between the w\text{opt} and the plasticity index of the sand-bentonite mixtures. The Δw\text{opt} and Δγ\text{dmax} values resulting from one-day versus seven-day curing periods before compaction of the S-GB and S-PB mixtures are ~0.5 percentage points and ~0.08 kN/m 3 (~0.5 pcf), respectively, and result in different trends in γ\text{dmax} versus bentonite content for the two types of sand-bentonite mixtures. Also, mixing the sand and bentonite in a dry condition before adding water consistently results in greater w\text{opt} and γ\text{dmax} values than mixing the sand with the appropriate amount of water before adding the bentonite regardless of the type of bentonite. Finally, mixing the attapulgite clay and granular bentonite together in small amounts for each individual compaction point for the S-AC-GB mixtures consistently results in higher γ\text{dmax} and w\text{opt} values relative to mixing the attapulgite clay and granular bentonite together in large amounts sufficient to cover all compaction points.

KEYWORDS: activity, attapulgite, Atterberg limits, bentonite, compaction, curing, granular bentonite, powdery bentonite, sand-attapulgite clay mixtures, sand-bentonite mixtures, sand-clay soil mixtures

Compaction control has a dominating influence on the hydraulic conductivity of compacted clayey soils used as low-permeability liners and covers for waste disposal (Lambe 1958; Bjerrum and Huder 1957; Mitchell et al. 1965). For example, Mitchell et al. (1965) illustrated that the laboratory-measured hydraulic conductivity of a compacted silty clay (liquid limit = 37%, plastic limit = 23%) was more than two orders of magnitude lower when the soil was compacted wet of optimum water content, w\text{opt}, versus dry of w\text{opt}. As a result of these and other studies, typical specifications for the construction of compacted clay liners and covers require that the field soil be compacted wet of w\text{opt} or wet of the line of optimum water contents to achieve the lowest possible hydraulic conductivity (Daniel and Benson 1990).

In some cases, natural clayey soils suitable for use as compacted clay liners and covers are not readily or economically available. In such cases, compacted sand-bentonite mixtures typically are considered for use primarily due to the abundance and availability of processed bentonite, typically sodium bentonite, and the ability of the compacted mixture to achieve a relatively low hydraulic conductivity (e.g., ~10^-7 cm/s) upon permeation with water using only relatively small quantities (e.g., ~20% by dry weight) of the bentonite admixture (Daniel 1987; Garlanger et al. 1987; Chapuis et al. 1992; O'Sadnick et al. 1995; Gleason et al. 1997; Howell and Shackelford 1997). The low hydraulic conductivity values for compacted sand-bentonite mixtures are attributed primarily to the high swelling potential of sodium bentonites in the presence of water, resulting in the formation of a relatively "tight" soil matrix.

However, studies also have shown that the hydraulic conductivity of compacted sand-bentonite mixtures permeated with an actual or simulated liquid waste or leachate can be significantly higher than the hydraulic conductivity of the same mixtures permeated with water (Gipson 1985, Shackelford 1994; Gleason et al. 1997). As a result, the use of other processed clay soils as admixture materials for waste containment applications has been investigated. In particular, attapulgite clay, also known as attapulgus, has been considered for use as a substitute for bentonite in vertical cutoff walls as well as in compacted clay liners (Tobin and Wild 1986; Ryan 1987; Broderick and Daniel 1990; and Day 1994). These studies have shown that the hydraulic conductivity of compacted attapulgite clay and attapulgite clay slurries is relatively unaffected when permeated with several different waste liquids.

The purpose of this paper is to present the results of a compaction study aimed at identifying the trends in w\text{opt} and maximum dry unit weight, γ\text{dmax}, for compacted mixtures containing sand and either sodium bentonite or attapulgite clay. In addition, compaction of sand-clay soil mixtures in which the clay soil admixture consists of mixtures of the bentonite and the attapulgite clay also are evaluated.
Materials

Soils

The soils used as mixture constituent materials in this study are attapulgite clay, granular bentonite, powdery bentonite, and sand. A qualitative comparison of the properties of attapulgite clay and bentonite is provided in Table 1. The physical and chemical properties of the constituent materials used in the soil mixtures in this study are summarized in Tables 2 and 3, respectively. The procedures used to measure the soil chemical properties are described by Shackelford and Redmond (1995).

In general, attapulgite crystals are needle-like, resulting in aggregates that form a "hay stack" structure. The attractive forces between the needles within a particle are considerable, and therefore attapulgite is not particularly susceptible to swelling. However, attapulgite is a highly sorptive material in terms of absorption of water into the channels between the crystals. Attapulgite clay also appears to be stable in high concentrations of electrolytes and, therefore, is not as susceptible as the plate-like clay minerals to dramatic changes in hydraulic conductivity after exposure to liquid waste (Tobin and Wild 1986). As a result, attapulgite clay may be used as a soil additive to help stabilize an otherwise unstable soil (Broderick and Daniel 1990). However, since the high swelling potential evident in sodium bentonite is not evident in attapulgite clay due to the difference in mineralogical composition of the soil, the primary concern with the use of attapulgite clay as a liner material is the ability to achieve a relatively low hydraulic conductivity when permed with water (Howell and Shackelford 1997).

Particle-size distributions of the soil constituents are shown in Fig. 1. For the clay soils, the results of both hydrometer analyses (ASTM D 421) and mechanical sieve analyses (ASTM D 422) performed on the unaltered, air-dried soil constituents are shown to distinguish individual particle sizes from the clod sizes that occur at the natural (gravimetric) water contents ranging from 5 to 6.5%.

The classifications of the soils based on the Unified Soil Classification System (ASTM D 2487), USCS, also are shown in Fig. 1. The attapulgite clay and powdery bentonite are classified as CH regardless of whether the distribution is based on the hydrometer analysis or the mechanical sieve analysis of the air-dried clay soil. However, the granular bentonite classifies as a clayey sand, SC, according to the USCS based on the results of the mechanical sieve analysis. Thus, the initial particle-size distribution of the granular bentonite (i.e., before compaction) is similar to that of a clayey sand in that the particles actually represent small clods. This difference in initial particle-size distributions for the granular bentonite may affect the performance of the granular bentonite in the sand-clay soil mixtures since no attempt is made during specification procedures to measure the soil chemical properties described by Shackelford and Redmond (1995).

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men preparation to destroy the intact clods of the granular bentonite.

Index Properties of Soil Mixtures

Four soil mixtures were used in this study: sand mixed with granular bentonite (S-GB), sand mixed with powdery bentonite (S-PB), sand mixed with attapulgite clay (S-AC), and sand mixed with attapulgite clay and granular bentonite (S-AC-GB). The total clay soil contents (i.e., AC, GB, PB, or AC + GB) in the sand-clay soil mixtures are 10, 15, and 20% of the dry weight of the soil mixture. The clay soil content differs from the clay particle content (i.e., % < 2 μm) in that the clay soil content is the amount of attapulgite clay and/or bentonite added to the sand-clay soil mixture and, therefore, includes particle sizes > 2 μm as indicated in Fig. 1. The use of clay soil content is in accordance with practical applications where the amount of the processed clay soil added to the sand is the primary interest (e.g., amount of bentonite in a sand-bentonite mixture). The clay soil content of the sand-clay soil mixtures containing both bentonite and attapulgite clay was composed of equal amounts of the two processed clay soils (i.e., 50% each by dry weight of the clay soil admixture).

The minimum clay soil content of 10% was based primarily on the study by Kenney et al. (1992), who found that many void spaces did not contain bentonite due to inadequate distribution for bentonite contents ≤7.4%. Instead, Kenney et al. (1992) found that adequate distribution of the bentonite in the mixture occurred for bentonite contents ≥9%. This lower limit on the bentonite content also is consistent with the bentonite contents based on field mixing criteria reported by Lundgren (1981), Garlanger et al. (1987), and O’Sadnick et al. (1995). Clay soil contents greater than 20% were considered unreasonable from a practical viewpoint due to the likelihood of excessive cost.

The measured and calculated properties of the soil mixtures are summarized in Table 4. Plots of plasticity index, PI, versus percent clay particles (% < 2 μm) are shown in Fig. 2 for all mixtures. Based on Skempton (1953), the slopes of these plots should be a straight line representing the activity, A (= PI/% < 2 μm), of the soil. Also, Skempton (1953) found that the relationship between PI and % < 2 μm intercepted the origin for naturally occurring soils (i.e., as opposed to soil mixtures). However, Seed et al. (1964a) typically found that there is an intercept on the x-axis for % < 2 μm (i.e., the line does not pass through the origin) for mixtures of sand and processed clay soils. Based on their observations, Seed et al. (1964a) modified Skempton’s original activity equation as follows:

$$A = \frac{\Delta PI}{\Delta(\% < 2 \mu m)}$$  

(1)

where $\Delta PI$ is the change in plasticity index, and $\Delta(\% < 2 \mu m)$ is the corresponding change in percent of clay particle sizes. Results from Seed et al. (1964a) consistently indicated an x-intercept, $x_0$, of 9. As indicated in Fig. 2, the soil mixtures in this study yield $x_0$ values ranging from 5.1 to 5.7. The activities of the sand-clay soil mixtures based on Eq 1 also are shown in Fig. 2.

Compaction Water

A processed tap water (PTW) was used for compaction. Tap water was passed through three Barnstead® columns to obtain the processed tap water (PTW). The measured pH and specific (electrical) conductance of the PTW at 25°C were 7.1 and 32.8 μS/cm, respectively.

Methods

Specimen Preparation

Two mixing procedures were used to evaluate the effect of mixing on compaction. Mixing Procedure 1 consisted of mixing
TABLE 4—Physical properties of soil mixtures.

<table>
<thead>
<tr>
<th>Mixture No.</th>
<th>AC</th>
<th>GB</th>
<th>PB</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
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<td>...</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
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<td>16</td>
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<tr>
<td>12</td>
<td>10</td>
<td>10</td>
<td>...</td>
<td>20</td>
</tr>
</tbody>
</table>

**Atterberg Limits**

<table>
<thead>
<tr>
<th>Mixture No.</th>
<th>Liquid Limit, LL (%)</th>
<th>Plasticity Index, PI (%)</th>
<th>Specific Gravity, (G_s) ((0.074-4.75) mm, %)</th>
<th>Silt ((0.002-0.074) mm, %)</th>
<th>Clay (&lt;2 (\mu)m, %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>90.7</td>
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<td>2.67</td>
<td>81.3</td>
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</tr>
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<td>35</td>
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<td>90.5</td>
<td>2.0</td>
</tr>
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<td>30</td>
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<td>81.2</td>
<td>4.9</td>
</tr>
</tbody>
</table>

**Particle Sizes**

- AC = attapulgite clay; GB = granular bentonite; PB = powdery bentonite.
- Measured according to ASTM D 4318.
- Calculated from individual soil constituents.

For samples containing both clay soils, two different variations of Mixing Procedure 1 also were evaluated considering only a one-day curing period: the batch mixing procedure and the individual mixing procedure. The batch mixing procedure involved mixing a large batch of equal amounts by dry weight of attapulgite clay and granular bentonite and taking the appropriate amount of clay soil mixture from the batch to add at arbitrary intervals to the wet sand. The individual mixing procedure involved weighing out the desired amounts of attapulgite clay and granular bentonite for each individual compaction test, mixing the two clay soils into a
combined clay soil mixture, and then adding that clay soil mixture at arbitrary intervals to the wet sand.

**Specimen Compaction**

Specimens for each soil mixture were compacted in accordance with standard compaction procedures (ASTM D 698). The optimum water content, \( w_{\text{opt}} \), and the maximum dry unit weight, \( \gamma_{\text{dmax}} \), for the resulting compaction data were determined by regressing the measured data with a third-order polynomial equation of the following form:

\[
\gamma_d = Aw^3 + Bw^2 + Cw + D
\]

where \( \gamma_d \) is the dry unit weight, \( \text{kN/m}^3 \), \( w \) is the corresponding molding (compaction) water content, \( \% \), and \( A, B, C, \) and \( D \) are constants resulting from the fitting process. Both second-order and fourth-order polynomial equations were also considered. However, a second-order polynomial equation does not allow for the possibility of an increase in \( \gamma_d \) with a decrease in \( w \) that can occur when the molding water content is significantly dry of \( w_{\text{opt}} \) (Hausmann, 1990), whereas a fourth-order polynomial equation fits four data points exactly and does not provide significantly greater accuracy relative to a third-order polynomial equation for more than four data points. Thus, a third-order polynomial equation is reasonable.

The local maximum and minimum of a third-order polynomial fit can be ascertained by setting the derivative of Eq 2 with respect to \( w \) equal to zero, or

\[
\frac{d\gamma_d}{dw} = 3Aw^2 + 2Bw + C = 0
\]

and solving the resulting quadratic equation for the two roots of \( w \), or

\[
w = \frac{-B \pm \sqrt{B^2 - 12AC}}{6A}
\]

The value of \( w \) corresponding to \( \gamma_{\text{dmax}} \) is \( w_{\text{opt}} \) and \( \gamma_{\text{dmax}} \) is determined by substituting \( w_{\text{opt}} \) into Eq 2, or:

\[
\gamma_{\text{dmax}} = Aw_{\text{opt}}^3 + Bw_{\text{opt}}^2 + Cw_{\text{opt}} + D
\]

Since most software plotting packages provide for third-order polynomial fitting, and the roots of the fitted curve (Eq 4) can be determined using a hand-held calculator, the above analysis for \( w_{\text{opt}} \) and \( \gamma_{\text{dmax}} \) is straightforward, yet provides a consistent and rational basis for evaluating the differences among different compaction curves. A summary of the resulting fitting parameter values and corresponding \( w_{\text{opt}} \) and \( \gamma_{\text{dmax}} \) values for the compaction tests performed in this study is provided in Table 5. Presentation of the measured data and discussion of the results follows.

**Results and Discussion**

**Effect of Clay Soil Type**

The standard compaction curves (ASTM D 698) for Test Nos. 1–12 (Table 5) performed to distinguish the type of processed clay soil in the sand-clay soil mixtures on \( w_{\text{opt}} \) and \( \gamma_{\text{dmax}} \) are shown in Fig. 3. The shape of the third-order polynomial fit to the measured data for powdery bentonite (Fig. 3e) may be due to the arching effect that results from compaction at molding water contents that are significantly dry of \( w_{\text{opt}} \) as described by Hausmann (1990), or simply may be the result of scatter in the data on the dry side of \( w_{\text{opt}} \).

The trends in \( w_{\text{opt}} \) and \( \gamma_{\text{dmax}} \) with clay soil content for the compaction curves in Fig. 3 are shown in Fig. 4. As expected, \( w_{\text{opt}} \) increased and \( \gamma_{\text{dmax}} \) decreased as the amount of attapulgite clay in the mixture increased from 10 to 20%. These trends are expected since clay soils typically have lower \( \gamma_{\text{dmax}} \) values and higher \( w_{\text{opt}} \) values than sands; thus, an increase in clay soil content is expected to decrease \( \gamma_{\text{dmax}} \) and to increase \( w_{\text{opt}} \). However, the same trends in \( w_{\text{opt}} \) and \( \gamma_{\text{dmax}} \) are not evident for the mixtures containing bentonite.

For example, \( \gamma_{\text{dmax}} \) for the sand-groovy bentonite (S-GB) mixtures is relatively insensitive to the clay soil content, whereas \( \gamma_{\text{dmax}} \) for the sand-powdery bentonite (S-PB) mixtures increases as the powdery bentonite content increases from 10 to 20%. The relative insensitivity of the \( \gamma_{\text{dmax}} \) values to the clay soil content for the S-GB mixtures may be attributed, in part, to the similarity between the particle-size distribution for the sand and the particle-size distribution for the granular bentonite based on the mechanical (sieve) analysis of the air-dried soil as shown in Fig. 1.

The trend in \( \gamma_{\text{dmax}} \) versus clay soil content for the S-PB mixtures is somewhat consistent with Kenney et al. (1992), who reported an increase in \( \gamma_{\text{dmax}} \) until about 16% bentonite content followed by a decrease in \( \gamma_{\text{dmax}} \) with increasing bentonite content. In this case, the smaller particles of the powdery bentonite fill the void spaces between the larger sand particles. The difference between the results reported by Kenney et al. (1992) and those reported for the powdery bentonite mixtures in this study may be due, in part, to the differences between the sand and bentonites used in both studies. For example, the sand used by Kenney et al. (1992) contained 2% fines (% < 0.075 mm), whereas the sand used in this study contained no fines (Table 2).

Since the \( \gamma_{\text{dmax}} \) values for the granular and powdery bentonites are both lower than the \( \gamma_{\text{dmax}} \) values reported in Table 5 and shown in Figs. 3 and 4 for the S-GB and S-PB mixtures, the \( \gamma_{\text{dmax}} \) values for the sand-bentonite mixtures should decrease eventually as the bentonite content increases toward 100%. In the case of the S-PB mixtures, a peak \( \gamma_{\text{dmax}} \) value at a clay soil content past 20% also would be consistent with the trends reported by Kenney et al. (1992). Thus, additional compaction curves were generated for bentonite contents of 30, 40, 60, and 80% to investigate this expected trend. The resulting \( \gamma_{\text{dmax}} \) values for these compaction curves are plotted together with the previously reported \( \gamma_{\text{dmax}} \) values for bentonite contents of 10, 15, 20, and 100% as a function of bentonite content in Fig. 5.

The data in Fig. 5 for both the S-GB and S-PB mixtures indicate the expected trend. The data in Fig. 5 also indicate that the differences in \( \gamma_{\text{dmax}} \) values, or \( \Delta \gamma_{\text{dmax}} \), for bentonite contents ranging from 10 to 20% are small relative to the overall \( \Delta \gamma_{\text{dmax}} \) for bentonite contents ranging from 10 to 100%. For example, the maximum \( \Delta \gamma_{\text{dmax}} \) values for bentonite contents between 10 and 20% are only 2.1 and 9.2% of the maximum \( \Delta \gamma_{\text{dmax}} \) values for bentonite contents between 10 and 100% for the S-GB and S-PB mixtures, respectively.

As shown in Fig. 4, there is no significant peak in the trend of \( \gamma_{\text{dmax}} \) versus bentonite content for the sand-groovy bentonite (S-GB) mixtures, whereas the peak \( \gamma_{\text{dmax}} \) value occurs for the bentonite content of 20% for the sand-powdery bentonite (S-PB) mixtures. However, the second-order polynomial fit to the data for the S-PB mixtures is essentially a straight line (i.e., third term in equation...
The trend of decreasing $w_{\text{opt}}$ versus increasing bentonite content also may be related to the correlation between $w_{\text{opt}}$ and PL previously noted by Leroueil et al. (1992), and the correlation between the PL and clay particle content (% < 2 μm) for sand-clay soil mixtures previously noted by Seed et al. (1964a, b). In terms of a correlation between $w_{\text{opt}}$ and PL, Leroueil et al. (1992) indicated that $w_{\text{opt}} \approx PL$ for natural clay soils (i.e., as opposed to sand-bentonite mixtures). As shown by the data plotted in Fig. 6a, the correlation between $w_{\text{opt}}$ and PL for several compacted clay soils is close to 1:1, but there is significant scatter in the data ($r^2 = 0.951$). Thus, there appears to be a correlation between $w_{\text{opt}}$ and PL, but this correlation is not consistent between natural clay soils and pure clay minerals.

The difference in the trend of $w_{\text{opt}}$ versus bentonite content for the sand-bentonite mixtures relative to the S-AC mixtures may be due, in part, to the greater sorptivity and lower swelling potential of the attapulgite clay relative to the bentonite, as indicated in Table 1. As a result, attapulgite clay absorbs water without significant swelling. This higher water holding capacity for attapulgite clay is reflected by a $w_{\text{opt}}$ for attapulgite clay of 59.3%, whereas the $w_{\text{opt}}$ values for the granular and powdery bentonites are only 28.4 and 35.9%, respectively (Table 5).

As shown in Fig. 4, $w_{\text{opt}}$ for both types of sand-bentonite mixtures decreases with increasing bentonite content regardless of the type of bentonite. This trend is not consistent with the sand-attapulgite clay (S-AC) mixtures, nor with Kenney et al. (1992), who found an increase in $w_{\text{opt}}$ with increasing bentonite content. Also, the trend of decreasing $w_{\text{opt}}$ with increasing bentonite content is not due to the two different types of bentonite considered in this study since the same trend is observed for both types of sand-bentonite mixtures.

The difference in the trend of $w_{\text{opt}}$ versus bentonite content for the sand-bentonite mixtures relative to the S-AC mixtures may be due, in part, to the greater sorptivity and lower swelling potential of the attapulgite clay relative to the bentonite, as indicated in Table 1. As a result, attapulgite clay absorbs water without significant swelling. This higher water holding capacity for attapulgite clay is reflected by a $w_{\text{opt}}$ for attapulgite clay of 59.3%, whereas the $w_{\text{opt}}$ values for the granular and powdery bentonites are only 28.4 and 35.9%, respectively (Table 5).

The trend of decreasing $w_{\text{opt}}$ versus increasing bentonite content also may be related to the correlation between $w_{\text{opt}}$ and PL previously noted by Leroueil et al. (1992), and the correlation between the PL and clay particle content (% < 2 μm) for sand-clay soil mixtures previously noted by Seed et al. (1964a, b). In terms of a correlation between $w_{\text{opt}}$ and PL, Leroueil et al. (1992) indicated that $w_{\text{opt}} \approx PL$ for natural clay soils (i.e., as opposed to sand-bentonite mixtures). As shown by the data plotted in Fig. 6a, the correlation between $w_{\text{opt}}$ and PL for several compacted clay soils is close to 1:1, but there is significant scatter in the data ($r^2 = 0.732$). Also, as alluded to by Leroueil et al. (1992), Lambe (1959) had criticized the assumption that $w_{\text{opt}} \approx PL$ on the basis that the correlation between $w_{\text{opt}}$ and PL is not unity for pure clay minerals. This criticism is supported by the data in Fig. 6b that indicate $w_{\text{opt}} \approx 0.5PL$ for pure clay minerals, although there is less scatter in the data in Fig. 6b ($r^2 = 0.951$) relative to Fig. 6a. Thus, there appears to be a correlation between $w_{\text{opt}}$ and PL, but this correlation is not consistent between natural clay soils and pure clay minerals.
FIG. 3—Standard compaction curves (ASTM D 698) for processed clay soils and sand-clay soil mixtures for a one-day curing period and Mixing Procedure 1.

(a) Attapulgite Clay (AC)  
(b) Sand-Attapulgite Clay (S-AC)  
(c) Granular Bentonite (GB)  
(d) Sand-Granular Bentonite (S-GB)  
(e) Powdery Bentonite (PB)  
(f) Sand-Powdery Bentonite (S-PB)  

Molding Water Content, w (%)  
Dry Unit Weight, \( \gamma_d \) (kN/m\(^3\))

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and no such correlation between \( w_{opt} \) and PL has been established for sand-clay soil mixtures.

In terms of a correlation between PL and clay particle content, Seed et al. (1964b) evaluated measured plastic limits of various mixtures of a washed sand and several processed clay soils (bentonite, kaolinite/bentonite, and illite/bentonite) at several clay particle contents (% < 2 \( \mu m \)). Seed et al. (1964b) found that the PL of the mixtures initially decreased with increasing clay particle contents to a minimum PL of approximately 20 at clay particle contents ranging from ~30 to ~40% after which the PL of the mixtures increased and ultimately approached the limiting PL value associated with the processed clay soil. The initial decline in PL with increasing clay particle content was explained by Seed et al. (1964b) as due to the dominance of the nonclay fraction of the mixture at relatively low clay particle contents (i.e., ≤40%) wherein the clay particles are filling the void spaces between the load-bearing sand matrix. As the clay particle contents increased, the sand particles are displaced such that the mixture consists of sand embedded in clay, and the PL of the mixture accordingly increases with increasing clay particle contents.

An evaluation of these concepts for the compacted sand-bentonite mixtures considered in this study is represented by the data shown in Fig. 7, wherein the PL and \( w_{opt} \) values are plotted as a function of bentonite content for all sand-bentonite mixtures, including the additional mixtures corresponding to bentonite contents of 30, 40, 60, and 80% that were developed to evaluate the \( \gamma_{dmax} \) trends previously

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**FIG. 4**—Influence of clay soil content on (a) optimum water content and (b) maximum dry unit weight for a one-day curing period and Mixing Procedure 1.
FIG. 5—Influence of bentonite content on maximum dry unit weight for a one-day curing period and Mixing Procedure 1.

FIG. 6—Correlation between plastic limit and optimum water content for (a) natural clayey soils, and (b) pure clay minerals.
increasing bentonite content followed by an increase in PL values and corresponding clay particle contents agree very closely. The minimum PL of 18.5 occurs at a bentonite content of 44.7%, corresponding to a clay particle content of 33.5% for the S-GB mixtures (Fig. 7a), whereas a minimum PL of 20.3 occurs at a bentonite content of 35.5% for the S-PB mixtures (Fig. 7b). However, no simple linear correlation passing through the origin is apparent. Thus, even though there appears to be some correlation between $w_{opt}$ and PL that may explain partially the initial decrease in $w_{opt}$ for the sand-bentonite mixtures evaluated in this study, no quantifiable conclusion can be made in this regard from the results of this study.

Effect of Curing Period

The standard compaction curves (ASTM D 698) for Test Nos. 13–18 (see Table 5), performed to evaluate the effect of curing period for the S-GB and the S-PB mixtures, are shown in Fig. 9. Curing period refers to the time allowed between mixing and compacting the sand-bentonite mixtures. The compaction results for the one-day curing period using Mixing Procedure 1 are represented by Test Nos. 6–8 for the S-GB mixtures and Test Nos. 10–12 for the S-PB mixtures as previously presented. The compaction results for a seven-day curing period using Mixing Procedure 1 are represented by Test Nos. 13–15 for the S-GB mixtures and Test Nos. 16–18 for the S-PB mixtures. The trends in $w_{opt}$ and $\gamma_{d,max}$ values versus bentonite content for all of these tests are presented in Fig. 10.

As shown in Fig. 10a, the general trend of decreasing $w_{opt}$ with increasing bentonite content for the seven-day curing period is the same as that for the one-day curing time. Also, except for the S-
GB mixture at 20% bentonite content, the difference in \( w_{\text{opt}} \) resulting from the different curing periods for the same sand-bentonite mixture and bentonite content is less than ~0.5 percentage points.

The trends in the \( \gamma_{\text{dmax}} \) versus bentonite content for both the S-GB and the S-PB mixtures shown in Fig. 10b based on the seven-day curing period are essentially identical to those based on the one-day curing period. Also, the \( \Delta \gamma_{\text{dmax}} \) values resulting from the different curing periods for the same sand-bentonite mixture and bentonite content are \( \leq 0.08 \text{ kN/m}^3 \) (\( \leq 0.5 \text{pcf} \)).

Based on the comparison of results for Test Nos. 13–18 relative to Test Nos. 6–8 and 10–12, the two different curing periods have a small effect on the \( w_{\text{opt}} \) and \( \gamma_{\text{dmax}} \) values for the S-GB and the S-PB mixtures at the same bentonite contents and for the same mixing procedure. Except for the trend in \( w_{\text{opt}} \) versus bentonite content for the S-GB mixtures prepared using a seven-day curing period, the trends in \( w_{\text{opt}} \) and \( \gamma_{\text{dmax}} \) with bentonite content for the two different sand-bentonite mixtures and the two different curing periods are essentially the same. Thus, the compaction results based on the seven-day curing period tend to support the previously reported compaction results based on the one-day curing period for the S-GB and the S-PB mixtures and the same mixing procedure.

Additional data attributing the difference in the trends in \( w_{\text{opt}} \) versus bentonite content for the S-GB mixtures based on the two curing periods to the difference in curing periods is provided in the subsequent discussion.

**Effect of Mixing Procedure**

A second mixing procedure, Mixing Procedure 2, that involves mixing the dry sand and bentonite before adding the appropriate amount of water to the soil with a spray bottle also was evaluated for a seven-day curing period. The resulting standard compaction curves (ASTM D 698) based on Mixing Procedure 2 for the S-GB and the S-PB mixtures (Test Nos. 19–24, Table 5) also are shown in Fig. 9 for comparison with the compaction curves for Mixing Procedure 1 and a seven-day curing period (Test Nos. 13–18, Table 5).

The trends in \( w_{\text{opt}} \) and \( \gamma_{\text{dmax}} \) values versus bentonite content based on all of the compaction curves in Fig. 9 are shown in Fig. 11. In general, the trends in the data for both the S-GB and S-PB mixtures are identical regardless of whether Mixing Procedure 1 or Mixing Procedure 2 is used in the compaction. Thus, the different trend in \( w_{\text{opt}} \) versus bentonite content obtained for the S-GB mix-
Bentonite content of 10%. Both of these relative differences are 0.18 kN/m³ (1.0 pcf) for the S-PB mixture occur at the lowest curing period previously illustrated in Fig. 10a is consistent with respect to the different mixing procedures and, therefore, can be attributed partially to the difference in the curing periods.

Although the trends in $W_{\text{opt}}$ and $\gamma_{\text{dmax}}$ versus bentonite content shown in Fig. 11 are consistent regardless of the mixing procedure, some differences in the $W_{\text{opt}}$ and $\gamma_{\text{dmax}}$ values based on the different mixing procedures are apparent. Except for the S-PB mixture at 20% bentonite content, the use of Mixing Procedure 2 consistently results in greater $W_{\text{opt}}$ and $\gamma_{\text{dmax}}$ values than when Mixing Procedure 1 is used regardless of the type of bentonite. In addition, the greatest differences in $W_{\text{opt}}$ or $\Delta W_{\text{opt}}$ of 1.9 percentage points for the S-GB mixture and 0.7 percentage points for the S-PB mixture occur at the highest bentonite content of 20%, whereas the greatest $\Delta \gamma_{\text{dmax}}$ values of 0.26 kN/m³ (1.7 pcf) for the S-GB mixture and 0.18 kN/m³ (1.0 pcf) for the S-PB mixture occur at the lowest bentonite content of 10%. Both of these relative differences are consistent with the expected effects of an increase in bentonite content on $W_{\text{opt}}$ and $\gamma_{\text{dmax}}$. However, the $\Delta W_{\text{opt}}$ at 20% bentonite content and $\Delta \gamma_{\text{dmax}}$ at 10% bentonite content are greater for the S-GB mixtures than for the S-PB mixtures. Thus, the particle-size distribution of the bentonite in an air-dried condition apparently affects the results in $W_{\text{opt}}$ and $\gamma_{\text{dmax}}$ at the relatively high and the relatively low bentonite contents evaluated in this study, respectively.

Except for the S-GB mixture with a 20% bentonite content where the $\Delta W_{\text{opt}}$ is 1.9 percentage points, the $\Delta W_{\text{opt}}$ values due to the two different mixing procedures ($\leq 0.7$ percentage points) are approximately the same as the $\Delta W_{\text{opt}}$ values due to the two curing periods ($\leq 0.5$ percentage points). Thus, the effects of the two different mixing procedures on $W_{\text{opt}}$ are approximately the same as the effects of the two different curing periods on $W_{\text{opt}}$. However, the effect of mixing procedure on $W_{\text{opt}}$ may be greater than the effect of the curing period when the initial particle sizes of the bentonite in the air-dried condition are relatively large and the bentonite content is relatively high (e.g., 20%).

Except for the S-PB mixture with a 15% bentonite content, the $\Delta \gamma_{\text{dmax}}$ values based on the two mixing procedures [i.e., 0.16 kN/m³ (1.0 pcf) $\leq \Delta \gamma_{\text{dmax}} \leq 0.26$ kN/m³ (1.7 pcf)] tend to be greater than the $\Delta \gamma_{\text{dmax}}$ values based on the two curing periods [i.e., $\Delta \gamma_{\text{dmax}} \leq 0.08$ kN/m³ (0.5 pcf)]. Thus, the effect of mixing procedure on $\gamma_{\text{dmax}}$ of the sand-bentonite mixtures in this study tends to be more significant than the effect of the curing period on $\gamma_{\text{dmax}}$.

### Sand-Attapulgite Clay-Granular Bentonite Mixtures

Mixing Procedure 1 with a one-day curing period was used to develop compaction curves (Test Nos. 25–30) for the sand-attapulgite clay-granular bentonite (S-AC-GB) mixtures. In this case, two variations in Mixing Procedure 1 were evaluated: (1) a large batch of equal amounts of attapulgite clay and granular bentonite were mixed by dry weight, and the appropriate amount of clay soil from the batch was added in intervals to the wet sand; and (2) appropriate amounts of attapulgite clay and bentonite for each compaction test were weighed individually, mixed together, and then added in intervals to the wet sand. The former procedure is termed the “batch mixing procedure” while the latter procedure is termed the “individual mixing procedure.”

The standard compaction curves (ASTM D 698) for Test Nos. 25–30 (Table 5) are shown in Fig. 12, and the trends in the resulting $W_{\text{opt}}$ and $\gamma_{\text{dmax}}$ values versus clay soil content are illustrated in Fig. 13. In general, both the batch mixing procedure and the individual mixing procedure result in the same trends of decreasing $\gamma_{\text{dmax}}$ and decreasing $W_{\text{opt}}$ with increasing clay soil content. The trend of decreasing $W_{\text{opt}}$ with increasing clay soil content is similar to the same trend previously described for the S-GB mixtures, indicating that the granular bentonite has a dominating effect on $W_{\text{opt}}$ in the S-AC-GB mixtures. However, the trend of decreasing $\gamma_{\text{dmax}}$ with increasing clay soil content is similar to the same trend previously described for the S-AC mixtures, indicating that the attapulgite clay has a dominating effect on $\gamma_{\text{dmax}}$ for the S-AC-GB mixtures.

The individual mixing procedure results in consistently higher $W_{\text{opt}}$ and $\gamma_{\text{dmax}}$ values than the batch mixing procedure. Except for the lowest clay soil content of 10%, where $\Delta \gamma_{\text{dmax}} = 0.27$ kN/m³ (1.7 pcf), the $\Delta \gamma_{\text{dmax}}$ values tend to be low ($\Delta \gamma_{\text{dmax}} \leq 0.05$ kN/m³ ($\leq 0.3$ pcf)). This is consistent with the effect of the mixing procedure on the $\Delta \gamma_{\text{dmax}}$ values for the S-GB and S-PB mixtures previously described. However, the $\Delta W_{\text{opt}}$ values based on the individual mixing procedure and the batch mixing procedure are more significant, ranging from 1.2 percentage points to 2.7 percentage points. Therefore, some consideration should be given to the potential effect on $W_{\text{opt}}$ resulting from differences in mixing procedure when dealing with S-AC-GB mixtures.
FIG. 11—Influence of bentonite content on (a) optimum water content and (b) maximum dry unit weight for a seven-day curing period and two mixing procedures.
Practical Significance

The results of this study indicate that differences in $w_{opt}$ and $\gamma_{dmax}$ values based on laboratory compaction of sand-processed clay soil mixtures can occur due to differences in the amount and type of processed clay soil used in the mixture as well as differences in the curing period and the mixing procedure used with a given sand-clay soil mixture at a given clay soil content. Although the differences in $w_{opt}$ and $\gamma_{dmax}$ values reported in this study are relatively small in most cases, the magnitudes of these differences may be significant in some practical applications. For example, in the case of construction specifications for compacted clay liners and covers that require compaction at a field water content, $w_f$, greater than or equal to the optimum water content based on laboratory compaction (i.e., $w_f \geq w_{opt}$), a small difference in $w_{opt}$ can have a significant effect on the resulting hydraulic conductivity of the compacted clay liner. However, this effect will depend on the sensitivity of the hydraulic conductivity to the compaction water content which, in the case of the use of sand-clay soil mixtures, may not be as significant as in the case of natural clay soils (e.g., Kraus et al. 1997). Nonetheless, the potential significance of this effect must be evaluated on a case-by-case basis.

Summary and Conclusions

The expected trends of increasing $w_{opt}$ and decreasing $\gamma_{dmax}$ with increasing clay soil contents from 10 to 20% were observed for the sand-attapulgite clay (S-AC) mixtures. However, for clay soil contents ranging from 10 to 20%, $w_{opt}$ decreased with increasing clay soil content for both the sand-granular bentonite (S-GB) mixtures and the sand-powdery bentonite (S-PB) mixtures, whereas $\gamma_{dmax}$ increased for the S-PB mixtures and remained relatively constant for the S-GB mixtures. The relative differences in these trends are attributed, in part, to (1) the greater water sorptivity and lower swelling potential of attapulgite clay relative to the two bentonites, (2) the larger particle sizes of the granular bentonite in the air-dried condition relative to the powdery bentonite, and (3) the possible correlation between the $w_{opt}$ and the PI of the sand-bentonite mixtures.

In general, the two different curing periods (one-day and seven-day) considered in this study had a small effect on the $w_{opt}$ and $\gamma_{dmax}$ values for the S-GB and S-PB mixtures at the same clay soil contents and for the same mixing procedure. For example, the $\Delta w_{opt}$ and $\Delta \gamma_{dmax}$ values resulting from the two different curing periods were ~0.5 percentage points and ~0.08 kN/m$^3$ (~0.5 pcf), respectively. However, the different curing periods did result in different trends in $\gamma_{dmax}$ versus bentonite content for the S-GB mixtures relative to the S-PB mixtures, possibly due to the different particle-size distributions of the two bentonites in the air-dried condition.

Mixing the sand and bentonite in a dry condition before adding water consistently resulted in greater $w_{opt}$ and $\gamma_{dmax}$ values than mixing the sand with the appropriate amount of water before adding the bentonite regardless of the type of bentonite. However, the $\Delta w_{opt}$ values tend to be the greatest at the 20% bentonite content, whereas the $\Delta \gamma_{dmax}$ values tend to be the greatest at the 10% bentonite content for a given sand-bentonite mixture. Also, the difference in $w_{opt}$ at 20% bentonite content and $\gamma_{dmax}$ at 10% bentonite content are greater for the S-GB mixtures than for the S-PB mixture. This difference between the S-GB mixtures and the S-PB mixtures again is attributed, in part, to the different particle-size distributions of the two bentonites in the air-dried condition.

The mixing of the attapulgite clay and granular bentonite together in small amounts for each individual compaction point for the sand-attapulgite clay-granular bentonite (S-AG) mixtures consistently resulted in higher $\gamma_{dmax}$ and $w_{opt}$ values relative to mixing the attapulgite clay and granular bentonite together in larger amounts sufficient to cover all compaction points for the S-AG mixtures. Whereas the $\Delta \gamma_{dmax}$ values resulting from these two mixing procedures tend to be low ($\Delta \gamma_{dmax} \leq 0.05$ kN/m$^3$ (~0.3 pcf)), the $\Delta w_{opt}$ values are more significant, ranging from 1.2 percentage points to 2.7 percentage points. Therefore, some consideration should be given to the potential effect on $w_{opt}$ resulting from differences in mixing procedure when dealing with the same or similar S-AG mixtures.

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FIG. 13—Influence of clay soil content on (a) optimum water content and (b) maximum dry unit weight for sand-attapulgite clay-granular bentonite (S-AC-GB) mixtures for a one-day curing period and two different mixing procedures.

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References


