

Some design challenges for fine-grained fill in urban environments

Quelques défis de conception pour les remblais à grain-fin dans les environnements urbains

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ABSTRACT

Engineered fills are an integral part of nearly all civil projects in urban environments. In the United States the construction of highway embankments is generally governed by standard specifications that impose a minimum density and required water content range for compacted soil. Research reveals that even soils compacted according to engineering specifications may exhibit problematic behavior, especially upon wetting. Furthermore, settlement predictions based on oedometer tests may fail to capture the true behavior of embankment soil in the field. Sometimes chemical additives such as lime or other calcium-based products are used to chemically stabilize the soil, particularly fine-grained soils; thus, enhancing the overall mechanical behavior. In some cases, however, the use of calcium-based stabilizers such as lime can be detrimental if sulfates are present, or may simply cause unexpected results. This paper presents some results of laboratory tests that reveal important aspects of volume change behavior and shear strength characteristic of compacted and chemically treated soils; emphasis is on problematic behavior and shortcomings with laboratory testing. Further, the paper provides suggestions for developing enhanced design approaches for engineered fills.

RÉSUMÉ

Les remblais sont une part intégrale de presque tout les projets civils dans les environnements urbains. Aux États-Unis, la construction des remblais d'autoroute est généralement dirigé par des spécifications standards qui imposent une densité minimale et nécessite une gamme de teneurs en eau pour un sol compact. Des recherches révèlent que même les sols compacts, selon les spécifications d'ingénieurs, peuvent montrer des comportements problématiques, spécialement pendant le mouillage. De plus, les prédictions du tassement basé sur les tests des oedomètres peuvent échouer à capturer le vrai comportement du remblai sur le site. Parfois, l'ajout de produits chimiques tels que la chaux ou d'autres produits contenant du calcium sont utilisés pour stabiliser le sol chimiquement, particulièrement pour les sols à grain-fin; cela améliore ainsi l'ensemble du comportement mécanique. Cependant, dans certain cas l'utilisation de stabilisants contenant du calcium tels que la chaux, peuvent être nuisible en présence de sulfate, ou peuvent simplement causer des résultats inattendus. Cet exposé présente certains résultats obtenus par des tests effectués en laboratoire qui révèlent des aspects importants du comportement du changement volumétrique et la caractéristique de la résistance au cisaillement des sols compactés et chimiquement traités; l'accent est mis sur le comportement problématique et les défauts provenant des tests de laboratoire. En outre, l'exposé fournit des suggestions pour développer des approches de conception améliorées pour les remblais.

1 INTRODUCTION

Nearly every civil engineering project involves placement of soil fill. Some structures are composed almost entirely of fill such as earth dams and highway embankments. Fill also plays an integral role in building construction, particularly for slab-on-grade construction. Civil engineers have been designing and working with compacted soils for a very long time; nevertheless, there are still problems encountered that result from poor mechanical behavior exhibited by compacted soils that compose the fill. This paper addresses some specific issues and problems encountered with fine-grained Oklahoma soils that have been the focus of research at the University of Oklahoma; however, these problems are not unique to Oklahoma or the United States. Specifically, the paper

examines: 1) potential for adverse volume change behavior of soils compacted within typical specifications for highway embankment construction; 2) some shortcomings of oedometer tests used to model compression behavior of fills, 3) some important issues regarding chemical stabilization of fine-grained soils, and 4) some possible means to improve the design and performance of compacted soils.

2 VOLUME CHANGE BEHAVIOR OF COMPACTED FINE-GRAINED SOILS

Fine-grained soils may experience volume change due to external loading/unloading, changes in water content and changes in soil chemistry. Generally, the first two mechanisms are responsible for settlement and/or

heave of compacted soil used in highway embankments or structural fills for buildings. Compacted soil is unsaturated and subject to shrinking/swelling and wetting-induced collapse from changes in moisture content, in addition to load-induced deformation. Volume change associated with changes in total stress or due to wetting can be modeled reasonably well in the laboratory using the incremental loading oedometer. Typical procedures include incremental loading of soil specimens submerged in water, unsaturated specimens at constant water content, and specimens subjected to a stress increase followed by inundation with water to examine the corresponding swell or collapse potential. In the United States the primary testing procedures can be found in ASTM Standards D 2435, D 4546 and D 5333 (ASTM 2006).

Interestingly, research at the University of Oklahoma revealed that wetting-induced volume change can be substantial even for soils compacted within typical specifications for highway construction (Lim & Miller 2004). For example, in Fig. 1 compression curves from single-oedometer collapse tests are shown for three specimens of a clayey soil compacted to the same dry density but different moisture contents relative to the optimum moisture content (OMC). The relative compaction was 95% based on the standard (Proctor) test and the compacted moisture content was within $\pm 2\%$ points of the OMC. This puts the state of soil in compliance with typical specifications for highway embankment construction in the United States. Samples were loaded incrementally to a vertical stress of 200 kPa and then inundated with water in general accordance with ASTM D 5333.

Generally, in Fig. 1 the soil is more compressible at higher water content prior to inundation with water at a vertical stress of 200 kPa. However, the collapse strain or collapse index after inundation is reduced with increasing water content. These results were expected based on previous work (e.g. Basma & Tuncer 1992, Lawton et al. 1992, Fredlund & Gan 1995); however, the magnitude of collapse settlement that is possible in a fill meeting specifications is alarming, especially at lower water contents. Even at water contents 2% wet of the OMC there is a possibility for

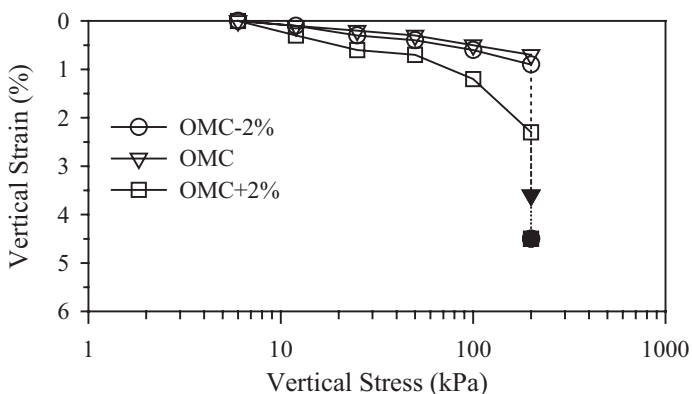


Figure 1. Results of single-oedometer collapse tests on Vanoss Clay at 95% relative compaction.

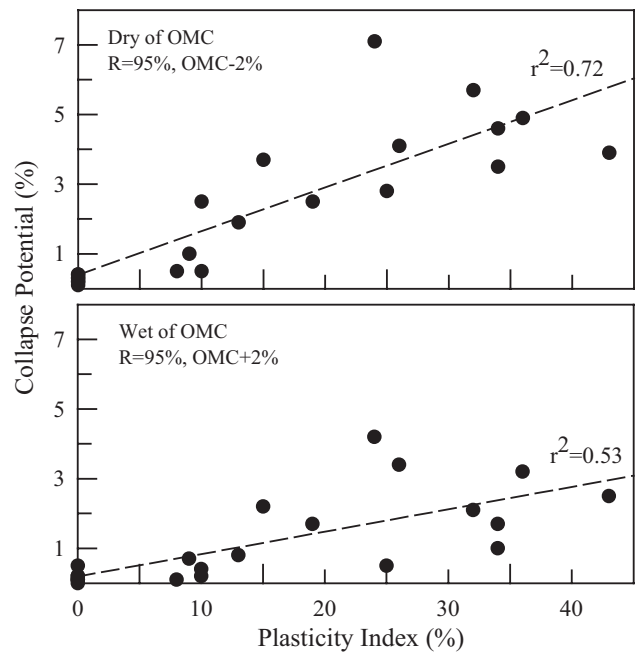


Figure 2. Plasticity index vs. collapse potential at a vertical stress of 200 kPa from single-oedometer collapse tests on compacted soil (after Lim & Miller 2004).

significant collapse for some soils as shown in Fig. 2 where a summary of similar test results on different soil types is presented (after Lim & Miller 2004). The explanation is that while the moisture content is wet of optimum, relative compaction of 95% places the state of the soil slightly dry of the line of optimums where wetting-induced compression is more probable. In Fig. 2 it is observed that some empirical relationship may exist between the soil type, moisture condition, and magnitude of collapse strain.

While the results shown in Figs. 1 and 2 demonstrate that most fine-grained soils will exhibit wetting-induced compression even when compacted within typical specifications, there are some other issues that must be considered. First, soils with high plasticity may also experience significant swelling at lower vertical stress levels and secondly, there are some issues to address regarding the laboratory oedometer test procedure.

3 SOME PROBLEMS WITH THE STANDARD INCREMENTAL LOADING OEDOMETER FOR MODELING COMPRESSION BEHAVIOR OF COMPACTED SOIL

There are numerous factors that influence the soil behavior during incremental loading oedometer tests and subsequent interpretation for modeling field behavior. These factors include the influence of ring friction on the soil response, load increment ratio, and duration of load increments, to mention a few. The intent here is not to address all of the important factors but to address issues specifically related to compacted soil.

Compacted soil is unsaturated and so it may be argued that oedometer testing should include provisions for measuring/controlling the matric suction and net normal stress. At a minimum the interpretation of oedometer tests should at least consider the importance of the initial water content on the compression behavior as demonstrated in Figs. 1 and 2. Ideally the tests should be conducted under suction control; however, in reality most state and commercial labs are not equipped for this type of testing. A traditional oedometer, without pore air and pore water control, can merely provide information for examining the vertical compression as a function of total stress under nearly constant water content conditions. Nevertheless, the information can be useful for predicting settlements of fills under similar conditions.

A second factor to consider is that nearly complete wetting occurs in the oedometer collapse test, while in the field partial wetting is possible, both for swelling and collapse conditions. This issue has been addressed by other researchers and a method for predicting deformations due to partial wetting has been proposed (e.g. Houston 1992).

One issue that has been the subject of research at the University of Oklahoma is the influence of fabric- and sample size-induced scale effects (Miller & Cleomene 2007). The latter effect results from samples that are too small to accurately capture the behavior of the compacted soil. For the fine-grained soils studied, this effect seems to be negligible; however, differences in fabric or geometric arrangement of the soil grains can be important. In the field, soil particles may be aggregated to form large clods or chunks of soil that can be 50 to 75 mm, or more in length. In the laboratory, the soil is typically processed over a #4 (4.75 mm) or #10 (2 mm) sieve prior to compaction. Furthermore, the method of preparing the soil for the oedometer, via standard proctor compaction test or moist tamping directly in the oedometer ring, does not simulate very well the method of compaction in the field. These differences in clod size and compaction method may result in differences in compression behavior between the field and laboratory soil.

Research at OU has revealed that in some cases there is poor agreement between compression behavior for field and lab samples, while in other cases behavior is similar, as illustrated in Fig. 3. Data in Fig. 3 representing the field compaction were obtained from oedometer tests in a large ring (0.56 m diameter) whereby soil was taken directly from a construction site and compacted in the large ring using a simulated field compaction method (Miller & Cleomene 2007).

The soil was obtained from construction sites just prior to compaction and brought to the laboratory in sealed buckets. Moisture contents were obtained and then the soil was compacted in the large ring using the simulated compaction method. Thus, the large clods or chunks of soil were present and incorporated into the compacted fabric. Small samples were also prepared in the standard oedometer rings (0.064 m diameter)

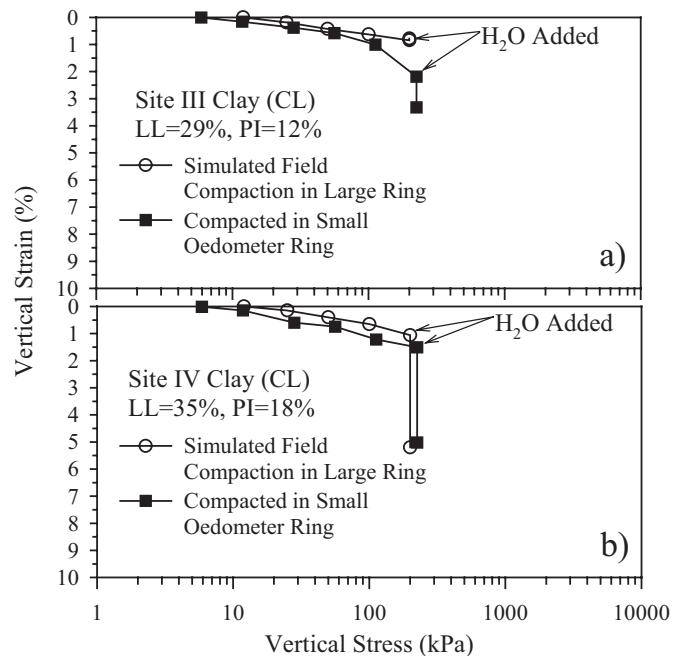


Figure 3. Results of single-oedometer collapse tests on differently prepared samples at similar water content and dry density showing: a) presence of fabric effect and b) absence of fabric effect.

using moist tamping after air-drying and processing the soil over a #10 sieve. Small and large samples were compacted to nominally the same water content and dry density. Interestingly, the comparisons in Fig. 3 suggest that for some soils, fabric effects may be important while for others they may not. Nevertheless, the results indicate that standard incremental loading oedometer tests may not always properly model field soil behavior. In Fig. 3 a) the results of the standard laboratory collapse test are conservative with respect to field performance; i.e. collapse was not observed in the simulated field specimen. However, observations of swelling behavior in some other cases (not shown) indicated greater swelling in the simulated field samples relative to the standard laboratory samples.

4 ASPECTS OF CHEMICAL STABILIZATION OF COMPACTED SOIL

In Oklahoma it is common to use calcium-based chemical additives such as lime, fly ash, or cement kiln dust to stabilize fine-grained soils during construction of fills, particularly highway embankments. Ideally, a mix design should be performed to determine the optimum additive content (OAC) following some standard procedure such as ASTM D 4609. However, because some amount of curing is necessary, typically 14 days, to allow for the chemical processes to occur, the mix design process can lead to delays in construction. This typically occurs when unexpected changes in soil type occur along roadway alignments during construction, requiring a change in the initial mix design. Thus, it is desirable to have quick methods of testing to determine the optimum additive content for a given soil-additive

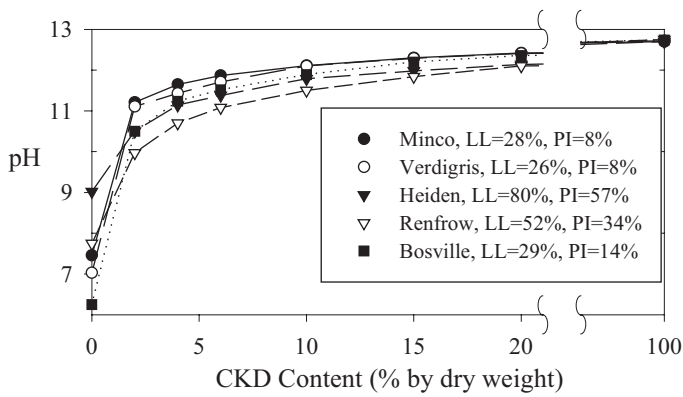


Figure 4. Cement Kiln Dust (CKD) content versus pH for five different soils.

combination. To this end, research is being conducted at the University of Oklahoma to examine different empirical approaches to mix design to supplement the full mix design process.

Cement kiln dust (CKD) is a byproduct of Portland cement production and is becoming an increasingly popular soil stabilizer due to its intrinsic cementitious properties and high pH. Research at the University of Oklahoma has focused on the efficacy of CKD as a reliable soil stabilizer. This has included research into the variability of CKD from different sources and its effectiveness for different soil types. Part of this research has looked at empirical relationships between the optimum additive content (OAC) and various soil and soil-CKD index properties. As mentioned, these relationships can be useful for streamlining the mix design process when necessary. Two promising empirical relationships are examined in Figs. 4, 5 and 6.

In Fig. 4, the pH response curves for CKD mixed with five different soil types ranging from low plasticity to high plasticity are shown. Looking at Fig. 4, it is clear the soil type has an influence on the pH response. Generally, the pH for soils with higher PI rises more slowly as the CKD content is increased. This is consistent with the higher reactivity of the clay size particles in the higher PI soils. Since the pH

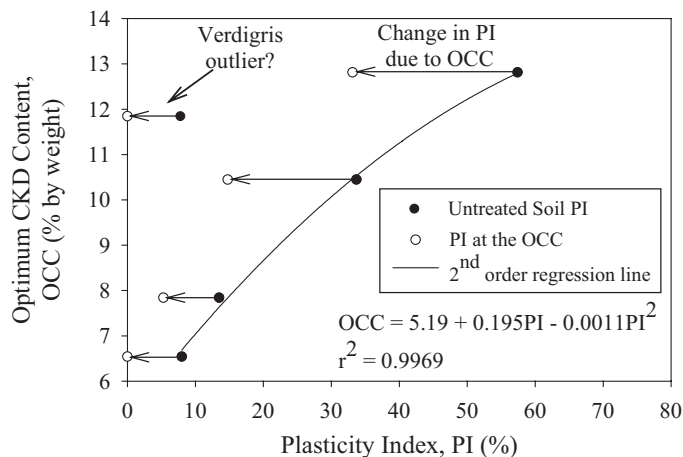


Figure 5. Plasticity Index versus Optimum CKD Content for five different soils.

is an indicator of the potential for soil-CKD chemical reactions, this relationship between pH response and soil type was explored further in relationship to the CKD effectiveness as measured by the unconfined compression strength.

To examine the increase in unconfined compression strength relative to soil type, Fig. 5 was prepared, which shows a relationship between the optimum CKD content (OCC) and the plasticity index of the raw soil. In this figure the OCC is defined as the CKD content that will produce an increase in unconfined compression strength of 350 kPa above the strength of the raw soil. It is determined by a mix design process requiring preparation of multiple unconfined test specimens with increasing CKD content. The 350-kPa mark is the minimum increase required to deem the stabilizer effective according to ASTM Standard D 4609. In Fig. 5, the influence of PI on the OCC is clearly demonstrated for all but the Verdigris Soil. Thus, as a first approximation, the OCC can be estimated using the second order regression curve (not including the Verdigris outlier) given as,

$$OCC = 5.19 + 0.195(PI) - 0.0011(PI^2) \quad (1)$$

where: OCC = Optimum CKD Content, and PI = Plasticity Index of the raw soil.

It must be noted that the relationship expressed by Eq. 1 is based on a single source of CKD and will likely be different for other CKD types with different chemical characteristics. To investigate the relationship between the OCC and pH response of the soil-water-CKD mixtures, the pH data shown in Fig. 4 was used to prepare Fig. 6, which shows the OCC plotted against the change in pH from the initial slope of the pH curves (from 0–2% CKD). After trying different parameters that characterized the pH response of soil-CKD mixtures, it was found that this portion of the pH curve best reflected the soil stabilization effect. Not including the Verdigris outlier, there is a trend that can be expressed by the following first order equation,

$$OCC = 15.29 - 2.01(\Delta pH) \quad (2)$$

where: ΔpH = change in pH from 0 to 2% CKD.

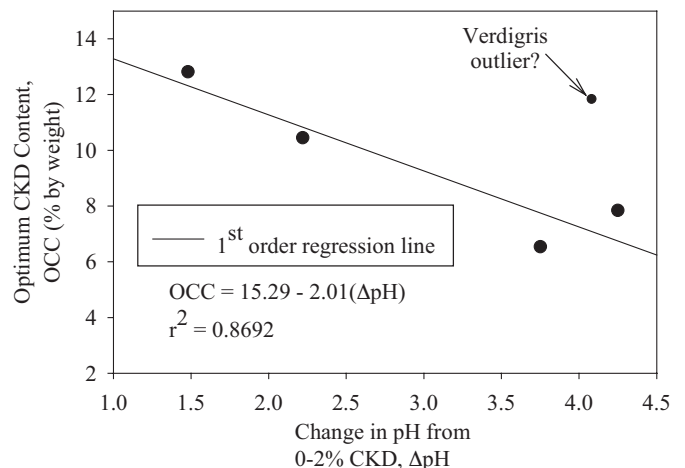


Figure 6. Change in pH from 0–2% CKD content from Fig. 4 vs. Optimum CKD Content.

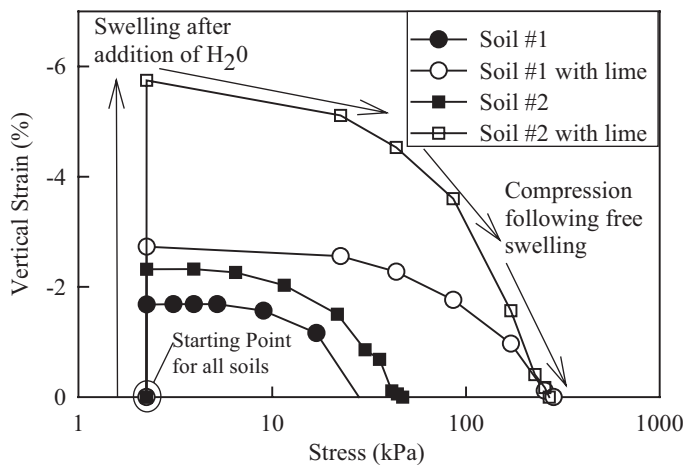


Figure 7. Swelling and compression curves for sulfate bearing soils; Soil #1 and Soil #2 contain approximately 80,000 and 9,000 ppm sulfate, respectively.

As a first approximation, the OCC can be estimated using Eq. 2, keeping in mind that the data is limited and represents a single CKD source. Possibly, as more soil types and CKD sources are investigated this expression will be refined and validated. It is unclear why the Verdigris Soil did not respond as expected; this anomaly is the subject of continuing investigation. However, it is expected that other soil chemical factors such as organic content, carbonates, sulfates, and others will be important. The response of the Verdigris Soil stresses the importance of using a full mix design process whenever possible.

Finally, it is very important to test soils for the presence of sulfate when using calcium-based stabilizers such as lime, CKD, and fly ash, as there is significant potential for adverse reactions. These reactions result in the formation of expansive minerals such as Ettringite, which can cause continued expansion of the fill in the presence of water (e.g. Mitchell 1986, Hunter 1988, and Kota et al. 1996). Thus, the addition of lime to a high PI sulfate-bearing soil will produce the opposite of the desired effect; instead of reducing the expansion potential, it is increased. Research at the University of Oklahoma is examining the swelling potential of various sulfate-bearing Oklahoma soils. The work is also focusing on developing improved laboratory methods for determining sulfate concentrations and potential for adverse reactions. In Fig. 7, an example of swelling behavior for sulfate-bearing soils with and without lime is shown. Clearly, the lime had a detrimental effect on the swelling behavior, especially for Soil #2.

It is interesting that the Soil #2 with significantly lower sulfate content exhibited more swelling with lime than Soil #1 with sulfate content nearly an order of magnitude higher. These results show that other soil mineralogical and chemical factors are important to these reactions. Research is continuing in an effort to identify the primary factors affecting the lime-sulfate reactions in the soil.

5 SUMMARY AND CONCLUSIONS

Some factors that are important to the design and behavior of compacted soils and that are the focus of ongoing research at the University of Oklahoma were presented and discussed. The main conclusions that can be drawn from the work performed so far are as follows.

- 1) Results from one-dimensional oedometer tests suggest that soils compacted within typical specifications for highway embankments may experience adverse volume changes due to wetting. Oedometer data suggest that wetting-induced collapse may increase with increasing plasticity index. For large embankments or critical fill structures it is recommended that one-dimensional compression tests be conducted on representative compacted soil samples. In addition, it may be necessary to impose more stringent construction specifications if adverse volume changes are possible.
- 2) Results of small and large oedometer tests on laboratory prepared and simulated field compacted specimens revealed that fabric differences between field and laboratory soil may lead to differences in volume change behavior.
- 3) Results of laboratory tests on fine-grained soil treated with cement kiln dust suggest that useful correlations may exist between the optimum additive content and soil type. Such relationships may be useful to streamline the mix design process for stabilized soil.
- 4) Results of swell tests on sulfate-bearing soils with and without lime treatment show that detrimental swelling may occur when lime is mixed with sulfate-bearing soils. The tests also reveal that there are other factors besides sulfate content that affect the chemical reactions that lead to swelling. Whenever a soil is suspected of containing sulfates significant caution should be exercised with regard to chemical treatment, and possibly chemical treatment with calcium-based stabilizers should be avoided.

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