Low-Temperature Effects on the Compaction and Strength of a Sandy Clay

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With the feasibility of increased cold-weather earthwork as a practical motivation, the compaction and strength characteristics of a sandy clay were studied in the laboratory over a temperature range of 35 to 85 F. The soil was compacted with the Harvard miniature device at three effort levels and at four water contents matched to each level. The experimental program followed a statistical design and the data were interpreted in accordance with a fixed-effects analysis of variance model. Six dependent variables were considered: dry unit weight, unconfined compressive strength, axial strain at peak strength, initial tangent modulus, secant modulus to peak stress, and secant modulus to one-half the peak stress. An analysis of variance was performed to determine which independent variables (compaction effort, compaction temperature, testing temperature, and water content) and interactions were significantly related to each dependent variable.

It was found that the strength and stiffness of soil tested at one temperature but compacted at different temperatures increased with increasing compaction temperature. For soil compacted at the same temperature, the strength and stiffness increased with decreasing test temperature. Low-temperature compaction is approximately equivalent to reducing the effective compactive effort, and consequently it may be possible to compensate for the temperature factor by increasing the effort level of field compaction. The available evidence suggests there is no major deterrent to the compaction of clayey soils in a cold, but unfrozen, condition.

UNTIL RECENTLY, cold-weather earthwork was strictly avoided in highway construction. The required technology was recognized to be more complex and costly in the winter, and it was presumed that these factors were more important than the benefits that could be derived from earlier completion dates and continuous use of construction forces.

As the need for modern highway facilities has grown, limited exceptions to the cold-weather shutdown have occurred and a state of the art has begun to develop (1, 2). Most of the initiative has been exercised in regions where the length of the cold season is the greatest, and accordingly, most restrictive. However, the feasibility of "stretching" the construction season is also of growing interest where the winters are relatively mild.

In general, it is not advisable to place frozen materials in subgrades or embankments. On the other hand, moist soils are difficult to freeze because of their high heat capacity, and it may be entirely practical to (a) strip off a frozen crust; (b) excavate the underlying cold, but unfrozen, soil; and (c) haul, spread, and compact it prior to any freezing induced by the exposure. Operations of this sort are not envisioned in the

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normal specifications and standards of state highway agencies and cannot be undertaken with confidence until a number of questions have been answered by means of laboratory experimentation and field experience. Some of the more obvious questions relate to the effect of low temperatures on the compaction process and the post-compaction soil response at low, as well as normal, temperatures.

If the effects of low-temperature compaction are minor or if they can be compensated for with reasonable economy, it may soon become conventional to schedule certain earth-moving activities in the cold season. For example, in embankment construction, efforts can be areally concentrated to minimize the problems of soil freezing before compaction.

The purpose of this research was to contribute experimental evidence that would help to define more clearly the feasibility of cold-weather earthwork.

LITERATURE REVIEW

For the purposes of this paper, evidence accumulated by previous investigators may be conveniently subdivided into two categories: the effect of temperature on compaction and the effect of temperature on post-compaction strength characteristics.

Available evidence is in agreement on the effect of temperature on compaction. Hogentogler and Willis (3) showed that a decrease in compaction temperature will have the same general effect as a decrease in compaction effort; i.e., the maximum unit weight will decrease and the optimum moisture content will increase. This is the trend reported by Johnson and Saltberg (4), Burmister (5, 6), Youssef and others (7), Laguros (8), and others. The trend appears to exist for the temperature range of about 35 to 100 F. A popular, if qualitative, explanation for the observations is one in which the water is viewed as a "lubricating agent". Lower temperatures increase the water viscosity and restrain the soil particle movements that are required to achieve close packing.

The conclusions with respect to strength characteristics are confounded by the fact that comparisons have been made between (a) soils compacted at a common temperature and tested at different temperatures, and (b) soils compacted at different temperatures and tested at a common temperature. It is not always clear which comparison has been made.

From fundamental physicochemical considerations, Lambe (9) employed the Gouy-Chapman theory to predict that low temperatures should mean a thicker double layer and a more dispersed compacted clay soil fabric. Mitchell (10) used a somewhat more sophisticated approach to demonstrate that temperature may have no practical effect on the double layer thickness.

Laguros (8) and Noble and Demirel (11) concluded that a decrease in compaction temperature (all other factors constant) is associated with a decrease in unit weight, degree of saturation, and undrained strength. A decrease in testing temperature (all other factors constant) is associated with an increase in undrained strength according to Mitchell (12) and Sherif and Burrous (13). Lambe (14) and Campanella and Mitchell (15) found that initial pore pressures are decreased by a decrease in testing temperature; the cooled samples should also experience lesser pore pressures during shear (12). Murayama and Shibata (16) and Noble and Demirel (11) report that clays are stiffer at lower testing temperatures. It is not possible to determine conclusively from the literature the effects of low temperature (compaction or testing) in-service on the strength response of compacted clays.

EXPERIMENTAL PROCEDURES

Sandy clays are fairly common in the northern portion of Indiana, where it is felt that cold-weather earthwork may be feasible. However, it was decided to procure such a texture with commercial products, rather than by sampling natural soils. Accordingly, Edgar Plastic Kaolin was combined with No. 285 crushed Ottawa sand in a weight ratio of 4 to 1. Table 1 gives pertinent indexes of the components and of the mix, while Figure 1 shows the cumulative frequency distribution of sizes.
TABLE 1
RESULTS OF INDEX TESTS ON THE CONSTITUENT SOILS

<table>
<thead>
<tr>
<th>Index Test</th>
<th>Edgar Plastic</th>
<th>No. 285 Ottawa Sand</th>
<th>Mixturea</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid limit (percent)</td>
<td>60</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Plastic limit (percent)</td>
<td>37</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Plasticity index (percent)</td>
<td>23</td>
<td>NP</td>
<td>23</td>
</tr>
<tr>
<td>Specific gravity of solids</td>
<td>2.60</td>
<td>2.65</td>
<td>2.61</td>
</tr>
<tr>
<td>Clay size (percent)</td>
<td>78</td>
<td>–</td>
<td>63</td>
</tr>
</tbody>
</table>

a 80 percent kaolin and 20 percent sand.

The constituents were mixed with water in a single-speed Porter mixer by procedures found to yield a nearly homogeneous batch. Kneading compaction was accomplished with the Harvard miniature device at efforts that produced peak densities of about 93, 95, and 98 percent of that produced by the standard test (AASHO T-99). This was accomplished respectively with the following combinations of layers, tamp per layer, and pounds of spring compression: 5, 20, 20; 5, 20, 30; and 5, 25, 40.

Compaction was performed under controlled temperature conditions. Compacted samples were extruded from the mold and placed in polyethylene sandwich bags. Samples from a batch (as many as 30) were sealed in a common large polyethylene bag, which was then submerged in American White Oil (USP 31) during curing. A 5-day curing period was permitted at the temperature planned for strength testing.

The selected curing time was based on evidence of a strength change after extrusion from the mold. It is believed that relief of the mold confinement allows some swelling of the sample, which in turn decreases the already negative pore pressures, especially near the sample boundary. The subsequent local increase in effective stress affected the undrained strength for a period of about 3 days. In this time, the transient pore pressure gradient apparently dissipated and the strength decreased to a constant or equilibrium value.

After the 5-day cure, unconfined compression tests were undertaken at a constant rate of strain of 0.03 in. per sec, again under controlled temperature conditions.

Figure 1. Grain size distribution curves.
STATISTICAL ANALYSIS

The analysis of variance (ANOVA) method was used to interpret the data. This method allows a total statistical variance to be reduced to its component parts. The fixed ANOVA Model I was applied to a complete factorial experimental design with partial nesting. The four factors (independent variables) studied were (a) compaction effort, (b) water content, (c) compaction temperature, and (d) strength testing temperature.

The number of levels of these factors were three compactive efforts, four water contents per compactive effort, three compaction temperatures, and three testing temperatures. The numerical values of the temperature variables were 35, 55, and 85 F. The water contents were selected relative to the optimum value for a given compactive effort and, accordingly, the water content factor was nested in compaction effort. Because of this nesting effect, factor b was tested for significance in the following combinations: b in a; bc in a; and bd in a; where bc is an interaction of water content and compaction temperature and bd is the water content-testing temperature interaction.

The statistical model assumes a completely randomized design. This condition was incompletely satisfied in the experimentation because it was not physically practicable. Accordingly, the mean square of the highest-order interaction (factors bc in a for dry unit weight and factors bcd in a for the other dependent variables) was substituted for the usual mean-square-of-error term in the F-ratio test for significance.

The ANOVA procedure essentially tests a series of hypotheses concerning the equality of certain mean values and variances between various cells of the statistical model. A Type I error, \( \alpha = 0.05 \), was used in this study. This error is the rejection of a correct hypothesis; the \( \alpha \) value is then the probability associated with making the error.

Six dependent variables were considered: dry unit weight, \( \gamma_d \); unconfined compressive strength, \( q_u \); axial strain at peak stress, \( \epsilon_f \); initial tangent modulus, \( M_t \); secant modulus to peak stress, \( M_sp \); and secant modulus to one-half the peak stress, \( M_sp/2 \). An ANOVA was performed to determine which independent variables and interactions were significantly related to each dependent variable.

Although the compaction temperature and testing temperature factors showed no significant effect on \( q_u \) or \( M_sp \) when considered separately, their interaction was significant. In such cases, Scheffe (17) concluded that there is a difference in the dependent variable, even though no difference is demonstrated when the effects of one factor are averaged over the levels of the other.

RESULTS

Table 2 gives the significance of each factor or factor interaction on each dependent variable. The compaction effort and water content are observed to have a significant effect on all dependent variables. It is felt that these factors operate directly on the dry unit weight and the compacted structure, and the latter, in turn, influences all other dependent variables.

The compaction temperature had a significant effect on \( \gamma_d \), \( q_u \), \( \epsilon_f \), and \( M_sp \). Again, the direct effect is on \( \gamma_d \) and (probably) structure, and these subsequently influence the three strength characteristics. The experimental data (Fig. 2) suggest that it may be practicable to compensate for the apparently unfavorable influence of low compaction temperature by increasing the compactive effort. This will increase the uncompacted strength, but its effect on the swelling characteristics and soaked strength (for simulation of the service environment) needs to be established.

The testing temperature had a statistically significant effect on \( q_u \) and \( M_sp \). These variables generally increased with decreasing testing temperature, except that at the higher water contents the influence was usually quite small. Figure 3 shows selected levels of the data.

The compaction effort-compaction temperature interaction significantly affected \( q_u \), \( \epsilon_f \), and \( M_sp \). It was expected that this interaction would also affect \( \gamma_d \), but this was not verified statistically. However, as shown in Figure 4, small changes in unit weight and water content can substantially change the strength.

The interaction of compaction effort and testing temperature had a significant effect on \( \epsilon_f \) and \( M_sp \). At a given compaction effort, \( \epsilon_f \) decreased and \( M_sp \) increased with de-
Figure 2. Effect of compaction temperature on moisture-density relationship.

Figure 3. Effect of testing temperature on unconfined compressive strength.
TABLE 2
SIGNIFICANT FACTORS AND FACTOR INTERACTIONS

<table>
<thead>
<tr>
<th>Independent Variables and Interactions</th>
<th>Dry Density ($q_d$)</th>
<th>Unconfined Compression Strength ($q_u$)</th>
<th>Strain at Failure ($e_t$)</th>
<th>Tangent Modulus ($M_t$)</th>
<th>Secant to $q_u$</th>
<th>Secant to $q_u/2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (compaction effort)</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>2 in 1 (water content)</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>3 (compaction temperature)</td>
<td>S</td>
<td>S*</td>
<td>S</td>
<td>S</td>
<td>S*</td>
<td>NS</td>
</tr>
<tr>
<td>4 (testing temperature)</td>
<td>NC</td>
<td>S*</td>
<td>S</td>
<td>NS</td>
<td>NS</td>
<td>S*</td>
</tr>
<tr>
<td>13</td>
<td>NS</td>
<td>S</td>
<td>S</td>
<td>NS</td>
<td>NS</td>
<td>S*</td>
</tr>
<tr>
<td>14</td>
<td>NC</td>
<td>NS</td>
<td>NS</td>
<td>S*</td>
<td>NS</td>
<td>S*</td>
</tr>
<tr>
<td>23 in 1</td>
<td>NC</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>S*</td>
</tr>
<tr>
<td>24 in 1</td>
<td>NC</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>34</td>
<td>NC</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>

Note: S—significant; NS—not significant; NC—not considered; *—significant because their interaction is significant.

Figure 4. Density-moisture and strength-moisture relationships.

Increasing test temperature. This is probably caused by lower pore pressures and higher effective stresses in the colder samples.

The compaction temperature-testing temperature interaction was significant with respect to $q_u$ and $M_t$. For a given testing temperature, both dependent variables increased with increase in compaction temperature; this is ascribed to the previously noted effect of unit weight. At a given compaction temperature, the dependent variables increased with a decrease in testing temperature, presumably due to lower pore pressures extant during the low-temperature shear testing.

CONCLUSIONS

Based on the variables and the selected levels of variables subjected to experimental examination, the following conclusions may be made:

1. Low-temperature compaction reduces unit weight and as-compacted undrained strength.
2. Compacted samples are both stronger and stiffer when tested at low temperatures.
3. It should be possible to compensate for low-temperature compaction effects by increasing the compaction effort.
4. Physical explanations for the observed trends are probably seated in the factors of soil structure and pore water pressure.
5. There seems to be no major deterrent to compaction of clayey soils in a cold, but unfrozen, condition.

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REFERENCES