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Research Article

Cracking in Liner Behavior and Desiccation of Compacted Landfill Liner Soils

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Abstract

Tests were conducted to investigate desiccation cracking of three compacted liner soils obtained from local landfills in southeast Michigan. The soils had low plasticity with varying fines content. Large-scale samples of the soils were subjected to wetting and drying cycles. Surficial dimensions of cracks and suction in the soils were monitored. Surficial dimensions of cracks were quantified using the crack intensity factor (CIF), which is the ratio of the surface area of cracks to the total surface area of a soil. All of the soils were subjected to a compaction–dry cycle (i.e. soils were allowed to dry after compaction) and a subsequent wet–dry cycle. An additional sample of one of the soils was subjected to a compaction–dry cycle and three wet–dry cycles. The maximum CIF obtained in the tests was 7% and suctions exceeding 6000 kPa were recorded. It was observed that cracking was affected by the fines content of the soils. In general, high suctions, rapid increases in suctions, and high amount of cracking were observed in soils with high fines content, with less cracking observed in soil with low fines content. In addition, it was observed that cracking increased significantly due to addition of moisture to the soils. The CIF for wet–dry cycles were significantly greater than the CIF for compaction–dry cycles.

Keywords: *Cracking, Soil, Liner, Landfill*

Introduction

Desiccation cracks form as a result of water loss to the atmosphere from a drying soil mass. Drying causes shrinkage and subsequent cracking of the soil. In particular, fine-grained soils are affected by desiccation cracking. Mitchell (2010) indicates that type and amount of clay minerals present in a drying soil control desiccation cracking. The extent and rate of cracking is dependent on various factors including negative pore water pressures (suction) which develop in a soil during drying, and elastic properties of the drying soil (Morris et al., 2012; Fredlund and Rahardjo, 2010).

In addition, moisture and density conditions, confining pressures, temperature, and cycles of wetting and drying affect desiccation cracking (Morris et al., 2012; Mitchell, 2010). This study was conducted to investigate desiccation cracking of local soils used for construction of compacted soil liners in southeast Michigan. Large-scale samples of the soils were subjected to wetting and drying cycles.

Surficial dimensions of cracks and magnitude of soil suctions were monitored during the cycles. The amount of cracking on the surface of the soils was quantified using an image analysis method. The changes in the amount of cracking with soil suction were investigated. In addition, critical suctions that caused a significant change in the amount of cracking were determined.

Capillary forces associated with soil moisture loss to the atmosphere cause a soil mass to shrink. Suction develops in the soil due to drying. This suction increases the effective stresses (i.e. intergranular stresses) in the soil. In turn, volume of the soil starts decreasing and cracks develop in the soil mass. Cracking progresses with increasing suctions in a drying soil mass.

Fine-grained soils are more susceptible to the development of cracks than coarse-grained soils due to the presence of small pores, which allow for the development of high suctions (Holtz and Kovacs, 2011; Mitchell, 2010). Adding coarse-grained materials to clay soils can reduce the amount of shrinkage and cracking significantly (DeJong and Warkentin, 2011; Kleppe and Olson, 2011), although this might change the engineering properties of the soils. The presence of high amounts of clay particles in a soil, particularly highly active clay minerals such as smectites and vermiculites, promotes the formation of cracks (Holtz and Kovacs, 2011; Mitchell, 2010).

A high plasticity index (PI) and low shrinkage limit indicates high potential for shrinkage and swelling. For PI>35, excessive shrinkage can be expected (Daniel, 2011). The chemistry of the pore fluid also affects

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crack formation. For compacted clay soils, compaction conditions affect the desiccation behavior of the soil. Daniel and Wu (2010) recommend compaction at low water contents (dry of optimum) using great effort to minimize potential for cracking in arid areas. However, a soil compacted in this manner may swell extensively if it comes in contact with water and this soil may then shrink excessively upon subsequent drying. Holtz and Kovacs (2011) indicate that compaction at wet of optimum and at low densities can reduce swelling. However, a soil compacted in this manner can shrink and dessicate excessively if it is subjected to drying. Hence, compaction conditions tend to promote either low shrinkage or low swelling. Albrecht (2006) conducted tests on 11 compacted clay soils to determine the effects of wetting and drying cycles on soil hydraulic conductivity.

Large increases occurred in the hydraulic conductivity of high-plasticity soils compacted at wet optimum water contents due to wetting and drying cycles. However, small changes occurred in the conductivity of the soils compacted at dry of optimum water contents due to the cycles. Albrecht (2006) stated that this difference resulted from the presence of large cracks in the wet of optimum soils due to drying. The hydraulic conductivity of low-plasticity soils at the wet and dry of optimum water contents did not vary significantly. In the study conducted by Kleppe and Olson (2011), the cracking level was determined for compacted clay soils prepared with two different moisture conditions. In the first set of tests, samples of compacted clay soils were allowed to dry immediately after compaction. In the second set of tests, samples of the same clay soils were compacted and then saturated prior to drying. The saturated samples cracked more than the unsaturated soils (Kleppe and Olson, 2011).

Increases in the water content of similar compacted soils increased desiccation cracking. Observations of cracking of compacted liner soils in the field have been presented in various studies. Basnett and Brungard (2012) observed desiccation cracks on the side slopes of a clay liner during landfill construction. The cracks were 13– 25 mm in width and extended to a depth of 0.30 m. Miller and Mishra (2009) observed desiccation cracks during their field investigation of landfill liners. The cracks exceeded 10 mm in width and some penetrated the entire depth (0.30 m) of the compacted clay layer. Montgomery and Parsons (2009) observed desiccation cracking at test plots simulating covers constructed at a landfill in Wisconsin. Subsequent to 3 years of exposure, the upper 0.20–0.25 m of the compacted clay plots had become desiccated, with crack widths exceeding 13 mm. Maximum crack depths of 1.0 m were reported at a number of locations in the test plots. Corser and Cranston (2011) reported observations of cracks extending to 0.10 m depth within the compacted cover sections from a test fill in an arid part of California.

Quantification of cracking

Crack dimensions are generally measured using approximate methods. In most cases, qualitative descriptions are provided to estimate the extent of cracking. The irregular shape and complex geometry of cracks prevent accurate measurements of length, width, and depth. The width and depth of cracks are not uniform along the length of a crack. Maximum length, width, and depth are commonly recorded using measurements with rulers and/or thin gauge wires.

Kleppe and Olson (2011) developed a scale that ranged from 0 to 4 to describe severity of cracking. A crack severity number of 0 indicates absence of cracking, whereas, cracks with widths >20 mm and with substantial depths are described by a crack severity number of 4. Al Wahab and El-Kedrah (2011) developed a cracking index to quantify the extent of cracking. The cracking index is the ratio of the area of cracks to the total surface area of a soil. The area of a crack is equal to the product of its length and width. Calculations were made for crack depths exceeding 2 mm.

Al Wahab and El-Kedrah (2011) did not present methods for the determination of the length and width of cracks. It is believed that these dimensions were determined using a ruler. This potentially leads to overlooking the effects of the irregular shape of cracks in the calculation of the cracking index. Mi (2011) and Miller et al. (2008) described a similar approach. The crack intensity factor (CIF) was introduced as a descriptor of the extent of surficial cracking. CIF is defined as the ratio of area of cracks (A) to the total surface area (A) of c t a drying soil mass. A computer aided image analysis program was used to determine the CIF values. The areas were determined using photographs of desiccating soils. Cracks appear darker than remaining uncracked soil surface in photographs of a drying soil. The contrast between the color of the cracks and the uncracked soil is used to calculate the CIF. Scanned photographs of soil surfaces were analyzed using matlabA to determine CIF. In this study, CIF was used to quantify the amount of cracking in compacted clay soils.

Shrinkage during the first drying cycle in a clay soil causes irreversible fabric changes (Yong and Warkentin, 2011). Particle bonds may be broken during this cycle effectively weakening the soil. Upon wetting, the rearranged soil structure will be further weakened by the addition of water. Subsequent drying will again cause shrinkage. Cracking will occur during this drying cycle at the weakest locations of the soil structure.

Yong and Warkentin (2011) stated that cracking will occur at locations with low cohesion, which can correspond to the wettest locations in the soil. The broken bonds caused during the first drying cycle may attract water and become preferential zones of cracking. Effects of cyclic shrinkage and swelling were investigated in a number of studies. Al Wahab and El-Kedrah (2011) reported the results of tests conducted on a compacted clay with a medium.

Experimental setup

The testing program consisted of two main steps; soil preparation and compaction; and wetting and drying cycles. The loose soil was then placed in the plexiglas tank and compacted using a square steel pad (0.25 m×0.25 m) with a weight of 96 N. The pad was lifted 0.6 m and dropped freely to the soil surface. The soils were compacted in three equal lifts of approximately 60 mm thickness. Compaction energy was equal to the compaction energy used in standard Proctor compaction tests, 593 kJ m−3. Final depth of the soil in the tank was 170 mm. Water content and dry unit weight of soils were determined at completion of the compaction, before the initiation of cyclic wetting and drying tests. Water contents were determined to be 11, 11.5, and 11.3% for Soils 1, 2, and 3, respectively. Dry unit weights were determined to be 17.9, 18.7, and 18.8 kN m−3 for Soils 1, 2, and 3, respectively.

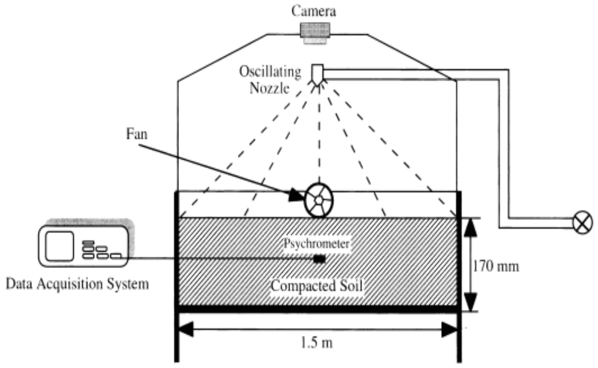

Fig.1 Test Setup

Initially, all soils were subjected to two cycles: a compaction–dry cycle and a wet–dry cycle. The compaction–dry cycle consisted of the drying period immediately after compaction. The compaction–dry cycle ended when the suction was stabilized at a constant value or increased above 6000 kPa, the upper limit for reliable measurements with the psychrometers used in this study. Wetting and drying cycles started subsequent to the compaction–dry cycle. The wetting cycle started with the application of simulated rainfall to the dry soil.

Table 1 Soil Characterization

Property	Soil 1	Soil 2	Soil 3
Specific Gravity	2.70	2.70	2.73
%Sand	25	19	68
%Silt	45	39	21
%Clay	30	42	11
LL	22	29	17
PP	6	16	6
USCS Classification	CL-ML	CL	SM-SC
Optimum Water Content	13	12	12
Max dry unit weight	19.3	19.7	19.8
Hydraulic conductivity	1.1x10^{-8}	7.8x10^{-8}	1.0x10^{-8}

The rainfall was applied at a rate of approximately 25 mm h−1. Rainfall application was terminated when the ponded water level above the soil surface reached 25 mm or at the end of 2 h of application, regardless of the depth of the ponded water. In most cases, this provided sufficient water to completely saturate the soil. The soil tank was sealed with a glass cover during the infiltration phase to prevent evaporation of moisture.

The end of a wetting cycle was defined as decrease of suction to a value below 500 kPa, in most cases to 0 kPa (i.e. saturation of the soil). When the wetting cycle was completed, the soil was again allowed to dry. Fans on the sides of the tank were used for the drying cycle. Similar to the compaction–dry cycle, the end of a drying cycle was defined as the stabilization of the suction at a constant value or increase of suction above 6000 kPa. It was expected prior to testing that highest amount of cracking would occur in Soil 2 due to its higher plasticity compared with the other soils. Therefore, this soil was selected for further analysis of cracking. An additional sample of the soil was subjected to second and third wetting and drying cycles in addition to the compaction–dry cycle and the first wet–dry cycle. The second and third cycles were initiated and terminated using the criteria described above.

Results and discussion

Initially, variations in soil suction and CIF with time were analyzed. Variation of the extent of cracking on the surface of the soils with suction was then analyzed using CIF values. in Soil 1 was higher than suction in Soils 2 and 3. Suction in Soil 1 reached 6000 kPa in both compaction–dry and wet–dry cycles. Suction in Soils 2 and 3 reached approximately 4000 and 5000 kPa in compaction–dry cycles and wet–dry cycles, respectively. Suction in Soils 1 and 2 increased more rapidly than suction in Soil 3 during both compaction–dry and wet–dry cycles.

Changes in suction during the wetting period occurred faster than the changes during the drying periods. Soils 1 and 2 have 75 and 81% fines content (%fines=%silt +%clay), respectively, and Soil 3 has 32% fines content. In general, high suctions and fast increases in suction were obtained for the soils with high fines content. Higher suctions are associated with smaller pore sizes. Small pores are expected to develop in compacted soils with high amounts of fine particles. As the pore sizes decrease, high suctions develop easily in the soil mass.

A new sample of Soil 2 was prepared and subjected to three wetting and drying cycles subsequent to a compaction–dry cycle (Fig. 3). Suction in the soil reached 3700 kPa during the compaction–dry cycle. Suction reached approximately 5000 kPa in the first and third drying cycles and 5700 kPa in the second cycle. In Figs. 2 and 3, it was observed that suctions in the soils were higher after the first wetting period compared with the suctions obtained in the compaction–dry period. It is believed that the soils experienced shrinkage and irreversible fabric changes during the first time they were dried (compaction–dry cycle) similar to the observations of Yong and Warkentin (2011). The shrinkage caused decreases in the size of the pore spaces and resulted in increased suction in the subsequent drying periods (e.g. first wet–dry cycles). CIF was calculated using a number of photographs obtained in a cycle. During the compaction–dry period the CIF was low. The CIF increased significantly after the first wetting period. Less than 1% of the surface area of Soils 1 and 2 were cracked.

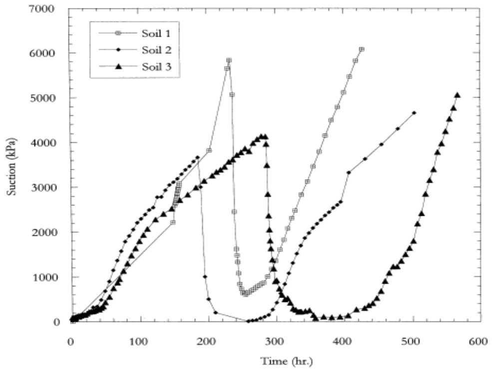

Fig.2 Variation of suction with time for Soils 1-3 for compaction dry and wet dry cycle

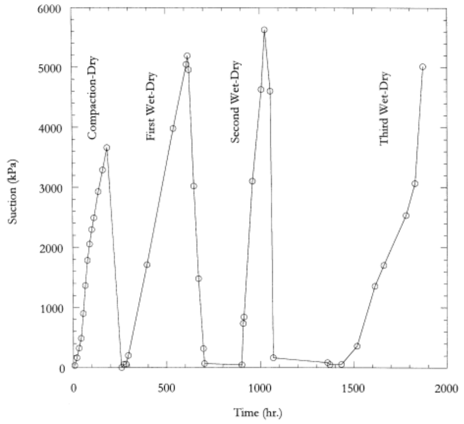

Fig.3 Variation of suction with time for Soils 2 for multiple cycle tests

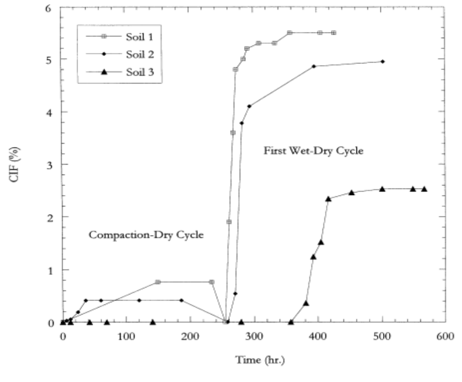

Fig.4 Variation of CIF with time for suction for Soils 1-3 for compaction dry and wet dry cycle

It was observed that the fines content was related to the CIF. The high CIFs were obtained for the soils with the high fines content. The lowest CIF was obtained for the soil with the lowest fines content. Although Soils 1 and 3 had the same PI, their cracking behavior was not similar. The difference in the CIF for these two soils is explained by the amount of fine particles in these soils.

Prior to testing, it was expected that the cracking in the soils be correlated to the PI of the soils. However, it was observed that fines content was more important in the cracking behavior of the soils than the PI. It is believed that small pores that allow the development of high suctions were formed in the soils with a high fines content. However, a sufficient amount of small pores that allow the development of high suctions did not form in the soil with a low fines content. Cracks developed rapidly in the soils at the beginning of a drying cycle (e.g. for Soil 1, CIF increased from 0 to 4.8% in 1.5 days). Cracking progressed slowly after the initial rapid crack development period (e.g. for Soil 1, CIF increased from 4.8 to 5.5% in 5 days and essentially remained at this value for the subsequent 3 days).

Summary and conclusions

Desiccation cracking was investigated in three compacted landfill liner soils obtained from southeast Michigan. The soils had low plasticity with varying fines content. Large-scale samples of the soils were subjected to wetting and drying cycles. Surficial dimensions of cracks and soil suctions were monitored during wetting and drying cycles. The extent of cracking on the surface of the soils was quantified using the CIF.

All of the soils were subjected to a compaction–dry cycle and a subsequent wet–dry cycle. An additional sample of Soil 2 was subjected to a compaction–dry cycle and three wet–dry cycles. It was observed that fines content in the soils affected the cracking behavior significantly. The greatest amount of cracking was observed in the soils with the greatest amount of fines fraction and the least amount of cracking was observed in the soil with least amount of fines fraction. The extent of cracking was not correlated directly to the PI of the soils used in this study.

Fines content was a better indicator of cracking than plasticity. Suctions also increased faster in the soils with the high fines content. Small pores were formed in the soil with high fines content, which allowed for the development of high suctions in the soil. In addition, it was observed that cracking subsequent to wetting was greater than cracking subsequent to compaction. The CIF for wet–dry cycles were significantly greater than the CIF for compaction–dry cycles although high suctions were measured during both cycles.

The extent of cracking is a function of both the amount of water in the soil at the onset of drying and suction attained during drying. The extent of cracking was observed to be more directly correlated to water content than suction. At the beginning of the compaction– dry period the soil strength is near maximum for the given compaction conditions. This high strength results in a high resistance to cracking, as the soil can resist the large tensile stresses associated with high suction values.

Upon wetting, the soil experiences softening and a decrease in strength. Subsequent drying induces suction, which exceed the resistance of the weakened soils causing cracking at locations of decreased soil strength. Subsequent to the addition of water to the soils (first wetting period), at the beginning of drying, cracking progressed significantly at relatively low suction.

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