Jouko Saarela and Thomas Zimmie (Eds)

First International Workshop on the Use of Paper Industry Sludges in Environmental Geotechnology and Construction

Proceedings, 11-16 August 1997
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ACKNOWLEDGEMENTS

The First International Workshop on the Use of Paper Industry Sludges in Environmental Geotechnology and Construction was planned and organised in a very short time, and without Internet and E-mail it would not have been possible. The idea to arrange this workshop originates in discussions with prof. Thomas Zimmie during the 3rd International Symposium on Environmental Geotechnology in San Diego, U.S.A, in summer 1996. We hope that the 1997 workshop in Finland was the start for a succession of workshops on the use of paper industry sludges in environmental geotechnology and construction. The next workshop will be organised by prof. Thomas Zimmie in Rensselaer Polytechnic Institute in Troy, U.S.A., probably already in June 1998.

As for the workshop held in Finland in August 1997, I want to express my thanks to the sponsors, US National Science Foundation and the Finnish Nessling Foundation, for financing the workshop, as well as to the Finnish Environment Institute for hosting it. Likewise, I am very grateful to the enterprises connected with the workshop as documented in the programme (see page 82) and the cities of Helsinki and Espoo for their participation in the arrangements.

I greatly appreciate the work done by the organising committee and all workshop participants. In addition, I would like to thank our guide during the excursion in Estonia, Dr. Vello Karise. I also express my gratitude to Ms. Rauni Paronen for her assistance during the workshop, and Ms. Katri Salmela for finishing the layout of this publication, both from the Finnish Environment Institute.

Helsinki, 10 March, 1998

Jouko Saarela, Chairman of the workshop
INTRODUCTION

By Thomas F. Zimmie, Professor, Civil Engineering Department, Rensselaer Polytechnic Institute, Troy, Ny 12180 and Jouko Saarela, Dr.Tech., Finnish Environment Institute, Kesäkatu 6, P.O.Box 140, FIN-00251 Helsinki Finland

First International workshop on the use of paper industry sludges in Environmental Geotechnology and Construction was held at the Finnish Environment Institute in Helsinki, Finland from 11-16 August, 1997. The workshop consisted of technical presentations and discussions, and field trips in Finland and Estonia. Delegates from several countries attended. Most countries of the world produce paper. The paper manufacturing process utilizes large quantities of water, and thus the potential for water pollution is high. Prior to the strict environmental regulations, process water was often directly disposed of in an untreated state into nearby bodies of water, causing serious environmental problems. This practice is unacceptable today, and the process water is treated in water treatment plants which purify the water and remove most of the solids. These solids produced from the water treatment process are the subject of this workshop, that is, waste paper sludges. The waste paper sludge is a solid waste, and must be disposed of properly. Most paper sludges are non-toxic, generally consisting of about half non-organic components (caolin clays, mineral oxides, and numerous non-organic compounds used to coat paper) and half organic components (largely cellulose products from wood, which provides the fiber necessary to make paper). Landfill regulations have become increasingly strict in recent years, requiring the disposal of waste paper sludge into modern composite lined landfills. These modern landfills are quite expensive to construct and operate, and waste disposal costs have greatly increased, adding costs to the paper manufacturing process.

The paper manufacturing industry is generally a highly competitive industry, and thus there is considerable interest in reducing paper sludge disposal costs by recycling and reusing the sludges. That of course was the primary purpose of this workshop, to consider and discuss methods of recycling and reusing waste paper sludge.

As the workshop title suggests, emphasis was on utilizing paper sludges in the area of environmental geotechnology and construction, a number of papers were presented on the use of paper sludges as impermeable barriers in landfill covers and liners. The sludge replaces compacted clay, which is usually utilized as the impermeable barrier layer. This is an especially successful use of paper sludge, since landfill covers and liners use large quantities of sludge, also, since the paper sludge is provided at little or no cost to the landfill covers, saving the cost of compacted clay, typical savings of 50-100 000 US $ per hectare have been achieved in landfill closures. This of course is a win-win situation for the paper companies and the landfill owners (typically local taxpayers).

Waste paper sludge shows promises as roadway and embankment construction material when mixed with cementing agents (fly ash, cement). Pure paper sludges generally have low strengths, sufficient for landfill covers, but generally too low for roadways and embankments. However, when mixed with certain
types of fly ash (another solid waste product), a cementing action takes place, resulting in relatively high shear strengths sufficient for roadway subbases and embankments.

Although the emphasis of the workshop was on the use of paper sludge in environmental geotechnology and construction, other uses of paper sludge were discussed, for example, using paper sludges for dust control in mining operations, as daily cover for landfill operations, as vegetative layers and covers, as reactive barriers for groundwater contaminant treatment, as adsorbents for oil and other wastes, and to manufacture building blocks.
UTILIZING A PAPER SLUDGE BARRIER LAYER IN MUNICIPAL LANDFILL COVERS

Thomas F. Zimmie, Professor, Civil Engineering Department, Rensselaer Polytechnic Institute, Troy, NY 12180.

ABSTRACT

This paper evaluates the use of paper sludges from the Hudson River Mill as the impermeable barrier in a landfill cover in Corinth, NY. Paper mill sludges are characterized by a high water content, low specific gravity, and high organic content in comparison to clays. In spite of a high water content, the paper sludges from the Hudson River Mill were compacted to a low hydraulic conductivity. The permeability and compressibility of the paper sludges are influenced by the water content and organic content. Although a paper sludge cover system may not initially meet the regulatory requirement for permeability when constructed at the natural water content, the change in void ratio that results from consolidation and dewatering under a low effective stress can the hydraulic conductivity to an acceptable value. The Corinth landfill cover was instrumented to measure the depth of frost penetration into the cover system.

INTRODUCTION

Compacted clays have been commonly utilized as the low hydraulic conductivity barrier layer in landfill covers in Northeastern United States. However, the cost of landfill closure is greatly increased, when an abundant source of clay is not readily available. To reduce the cost of landfill closure, municipalities throughout the Northeast have investigated the use waste sludges (paper mill sludges and water treatment plant sludges) as the low hydraulic conductivity barrier in landfill covers. Numerous studies have been conducted to find an alternative uses for paper mill sludges in the waste containment industry (Stoffel and Ham 1979; NCASI 1992; Swann 1991; Kraus and Benson 1994; Moo-Young 1995; Moo-Young and Zimmie 1995a, 1995b, 1995c, 1996a; Zimmie and Moo-Young 1995; Zimmie et al. 1995; Floess et al. 1995). These studies have shown that paper mill sludges, in spite of high water contents and low solids contents in comparison to clays, are compactable to low permeabilities and are acceptable substitutes for clays in landfill covers. Moreover, the major advantage of using paper sludge is that it is provided to the landfill owner at little to no cost which can decrease construction cost by $20,000 to $50,000 per acre. (Moo-Young 1995).

In 1991, the town of Corinth, New York capped its municipal landfill in accordance with New York State Department of Environmental Conservation (NYSDEC) regulations. In an effort to reduce the cost of closure, the town explored the feasibility of an alternative capping system using paper sludge from the Hudson River Mill (International Paper Company) in Corinth, New York. In addition to reducing costs of
final closure of the landfill, the paper sludge capping system provided a beneficial use for the paper sludge that would otherwise be landfilled in a sludge monofill. This paper evaluates the feasibility of using paper sludge as the impermeable barrier in landfill covers in lieu of conventional clays. Moreover, the geotechnical properties, permeability, and consolidation behavior were studied. The effects of freezing and thawing on the permeability of the sludge was also determined. The procedure for the design and construction of a landfill cover that uses paper sludge as the impermeable barrier is also discussed.

GEOTECHNICAL PROPERTIES

International paper sludge (IP) is a blended sludge from an integrated paper mill and is composed of kaolin clay, wood pulp, water, and organics. IP sludge was obtained from a sludge monofill that was in operation since 1973. Samples were collected at different elevations in the monofill. Surficial samples represent one week (IP1) old sludge, mid-depth sampling (5-6 meters) represented 2-4 years old sludge (IP2), and deep sampling (10 meters or greater) represented 10-14 years old sludge (IP3). The major geotechnical properties tested in this study were the water content, organic content, and specific gravity.

Water content was determined according to American Society for Testing and Materials (ASTM) procedure D2974. To avoid burning off some of the organics, the oven temperature was lowered from 105 °C to 70 °C (Goodman and Lea 1962; MacFarlane and Allen 1964; Raghu et al. 1987; Alvi and Lewis 1987; Moo-Young 1992; LaPlante 1993). To obtain an accurate prediction of water content, a larger sample (200-300 grams) was used (Moo-Young and Zimmie 1996a). Two to three days were required to completely dry the specimen. The ranges of initial (natural) water contents of the IP sludges used in this study are summarized in Table 1. In comparison to clays, IP sludges are characterized by high initial water contents ranging from 150 to 266 percent for the various sludges.

Organic content tests were performed on the sludges according to American Society for Testing and Materials (ASTM) procedure D2974 method C for geotechnical classification. A muffle furnace was used to burn off the organics at a temperature of 440° C and form an ash from the mineral constituents (kaolinite). The organic content results are summarized in Table 1. IP paper mill sludges are characterized by a high organic content in comparison to typical clays used in waste containment systems. Soils (e.g., peats) with high organic contents have a greater capacity to hold moisture in the soil matrix (MacFarlane 1969; Moo-Young 1992; Moo-Young and Zimmie 1996a). Moreover, the organic content decreases as the sludge age increases.
TABLE 1--Results of water content, organic content, and specific gravity tests

<table>
<thead>
<tr>
<th>Material</th>
<th>Age</th>
<th>Water Content, %</th>
<th>Organic Content, %</th>
<th>Specific Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP1</td>
<td>1 week</td>
<td>255-268</td>
<td>50-65</td>
<td>1.80-1.84</td>
</tr>
<tr>
<td>IP2</td>
<td>2-4 years</td>
<td>150-200</td>
<td>40-55</td>
<td>1.90-1.93</td>
</tr>
<tr>
<td>IP3</td>
<td>10-14 years</td>
<td>150-240</td>
<td>30-45</td>
<td>1.96-2.15</td>
</tr>
<tr>
<td>Niagara Clay</td>
<td>15-25</td>
<td>&lt;1</td>
<td></td>
<td>2.73</td>
</tr>
</tbody>
</table>

Specific gravity tests were performed on the sludges according to ASTM procedure D854 with slight modifications (LaPlante 1993; Moo-Young 1995). Specific gravity results are summarized in Table 1. IP paper sludges are characterized by low specific gravity in comparison to clays. As the organic content increases, the clay content decreases, and the specific gravity decreases.

CONSOLIDATION TESTS

Paper sludges are characterized by large reductions in water content and void ratio resulting from the application of applied stresses (Raghu et al. 1987; Alvi and Lewis 1987; Wang et al 1991; Moo-Young 1992; LaPlante 1993; Moo-Young 1995; Moo-Young and Zimmie 1996). To obtain a greater understanding of the compressibility of IP paper sludge, the influence of the organic content and water content on the consolidation of IP paper sludges was studied.

Influence of Water Content

One dimensional consolidation tests were conducted on IP sludge samples following ASTM procedure D2435 methods A and B at the initial water content. The compression index was plotted against the initial water content for the IP paper sludges as shown in Figure 1. The relationship between the compression index, $C_c$, and initial water content, $w_o$ (%), is as follows assuming a first order linear regression passing through the origin:

$$C_c = 0.008w_o$$  \hspace{1cm} (1)

where

$C_c$ = Compression Index, and

$w_o$ = initial water content, %. 
Various researchers have quantified the correlation between the compression index and compositional and state parameters for cohesive soils (Djoenaidi 1985). Similar relationship between compression index and initial water content have been obtained for peats.

Influence of Organic Content on Compressibility

Consolidation tests were performed on IP sludges to obtain a relationship between compressibility and organic content. Figure 2 plots the organic content versus the compression index for IP sludges using the first order linear regression model that passes through the origin (solid line). The ±95% prediction interval is also plotted which illustrates upper and lower range values with respect to the first order linear regression on which a future observed response for the organic content with respect to the compression index may be predicted. From Figure 3, the relationship between the compression index, \( C_c \), and the organic content, \( O_c \) (%), is as follows:

\[
C_c = 0.03 \, O_c
\]

where

\( C_c \) = Compression Index, and
\( O_c \) = Organic Content, %

Figure 1  Compression index and water content relationship.
Figure 2  Compression index and organic content relationship.

Figure 3  Hydraulic conductivity and organic content relationship.
As the organic content decreases, compressibility of IP sludges decreases. Sludge IP3 which has the lowest average initial organic content is expected to have the lowest amount of primary settlement in situ in comparison to sludges IP1 and IP2. There is little or no data in the literature relating the organic content to compressibility for sludges.

LABORATORY HYDRAULIC CONDUCTIVITY

The flexible wall permeameter was used to determine the laboratory hydraulic conductivity of IP paper sludge samples following the American Society of Testing and Materials procedure D5084-90. Figure 4 illustrates the relationship between the organic content and permeability for IP sludges. The regression correlation coefficient between the organic content and hydraulic conductivity is 1.19 which indicates that there is a linear association between the organic content and hydraulic conductivity with a positive slope when plotted on a semilogarithmic scale.

Figure 4 also shows the ± 95% prediction intervals which illustrate an upper and lower range of values with respect to the first order regression model on which a future observed response for the organic content with respect to the permeability may be predicted. Figure 3 shows that as the organic content decreases, there is a decrease in hydraulic conductivity. From these results, sludge IP3 was chosen as the hydraulic barrier in the landfill cover.

Hydraulic conductivity tests using a triaxial permeameter were also performed at various effective confining pressures: 34.5 kPa, 69 kPa, 138 kPa, 207 kPa and 276 kPa. Figure 5 displays the hydraulic conductivity and effective stress relationships for IP sludges and Niagara clay using flexible wall triaxial permeameters and one dimensional consolidometers. Figure 5 plots the range of effective stress that are applicable for landfill covers. Triaxial and consolidometer results follow as similar trend; As the effective stress increases, consolidation of the paper sludge increases, and the permeability of paper sludge decreases (Figure 5). Similar results were obtained from studies conducted on organic clays and peats (Hanrahan 1954; Lea and Brawner 1963; Cedergren 1989). Hydraulic conductivity and effective stress relationships from the one dimensional consolidometer are a less conservative estimate than those from the triaxial permeameter at lower effective stresses (5-100 kPa) (i.e. the hydraulic conductivity values from consolidation tests are lower than those from triaxial permeameter tests). At lower effective stresses, the hydraulic conductivity from consolidation tests are lower than the hydraulic conductivity from triaxial tests by a less than an order of magnitude. As the effective stress increases, the hydraulic conductivities from consolidation and triaxial tests converge (Figure 5). Paper sludges exhibits a decrease in permeability five times that for a typical clay for an effective stress range of about 35 to 140 kPa (5 to 20 psi) (Moo-Young and Zimmie 1995b).
CONsolidation TESTS
- IP1 (250%, 4.5)
- IP2 (190%, 3.6)
- IP3 (200%, 4.1)

Triaxial TESTS
- IP1 (250%, 4.5)
- IP2 (190%, 3.6)
- IP3 (250%, 4.9)

Figure 4  Hydraulic conductivity and void ratio relationship.

Figure 5  Hydraulic conductivity and effective stress relationship.
Figure 5 shows the effects of a change in void ratio on the hydraulic conductivity of samples of IP sludge which were molded at various water contents using a triaxial permeameter and a one dimensional consolidometer. IP1, IP2, and IP3 triaxial and consolidation sludge samples had initial water contents of 250%, 190% and 250% respectively, and had initial void ratios of 4.5, 3.6, and 4.9, respectively. Triaxial and consolidation data show as similar where the hydraulic conductivity decreases as the void ratio of the paper sludge decreases. These results are comparable to the results for clays (25). Consolidation data have a slight decrease in hydraulic conductivity at higher void ratios (which correlates to lower effective stresses).

CONSTRUCTION OF THE CORINTH LANDFILL COVER

New York Department of Environmental Conservation allowed the Town of Corinth to cover their ten acre municipal landfill with paper sludge from the Hudson River Mill as a demonstration project. A 36 inch (91.4 cm) layer of IP3 sludge was used as the low permeability barrier layer in the Corinth landfill. Three acres of the This configuration was also used at the Hubbardston landfill in Hubbardston, Massachusetts that used Erving paper sludge as the impermeable barrier (Moo-Young 1992; Floess et al. 1995; Moo-Young 1995; Moo-Young and Zimmie 1996a). The impermeable barrier was mined from the sludge monofill. Miscellaneous pieces of wood were removed by sieving the sludge through screens.

Since freezing and thawing was a major concern in the design of the landfill cover, a nineteen inch (48.3 cm) layer of IP1 sludge was used as a frost protection layer for the lower hydraulic barrier (Moo-Young 1992; Mitchell 1993; Moo-Young 1995; Zimmie et al. 1995; Moo-Young and Zimmie 1996b). A seven inch (17.8 cm) vegetation layer and a twenty-five inch (63.5 cm) drainage layer were placed above the frost protection layer.

Previous research conducted on the material workability indicates that the paper sludge landfill covers should be constructed at the natural water content (Moo-Young 1992; LaPlante 1993; Floess et al. 1995; Moo-Young 1995; Moo-Young and Zimmie 1995c; Zimmie et al. 1995; Moo-Young and Zimmie 1996a). The low hydraulic conductivity layer (IP3) was constructed at an initial water content ranging from 150-200%. The frost protection layer (IP1) was dewatered to an initial water content ranging from 180-220%. A small ground pressure dozer was used to place and compact the sludge layer. This equipment successfully eliminated large voids from the sludge and kneaded the material homogeneously (Moo-Young 1995; Moo-Young and Zimmie 1995c; Moo-Young and Zimmie 1996a).
From the Hubbardston project, approximately six inches (15.2 cm) of primary settlement occurred in the landfill after one year. Since IP sludge has similar geotechnical properties to Erving sludge, similar amounts of settlement were expected in the Corinth landfill cover.

INSITU FROST PENETRATION MEASUREMENTS

Frost penetration is a major environmental concern in landfills in the Northeast. Freezing and thawing cycles may deteriorate the hydraulic conductivity of the landfill liner or cap. A considerable amount of research has been conducted on the effects of freezing and thawing on compacted clays. In general, the hydraulic conductivity of compacted clays increases from one to three orders of magnitude due to freezing and thawing (Othman et al. 1994). Paper sludge exhibit a similar one to two order of magnitude increase in hydraulic conductivity due to freezing and thawing (Moo-Young 1992; Kraus and Benson 1994; Moo-Young 1995; Moo-Young and Zimmie 1996a, 1996b).

The depth of frost penetration into the paper sludge landfill cover at the Corinth Landfill in New York was measured using a frost measurement system. Thermistor probes measured the temperature at various depths in the soil and consisted of eight thermistors spaced 7.62 cm apart. Although temperature measurements are important, soil resistivity measurements are required to accurately predict the freezing level, since soil resistivity increases greatly upon freezing. A conductivity probe measured the half bridge voltage between conductivity rings that are spaced 7.62 cm apart. An increase in the measured voltage indicates the formation of ice lenses. Data was collected in data logger, and the data loggers were changed periodically.

Two sets of instrumentation equipment were placed in the south west corner of Corinth landfill. Set 1 was placed in the IP3 sludge impermeable barrier layer, and Set 2 was placed in the IP1 sludge frost protection layer. Figure 6 shows the vertical configuration of the instrumentation equipment into the landfill cover. For set 1, the top bands (level #1 and #2) of the conductivity and thermistor probes were installed in the sand drainage layer. For set 2, the top bands (level #1 and #2) were installed in the lower portion of the frost protection layer. The installation procedure and equipment specifications are detailed in the paper by Zimmie et al. (1994).

Figure 7 plots the temperature profiles for Levels #1, 2, and 3 for the instrumentation in the frost protection layer (Set 1) and the impermeable layer (Set 2) from November 4, 1994 to April 11, 1995. For Set 1, levels #1 and 2 are located in the lower portion of the sand drainage layer, and level #3 is located at the top of the frost protection layer. The temperature in Set 1 level #1 (sand drainage layer) decreased from 13 °C to 1 ° from November 4, 1994 to March 19, 1995 (0 to 135 days) (Figure 7). During the same time, voltage reading for Set 1 level #1 remained a low constant value.
with an average of 0.1 V. From March 19, 1994 to April 11, 1995 (135 to 158 days), the temperature increased (Figure 7), and the voltage remained constant at 0.1 V. Levels #2-3 for Set 1 have a similar trend in temperature (Figure 7). Although not shown, Levels #4-8 display a similar trend to level #3. Since the temperature did not decrease below 0 C and the voltage did increase, it can be concluded that there was no frost penetration into the lower portion of the sand drainage layer and into the frost protection layer.

For Set 2, level #1 and 2 are located in the lower portion of the frost protection layer, and level #3 is located at the top of the impermeable barrier layer. For level #1 in Set 2, the temperature decreased from 15 C to 3 C from November 4, 1994 to March 19,
1995 (0 to 135 days) (Figure 7). The voltage readings during this time period remained constant at 0.1 V (Figure 7). From March 19, 1995 to April 11, 1995, the temperature for level #1 increased (Figure 7), and the voltage remained constant at 0.1 V. Levels #2-8 exhibit a similar temperature and voltage behavior to level #1. These results indicate that no freezing occurred into the lower portion of the frost protection layer and into the impermeable layer.

The lack of frost penetration into the sludge layers of the Corinth landfill may result from the increase in the effective overburden pressure (i.e., the increased height of the sand drainage layer and the addition of a frost protection layer). Heavy snow cover during the winter of 1994-1995 may also contribute to the lack of frost penetration into the landfill cover by insulating the landfill. The high water content of paper sludge also contributes to the lack of frost penetration into the landfill cover, since the high water content requires more energy loss to freeze the water in the sludge matrix as compared to sands and clays.

CONCLUSIONS

The following conclusions can be drawn about the use of IP paper sludges in landfill covers:

1. IP paper mill sludges are characterized by a high water content, high organic content and low specific gravity in comparison to clays.

2. IP paper mill sludges are characterized by high compressibility. The consolidation of paper mill sludges results in large reductions in void ratios and water contents. As the molding water content increases, the compressibility increases. The organic content also influences the compressibility of paper sludges. As the organic content decreases, the compressibility decreases.

3. As the organic content of paper sludge decreases, the permeability decreases.

4. The depth of frost penetration into the paper sludge cap was measured using a frost measurement system during the winter 1994-1995. Soil resistivity and temperature measurements indicate that no freezing occurred in the impermeable layer. The lack of frost penetration into the sludge layer was attributed to the high water content of the paper sludge, heavy snow cover during the winter, and the increased in the effective overburden pressure on the landfill cover.
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LABORATORY TESTING OF SEVERAL PAPER SLUDGES AS RAW MATERIALS FOR LANDFILL COVERS

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ABSTRACT

This paper evaluates the properties of 4 paper sludges as barrier layer in landfills as substitute of clays. The inocuity of this wastes as construction materials is verified by lixiviation tests and ecotoxicity tests. Hydraulic conductivity has been measured at different water content in order to find a windows of water contents where the permeability is lower than $10^{-7}$ cm/s.

Introduction

Compacted clays, commonly used as low hydraulic conductivity barrier layer in landfill covers, are not locally available in the Basque Country. In that places the cost of landfill closure is greatly increased due to the high prices of synthetic materials and the lack of natural clays. However in that region there is a high-concentration of paper industry whose residues are generally landfilled. Several studies (Schultz and Stoffel 1984; NCASI 1989; Aloisi and Atkinson 1990; Moo-Young 1995) have shown that paper sludges performed as well, sometimes even better, than clays in landfill covers. Therefore the use of paper sludges as alternative materials for landfill construction would decrease construction costs altogether with a reduction of waste disposal cost for the paper industry.

This paper characterises the properties of 4 paper sludges as alternative materials for landfills covers.

Sludge characterisation

Samples of four paper sludges has been collected at the exit of the waste treatment areas. The production processes that generated the effluents treated are compiled in Table 1:
Table 1. Origin of paper sludges

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Production process</th>
<th>Treatment system</th>
<th>Sludge production ( dry tons/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tissue recycled</td>
<td>1° Belt filter press</td>
<td>18.000</td>
</tr>
<tr>
<td>2</td>
<td>Upgraded papers</td>
<td>1° Pressure filtration</td>
<td>3.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2° Aerated lagoons</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Paper recycled</td>
<td>1°: Centrifuge</td>
<td>4.000</td>
</tr>
<tr>
<td>4</td>
<td>Paper decor</td>
<td>1°: Vacuum filter</td>
<td>950</td>
</tr>
</tbody>
</table>

**Water content**

Water content is calculated as the ratio between the weight of water and the dry sample weight expressed as a percentage following ASTM D2974. To avoid partially burning of the organic fraction the temperature was lowered to 70°C (Moo-Young, 1994). Samples of 20 gr. were used and the complete drying of the sample require 3-4 days depending on samples. The values of initial water contents of the sludges are summarised in table 2.

**Organic / Inorganic content**

Organic/Inorganic content was determined according to ASTM D2974-C. Samples (about 20 gr.) were placed into an oven at 550°C to obtain an ash of the inorganic constituents (mainly kaolinite).

Table 2. Water content and inorganic content for the various sludges

<table>
<thead>
<tr>
<th>Sample</th>
<th>Water content (%)</th>
<th>Ashes (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td># 1.1</td>
<td>107.7</td>
<td>58.6</td>
</tr>
<tr>
<td># 1.2</td>
<td>82.7</td>
<td>68.3</td>
</tr>
<tr>
<td># 2.1</td>
<td>69</td>
<td>70.6</td>
</tr>
<tr>
<td># 2.2</td>
<td>82.3</td>
<td>70.7</td>
</tr>
<tr>
<td># 3</td>
<td>127.9</td>
<td>67.8</td>
</tr>
<tr>
<td># 4</td>
<td>159.8</td>
<td>57.3</td>
</tr>
<tr>
<td>Reference soil</td>
<td>N.D.</td>
<td>92.1</td>
</tr>
</tbody>
</table>

* N.D. not detected

All the sludges have an inorganic content in a range [55-75]%.  

**Atterberg limits**

Atterberg limits has been measured following ASTM D4318. using ASTM brass groove tool for the liquid limit determination as it cuts smoothly leading to better results. Specimens were prepared
from the wet side for the plastic limit, and from the dry side for the liquid limit in most of the sludges.

Table 3. Summary of Atterberg limits

<table>
<thead>
<tr>
<th>Sample</th>
<th>Liquid limit (%)</th>
<th>Plastic limit (%)</th>
<th>Plasticity index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1.1</td>
<td>222.8</td>
<td>126.4</td>
<td>96.4</td>
</tr>
<tr>
<td>#1.2</td>
<td>160.0</td>
<td>95.5</td>
<td>64.5</td>
</tr>
<tr>
<td>#2.1</td>
<td>117.8</td>
<td>44.3</td>
<td>73.5</td>
</tr>
<tr>
<td>#2.2</td>
<td>124.9</td>
<td>53.7</td>
<td>71.2</td>
</tr>
<tr>
<td>#3</td>
<td>134.2</td>
<td>104.6</td>
<td>29.6</td>
</tr>
<tr>
<td>#4</td>
<td>203.1</td>
<td>N.D.</td>
<td>N.D.</td>
</tr>
<tr>
<td>Reference soil</td>
<td>68.6</td>
<td>33.6</td>
<td>35.0</td>
</tr>
</tbody>
</table>

* N.D. not detected

Reference soil fulfills the USEPA regulación for its use as reference for hydraulic conductivity tests (values established for USEPA norm):

- Fines content: 95.45% (>30%)
- Gravels: 20.3% (<30%)
- Particle diameter < 25 mm
- Plasticity index: 65.0% (>10%)
- Clay content: 48.54% (>10%)
- Activity: 0.72 (between 0.5 and 1)

Paper sludges are characterised by high Atterberg limits. Moo-Young 1995 gave values for the plastic limit above a 100% and for the liquid limit higher than 200% with plasticity in a range [77,191] %. But for sludge #1 our sludges have lower values, although they are higher than the values of reference soil.
Test of compactation

Proctor tests were performed following ASTM D698-78 over samples placed into a tray and left to dry at room temperature and for water contents higher than the initial values more water is added. Figure 1 shows the Proctor curve for the 4 sludges with an optimum density and moisture content around 50% for sludges 1, 2 and 3 and around 80-100% for sludge 4. These values are higher than typical values for clay, optimum density around a 10-15%.

At water contents close to the optimum all the sludges are stiff and difficult to work with. As the water content increase the sludges become more workable. For water contents higher than 100% all the Proctor curves overlap.

![Proctor curves for various paper sludges.](image)

Porosity:

It has been calculated as:

\[ S_t = 1 - \frac{\text{bulk density}}{\text{particle density}} \]

where bulk density determined through clod method and particle density calculated by Picnometer method. Results are plotted in figure 2. All the sludges follow the same curve while they are
saturated and all the void are filled with water and more water content is due to higher porosity. In the left side of the plot the curves start to diverge as some voids are not filled with water.

![Figure 2. Porosity](image)

**Waste leaching and ecotoxicity tests**

Compliance tests for leaching of sludges has been carried out following European standard CEN/TC292/WG2/DOC25.

Ecotoxicity tests have been performed to evaluate the global impact of all the components with a degree of contamination, measured or not in leaching tests. We have chose the toxicity test of luminescence inhibition, based in the light emission reduction of a culture of (Photobacterium)-plusphoreum NRRL-B-11177 in presence of the leachate extracted from the sludges.

Table 4 summarised the results of both tests.

Regarding the composition of leachates sludges #1 and #2 showed high concentrations of cianures, ammonium and clorures, while sludges #3 and #4 have too many sulphates and lypophylic compounds.

Notwithstanding considering results of the ecotoxicity all the sludges can be considered as nontoxic as their EC$_{50}$ (concentration of the leachate in water at which half of the bacterium died in a fixed period of time) as all have values substantially higher than 3.000 mg/l, that is the value under with a material is considered ecotoxic.
Table 4. TLCP and ecotoxicity results.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Sludge 1.1/1.2</th>
<th>Sludge 2.1/2.2</th>
<th>Sludge 3</th>
<th>Sludge 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCB’s (µg/l)</td>
<td>&lt;0.01 / &lt;0.7</td>
<td>&lt;0.11</td>
<td>&lt;1.16</td>
<td>&lt;0.11</td>
</tr>
<tr>
<td>VOC’s (µg/l)</td>
<td>&lt;10 / &lt;10.0</td>
<td>&lt;35.0</td>
<td>&lt;35.0</td>
<td>&lt;35.0</td>
</tr>
<tr>
<td>C&lt;sub&gt;total&lt;/sub&gt; (mg/l)</td>
<td>181</td>
<td>318</td>
<td>356</td>
<td>80.7</td>
</tr>
<tr>
<td>C&lt;sub&gt;ion&lt;/sub&gt; (mg/l)</td>
<td>70.7</td>
<td>80.9</td>
<td>63.2</td>
<td>19.1</td>
</tr>
<tr>
<td>C&lt;sub&gt;organ_tot&lt;/sub&gt; (mg/l)</td>
<td>110</td>
<td>237</td>
<td>293</td>
<td>61.6</td>
</tr>
<tr>
<td>CN⁻ (µg/l)</td>
<td>22.3 / 15.0</td>
<td>18.1 / 9.53</td>
<td>9.49</td>
<td>10.46</td>
</tr>
<tr>
<td>Phenols (mg/l)</td>
<td>&lt;0.20</td>
<td>1.65</td>
<td>&lt;0.20</td>
<td>&lt;0.20</td>
</tr>
<tr>
<td>Ammonium (mg/l)</td>
<td>15.8 / &lt;0.10</td>
<td>105.0 / 37.0</td>
<td>&lt;0.20</td>
<td>&lt;0.20</td>
</tr>
<tr>
<td>Chlorures (mg/l)</td>
<td>11.50</td>
<td>17.70</td>
<td>4.96</td>
<td>4.20</td>
</tr>
<tr>
<td>Fluorures (mg/l)</td>
<td>&lt;0.10</td>
<td>&lt;0.10</td>
<td>&lt;0.10</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>Sulphates (mg/l)</td>
<td>26.30 / 21.30</td>
<td>14.40 / 14.90</td>
<td>49.60</td>
<td>51.80</td>
</tr>
<tr>
<td>Nitrites (mg/l)</td>
<td>&lt;0.10</td>
<td>0.43</td>
<td>0.12</td>
<td>0.19</td>
</tr>
<tr>
<td>Lipophylic compounds (g/l)</td>
<td>37.0 / 24.0</td>
<td>14.0 / 70.0</td>
<td>70.0</td>
<td>60.0</td>
</tr>
<tr>
<td>Arsenic (mg/l)</td>
<td>&lt;0.10</td>
<td>&lt;0.10</td>
<td>&lt;0.10</td>
<td>&lt;0.10</td>
</tr>
<tr>
<td>Cadmium (mg/l)</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Chromium (mg/l)</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Copper (mg/l)</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Nickel (mg/l)</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Lead (mg/l)</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Zinc (mg/l)</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>EC&lt;sub&gt;50&lt;/sub&gt; (mg/l)</td>
<td>74.200 / &gt; 900.000</td>
<td>50.000 / 21.500</td>
<td>&gt;900.000</td>
<td>&gt;900.000</td>
</tr>
</tbody>
</table>

**Permeability (laboratory)**

Hydraulic conductivity has been measured with a rigid-wall permeameter. Samples of 300-400 gr. (a high of 113 mm and diameter 100 mm) prepared with Proctor method were placed in the permeameter and K is measured by falling-head method.

Hydraulic conductivities were measured at different water contents for all the sludges in order to determine the range of water contents within the sludge permeability is low enough to perform as an hydraulic barrier (K≤10⁻⁷ cm/s). Data are showed in figure 3.
Sludges #1 and #2 at the initial water content have hydraulic conductivities low enough to perform as an hydraulic barrier layer in the cover of a landfill. Sludge #2 showed this behaviour in a wide range of water contents [80,110]%. For sludge #2 more values of K should be measured for water contents lower than 100%. Sludge #3 and #4 display higher values of the hydraulic limit, one order higher than the value limit for materials to act as hydraulic barriers. The minimum values of K for sludge #2 occurs for a water content about 90% almost the double than the optimum value (maximum of Proctor plot, see figure 1).

Considering the paper process where the sludge has been originated sludges #1 and #3 should be mainly deinking sludge whereas sludge #2 and #4 are originated in processes where upgrades papers are manufactured and their higher inorganic content is due to the addition of inorganic compounds to the pulp as fillers or with other specific purpose. However considering permeability sludges #3 and #4 in one side and sludges #1 and #2 have shown values quite close.

References


IN-SITU STRENGTH TESTING ON A PAPER MILL SLUDGE LANDFILL COVER

Juan D. Quiroz and Thomas F. Zimmie, Civil Engineering Department, Rensselaer Polytechnic Institute, 110 8th Street, Troy, NY 12180-3590

ABSTRACT

This paper deals with in-situ strength testing on a paper mill sludge landfill cover utilizing a field vane to determine the undrained shear strength of the paper sludge barrier layer. Stable and unstable slope areas were tested and an undrained shear strength versus water content relationship was established. Values of undrained shear strength varied from about 35 kPa to 2 kPa and the water content range was between 122% and 200%. A remolding phenomenon was noticed in the test results for the unstable slope areas which were lower in undrained shear strength. The objective of this study was to establish in-situ undrained shear strength results for slope stability and to capture some aspects of the strength behavior of paper mill sludges.

INTRODUCTION

The emergence of paper mill sludge as an effective hydraulic barrier and its economic advantage over traditional clay caps has given rise to the construction of many paper mill sludge landfill cover systems in the northeastern United States. A great deal of research has dealt with the characteristics of paper mill sludges used for landfill covers in terms of its hydraulic barrier potential (Pepin 1984; NCASI 1989; Aloisi and Atkinson 1990; Zimmie et al. 1993; Moo-Young 1995; Zimmie and Moo-Young 1995; Moo-Young and Zimmie 1996; Kraus et al. 1997).

Many design issues must be considered for construction of a landfill closure. The main performance criterion is hydraulic conductivity, typically less than $10^{-7}$ cm/s. The ability of paper mill sludges to achieve low hydraulic conductivities (k) has
been well established. However, other factors contribute to the overall integrity of landfill covers. One such factor is the strength properties of the hydraulic barrier material. Paper mill sludges are characterized by high water contents, high organic contents and low shear strengths. Slope stability analyses can be performed to assess the structural integrity of a landfill cover system, but the first step is to evaluate the shear strength properties of the paper mill sludge. Thus, the shear strength properties and/or strength behavior of paper mill sludges must be evaluated to properly design a paper sludge landfill cover. To date, little data exists on undrained testing of paper mill sludges.

In this investigation, in-situ strength testing of a paper mill sludge landfill cover was performed using field vane testing methods. The objective of this field study was to establish the range of in-situ undrained shear strengths \( (\tau_u) \) for the paper sludge barrier. An undrained shear strength versus water content relationship was determined. These values can later be used for slope stability analyses. In-situ testing using field vanes can serve many functions such as providing in-situ undrained shear strengths, assisting in investigative studies related to slope stability and also shows potential for providing Construction Quality Assurance (CQA) in landfill construction.

**LANDFILL SITE CHARACTERISTICS**

The municipal solid waste landfill closure that was tested has an area of approximately 3.5 hectares and is located in Montague, Massachusetts. The landfill closure construction has been ongoing from 1993 to 1997. The oldest part of the landfill is about 0.9 hectares in size and has a completed landfill cover system with a fully grown vegetative cover. The other parts of the landfill also have a completed cover system but do not have a vegetative cover as of the summer of 1997. The landfill side slopes varied from about 3.5H : 1V to 4H : 1V. Landfill closure construction is expected to continue until the end of the construction season for 1997, at which point the project will be completed.
The landfill cover system profile consists of the following components:
- 30 cm - topsoil
- 15 cm - sand drainage layer (k \geq 10^{-3} \text{ cm/s})
- 76.2 cm - paper sludge hydraulic barrier (k \leq 10^{-7} \text{ cm/s})
- 15 cm - sand gas vent layer (k \geq 10^{-3} \text{ cm/s}).

PAPER SLUDGE CHARACTERISTICS

The paper sludge used in the Montague Landfill cover is produced by the Erving Paper Mill in Erving, Massachusetts. The wastewater treatment plant receives about 96% of the influent from the paper mill (a paper recycling plant) and 4% from the town of Erving. The sludge is a blended primary and secondary sludge with an organic content of approximately 50%. The fixed solids are kaolin clay which is used as a filler to produce a smooth finish for writing and printing paper. The sludge has a high percentage of tissues and fibers.

Zimmie et al. (1993) evaluated the general geotechnical properties of the Erving Paper Mill sludge for another landfill cover project previously completed in Hubbardston, Massachusetts. The following information represents the general ranges of the Erving Paper Mill sludge properties. These values may vary if the quality of the paper sludge changes during production. Table 1 lists the general geotechnical characteristics of the Erving Paper Mill sludge. A hydraulic conductivity versus water content relationship is presented in Figure 1 to show the common range of water contents required to achieve a low hydraulic conductivity, k \leq 10^{-7} \text{ cm/s}.

Table 1. Erving Paper Mill Sludge General Geotechnical Characteristics

<table>
<thead>
<tr>
<th>Water Content (%)</th>
<th>Organic Content (%)</th>
<th>Specific Gravity</th>
<th>Plastic Limit (%)</th>
<th>Liquid Limit (%)</th>
<th>Plasticity Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>150-250</td>
<td>45-50</td>
<td>1.88-1.96</td>
<td>94</td>
<td>285</td>
<td>191</td>
</tr>
</tbody>
</table>

*After Zimmie et al. (1993).*

IN-SITU TESTING PROCEDURE

A Geonor field vane, model H-70 with a tapered vane blade (7.58 cm x 15.16 cm) was used to evaluate the in-situ undrained shear strength of the paper mill sludge hydraulic barrier. A Torqueleader torque wrench that allowed for direct measurement of the peak undrained shear strength was utilized. The range of the torque wrench is from 0 T/m² to 6 T/m² which was within the limits of the expected in-situ undrained shear strength of the paper sludge.

ASTM Standard 2573 guidelines were followed for the field testing procedure of the barrier layer. First, a post-hole digger was used to excavate a uniform round hole, approximately 15 to 20 cm in diameter, down to the paper sludge barrier layer. The landfill cover components were separated during excavation so that they could be placed back in their respective locations after testing. The field vane was inserted approximately 40 cm into the middle of the paper sludge barrier and the undrained shear strength was determined. Water content samples were then retrieved from the test location. Test times varied from 10 to 15 minutes, including excavation. Since this test is simple and fast, many tests can be performed in a short time period.
RESULTS AND DISCUSSION

Two field test investigations were performed on the paper sludge barrier layer of the Montague Landfill cover system. In mid-July 1997 a local failure about 0.1 hectares in size was noticed along the northwest side of the landfill and slight bulges were also visible on the east side of the landfill. The first testing round consisted of 18 field vane tests with the intent of trying to characterize the variation of undrained shear strength for the whole landfill cover system. Then, in late-July 1997, the local failure on the northwest side increased to about twice its original size and two new but smaller local failures were also observed on the east and west side of the landfill. Tension cracks of considerable depth were visible at and around the failed slope areas. The second round of testing consisted of 17 field vane tests that were concentrated around the failed areas.

From these tests, an undrained shear strength versus water content relationship was established, see Figure 2. A similar trend for that of clays is obtained, whereas the undrained shear strength decreases with increasing water content (Lambe and Whitman 1969). Figure 3 illustrates a classic example of the undrained shear strength versus water content relationship for kaolin clay.

FIGURE 2. Undrained Shear Strength versus Water Content Relationship for Erving Paper Sludge for slopes not steeper than 3H:1V.
There are two obvious ranges of undrained shear strength which can be separated into stable (implying field vane tests on stable slopes) and unstable (implying field vane tests on unstable slopes) undrained shear strengths. The range for the stable undrained shear strengths is from about 35 kPa to 10 kPa while the range for unstable undrained shear strengths is from approximately 18 kPa to 2 kPa. The water content range in both cases was between 122% and 200%. The results for the oldest and most stable section (constructed in 1993) of the landfill show the highest undrained shear strengths with correspondingly low water contents. This is a direct result of consolidation of the paper sludge barrier. The values associated with the lower undrained shear strengths pertain to the unstable slope areas and represent remolded strengths after slope movements which alter the paper sludge structure.

![Figure 3](image)

**FIGURE 3.** Relationship Between the Undrained Strength from Laboratory Vane Tests and Moisture Content (adapted from Mahmud, 1997).

Field vane tests on paper mill sludges are unlike that for clays. In general, most field vane shear results overestimate the actual undrained shear strength so correction factors are utilized which are commonly correlated with plasticity index. Atterberg limits for paper mill sludges are questionable (LaPlante 1993) thus any correction factor may require another method for correcting the undrained shear strength. Flaate (1966) discusses factors influencing vane results and should be referenced to help minimize data variation.
If a comparison is made between Figures 2 and 3 we notice relatively similar undrained shear strengths for kaolin clay and paper sludge. However, the water contents are shifted by about 100%. This is an interesting observation since the paper mill sludge tested consisted of about 50% kaolin clay. If the kaolin clay were to have as high water contents as the paper sludge, it would be considered a slurry with little strength. This suggests that the paper sludge fibers present in the sludge matrix account for the additional strength at high water contents.

CONCLUSIONS

A total of 35 field vane tests were conducted on the paper sludge landfill cover of the Montague Landfill. An undrained shear strength versus water content relationship was established for both stable and unstable slopes. The values of the stable slope undrained shear strength varied from 35 kPa to 10 kPa while the range for unstable slope undrained shear strengths was from approximately 18 kPa to 2 kPa. The water content varied from 122% to 200%. The lower strengths for the unstable slopes represent remolded undrained shear strengths due to the disturbed nature of the unstable slopes. Consolidation increases the undrained shear strength and decreases the water content observed from the data pertaining to the oldest section of the landfill cover.

The advantages of field vane testing are as follows: (1) ease and speed of test performance, (2) in-situ undrained shear strength is obtained and sample (i.e., paper sludge barrier) disturbance is minimized, and (3) has the potential for CQA of construction. The information provided by field vane testing can be used to perform an undrained (short-term) slope stability analysis which is the critical condition for paper mill sludge landfill cover systems. In addition, these undrained shear strength results can provide analytical parameters and insight as to the behavior of paper mill sludge landfill cover systems in terms of slope stability.
ACKNOWLEDGEMENTS AND DISCLAIMER

Cooperation for this research was received from the following organizations: Erving Paper Mill, Inc., Erving, MA; and Rensselaer Polytechnic Institute (RPI), Troy, NY. Special thanks goes to Carl Selfridge, Craig D’Allard and Ben Rosenthal for their help in this field study while at RPI. The views and opinions of the author expressed herein do not necessarily reflect those of RPI or Erving Paper Mills, Inc.

REFERENCES


TECHNIQUE FOR DEWATERING PAPER WASTE SLUDGE

by
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University of Delaware, Newark DE. 19716

ABSTRACT

- OBJECTIVE: To separate solids and liquid inexpensively.

- TECHNIQUE: The geotextile tube is performing as a "cheese cloth." That is, a geotextile encapsulates sludge that was pumped in hydraulically. The pervious geotextile then serves as a filter allowing liquid to flow out while retaining the solid particles inside.

- RELEVANT CASE HISTORY: This technique has been used successfully to contain clayey dredged material. Separation of water and solid clay particles was achieved at about 10 to 20 times faster as compared to the conventional alternative using shallow dredged material containment facilities.

- KEY QUESTIONS IN DESIGN:
  1. Required strength of geotextile forming the tube.
  2. Filter criteria for geotextile confining the slurry.
  3. Shape of geotextile tube and its sludge storage capacity.

- EXISTING ANSWERS AND NEED FOR FURTHER STUDIES: Some answers are given by Leshchinsky et al. ("Geosynthetics Tubes for Confining Pressurized Slurry: Some Design Aspects," Journal of Geotechnical Engineering, August 1996, pp. 682-690). In particular, the questions of strength and permeability for the adequate geotextile are provided. However, the consolidated height issue needs further studies, especially as related to paper waste. Also, a field study is needed to determine the maximum length of a tube into which paper sludge could be pumped effectively from a single inlet.

- CONCLUSION: Experience with clayey sludge indicates that geotextile tubes have the potential to serve as an efficient and inexpensive separator of solids and liquid when filled with paper sludge. The simplicity of this technique in terms of both design and construction is appealing. Only minor refinements are needed for use of geotextile tubes in waste paper sludge.
DESIGN OF WASTE CONTAINMENT SYSTEMS
UTILIZING A PAPER SLUDGE CAPPING LAYER

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ABSTRACT

Waste containment of municipal solid waste has become a major environmental issue for the world. Designing a waste containment facility is a very costly endeavor in regions where there is no source of low permeability material. Paper mill sludges can substitute for the impermeable barrier in waste containment facilities where a source of clay is not available, and can reduce the cost of construction considerably. A high water content and organic content in comparison to clays characterize paper mill sludges. Laboratory tests were conducted on seven paper sludges to obtain the geotechnical properties such as the compaction characteristics, water content, specific gravity, and organic content. Typical laboratory procedures used for clays were altered for paper sludge due to the high initial water content. This paper will discuss the design consideration for a waste containment facility using paper sludge. The design procedures in this paper are based on laboratory testing data. A paper sludge may not initially meet the regulatory requirement for permeability (when the sludge cover system is constructed at the natural water content); However, the change in void ratio that results from consolidation and dewatering under a low effective stress can reduce the hydraulic conductivity to an acceptable value.

INTRODUCTION

The high price of solid waste disposal has sparked interest in the development of alternative uses for waste sludges (paper mill sludges and water treatment plant sludges). Compactable to a low permeability in spite of high water contents and low solid contents in comparison to clays, paper mill sludges can substitute for clays in landfill covers. Paper sludges are considered a waste product and are provided to the landfill owner at little or no cost. This may reduce
the cost of construction by $20,000 to $50,000 per acre. Since 1975, paper mill sludges have been used to cap landfills in Wisconsin and Massachusetts (Stoeffel and Ham, 1979; Pepin, 1984; Aloisi and Atkinson, 1990; Swann, 1991; Zimmie et al., 1995; Moo-Young and Zimmie, 1996a; Moo-Young and Zimmie, 1996b). This paper reviews the design consideration for a waste containment system that utilizes a paper sludge barrier layer in the cover system.

Seven sludges were used in this study. Sludge A is a wastewater treatment plant sludge from a deinking recycling paper mill. Sludge B is a blended sludge from a wastewater treatment plant, which receives its effluent from a recycling mill and the neighboring community. Sludge C is a blended sludge from an integrated paper mill and is comprised of kaolin clay, wood pulp and organic. Sludge C was mined from a sludge monofill landfill, which was in operation since 1973. Samples were collected from different sections of the monofill to represent different sludge ages: one-week (C1), 2-4 years (C2), and 10-14 years (C3). Sludge D is a primary wastewater treatment plant sludge from a recycling paper mill. Sludge E is a primary wastewater treatment plant sludge from a non-integrated paper mill.

GEOTECHNICAL CLASSIFICATION

The geotechnical classification of paper mill sludges is not like that of typical clays used in landfill covers. For example, Atterberg Limits tests are very difficult to perform on paper sludges and the results may not be meaningful in terms of geotechnical classification (Moo-Young and Zimmie, 1996a). Organic content, specific gravity, and natural water content appear to be the major physical properties of interest.

The ranges of natural water contents, organic content, and specific gravity are summarized in Table 1. Water contents were 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. A large sample of sludge is required to obtain an accurate prediction of water content. Two to three days were required to completely dry the specimen. Paper sludges are characterized by a high water content ranging from 150-270% (Table 1).

The organic contents of paper sludges were determined according to ASTM procedure D2974, method C for geotechnical classification purposes. 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. Paper mill sludges are distinguished by a high organic content ranging from 35-60%.

Specific gravity tests were performed on the sludges according to ASTM procedure D854. Slight modifications were made to apply the ASTM procedure to paper sludge. An aspirator was used to remove the entrapped air from the sample. Boiling the sample was avoided to reduce possible thermal reactions from occurring. The sludge samples were taken at their natural water content and 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. The specific gravity of paper sludges ranges from 1.8-2.2.

<table>
<thead>
<tr>
<th>SLUDGE</th>
<th>WATER CONTENT (%)</th>
<th>ORGANIC CONTENT (%)</th>
<th>SPECIFIC GRAVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>150-230</td>
<td>45-50</td>
<td>1.88-1.96</td>
</tr>
<tr>
<td>B</td>
<td>236-250</td>
<td>50-60</td>
<td>1.83-1.85</td>
</tr>
<tr>
<td>C1</td>
<td>255-268</td>
<td>50-60</td>
<td>1.80-1.84</td>
</tr>
<tr>
<td>C2</td>
<td>183-198</td>
<td>40-50</td>
<td>1.90-1.93</td>
</tr>
<tr>
<td>C3</td>
<td>222-230</td>
<td>30-40</td>
<td>1.96-2.15</td>
</tr>
<tr>
<td>D</td>
<td>150-185</td>
<td>42-46</td>
<td>1.93-1.95</td>
</tr>
<tr>
<td>E</td>
<td>150-200</td>
<td>35-40</td>
<td>1.96-2.08</td>
</tr>
</tbody>
</table>
MATERIAL WORKABILITY

Proctor tests were performed following 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. 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 sludges were 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.

Figure 1 shows the Proctor curve (the water content versus the dry density) 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 density obtained from the Proctor curve for the various sludges is similar. At the optimum density and moisture content, the sludge is dry, stiff, and unworkable. A very high water content is desirable, if the sludge is to be used as a landfill capping material (Zimmie et al., 1995). These test results compare favorably to research conducted on water treatment plant sludges (Raghu et al., 1987; Alvi and Lewis, 1987; Wang et al., 1991).
During the construction of the Hubbardston landfill in Hubbardston, Massachusetts and Erving Paper mill test plots in Erving, Massachusetts, 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 sheepfoot roller, and a low ground pressure track dozer. 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.

**DESIGN PROCEDURES FROM LABORATORY DATA**

Design procedures for the hydraulic barrier of landfill cover utilizing IP paper sludge were established from laboratory testing results. These procedures can be used for landfill covers using other paper sludges. However, to assure that the accuracy of the design, the properties of the paper sludges should be determined since paper sludges vary according to the wastewater treatment process (Moo-Young 1995).

1. The initial hydraulic conductivity, water content, and organic content of the paper sludge should be determined.
   a) If the initial hydraulic conductivity is $1 \times 10^{-7}$ cm/sec or less, then proceed to number 3.
   b) If the initial hydraulic conductivity is greater than $1 \times 10^{-7}$ cm/sec, then proceed to number

2. Because paper sludges exhibit high compressibility, they may show a permeability decrease substantial enough to change from being an unacceptable cover to an acceptable cover in less than one year.
   a) Determine the amount of reduction in hydraulic conductivity needed to obtain the regulatory requirements (most agencies require that $k \leq 1 \times 10^{-7}$ cm/sec).
   b) As the void ratio (water content) decreases due to consolidation, the permeability of the sludge will be reduced. Determine the initial void ratio of the paper sludge.
c) From the hydraulic conductivity and void ratio relationship in Figure 2, estimate the void ratio and change in void ratio needed to satisfy the regulatory requirement for hydraulic conductivity from triaxial and consolidation curves.

d) Compute the initial water content at the required hydraulic conductivity and the estimated void ratio from 2c.

e) From the hydraulic conductivity and effective stress relationship in Figure 3, estimate the effective stress (the change in effective stress) required to obtain the hydraulic conductivity from triaxial and consolidation data.

f) Compare the void ratio and effective stresses obtained from triaxial and consolidation data to determine the most conservative estimate of hydraulic conductivity reduction caused by an effective overburden pressure (Note that this is only a rough estimation, since secondary compression will also contribute to the reduction in hydraulic conductivity.)

g) Using the most conservative estimate of void ratio and effective stress, determine the time required for 100% of primary consolidation to occur using Terzaghi's theory. (Note that three dimensional consolidation in a triaxial device and one dimensional consolidation in a consolidometer yield slightly different results (Lambe and Whitman 1969; Craig 1992).)
h) If the time required for the completion of primary consolidation is less than 1 year, then go to step 3 (One year is the maximum time that would be allowed for the sludge layer to meet the requirements). If the time required for the completion of primary consolidation is greater than 1 year, the material should either undergo further testing (e.g. centrifuge testing to determine long term infiltration effect) or be disregarded as a potential barrier.

![Consolidation Tests Diagram]

Figure 3 Hydraulic Conductivity and Effective Stress Relationship

3. The configuration of the landfill cover should be determined. Estimate the effective stress at the mid-depth of the sludge layer.

a) If the effective stress estimated from the one dimensional consolidation test is less than or equal to the effective stress at the mid-depth of the sludge layer, then the sludge can provide an adequate hydraulic barrier in less than one year. Proceed to step 4.

b) If the effective stress estimated from the one dimensional consolidation test is greater than or equal to the effective stress at the mid-depth of the sludge layer, then the sludge will not provide an adequate hydraulic barrier in less than one year.
4. A three-foot (91.4-cm) barrier layer is suggested when using paper sludge. A six-inch (15.2-cm) drainage layer and a twelve-inch (30.5-cm) vegetation layer are placed above the hydraulic barrier. In regions where the depth of frost penetration is a concern, a frost protection barrier layer should be considered. Another possible solution to reducing the effects of freezing and thawing is to increase the effective overburden pressure by increasing the height of the drainage and vegetation layers.

CONCLUSION

This paper reviewed the geotechnical properties of paper mill sludges for use in the design of waste containment systems. When designing a landfill cover system using paper sludge as impermeable barrier, the sludge layer should be constructed at the initial water content to increase material workability during construction. Initially, the sludge may not meet the regulatory requirement for permeability (often $1 \times 10^{-7}$ cm/sec or less). However, the change in void ratio that results from the application of an overburden pressure (i.e., drainage layer and vegetation support layer) can reduce the permeability to an acceptable value in a short period of time.

REFERENCES


Environmental and Operational Considerations in the Use of Paper Waste Sludge for Dust Control on Iron Ore Mine Tailings

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ABSTRACT

Due to the large amount of iron ore that must be processed to produce an economically viable iron ore concentrate, very large mine tailings waste disposal basins are constructed, some of which can exceed 20,000 hectares in size. To minimize the amount of land required for these basins, many tailing disposal basins are constructed utilizing an upstream dike construction technique. This construction technique uses a system of dikes that are constructed on top of each other and partly on the tailings that the dikes hold. The benefit of this technique is that it nearly doubles the size of the basin by allowing the basins to increase vertically, although dike stability does remain an issue. While the upstream dike concept maximizes land use, it also places the tailings higher above the ground surface exposing the tailings to higher velocity wind. In general most iron ore tailings have particle sizes between 20 and 30 microns making them very susceptible to erosion and dusting events. The first strategy to control dusting would be to raise the water level of the basin so that most of the basin will be inundated by water. However, this may cause instability in the dikes and so water ponding is not possible. An additional problem for tailing basins in cold regions is the possibility that the surface of the tailings will sublimate or dry-freeze during cold weather. The effect of the freeze-drying is to remove available water increasing the potential for dusting to occur. It has been observed at mine tailing basins that dusting events are most common during initial freezing periods in the fall followed in the spring when the snow cover is lost.

A solution that has been suggested to prevent dust events is to use paper waste sludge as a thin layer on the surface of the tailings. Since paper sludge is composed of paper fiber and clay, it may bond to the tailing’s surface providing better resistance to wind erosion. An additional benefit of paper sludge is that the layer may also act as an initial insulating layer during the initial freezing period. While this will not stop freezing of the tailings, it will act as a thermal conductivity discontinuity, since the thermal conductivity of the paper fiber and clay is significantly less than that of quartz, which comprises the majority of the iron ore tailings. The result of the thermal conductivity difference between the paper sludge and the tailings is to alter the heat flow rate and allow moisture to collect at the interface between the paper sludge and the tailings. The collection of moisture at the interface may then freeze into a thin ice sheet preventing the dry freezing of the tailings.

The obvious benefit of using paper sludge waste is that it is relatively inexpensive. However, both environmental and operational concerns exist with the application of paper sludge for dust control of iron ore tailing basins. First, most tailings are deposited into a basin in the form of slurry at about 50% solids by volume. Consequently, the bearing capacity of the tailings is poor and the application of the paper waste may be difficult, since machinery will have to be used to apply the paper waste. Second, most water deposited in the
basin is reused through a clarification process. It is possible that the paper waste may cause problems with the clarifiers. Third, while most paper mills do not use chlorinated processes, paper sludge waste is still associated with dioxins, which are regulated as hazardous materials. Some states within the United States still require paper sludge waste to be disposed of in lined landfills. Even though regulatory agencies are now allowing the use of paper waste sludge in a number of civil construction projects, mining companies are reluctant to allow paper waste to be used in tailing basins. This is due to the possibility that paper sludge waste may in the future be again regulated, thus placing the entire tailing basin in a potential expensive environmental remediation problem. Although this is very unlikely to happen, its possibility must be considered. However, for tailing basins with paper mills nearby it is believed that paper waste may still prove effective at controlling dust. Therefore, it is proposed that technical feasibility of using paper waste sludge be considered. Problems as to accessibility on the tailings and clarifier operation are also associated with other dust control technologies and are being successfully solved.
CONTROLLED CLOSING AND AFTER-TREATMENT OF LANDFILLS WITH THE WASTE MATERIALS OF ENERGY PRODUCTION AND INDUSTRY - METHOD DEVELOPMENT

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Stig Lönnqvist, West Uusimaa Regional Solid Waste Management (Rosk and Roll Ltd.), Finland

ABSTRACT

The aim of this development project is to generate a new model for controlled closing of landfills that would be financially feasible as well as environmentally sound to be proved by environmental authorities. The model is suitable for both municipal and industrial landfills.

All methods and action will comply with the present environmental regulations both in Finland and the EU (drafted).

Under the project 20 landfills in the western Uusimaa will be selected for closing and aftertreated in an environmentally sound and sustainable way. This will be done by using the by-products of the local industry and energy production.

The method to be developed will
- increase the costefficiency of landfill closing
- guarantee the quality of surveys and plans of closing
- promote the environmental risk control during and after the closing
- decrease the amount of natural materials used
- promote the reuse of industrial by-products constructions larger and better than nowadays
- create jobs in the region
- increase co-operation between the industry, municipalities and authorities

The experiences will be applied later to other landfills both in Finland and in other EU countries. The methods may be used for other sustainable constructions, too, e.g. groundwater protection and road construction.

The new method will include environmental risk assessment and modern geological measurement methods. The new procedure will contain the following parts:

for every landfill
- a somewhat standardised survey of geohydrological and filling history
- indirect measurements of the structure and conditions of the landfill bank and the surrounding environment
- further geological measurements and analyses of the by-products from industry
- environmental risk assessment
- estimation of the preliminary construction needs and geological stability of the landfill bank
- standardised planning of the covering constructions
- standardised plan for processing the covering constructions
- standardised budget calculating model
for the whole western Uusimaa region
- work programme for closing and after-treatment of landfills.

In the project only the by-products (waste products) of the industry and energy production are used. The excess soil from construction sites may also be included. The material studies have been implemented. The purpose of the material studies was to find out all the possible by-products utilizable in the area and use them the most feasible way. Potential materials are sludge, ashes, foundry sands, glass, excess soil etc.

Sludge produced by Kirkniemi papermill of Metsä-Serla Ltd. and UPM-Kymmene, Lohjan Paperi, can be used for after-treatment. The technical characteristics, processing method and environmental utilizability have been investigated. The material studies confirmed that sludge is suitable for controlled after-treatment of landfills.

Ashes are produced by Metsä-Serla Ltd. In Kirkniemi, by Helsingin Energia and by Espoon Sähkö. The characteristics of the ashes have been investigated. The study showed that the ashes need to be processed using additives and fillers in order to make the rupture and packing characteristics better. The environmental quality of the Kirkniemi ashes has been found to be suitable for landfill locations when packed and isolated.

The end-product of desulphurization comes from Helsingin Energia, Hanasaari powerplant. It has been found to be suitable to be used as an additive with ashes.

The properties of foundry sand from Högfors foundry in Karkkila has been investigated for the technical feasibility. The environmental utilizability studies will be done. The packing and strength characteristics are found excellent. Reclaimed glass can be used for some structure layers even without sorting.
UTILIZATION OF INDUSTRIAL BY-PRODUCTS
FOR SOIL CONSTRUCTIONS IN FINLAND

FIBRE WASTES AND ASHES

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Introduction

In Finland, the development of soil construction materials based on different industrial by-products has brought along a wide and versatile choice of different materials and applications for soil construction. For utilization, the most important by-products are generated in energy production and by the metallurgical, chemical, forest and mining industries. Most of the applications are created for the road construction and landfill constructions (Annexes 1 and 2).

The increasing public pressure on environmental protection is one of the most important reasons for the development stated above. The environment will benefit from the savings of un-renewable natural materials and from the decreasing need to use land for waste disposal. However, there are also both technical and economical benefits from the utilization of new materials based on industrial by-products compensating for traditional construction materials.

Ashes

In Finland, around 1,2 million tons of different ashes are generated each year. Out of this, appr. a half is from the coal combustion processes and the other half from power plants combusting peat, wood and miscellaneous feedstock as fuel.

Apart from the environmental benefits there are both technical and cost related reasons to support the use of ashes as construction material: for example most of the ashes are beneficial for road base and sub-base courses due to their significant strength development, frost resistance and lightness. This fact brings along economic benefits; for example, sometimes a road can be constructed and maintained with even 50% less costs than by using traditional construction materials. Nowadays, research and development of ashes is concentrated on the utilization of ashes as stabilization component for different types of soil and as a binder component for materials based on other industrial by-products.
Fibre wastes

Each year the Finnish forest industry is generating around 0.5 million m$^3$ of fibre wastes which can be utilized in soil construction. The development of fibre wastes for soil construction applications started in Finland at the beginning of the 1990’s. The most important applications are the sealing layers of landfills and the different courses and structures of road constructions.

In Finland, the fibre-ashes and stabilized fibre waste has been used in road test constructions. The preliminary results are very promising. The fibre waste gives the road resilience or deformation resistance, which is important for road constructions on slightly frost heaving or yielding sites. Road construction materials based on fibre waste also bring along cost savings in construction.

The sealing layers (caps and liners) for landfills can be constructed by using fibre wastes. This kind of application is especially interesting as an effective way to utilize a current waste material. The permeability of compacted fibre waste can be as low as $10^{-9}$...$10^{-9}$ m/s, even lower when mixing the fibre waste with certain additives. Fibre wastes are beneficial when plasticity of construction materials is essential, like for sealing caps on landfill sites with unevenly bending deformation. In case the material based on fibre waste is required strength, frost resistance and freeze-thaw performance, it must be mixed with commercial stabilizers or other industrial by-products (like ashes).

Development of new soil construction materials

Re-use of industrial by-products in soil construction requires massive and wide research and development. For example, during the development there have been separate test arrangements for the resistance to fatigue in different climatic circumstances and with different traffic loads. Further, Viatek Ltd/SGT has developed a laboratory testing system where a sample is tested for durability and resistance to fatigue with different successive stress factors like acid seepage water, freeze-thaw cycles, impregnation with water and loading. The environmental acceptability of new materials is essential, and it is studied mostly by leaching tests and by analysing the content of environmentally harmful substances in leachates and in by-product itself. The environmental tests are run parallel with the technical tests.

Following schema (p. 3), created by SGT, is a description about the development process of soil construction materials based on re-usable by-products. As an example, materials based on industrial by-products have been developed for basically 12 different road structure applications. A different test programme is required for each of the applications (see Annex 3).
BASIC INFORMATION OF THE RESIDUES

STUDIES OF TECHNICAL POSSIBILITIES
- CHOSEN MIXES
- CRITICAL PROPERTIES

OPTIMIZATION OF MIXES
- MIXING RATIO
- AMOUNT OF BINDER OR ADDITIVE

TESTING OF ENVIRONMENTAL ACCEPTABILITY
- leaching of harmful substances by diffusion / infiltration
- degradation (biological, chemical)
- chemical changes in material in the long term
- changes in organic content in the long term

TESTING OF TECHNICAL PROPERTIES AND ACCEPTABILITY
- compressibility
- stress-strain properties
- dynamic stress behaviour
- water resistance
- frost susceptibility
- freeze-thaw durability
- creep
- permeability (of water)
- infiltration (long-term)

TEST CONSTRUCTION

COMMERCIALIZATION
ANNEX 1

TECHNOLOGY OF RECYCLED MATERIALS
ANNEX 2

PROTECTION AND SEALING CONSTRUCTIONS
BY STABILIZATION

I. PROTECTING LINER BY STABILIZATION

II. SEALING CONSTRUCTION BY STABILIZED CAP AND LINER

III. DAM WALL BY STABILIZATION
# ANNEX 3

## BY-PRODUCT APPLICATIONS IN ROAD- AND STREET STRUCTURES

1. **PAVEMENT**
2. **LAYERS OF THE STRUCTURE**
3. **FROST INSULATION**
4. **EMBANKMENT**
5. **SLOPE COVER**
6. **GROUND WATER PROTECTION**
7. **DRAINAGE STRUCTURE**
8. **TRENCH FILLING**
9. **GRATE STRUCTURES**
10. **NOICE WALL**
11. **DEEP STABILIZATION STRUCTURE**
12. **MASS STABILIZATION STRUCTURE**

<table>
<thead>
<tr>
<th>PROPERTY TO STUDY</th>
<th>APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMPOSITION (BY-PRODUCTS)</td>
<td>1 2 3 4 5 6 7 8 9 10 11 12</td>
</tr>
<tr>
<td>COMPRESSIBILITY</td>
<td>X X X X X X X X X X X X</td>
</tr>
<tr>
<td>STRESS-STRAIN</td>
<td>X X X X X X (X) X X X X</td>
</tr>
<tr>
<td>WATER RESISTANCE</td>
<td>X X X X X X X (X) X X X</td>
</tr>
<tr>
<td>DYNAMIC STRESS BEHAVIOUR</td>
<td>X X X (X)</td>
</tr>
<tr>
<td>CREEP</td>
<td>X X X</td>
</tr>
<tr>
<td>FREEZE-THAW DURABILITY</td>
<td>X X X (X)</td>
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<tr>
<td>THERMAL CONDUCTIVITY</td>
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<tr>
<td>FROST SUSCEPTIBILITY</td>
<td>X X X</td>
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<td>PERMEABILITY (OF WATER)</td>
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<td>INFILTRATION (LONG-TERM)</td>
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<td>ENVIRONMENTAL SAFETY</td>
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<td>DEGRADATION (LONG-TERM)</td>
<td>X X X X X X X X X</td>
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</tbody>
</table>

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DEINKING SLUDGE AND FLY ASH ROAD IN LUOPIOINEN

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ABSTRACT

Two industrial secondary materials: deinking sludge and fly ash were evaluated in the test construction of the road in Luopioinen. These materials were used in one of the layers as a 200 mm thick construction. There were two different mixtures of these materials included in the test construction.

The road of Rajalantie in Luopioinen was in very bad condition because of the frost heave during winters. During the summer 1996 the entire road was dig open to the depth of about 0.5 meters by using excavator. After that new layers were constructed. Two different industrial secondary materials were used in this 800 meters long road. The materials were deinking sludge and fly ash.

The test road was divided into four sections. The first part was constructed by using fly ash togerther with a binder. The second section was made of the mixture of deinking sludge, fly ash and a binder. The next part of the road was constructed in a normal way using crushed gravel. This part is the reference construction. The last section was made from another mixture of deinking sludge, fly ash and a binder. The rations were different. This mixture contains more deinking sludge and less fly ash than the first one.

This project was financed by the paper mill of Nokia Paper Ltd., the municipal of Luopioinen and Kemira Fibres Ltd. A part of the financing came from the developement funds of European Union. Also Technology Development Centre Finland has supported Nokia Paper Ltd. in its development project before this test road construction.

Changes of the properties were measured with several test methods. The results were compared with each other and also with reference constructions. Experiences after a year indicate that test construction has fulfilled its purposes.
USE OF PAPER MILL SOLID WASTES AS LANDFILL COVER MATERIAL: A LABORATORY STUDY

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ABSTRACT

The geotechnical properties of sludge and ash from a paper mill were studied in the laboratory to evaluate the suitability of these wastes as landfill cover material. The effect of bentonite on permeability was also investigated. The individual materials and various mixes were subjected to permeability and shear strength tests. The sludge and mixtures of sludge and small amounts of ash generally were close to $1 \times 10^{-9}$ permeability values and easily met the draft guideline limit values of $5 \times 10^{-9}$ permeability for cover material of existing landfills. The addition of bentonite decreased the permeability only slightly for sludge, but for samples with 35% of ash the decrease of permeability was significant.

INTRODUCTION

The increasing amount of solid wastes generated at the pulp and paper mills and more stringent landfill regulations have lead to elevated landfill costs. This has urged the industry to find new ways of utilizing solid wastes.

In addition, more stringent requirements concerning landfill liners and covers may be financially burdensome for the mills. About 500 municipal and other landfills in Finland are expected to be closed by the end of this century (Saarela 1997) and the need of suitable cover material is increasing.

One potential way to increase utilization of solid wastes and to decrease landfill closure costs at the same time is to substitute the commonly used clay in landfill constructions with sludges and ashes generated in the pulp and paper industry. Paper mill sludges containing kaolin used in the manufacturing have similar impervious properties as clay. Moreover, the fibrous organic material in the sludge gives the material a more flexible character, which decreases cracking in the capping material.

The purpose of this laboratory study was to investigate the geotechnical properties of solid wastes produced at one paper mill in order to evaluate their suitability as cover material for landfills. To achieve these objectives laboratory tests included permeability tests, moisture-density relationships, strength and compressibility of sludges and ashes with and without admixtures. This paper concentrates on the results of the laboratory tests made on the hydraulic permeability properties.

NATIONAL REQUIREMENTS FOR LANDFILL COVERS

National guidelines for landfill constructions are being prepared for both existing and closed landfills (FEI 1997a, FEI 1997b). The draft limit value requirement for the
permeability of the coverconstruction is $5 \times 10^{-9}$ for existing landfills. Closed landfills situated in groundwater areas have the draft permeability requirement of $1 \times 10^{-9}$ and closed landfills outside groundwater areas $1 \times 10^{-8}$. In addition to provide a barrier to water infiltration the construction has to be durable, stable and inert. These draft limit values presented are guide values and the final requirements are set by the regional environmental authorities case by case.

**MATERIALS AND METHODS**

Sludge from the wastewater treatment plant and fly ash from the energy production of one Finnish paper mill were investigated.

The papermill in question produces 500 000 tonnes of wood containing paper annually using kaolin clay in the paper manufacturing.

In 1995, 21 000 tonnes of sludge and 14 000 tonnes of ashes were deposited at the company's landfill.

The main fuel for energy production is coal. Natural gas, bark and oil are incinerated as well.

Based on previous studies (NCASI 1989, Zimmie et al. 1995) it was presumed that the permeability properties of sludge were close to requirements set by authorities and that plain ash would not meet requirements. Ash was added to sludge to determine the influence on different properties (i.e. strength and permeability).

The influence on hydraulic permeability of the addition of small quantities of bentonite to the sludge and sludge/ash mixtures was also investigated.

**PROPERTIES OF THE WASTES TESTED**

The combined sludge consists of primary sludge from the sedimentation basin and biological sludge from the activated treatment plant. The sludge contains about 50 % kaolin clay originating from the paper production.

The moisture content of the sludge varied from 145 to 165 % and the moisture content of the ash from about 18 to 22 %. Based on dry weight of sludge it is of equivalent to 41 % and 38 % dry solids, respectively and of ash 85 % and 82 % dry solids, respectively.

The inorganic content of the sludge was approximately 42 % of dry solids. The inorganic content of the ash varied from 75 to 85 %.

The heavy metal content and the leachability of heavy metals from the wastes were analyzed to assess the transportation of these harmful compounds to the environment. The heavy metal content was fairly low in all wastes and the leachability of heavy metals very low. The heavy metal content in the leachate in the EPA TCLP-test was far below the limit values.
HYDRAULIC PERMEABILITY TESTS

Sample preparation

The sludges and ashes were thoroughly blended in 90:10 and 65:35 ratios of dry weight. The effect of addition of bentonite on the permeability was investigated by adding 2 %, 4 % and 6 % of bentonite to the sludge and to the mixtures of sludge and ash. The amount of bentonite to be added was calculated in wet weight (approximately 12 %) in relation to the dry weight of the sludge/ash sample.

The mixtures of 65/35 were chosen based on the approximate equal sludge/ash ratio produced at the mill. The quantities of added bentonite were kept fairly low to keep the assumed landfill cover construction costs realistic.

The samples were compacted using the modified Proctor method. The plain fly ash sample was compacted to 96 % of the optimum water content (37 %). All other samples were compacted in moisture contents as received from the mill. The dry solids content of the sludge reached (38-41 %) with the belt filter presses used at the mill is below the optimum water content, but at this stage it was not seen important to dry the samples to optimized moisture content from a practical point of view. The sludge is, however, quite wet in this moisture content and free water squeezes from the samples when compacted. Even after mixing 35 % of ash with sludge the optimized moisture content was not reached using modified Proctor method. Zimmie et.al. (1995) have on the other hand reported that the workability of paper mill sludge at optimum density and moisture content is poor and a high water content is desirable if the sludge is to be used as capping material.

Hydraulic permeability test equipment

Hydraulic conductivity test conducted during this research were made with flexible wall permeameter cells. The test equipment is shown in Fig. 1.

Permeameters were operated with constant head hydraulic systems with hydraulic gradients ranging from 11 to 40. The tests started at lower pressures and the pressures were raised in the end to assess sensitiveness to erosion.

Back pressure was applied to all samples to maximize sample saturation. The cell pressure was 215 kPa and the effective pressure in the samples was kept at about 30 kPa.

Figure 1. Hydraulic permeability equipment
Results of the permeability tests

The results of the permeability tests are shown in Tables 1 and 2. All the results in the Tables are based on single tests. Duplicate tests for all samples in Table 1 were run, with results very close to the reported.

Table 1. Permeability of the wastes

<table>
<thead>
<tr>
<th>Material</th>
<th>Moisture content(%)</th>
<th>Dry density kN/m³</th>
<th>k (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sludge</td>
<td>163</td>
<td>3.9</td>
<td>2.3x10⁻⁹</td>
</tr>
<tr>
<td>ash</td>
<td>312</td>
<td>10.7</td>
<td>3.8x10⁻⁷</td>
</tr>
<tr>
<td>sludge/ash 90/10</td>
<td>140</td>
<td>4.8</td>
<td>2.0x10⁻⁹</td>
</tr>
<tr>
<td>sludge ash 65/35</td>
<td>105</td>
<td>5.3</td>
<td>4.7x10⁻⁸</td>
</tr>
</tbody>
</table>

Table 2. Permeability of the wastes with bentonite added

<table>
<thead>
<tr>
<th>Material</th>
<th>Moisture content(%)</th>
<th>Dry density (kN/m³)</th>
<th>k (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90/10 + 2 % AC200</td>
<td>146</td>
<td>4.5</td>
<td>2.8x10⁻⁹</td>
</tr>
<tr>
<td>65/35 + 2 % AC200</td>
<td>107</td>
<td>5.5</td>
<td>2.0x10⁻⁹</td>
</tr>
<tr>
<td>100/0 + 4% AC200</td>
<td>153</td>
<td>4.0</td>
<td>1.2x10⁻⁹</td>
</tr>
<tr>
<td>90/10 + 4% AC200</td>
<td>140</td>
<td>4.6</td>
<td>1.9x10⁻⁹</td>
</tr>
<tr>
<td>65/35 + 4% AC200</td>
<td>108</td>
<td>5.4</td>
<td>1.5x10⁻⁹</td>
</tr>
<tr>
<td>100/0 + 6% AC200</td>
<td>145</td>
<td>4.3</td>
<td>1.7x10⁻⁹</td>
</tr>
<tr>
<td>90/10 + 6% AC200</td>
<td>140</td>
<td>4.5</td>
<td>1.6x10⁻⁹</td>
</tr>
<tr>
<td>65/35 + 6% AC200</td>
<td>106</td>
<td>5.5</td>
<td>1.1x10⁻⁹</td>
</tr>
</tbody>
</table>

All samples tested demonstrated a decrease in hydraulic permeability approaching a steady state value as a permeability run progressed. The increase of the hydraulic gradient in the end of the tests did not have any significant effect on permeability.

Plain paper mill sludge gave a coefficient of permeability of about 2x10⁻⁹ m/s. The permeability decreased further as the test continued. Plain fly ash gave a permeability of the order of 4x10⁻⁷ m/s.

The addition of small amounts of ash to the sludge decreased slightly the permeability, but the addition of 35 % of ash increased the permeability significantly.
The addition of bentonite didn't have a significant effect on permeability, except for the sample with 65/35 % mixture of sludge and ash, for which permeability was one order of magnitude lower than the sample without bentonite. Similar results have been obtained in other studies, where bentonite was added to ash and mixtures of ash and desulfurization products (Kotola 1997).

**SHEAR STRENGTH TESTS**

The shear strength of some samples were determined using drained triaxal compression tests.

The samples were compacted by hand in 5.0 cm diameter tubes. The height of the samples were approximately 10 cm. The samples tested were, plain sludge, plain ash and 65/35 mixture of sludge and ash.

The test series used consolidation pressures of 25, 50 and 100 kPa.

Failure was difficult to determine from the stress-strain curves of the sludges, which are typical of soft compressible material in that they exhibit no sharp yield point (Zimmie et al. 1995). The sludge and the 65/35 % sludge/ash samples were compressed until 40 % and still no failure point could be determined. For that reason the failure was defined at 20 % of strain. The plain ash sample failed at below 5 % of strain.

At 20 % of strain for sludge the effective angle of internal friction was 26 degrees with a cohesion of 17. For the 65/35 mixture of sludge and ash the angle of internal friction was 31 degrees and the cohesion 28. When defining failure at a different strain the parameters will naturally change.

**EFFECTS OF DRYING ON THE MATERIALS**

Samples of sludge and mixtures of sludge and ash (65/35) were air dried in room temperature for several weeks. Air drying indicated a change of 6-8 % of volume in the sludge sample and a change of 4 % in the mixed sludge/ash sample. Only minor shrinkage cracks were visible in the samples. Stoffel and Ham (1979) have reported that paper mill sludge has the capability of "self-healing" of cracks when rewetted (Jedele 1987).

**CONCLUSIONS**

According to the laboratory test made, papermill sludges and ashes could be potential sources of material for use as a cover of landfills. Sludge itself is rather impervious and its fibrous nature gives it a flexible character. Plain ash is not impervious enough in itself, but small amounts of ash added to sludge even improves the impervious properties of sludge. Plain ash is also non-plastic on its own and may be subject to cracking (Sarsby & Finch 1995).
As stated previously, the permeability of plain sludge and different mixtures of sludge and ash were only slightly higher than $1 \times 10^{-9}$, and easily meet the draft requirements of cover materials for existing landfills.

The addition of bentonite to sludge samples didn't decrease the permeability significantly. Interesting was to note that the addition of only 2% of bentonite to the sludge/ash 65/35 mixture decreased the permeability one order of magnitude. An increased amount of bentonite didn't further effect the permeability significantly. Obviously, already small amounts of bentonite decreases the permeability of ashes but has no significant effect on sludges. The negligible effect on sludge is probably also due to difficulties of mixing bentonite to wet sludge.

The sludge and the mixed sludge/ash samples are very compressible and no sharp yield point could be determined in the triaxial shear strength tests. The placement of a 1-1.5 meter thick surface layer would increase the effective stress to about 25 kPa on top of the barrier material, which shouldn't cause any major problems according to the strength tests. The peak overburden of construction machines working on landfills must however also be taken into consideration.

It should be noted that the permeability in field conditions might increase due to difficulties in compaction of the material, cracking, biodegradation etc. Consolidation of the material will on the other hand probably decrease the permeability when placed on landfills due to placement of larger overburden. The effects of freezing and thawing will presumably be negligible due to frost penetration protection properties of the surface layers, which will be required in landfill closures.

ACKNOWLEDGEMENTS

This study was made in the Laboratory of Environmental Protection at the Helsinki University of Technology. The hydraulic permeability tests were conducted at the Laboratory of the Finnish Environment Institute. The study is financed by the Foundation Maj and Tor Nessling, which is greatly acknowledged.

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FEI. (1997b). Guidelines for planning of landfill covers (draft). Finnish Environment Institute, Helsinki, Finland (in Finnish)


LYSIMETER STUDY OF MINERAL-BASED LANDFILL COVER MATERIALS IN KUJALA LANDFILL

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ABSTRACT

Mineral-based hydraulic barrier materials are studied in a test field in Kujala landfill (Lahti, Southern Finland). The test field consist of five lysimeters, each 5m×50m, for studying clayey silt, sand-bentonite, fly ash and two engineered fly ashes. Thickness of the barrier layer is 30 or 80 cm and layers are covered with 80 cm sand and 10 cm mould. The test field have been monitored both automatically and manually since autumn 1995. The measured subsidence of the test field has been extensive and differential. Approximately 1.5 m thick test structure has remained unfrozen excluding thin upper layer also during winter because of snow cover and heat produced by decomposition of the waste. Percolation through different barrier layers has varied in large scale. Sand-bentonite has proven to be the most and fly ash the least effective hydraulic barrier of the studied materials.

1. TEST FIELD, MONITORING SYSTEM AND CONSTRUCTION

This research project started in autumn 1994 and a year later the test field was constructed. The test field is situated in Kujala landfill and there is approximately 15 m of municipal solid waste under the test field. The test field consist of five 5×50 m² lysimeters for studying different hydraulic barrier materials (Fig. 1). The slope is 3 % along the longer axis and 0 % along the crossing axis. The barrier materials being tested and the thickness of layers are: clayey silt and fly ash 80 cm, sand-bentonite and two engineered fly ashes 30 cm. Barrier layers are covered with 80 cm of fine sand and 10 cm of mould as a protective and vegetation layer (Fig 2).

Each lysimeter discharge is collected into its own measuring well where a pressure sensor is recording the water level. The measuring well is used as a storage tank and pumped empty when the water has risen to the desired level. There is a measuring weir in the upper part of the well, which can be used to measure the discharge when the well is not pumped. Surface runoff is collected into one measuring well from the area of the whole test field (Fig. 1).
Subsidence monitoring plate
Pipe for soil moisture measurements (neutron-based)
Soil temperature probes (10, 50, 100 cm)

1 Engineered fly ash 1
2 Engineered fly ash 2
3 Sand-bentonite
4 Fly ash
5 Clayey silt

Figure 1. Test field overview and instrumentation.

Figure 2. Principal cross section of a lysimeter.
The system for monitoring the test field is both automatic and manual. Measuring well pressure sensors, weather station and soil temperature probes are connected to a central unit, which stores data on a computer disc at 15 minutes intervals. Once a day data is transferred via modem to an office computer in HUT. Manual monitoring consist of subsidence and soil moisture measurements.

Because of the large scale it was possible to use normal working methods and machines when constructing the test field. However, some problems occurred during the construction. HDPE insulating sheets between barrier layers (Fig. 2) caused some limitations and it was impossible to compact barrier layers properly next to the sheet. Also fly ashes were difficult to compact and the desired compaction was not quite achieved.

2. SUBSIDENCE

Test field subsidence has been monitored with subsidence monitoring plates situated in the top of the barrier layer. There are totally 20 plates, four plates in each lysimeter (Fig. 1). Subsidence of the test field has been 29-66 cm in one year (Fig. 3). Subsidence has been differential and the biggest subsidence has occurred in the lower end and the smallest in the upper end of the test field.

![Figure 3. Test field subsidence during the first monitoring year.](image)

3. AIR AND SOIL TEMPERATURES

Air and soil temperatures have been measured automatically at 15 minutes intervals. There are soil temperature probes in two lysimeters 10, 50 and 100 cm from surface (Fig. 1). Only thin upper layer of the protective/vegetation layer was frozen and only short time in winter 1995-1996 despite low air temperatures in winter (Fig. 4 and 5). Hydraulic barriers and most of the protective layer remained unfrozen whole winter 1995-1996 (Fig. 4 and 5).
4. k-VALUES OF THE BARRIER MATERIALS

In the beginning of the project different materials and mixtures were tested in laboratory to select suitable barrier materials for the test field. Hydraulic conductivity (k-value) was an important selection criteria. k-values were measured also 27.11.1996 (approximately 14 months after construction) when samples from hydraulic barriers were taken. Hydraulic conductivity of fly ashes was much lower when compacted in laboratory than in the test field (Table 1). Hydraulic conductivity of the sand-bentonite was lower in the test field than in the laboratory (Table 1) because swelling of the bentonite may last few months.
Table 1. Hydraulic conductivity (k-value) of the barrier materials. A) Test sample compacted in laboratory conditions. B) Sample taken from the test field 27.11.1996.

<table>
<thead>
<tr>
<th>Material</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand-bentonite</td>
<td>$2 \times 10^{-9}$ m/s</td>
<td>$3 \times 10^{-10}$ m/s</td>
</tr>
<tr>
<td>clayey silt</td>
<td>(not measured)</td>
<td>$7 \times 10^{-9}$ m/s</td>
</tr>
<tr>
<td>engineered fly ash 1</td>
<td>$3 \times 10^{-9}$ m/s</td>
<td>$7 \times 10^{-7}$ m/s</td>
</tr>
<tr>
<td>engineered fly ash 2</td>
<td>$4 \times 10^{-10}$ m/s</td>
<td>$3 \times 10^{-7}$ m/s</td>
</tr>
<tr>
<td>fly ash</td>
<td>$2 \times 10^{-7}$ m/s</td>
<td>$9 \times 10^{-7}$ m/s</td>
</tr>
</tbody>
</table>

5. WATER BALANCE

Precipitation, percolation through barrier layers and surface runoff has been measured. There has been some problems when calculating the water balance: percolation through fly ash seems to be greater than precipitation (Fig. 6). Reason for this can be found in the test field structure. The insulating sheet between lysimeters covers only barrier layers allowing water to flow from one lysimeter to another via protective and vegetation layers above the barriers (Fig. 2). Obviously there has been flow from the most impermeable lysimeters, sand-bentonite and clayey silt, to the fly ash lysimeter.

Percolation has varied in large scale (Fig. 6). Sand-bentonite has been most effective barrier and percolation only few mm/year. Percolation through fly ashes has been greater than expected beforehand. It was difficult to compact fly ashes properly and achieve the same permeability in a test field scale as in a laboratory scale. Engineered fly ash 2 proved to be very inelastic which may cause cracks and increase in permeability, especially if there are displacements and settlements. It must be taken into account that properties of fly ashes depend on raw materials and processes.

![Figure 6. Cumulative precipitation, surface runoff and percolation through barrier layers.](image-url)
REFERENCE


Colucci P. & Lavagnolo M. C. Three years field experience in electrical control of synthetic landfill liners. Proceedings Sardinia 95, Fifth International Landfill Symposium, S. Margherita di Pula, Cagliari, Italy; 2-6 October 1995, s. 437-452.


DETERMINATION OF THE ADSORPTION CAPACITY OF PAPER SLUDGES FOR USE AS A REACTIVE IMPERMEABLE BARRIER

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ABSTRACT

Heavy metals such as chromium, lead, and iron, and volatile organic compounds such as benzene, toluene, ethylbenzene and xylene, are difficult to remove from ground water. Methods of remediation for heavy metals include containment, pump and treat, and electrokinetics. For volatile organic compounds, the source substance may be treated by proven methods of remediation such as air stripping, soil vapor extraction, bio-venting or bio-degradation. However, residual saturation provide these compounds with continuous access into the aqueous phase. Pump and treat methods require extraction of large amounts of groundwater to the surface for treatment. When the aqueous concentrations of the contaminants are low, these methods may not be feasible or effective.

An alternative to the treatment of contaminated soil/ground water is containment of the contaminant in-situ. Slurry walls are currently used as passive vertical barriers to control the horizontal flow of contaminated ground water. To date, slurry walls have not been utilized for treating contaminated ground water that passes through the wall.

This study aims to look at the feasibility of constructing a reactive impermeable barrier utilizing paper mill sludge. The proposed barriers will utilize the best properties of the material: high organic content, low permeabilities and high water contents and/or low solid contents. Since paper mill sludges are considered a waste product, they are provided to the user at little or no cost.

Preliminary batch equilibrium tests indicate paper sludge may be an excellent sorbent for the heavy metals chromium, lead, and zinc.

1. Background

Contamination of the world's aquifers by heavy metals, such as lead, zinc and chromium, continues to be a major threat to drinking water supplies in industrialized countries. From smelting operations in Poland, to metal plating facilities on military bases across the United States, heavy metal wastes in the form of tailings, waste water, slags, etc., have produced unacceptable environmental conditions which cost governments and industry billions of dollars each year for clean-up efforts.

Current remediation technologies, including pump and treat methods and electrokinetics, have been employed with varying degrees of success. These efforts
have been time and energy consuming, expensive, and/or ineffective, depending on site geology, soil structure, and contaminant constituents and concentrations. Therefore, research and developmental technologies which stress in-situ containment and treatment should be promoted. This approach limits the migration of contaminants while providing relatively inexpensive remediation.

Slurry walls are widely used as passive vertical barriers to control the horizontal flow of contaminated ground water. Soil-bentonite is the most commonly employed slurry wall, composed of a backfill mixture of soil, bentonite, and water. The term 'slurry trench' is derived from the method of construction where a bentonite-water slurry is placed in the excavated trench in order to maintain side-wall stability. This technique has been used for over 40 years in various applications, including vertical barriers for subsurface control of migration of sewage, acid mine waste, chemical wastes, and municipal landfill leachate.

Raw sodium bentonite utilized in the construction of slurry walls currently cost approximately $70-100 per ton (excluding shipping, handling, and construction costs). Once a contaminant has been contained by a slurry, pump and treat technologies are often utilized to remove the contaminant from the subsurface. Pump and treat systems are usually designed for a 20 to 30 year life span, dramatically increasing the total cost of remediation through maintenance, energy and monitoring costs.

To date, the actual slurry wall structure has not been used as a medium to treat contaminated ground water migrating through the wall. The aim of this study is to assess the feasibility of utilizing paper-mill sludges for "active" barrier applications. These slurry walls not only contain the contaminants, but also attenuate the contaminants as the ground water passes through the barrier system.

Paper mill sludges have high water contents and low solids contents when compared to clays. However, they can still be compacted to low permeabilities and have been used as a substitute for clays in landfill covers. Since 1975, paper mill sludges have been used to cap landfills in Wisconsin, and more recently, new landfill covers have been constructed in Massachusetts and New York State with paper sludge cap systems (Pepin, 1984; Swann, 1991; NCASI, 1992; Moo-Young and Zimmie, 1996). Paper mill sludges typically consist of 50% clay and 50% organic fibers and tissues. Since paper mill sludges are considered a waste product by the paper industry, they are provided to the user at little or no cost.

Figure 1 shows a conceptual layout for a reactive impermeable barrier. Contaminants transported by the natural hydraulic gradient would be immobilized by the sludge. Paper sludge contains a high organic content which acts as a carbon source to support microbial growth and functions as an electron acceptor in oxidation and reduction reactions.

Paper sludge has a low hydraulic conductivity $(1 \times 10^{-7} \text{ cm/sec or less})$, which makes the material ideal as a hydraulic barrier. Other properties that make paper sludge an ideal candidate for use as a slurry material are a high initial water content (200% or greater) and a low initial solids content (15-20%). Most slurry walls are constructed with bentonite which has a solid content of 5-15% before the addition of backfill soil.

In this preliminary study, sequential batch equilibrium tests were conducted on paper sludge and heavy metals (chromium, lead and zinc) to determine adsorption isotherms for each metal. Isotherms reveal the magnitude of adsorption, estimates of how much contaminant is sorbed, and change in absorption capacity with respect to contaminant concentration.
2. Analytical Procedures

Batch Adsorption Tests

A series of sequential batch equilibrium tests of heavy metal aqueous solutions at varying concentrations were conducted on paper sludge from a local paper mill. Sequential batch leaching is a procedure for determining how the equilibrium distribution of contaminants between solid phase and aqueous phase changes during elution with water. Batch tests are used as a screening mechanism to determine the magnitude of sorption that occurs. Equilibrium isotherms were developed from the batch test data for a specific sorption media exposed to various concentrations of specific contaminants in aqueous solution.

Batch tests are normally conducted on reactive mixture suspensions prepared with air dried soil and distilled-deionized water mixed with a specific amount of dissolved contaminant in a sealed container (Roy et al., 1991). However, due to the nature of paper sludges, the material was not allowed to dry beyond a critical point in order to maintain the desired hydraulic and moisture-density characteristics (Moo-Young & Zimmie, 1996). Therefore, the sludge was tested “as received” from the paper mill.

The contaminant and paper sludge were combined in a 200 ml container. The container was then agitated until equilibrium occurs (typically 24 hours, however 48 hours will be used in the preliminary study). The equilibrium concentration of the contaminant was obtained from measurements of the liquid phase ions following centrifuge separation of the liquid from the solids. This value was compared to the initial
concentration of the contaminant, and used for construction of the adsorption isotherm. The mass balance relationship used to determine the amount of contaminant sorbed to the soil surface was as follows:

\[ q_{\text{batch}} = \frac{(C_0 - C_{\text{eq}})(V - m/\rho)}{m} \]  

(1)

where:
- \( q_{\text{batch}} \) = sorption capacity of the solid for the solvent (mg/g),
- \( C_0 \) = initial contaminant concentration (mg/L)
- \( C_{\text{eq}} \) = equilibrium contaminant concentration in solution at the end of test (mg/L)
- \( V \) = total volume of the batch reactor (L)
- \( m \) = mass of sorbent placed in reactor (g)
- \( \rho \) = mass concentration of the sorbent (g/L).

There are three commonly used adsorption models that can be fitted to the sorption data produced by the batch sorption tests: the linear adsorption isotherm, the Freundlich adsorption isotherm, and the Langmuir adsorption isotherm. These are described in the following equations (Roy et al., 1991):

Linear adsorption isotherm

\[ q_{\text{batch}} = K C_{\text{eq}} \]  

(2)

Freundlich adsorption isotherm

\[ q_{\text{batch}} = K_f C_{\text{eq}}^{1/n} \]  

(3)

Langmuir adsorption isotherm

\[ q_{\text{batch}} = \frac{K_L M C_{\text{eq}}}{1 + K_L C_{\text{eq}}} \]  

(4)

where:
- \( K \) = partition coefficient (L/g)
- \( K_f \) = Freundlich equilibrium isotherm empirical constant (\((L^{1/n} \text{mg}^{(1-n)/n})/g\))
- \( n \) = empirical constant (dimensionless)
- \( K_L \) = Langmuir equilibrium isotherm empirical constant (L/mg)
- \( M \) = empirical constant (mg/g)

By linearizing equations 3 and 4, a least square regression analysis was performed on the data. In this study, the adsorption isotherm which yields the best fit (as indicated by the \( r^2 \) or 'goodness of fit' calculation) for each individual contaminant/adsorbent system was used (Freundlich). Three useful pieces of information were provided by the adsorption isotherms:

a. The adsorption magnitude of the contaminant.
b. The development of an equilibrium capacity to provide a basis for preliminary estimate for how much contaminant is sorbed.
c. The adsorptive capacity changes relative to contaminant concentrations.
Chemical Analysis

Analysis of heavy metals were conducted using standard EPA lab procedures for batch studies (Roy, et. al. 1991) in the geotechnical and environmental laboratories at Lehigh University in Bethlehem, Pennsylvania. Heavy metal concentrations were determined using an Perkin Elmer AAnalyst 100 Atomic Adsorption Spectrometer.

3. Initial Batch Study Results

Initial batch equilibrium studies were completed to determine the feasibility of employing paper sludge as a sorbent for heavy metals (zinc, chromium and lead). In these tests, the 'as-received' paper sludge was batch reacted with zinc, chromium and lead aqueous solutions at concentrations of 1,000 ppm, 5,000 ppm, and 10,000 ppm. Figures 2, 3 and 4 show the adsorption isotherms for zinc, chromium and lead, respectively. Isotherms developed for zinc, chromium and lead show positive trends for utilizing paper sludge to attenuate these metals from solution (Figures 2, 3 and 4). The Freundlich isotherm model yielded the best fit for all three heavy metals during the initial batch studies. It should be noted that while the initial results cast a positive light on using paper sludge as a reactive impermeable barrier, further testing is still required. In comparison to kaolinite clay, the paper sludge adsorbed more contaminants. For zinc, paper sludge adsorbed a higher amount of contaminant in comparison to kaolinite (Shackelford and Daniel, 1991).

![Zinc Sorption Isotherm](image)

Figure 2 - Zinc Sorption Isotherm
Chromium Freundlich Isotherm

\[ q = 0.0002 \times C_{eq}^{(1/0.65961)} \]

\[ r^2 = 0.962 \]

Figure 3 Chromium Sorption Isotherm

Lead Sorption Isotherm

\[ q = 1.31936 \times C_{eq}^{(1/2.8463)} \]

\[ r^2 = 0.976 \]

Figure 4 Lead Sorption Isotherm
The transfer by adsorption or other chemical processes of contaminant mass from the pore water to the solids during flow causes the advancing front to be retarded. To take this into account, the retardation factor is computed. Fick's second law for reactive solutes subjected to reversible sorption reactions during diffusive transport in soils takes retardation into account where:

$$\frac{\partial c}{\partial t} = \left( \frac{D^*}{R_d} \right) \left( \frac{\partial^2 c}{\partial x^2} \right)$$  \hspace{1cm} (5)

where:
- \( c \) = concentration
- \( t \) = time
- \( D^* \) = effective diffusion coefficient,
- \( R_d = \) Retardation factor = \(-1 + \rho/n^{K_p} \)  \hspace{1cm} (6)
- \( \rho \) = density
- \( n \) = porosity
- \( K_p \) = Partition coefficient = dq/dc.

When the \( q \) versus \( c \) relationship is linear, the partition coefficient is termed the distribution coefficient. If \( q \) versus \( c \) is nonlinear, then the partition coefficient is a function of the equilibrium concentration in the porewater of the soil. For nonreactive solutes, the partitioning coefficient is equal to zero. For the paper sludge, the retardation factors based on equation 6 are 1.5 to 3 for zinc, 6 to 17 for chromium, and 3 to 11 for lead. These results compare favorably to results obtained for kaolinite clay which is expected since paper sludge is 50% kaolinite (Shackelford and Daniel, 1991).

4. Conclusion

In this study, the feasibility of utilizing paper mill sludge as a reactive impermeable barrier to mitigate against the movement of heavy metal contamination in the subsurface was studied by conducting sequential batch equilibrium tests. Initial batch test results show that paper sludge may provide an adequate sorbent to stop the movement of contaminants in the subsurface. In comparison to kaolinite clay, paper sludge which is composed of 50% clay and 50% organics adsorbed two times the amount of contaminant.

5. Future Work

Although these initial test results are promising, there is much work to be done to further define the feasibility of utilizing paper sludge to mitigate subsurface contamination. The specific objectives of future work are itemized below:

1. A series of batch equilibrium tests of selected pure and mixed compounds will be conducted using paper mill sludge, fly ash, and lime mixtures. Equilibrium isotherms will be developed from the batch test data for different paper sludge mixtures exposed to various concentrations of contaminant.
2. One dimensional column studies will be conducted to quantify the metal immobilization efficiency of the paper sludge.
3. The results of both the batch studies and column tests will be compared to
current remediation methods to determine overall effectiveness, cost differences, and time-frames for desired attenuation.

4. Once the feasibility is established, then the reactive impermeable barrier will be engineered and tested with selected parameters to optimize attenuation. These parameters are:
   a. mix formula of the barrier component
   b. physical properties of the barrier
   c. required liquid retention time
   d. influent concentration of the contaminant
   e. constructability of the barrier (i.e. mixing, compacted, poured)

6. REFERENCES


Appendix 1. List of Participants

FIRST INTERNATIONAL WORKSHOP ON
THE USE OF THE PAPER INDUSTRY SLUDGES IN THE ENVIRONMENTAL GEOTECHNOLOGY AND CONSTRUCTION
11-16 August 1997, HELSINKI, FINLAND

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Mr. Kaj FORSIUS, FEI, Finland
Mr. Erkki HAARTO, UPM-Kymmene, Finland
Mr. Keijo HAAVIKKO, Viatek Group Ltd., Finland
Mr. Matti HAKULINEN, Geomatti Ltd., Finland
Mr. Jorma HAVUKAINEN, City of Helsinki, Finland
Mr. Göran HOLM, Geotechnical Institute, Sweden
Dr. Pertti HYNINEN, Helsinki University of Technology, Finland
Dr. Pilar IZU, Gestep, Spain
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Mr. Kari RUOHONEN, Soil and Water Ltd.
Dr. Jouko SAARELA, FEI, Finland
Prof. Bob W. SARSBY, Bolton Institute, Great Britain
Mr. Erich SCHWAB, ÖFPZ, Austria
Mr. Jaakko SOIKKELI, VAPO Ltd., Finland
Mr. Markku TUHOLA, Finnish Geotechnical Society, Finland
Prof. Stanley J. VITTON, Michigan Technical University, U.S.A.
Prof. Thomas F. ZIMMIE, Rensselaer Polytechnic Institute, U.S.A.
Dr. Aitor ZULUETA, Terra Nova, Spain

SECRETARY:
Ms. Rauni PARONEN, FEI, Finland
Appendix 2. Programme

FIRST INTERNATIONAL WORKSHOP ON THE USE OF THE PAPER INDUSTRY SLUDGES IN THE ENVIRONMENTAL GEOTECHNOLOGY AND CONSTRUCTION
Finnish Environment Institute 11-16 August 1997 Helsinki

Sunday 10 August 18.00 - 20.00
Registration at the Finnish Environment Institute

Monday 11 August

09.00 - 10.30 Registration at the Finnish Environment Institute

10.30 - 11.00 Introduction to pre-workshop technical visits 11-12 August

11.00 Visit to Finland’s biggest landfill (Ämmässuo),
hosted by Manager Varho Laine-Juva, Vesihydro Consulting Engineers

13.30 Lunch at Vesihydro Consulting Engineers

15.00 - 17.00 Visit to Viatek Consulting Ltd.,
hosted by Managing Director Jaakko Heikkilä and
Manager Mikko Leppänen

Tuesday 12 August

09.00 - 09.30 Registration at the Finnish Environment Institute

09.30 - 14.00 Technical visit to Koivissilta landfill in Lohja and discussions about the use of paper sludges in landfill structures,
hosted by Managing Director Stig Lönnqvist, Solid Waste Management of West-Uusimaa, and Manager Keijo Haavikko, Viatek Consulting Ltd.
(Lunch included)

15.00 - 18.00 Technical visit to City of Helsinki and discussions about the use of ashes in environmental structures, visits to contaminated soil site planned for building (Arabianranta) and the construction site using vacuum consolidation in the house foundations,
hosted by Manager Kyösti Oasmaa, Energy Administration Department, Manager Jorma Havukainen, Real Estate Department, Geotechnical Division, and Manager Raimo Kuokkanen, Public Works Department
Wednesday 13 August

09.00 - 10.00  Registration at the Finnish Environment Institute

OPENING CEREMONIES

10.00 - 11.30  Welcome words:
Dr. Jouko Saarela, FEI
Opening addresses:
Director General Lea Kauppi, FEI
Dr. Jouko Saarela, Chairman of The Workshop
Prof. T.F. Zimmie, Vice Chairman of the Workshop, U.S.A.
Head of Geotechnical Group, Dr. Erkki Loukola, FEI
Head of Waste Group, Civ. Eng. Juhani Puolanne, FEI

Keynote Lecture, Prof. T.F. Zimmie

11.30 - 12.30  Lunch

12.30 - 14.00  Session 1: "The use of paper sludges in different countries today"

Pilar Izu & Aitor Zulueta, Spain,
Laboratory testing of several paper sludges as raw materials for landfill covers

Juan Quiroz, U.S.A.,
In situ strength testing on a paper mill sludge landfill cover

Horace Moo-Young, U.S.A.,
Design of waste containment systems utilizing a paper sludge capping layer

14.00 - 14.30  Coffee break

14.30 - 16.00  Session 1 continues

Stan Vitton, U.S.A.,
Using waste paper sludge for dust control

Dov Leshchinsky, U.S.A.,
Technique for dewatering paper waste sludge

Erkki Haarto, Finland,
The use of paper sludges in UPM-Kymmene Ltd., Kymi

18.00 - 19.30  Reception hosted by City of Espoo
at Gumböle manor in Espoo
(Bus 17.15 at Hotel Hesperia, 17.30 at FEI)
Welcome liquor
Address by Ms. Sirkka Manni-Loukkola,
Environment Protection Inspector, City of Espoo

Piano solo,
Ms. Marjaana Okkonen from Music Institute Juvenalia, Espoo

Address by Mr. Jussi Eerolainen,
Head of the Building Site Unit, City of Espoo

Buffet supper

Music by J. Peltosen Rytmiorkesteri
Juho Peltonen, clarinet
Susanna Ertolahti, trumpet
Samppa Leino, saxophone
Kaisa Pippuri, piano
Kusti Kaukoniemi, bass
Jaska Raatikainen, drums

Address on behalf of the visitors by Professor Thomas Zimmie

Thursday 14 August

09.00 - 14.00 Technical visit to road construction sites using paper industry sludge from UPM-Kymmene Ltd., hosted by Manager H. Rautakorpi, UPM-Kymmene Ltd. and Manager K. Haavikko, Viatek Group Ltd.
(Lunch included)

15.00 - 18.00 Session 2 (in Luopioinen): "Paper industry sludge in environmental geotechnology and construction"

Arrival in Luopioinen Town Hall
Presentation of Luopioinen by the host, municipal manager Rauno Haapanen in the municipal council session hall “Metsola"

Visiting the fibre-ash road Rajalantie, presentation by Development Manager Pentti Lahtinen from Viatek Group Ltd.

Visiting the geotechnical laboratory of Viatek Group Ltd /SGT

18.00 Arrival in Vohlisaari
Lectures by Mr. Pentti Lahtinen and Ms. Marjo Ronkainen
Sauna and light supper

Sponsors: Luopioinen Town and Viatek Group Ltd.

22.00 (approx.) back in Helsinki
Friday 15 August

09.15  Session 3: "Future use of paper industry sludges"

09.15 - 09.45  **Keynote Lecture**, Prof. B. Sarsby, United Kingdom

09.45 - 10.30  Kaj Forsius, Finland,
Use of paper mill solid wastes as landfill cover material. A laboratory study.

Jyrki Kotola, Finland,
Lysimeter study of mineral-based landfill cover materials in Kujala landfill

10.30 - 10.45  Coffee break

10.45 - 11.45  Horace Moo-Young, U.S.A.,
Determination of the adsorption capacity of paper sludges for use as a reactive impermeable barrier

11.45 - 12.45  Lunch

12.45 - 14.00  **Session 4: Group works "How to improve the use of paper sludge?"
(starts with video by Prof. Zimmie)

14.00 - 14.30  Coffee served in the 8th floor lounge

14.30 -  16.00  Results of the group works and discussion

16.00  Departure by bus from FEI

17.30  **Boat to Tallinn, Closing Ceremonies and Dinner**
Overnight in Tallinn

Saturday 16 August

09.00 - 19.00  **Technical Excursion in Tallinn, Estonia**

Technical visits to Muuga harbour and Paldiski former Soviet submarine training center

Lunch and coffee during the excursion

20.00 - 21.40  Return to Helsinki
This publication includes papers presented in the First International Workshop on the Use of Paper Industry Sludges in Environmental Geotechnology and Construction held in Helsinki 11-16 August 1997.

The aim of the workshop was to provide an international forum where participants could meet to exchange ideas in the research, use regulations and legislation concerning paper industry sludges in order to decrease environmental problems and increase the use of sludge in environmental geotechnology and construction, for example, in landfill structures, road building and in other environmental structures.

Keywords
forest industry, landfills, reclamation, sludge, utilization

Other information

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