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Compacted Clay Liners and Covers for Arid Sites

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Abstract: Tests were performed on a clayey soil from a site in Texas to define ranges of water content and dry unit weight at which compacted test specimens would have: (1) Low hydraulic conductivity; (2) minimal potential for shrinkage upon drying; and (3) adequate shear strength. Test specimens were compacted with three compactive energies over a range of water content. Low hydraulic conductivity could be achieved over a broad range of water content, but relatively wet specimens underwent large shrinkage upon drying. A range of water content near the optimum value measured with the highest compactive energy proved to be suitable in meeting the objective of low hydraulic conductivity and shrinkage potential. The dry unit weight had to be greater than 96–98% of the maximum value from modified compaction (ASTM method D1557) to meet hydraulic conductivity, shrinkage, and strength objectives. A similar approach is suggested for development of compaction criteria at other projects in which low-hydraulic-conductivity liners or covers must be constructed in relatively arid regions or other situations in which potential cracking caused by desiccation is of concern.

Introduction

Clay-rich soils used in constructing low-hydraulic-conductivity liners and covers for waste containment units are typically placed and compacted wet compared to optimum water content (Mitchell et al. 1965; Daniel 1987; Oakley 1987; Herrmann and Elsbury 1987). This practice minimizes the hydraulic conductivity of the compacted soil at the time of construction. However, at relatively arid sites or sites where the clay could be subjected to seasonal drying, this practice could be counterproductive if the liner will eventually desiccate. Large cranks can occur in wet, compacted clays that are allowed to dry. For example, large cracks in the test pad shown in Fig. 1 occurred at a site in the Southeastern United States after the unprotected clay was left exposed for several days.

At the heart of the problem is the fact that as the molding water content of a compacted soil is increased, the shrinkage potential of the soil increases as well. Engineers almost always specify that soil liners be compacted wet compared to optimum water content to comply with requirements that the hydraulic conductivity of the compacted soil not exceed a specified maximum (1×10^{-9} m/s for most categories of waste). However, while the engineer may find this practice of wet-side compaction to be effective in terms of regulatory compliance, one wonders whether the practice of constructing wet clay barriers is sound in arid regions or even in less arid locations where near-surface clays may desiccate during periods of drought. Will a wet soil liner or cover eventually dry out, crack, and become ineffective? Is it possible to compact the soil such that regulatory requirements for low hydraulic

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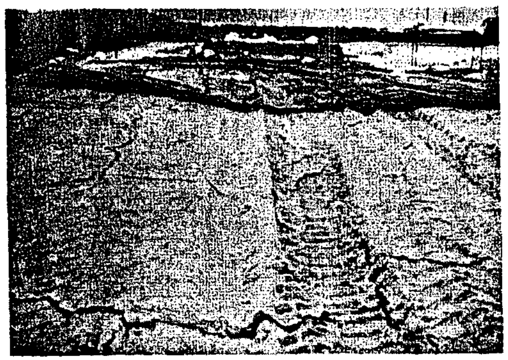

FIG. 1. Example of Cracking that Can Occur in Compacted Clay that Desiccates

conductivity are met and, at the same time, provide a compacted soil barrier with minimal potential to shrink or crack when drying occurs? If so, how?

The primary purpose of this study was to perform tests on a compacted, clay-rich soil to determine if it is possible to compact the soil such that the material has both low hydraulic conductivity and low shrinkage potential. The testing procedures and results are described, and a methodology for developing compaction criteria is suggested.

Literature on Desiccation-Induced Cracking

Several studies of desiccation-induced cracking of low-hydraulic-conductivity, compacted soil barriers have been performed. Kleppe (1981) and Kleppe and Olson (1985) investigated desiccation of two highly plastic clays (Taylor marl and Elgin fire clay) and sand/bentonite mixtures. Kleppe and Olson compacted cylindrical specimens and found that the volumetric shrinkage produced by desiccation was linearly proportional to molding water content but was insensitive to dry density. Cylindrical specimens shrank into smaller cylinders but did not crack significantly. To study cracking, Kleppe and Olson compacted slabs of clay and constrained the slabs along their edges during air drying. Major cracking, which Kleppe and Olson defined as development of cracks greater than 10 mm wide, occurred when volumetric shrinkage strains in cylindrical specimens compacted to the same water content and dry density were greater than 4%. Kleppe and Olson also found that shrinkage strains were far less in clayey sands than in soils with little sand. For example, at the same molding water content, shrinkage strains in mixtures of sand and bentonite containing 88%, 50%, 25%, and 0% sand were 4%, 11%, 14%, and 18%, respectively.

DeJong and Warkentin (1965) mixed Leda clay at the liquid limit with small glass beads in varying percentages, then measured the linear shrinkage strains that occurred in bars. Practically no shrinkage occurred when at least 70% of the material was glass beads. DeJong and Warkentin noted that

when the glass beads were in contact with one another and the clay simply filled the pores between the beads, shrinkage was minimal.

Boynton (1983) and Boynton and Daniel (1985) describe research in which 64 mm (2.5 in.) thick slabs of soil were compacted and desiccated. Cracks that fully penetrated the compacted slabs developed in less than 24 h. When undisturbed specimens trimmed from the slabs were back-pressure saturated and permeated, the hydraulic conductivity was sensitive to the effective confining stress (Fig. 2), which was sequentially increased after each permeation stage. At low stress, rewetting the soil did not result in full self-healing. These data suggest that desiccation cracks are of particular concern for final cover systems where the overburden stress on the compacted soil liner is low. For compacted clay buried beneath substantial overburden, the compressive stress from the overburden will help close preexisting desiccation cracks, and prevent the development of new ones, providing the foundation is properly prepared.

Hawkins and Horton (1965) describe lysimeter experiments at a site in South Carolina in which thin layers of bentonite were overlaid by either 300 mm (1 ft) or 600 mm (2 ft) of topsoil. After two years of exposure, during which time 2.6 m (102 in.) of rainfall occurred, substantial shrinkage cracks were observed in the bentonite layers covered with 300 mm (12 in.) of topsoil, but no cracking was seen when 600 mm (2 ft) of soil cover was used. Hawkins and Horton noted that some overlying soil became trapped in the cracks when the bentonite was rewetted and allowed to swell.

Montgomery and Parsons (1989) describe test plots in which 1.2-m (4-ft) thick compacted clay barriers were covered with either 150 mm (6 in.) or 450 mm (18 in.) of topsoil at a site near Milwaukee. After three years, the topsoil was removed and the condition of the clay examined. In both test plots, desiccation cracks up to 12 mm (0.5 in.) wide were observed. Cracks extended into the compacted clay to a depth of more than 1 m (40 in.). Unusually warm, dry conditions prevailed during the second summer of observation. These tests demonstrate that even in areas that are not arid,

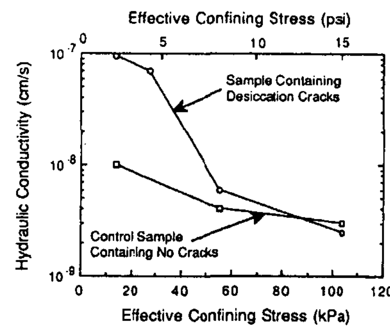

FIG. 2. Effect of Compressive Stress on Hydraulic Conductivity of Test Specimens that Had Been Subjected to Desiccation (from Boynton and Daniel 1985)

significant desiccation cracking can occur in a compacted soil barrier even with 150–450 mm (6–18 in.) of protective cover soil.

Corser and Cranston (1991) present data on test plots constructed at an arid site in California. A low-hydraulic-conductivity, compacted soil barrier was covered with: (1) An unprotected geomembrane; (2) a 450-mm- (18-in.-) thick layer of protective soil; and (3) a geomembrane overlaid by 600 mm (24 in.) of protective soil. After six months, the condition of the compacted barrier layers was examined. Substantial drying and cracking was observed in all of the test plots except that one in which the barrier soil was covered with a geomembrane and 600 mm (24 in.) of protective soil. One of the most effective ways to control drying of a clay barrier placed near the ground surface appears to be to protect the clay with both a geomembrane and a layer of soil.

In summary, both laboratory and field studies have demonstrated that compacted clay cracks when dried. Cover systems are especially vulnerable due to the potential for drying of soils located near the surface and the low compressive stress acting on the liner. Water content and percent of coarse material (e.g., sand) seem to be the most important soil characteristics that affect desiccation cracking; Sandy soils compacted at the lowest possible water content have the lowest potential for shrinkage cracking upon drying. Protection of clay from drying is also critical; a thin layer (less than or equal to 450 mm, [18 in.]) of cover soil alone is probably not adequate.

Project at Arid Site

The Texas Low-Level Radioactive Waste Disposal Authority is responsible for developing and operating a disposal facility in Texas for low-level radioactive waste. At the time that this study was initiated (1990), an arid site in west Texas, about 100 km east of El Paso, was being studied as a possible location of the required facility. Preliminary designs called for below-ground reinforced concrete vaults surrounded by various layers of materials, including a layer of low-hydraulic-conductivity, compacted soil. Applicable regulations do not specify a particular maximum hydraulic conductivity for barriers such as this, but analysts performing fate and transport studies for radionuclides in the waste assumed a hydraulic conductivity of 1×10^{-8} m/s for the low-hydraulic-conductivity backfill. In preparing this paper, the writers used a maximum allowable value of hydraulic conductivity equal to 1×10^{-9} m/s (which is the common regulation-mandated value) as the primary performance criterion for the soil barrier. The disposal facility was required to be designed to function effectively for at least 10,000 years. Because the region receives less that 250 mm (10 in.) of precipitation per year, long-term desiccation of the low-hydraulic-conductivity barrier layer was of concern.

At the beginning of this study, it was not known whether on-site soils could be compacted to meet the objective of low hydraulic conductivity and simultaneously have adequate resistance to shrinkage cracking upon drying. The purpose of this study was to determine if hydraulic conductivity and minimal shrinkage potential could both be provided, and, if so, to develop appropriate guidance for construction.

Approach

Daniel and Benson (1990) describe a procedure for determining compaction criteria for soil liners and covers. The procedure (Fig. 3) involves

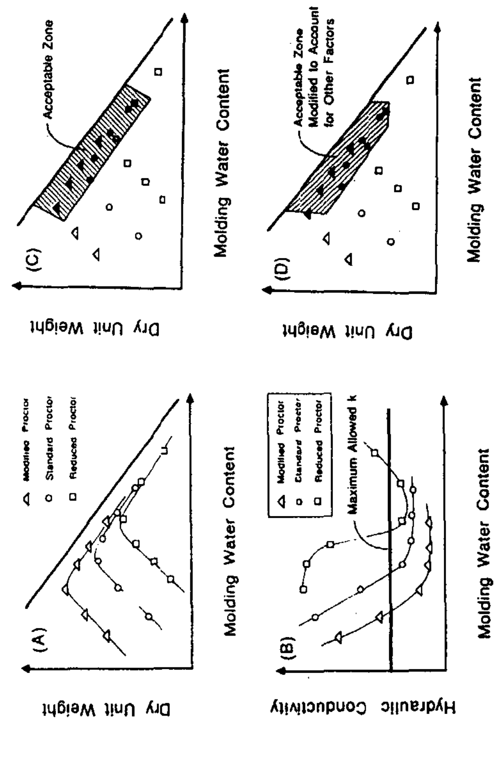

FIG. 3. Procedure for Establishing Zone of Water Content and Dry Unit Weight that Will Meet Hydraulic Conductivity (*k*) Objectives: (*a*) Test Specimens Are Compacted with Three Energies; (*b*) Specimens Are Permeated; (*c*) Acceptable Zone Is Drawn (Solid Symbols Represent Specimens with Acceptably Low *k*); and (*d*) Acceptable Zone Is Modified to Account for Factors Besides Hydraulic Conductivity (from Daniel and Benson 1990).

compaction and permeation of soil over ranges of water content and compactive energy as well as definition of an acceptable zone of suitable water contents and dry unit weights. Daniel and Benson discuss how other geotechnical tests besides hydraulic conductivity tests, e.g. strength tests, can also be used to define an acceptable zone that satisfies all criteria of concern on a project.

The procedure recommended by Daniel and Benson (1990) was used in this study. Three criteria were established. First, the compacted soil was required to have low hydraulic conductivity. It was assumed that the hydraulic conductivity could not exceed 1×10^{-9} m/s.

A second criterion was that shrinkage cracking caused by desiccation could not be excessive. Kleppe and Olson (1985) carefully tested three soils and found that major or severe cracking only occurred in compacted slabs when compacted cylinders of the same material underwent more than 4% volumetric strain when dried. It was assumed that 4% volumetric shrinkage of compacted cylinders upon drying was the maximum allowable value for this project. The writers will readily admit that the data to support the arbitrary cutoff of 4% volumetric shrinkage upon drying are meager, but there can be no doubt that, in principle, soils with minimal volumetric shrinkage upon drying have minimal potential to crack upon drying. A different threshold could be employed for other materials or circumstances, and the writers strongly encourage more research to relate shrinkage strain upon drying to potential for cracking.

Compacted soils used for liner and cover systems must have adequate shear strength. A third criterion applied to the soil tested in this investigation was that the shear strength exceed a reasonable minimum value. At the time these tests were performed, no information for this particular project existed on the minimum required strength. A minimum unconfined compressive strength of 200 kPa (30 psi) was arbitrarily selected. This strength is the lowest value for very stiff soils based on the terminology of Peck et al. (1974). Other criteria would obviously be appropriate for other projects. Each project would have to be evaluated individually to determine minimum strength requirements, and other types of strength tests (rather than the unconfined compression test) might be more appropriate for some projects.

The final objective was to relate compaction criteria (water content and dry unit weight) to hydraulic conductivity (maximum of 1×10^{-9} m/s), volumetric shrinkage upon drying (maximum of 4%), and unconfined compressive strength (minimum of 200 kPa [30 psi]). An attempt was made to define an acceptable zone for each criterion and, by superposition, to define an overall acceptable zone that satisfied all three criteria as shown in Fig. 4.

Soil

The materials employed for this study were taken from the walls of a large test pit at the site. The material was placed in buckets and shipped to the University of Texas for testing.

The liquid limit and plasticity index of the soil were 30 and 12%, respectively. About 2% of the soil was gravel and 65% was sand. Thirty-three percent of the soil passed the No. 200 sieve and 15% was finer than 0.005 mm. The soil was classified SC, which is clayey sand. Based on these properties, the clayey sand was thought to be nearly ideal for the proposed application. The soil appeared to be adequately plastic to yield low hydraulic

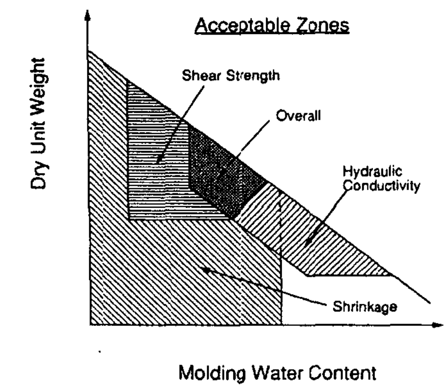

FIG. 4. Acceptable Zone Based on Low Hydraulic Conductivity, Low Desiccation-Induced Shrinkage, and High Unconfined Compressive Strength

conductivity, and the high percentage of sand was expected to minimize volumetric shrinkage upon drying.

Procedures

The soils were compacted with three energies (modified, standard, and reduced) as recommended by Daniel and Benson (1990). Modified and standard procedures are outlined in ASTM methods D1557 ("Laboratory" 1992b) and D698 ("Laboratory" 1992a), respectively. Reduced compaction was identical to standard compaction except that only 15 drops of the hammer per lift were used rather than the usual 25. This range of energy was selected in an effort to bracket the range of reasonable compactive energy. Resulting compaction curves are shown in Fig. 5.

Hydraulic conductivity was measured in compaction-mold permeameters following an unpublished draft ASTM procedure, "Measurement of Hydraulic Conductivity of Porous Material Using a Rigid-Wall, Compaction Mold Permeameter," being developed by Committee D18.04 (latest draft, April 7, 1992). Test specimens were free to swell vertically (i.e., no vertical stress was applied). The permanent liquid was deaired tap water, and hydraulic gradients ranged between 14 and 70. Tests lasted several weeks and were only discontinued when hydraulic conductivity was steady and rates of inflow and outflow were equal. Experience has shown that tests performed in this manner on laboratory-compacted specimens yield the same results as those performed in flexible-wall permeameters with back pressure (Boynton and Daniel 1985; Foreman and Daniel 1986; Benson and Daniel 1990; Daniel and Benson 1990).

Unconfined compression tests were performed on cylindrical specimens having a diameter and length of 50 and 100 mm (2 and 4 in.), respectively,

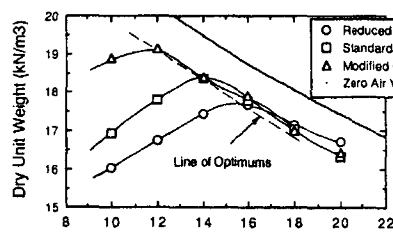

FIG. 5. Compaction Curves

that were trimmed from the larger compacted cylinders. Volumetric shrinkage upon drying was measured by extruding a compacting cylinder from the compaction mold and allowing the cylinder to dry on a laboratory table in an air-condition building in the same manner as Kleppe and Olson (1985). Two measurements of the diameter and four measurements of the height were obtained every 12 h with a caliper accurate to 0.025 mm (0.001 in.). Average diameter and height were used to compute volume, and the measurements were continued until the volume ceased to change further.

Results

Hydraulic Conductivity

Hydraulic conductivity is plotted as a function of molding water content and method of compaction in Fig. 6. The soil could be compacted to achieve a hydraulic conductivity of 1×10^{-9} m/s or less. However, the range of molding water content needed to achieve this maximum varied greatly with the energy of compaction: The greater the energy of compaction, the broader the allowable range of water content.

The acceptable zone of water contents and dry unit weights that yielded the required hydraulic conductivity of 1×10^{-9} m/s or less is shown in Fig. 7. The line of optimums from Fig. 5 is shown for reference. The shape of this acceptable zone is similar to the ones presented by Daniel and Benson (1990).

The lower limit of the acceptable zone in Fig. 7 is located slightly below the line of optimums for water contents less than about 15%. This soil can be compacted slightly dry compared to optimum water content from either standard or modified compaction and still possess a hydraulic conductivity that is less than or equal to 1×10^{-9} m/s. This fact is advantageous in terms of minimizing shrinkage potential of the soil and still producing a compacted soil with low hydraulic conductivity.

Volumetric Strain

The relationship between desiccation-induced volumetric shrinkage strain and molding water content is presented in Fig. 8 for three energies of compaction. Volumetric strains varied from 1% to almost 10%. Shrinkage strains produced by desiccation were essentially unaffected by the energy

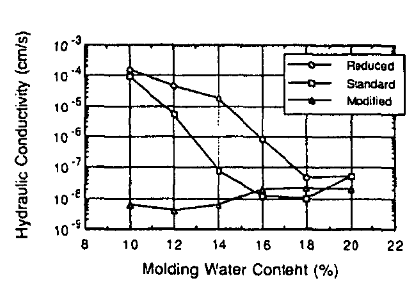

FIG. 6. Hydraulic Conductivity versus Molding Water Content

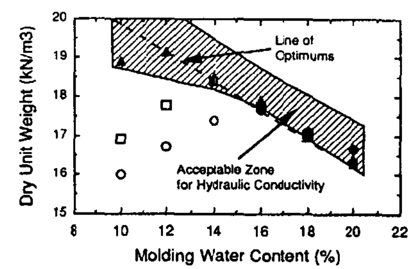

FIG. 7. Acceptable Zone Based on Hydraulic Conductivity Considerations (Solid Symbols Correspond to Compacted Specimens with Hydraulic Conductivity less than or equal to 1×10^{-9} mm/s)

of compaction or the dry unit weight of the soil (Fig. 8), which was also the case in the study described by Kleppe and Olson (1985).

As discussed earlier, a threshold volumetric shrinkage strain of a 4% was used to differentiate between compacted specimens that were acceptable or unacceptable. This distinction was made based on data published by Kleppe and Olson (1985) that related volumetric shrinkage strains in compacted cylinders to development of desiccation cracks in compacted slabs. The range of acceptable water contents and dry unit weights based on this assumption is shown in Fig. 9.

Unconfined Compressive Strength

Unconfined compressive strengths varied between 45 and 480 kPa (8 and 72 psi) (Fig. 10). The range of molding water contents and dry unit weights that yielded compacted specimens with unconfined compressive strengths in excess of 200 kPa (30 psi) is shown in Fig. 11.

Overall Acceptable Zone

The acceptable zones based on hydraulic conductivity, volumetric shrinkage strain, and unconfined compressive strength are superimposed in Fig.

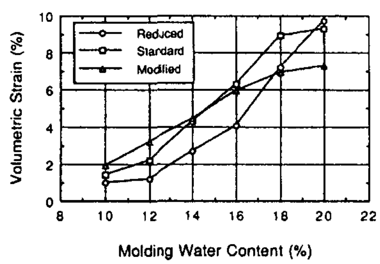

FIG. 8. Volumetric Strain Caused by Drying versus Molding Water Content

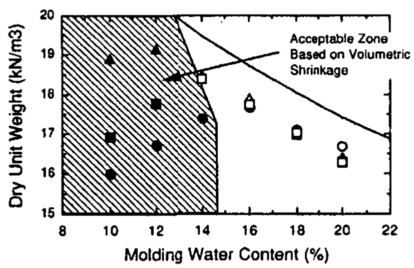

FIG. 9. Acceptable Zone Based on Volumetric Shrinkage Considerations (Solid Symbols Correspond to Compacted Specimens with Desiccation-Induced Volumetric Shrinkage less than or equal to 4%)

12. For this soil, a range of molding water content and dry unit weights existed that satisfied all three established criteria.

The overall acceptable zone shown in Fig. 12 could have been recommended directly. However, because the backfill would probably be viewed by the contractor as structural backfill around concrete waste containment cells, it seemed desirable to develop a recommended acceptable zone with a form that is typical of structural backfill. Judgment was used in development of a final recommended acceptable zone, which Daniel and Benson (1990) indicate is appropriate with their recommended procedure. The recommended compaction criterion was as follows: (1) The soil shall be placed and compacted at a water content of ±2% from the optimum value determined from modified compaction [ASTM D1557 ("Laboratory" 1992b)]; and (2) the soil shall be compacted to a minimum dry unit weight of 98% if the water content is between 2% dry compared to optimum and optimum, or 96% if the water content is between optimum and 2% wet compared to optimum. This recommended acceptable zone is shown in Fig. 13.

The recommended acceptable zone (Fig. 13) is slightly more restrictive that the actual acceptable zone (Fig. 12) in terms of minimum dry unit

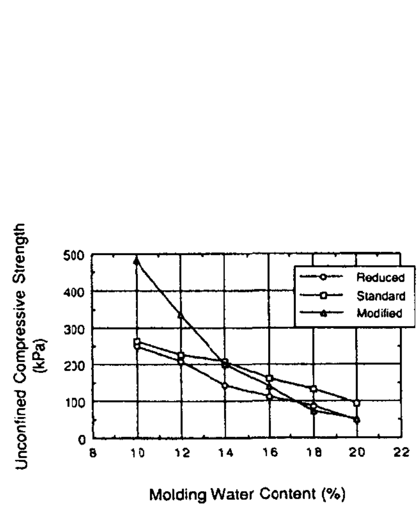

FIG. 10. Unconfined Compressive Strength versus Molding Water Content

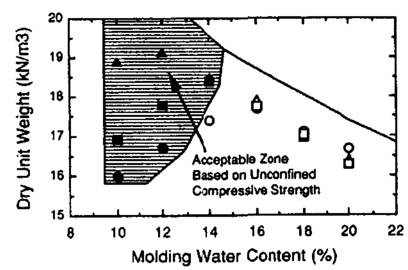

FIG. 11. Acceptable Zone Based on Unconfined Compressive Strength Considerations (Solid Symbols Correspond to Compacted Specimens with Unconfined Compressive Strengths greater than 200 kPa [30 psi])

weights that must be achieved. The benefits gained from employing specification language that describes the acceptable zone in simple, easily understood terms that are familiar to earthwork contractors placing structural backfill was thought to more than outweigh the penalty associated with slightly increasing minimum compaction requirements.

A small segment in the upper right-hand corner of the recommended acceptable zone was actually outside the limit of the overall acceptable zone (Fig. 13). It was decided to include this small segment in the recommended acceptable zone for the following reasons: (1) Inclusion of this segment makes the description of the acceptable zone very simple; (2) the segment is small and of little practical consequence since it lies above the modified compaction curve (compaction to these densities in the field would be improbable); and (3) the segment was excluded from the overall acceptable zone based on volumetric shrinkage (Fig. 9), and the shrinkage data shown in Fig. 9 could have been interpreted slightly differently (but consistent with the data) to include the small segment in the overall acceptable zone.

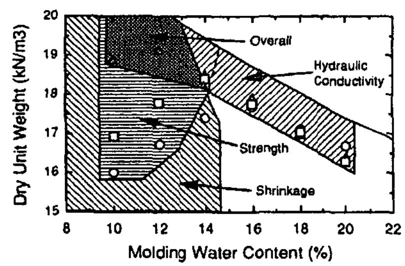

FIG. 12. Acceptable Zone Based on Design Objectives for Hydraulic Conductivity, Volumetric Shrinkage, and Unconfined Compressive Strength

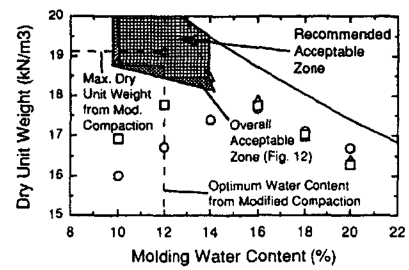

FIG. 13. Overall Acceptable Zone and Recommended Acceptable Zone

Design Principles for Arid Sites

The literature cited earlier plus the results just presented suggest several strategies for engineers who design low-hydraulic-conductivity, compacted soil liners and covers for sites in arid areas or for facilities where desiccation might be expected for other reasons. The engineer does not need to be restricted to just one of the control measures: The engineer can employ any or all of the available measures.

The available design principles are summarized as follows.

1. Use soils rich in sand. DeJong and Warkentin (1965) and Kleppe and Olson (1985) demonstrated that desiccation shrinkage increases with increasing clay content. Clayey sand (SC) combines the attributes of low hydraulic conductivity and low compressibility to minimize the amount of shrinkage that takes place upon drying. If clayey sands are unavailable, mixtures of locally available sandy materials with processed clay (e.g., sodium bentonite or a nonexpandable clay such as kaolinite) should be given consideration.

2. Place soil at the lowest practical water content. The results of this investigation demonstrate that some soils can be compacted relatively dry, with high compactive energy, and achieve both low hydraulic conductivity and low shrinkage potential. Even if some drying of the soil takes place, the soil will undergo minimal shrinkage and desiccation cracking.

3. Be especially cautious with cover systems. Boynton and Daniel (1985) demonstrated that desiccated clay swells when rewetted but does not regain the original low hydraulic conductivity if the compressive stress from overburden is low (Fig. 2). Desiccation has a greater potential for permanently damaging clay barriers in cover systems (where the clay is subjected to a low stress) than in liner systems subjected to large compressive stress from the loading provided by the overlying waste.

4. Protect the soil barrier. Neither a thin layer of topsoil (Hawkins and Horton 1965; Montgomery and Parsons 1989) nor an uncovered geomembrane (Corser and Cranston 1991) can be counted on to prevent an underlying compacted soil barrier from drying out and cracking. However, an adequately thick soil cover in a humid region (Hawkins and Horton 1965) or a protective geomembrane overlaid by topsoil in an arid region (Corser and Cranston 1991) has been shown to be effective in stopping desiccation of an underlying compacted soil liner. Designers should consider a composite geomembrane/protective soil layer to minimize drying of the barrier layer in cover systems. For low-hydraulic-conductivity soil liners placed on very dry soils with suctions that are far greater that the compacted liner, consideration should be given to separating the soil liner from the dry subsoil with a geomembrane. At arid sites, the only practical way of stopping a clay-rich, low-hydraulic-conductivity barrier soil from drying out may be to place geomembranes above and below the soil barrier.

Some combination of the outlined strategies and perhaps others that have not occurred to the writers will likely provide the most cost-effective solution for a particular project.

Conclusions

The primary purpose of this investigation was to determine whether a clayey sand from a site in west Texas could be compacted to meet three objectives: (1) Have low hydraulic conductivity; (2) have low potential to shrink and crack when dried; and (3) have adequate shear strength to support structural loadings. Test specimens were compacted over a range of molding water and compactive energy. Hydraulic conductivity, volumetric shrinkage strain, and unconfined compressive strength were measured. All three objectives could be met by compacting the soil at a water content ±2% from the optimum value determined from modified compaction [ASTM D1557 ("Laboratory" 1992b)] and to a dry unit weight of at least 96–98% of the maximum value from modified compaction. This study illustrates that it is possible to compact a clayey sand to a low hydraulic conductivity and simultaneously produce a compacted material with minimal potential to shrink and crack when desiccated.

The engineer has at least four ways to deal with the problem of desiccation of low-hydraulic-conductivity, compacted soil barriers: (1) Use clayey sands, which combine the attributes of low hydraulic conductivity and low shrinkage upon drying; (2) specify a range of compaction water content and dry unit weight that ensures both low hydraulic conductivity and low shrinkage potential; (3) rely on large compressive stress, where such stress will exist, to close preexisting desiccation cracks and prevent the development of new ones; and (4) protect the soil from drying by placing a thick layer of topsoil or placement of geomembranes above, below, or both above and below the soil barrier to minimize drying, but be sure that an overlying geomembrane is covered with a protective layer of soil.

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