THE INFLUENCE OF AMENDMENTS ON THE VOLUMETRIC SHRINKAGE AND INTEGRITY OF COMPACTED CLAY SOILS USED IN LANDFILL LINERS *

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Abstract. Clay liners remain an important component of composite liners used in landfill construction. Because their hydraulic integrity is frequently lost due to desiccation cracking, either during construction or shortly thereafter. The present study was initiated to evaluate the effects of common soil additives including lime, cement, and sand on the shrinkage and hydraulic conductivity of compacted clay soils commonly used in clay liner construction. Three soils having predominant clay minerals of smectite, illite and kaolinite were amended with varying amounts of lime, cement or sand; compacted using the Harvard miniature compactor; and the volumetric shrinkage was measured on the compacted samples. Additional samples of each treated soil were compacted according to ASTM 698 and used for measurement of the hydraulic conductivity. The results show that the majority of shrinkage occurs when the samples were dried to 25 °C with little additional shrinkage at temperatures up to 105 °C. The amendments of either 4% lime or 40 to 50% sand resulted in reduced shrinkage and increased hydraulic conductivity. The addition of 3% cement reduced shrinkage by up to 50% and simultaneously reduced hydraulic conductivity by 2 orders of magnitude. Thus, amendment of clay soils having a high shrink-swell potential with Type I Portland cement has the greatest poetential for field application as an amendment to help maintain the integrity and improve the long term performance of compacted clay liners.

1. Introduction

Compacted clay textured soils are used as components of composite landfill liners and as such serve as a barrier to the migration of harmful contaminants into groundwater from both municipal and hazardous waste landfills. It is well accepted and required by law that the clay soil material should have a saturated hydraulic conductivity, K, not exceeding 1×10^{-7} cm sec^{-1}. For the liner to be effective, the K should remain low for the entire lifetime of the landfill. Most clay liner materials tested in the laboratory exhibit hydraulic conductivities lower than 1×10^{-7} cm sec^{-1}, however these same materials in the field may have K values, 10 to 10 000 times (1 to 4 orders of magnitude) greater than that measured in the

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laboratory (Daniel, 1984). These differences have been attributed to various failure mechanisms including piping, dissolution, and cracking.

Disiccation cracks in soil liners have been measured to be over 3 cm wide and 2.5 m deep (Anderson *et al.*, 1984). The mechanism of crack formation involves a reduction in water potential in the upper soil as water evaporates into the atmosphere. This results in the development of tension forces inside the soil pores which draw the soil particles closer together. Cracks then form when the tension forces in the pores exceed the tensile strength of the soil. Various amendments including lime, cement, fly ash, and sand have been added to soils which exhibit a high amount of volumetric shrinkage, prior to their use as subbase or to support foundations, to help minimize the amount of skrinkage. However, little attention has been directed toward the effect of these amendments on the hydraulic conductivity of the soils.

Picornell and Idriss (1989) concluded that additives of inert clays or coarse aggregate to a liner mix are a feasible means to reduce shrinkage of the mix while maintaining a reasonably low permeability. They found that the best gradation of coarse aggregates was the gradation of the theoretical Fuller's curve (Fuller, 1961) for maximum size of aggregate being used.

George (1970) showed that the addition of lime to clay soils results in a lowering of shrinkage and hence cracking intensity. Addition of lime to clayey soils also improves the workability (Cibor *et al.*, 1989) and results in lower shrinkage (George, 1968a) and hence less cracking. The major disadvantage is that the addition of lime causes the hydraulic conductivity to increase by a factor of 10 to 1000.

George (1968b) studied the effects of cement on soil and reported that shrinkage of a soil-cement mixture decreased as the fraction of cement increased, attained a minimum, and thereafter increased only slightly with additional cement additions. Therefore, it may be possible to find an optimum amount of cement to stabilize soils against excessive shrinkage.

Increased sand content and decreased clay content leads to decreased shrinkage and increased hydraulic conductivity. Therefore, a balance between the two particle sizes is needed to obtain the desirable end result of a soil with both low shrinkage and low hydraulic conductivity. Tiles (1951) investigated shrinkage and strength of compacted sand-clay mixtures. As the sand contents of mixtures of Ottawa sand and kaolinite increased, the optimum water content decreased and the dry density increased. The mixture containing 40% sand had, concurrently, the lowest shrinkage and the highest strength. Strength generally decreased with increased sand contents. For samples containing more than 40% sand, shrinkage increased gradually with increased sand contents until the sand content reached 60%. Shrinkage decreased with further additions of sand, reaching a minimum at 80%.

Thus, the data of Boynton (1983) and Picornell and Idriss (1989) as reported in the literature suggest that it may be possible to amend clay soils using either lime, cement, or sand to achieve a liner material with minimum shrinkage and minimum hydraulic conductivity. Therefore, the objective of the preset research was to study the effect of commonly used soil additives including lime, cement, and sand on the shrinkage and hydraulic conductivity of compacted clay soils.

2. Materials and Methods

Three soils were selected to represent a wide range of mineralogical and physical properties. The first soil was Beaumont clay which commonly occurs along the gulf coast, has a predominantly smectitic clay mineralogy, and is frequently used in the construction of soil liners. The predominant clay minerals of the other two soils were illite, and kaolinite. All future references to the soils will be by their predominant mineral component (Table I). In the selected soils, the liquid limit ranged from 19 to 52 and Plasticity Index ranged from 5 to 37. Atterberg limits were measured for all soils using ASTM methods D-423-66 and D-424-59 for the liquid and plastic limits, respectively. The density and moisture content relations for each soil were established using ASTM procedure D-698-70. The particle size distribution of each soil was measured using the hydrometer technique of Gee and Bauder (1986).

Each of the three soils was amended by adding 0, 4, 7, and 9% (wt/wt) hydrated lime or 0, 3, 7 and 12% (wt/wt) Type I Portland cement; or 0, 10, 20, 30, 40, 50, and 60% (wt/wt) sand. Lime and cement application rates were selected to span the range of application rates known to be useful for other construction related activities such as soil stabilization. Sand application rates were based on the work of Tiles (1951) and Picornell and Idriss (1989). Three replicates of each soil and soil/amendment combination were evaluated for volumetric shrinkage and hydraulic conductivity. The use of three replicates allowed the computation of standard deviations for use as an estimator of the variability inherent to the treatments. Due to the high sand content (63.8%) of the native kaolinitic soil, it was not possible to amend it with additional sand.

For measurement of shrinkage, three replications of each soil and treatment were compacted using the Harvard miniature compaction method. The soils were brought to the desired moisture content, equilibrated overnight, added to the mold (3.174 cm i.d., and 7.144 cm tall) in 7 lifts of approximately 20 g each and compacted with 15 tamps of a pre-stressed 18.2 kg spring hammer per lift (Wilson, 1950). The surface of each lift was scarified to insure bonding and any excess soil from the last lift was trimmed off. Compacted samples were extruded, weighed, and quickly dipped 2 to 4 times in a 1:7 Saran resin:acetone mixture. Samples were allowed to air dry for 10 to 15 minutes between coatings and 30 min after the final coat. The samples were weighed in air and then water, left at ambient room temperature for 24 hr and then oven dried at 105 °C to constant weight. The saran prevented bulk flow of water into the soil during weighing yet allowed diffusion

TABLE I

Physical properties of the three soils used in this study

Predominant clay mineral	Texture				Engineering properties			Unified class.	Optimum moisture content (%)
	Sand	Silt	Clay	USDA class.	Liquid limit	Plastic limit	Plasticity index		
	%								
Smectitic	16.28	31.4	52.4	Clay	51.18	14.61	36.57	CH	18.5
Illitic	5.1	49.6	45.3	Silty clay	43.1	23.36	19.74	CL	18.0
Kaolinitic	63.8	12.7	23.5	Silty clay loam	18.6	13.4	5.2	SF	12.5

of water vapor out of the soil during periods of drying. The amount of shrinkage was calculated as the difference between the initial and final volumes divided by the initial volume. The volume and weight measured in this manner were corrected for the weight and volume of Saran using a saran density of 1.3 g cm^{-3}.

To evaluate the effect of initial moisture content and drying temperature on volumetric shrinkage, an additional set of experiments was conducted using the three unamended soils at three moisture contents from slightly wet of optimum to about 5% dry of optimum and dried at three temperatures.

The hydraulic conductivity was measured in three replicates using fixed wall permeameters (Soil Test Cat. #K-610). Air dried soil passing a No. 4 (4.74 mm) sieve was moistened to 3% above the optimum moisture content, equilibrated overnight and compacted in 10.16 cm diameter compaction molds following the Standard Proctor procedure ASTM D 698) including scarification between lifts. After compaction, the excess soil was trimmed off, the permeameter was assembled, filled with tap water, and allowed to hydrate overnight before air pressure of 20 psi (a gradient of approximately 130) was applied. Outflow was collected in a vented flask to prevent excessive evaporation and weighed until a steady state outflow was reached.

The saturated hydraulic conductivity (K) was calculated as:

$$K = \frac{Q\,L}{h\,A}$$

where

K = saturated hydraulic conductivity (cm sec^{-1})

Q = outflow (cm^3 sec^{-1})

L = length of the soil sample (cm)

h = total hydraulic head (cm)

A = cross sectional area of soil (cm^2).

3. Results and Discussion

The volumetric shrinkage of the smectitic soil was always the greatest of the three soils at any given moisture content or drying temperature (Table II) followed by the illitic and then the kaolinitic soil. For all three soils, the majority of volumetric shrinkage occurred by drying the soil at 25 °C and only 0.17 to 1.45% additional shrinkage was measured in the samples dried at 105 °C. Since 25 °C (77 °F) is a very common summer temperature, these data indicate that the majority of volumetric shrinkage could occur under normal weather conditions. Each of the soils showed a direct correlation between initial moisture content and total volumetric shrinkage. Thus, while soils compacted at moisture contents wet of optimum will have low hydraulic conductivities, they will be more susceptible to volumetric shrinkage

TABLE II

Average volumetric shrinkage for unamended smectitic, illitic and kaolinitic soils at three different initial moisture contents and dried to different final temperatures

Soil	Initial moisture content (%)	Drying temperature (°C) 25 °C		40 °C		105 °C	
		Volumetric shrinkage (%)[a]					
		Mean	S.D.	Mean	S.D.	Mean	S.D.
Smectitic	14.82	11.54	(0.17)	11.84	(0.22)	12.47	(0.23)
	16.74	13.62	(0.10)	14.20	(0.12)	14.87	(0.23)
	20.15	17.15	(0.69)	17.46	(0.53)	18.30	(0.39)
Illitic	13.08	6.68	(0.58)	7.60	(0.78)	8.13	(0.53)
	17.00	11.44	(0.10)	11.66	(0.11)	11.93	(0.21)
	20.63	14.65	(0.12)	15.21	(0.29)	15.57	(0.13)
Kaolinitic	6.97	1.42	(0.17)	1.52	(0.11)	1.64	(0.09)
	10.54	2.42	(0.36)	2.53	(0.36)	2.59	(0.39)
	12.46	3.41	(0.10)	4.05	(0.13)	4.32	(0.09)

[a] Each value is the average of three measurements; S.D. is the standard deviation.

TABLE III

Average volumetric shrinkage for smectitic, illitic and kaolinitic soils amended with lime

Soil	(%) Lime added to soil 0		4		7		9	
	Volumetric shrinkage (%)[a]							
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Smectitic	16.05	(0.21)	8.07	(0.18)	7.11	(0.31)	7.49	(0.55)
Illitic	11.12	(0.67)	7.41	(0.15)	6.90	(0.23)	7.03	(0.12)
Kaolinitic	3.13	(0.05)	2.09	(0.04)	2.16	(0.15)	2.09	(0.10)

[a] Each value is the average of three measurements; S.D. is the standard deviation.

and possible cracking which may result in greatly increased conductivity (Omidi, 1993).

The addition of 4% lime to the smectitic soil resulted in a 50% decrease in volumetric skrinkage from 16.05% in the unamended soil to 8.07% (Table III).

TABLE IV

Average hydraulic conductivity of water by three soils of diverse mineralogies amended with various amounts of lime

		(%) Lime			
		0	4	7	9
		Hydraulic conductivity (cm sec^{-1})[a]			
Smectitic	Mean	7.81×10^{-10}	4.93×10^{-9}	1.14×10^{-8}	4.52×10^{-8}
	S.D.	4.76×10^{-10}	2.10×10^{-9}	0.23×10^{-8}	4.17×10^{-8}
Illitic	Mean	9.31×10^{-9}	1.71×10^{-7}	6.35×10^{-7}	1.12×10^{-6}
	S.D.	0.70×10^{-9}	0.47×10^{-7}	1.63×10^{-7}	0.10×10^{-6}
Kaolinitic	Mean	7.15×10^{-8}	6.77×10^{-7}	1.20×10^{-6}	4.24×10^{-6}
	S.D.	0.99×10^{-8}	1.34×10^{-7}	0.45×10^{-6}	1.13×10^{-6}

[a] Each value is the average of three measurements; S.D. is the standard deviation.

Addition of 7 and 9% lime only decreased the volumetric shrinkage slightly more than that of the 4% treatment. Thus, for this smectitic soil, addition of 4% lime would achieve the maximum reduction in shrinkage per unit of lime added. The illitic soil behaved similarly and although the unamended soil had a lower volumetric skrinkage, the addition of 4% lime resulted in a 34% decrease in volumetric shrinkage to 7.41%. Addition of 7 or 9% lime to the illitic soil resulted in only very small decreases in the amount of shrinkage. The kaolinitic soil only had a volumetric shrinkage of 3.13% in its native state, however, the addition of 4% lime to this soil reduced the shrinkage by one third to 2.1%. Further additions of lime had no benefit in terms of decreased shrinkage. Thus, for all three soils studied, the addition of 4% lime resulted in a 33 to 50% reduction in volumetric shrinkage.

The addition of lime to the smectitic soil resulted in increased hydraulic conductivity of the soil (Table IV). Additions of 4, 7 and 9% lime resulted in conductivities which were 6.3, 14.6 and 57.9 times, respectively greater than that of the unamended soil. The initial conductivity of the smectitic soil was very low and the conductivities of all the lime amended treatments remained below the 1×10^{-7}cm sec^{-1} standard for clay liner use. Addition of 4, 7, and 9% lime to the illitic soil resulted in conductivities which were 18.4, 68.2, and 120 times that of the respective unamended soil. All lime-amended illitic samples had conductivities in excess of the 1×10^{-7} cm sec^{-1} criterion. The kaolinitic soil exhibited increases of 9.5, 16.8 and 59.3 times the unamended soil for the soil amended with 4, 7, and 9% lime, respectively. Thus, the data show that the addition of 4% lime to a smectitic soil reduced shrinkage by 50% but still maintained a saturated hydraulic conductivity of less than the 1×10^{-7} cm sec^{-1}.

TABLE V

Average volumetric shrinkage for smectitic, illitic and kaolinitic soils amended with cement

Soil	(%) Cement added to soil							
	0		3		7		12	
	Volumetric shrinkage (%)[a]							
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Smectitic	16.05	(0.21)	10.44	(1.40)	7.68	(0.34)	8.26	(0.18)
Illitic	11.12	(0.67)	9.53	(0.38)	8.37	(0.20)	7.90	(0.28)
Kaolinitic	3.13	(0.05)	2.88	(0.08)	2.70	(0.24)	2.22	(0.10)

[a] Each value is the average of three measurements; S.D. is the standard deviation.

TABLE VI

Average hydraulic conductivity of water by three soils of diverse mineralogies amended with various amounts of cement

Soil		(%) Cement 0	3	7	12
		Hydraulic conductivity (cm sec^{-1})[a]			
Smectitic	Mean	7.81×10^{-10}	6.43×10^{-9}	4.71×10^{-10}	1.37×10^{-10}
	S.D.	4.76×10^{-10}	4.80×10^{-9}	2.10×10^{-10}	0.52×10^{-10}
Illitic	Mean	9.31×10^{-9}	7.22×10^{-10}	8.51×10^{-11}	3.21×10^{-11}
	S.D.	0.70×10^{-9}	1.22×10^{-10}	3.27×10^{-11}	2.57×10^{-11}
Kaolinitic	Mean	7.15×10^{-8}	1.51×10^{-8}	6.09×10^{-9}	8.15×10^{-10}
	S.D.	0.99×10^{-8}	0.35×10^{-8}	0.85×10^{-9}	1.74×10^{-10}

[a] Each value is the average of three measurements; S.D. is the standard deviation.

The addition of 3, 7 and 12% cement to the smectitic soil also decreased the volumetric shrinkage from 16.05% in the untreated soil to 10.44, 7.68 and 8.26% in the soils which were amended with 3, 7 and 12% cement, respectively. For this soil, the addition of 7% cement resulted in the maximum decrease in the amount of shrinkage. For the illitic soil the addition of 3 and 7% resulted in notable decreases in shrinkage from the 11.12% in the unamended soil to 9.53 and 8.37% in the treated soils. Addition of 12% cement resulted in only a slight further decrease to 7.9% shrinkage. The kaolinitic soil exhibited a uniform decrease in shrinkage with added cement.

TABLE VII

Average volumetric shrinkage of two soils of diverse mineralogies amended with various amounts of sand

Soil	(%) Sand 0	10	20	30	40	50	60
Smectitic	13.5	12.9	11.5	10.8	9.5	6.5	6.2
Illitic	9.6	8.0	6.6	6.2	4.5	3.6	2.5
Kaolinitic[a]							

[a] Not tested due to the high sand content of the original soil material.

Addition of Portland cement to the smectitic soil resulted in an increase in conductivity of up to 1 order of magnitude but all values for this soil remained below the 1×10^{-7} cm sec^{-1} limit (Table VI). Addition of cement to the illitic soil decreased the hydraulic conductivity of the soil by up to 2 orders of magnitude. All soil/cement mixtures using the illitic soil had hydraulic conductivity values less than the required 1×10^{-7} cm sec^{-1}. The kaolinitic soil behaved similarly to the illitic soil and also exhibited a decrease in hydraulic conductivity with the addition of cement. The 12% treatment resulted in a large decrease of almost 2 orders of magnitude.

Addition of sand to the smectitic soil resulted in gradual reductions in volumetric shrinkage (Table VII). To obtain a 50% reduction as seen with other amendments would require the addition of 50% sand to this soil. The illitic soil behaved similarly and would necessitate a 40% addition of sand to achieve a 50% reduction in volumetric shrinkage. Addition of these volumes of sand increased the hydraulic conductivities of the smectitic and illitic soils by slightly over 1 order of magnitude (Table VIII). Even with the addition of these amounts of sand, both soils had hydraulic conductivities close to 1×10^{-8} cm sec^{-1} and remained below the 1×10^{-7} cm sec^{-1} regulatory limit. Addition of 50% or more sand to the illitic soil increased the hydraulic conductivity to unacceptable levels. Thus. it appears that it may be possible to find combinations of soil and sand which will reduce shrinkage, thus reducing susceptibility to cracking while maintaining an adequately low hydraulic conductivity.

The results of this study indicate that addition of 4% hydrated lime, 7% Type I Portland cement, or 40-50% sand were effective in reducing the volumetric shrinkage of compacted clays. In general, the addition of lime resulted in increased conductivities and for many soils would not be acceptable. Lime is an excellent calcium source and the added calcium reduces soil plasticity, increases strength and decreases water absorption and swelling (Kezdi, 1979). These effects are accomplished through three mechanisms: flocculation, carbonization, and the pozzolanic

TABLE VIII

Average hydraulic conductivity of two soils of diverse mineralogies amended with various amounts of sand

		(%) Sand						
		0	10	20	30	40	50	60
		Hydraulic conductivity (cm sec^{-1})[a]						
Smectitic	Mean	7.81×10^{-10}	3.00×10^{-9}	4.71×10^{-9}	7.31×10^{-9}	7.63×10^{-9}	1.40×10^{-8}	1.78×10^{-8}
	S.D.	4.76×10^{-10}	0.96×10^{-9}	2.14×10^{-9}	2.03×10^{-9}	0.53×10^{-9}	0.76×10^{-8}	0.49×10^{-8}
Illitic	Mean	9.31×10^{-9}	1.10×10^{-8}	1.19×10^{-8}	1.20×10^{-8}	3.02×10^{-8}	4.14×10^{-7}	8.41×10^{-6}
	S.D.	0.70×10^{-9}	0.14×10^{-8}	0.04×10^{-8}	0.16×10^{-8}	0.50×10^{-8}	1.52×10^{-7}	4.55×10^{-6}
Kaolinitic[b]								

[a] Each value is the average of three measurements; S.D. is the standard deviation.

[b] Not tested due to the high sand content of the original clay soil material.

reaction. Basically, the calcium causes the soil particles to aggregate which results in the formation of stable macropores which results in the observed increase in hydraulic conductivity.

The addition of sand also increased the hydraulic conductivities of the amended soils but may be acceptable for use given careful laboratory testing and field blending. Since sand particles are very rigid they provide a stable matrix which is resistant to shrinkage, however due to their large particle size the hydraulic conductivity is very high. For use in a liner application, a careful balance is needed to get the optimum amount of sand for rigidity and the optium amount of clay soil for reduced hydraulic conductivity.

The addition of cement decreased the hydraulic conductivity of the illitic and kaolinitic soils and only slightly increased the conductivity of the smectitic soil. When mixed with fine grained soil, cement creates strong bonds between the soil minerals and forms a matrix which reduces soil placticity, soil water retention, hydraulic conductivity, and increases soil shear strength (Kezdi, 1979). Thus, the use of cement as an amendment had the optimum combination of both reduced shrinkage and reduced conductivity. Additional testing may be needed to evaluate the ability of the amended soils to support the overburden weight without cracking or otherwise compromising the integrity of the clay liner.

4. Conclusions

The majority of volumetric shrinkage resulting from the evaporative loss of water from compacted clay soils occurred when soils were dried at 25 °C, while drying at temperatures up to 105 °C resulted in little additional shrinkage. For the three soils tested, shrinkage increased in proportion to the initial moisture content. The addition of 4% lime to the soil resulted in approximately a 50% reduction in volumetric shrinkage but simultaneously increased the hydraulic conductivity by 2 orders of magnitude. The addition of cement reduced shrinkage by up to 50% and also reduced the hydraulic conductivity in two of three soils by up to 2 orders of magnitude. The addition of 40 to 50% sand resulted in reduced shrinkage and increased hydraulic conductivity. Of the three amendments tested, the addition of Type I Portland Cement shows the greatest potential for stabilizing the soil against shrinkage and yet maintaining a sufficiently low hydraulic conductivity. Additions of 3% cement to the smectitic and illitic soils used in this study were adequate to lower the volumetric shrinkage to below the suggested maximum of 11% (Omidi, 1993) needed to minimize cracking in the field, however, other soils may require the addition of larger amounts of amendment. Addition of 7% cement was sufficient to lower the shrinkage to 50% of that of the unamended soils. Uncertainty exists as to the potential of the cement amended soil to crack due to shear stresses imposed by overburden weight or other forces in the soil.

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