Compaction and Strength Characteristics of Engineered Water Repellent Frost Susceptible Soils

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ABSTRACT

In this work, the mechanical properties of three frost susceptible soils are investigated after treatment with organosilanes (OS). Compaction and strength characteristics tests are carried out on treated and untreated samples by means of a Harvard miniature compaction apparatus and a pocket penetrometer, respectively. The soils were treated with TerraSil, initially diluted at a ratio of 1:100 (OS:water) batched gravimetrically. It was determined that there was an overall decrease in optimum moisture content (from 1.07% to 2.26%) with samples treated with TerraSil. The influence on density varied with soil type, with modest increases (from 1,776 kg/m^3 to 1,808 kg/m^3) for one soil (Keokuk County) with a measurable plasticity index. The penetrometer results showed similar trends for the treated and untreated samples. The treated samples had slightly lower compressive strength overall. The most significant strength decrease (from untreated to treated for the same moisture content) for Ashe County was from 5 kg/cm^2 to 3.167 kg/cm^2, Hanover from 5 kg/cm^2 to 4.5 kg/cm^2, and Keokuk County from 2.75 kg/cm^2 to 2 kg/cm^2. These results are expected to be useful for engineering applications of TerraSil.

INTRODUCTION

Frost heaving occurs in cold regions and leads to damages in geotechnical infrastructure such as road pavement, building foundations and underground utilities. As documented by Taber (1929), the primary cause of frost heaving occurs when freezing temperatures are reached and water in the frost susceptible soils solidifies to ice. Large negative pore pressures (cryogenic suction) develop which further draws free water from the unfrozen region of the soil to feed the growing ice lens. The formation of ice lenses generates pressures large enough to exceed the overburden stress and leads to an upward movement of the ground surface. A schematic of the process is illustrated in Figure 1.

The following conditions are necessary for frost heaving to occur: (a) freezing temperatures, (b) frost susceptible soils (generally fine-grained soils) and (c) availability of water and techniques to mitigate the detrimental effects of frost heave have generally relied on inhibiting any one of these conditions. These include substituting frost-susceptible soils for granular materials such as sands which offer better drainage (Rengmark, 1963) and restricting the propagation of freezing front using plastic foams as heat insulating materials (Gandahl, 1982). To restrict the supply of water, capillary barriers such as the use of geotextiles (Henry, 1990) and geocomposite drainage nets (Evans *et al*. 2002) have traditionally been used. A relatively new technique to prevent migration of water towards ice lenses include the use of water repellent soils which show little to no water affinity. Water repellent soils have been used for water harvesting applications in arid areas (Meyers and Fraser, 1969) and their use in engineering applications have previously been proposed to reduce the expansion of swelling clays (Hernandez *et al*. 2005) and capillary rise (Orozco and Caicedo, 2017). Their implementation as capillary barriers in a geotechnical context for infiltration control in landfills (Keatts *et al*. 2018) and as slope covers (Lourenço *et al*. 2017) have also been investigated. Thus, deploying soils which exhibit water repellency as barriers to moisture is expected to contribute to a reduction in ice lens formation and their thicknesses.

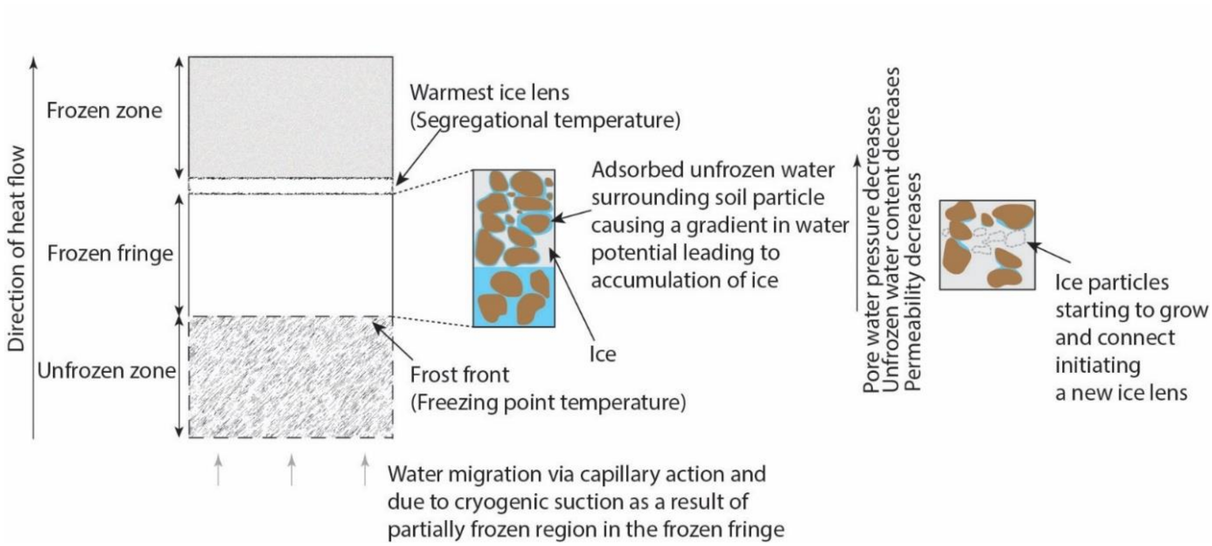

Figure 1. Schematic of frost heave occurring in frost-susceptible soils

Although water repellent soils are naturally present in the environment due to anthropogenic and physical processes, for instance as a result of organic compounds such as humic materials adsorbed on the surfaces of silicate minerals present in soils (Roberts and Carbon, 1972), the resulting water repellency induced have been reported to be transient and has a non-uniform distribution (Morley *et al*. 2005; Jackson and Roering, 2009). Furthermore, the relationship between organic compounds and water repellency is not conclusive and works by Horne and McIntosh (2000) show that water repellency is a function of quality of organic materials. Therefore, for use in engineering applications, soils are instead treated with chemical agents to overcome the above limitations. Examples of chemical agents used to enhance the water repellency of soils include organosilanes in their pure form such as dimethyldichlorosilane (Saulick *et al*. 2021) and in commercial form as Zycosil® and TerraSil® (Daniels and Hourani, 2009; Mahedi *et al*. 2020). The chemical reaction of soils with organosilanes essentially involves four stages: (i) hydrolysis, where adsorbed water on the surfaces of soil particles and/or atmosphere react with the silane bonds (ii) condensation reaction to form oligomers, (iii) formation of hydrogen bonds and (iv) formation of strong covalent Si-O-Si bonds. Figure 2 illustrates two soil samples made water repellent.

Figure 2. Water beading on surfaces of soil samples treated with chemical agents (diameter of samples are each 32.85 mm)

In addition to lowering their surface energy, soils treated with organosilanes impacts several characteristics, amongst which are their mechanical behavior. From the few studies in the literature aiming at understanding the mechanical behavior of water repellent soils compared to untreated soils, Byun *et al*. (2011) and Bardet *et al*. (2011) found conflicting results when examining shear strengths. A possible reason for such discrepancy is the chemical agents used to render the soil water repellent. Thus, determining the mechanical behavior of water repellent soils is necessary prior to deployment in ground engineering and currently lacking in the literature. However, the resulting mechanical characteristics of water repellent soils are not only dependent on the type of chemicals and inherent soil properties (e.g., particle size) but also on the sample preparation method.

In this paper, to investigate the influence of water repellency on the mechanical behavior of soils, frost-susceptible soils from three states across the US were used. To further determine the influence of water repellency on the workability of soils following treatment, the compressive strength obtained from a pocket penetrometer was used to obtain their resistance to vertical penetration in relation to the water content of the soil. The specific objectives of this paper are to investigate the effect of water repellency on the (1) maximum dry density and the optimum moisture content and (2) compressive strength for field workability purposes.

SAMPLE PREPARATION

Three frost susceptible soils from Keokuk County, Iowa (KC), Hanover, New Hampshire (H) and Ashe County, North Carolina (AC) were used in this study. Figure 3 shows SEM microphotographs of NC Boone at different magnifications demonstrating the range of particle sizes present in the soil. The index properties of all soils are illustrated in Table 1.

Table 1. Index properties of soils

Soils	*Keokuk County IA*	*Ashe County NC*	*Hanover, NH*
USCS Classification	CL	SM/SC	SM/SC
Specific Gravity	2.72	2.67	2.68
Liquid Limit	43	38	42
Plasticity Index	25	-	-

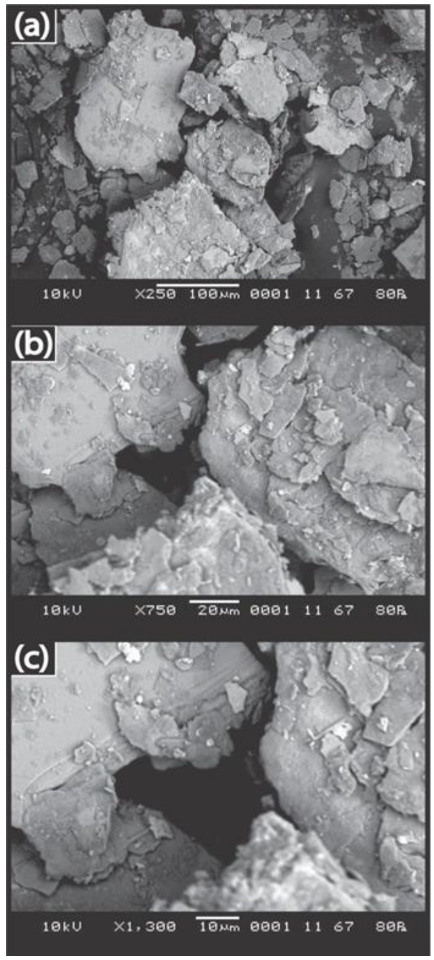

Figure 3. Scanning electron microphotographs of Boone NC at magnifications of (a) x250, (b) x750 and (c) x1300.

Soil Treatment

The soil sample used was first sieved through a No. 4 sieve (4.75 mm). To induce water repellency in the soils, a commercially available product (TerraSil from Zydex Industries) containing approximately 65% of alkoxy-alkylsilyl compounds was used. The chemical agent is water soluble and has a density of 1.01 g/cm3. For hydrolysis to occur, TerraSil is first diluted in a ratio of 1:100 (batched gravimetrically) and the solution mixed with a handheld mixer. Once fully mixed, the TerraSil and water solution was added to the oven dried soil sample depending on the targeted moisture content. For example, to achieve a moisture content of 15% on a 100-g soil sample, 15g of water and 0.15g of TerraSil would be used to form the solution. To ensure proper conditioning, the soil was sealed in a plastic bag for at least 24 hours.

Compaction test

The compaction process was carried out using the Harvard miniature (HM) apparatus and followed the procedure outlined in ASTM D1557. The soil was compacted into five layers using a 17 kg hammer weight with 25 blows (i.e., spring compressions in HM apparatus) being applied to each layer. A TerraSil to water dilution ratio of TerraSil to soil mass ratio of 1:100 was selected based on studies by Uduebor *et al*. (2022) who showed that contact angles above 90° were reached at this ratio when added to frost-susceptible soils. The target moisture content values were selected to define the compaction curve.

Strength test

To investigate the relation of water content to penetration resistance of the untreated and treated soil samples, measurements from a pocket penetrometer were used as a proxy for conventional strength test. While a companion experimental campaign involves other methods of strength determination (e.g., unconfined compression, direct shear), the intent of this work was to complement ongoing field testing of a low-volume road as well as field application generally. Such applications involve the use of the pocket penetrometer during construction, to inform decisions of dosage and dilution ratio relative to workability. For example, weather conditions and soil types can change as construction proceeds along an alignment. This, in turn, can require more or less chemical and water to meet dosage specifications while enabling equipment (e.g., water truck, mixer, grader) to work the subgrade without excessive rutting and deformation. The penetrometer (Figure 4) has a measurement range of 0 to 5 kg/cm^2 and quantifies the undrained strength of soils by means of a calibrated spring. The samples were mixed to a range of water contents and compacted into molds for testing. The needle was placed in the soil sample, to the specified mark, away from the edge of the mold. A total of three measurements were taken and averaged for each point.

Figure 4. Pocket Penetrometer

RESULTS AND DISCUSSION

Figure 5 displays the compaction curves of the three tested soils (treated and untreated). An overall decrease in optimum moisture content (OMC) for treated samples was observed, indicating that less water is needed to reach the maximum dry density regardless of the type of soil. For instance, OMC decreased from 10.75% to 8.49%, 16.1% to 14.83%, and 15.07% to

14.0% for H, AC, and KC respectively. Although, clear comparisons were not able to be made with the maximum dry density of treated and untreated samples. A previous study done by Uduebor *et al*. (2022) similarly indicated a reduction in OMC for a sample treated with TerraSil, accompanied by an increase in maximum dry density.

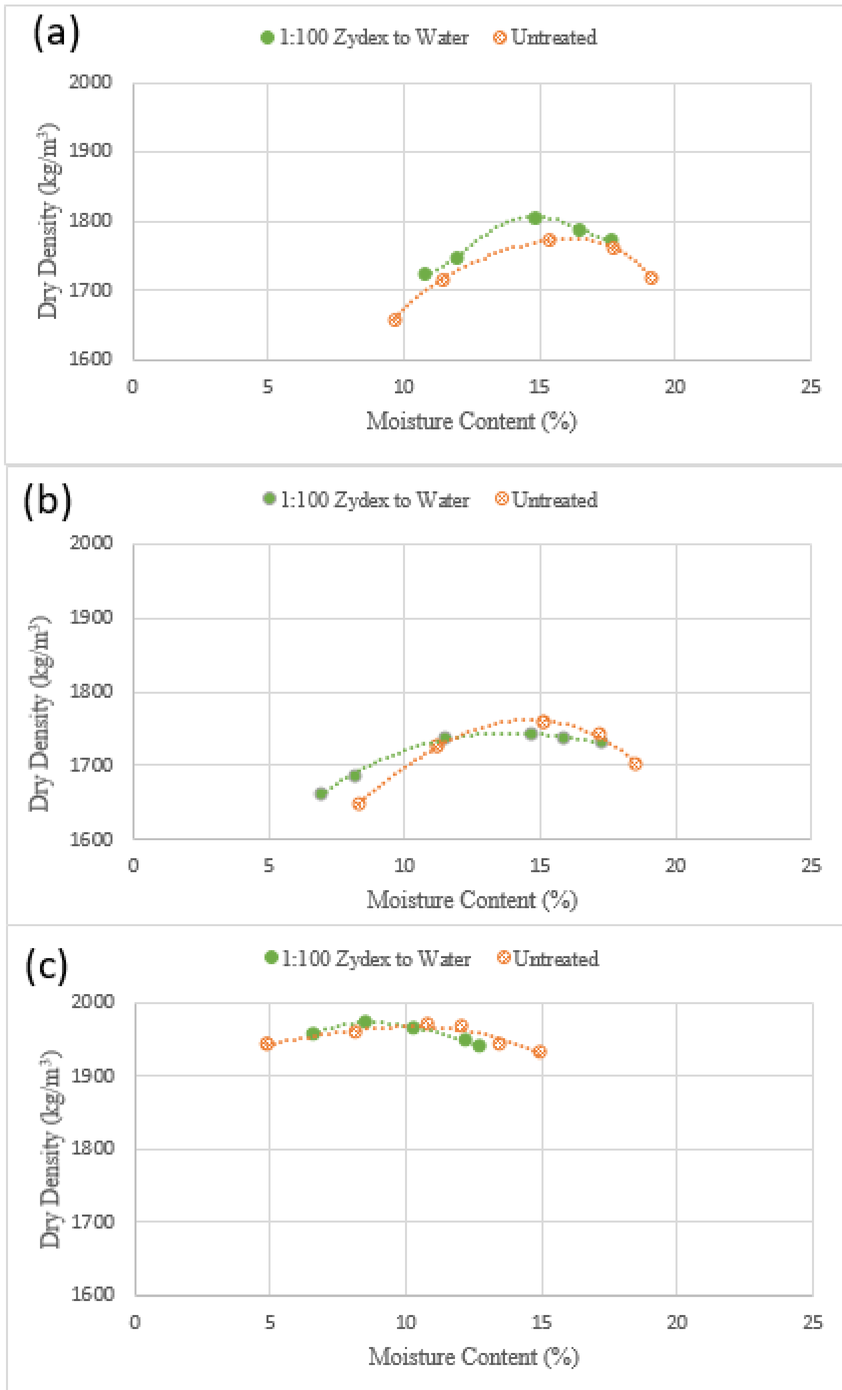

Figure 5. Compaction curves of treated and untreated soils: (a) Keokuk County, (b) Boone, and (c) Hanover

Figure 6 displays the penetrometer test results, indicating a reduction in compressive strength for treated samples. The compressive strength for the Boone soil had a maximum difference in treated and untreated samples of 0.75 kg/cm^2, Keokuk County at 0.5 kg/cm^2, and Hanover County at 1.833 kg/cm^2, with the treated soil in each case demonstrating a lower magnitude.

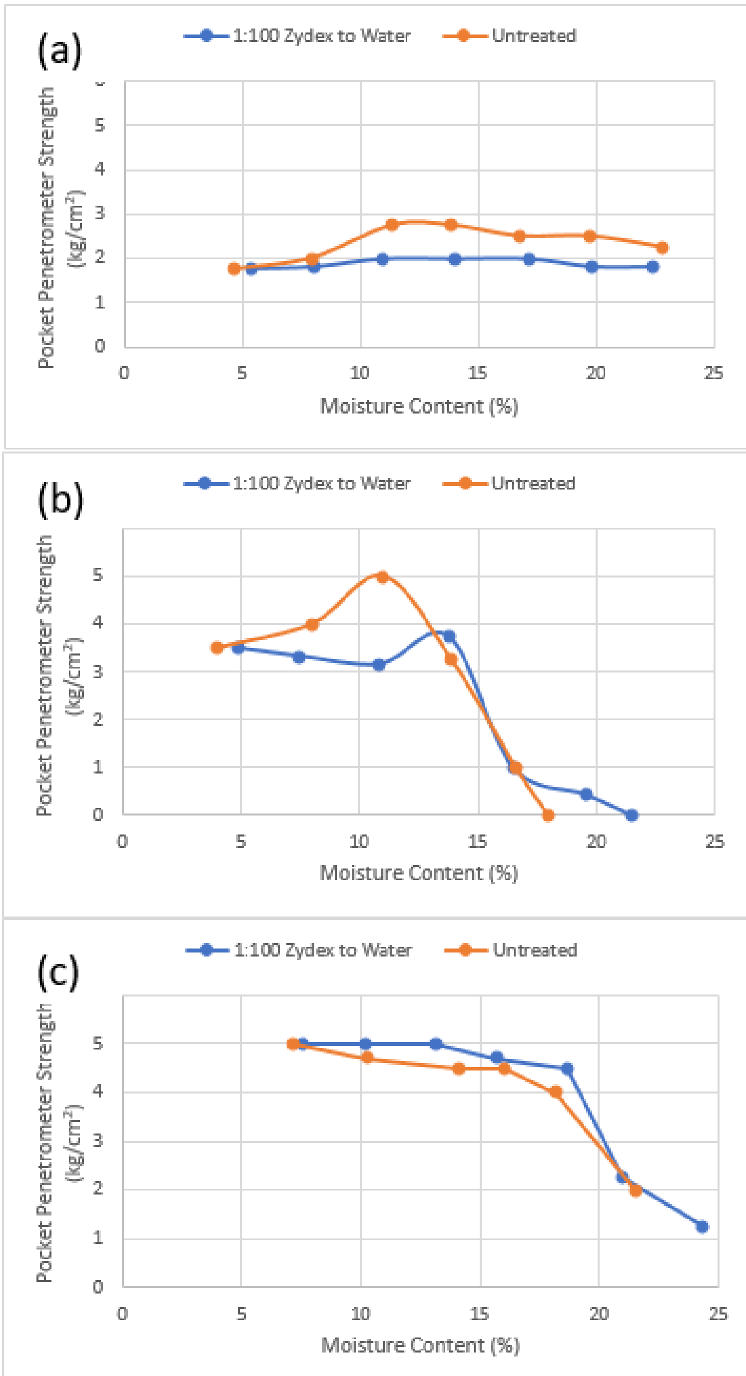

Figure 6. Penetrometer results of treated and untreated soils: (a) Keokuk County (b) Ashe County, and (c) Hanover pocket penetrometer results

The use of organo-silanes in road applications involves either spray application or usage of the chemical/water mixture as the molding moisture content. In either case, one needs to know the in-situ moisture content and the extent to which subsequent addition of moisture can be tolerated while meeting compaction criteria and workability requirements. If the in-situ moisture content is too high, then a higher concentration of chemical (in a lower volume of water) is added to meet the desired target concentration in terms of mass of chemical per mass of soil. In the case of low volume roads, there often is no compaction criteria per se. Rather, the determining factor is workability, the extent to which heavy equipment (water trucks, dozers, rollers, graders, mixers) can work the subgrade without excessive deformation or rutting. Since water is the solvent and mechanism for delivering organo-silanes (for aqueous products such as TerraSil), a logical question that arises is how much water/organo-silane mixture can be added before workability becomes a problem. In reviewing Figure 6, this question appears, predictably, to be a function of soil type. KC soil is a relatively high plasticity soil, as compared to AC and H. KC can tolerate significantly more moisture and retain significant strength. In the case of KC and H, the strength dropped 0.2 kg/cm^2 when the moisture content increased 5% post optimum. By comparison, AC dropped 2.4 kg/m^2. AC and H have clear points where the strength greatly decreases after reaching a certain moisture content.

Mousavi *et al*. (2020) compared the usage of the pocket penetrometer with the unconfined compression test to determine if the penetrometer test would reproduce accurate values for compressive strength. It was found that the penetrometer test could accurately predict unconfined compressive strength with an R^2 value of 0.98. Davidson (1965) described the penetrometer as being useful in determining rolling resistance and trafficability of wheels, which is an indicator of soil consistency. Therefore, penetrometer results would give an indication of the workability of soil layers treated with organosilanes.

CONCLUSION

In this study, the behavior of samples treated with an organosilane were compared to untreated samples. It is concluded that treated samples are expected to have lower OMC values, as well as lower compressive strength. These results may be significant to those implementing organosilanes in field applications. Preliminary work indicated the effectiveness of using the selected ratios of TerraSil. This work was based on contact angle measurements that indicated when a material goes from hydrophilic to hydrophobic. Previous studies indicated that this occurs when the contact angle exceeds 90° when testing with organosilanes (Feyyisa and Daniels 2016). Results may be more significant with higher dosages of TerraSil or the use of a different organosilane.

Due to the volume of the Harvard miniature mold being 62.4 cm^3, larger scale tests may be more accurate at determining the effects TerraSil may have on compaction characteristics. Further studies on varying soil classifications as well as varying organosilanes may also be useful in determining these compaction characteristics. Significant work remains to elucidate the effect of water repellency on strength properties under various load paths and methods of sample preparation.

The penetration results are limited to a reliability of ± 20% according to Davidson (1965). Further considerations of workability may explore the plastic and liquid limit comparisons of treated and untreated soils.

Work also remains to establish long-term efficacy. While there are few results in soils, similar work with concrete suggests efficacy may be longer than 20 years, notwithstanding various environmental conditions (Christodoulou et al. 2013). Ley et al. (2015) notes that in the case of concrete, deterioration in water repellency derives from high pore fluid pH common in concrete, not from abrasion or other factors. Soils do not commonly have high pH and their durability is expected to be commensurately improved

ACKNOWLEDGMENTS

This work was part of a larger experimental campaign, inclusive of field, laboratory, and numerical aspects as funded by the U.S. National Science Foundation (Award #1928813). Soil was provided from the Iowa Highway Research Board (Keokuk County), the North Carolina Department of Transportation (Ashe County) and the Cold Regions Research and Engineering Laboratory, a U.S. Army Corps of Engineers, Engineer Research and Development Center.

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