Soil Improvement with Organo-silane

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ABSTRACT: This manuscript provides insight into a new approach to chemically-based soil improvement with organosilanes (OS). In particular, OS creates a hydrophobic surface on virtually any silica-based material through covalent bonding. In contrast to ion exchange techniques, grafting OS on soils results in near permanent modification. As an illustration, laboratory testing was conducted to evaluate the influence of OS modification on the compaction, strength, swell, erosive and hydraulic properties of several soils. OS modification resulted in modest changes to strength and swell potential and a dramatic reduction in infiltration capacity. Likewise, use of OS on a 2H:1V slope reduced the mass of eroded soil by a factor of nearly 50. Overall, these results suggest that OS modification may have wide application in geotechnical and geoenvironmental engineering.

INTRODUCTION

Ground modification is often performed to improve strength, reduce volume change, and or alter the hydraulic characteristics of soil. Chemical additives used in this process typically bind particles together (e.g., resins, polymers, cement) and/or react to change the prevailing physicochemical force balance (e.g., ion exchange reactions). More recently, a form of organic modification that uses organo silanes (OS) to covalently bond with soil particles has been introduced (Daniels et al. 2009). Relevant background of this area is more readily found in the fields of applied clay science and catalysis. For example, the process of permanently grafting organic molecules to various substrates has been explored to develop polymer-clay nano composites Dean et al. (2007), Tartaglione et al. (2008), Xue and Pinnavaia (2008) and to strengthen calcium silicate hydrates in cement paste systems Pelleng et al. (2007). The purpose of this manuscript is to present example data related to soil improvement, as assessed in the laboratory through compaction, strength, swell and hydraulic conductivity as well as in the field through infiltration and erosion measurements.
MATERIALS AND METHODS

The work presented herein comprises two separate experimental components. First, the influence of OS on laboratory measurements of compaction, strength, swelling and hydraulic conductivity was evaluated for local Piedmont residual soil (PRS). Separately, a field trial was conducted to evaluate the potential for OS use in erosion control, also for a local PRS. OS was obtained from Zydex Industries (Vadodora, India) through Hero Global Services (Fort Mill, SC, USA) and has the commercial names Zycosil and Zycosoil. Details regarding the source product have been presented in Daniels et al. (2009). Briefly, the source product consists of a mixture of 3-(trimethoxysilyl)propyl dimethyloctadecyl ammonium chloride and ethylene glycol. This solution is then diluted in water and applied to soil where siloxane (=Si-O-Si=) bonds form with individual particles. In addition, there is an organic group with a long alkyl chain (C_{18}H_{37}) which imparts molecular level hydrophobicity on the treated surface.

Laboratory Measurements

Two bulk disturbed samples of a local PRS are collected and visually classified as a red-brown elastic silt and a brown micaceous silt. For this work, a grain-size distribution and plasticity index were not determined. Treated soils were prepared by mixing dry soil with a solution composed of 100 parts water for every part of OS (100:1, by volume). This mixture was then allowed to fully air-dry prior to subsequent testing, which included adjusting the moisture content to within 2% of optimum moisture content. Treated and untreated samples were tested for both soils for moisture-density relationships and California Bearing Ratio (CBR) while the elastic silt was also evaluated for hydraulic conductivity. Samples used for CBR or hydraulic conductivity were prepared at or above 94% of the maximum dry density. One dimensional swell tests were also conducted with the elastic silt modified with 5% bentonite, by dry weight. The bentonite was added to create a high plasticity soil which would exhibit a greater change in physical properties (e.g., swell) in response to OS treatment. The bentonite has the commercial name Quik-Gel Powder, has procured from Barold Industrial Drilling Products, Houston, Texas.

Current ASTM standards were generally used to guide laboratory protocol, as follows (ASTM 2008a,b,c,d). Moisture-density relationships were evaluated in accordance with ASTM D698, Method A with standard Proctor effort. The CBR test was conducted as per ASTM D1883. Hydraulic conductivity was evaluated in accordance with ASTM 5084 using the constant head method, a back pressure of 345 kPa and a hydraulic gradient of 12.5. Swell was measured as part of ASTM D1883, and in the case of bentonite modified elastic silt, as part of ASTM D4546 using a 1.55 kg surcharge.

Field Measurements

Infiltration and erosion measurements were made on a 2.75 m length slope (~2H:1V) constructed with a local PRS in Charlotte, NC. The soil was visually
classified as a red-brown silty clay loam. A 1.5 m wide section of the slope was manually treated by pouring a 64:1, by volume, OS solution from an 8 liter container outfitted to an outlet with ~2 mm apertures. An additional 0.5 m section at the top and base of the slope was treated such that the entire exposed surface area of treatment was 3.25 m x 1.50 m or nearly 5.0 m². In an effort to isolate erosion measurements from the rest of the site, a brick sediment trap was installed at the top and base of the treated section as well as at a corresponding control section. A sheet of plastic (60 cm x 71 cm, 0.42 m² in area) was placed at the base of the treated and untreated slope sections to capture soil eroded in response to a rain event. Approximately two days after OS application, approximately 33 mm of rain fell on the site. Soil collected on the plastic sheets were collected, dried and weighed.

Soil infiltration properties were evaluated with a Mini Disk Infiltrometer from Decagon Devices. The device works by measuring the rate of seepage into partially saturated soils using a slightly negative (suction) pressure. Measurements were taken at a constant suction of -0.5 cm. Details on this device and its application may be found in the manual (Decagon 2007) with additional background discussion provided by Zhang (1997) and a comparison with other field techniques given by Daniels and Das (2008).

RESULTS AND DISCUSSION

The results for the moisture density relationships, hydraulic conductivity and CBR tests are provided in Table 1. The results from the one dimensional swell test of the bentonite-modified elastic silt are reported separately in the discussion below.

Table 1. Summary of experimental results

<table>
<thead>
<tr>
<th>Soil</th>
<th>OMC* (%)</th>
<th>MDD** (kN/m³)</th>
<th>K₂₀ *** (cm/s)</th>
<th>CBR**** @2.5 mm</th>
<th>CBR**** @5.0 mm</th>
<th>CBR**** @ 4.5 kg surcharge during CBR soak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic silt (Untreated)</td>
<td>29.2</td>
<td>14.0</td>
<td>1.5 x 10⁻⁶</td>
<td>13.0</td>
<td>10.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Elastic silt (OS Treated)</td>
<td>28.4</td>
<td>14.2</td>
<td>3.9 x 10⁻⁷</td>
<td>17.0</td>
<td>13.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Micaceous silt (Untreated)</td>
<td>17.1</td>
<td>16.8</td>
<td>Not tested</td>
<td>0.9</td>
<td>1.4</td>
<td>6.5</td>
</tr>
<tr>
<td>Micaceous silt (OS Treated)</td>
<td>18.8</td>
<td>16.2</td>
<td>Not tested</td>
<td>5.4</td>
<td>6.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

*Optimum Moisture Content, **Maximum Dry Density, ***Hydraulic Conductivity, corrected for 20°C, ****California Bearing Ratio, calculated at penetration shown
As indicated by Table 1, the influence of OS treatment on the optimum moisture content and maximum dry density was relatively modest. By comparison, Daniels et al. (2009) also reported a modest but consistent trend of increasing OS dosage correlating with increasing dry density and decreasing optimum moisture content for a Class F coal combustion fly ash. No such trend was observed here and this is attributed to the differences in material mineralogy. Likewise, OS treatment resulted in a reduction of hydraulic conductivity by a factor of four for the elastic silt. This is considerably more modest than observed previously in Daniels et al. (2009), whereby the hydraulic conductivity of an A-7-5 soil was reduced from 9.2x10^{-3} cm/s to 1x10^{-7} cm/s at a similar level of OS treatment. In terms of CBR results, the strength of both soils increases, with more dramatic results observed for the micaceous silt. Specifically, there was an approximately five fold increase in penetration resistance, with a commensurate reduction in swell. These results are also consistent with the aforementioned A-7-5 soil where the CBR increased from 3.2 to 6.3 in response to OS treatment. For the elastic silt, the influence of OS-treatment is not particularly significant in terms of swelling measured as part of the CBR test (while soaking), consistent with a lack of plasticity that was observed by handling (although not measured specifically in terms of a plasticity index). However when the elastic silt was modified with 5% bentonite, the swell as measured by the one-dimensional swell test at 48 hours was found to be 7.9% and 3.7% for the untreated and OS-treated samples, respectively. As such, OS-treatment appears to mitigate volume changes in soils that would otherwise be susceptible to swelling.

As for the field investigation, Figure 1 shows a picture of the slope after treatment and the rain event. Figure 2 shows a picture of the soil retained by the plastic liners at the base of the slope.

**FIG. 1.** Elevation view in the down slope direction, after instrumentation and 33 mm rain event during a ~24 hour period.
FIG. 2. Close-up picture of soil retained by plastic liners at base of slope.

As noted in Figure 2, the dry mass of soil retained on the plastic liner at the base sediment trap was 5028.0 g and 108.0 g, for the untreated and treated sections, respectively. Assuming the upslope sediment traps relegated much of the erosion to the individual study slope sections, which covered an area of approximately 5 m², the individual erosion rates correspond to 1005.6 g/m² and 21.6 g/m². It appears that much of the soil loss could be attributed to sheet and rill erosion. By way of context, the US Department of Agriculture estimated the average of such water-induced erosion to be 762 g/m²/year for the entire South Atlantic Gulf region, in which the site is located (reported as 3.4 tons/acre/year in NRI 2003). Normalizing this value to the amount of rainfall for Charlotte NC (1105 mm/year), the average rate of erosion may be computed as 0.69 g/m²/mm rain. Likewise, the results herein may be reported as 30 g/m²/mm rain (untreated) and 0.65 g/m²/mm rain (treated). Note that the relatively high rate of erosion for the untreated section is consistent with the higher water velocity that develops along the steep slope of the site (~50%) as compared to the average slopes for the entire South Atlantic Gulf region (on the order of a few percent). In this sense, the net effect of OS-treatment is analogous to flattening of the slope. The figures presented here, the average rate of a erosion and an overall assessment of the site suggest that untreated soil may be somewhat dispersive and therefore subject to this type of erosion Sherard et al. (1976), Mitchell and Soga (2005).

The infiltration data are presented in Figure 4 where cumulative infiltration is plotted against the square root of time, as per Zhang (1997).
FIG. 3. Plot of cumulative infiltration versus square root time for estimation of hydraulic conductivity

As noted in Decagon (2007) the polynomial used to fit the infiltration data collected on the untreated section is of the form:

\[ I = C_1 t + C_2 \sqrt{t} \]  

(1)

In Eq. 1, \( I \) is the cumulative infiltration, \( C_1 \) is related to the hydraulic conductivity, \( C_2 \) is related to the soil sorptivity at \( t \) is the elapsed time. Inspection of Fig. 3 indicates values of 0.002 and 0.0432 for \( C_1 \) and \( C_2 \), respectively. Hydraulic conductivity, \( k \), is then given by:

\[ k = \frac{C_1}{A} \]  

(2)

In Eq. 2, \( A \) is computed for a given level of suction pressure and soil properties, as per details provided in Decagon (2007). In particular, it is related to van Genuchten parameters, as tabulated for example in Carsel and Parrish (1988). Accordingly, a value of \( A \) equal to 8.1 was selected, which approximates a silt loam at the -0.5 cm suction applied by the infiltrometer to measure hydraulic conductivity. Note that the value computed by Eq. (2) is the corresponding in situ hydraulic conductivity at the prevailing moisture content and level of suction. The hydraulic conductivity for the untreated section was found to be \( 2.8 \times 10^{-4} \) cm/s and 0 cm/s (i.e., no measurable
infiltration) for the treated section. Note that this soil (silty clay loam) is not radically different from the soil tested for saturated hydraulic conductivity (elastic silt). Likewise, the OS treatment level is relatively similar (100:1 vs. 64:1). As such, it's worth considering why laboratory samples responded modestly (factor of four) in terms of saturated hydraulic conductivity while the influence was far more dramatic (several orders of magnitude) in the case of infiltration-derived values of unsaturated hydraulic conductivity. These results underscore a critical point as it relates to determining the value of hydraulic conductivity in the laboratory, versus what may realistically manifest in the field. In particular, saturated hydraulic conductivity is typically used as a design variable, and laboratory tests commonly ensure saturation through back pressurization, as was likewise reported herein (345 kPa) for the elastic silt. Indeed the hydraulic conductivity of a soil is at a maximum in the saturated condition, which with time, can develop in natural field conditions (e.g., near or below the groundwater table, landfill liners with sufficient head, etc.). However, it is not at all clear that soils treated with OS can be saturated in the absence of a considerable artificial pressure. Soil water interaction is more often characterized by a contact angle of approximately zero, implying near perfect wettability (Fang and Daniels 2006). After OS-modification, however, the contact angle is likely greater than 90° (Daniels 2009). The relationship between moisture content and suction pressure was not measured. However the results indicate, by definition, that for the in situ condition, the prevailing matric potential was approximately zero (> -0.5 cm), i.e., there was no apparent suction for the treated soil. As such, one can make a comparison between water/OS-modified soils system and a Mercury/unmodified soil system. The reader may recall a technique referred to as the mercury intrusion method (Mitchell and Soga 2005) which measures the pressure required to force mercury into soils. This pressure varies according to pore size and so one can determine the prevailing pore size distribution. Likewise, water only penetrates OS-treated soils provided sufficient pressure is available. This characteristic implies a need to carefully match laboratory testing against anticipated field conditions.

CONCLUSIONS

OS modification represents another approach to soil improvement, with possible increases in strength and reductions in swell potential and hydraulic conductivity. More dramatic results were observed for in situ measurements of infiltration and erosion. In particular, the hydraulic conductivity, as measured with a negative pressure of -0.5 cm, was reduced from $2.8 \times 10^{-4}$ cm/s to 0 cm/s, upon treatment with OS. Likewise use of OS on a 2H:1V slope reduced the mass of eroded soil by a factor of nearly 50. For all of these observations, water repellency is a mechanism which would explain such improvements. These results suggest that OS modification may find considerable use in geotechnical and geoenvironmental engineering.

REFERENCES

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