Consolidation and Strength Characteristics of Biofilm Amended Barrier Soils

J.L. Daniels, R. Cherukuri, and V.O. Ogunro

Abstract Experimental work was conducted to investigate the influence of biofilm on the consolidation and strength characteristics of two barrier soils. Biofilm has potential as a low-cost additive for soil stabilization, and it may be formed naturally in landfills throughout the developing world. The EPS-producing bacterium *Beijerinckia indica* was used to prepare solutions of varying concentration of exopolymeric substances (EPS). These solutions were then used as the molding moisture for compacted specimens of locally available clay ("red bull tallow," RBT) as well as a mix of 65% sand and 35% bentonite (65:35 mix). As compared to tap water, the influence of the nutrient solution or biofilm on RBT is to increase the compression index (C_c), although this trend is variable for increasing EPS concentration. While the effect of biofilm on the 65:35 mix is less uniform, the largest increase in C_c was observed for the highest level of biofilm amendment (EPS-5, 300 mg/L). Amendment with biofilm results in both increases and decreases in the rate of consolidation (c_v). The c_v values ranged from 0.4 to 13.6 m^2/year and from 0.2 to 19.3 m^2/year for RBT and 65:35 mix, respectively. In general, EPS has a decreasing effect on observed strength. For example, the peak unconfined compressive strengths for unmodified RBT and 65:35 mix were found to be 667.0 and 395.3 kPa, respectively. Many of these values decreased with increasing biofilm amendment, and for the highest level of amendment, the observed peak strengths were 159.1 and 98.8 kPa. To the extent that naturally-occurring methanotrophic activity in landfill cover systems results in biofilm production, the results suggest potential concerns with cover stability.

Keywords Polymers · biofilm · waste management · barriers · strength

J.L. Daniels (✉) and V.O. Ogunro
Associate Professor, Department of Civil and Environmental Engineering and Global Institute for Energy and Environmental Systems, University of North Carolina, 9201 University City Blvd, Charlotte, NC 28223, USA

R. Cherukuri
Graduate Research Assistant, Department of Civil and Environmental Engineering and Global Institute for Energy and Environmental Systems, University of North Carolina, 9201 University City Blvd, Charlotte, NC 28223, USA

E.K. Yanful (ed.), *Appropriate Technologies for Environmental Protection in the Developing World*,

1 Introduction

Despite the recent emphasis on source reduction as well as the growth of recycling and incineration, land disposal continues to be the dominant form of municipal solid waste (MSW) disposal, particularly in developing countries. In addition to MSW, industrial development and military legacies lead to the production of hazardous and radioactive waste. The primary objective of landfill facilities is to isolate waste from the natural environment. While the geotechnical performance of landfill components has been tested extensively in response to physical and chemical stress, little is known about microbiological effects. At issue is the recently documented presence of biofilm-producing methanotrophic bacteria in landfill cover soils (Hilger et al. 1999, Hilger and Barlaz 2000; Wise et al. 1999; Borjesson et al. 1998a, b; Kightley et al. 1995). Biofilm is composed largely of exopolymeric substances (EPS) and polysaccharides in particular. The presence of biofilm is expected to influence both the friction angles and adhesion/cohesion properties of various landfill components, yet little effort has been made to investigate its significance. Indeed, work performed by Daniels et al. (2002), Yen et al. (1996) and Yang et al. (1993) as well as literature from soil science suggests that the presence of biofilm-type substances can result in either decreases or increases in shear strength. Any change in shear strength is of direct interest for the stability of landfill covers with respect to sliding. Given the multi-component nature of virtually all landfill covers and liners, sliding failure is a particularly common concern. Sliding failure may occur in covers or liners, the most notable of which occurred at the Kettleman Hills Landfill as described by Seed et al. (1990) and Mitchell et al. (1990). The nature of biofilm is also quite similar to aqueous polymers used to mitigate freeze-thaw and desiccation induced stresses in landfill cover systems, as proposed by Daniels et al. (2003) and Daniels and Inyang (2004). The polymers considered included guar gum polysaccharide and polyacrylamide, which were dissolved in solution and used as the molding water at compaction. Results from this work indicate that these macromolecules can bind soil particles, ostensibly increasing the resistance to crack and fissure formation. Daniels et al. (2005) observed that biofilm amendment appears to reduce strength, while having a modest effect on compression and desiccation characteristics. However, while a range of biofilm concentrations may be relevant in field situations, the previous investigation included only one level of biofilm concentration.

Considering the potential presence of biofilm in landfill cover systems and the previous use of similar polymeric substances in barrier material improvement, the objectives of this paper are to (1) evaluate a range of biofilm concentrations on the consolidation and strength characteristics of two soils that could be used in waste containment applications and (2) comment on the significance of biofilm production in landfill cover soils as related to geotechnical performance.

2 Background

Biofilm research is broad in scope, and includes efforts related to problems connected to artificial recharge and/or sewerage infiltration (Mitchell and Nevo 1964; Wood and Bassett 1975; Okubo and Matsumoto 1979, 1983), efforts to enhance oil recovery (Hart et al. 1960; Shaw et al. 1985); biofouling or clogging of well systems for water supply or groundwater remediation (Clement et al. 1996) and drainage systems in landfill leachate collection systems (Brune et al. 1991; Rowe et al. 1998). In essence, the production of EPS and the formation of biofilm is the mechanism by which microorganisms can control their local environment. In porous media, a network of EPS forms a complex geometry on particle surfaces in response to spatial and temporal variations in nutrients, temperature, contaminants and predators (Costerton et al. 1978). Microbiological colonies use EPS to develop localized channels and pathways as a circulatory system to control such processes as nutrient delivery and waste rejection (Wingender et al. 1999). The result of this microbiological activity is a reduction in hydraulic conductivity as well as a change in the frictional and cohesive properties of a soil mass. One of the first reports regarding the influence of biofilm on hydraulic conductivity was given by Allison (1947). Extensive work has been conducted since that time and several investigators have assembled comprehensive summaries, including Taylor and Jaffe (1990), Wu et al. (1997), Dennis and Turner (1998) and Daniels and Cherukuri (2005).

While it is generally agreed that biofilm formation results in a decrease in hydraulic conductivity, the effect on strength and compressibility is less clear. Much depends on the extent to which the biofilm matrix bonds particles together versus simply coating the particles. Depending on the intensity of biofilm production, it may only consist of dispersed microcolonies with vast separation in between, or with continued growth, these may coalesce to form a contiguous film that coats all available surface area (Clement et al. 1996). Yang et al. (1993) investigated the influence of different commercial biopolymers (polyhydroxybutyrate, xanthan gum and sodium alginate) as well as a "slime-forming" bacterial suspension on the shear strength of sand and clay. The authors reported increases in strength for all cases, with improvements ranging from 2% to nearly 200%. Yen et al. (1996) continued the research by evaluating the effect of xanthan gum and a bacterial suspension composed of *Alcaligenes eutrophus* on the shear strength of silt as measured through triaxial compression tests. The authors noted that either of the additives increased the maximum deviatoric stress by 50% after an "aging" period of 10 to 15 days. This strength was maintained for the duration of the 45 day testing period, while concomitant permeability measurements revealed sustained reductions (implying continued presence) for 6 months. The authors concluded that biopolymers may represent a possible soil modifier with applications in waste containment. Though not discussed by the authors, it appears that polymeric bridging among particles may have contributed to the observed strength increases. The influence of a dissolved polysaccharide (from guar gum) on the unconfined compressive strength was investigated by Daniels et al. (2002). The soil tested contained a large amount of illitic clay, and is commonly referred to as Boston Blue Clay (BBC). Results showed that increasing the concentration of polysaccharide, analogous to increasing the level of EPS in the matrix, led to lower strength and increased ductility. Thus, for this particular case, it appears the polymer coated the particles, reducing the internal angle of friction.

3 Materials and Methods

The materials and sample preparation are largely as reported by Daniels et al. (2005), with the exception that for this contribution, solutions of varying biofilm concentration were prepared. The EPS-producing bacterium *Beijerinckia indica* was used in this research and obtained from the American Type Culture Collection (ATCC). Certain strains of *Beijerinckia* have since been reclassified as *Sphingomonas* (Gibson 1999). Dennis and Turner (1998) observe that *B. indica* has several characteristics that make it favorable from a research perspective. It is a free-living, non-pathogenic species that produces significant EPS. Although *B. indica* is classified as a strict aerobe, it tends to tolerate relatively wide fluctuations in oxygen partial pressure, pH, and functions optimally at 26 °C.

Cultures of *B. indica* were grown in Azotobacter #13 broth nutrient solution (ATCC 2002). The nutrient solution was prepared by adding the following constituents to distilled water, raised to 1,000 mL: 20 g glucose, 1 g NaCl, 1 g yeast extract, 5 mL of 10% $MgSO_4$, 8 mL of 10% K_2HPO_4, 2 mL 10% KH_2PO_4, 150 µL 5% $FeCl_2$, 2% glucose solution, and 100 mL of soil extract. The soil extract was prepared by adding 77.0 g of African violet soil, 0.2 g of Na_2CO_3 and 200 mL of distilled water. The pH of the suspension was adjusted to 6.0 and then autoclaved for 1 h, after which 100 mL of the extract was obtained by filtering the suspension through a sterilized Whatman filter paper #1. In certain cases, 10% sucrose (i.e. 100 mL of total 1,000 mL nutrient solution) was added to enhance EPS production. Optical density (OD) measurements at 520 nm were made as a function of time to assess growth of bacteria and EPS. A calibration curve was developed to relate OD data to a known concentration of hyaluronic acid, which is used as an indicator of EPS (Blumenkrantz and Asboe-Hansen 1973). Solutions of varying EPS concentration were obtained by preparing and growing solutions for different lengths of time, up to 12 days. The EPS and nutrient solution were then used as the molding moisture content for compacted samples, discussed as follows.

Earthen barrier materials generally fall into two categories, locally-available fine-grained soils which have a low hydraulic conductivity, or coarser sands and silts which have to be amended with an expansive clay such as bentonite. With this in mind, two types of material were used in this research, a locally available expansive soil known as “Red Bull Tallow” (RBT) and a mixture of sand and bentonite. Samples of RBT were obtained from a construction site northeast of Charlotte, NC. Intermittent deposits of RBT exist throughout the region where its undesirable shrink/swell and strength properties are well-known locally. While unsuitable as a foundation soil, the low-permeability aspect of RBT makes it an ideal barrier material. The RBT had a natural in situ moisture content of 20%, and it was subsequently air dried and ground to obtain a homogeneous mixture for laboratory evaluation. The RBT classifies as a CL (lean clay) according to the Unified Soil Classification System. The other barrier material selected was a mixture of 65% sand and 35% bentonite, by weight (65-35 mix). The sand was obtained from Humboldt, Inc., given as density sand with the gradation defined between the #20 (0.85 mm) and #30 (0.60 mm) sieve sizes while the bentonite was obtained from the Texas Sodium Bentonite, Inc. The liquid limit, plasticity index, specific surface area (BET-N_2 Adsorption), optimum moisture content, specific gravity, coefficient of concavity and coefficient of uniformity are provided in Table 1.

The optimum moisture content was determined with both the Harvard Miniature (HM) device (Bowles 1992) and by Standard Proctor Effort, ASTM D698 (ASTM 2000a) as the former was to prepare samples for unconfined compression testing while the latter was used to prepare samples used in consolidation. The HM device has a spring loaded tamper, which was applied ten times for each of three layers. The resulting specimen dimension was 3.3 cm in diameter and 7.2 cm in length. Samples for consolidation testing were extracted from that which was compacted in the Proctor mold with a cutting ring and cut so that the specimen dimensions were 6.4 cm in diameter and 2.3 cm in height. In both cases, the optimum moisture content was determined using water alone, and applied to mixes which used the nutrient and/or nutrient + EPS solution. While there are slight differences in the moisture density relationship obtained from using water alone as compared to nutrient/EPS solution, this was neglected herein. In soil specimens mixed with similar nutrient and EPS solutions, Dennis and Turner (1998) note that there is essentially no difference as compared to water alone. Moreover, in the work performed herein, no obvious differences in workability during sample mixing and preparation were observed. In general, samples were prepared by mixing the appropriate amount of soil and molding liquid (water, nutrient solution, or nutrient solution + EPS), allowing hydration for 24 h and then compacting at a moisture content of approximately 1% post-optimum. The solutions used, expressed in terms of initial aqueous concentrations and subsequent solid phase concentrations upon compaction, are provided in Table 2 for RBT and 65-35. Solid phase concentrations vary somewhat between the RBT and 65-35 mixes because of the difference in molding moisture content.

Table 1 Barrier materials evaluated

Material	LL (%)	PI (%)	Specific surface area (m^2/g)	ω_{opt} (%)		$\gamma_{d(max)}$ (g/cm^3)		G_s	Coefficient of concavity	Coefficient of uniformity
				SP	HM	SP	HM			
RBT	30	14	2.61	15.5	12.0	1.74	2.33	2.71	0.18	62.5
65-35	40	24	10.10	16	12.3	1.73	2.36	2.60	0.27	13.3

Note: SP – standard proctor, HM – harvard miniature.

Table 2 Aqueous and solid phase concentrations of EPS tested

Solution ID	Initial solution concentration (mg/L)	Solid phase concentration (mg/kg)			
		Consolidation tests		Unconfined compression	
		RBT	65:35 Mix	RBT	65:35 Mix
TW	0	0	0	0	0
NS	0	0	0	0	0
EPS-1	11.6	1.9	2.0	1.5	1.6
EPS-2	51.7	8.5	8.8	6.7	7.0
EPS-3	79.9	13.2	13.6	10.4	10.7
EPS-4	112.0	18.5	19.0	14.6	15.1
EPS-5	300.0	49.6	50.9	39.0	40.5

One dimensional consolidation tests were performed using lever-arm type consolidometers in accordance with ASTM D2435 (ASTM 2000b). Specimens for the consolidation test were obtained by pressing the consolidation ring into a previously compacted mass of soil. The consolidation ring had a diameter of 6.37 cm and a height of 2.27 cm. The loading sequence consisted of pressures of 30.8, 61.6, 123.1, 246.2 and 492.5 kPa while rebound was measured with two load decrements, from 492.5 to 246.2 kPa and 246.2 to 123.1 kPa. Each load increment and decrement was completed in 24 h. Unconfined compression tests were conducted following ASTM D2166 (ASTM 2000c). Three tests were conducted for each material (RBT or 65-35 Mix) and molding moisture source (distilled water or nutrient solution + EPS). The shear rate for conducting all the experiments was kept constant at 0.3175 mm/min.

4 Results and Discussion

4.1 Consolidation

Compression and swelling indices are tabulated in Table 3, while Tables 4 and 5 summarize the coefficients of consolidation. The relationship between void ratio and effective stress is given in Figs. 1 and 2. Note that while all specimens were prepared with the same level of energy (Standard Proctor Effort), the initial void ratio was different for each sample. This difference in initial void ratio is attributed to the different molding moisture composition – i.e., tap water, nutrient solution and EPS levels 1–5 as shown in Table 2. The overall compressibility of these soils is very low, with the compression index (C_c) not exceeding 0.295 for all samples tested. These low values reflect the remolded and compacted nature of the material, in contrast with naturally occurring soils that would tend to have higher compression indices. For example, use of correlations based on natural soils that relate liquid limit (Terzaghi and Peck 1967) or plasticity index (Wroth and Wood

Table 3 Summary of consolidation test data

Solution ID	Compression index, C_c (31–123 kPa)		Compression index, C_c (123–493 kPa)		Swelling index, C_s (493–123 kPa)	
	RBT	65:35 Mix	RBT	65:35 Mix	RBT	65:35 Mix
TW	0.063	0.104	0.128	0.165	0.018	0.019
NS	0.157	0.142	0.252	0.222	0.040	0.029
EPS-1	0.101	0.087	0.171	0.151	0.012	0.023
EPS-2	0.122	0.091	0.169	0.160	0.018	0.026
EPS-3	0.071	0.155	0.145	0.195	0.016	0.021
EPS-4	0.149	0.062	0.214	0.178	0.024	0.024
EPS-5	0.131	0.095	0.207	0.295	0.015	0.006

Table 4 Coefficient of consolidation data – RBT

Solution ID	Coefficient of consolidation (c_v) (m^2/year) Load 1 30.8 kPa	Load 2 61.6 kPa	Load 3 123 kPa	Load 4 246 kPa	Load 5 493 kPa
TW	8.2	6.1	5.8	3.8	3.0
NS	7.2	13.6	6.5	2.5	2.2
EPS-1	5.9	2.6	6.2	2.7	9.6
EPS-2	8.5	10.9	2.9	1.4	0.8
EPS-3	7.8	11.8	5.4	12.4	4.2
EPS-4	8.6	7.0	7.9	7.8	2.9
EPS-5	4.0	9.4	1.8	0.4	11.0

Table 5 Coefficient of consolidation data – 65:35 Mix

Solution ID	Coefficient of consolidation (c_v) (m^2/year) Load 1 30.8 kPa	Load 2 61.6 kPa	Load 3 123 kPa	Load 4 246 kPa	Load 5 493 kPa
TW	5.1	6.0	4.9	4.9	5.5
NS	8.4	10.3	3.1	1.6	2.3
EPS-1	9.5	7.4	6.7	11.2	7.2
EPS-2	6.6	19.3	6.1	0.5	1.6
EPS-3	8.5	10.9	5.7	5.1	6.9
EPS-4	13.4	16.2	3.1	3.2	5.7
EPS-5	8.9	8.4	5.2	0.2	8.7

1978; Kulhawy and Mayne 1990) to C_c would predict values several times larger than measured for the unmodified RBT and 65:35 mix. While remolded samples such as those tested do not exhibit clearly defined preconsolidation pressures, there is a change in C_c as a function of applied load. In particular, C_c for RBT ranged from 0.063 to 0.157 when loaded from 31 to 123 kPa. This range increased to 0.128 to 0.252 for the load increment between 123 and 495 kPa. Similarly, C_c for the 65:35 mix ranged from 0.062 to 0.155 when loaded from 31 to 123 kPa, while the range increased to 0.151 to 0.295 for the load increment between 123

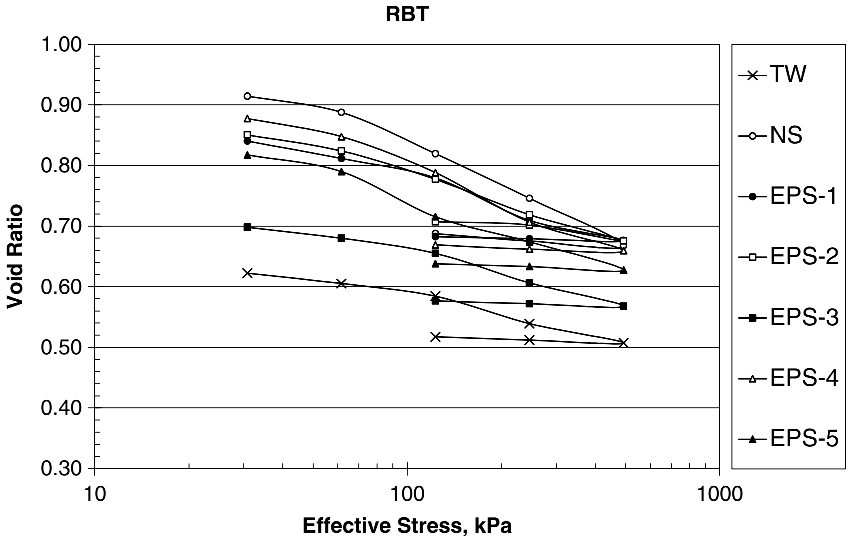

Fig. 1 Consolidation curves – RBT

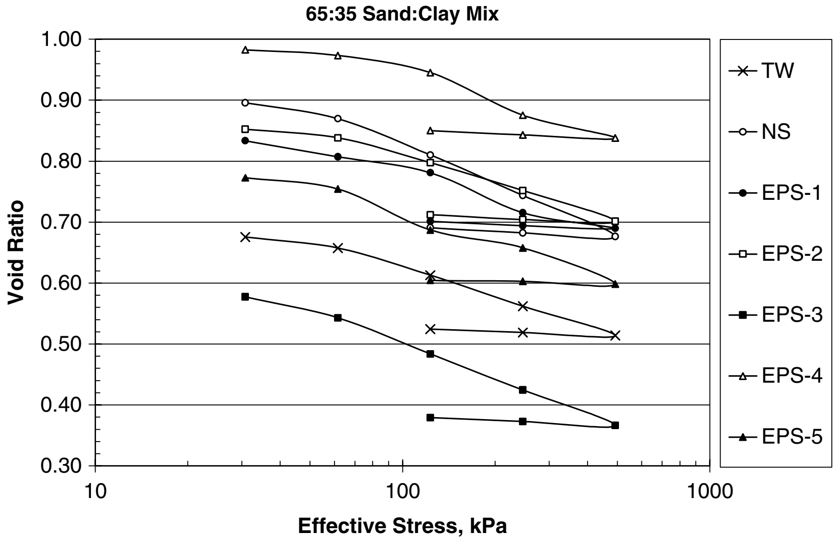

Fig. 2 Consolidation curves – 65:35 mix

and 495 kPa. As compared to tap water, the influence of the nutrient solution or biofilm on RBT is to increase the C_c, although this trend is variable for increasing EPS concentration. While the effect of biofilm on the 65:35 mix is less uniform, the largest increase in C_c was observed for the highest level of biofilm amendment

(EPS-5). In terms of the swelling index, observed values were generally less than the compression index by a factor of 10, which is typical for a variety of soils (Winterkorn and Fang 1975). The influence of biofilm on swelling is modest but consistent for both soils tested. While the extent to which changes in indices reflect natural variability instead of biofilm amendment is not certain, the overall tendency is toward increasing compressibility.

Amendment with biofilm results in both increases and decreases in the rate of consolidation. As shown in Table 4, the c_v values ranged from 0.4 to 13.6 m^2/year and from 0.2 to 19.3 m^2/year for RBT and 65:35 mix, respectively. By way comparison to natural clays, a particular study found that the range for montmorillonite, illite and kaolinite was 0.019 to 0.095, 0.095 to 0.757 and 3.78 to 28.38 m^2/year, respectively (Cornell University 1950; Mitchell and Soga 2005). As such, the values obtained herein are comparable to low plasticity clays. Based on correlations between the liquid limit and c_v, as published by the U.S. Navy (NAVFAC 1982), the unmodified RBT approaches the upper limit for completely remolded samples while the 65:35 mix exceeds this limit, suggesting behavior closer to an undisturbed sample. For both RBT and the 65:35 mix, the lowest c_v values were observed for the highest level of biofilm amendment (EPS-5). Since c_v values are directly proportional to hydraulic conductivity, this would imply that high values of biofilm amendment result in lower permeability. In fact, a negative exponential relationship was observed between hydraulic conductivity and biofilm concentration for the same combinations of soil, nutrient solution and bacteria when tested in flexible wall permeameters, as reported in Daniels and Cherukuri (2005). A complicating factor affecting all consolidation data is the extent to which bacteria continued to synthesize EPS during the several weeks over which the incremental loading and unloading was applied. Given that the soil specimens remained saturated with the same nutrient solution in which the bacteria were grown, it is possible that actual concentrations of EPS were greater than reported in Table 2. The kinetics of this growth is not sufficiently characterized to allow extrapolation, nor was any attempt made to determine actual concentrations at the conclusion of the consolidation test. It is also possible that EPS concentrations decreased during the course of the consolidation testing, as EPS is known to be subject to a variety of biotic and abiotic degradation processes (Wingender et al. 1999), and no attempts were made to limit bacterial activity to the source *B. indica*. While it is not clear whether EPS concentrations increased, decreased or remained constant during individual tests, the presumption is that the trend is similar for the different EPS solutions – such that the specimens remain comparable on the basis of initial EPS concentration. Continued EPS production in a compacted matrix of soil is such that intermittent micro-zones of EPS are possible. For example, Vandevivere and Baveye (1992) observed clusters of bacteria and EPS, separated by vast swaths of inactivity in columns of sand. The net effect of these micro-zones would be to introduce greater heterogeneity into the soil specimens.

4.2 Unconfined Compressive Strength

The maximum unconfined compressive strength, initial tangent modulus and secant modulus at 50% of the peak strength are provided in Table 6. Figure 3 illustrates the general decreasing effect of EPS concentration on observed strength. For example, the peak unconfined compressive strengths for unmodified RBT and 65:35 mix were found to be 667.0 and 395.3 kPa, respectively. Notwithstanding significant standard deviations, many of these values generally decreased with increasing biofilm amendment, and for EPS-5, the observed peak strengths were 159.1 and

Table 6 Summary comparison of strength and moduli

Solution ID	Peak unconfined compressive strength (kPa)		Initial tangent modulus (MPa)		Secant modulus at 50% maximum load (MPa)	
	RBT	65:35 Mix	RBT	65:35 Mix	RBT	65:35 Mix
TW	667.0 ± 9.9	395.3 ± 53.7	24.3 ± 0.2	15.2 ± 3.2	17.6 ± 0.8	11.0 ± 3.1
NS	615.9 ± 59.8	255.7 ± 68.4	3.8 ± 1.3	4.8 ± 0.7	7.0 ± 1.7	4.2 ± 0.9
EPS-1	615.4 ± 53.4	386.2 ± 35.4	3.8 ± 1.7	8.2 ± 1.5	7.4 ± 0.2	6.6 ± 0.5
EPS-2	585.4 ± 157.5	158.1 ± 67.3	5.5 ± 3.1	9.4 ± 8.7	9.6 ± 3.4	13.8 ± 9.9
EPS-3	561.6 ± 75.8	368.2 ± 13.3	7.8 ± 2.6	15.9 ± 2.6	13.1 ± 4.9	17.9 ± 5.6
EPS-4	663.8 ± 47.1	264.9 ± 28.9	37.2 ± 4.1	6.7 ± 2.0	59.0 ± 21.3	5.7 ± 3.0
EPS-5	159.1 ± 78.3	98.8 ± 27.4	4.4 ± 1.4	4.2 ± 1.6	3.6 ± 0.8	3.1 ± 0.6

Note: Values are reported as the average, plus or minus one standard deviation.

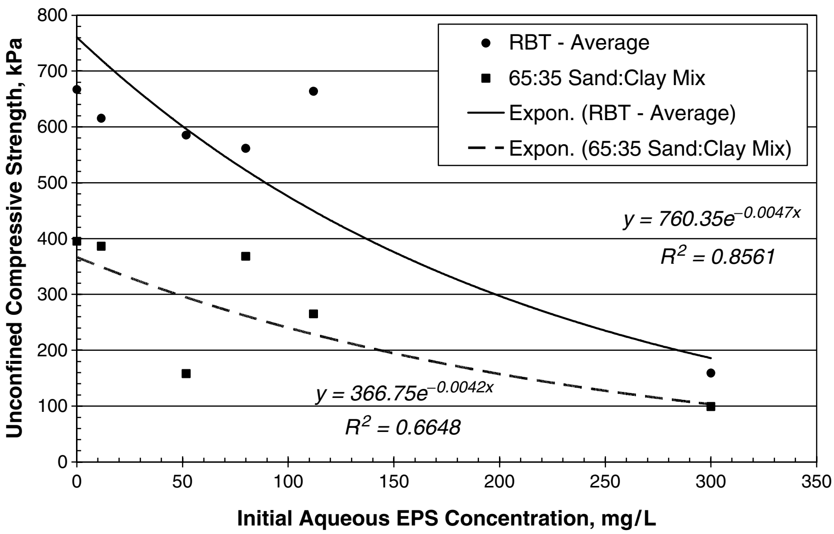

Fig. 3 Unconfined compressive strength as a function of initial EPS concentration

98.8 kPa. Likewise, the material becomes less stiff as observed from the initial tangent and secant modulus. The initial tangent moduli for RBT and 65:35 mix were found to be 24.3 and 15.2 MPa, respectively. For EPS-5, the corresponding moduli were 4.4 and 4.2 MPa, respectively. However, a closer inspection of the data suggests a more complicated relationship between biofilm amendment and strength or stiffness. In the case of RBT, increasing modification with EPS decreased the measured strength until EPS-4 (112 mg/L), at which point the strength was essentially the same as the unmodified soil (663.8 vs. 667.0 kPa) while the stiffness was even greater (37.2 vs. 24.3 MPa). Interestingly, this spike in strength is preceded by a modest but steady increase in initial tangent and secant modulus. Considering that the initial tangent modulus dropped from 24.3 to 3.8 MPa when mixed with the nutrient solution alone (which contains no bacteria or EPS), it might be argued that subsequent increases in stiffness (i.e., 3.8, 5.5, 7.8 and 37.2 MPa for EPS-1, EPS-2, EPS-3 and EPS-4, respectively) reflect the presence of EPS. These increases continue until EPS-5, where the initial tangent modulus is reduced to 4.4 MPa. One explanation is that low dosages of EPS results in particle binding up to some threshold value. Particle binding manifests when the polymers attach to multiple particles and prevent their relative movement, as discussed in Daniels and Inyang (2004). According to this model, strength is derived from both the interparticle friction and the apparent cohesion created by the polymeric bridging. As EPS concentration increases (i.e., to 300 mg/L as in EPS-5), it may well be that polymers cover entire particle surfaces. At this point, there is less resistance to particle movement as EPS has an inherently lower coefficient of friction as compared to soil. Similar behavior is observed with the 65:35 mix, although the noticeable peak in moduli occurred at the EPS-3 level, where the material was more stiff than the unmodified soil.

5 Significance of Biofilm in Waste Containment Systems

The foregoing results suggest that, at the least, biofilm production influences barrier material characteristics in general and strength in particular. Most of the effort, as reflected through both literature and regulations, given to the design and analysis of landfills has been directed toward minimizing impacts on groundwater quality through infiltration and leachate escape. However, system stability is also critical to landfill performance and yet has received relatively less attention, despite several significant failures (Qian et al. 2002). Landfills are susceptible to a number of different rotational, translational and sliding failure modes, including base failure of native soils as well as failure through the waste matrix itself. Within a multilayer cover system, there are several surfaces across which gravitational shear stresses must be transferred. While the critical interface in any given landfill system may vary considering the number of geosynthetic products on the market, different soil types and acceptable configurations, common interfaces of concern are those between a geosynthetic (i.e., geomembrane, geotextile, or geonet) and clay as well as between geosynthetics (e.g., between a geomembrane and a geosynthetic clay liner).

For materials such as compacted clay and geosynthetic clay liners used in cover systems, consideration of both internal and interface shear resistance is important. Because the mechanisms of strength in cover systems are unique and sensitive to slight changes in product specification and loading, the use of literature values for shear and interface strength is completely inappropriate (Qian et al. 2002; Koerner 1997). As such, current design practice involves laboratory testing of the proposed materials under anticipated loads to determine the requisite design parameters. Likewise, it is suggested herein that the initial design strength at construction may change after methane exposure and/or biofilm production. Site-specific field measurements of methane concentrations may help to identify the extent to which these changes are significant.

6 Conclusions

The results of this study suggest that biofilm amendment can influence the consolidation and strength characteristics of barrier materials. Specifically, modification with a mixture of nutrient solution, *B. indica* and EPS results in both increases and decreases in compression index and coefficient of consolidation for a local soil (RBT) and a 65:35 mixture of sand and bentonite clay. As compared to tap water, the influence of the nutrient solution or biofilm on RBT is to increase C_c, although this trend is variable for increasing EPS concentration. While the effect of biofilm on the 65:35 mix is less uniform, the largest increase in C_c was observed for the highest level of biofilm amendment (EPS-5, 300 mg/L). Amendment with biofilm results in both increases and decreases in c_v. The c_v values ranged from 0.4 to 13.6 m^2/year and from 0.2 to 19.3 m^2/year for RBT and 65:35 mix, respectively.

In general, EPS has a decreasing effect on observed strength. For example, the peak unconfined compressive strengths for unmodified RBT and 65:35 mix were found to be 667.0 and 395.3 kPa, respectively. Many of these values decreased with increasing biofilm amendment, and for the highest level of amendment, the observed peak strengths were 159.1 and 98.8 kPa. The relationship between EPS concentration and consolidation characteristics may be influenced by bacterial growth or decay which can occur with the time of testing. In terms of strength, the overall influence of EPS is one of weakening the peak strength, while intermediate increases in initial tangent and secant modulus were observed. Subsequent investigation of EPS on soil properties should involve efforts to distinguish between the nutrient solution, bacteria and EPS. To the extent that naturally-occurring methanotrophic activity in landfill cover systems results in biofilm production, the results suggest potential concerns with cover stability, given the observed strength reductions. As such, while biofilm has potential as a low-cost additive for soil stabilization, more work remains before it can be reliably deployed in that capacity.

Acknowledgements This research was supported by University of North Carolina at Charlotte and Duke Energy. Special thanks are given to Dr. James Oliver, Cone Distinguished Professor of Biology and his students Maya Dougler and Tonya Bates for their microbiological work.

References

Allison, L.E. (1947) Effect of microorganisms on permeability of soil under prolonged submergence. *Soil Science*, 63, 439–450.

ASTM (2000a) Standard test methods for laboratory compaction characteristics of soil using standard effort (12,400 t-lbf/ft^3) American Society for Testing of Materials, D698, Philadelphia, PA.

ASTM (2000b) D2435 Standard test method for one-dimensional consolidation properties of soils. American Society for Testing of Materials, Philadelphia, PA.

ASTM (2000c) D2166 Standard test method for unconfined compressive strength of cohesive soil. American Society for Testing of Materials, Philadelphia, PA.

ATCC (2002) American Type Culture Collection, growth instructions accompanying ATCC strain #9038.

Blumenkrantz, N. and Asboe-Hansen, G. (1973) New method for quantitative determination of uronic acids. *Analytical Biochemistry*, 54, 484–489.

Borjesson, G., Sundh, I., Tunlid, A., Frostegard, A., and Svensson, B.H. (1998a) Microbial oxidation of CH_4 at high partial pressures in an organic landfill cover soil under different moisture regimes. *FEMS Microbiology Ecology* 26, 207–217.

Borjesson, G., Sundh, I., Tunlid, A., and Svensson, B.H. (1998b) Methane oxidation in landfill cover soils, as revealed by potential oxidation measurements and phospholipid fatty acid analyses. *Soil Biology and Biochemistry*, 30(10/11), 1423–1433.

Bowles, J.E. (1992) *Engineering Properties of Soils and Their Measurement*, 4th edition, McGraw-Hill, Boston, MA.

Brune, M., Ramke, H.G., Collins, H.J., and Hanert, H.H. (1991) Incrustation processes in drainage systems of sanitary landfills. *Proceedings, Sardinia'91, 3rd International Landfill Symposium*, Cagliari, Italy, pp. 999–1035.

Clement, T.P., Hooker, B.S., and Skeen, R.S. (1996) Macroscopic models for predicting changes in saturated porous media properties caused by microbial growth. *Ground Water*, September–October, 934–942.

Cornell University (1950) Final Report, Soil Solidification Research Cornell University, Ithaca, NY.

Costerton, J.W., Geesey, G.G., and Cheng, K-J. (1978) How bacteria stick. *Scientific American* 238, 86–95.

Daniels, J.L. and Cherukuri, R. (2005) Influence of biofilm on barrier material performance. *ASCE Practice Periodical of Hazardous, Toxic and Radioactive Waste Management*, 9(4), 245–252.

Daniels, J.L. and Inyang, H.I. (2004) Contaminant barrier material textural response to interaction with aqueous polymers. *ASCE Journal of Materials in Civil Engineering*, 16(3), 265–275.

Daniels, J.L., Inyang, H.I., and Kurup, P. (2002) The influence of dissolved polymers on the properties of earthen barriers used in waste containment applications. In W.-P. Hong (Ed.), *Proceedings of the 6th International Symposium on Environmental Geotechnology and Global Sustainable Development*. Seoul, Korea, July 2–5, pp. 363–370. *Environmental Geotechnology*, Nanjing, PR China, pp. 326–333.

Daniels, J.L., Inyang, H.I., and Iskandar, I. (2003) Durability of Boston blue clay in waste containment applications. *ASCE Journal of Materials in Civil Engineering*, 15(2), 144–152.

Daniels, J.L., Cherukuri, R., Hilger, H.A., Oliver, J.D., and Bin, S. (2005) Engineering behavior of biofilm amended earthen barriers used in waste containment. *Management of Environmental Quality, An International Journal*, 16(6), 691–704.

Dennis, M.L. and Turner, J.P. (1998) Hydraulic conductivity of compacted soil treated with biofilm. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, 124, 120–127.

Gibson, D.T. (1999) Beijerinckia sp strain B1: A strain by any other name… *Journal of Industrial Microbiology and Biotechnology*, 23, 284–293.

Hart, R.T., Fekete, T., and Flock, D.L. (1960) The plugging effect of bacteria in sandstone systems. *Canadian Mining and Metallurgical Bulletin*, 53, 495–501.

Hilger, H.A. and Barlaz, M.A. (2000) Methane oxidation and microbial exopolymer production in landfill cover soil. *Soil Biology and Biochemistry*, 32, 457–467.

Hilger, H.A., Liehr, S.K., and Barlaz, M.A. (1999) Exopolysaccharide control of methane oxidation in landfill cover soil. *ASCE Journal of Environmental Engineering*, 125, 1113–1123.

Kightley, D., Nedwell, D.B., and Cooper, M. (1995) Capacity for methane oxidation in landfill cover soils measured in laboratory-scale soil microcosms. *Applied and Environmental Microbiology*, 61(2), 592–601.

Koerner, R.M. (1997) *Designing with Geosynthetics*, 4th edition, Prentice Hall, Upper Saddle River, NJ, 761 p.

Kulhawy, F.H. and Mayne, P.W. (1990) Manual on Estimating Soil Properties for Foundation Design, Final Report, Project 1493–6, EL-6800, Electric Power Research Institute, Palo Alto, CA.

Mitchell, R. and Nevo, Z. (1964) Effect of bacterial polysaccharide accumulation on infiltration of water through sand. *Applied Microbiology*, 12(3), 219–223.

Mitchell, J.K. and Soga, K. (2005) *Fundamentals of Soil Behavior*, 3rd edition, Wiley, New York.

Mitchell, J.K., Seed, R.B., and Seed, H.B. (1990) Kettleman Hills waste landfill slope failure. I. Liner-system properties. *ASCE Journal of Geotechnical Engineering*, 116(4), 647–668.

NAVFAC (1982) Soil Mechanics, DM 7.1, Naval Facilities Engineering Command, Alexandria, VA.

Okubo, T. and Matsumoto, J. (1979) Effect of infiltration rate on biological clogging and water quality changes during artificial recharge. *Water Resources Research*, 15, 1536–1542.

Okubo, T. and Matsumoto, J. (1983) Biological clogging of sand and changes of organic constituents during artificial recharge. *Water Resources Research*, 17, 813–821.

Qian, X., Koerner, R.M., and Gray, D.H. (2002) *Geotechnical Aspects of Landfill Design and Construction*, Prentice Hall, Upper Saddle River, NJ, 717 p.

Rowe, R.K., Armstrong, M.D., and Cullimore, D.R. (1998) Effect of particle size on the rate of clogging of a granular media using municipal solid waste leachate. Research Report, Geotechnical Research Center, University of Western Ontario, Ontario, Canada.

Seed, R.B., Mitchell, J.K., and Seed, H.B. (1990) Kettleman Hills waste landfill slope failure. II. Stability analysis. *ASCE Journal of Geotechnical Engineering*, 116(4), 669–690.

Shaw, J.C., Bramhill, B., Wardlaw, N.N., and Costerton, J.W. (1985) Bacterial fouling in a model core system. *Applied Environmental Microbiology*, 49, 693–701.

Taylor, S.W. and Jaffe, P.R. (1990) Biofilm growth and the related changes in the physical properties of a prorous medium. 2. Permeability. *Water Resources Research*, 26(9), 2161–2169.

Terzaghi, K. and Peck, R.B. 1967. *Soil Mechanics in Engineering Practice*, 2nd edition, Wiley, New York, 729 pp.

Vandevivere, P. and Baveye, P. (1992) Relationship between transport of bacteria and their clogging efficiency in sand columns. *Applied Environmental Microbiology*, 58, 2523–2530.

Wingender, J., Neu, T.R., and Flemming, H-C. (1999) What are bacterial extracellular polymeric substances? In J. Wingender et al. (Eds.), *Microbial Extracellular Polymeric Substances: Characterization, Structure, and Function*. Springer, Berlin/Heidelberg, Germany.

Winterkorn, H.F. and Fang, H.Y. 1975. Soil technology and engineering properties of soils, In H.F. Winterkorn and H.Y. Fang (Eds.), *Foundation Engineering Handbook (Chapter 2)*. Van Nostrand Reinhold, New York, pp. 67–120.

Wise, M.G., McArthur, J.V., and Shimkets, L.J. (1999) Methanotroph diversity in landfill soil: Isolation of novel type I and type II methanotrophs whose presence was suggested by culture-independent 16S ribosomal DNA analysis. *Applied and Environmental Microbiology*, 65(11), 4887–4897.

Wood, W.W. and Bassett. R.L. (1975) Water quality changes related to the development of anaerobic conditions during artificial recharge. *Water Resources Research*, 11, 553–558.

Wroth, C.P. and Wood, D.M. 1978. The correlation of index properties with some basic engineering properties of soils, *Canadian Geotechnical Journal*, 15(2), 137–145.

Wu, J., Gui, S., Stahl, P., and Zhang, R. (1997) Experimental study on the reduction of soil hydraulic conductivity by enhanced biomass growth. *Soil Science*, 162(10), 741–748.

Yang, I.C.-Y., Li, Y., Park, J.K., and Yen, T.F. (1993) The use of slime-forming bacteria to enhance the strength of the soil matrix. In E.T. Premuzic and A. Woodhead (Eds.) *Microbial Enhanced Oil Recovery – Recent Advances*. Elsevier, Amsterdam, pp. 89–96.

Yen, T.F., Yang, I.C.-Y., Karimi, S., and Martin, G.R. (1996) Biopolymers for geotechnical applications. Proceedings of the North American Water and Environment Congress, ASCE, 6 p.