Geotechnical Properties of Paper Mill Sludges for Use in Landfill Covers

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Abstract: This study investigates the geotechnical properties of seven paper mill sludges. Paper mill sludges have a high water content and a high degree of compressibility and behave like a highly organic soil. Consolidation tests reveal a large reduction in void ratio and high strain values that are expected due to the high compressibility. Triaxial shear-strength tests conducted on remolded and undisturbed samples showed variations in the strength parameters resulting from the differences in sludge composition (i.e., water content and organic content). Laboratory permeability tests conducted on in-situ specimens either met the regulatory requirement for the permeability of a landfill cover or were very close. With time, consolidation and dewatering of the paper sludge improved the permeability of cover. Freezing and thawing cycles increased the sludge permeability about one to two orders of magnitude. Maximum permeability changes occurred within 10 freeze and thaw cycles.

INTRODUCTION

The elevating cost of waste disposal may be reduced by the use of unconventional material in the construction of landfills. The high price of disposal has sparked interest in the development of alternative uses for waste sludges (paper mill sludges and water treatment plant sludges). Paper mill sludges, in spite of high water contents and low solid contents in comparison to clays, can be compacted to a low permeability and have been used to cap landfills in Wisconsin and Massachusetts (Stoffel and Ham 1979; Pipin 1984; Zimmie et al. 1995).

The National Council of the Paper Industry for Air and Stream Improvement Inc. (NCASI) is conducting research on the use of paper mill sludges as a cover material for landfills (''Field'' 1990; Swann 1991). Early reports for four landfill cover test cells have indicated that the sludge may perform as an effective hydraulic barrier. A similar study is being conducted by the Erving Paper Mill in Massachusetts, in which several test cells were constructed to simulate a landfill cover in situ. The results of the Erving study support the findings of NCASI (Aloisi and Atkinson 1990). Erving paper sludge is being used as the impermeable cover material for the Hubbardston Municipal Landfill in Massachusetts to examine the use of paper sludge as an alternative capping material.

This study investigated the geotechnical properties of seven paper sludges. Atterberg limits, standard compaction tests, shear-strength tests, field density, permeability, and consolidation tests were performed. The effects of freezing and thawing on permeability were also studied.

METHOD OF SLUDGE PRODUCTION

Seven sludges were used in this study. Sludge A is a wastewater treatment plant sludge from a deinking recycling paper mill. The treatment plant receives 96% of the flow from the paper mill and 4% of the flow from the town. Sludge A has a fixed solids content of 50% and is composed of approximately 50% kaolinite and 50% organics. Sludge B is a blended sludge from a wastewater treatment plant that receives its effluent from a recycling paper mill and the neighboring community. Sludge C is a blended sludge from an integrated paper mill and is composed of kaolin clay, wood pulp, and organics. Sludge C was mined from a sludge monofill that was in operation since 1973. Samples were collected from different sections of the monofill to represent different sludge ages: one wk (C1), 2–4 yr (C2), and 10–14 yr (C3). Sludge D is a primary wastewater treatment plant sludge from a recycling paper mill. Sludge D has a fixed solids content of 55%. Sludge E is a primary wastewater treatment plant sludge from a nonintegrated paper mill that uses titanium oxide as the primary filler.

WATER CONTENT, ORGANIC CONTENT, AND SPECIFIC GRAVITY

Water content was determined according to American Society for Testing and Materials (ASTM) procedure D2974. The oven temperature was lowered from 105°C to 70°C to avoid burning off some of the organics. The range of the initial water contents of the sludges used in this study is summarized in Table 1. Water contents range from 150% to 250% for the various sludges.

Organic content tests were performed on the sludges according to ASTM procedure D2974 method C for geotechnical classification. A muffle furnace was used to burn off the organics at a temperature of 440°C. At this temperature, the organic matter is burned off, and the mineral constituent, kaolinite or titanium oxide, forms an ash. Sludges with greater organic contents are capable of higher water contents and void ratios, and will be more compressible (LaPlante 1993). This relationship was also found to be true for peats (MacFarlane 1966). The test results are summarized in Table 1.

Specific gravity tests were performed on the sludges according to ASTM procedure D854. Slight modifications were made to apply the procedure to paper sludge (LaPlante 1993). An aspirator was used to remove the entrapped air from the sample. Boiling the sample was avoided to reduce possible thermal reactions from occurring and giving poor results. The sludge samples were taken at their natural water content and

TABLE 1. Water Content, Organic Content, Specific Gravity, and Atterberg Limits

Sludge (1)	Water content (%) (2)	Organic content (%) (3)	Specific gravity (4)	Plastic limit (%) (5)	Liquid liquid (%) (6)	Plasticity index (%) (7)
A	150–250	45–50	1.88–1.96	94	285	191
B	200–250	56	1.83–1.85	147	297	150
C1	255–268	54–56	1.80–1.84	—	—	—
C2	180–200	47–49	1.90–1.93	113.5	218	104.5
C3	220–240	42–46	1.96–1.97	143	220	77
D	150–200	44	1.93–1.95	137.5	255	117.5
E	150–200	35–40	1.96–2.08	—	—	—

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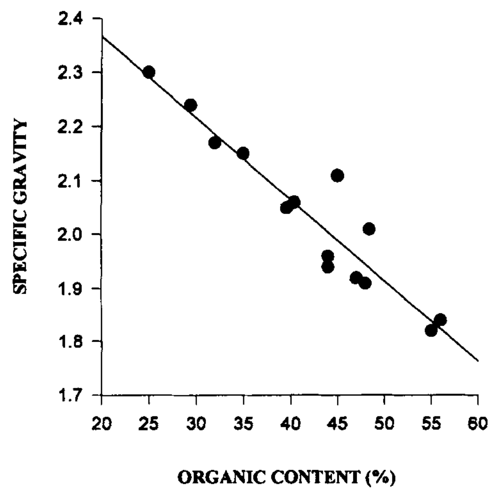

FIG. 1. Specific Gravity and Organic Content Relationship for Paper Sludges

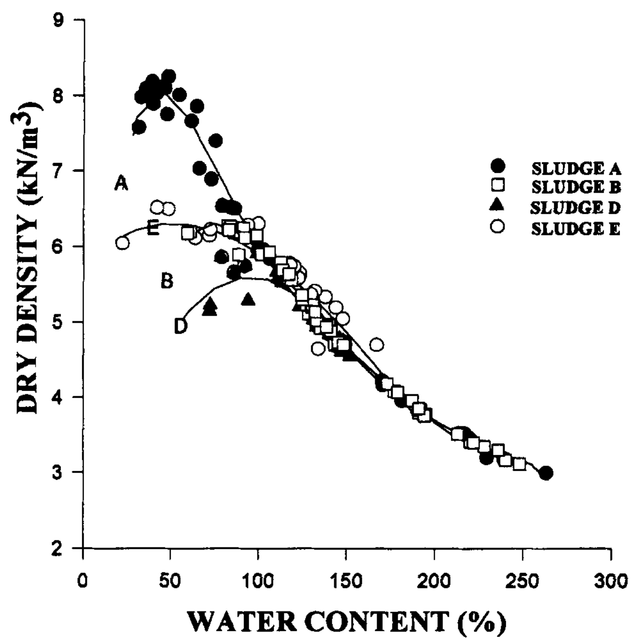

FIG. 2. Proctor Curves for Various Sludges

soaked in water for an hour before pulverization, since, upon drying, the sludge samples formed flocs, developed a coarse texture, and were not easily pulverized. This behavior was noted by Wang et al. (1991) for a water plant sludge and by Feustel and Byers (1930) for various peat types. Test results are summarized in Table 1.

Examination of Table 1 reveals a direct relationship between specific gravity and organic content. Paper mill sludges containing lower percentages of organics have higher percentages of kaolinite. Since the kaolinite mineral has a specific gravity of 2.60–2.65 and the fibers are estimated to have a specific gravity of 1.5, the higher kaolinite contents in the sludge will increase the overall specific gravity. Fig. 1 shows the relationship between the specific gravity and organic content. As the organic content decreases, the specific gravity increases.

ATTERBERG LIMITS

The Atterberg limits of the sludge were determined by following the ASTM procedure D4318 for liquid limit, plastic limit, and plasticity index of soils. The results for the Atterberg limits for the various sludges are shown in Table 1. High Atterberg limits are common for water treatment sludges. Wang et al. (1991) obtained similar results for a water treatment sludge.

The plastic limit was easily determined (i.e., it behaves similar to clay); the liquid limit, on the other hand, was difficult to determine. Specimens were prepared from the wet side. When paper sludges were air dried and passed through the number 4 sieve, the sludges formed flocs, were coarse in texture, and were not easily pulverized. Upon rewetting the dry sludge, large clods formed, and the sludge did not regain its initial plasticity, which made performing the Atterberg limit tests from the dry side difficult. Paper fibers and tissues in the sludge caused problems when cutting the groove for the liquid limit test. The ASTM plastic groove tool has a tendency of catching the fibers and tissues and results in an unsatisfactory groove. The ASTM brass groove tool cuts a smoother groove and leads to more satisfactory test results (Moo-Young 1992).

COMPACTION TESTS

Proctor tests were performed following the ASTM procedure D698-78. Because of the high water content, tests were conducted from the wet side rather than from the dry side as recommended by ASTM. Furthermore, when water was added to dry sludge, large clods formed, the clods were difficult to break apart, and the sludge lost its initial plasticity. During the drying process, the sludge was passed through the number 4 sieve and placed in a pan to air dry. Many trials were conducted to reach the optimum moisture content and density.

Fig. 2 shows the Proctor curve (water contents plotted against dry densities) for the various sludges. The Proctor curves show a wide range of moisture contents on the wet-of-optimum portion of the curve and a small range of water contents on the dry-of-optimum portion of the curve. At higher water contents, the dry densities obtained from the Proctor curve for the various sludges are similar, as shown in Fig. 2. At the optimum moisture content or dry of the optimum moisture content, the sludge is dry, stiff, and unworkable. Unlike a typical clay landfill cap, a high water content, at least 100% wet of the optimum moisture content, is desirable, if the sludge is to be used as a landfill capping material (Zimmie et al. 1995). At a high water content (typically 100% wet of the optimum water content), paper sludge is compactable to low permeabilities and has sufficient shear strength for supporting traffic (Zimmie and Moo-Young 1995). Upon the completion of the cap, the sludge layer should be covered immediately (e.g., with the drainage and vegetative support layers) to protect it from desiccation and shrinkage cracks, which increase the permeability of the paper sludges. These test results compare favorably to research conducted on water treatment plant sludges (Raghu et al. 1987; "Water" 1989; Wang et al. 1991).

During the construction of the Hubbardston landfill in Hubbardston, Mass. and Erving Paper mill test plots in Erving, Mass., different types of equipment were used to place the sludge cap. Four types of equipment were used: a small ground pressure vibratory drum roller, a vibrating plate compactor, a sheepsfoot roller, and a low ground pressure track dozer. The sheepsfoot roller, which is generally used to compact a clay liner, clogged immediately due to the cohesive nature of the sludge and the high water content. The vibratory methods did not provide homogeneous mixing and did not compact the sludge effectively. The small ground pressure dozer provided the best method for placement and compaction. This equipment successfully eliminated large voids from the sludge material and kneaded the material homogeneously.

IN-FIELD DENSITY

The density of sludge A was determined in the field using three methods: sand cone method following the procedure of

TABLE 2. In-Place Density Determination

Method (1)	Wet unit weight (kN/m^3) (2)	Water content (%) (3)
(*a*) Set 1 (July 1991)		
Sand cone	12.5	97.1
Balloon	13.7	145.3
Nuclear device		
15.2 cm depth	13.3	115.6
30.5 cm depth	13.0	127.2
(*b*) Set 2 (July 1991)		
Sandcone	11.4	159.6
Balloon	13.2	145.3
Nuclear device		
15.2 cm depth	12.4	129.4
30.5 cm depth	12.8	115.3
(*c*) Set 3 (October 1991)		
Sand cone	11.3	211
	11.4	221
(*d*) Set 4 (July 1993)		
Sand cone	11.2	116
Balloon	11.7	114.1
(*e*) Set 5 (July 1993)		
Sand cone	11.2	116
Balloon	10.9	114
(*f*) Set 6 (July 1993)		
Balloon	9.83	95.1

ASTM D1556, the rubber balloon method following the procedure of ASTM D2167, and the nuclear density method that complies with ASTM Standards D2922 and D3017. The nuclear density testing method was performed by Yankee Testing of Worcester, Mass. The results are shown in Table 2. Two sand cone, rubber balloon, and nuclear density tests (Sets 1 and 2) were performed in July 1991 on the Hubbardston landfill several weeks after construction. The sand cone method (Set 3) was performed in October 1991 on another section of the landfill several weeks after construction. The sand cone and rubber balloon methods (Sets 4 and 5) were performed on two sections of the landfill in July 1993, one year after completion. A rubber balloon test (Set 6) was conducted in July 1993 on the same section of the landfill as Sets 1 and 2, two years after completion.

The in-place density determinations at the landfill correlate with laboratory compaction test results. Visual observations of the samples taken from the landfill after one year (Sets 4 and 5) and two years (Set 6) revealed that the sludge matrix was more cohesive and clayey in texture. The wet unit weight of the landfill decreased with time as shown by the reduction in the wet unit weight of Set 6 from the initial values in Sets 1 and 2. Results using the nuclear density device deviated slightly from the sand cone and rubber balloon method. The nuclear density device should be calibrated using the sand cone method and the laboratory compaction test results.

REMOLDED PERMEABILITY AND WATER CONTENT RELATIONSHIP

Permeability tests were performed on the sludges at various water contents following the procedures of ASTM D5084 for measuring the hydraulic conductivity of saturated porous material using a flexible wall permeameter. Results of permeability tests performed on paper sludge are highly dependent upon the molding water content, which is similar to results obtained for clays (LaPlante and Thomas 1989). Moo-Young (1992) performed permeability tests at a wide range of water contents for paper sludge A, with the minimum permeability

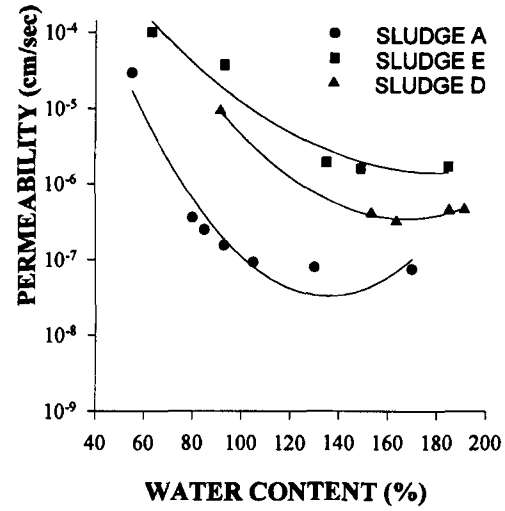

FIG. 3. Permeability versus Water Content Relationship

occurring at a water content nearly 100% wet of optimum (Fig. 3). The same relationship was obtained for sludges D and E, with minimum permeability occurring far wet of optimum (Fig. 3). Near the optimum water content, the permeability for paper sludges increases. For clays, the minimum permeability typically occurs near the optimum water content. The minimum permeability for paper sludges occurs at an initial water content that is at least 50–100% wet of the optimum water content.

The construction of a landfill cover layer using paper mill sludges near the optimum moisture content is undesirable, due to the high permeability and due to the unworkability of the material. A high water content is desirable for the construction of a landfill capping layer using paper mill sludge as the impermeable barrier layer (Zimmie et al. 1995). However, during the construction of the landfill cover, the paper sludge layer should be protected from the effects of desiccation and shrinkage cracks, which would cause an increase in the permeability of the cover system.

CONSOLIDATION TESTS

One-dimensional consolidation tests were conducted on all sludge samples following ASTM procedure D2435. Fig. 4 displays the results from typical consolidation tests run on paper sludge A at various water contents. Test results show that paper sludge is highly compressible. At higher consolidation pressures, high strain values were measured. Low strains were encountered during the first increment. Large reductions in water content and void ratio resulted from application of higher applied stresses. These results compare favorably to consolidation tests conducted on water treatment sludges (Wang et al. 1991; Raghu et al. 1987).

INFLUENCE OF WATER CONTENT ON CONSOLIDATION

The water content of paper sludge is the most useful parameter in predicting consolidation behavior. The sludge samples are assumed to be fully saturated so that the void ratio is equal to the specific gravity of the sludge multiplied by the water content. To simulate in-situ consolidation behavior, water contents were kept as close as possible to the initial value. Higher initial water contents result in higher initial void ratios, which increase the potential consolidation.

Consolidation tests were performed on sludge A at various water contents to show the highly compressible nature of the paper sludge and to establish a relationship between consoli-

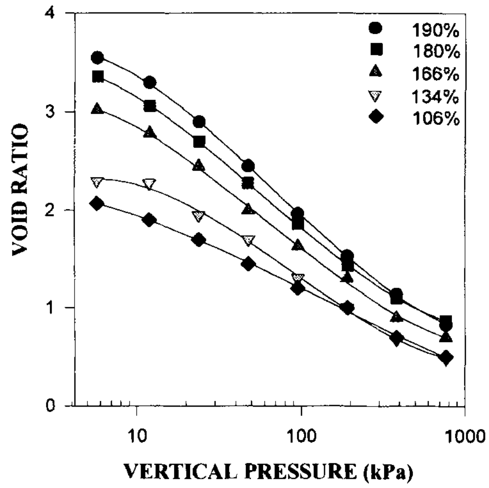

FIG. 4. Consolidation Test Results for Paper Sludge A

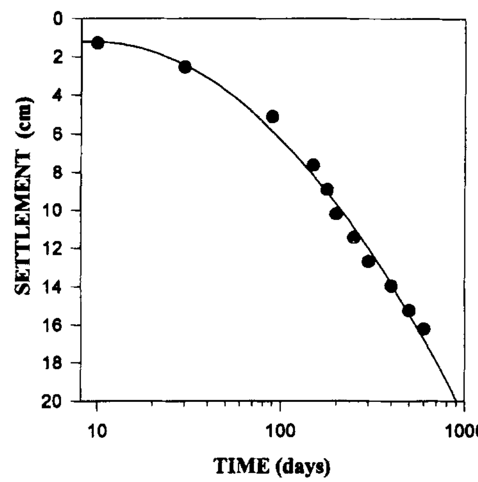

FIG. 5. Settlement Occurring in Sludge Layer at Hubbardston Landfill

dation behavior and initial water content (Fig. 4). The change in void ratio per log cycle of pressure (C_c = compression index) increases due to higher initial water contents as shown in Fig. 4. Higher initial water contents will result in higher void ratios, which account for the increasing magnitude of compression with increasing water content.

Consolidation tests were also performed on the other sludges at their natural water content. The compression index was plotted against the initial water content for the paper sludges and for water treatment sludge (Wang et al. 1991). The relationship between the compression index and water content is as follows:

$$C_c = 0.009w_o \quad (1)$$

The relationship between the compression index and void ratio is as follows:

$$C_c = 0.39e_o \quad (2)$$

Landva and LaRochelle (1983) established a relationship between compressed index and water content for peats that is similar to the one obtained for paper mill sludges.

SETTLEMENT CALCULATIONS

The Hubbardston Municipal Landfill in Hubbardston, Mass. uses sludge A as the impermeable layer of the landfill cover system. The sludge layer has a thickness of 91.4 cm and can drain freely from the top and bottom of the layer (double drainage). At the landfill, the impervious layer was overlain by a vegetative support and drainage layer with a minimum thickness of 45.7 cm (a top soil layer with a minimum thickness of 30.5 cm and a drainage layer with a minimum thickness of 15.2 cm and with a permeability equal to or greater than 1×10^{-3} cm/s). The initial water content of the sludge layer was approximately 190%. The estimated load on the landfill cover is approximately 23.9 kPa at the midheight of the sludge layer (Zimmie et al. 1995).

Four laboratory consolidation tests were performed on remolded samples of sludge A with an initial water contents ranging from 134% to 197% (Fig. 4). At a load of 23.9 kPa, an average strain of 16.5% occurred at the end of primary consolidation for the various tests. The predicted settlement was 14.9 cm. Secondary consolidation contributed an additional 3% strain, which corresponds to settlements of 17.8 cm.

The actual time settlement curve, obtained from a settlement gauge at the Hubbardston, Mass. landfill, is shown in Fig. 5. From Fig. 5, after 1 yr, the landfill cover system settled 14 cm (5.5 in.). This magnitude of settlement is similar to the estimated settlement from primary consolidation in Fig. 4. The field data gives a settlement of 16.19 cm (6.375 in.), or a strain of 17.7% after 2 yr, which is similar to the estimated settlement caused by primary and secondary consolidation (Fig. 4). The magnitude of settlement predicted from laboratory tests provided a good indication of the actual settlement behavior.

SHEAR-STRENGTH TESTS

The shear-strength behaviors of paper sludges A, B, C3, and D were determined using consolidated undrained triaxial compression tests with pore pressure measurements following ASTM procedure D4767. Two sets of tests were conducted on Sludge A. Table 3 summarizes the results. The effective angle of internal friction varied from 25° to 40°, while the effective cohesion ranged from 2.8 to 9.0 kPa.

During the consolidation phase of the triaxial tests, a large reduction in void ratio resulted due to the high compressibility of the sludge. This behavior is consistent with that observed during the consolidation testing reported previously. Moreover, the values of the pore pressure parameter A_f indicate that the sludges behaved in a similar manner to a normally consolidated clay.

Failure is difficult to determine from the stress-strain curves, which are typical of soft compressible material in that they exhibit no sharp yield point. Failure has to be arbitrarily selected at some reasonable strain. For the purpose of this study, failure is defined at 10% strain. Obviously, if failure is defined at a different strain, the strength parameters would change. The variation in shear strength for the various sludges may be attributed to the wide range of water contents, to the variations in sludge production, and to the high organic content. Moreover, differences in the amount of fibers in the sludge matrix may alter the amount of cohesion measured in the paper sludge.

In studying the stabilization of a water plant sludge from Virginia for the utilization as embankment material, Wang et al. (1991) concluded that both treated and untreated sludges were highly sensitive and thixotropic. They obtained similar results to the sludges tested in this study.

LABORATORY PERMEABILITY TESTS ON UNDISTURBED SPECIMENS

Laboratory permeability tests were conducted on undisturbed sludge A samples taken from the Hubbardston Landfill on five occasions: July 1991, October 1991, April 1992, January 1993, and July 1993. Permeability tests were performed following the procedures of ASTM D5084 for measuring the hydraulic conductivity of saturated porous material using a

TABLE 3. Summary of Shear-Strength Tests

Sludge (1)	Effective angle internal friction (φ') (2)	Effective cohesion (KPa) (3)	A_f (4)
A (test 1)	37	2.8	0.72
A (test 2)	25	9.0	0.74
B	37	5.5	0.9
C3	32	9.0	0.7
D	40	5.5	0.73

flexible wall permeameter with back pressure. Samples were tested at a low confining stress of 34.5 kPa, which is the most practical approach to simulate the worst case, that is, the highest permeability.

The best sampling procedure was discovered through trial and error using Shelby tubes. Slow static pressure (pushing the Shelby tube into the sludge layer with a constant vertical force) compressed the sludge during the sampling process and led to low recovery rates. A dynamic sampling process, like striking the Shelby tube with a hammer, resulted in high rates of recovery and minimal disturbance. Apparently, due to the fibers and tissues in the sludge matrix, a sharp blow was needed to cut through the sludge. The normal field procedure was to place the Shelby tube on the sludge, place a wood block on top of the Shelby tube, and strike the block with a hammer. This procedure resulted in the highest rates of recovery and the least disturbance (Moo-Young 1992).

Table 4 summarizes the permeability values of the samples. In general, the Shelby tube samples taken after construction of the landfill (samples 1, 2, and 4) either met the 1×10^{-7} cm/s Massachusetts regulatory requirement for landfill impermeable barriers or were very close (less than a half an order of magnitude from complying with the regulatory requirements). Examining Table 4, the water contents of the specimens taken from the landfill after construction varied from 170% to 185%.

Sample 3, taken after 9 months in situ from the same section of the landfill as sample 1, was dewatered and consolidated under a 45.7 cm (18 in.) overburden. It was markedly stiffer and denser than samples obtained shortly after construction. The permeability for the sample meets the Massachusetts regulatory requirement of 10^{-7} cm/s.

Sample 5 obtained in January 1993 was taken from the same section of the landfill as samples 1 and 3, 18 months after placement. Permeability tests on two of the Shelby tubes yielded an average permeability of 3.4×10^{-8} cm/s at a water content of 107%, which easily meets the 10^{-7} cm/s standard for landfill cover design. After 18 months of consolidation the sludge layer met the regulatory requirements. The sludge layer performs as an adequate hydraulic barrier at a water content of 107%. Sample 6 was taken after 24 month of in-situ consolidation from the same section as samples 1, 3, and 5. The permeability and water content of sample 6 were 3.8×10^{-8} cm/s and 91.5%, respectively (Table 4).

For landfill cover design, one of the common stipulations is that the cover should include an impermeable barrier layer with a permeability less than or equal to 10^{-7} cm/s (regulations do vary dependent on the state or country, and with the landfill type, that is, municipal waste or hazardous waste). Most sludges in this study do not initially meet that regulatory requirement for permeability when tested at the initial water content under a low confining stress (Moo-Young 1995; Zimmie and Moo-Young 1995). In general, most of the sludges met the 10^{-7} cm/s permeability requirement when tested at higher consolidation pressures (Moo-Young 1995). When the impermeable barrier of a landfill cover uses a paper mill sludge at the initial water content, the sludge is susceptible to large reductions in void ratio. The permeability of paper sludge is affected by the water content, organic content, and consolidation (Moo-Young 1995). As the void ratio decreases, the permeability of the sludge will be reduced. Moo-Young (1995) showed that as the organic fibers decomposed, the permeability of paper sludges decreases.

TABLE 4. Summary of Laboratory Permeabilty Tests on In-Situ Samples

Sample (1)	Permeability (cm/s) (2)	Initial water content (%) (3)
	(a) July 1991	
1	1.06×10^{-7}	170
	(b) October 1991	
2	4.0×10^{-8}	185
	(c) April 1992	
3[a]	4.5×10^{-8}	106
4	4.2×10^{-7}	170
	(d) January 1993	
5[b]	3.4×10^{-8}	107
	(e) July 1993	
6[c]	3.8×10^{-8}	91.5

[a]9 months.
[b]18 months.
[c]24 months.

Since paper sludges decrease in permeability with time, consolidation, and organic decomposition, it may be important to estimate how much consolidation will occur in the field to establish the effective stress that will estimate the long-term permeability (1–2 yr) of a paper sludge cover. The time for this reduction in permeability caused by consolidation must be short in duration for the material to be considered as a potential impermeable barrier. Short-term laboratory tests (1–2 weeks) can take consolidation effects into account but are not capable of judging long-term effects such as organic degradation. A low effective stress, usually 34.5 kPa (5 psi) or less, should be used to test the initial permeability of the sludge. Testing a paper sludge at low effective stress to measure the long-term permeability (1–2 yr later) may lead to results that may be higher than the actual long-term permeability. However, the use of excessively high effective stresses (280 kPa or higher) to estimate the long-term permeability of paper sludges may yield results that are slightly lower (Zimmie et al. 1995; LaPlante 1993). Obviously, to determine the effective stress that will yield an estimate of the long-term permeability of a paper sludge landfill cover, consolidation tests and knowledge of the configuration of the final cover system are required.

When designing a landfill cover system using paper sludge as the impermeable barrier, the sludge layer should be constructed at the initial water content. At the initial water content, the sludge may not meet the regulatory requirement for permeability of 1×10^{-7} cm/s or less. However, Zimmie and Moo-Young (1995) showed that the change in void ratio that results from the application of an overburden pressure (i.e., drainage layer and vegetative support layer) can reduce the permeability to an acceptable value.

EFFECTS OF FREEZE/THAW ON PERMEABILITY

One of the concerns in landfill design is the effect of freezing and thawing on the permeability of the cover material. A considerable amount of research has been conducted on the effects of freezing and thawing on compacted clays. The paper by Othman et al. (1995) summarizes the work on compacted clays. In general, the permeability of compacted clays increases from one to two orders of magnitude due to freezing and thawing. There is little or no information on the behavior of paper sludge due to freeze/thaw effects. Thus, two sets of freeze/thaw tests were performed on sludge A and B.

Remolded specimens that were subjected to one-dimensional freeze/thaw were made from sludge A, and specimens subjected to three-dimensional freezing and thawing were made from sludge B. All sludge A samples were molded at a water content of 170% (wet of optimum), which approximately represents the water content of the sludge after placement in the landfill cover. All sludge B samples were molded at a water content of 256.5%.

Procedure

Specimens were compacted into 10.2 cm high by 7.6 cm diameter PVC molds in three equal lifts, using six blows of a standard Proctor compaction hammer. For the method used, it was empirically (by trial and error) determined that six blows per layer would yield the proper density. For sludge A, the dry density and wet density were 4.24 kN/m^3 and 11.5 kN/m^3. For sludge B, the dry density and wet density were 3.30 and 11.75 kN/m^3. Specimens were sealed in plastic wrap and taped to prevent moisture loss.

The one-dimensional freeze/thaw process used in this study has been previously described in detail by Zimmie and LaPlante (1990) and LaPlante and Thomas (1989). Permeability tests were performed on various specimens frozen one dimensionally when 0, 1, 3, 5, 10, 15, 20, and 25 freeze/thaw cycles were reached. Permeability tests were conducted on various specimens frozen three dimensionally when 0, 1, 3, 5, 10, and 15 freeze/thaw cycles were reached. Specimens were removed from the environmental room (frozen to decrease disturbance), weighted, extruded, and placed in the triaxial permeameter.

Permeability testing followed ASTM procedure D5084 with backpressure application. Specimens were permeated under an effective stress of 34.5, 69, and 138 kPa. Due to the highly sensitive nature of the materials, a low hydraulic gradient (21) was chosen. The permeation phases of the tests were generally conducted for 2–3 d.

Results and Observations

Forty-eight permeability tests were performed on remolded sludge A samples that were subjected to a predetermined number of one-dimensional freeze/thaw cycles. Thirty-six permeability tests were performed on remolded sludge B samples that were subjected to a predetermined number of three-dimensional freeze/thaw cycles. The samples were highly compressible and decreased in moisture content from their initial value when placed under various cell pressures.

Fig. 6 shows the results of the effects of one-dimensional freezing and thawing on the permeability of sludge A at various cell pressures: 34.5, 69, and 138 kPa. There is an increase in permeability due to freeze/thaw. Significant increases in permeability occur within 10 cycles. At an effective stress of 34.5, 69, and 138 kPa, there is an increase of approximately one order of magnitude in permeability. Fig. 6 also shows the results of the effects of three-dimensional freezing and thawing on the permeability of sludge B at various cell pressures. A one to two orders-of-magnitude increase in permeability occurs within the first 10 cycles at the various cell pressures.

Fig. 7 shows the relationship for sludge A between effective stress and permeability for different freeze/thaw cycles. Since permeability is dependent on effective stress and void ratio,

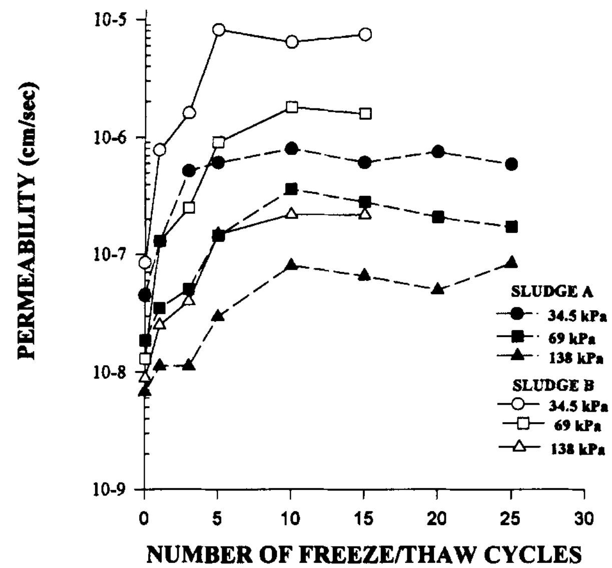

FIG. 6. Summary of Effects of Freeze/Thaw Cycles on Permeability of Paper Sludges

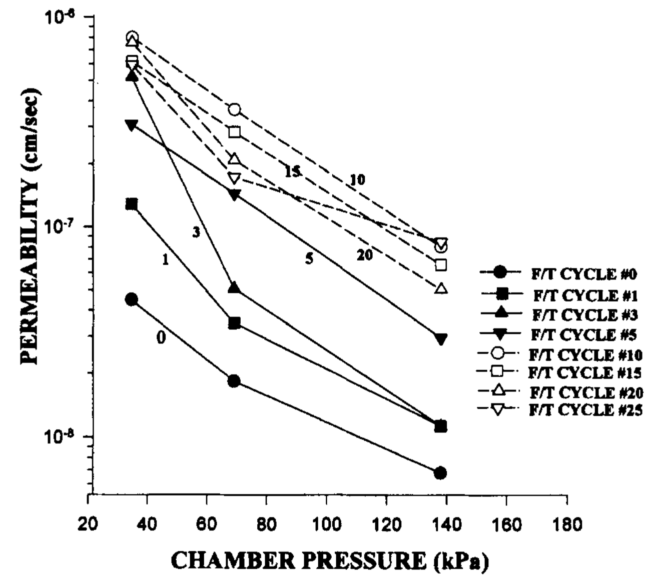

FIG. 7. Effects of Freeze/Thaw Cycling on Sludge A in Permeability versus Chamber Pressure Plane

the paper mill sludge was tested to evaluate the effects of effective stress as well as the effects of freeze/thaw on changes in permeability. In general, Fig. 7 indicates that permeability changes at low effective stresses result in similar changes in permeability as at higher effective stresses. At higher and lower effective stresses, it appears that the change in permeability is about one order of magnitude. However, these results may not be conclusive. For example, freeze/thaw cycles 10 and 15 appear to be parallel with the zero freeze/thaw cycle line, which would indicate that the change in permeability at lower effective stresses is the same as for higher effective stresses. However, freeze/thaw cycles 1 and 3 exhibit about one order of magnitude change in hydraulic conductivity at lower effective stresses and tend to decrease in permeability by one half an order of magnitude at higher effective stresses. Freeze/thaw cycles 1 and 3 display similar basic behavior to that of compacted clays. For the three-dimensional freeze/thaw study, the change in permeability at higher and lower effective stresses is similar to the results shown for sludge A. In comparison, a typical clay exhibits the largest changes in perme-

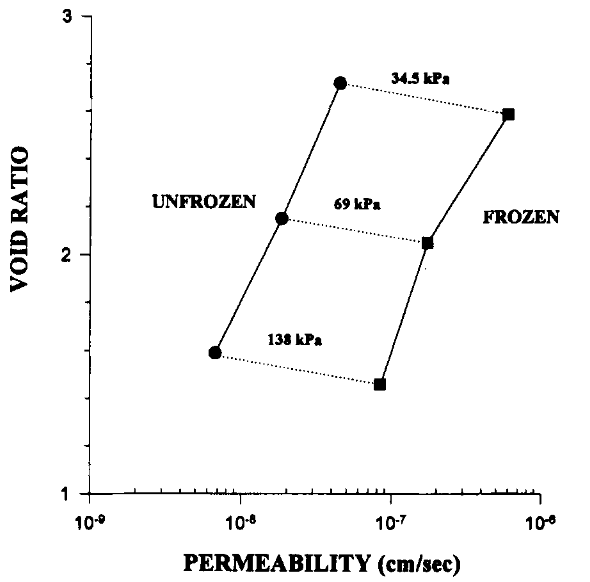

FIG. 8. Effects of Freeze/Thaw Cycling on Permeability versus Void Ratio Relationship for Paper Sludge A

ability at low effective stresses (Zimmie 1992; Benson and Othman 1991).

Fig. 8 shows the permeability versus void ratio relationship for frozen and unfrozen sludge A. At a low effective stress of 34.5 kPa, there is a 5% decrease in void ratio with an increase in permeability of one order of magnitude. The void ratio decreased by 5% at a confining stress of 69 kPa, while the permeability increased by one order of magnitude. At a high effective stress of 138 kPa, the void ratio decreased by 8%, but the increase in permeability was only one order of magnitude. Clays exhibit similar basic behavior to paper sludge in that freezing and thawing caused a considerable increase in permeability and a large reduction in void ratio (Chamberlain and Gow 1979).

The substitution of paper mill sludge for clay can reduce the cost of disposal and is an excellent alternative in areas that do not have a local source of clay. However, the low permeability sludge barrier used for the landfill cover must be protected against the effects of freezing and thawing. The placement of a higher effective stress on the landfill would further increase consolidation and reduce the natural permeability. Moreover, the placement of a larger overburden would increase protection against frost penetration.

CONCLUSION

In this study, many conclusions can be drawn about the geotechnical properties of paper sludge.

Paper mill sludges are characterized by a high water content, high compressibility, high Atterberg limits, and large amounts of organic fibers in the matrix.

Some of the test procedures developed for clays were modified when applied to paper sludge. For example, the standard Proctor compaction tests and the Atterberg limits test were conducted from the wet side.

The specific gravity of paper sludge is lower than a typical clay. As the organic content of paper sludge decreases the specific gravity increases.

Compaction tests were conducted from the wet side since paper sludge loses its plasticity upon drying and rewetting. At the optimum moisture content, paper sludge is unworkable. A high water content is desirable when designing a paper sludge landfill cover. However, drying of the paper sludge barrier should be avoided, since desiccation and shrinkage cracks will create void spaces in the sludge matrix and will increase the permeability.

The permeability of paper sludge increases as the molding water content decreases (approaches the optimum water content). The shear-strength behavior of the paper sludges is variable due to variations in organic content, fiber and tissue content, and water content. The effective angle of internal friction varied from 25° to 40° while the cohesion ranged from 2.8 to 9.0 kPa.

Shelby tube samples taken from a landfill that uses paper sludge as the hydraulic barrier indicate that paper sludge provides an effective impermeable cap. With time, the landfill cover consolidates, the water content will be greatly reduced, and the permeability of the landfill cover should easily meet the regulatory requirement.

Freezing and thawing increases the permeability of paper sludge by one order of magnitude. The change in permeability of the paper sludge due to freezing and thawing at lower effective stresses appears to be similar to that for higher effective stresses.

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