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COMPILATION OF ALTERNATIVE LANDFILL COVER EXPERIENCE USING WASTEWATER TREATMENT PLANT RESIDUALS

TECHNICAL BULLETIN NO. 900

MAY 2005

by
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Acknowledgments

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PRESIDENT'S NOTE

Since 1984, NCASI has conducted research to assess the potential for the use of paper industry wastewater treatment residuals as hydraulic barrier layers in landfill covers. The findings of this research, along with the research by others, indicate that the hydraulic performance of barrier layers constructed from residuals is as good as, or better than, the performance of barriers constructed from compacted clay. To date, more than 29 full-scale landfill closure projects have included final covers incorporating paper mill residuals as the hydraulic barrier construction material.

This technical bulletin will serve as a primary source of information for companies working with regulatory agencies and third parties to implement this particular beneficial use. It is designed as a compilation of information that encompasses landfill type, acreage, barrier thickness layer, placement practice including spreading and compaction, overburden stress layer thickness, landfill design details, initial and post placement hydraulic conductivity, placement difficulties, soil engineering characteristics, other tests, and anecdotal information. It also gathers into one report the considerable knowledge gained by NCASI staff during more than a decade of interaction with member companies, academics, and consultants during full-scale landfill closure projects.

Ronald A. Yeske

May 2005

MOT DU PRÉSIDENT

Depuis 1984, NCASI a effectué une recherche visant à évaluer le potentiel d'utilisation des résidus de traitement des eaux de l'industrie papetière comme couvertures servant de barrière hydraulique dans les recouvrements de sites d'enfouissement. Les résultats de cette recherche, tout comme ceux obtenus dans le cadre d'autres recherches, ont démontré que la performance hydraulique des barrières formées de résidus est équivalente ou meilleure à celle des barrières formées d'argile compactée. Jusqu'à ce jour, plus de 29 projets de fermeture de sites d'enfouissement comportaient un recouvrement final incorporant les résidus de fabriques de papiers afin de mettre en place des matériaux de construction servant de barrière hydraulique.

Ce bulletin technique servira de principale source d'information pour les compagnies travaillant conjointement avec les agences gouvernementales et les tierces parties afin d'implanter cette valorisation particulière des résidus. Le bulletin se présente sous la forme d'une compilation de l'information traitant du type de site d'enfouissement, la superficie, l'épaisseur de la couche faisant office de barrière, les pratiques de remplissage incluant l'épandage et le compactage, la contrainte de la couche de mort terrain, les détails de conception du site d'enfouissement, la conductivité hydraulique avant et après le remplissage, les difficultés de remplissage, les caractéristiques d'ingénierie du sol, d'autres essais et des anecdotes. Il regroupe également en un seul rapport les connaissances considérables acquises par le personnel de NCASI pendant les dix dernières années en interaction avec les compagnies membres, les institutions académiques et les firmes de consultants lors de projets de fermeture de sites d'enfouissement.

Ronald A. Yeske

Mai 2005

COMPILATION OF ALTERNATIVE LANDFILL COVER EXPERIENCE USING WASTEWATER TREATMENT PLANT RESIDUALS

TECHNICAL BULLETIN NO. 900
MAY 2005

ABSTRACT

This technical bulletin contains information on the use of paper industry wastewater treatment residuals as hydraulic barrier material in landfill covers. Information specific to residuals includes standardized hydraulic conductivity testing procedures, moisture density hydraulic conductivity testing, liquid and plastic limits, consolidation, slope stability, biological activity, freeze/thaw effects, HELP modeling, placement techniques, test pad construction, synthetic soils, summary information on 29 closures, and case histories on five enclosures.

KEYWORDS

beneficial use, construction, hydraulic barrier, hydraulic conductivity, landfill cover, landfills, placement, residuals

RELATED NCASI PUBLICATIONS

Technical Bulletin No. 848 (June 2002). *Laboratory hydraulic conductivity testing protocols for paper industry residuals used for hydraulic barrier layers.*

Technical Bulletin No. 759 (July 1998). *Effect of freeze-thaw on the hydraulic conductivity of three paper mill sludges: Laboratory and field evaluation.*

Technical Bulletin No. 750 (November 1997). *A field-scale study of the use of paper industry sludges in landfill cover systems: Final report.*

Technical Bulletin No. 595 (September 1990). *A field-scale study of the use of paper industry sludges in landfill cover systems: First progress report.*

Technical Bulletin No. 559 (January 1989). *Experience with and laboratory studies of the use of pulp and paper mill solid wastes in landfill cover systems.*

COMPILATION DE L'EXPÉRIENCE EN MATIÈRE DE RECOUVREMENT DE SITES D'ENFOUISSEMENT UTILISANT DES RÉSIDUS DE SYSTÈMES DE TRAITEMENT DES EAUX USÉES

BULLETIN TECHNIQUE NO. 900
MAI 2005

RÉSUMÉ

Ce bulletin technique contient de l'information sur l'utilisation des résidus de systèmes de traitement des eaux usées de l'industrie papetière comme matériel servant de barrière hydraulique pour le recouvrement de sites d'enfouissement. L'information traitant spécifiquement des résidus porte sur les procédures normalisées pour vérifier la conductivité hydraulique, la relation entre la conductivité hydraulique et le contenu en eau, les limites de liquidité et de plasticité, la consolidation, la stabilité de la pente, l'activité biologique, les effets du gel et du dégel, la modélisation HELP, les techniques de remplissage, la construction d'une plateforme d'essais, les sols synthétiques, l'information synthèse sur la fermeture de 29 sites d'enfouissement de même que cinq études de cas de fermetures.

MOTS CLÉS

valorisation, construction, barrière hydraulique, conductivité hydraulique, recouvrement de sites d'enfouissement, sites d'enfouissement, remplissage, résidus

AUTRES PUBLICATIONS DE NCASI DANS CE DOMAINE

Bulletin technique no. 848 (juin 2002). *Laboratory hydraulic conductivity testing protocols for paper industry residuals used for hydraulic barrier layers.*

Bulletin technique no. 759 (juillet 1998). *Effect of freeze-thaw on the hydraulic conductivity of three paper mill sludges: Laboratory and field evaluation.*

Bulletin technique no. 750 (novembre 1997). *A field-scale study of the use of paper industry sludges in landfill cover systems: Final report.*

Bulletin technique no. 595 (septembre1990). *A field-scale study of the use of paper industry sludges in landfill cover systems: First progress report.*

Bulletin technique no. 559 (janvier 1989). *Experience with and laboratory studies of the use of pulp and paper mill solid wastes in landfill cover systems.*

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1.0 INTRODUCTION

In 1984, NCASI embarked on an extensive multi-year research project to assess the potential for the use of pulp and paper industry wastewater treatment plant residuals as hydraulic barrier construction material in landfill covers. The project was divided into several components: a four-year laboratory study, an eight-year pilot field study, and the development of an ASTM Standard Guide for laboratory evaluation of engineering properties for residuals. The first 12 years of the research were partially funded as part of USEPA Cooperative Agreement No. CR811878-01-1 "The Use of Pulp and Paper Mill Sludge and Fly Ash as Barrier Material in Covers for Municipal, Industrial, and Hazardous Waste." Since 1990, more than 29 industrial and municipal landfills have been closed using residuals as the hydraulic barrier layer.

While laboratory hydraulic conductivity testing procedures are becoming standardized, there is considerable variation in the placement process of the residuals, thickness, compaction, overburden stress, and post-closure hydraulic conductivity monitoring. The biggest impediment to regulatory acceptance is the lack of compiled closure practices. Several states have explicitly indicated an unwillingness to consider alternative landfill cover construction materials without a summary of experience and technical details of sites where a specific alternative construction material was successfully used.

This technical bulletin reviews NCASI studies and provides a compilation of case histories that document technical information and engineering practices where residuals have been used in final cover on both municipal and industrial landfills. Information obtained encompasses state, landfill type, acreage, barrier thickness layer, residuals type, placement practice including spreading and compaction, overburden stress layer thickness, landfill design details, initial and post-placement hydraulic conductivity, placement difficulties, permitting requirements, other tests, and anecdotal information. The considerable knowledge gained by NCASI staff during more than a decade of interaction with member companies, academics, and consultants during full-scale projects is summarized. This research was partially funded by a USEPA Region 5 Beneficial Use Demonstration Grant.

2.0 BACKGROUND

A brief review of the technical bulletins that pertain to the landfill cover research is presented below.

2.1 Laboratory Studies

Technical Bulletin No. 559, *Experience with and Laboratory Studies of the Use of Pulp and Paper Mill Solid wastes in Landfill Cover Systems* (NCASI 1989), includes a review of literature on the physical and chemical characteristics of residuals, a summary of an NCASI survey to document industry experience with alternative cover materials, and the results of a laboratory investigation to physically and chemically characterize a spectrum of industry waste materials.

In 1989, NCASI identified fourteen locations where pulp or paper mill wastewater treatment plant residuals or fly ash had been used as landfill cover material. These locations included industrial, municipal, and industrial/municipal waste locations. Five sites were identified where residuals (combined primary and biological residuals) were used as hydraulic barrier material in the final cover. Residuals and fly ash were used as daily or intermediate cover at nine of the fourteen sites.

Fifteen residuals from wastewater treatment plants of mills that encompass major pulp and paper production categories, and eight fly ashes from mill boilers burning wood waste, coal, or a combination thereof were characterized for suitability as hydraulic barrier material in landfill covers. Typical soil engineering tests, as well as a limited chemical analysis, were applied to the waste materials. Hydraulic conductivity, the chief parameter of interest, was observed to range over four orders of magnitude for the materials tested. Primary and combined residuals exhibited hydraulic conductivities between 10^{-4} and 10^{-8} cm/sec. Coal, wood, and combined fly ash hydraulic conductivities ranged between 10^{-5} and 10^{-7} cm/sec.

An important observation from this portion of the research (similar observations are drawn in current research) is that hydraulic conductivities were generally higher during the earlier portion of a test, followed by a general reduction in hydraulic conductivity with time. For residuals, this reduction appeared to be caused primarily by consolidation due to overburden stress on the sample. The mechanism for hydraulic conductivity reduction in fly ash was not investigated. Biological activity of the residuals somewhat reduced the hydraulic conductivity. This effect was diminished by testing at 8°C in order to minimize biological activity.

Other geotechnical properties of residuals and fly ash such as moisture-density relationship, plastic and liquid limits, and particle size distribution, were investigated in this stage of the research. The results are discussed later in this bulletin.

2.2 Pilot Field Studies

In 1987, NCASI initiated an eight-year field pilot study to further evaluate the long-term performance of residuals used as hydraulic barrier material. The study had two main objectives. The first was to compare, under field conditions, the performance of residuals as landfill hydraulic barrier material with the performance of a typical compacted clay soil barrier material. The second objective was to diagnostically evaluate the reasons for differences in performance between clay and residual barriers.

2.2.1 *NCASI Technical Bulletin No. 595*

NCASI Technical Bulletin No. 595, *A Field-Scale Study of the Use of Paper Industry Sludges in Landfill Cover Systems: First Progress Report* (NCASI 1990), describes the first two years of NCASI's field study of two residuals identified in Technical Bulletin No. 559.

To facilitate the comparison, four landfill cover test cells were constructed in November of 1987. These test cells were designed as "typical" covers based on consultation with experts in the field. Cells 2 and 4 contained a locally available clay soil as the barrier material. Cells 1 and 3 contained primary and combined residuals, respectively. Both of the residuals were from nonintegrated fine papermaking processes and had relatively high ash contents (>40%). The particular residuals were selected because a) they were from mills using production processes used by large segments of the industry, b) the hydraulic conductivity values determined for these residuals indicated that they were likely suitable as barrier material, and c) the proximity of the sources minimized transportation costs.

A vertical profile of each cell consisted of a 15-cm (0.5-ft) layer of topsoil with vegetation. Below this was a 46-cm (1.5-ft) layer of the surface soil from the site, which was primarily sand mixed with small amounts of silt and clay. Below that was the 61-cm (2-ft) hydraulic barrier layer. Underlying each barrier layer was a 61-cm (2-ft) layer of compacted and graded clean sand. A 30-mil PVC flexible membrane liner (FML) was installed with no field seams other than those needed for various penetrations at the bottom of each cell. Perforated pipe collection systems embedded in each of the cells allowed for the separate collection of precipitation routed as either runoff from the surface of the cell or seepage through the barrier layer. Each collection system directed flow to a separate collection basin where the volume of water collected was measured. See Figure 2.1.

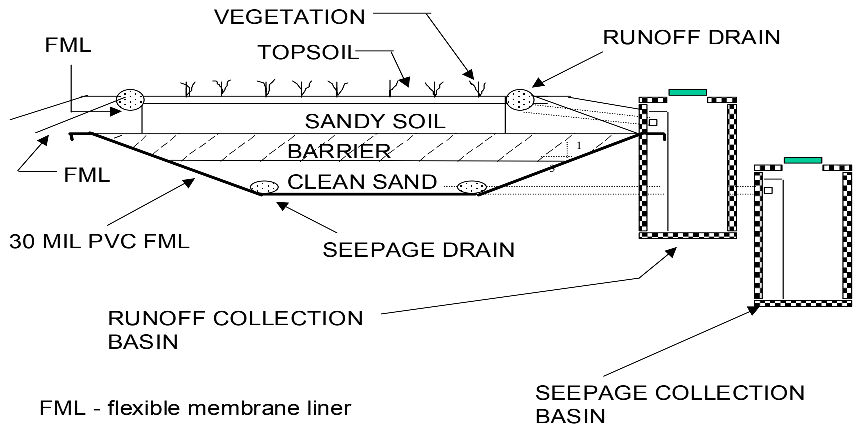

Figure 2.1 Cross Section of Typical Landfill Test Cell

2.2.2 *NCASI Technical Bulletin No. 750*

Technical Bulletin No. 750, *A Field-Scale Study of the Use of Paper Industry Sludges in Landfill Cover Systems: Final Report* (NCASI 1997a), presented the conclusions drawn from the long-term study described in Technical Bulletin No. 595. Results provided the a) field hydraulic conductivity of the barrier layers, b) comparison of field-measured hydraulic conductivities to hydraulic conductivities back-calculated using water balance methods, c) comparison of field-measured hydraulic conductivities to hydraulic conductivities measured in the laboratory on laboratory-compacted specimens of the same sludges, and d) characterization of the structure of the barrier layers to explain the different hydraulic conductivities obtained for the sludges and clays.

Long-Term Barrier Performance

At the effective overburden stress existing during the service life of the test plots, the combined sludge had a hydraulic conductivity of 4×10^{-8} cm/sec, whereas the primary sludge had a hydraulic conductivity of 1×10^{-7} cm/sec. The barrier layers in the clay plots had field hydraulic conductivities of approximately 1×10^{-6} cm/sec. For the duration of the field study, both sludge covers produced smaller volumes of seepage and greater volumes of runoff than either of the clay covers.

The effectiveness of the barrier layers was assessed by examining how water was routed as precipitation infiltrated down to the barrier layer. The three major vectors for water from precipitation are seepage, runoff, and evapotranspiration. Water balance data for all four cells were examined from July 1989 to May 1995.

Figure 2.2 shows that both of the residuals cells produced substantially less seepage than either of the clay cells. During the water balance collection period, the combined and primary residuals cells routed approximately 6 and 11%, respectively, of the precipitation as seepage. Over the same time period, the two clay cells routed approximately 45 and 49% of the precipitation as seepage.

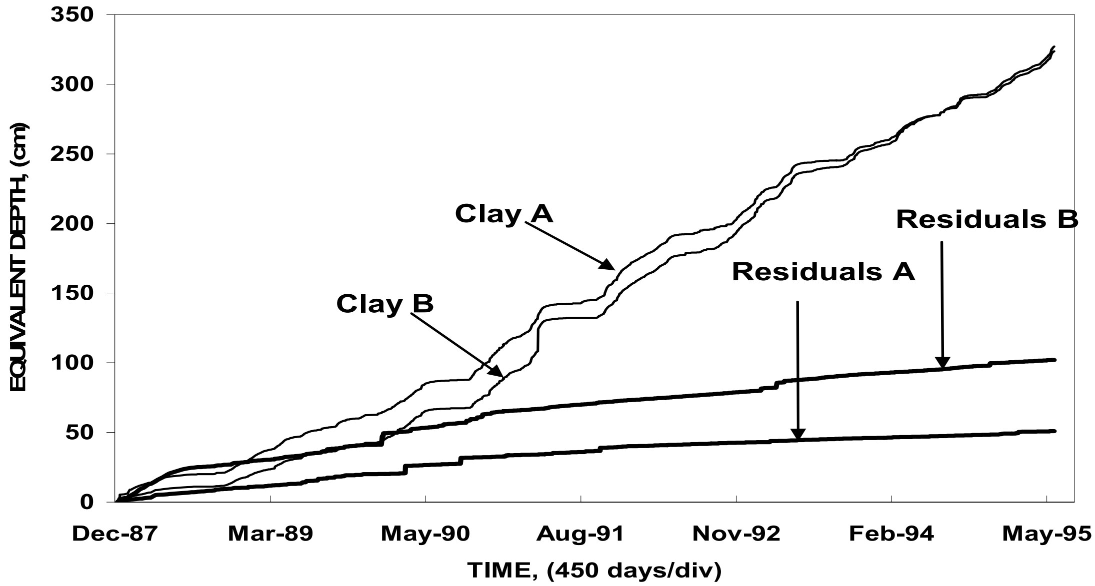

Figure 2.2 Seepage Expressed as Centimeters of Water on the Cell Surface

Conversely, Figure 2.3 shows that the residuals cells produced substantially greater amounts of runoff than either of the clay cells. During the water balance collection period, the combined residuals and primary residuals cells routed approximately 44 and 39%, respectively, of the precipitation as runoff. Over the same time period, the two clay cells routed approximately 21 and 4% of the precipitation as runoff.

Evapotranspiration was estimated by the difference from the other components of the water balance. Overall, evapotranspiration accounted for approximately 50% of the water balance for the residuals barrier cells and 34% and 47% of the water balance for the clay barrier cells. During the vegetative growing season, approximately 70% of the precipitation was routed as evapotranspiration (from all cells).

Using the volumes of either runoff or seepage produced as a performance indicator, the residuals barriers outperformed the clay barriers. Hydraulic conductivities of the primary and combined residuals barriers obtained from water balance computations (10^{-7} and 10^{-8} cm/sec, respectively) were an order of magnitude or more lower than similar hydraulic conductivities determined for the clay barriers (10^{-6} cm/sec).

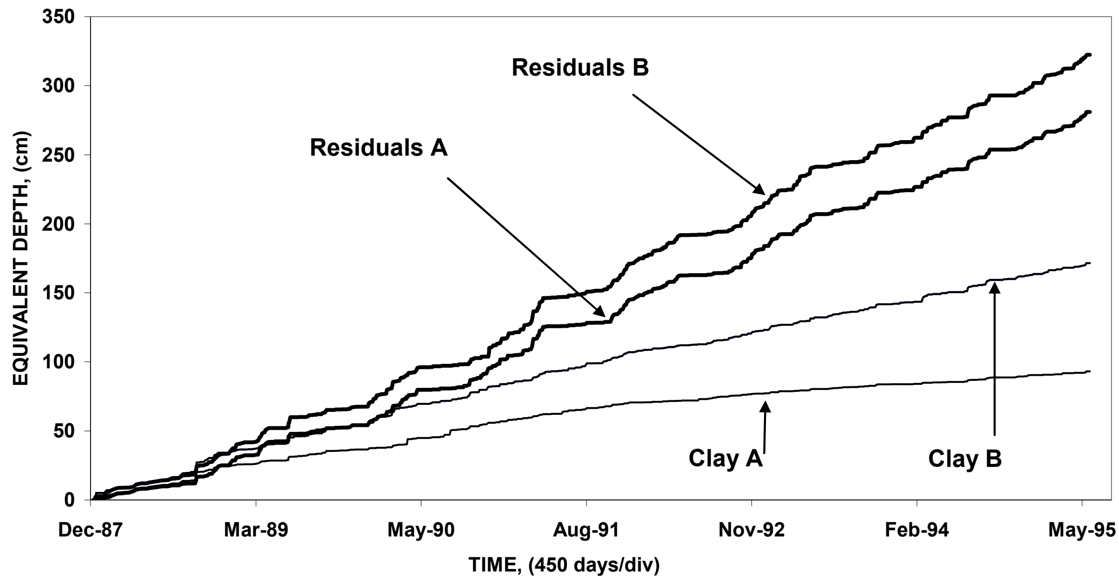

Figure 2.3 Runoff Expressed as Centimeters of Water on the Cell Surface

Other Testing

Consolidation of barrier residuals in response to overburden stress was monitored over the duration of the field testing and is displayed in Figure 2.4. The primary and combined residual cells consolidated 30 and 35% of the original thickness, respectively, whereas neither clay barrier consolidated appreciably. Long-term consolidation needs to be accounted for during design of residuals barrier layers to ensure adequate post-consolidation barrier layer thickness.

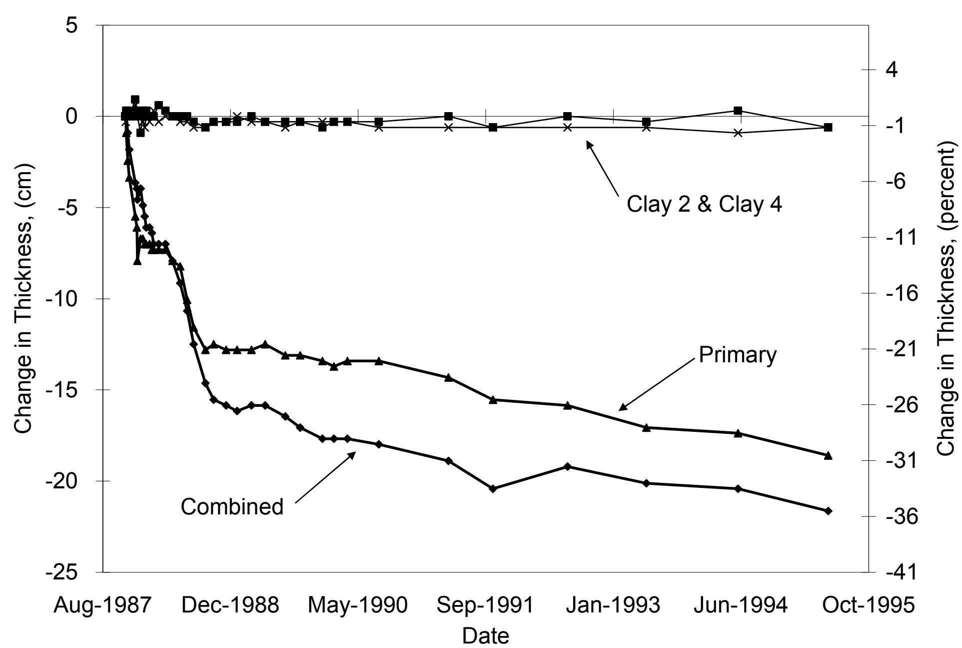

Figure 2.4 Barrier Layer Consolidation

At the end of the field study, the test cells were diagnostically examined and excavated in order to maximize the understanding of the differences in performance between the residuals barrier layers and the clay barrier layers. Hydraulic conductivity tests were conducted using sealed dual-ring infiltrometers (SDRI) (ASTM 2002), two-stage bore hole permeameters, and various laboratory permeameters. Finally, a dye-tracer study was conducted to detect the presence of preferential flow (secondary porosity) through the barrier layers.

Laboratory testing at different effective stresses confirmed that because residuals are soft and compressible, their hydraulic conductivities are sensitive to effective stress. Laboratory and SDRI hydraulic conductivity tests of field specimens under stresses equivalent to field conditions produced results comparable to field hydraulic conductivities generated from long-term water balance data. Thus, to obtain hydraulic conductivities representative of final cover conditions, field and laboratory tests must be conducted at stresses representative of conditions within a final cover.

Results of the dye-tracer study for one clay barrier and one residuals (combined) barrier are shown in Figures 2.5 and 2.6, respectively. Only one preferential flow path (not shown) existed in one of the residuals barriers (Figure 2.5), and this flow path appeared to be in a minor construction defect which did not significantly contribute to the overall water balance. In contrast, the clay barrier layers (Figure 2.6) were riddled with preferential flow paths, which contributed to much higher hydraulic conductivity than the paper mill residuals barriers. The clay used met all specifications for barrier material including compaction at the correct moisture content. Post-installation testing (sand cone, Shelby tube) indicated that density and hydraulic conductivity targets were met. However, diagnostic excavation revealed extensive preferential pathways. These were caused by the presence of clods that had not been broken up sufficiently during compaction. The design and size of the cells precluded the use of conventional compaction equipment such as sheep's foot rollers. The implication is that the relatively poor performance of the clay barriers may have been due to the design of the experiment rather than any inherent flaw in the material.

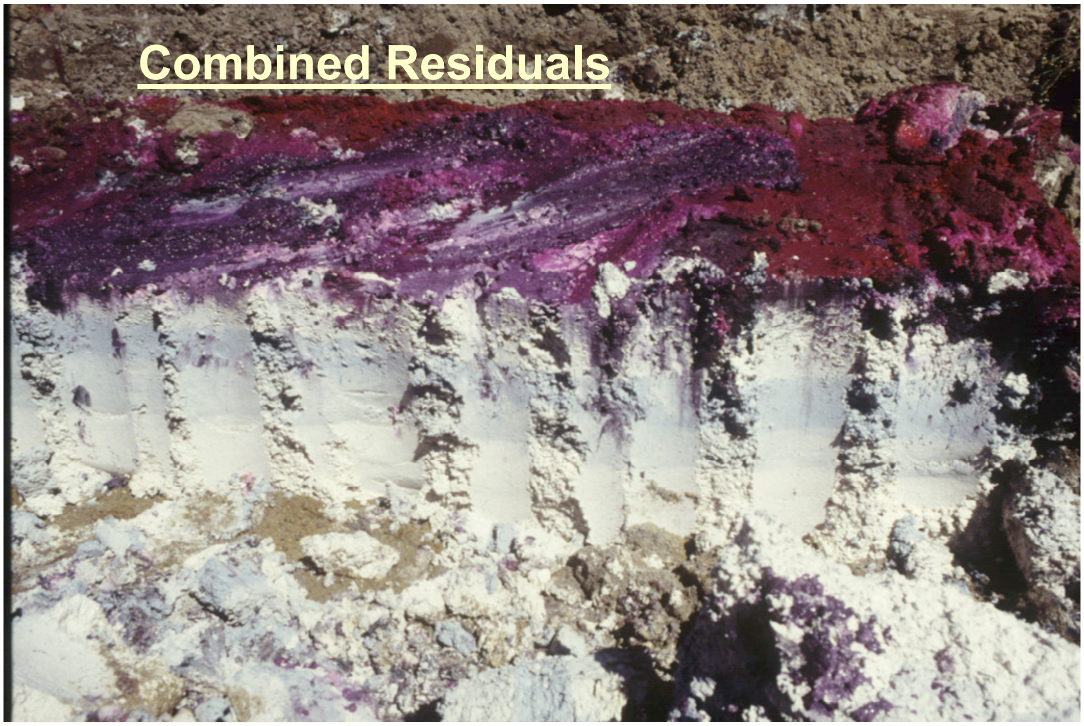

Figure 2.5 Combined Residuals Dye Results

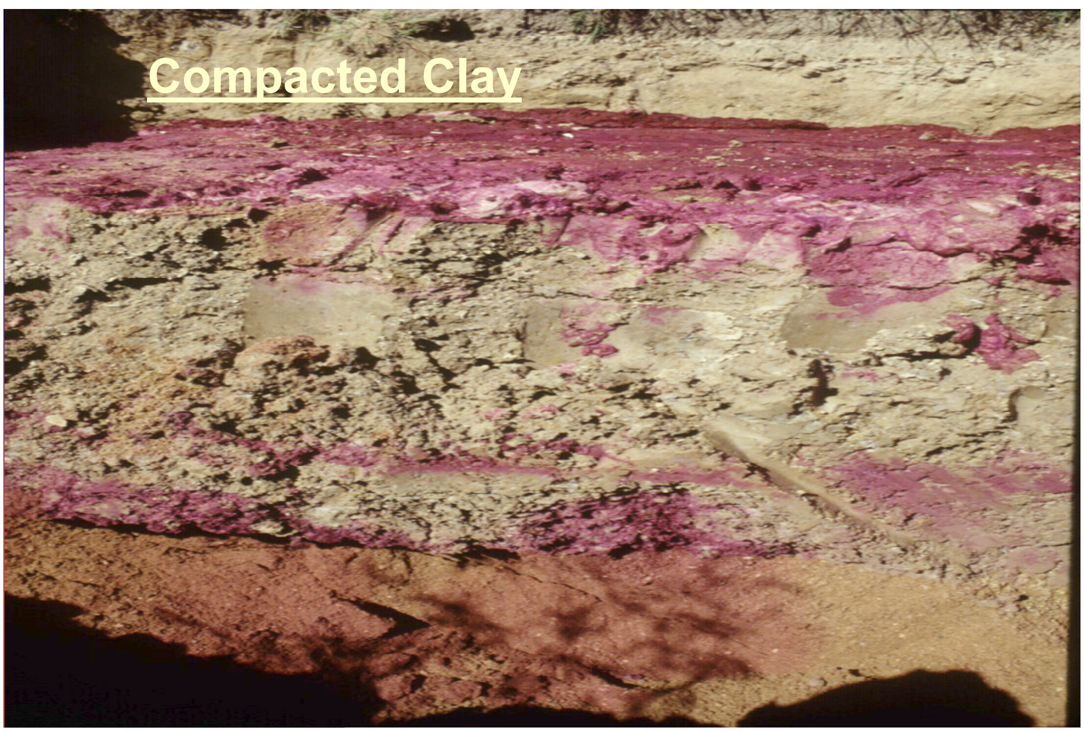

Figure 2.6 Compacted Clay Dye Results

2.2.3 *Technical Bulletin No. 759*

Technical Bulletin No. 759, *Effect of Freeze-Thaw on the Hydraulic Conductivity of Three Paper Mill Sludges: Laboratory and Field Evaluation* (NCASI 1998), evaluated and compared the effect that freezing and thawing had on the hydraulic conductivity of two clays and three paper industry residuals under field and laboratory conditions. A battery of hydraulic conductivity tests was performed on specimens prepared in the laboratory under conditions yielding low hydraulic conductivity. The hydraulic conductivity of each specimen was measured before and after exposure to a number of freeze-thaw cycles. Results of hydraulic conductivity tests performed on the paper mill residuals were compared to results obtained from a small-scale field study performed as part of this project.

Increases in hydraulic conductivity of two orders of magnitude were observed for clay specimens compacted, frozen, and thawed in the laboratory. The observed increase in hydraulic conductivity of the laboratory specimens was attributed to a macroscopic network of cracks caused by the formation of ice lenses and desiccation induced by freezing. Extensive cracking of the soil was observed in the laboratory experiments.

Results of hydraulic conductivity tests performed on paper mill residuals showed that conductivities less than 1 x 10^{-7} cm/sec can be achieved for each type of residual when compacted significantly wet of optimum water content (typically near the as-received water content). Slightly lower hydraulic conductivities were obtained for residuals A and C (the two combined residuals) relative to residual B (a primary residual). The slightly lower hydraulic conductivities of residuals A and C were attributed to the existence of additional biological material from secondary wastewater treatment processes that may have resulted in gas generation that impeded the flow of water.

Freeze-thaw affected each residual sample to some degree. For specimens of residual A compacted at the optimum water content, no change in hydraulic conductivity was observed for specimens permeated after each freeze-thaw cycle, whereas an increase in hydraulic conductivity was observed for specimens that were not permeated between freeze-thaw cycles. Also, for specimens of residual A compacted at the as-received water content, no increase in hydraulic conductivity was observed after exposure to freeze-thaw.

Increases in hydraulic conductivity of approximately one order of magnitude were observed for all specimens of residual B, regardless of the molding water content or whether the specimen was permeated between freeze-thaw cycles. This hydraulic conductivity increase was similar to the increase measured for compacted clays studied in this project. Similar behavior was observed for residual C.

Effective stress tests performed on the three paper mill residuals indicated that the hydraulic conductivity of the residuals decreased with increasing effective stress up to a certain effective stress, after which no further significant decrease in hydraulic conductivity occurred. Hydraulic conductivities as low as 1 x 10^{-8} cm/s were observed for specimens of residuals A and C at a limiting effective stress (typically slightly greater than 46 kPa for these residuals).

Results of the hydraulic conductivity tests conducted on specimens compacted in a pipe (frozen in the ground) were inconclusive. A decrease in hydraulic conductivity after freeze-thaw was observed when the residuals were permeated in the pipes, whereas an increase in hydraulic conductivity was observed in the slices tested in flexible-wall permeameters. Examination of the residual in the pipes revealed that exposure to freeze-thaw resulted in a blocky structure that fell apart easily during trimming. Nevertheless, it could not be determined whether formation of the blocky structure had an adverse impact on residual hydraulic conductivity. Large-scale field tests including morphological investigations are recommended to fully assess the impact of freeze-thaw on the hydraulic conductivity of paper mill residuals. Based on the results obtained in this project and the experiments of others, paper mill residuals are likely to perform well for a long period of time provided they are protected against detrimental stresses such as freeze-thaw.

3.0 CURRENT TECHNICAL ISSUES RELATED TO FULL-SCALE APPLICATION

Discussion of alternative landfill closure options with regulatory agencies often results in questions about geotechnical issues that arise because of the agency's unfamiliarity with paper industry residuals. NCASI has compiled the following information to address these questions. The information presented below results from NCASI research, research by other geotechnical experts, and data obtained during full-scale applications.

3.1 Standardized Hydraulic Conductivity Testing Procedures

Because hydraulic conductivity is the most important property affecting the suitability of residuals as material for the barrier layer in landfill cover, it often becomes the focus point of discussion with regulators. Because landfill liners and covers made from compacted clay have been utilized for a significantly longer period of time than covers made from residuals, regulators are often much more familiar with the geotechnical test procedures designed for clay and are likely to require the use of these tests to evaluate the suitability of residuals. While residuals have some geotechnical properties similar to clay, there are significant differences in other properties including ash content, water content, and organic content that require consideration when applying test procedures designed for fine-grained geologic materials such as clays to residuals. Table 3.1 provides a comparison of common index properties.

At the time of this publication, a method commonly used for determining the hydraulic conductivity for compacted clay is ASTM Standard D5084, Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible-Wall Permeameter (ASTM 2003). While it is possible to determine the hydraulic conductivity of residuals using this method, the soft plastic nature of residuals can result in significant underestimation of hydraulic conductivity, especially if test conditions are similar to those used for the testing of compacted clay. In 2002, NCASI worked with a geotechnical expert to evaluate how testing variables affect the hydraulic conductivity of residuals and to develop a laboratory test procedure specific to residuals. Tests were conducted on the 10 residuals samples identified in Table 3.1 to determine how hydraulic gradient, effective stress, and composition of the permeant water affect the hydraulic conductivity. Tests were also conducted to assess whether B-checks can be used to determine saturation and to evaluate various methods to prevent gas generation. The results of these tests were then used to develop a standard guide specifically for hydraulic conductivity testing of residuals.

Most of the results of this research were published as Technical Bulletin No. 848, *Laboratory Hydraulic Conductivity Testing Protocols for Paper Industry Residuals Used for Hydraulic Barrier Layers* (NCASI 2002). Key portions of the bulletin are in the next section.

Table 3.1 Average Values for Residuals Index Properties

Residuals	Production Category	Sludge Type	Water Content (%)	Specific Gravity	Fines Content (%)	Solids Content (%)	Ash Content (%)	Organic Content (%)	Fiber Content (%)	Baseline Hydraulic Conductivity (cm/s)
1A	NI fine	Comb.	184	1.98	52	35	58	42	23	$3.1x10^{-9}$
2B	NI fine	Comb.	403	1.66	34	23	30	70	24	$1.5x10^{-7}$
3C	Semi-chem	1°	200	1.78	49	34	38	62	35	$1.7x10^{-7}$
4D	Deink book	Comb.	152	1.9	49	40	48	52	30	$2.8x10^{-7}$
5E	BK	Comb.	195	1.94	36	34	42	58	17	$3.6x10^{-8}$
6F	GW	Comb.	248	1.89	54	29	39	61	25	$9.5x10^{-7}$
7G	UBK	Comb.	203	1.66	28	34	23	77	53	$5.4x10^{-8}$
8H	DI Tissue	1°	118	1.98	44	46	54	46	21	$4.6x10^{-8}$
9I	DI Market	1°	175	1.68	56	36	55	45	21	$7.8x10^{-8}$
10J	BK	1°	143	2.20	76	41	68	32	5	$6.0x10^{-8}$

3.1.1 *Hydraulic Gradient*

Hydraulic gradient is an important variable in hydraulic conductivity testing as it can significantly affect the outcome of the test. The hydraulic gradient is created primarily by the difference in pressure applied at the influent and effluent ends of the specimen. As water moves through a porous sample, it flows from a level of higher head (higher energy) to lower head (lower energy). While flowing, the water experiences a loss of energy or head due to friction against the walls and particles of the porous material. The amount of head loss divided by the sample length is the hydraulic gradient. As the hydraulic gradient across a sample is increased, the amount of time required to determine the hydraulic conductivity is reduced, and therefore, it is not uncommon for engineering laboratories determining the hydraulic conductivity of clays to use high hydraulic gradients (20-50) in order to expedite the testing process. As the gradient is increased on a residuals sample, the effective stress at the effluent end (sample discharge) of the specimen increases, often causing the compressible residuals to consolidate resulting in a lower hydraulic conductivity.

Soft and compressible materials such as residuals are often tested at a hydraulic gradient of 10 or lower to prevent consolidation due to seepage forces. Seepage force is the force that acts on a grain of material because of the differential head and is exerted in the direction of flow. However, testing at low hydraulic gradients can extend the testing period to weeks or more. Therefore, one specimen each of residuals 3C, 4D, 7G, and 8H was permeated over a range of hydraulic gradients to determine how hydraulic gradient affects hydraulic conductivity. Specimens were prepared and initially tested at the lowest practical hydraulic gradient (10). After equilibrium was established, the hydraulic gradient was increased and the test was conducted again until equilibrium was established. Each specimen was tested at hydraulic gradients of 10, 20, 40, 50, and 75.

Void ratios were calculated based on water levels in the cell burettes that were recorded at the same time the hydraulic conductivity readings were taken. Change in volume of the cell water was assumed to equal the reduction in volume of the specimen at a given hydraulic gradient. Void ratios reported at a given hydraulic gradient correspond to the last void ratio determined before the hydraulic gradient was increased.

Results indicated that the hydraulic conductivity decreased by approximately an order of magnitude as the hydraulic gradient was increased, as shown in Figure 3.1. Most of the reduction in hydraulic conductivity occurs as the gradient is increased from 10 to 40. Reductions in hydraulic conductivity as the hydraulic gradient was increased beyond 40 were less than a factor of 2.

Because measurement of hydraulic conductivity of residuals is somewhat sensitive to the hydraulic gradient used, the residuals should be tested using a hydraulic gradient as close as possible to that expected in the field. Field hydraulic gradients are commonly close to 1.0, but testing at a hydraulic gradient this low can be challenging because of the extended testing time required and the difficulty of accurately measuring the low flows involved. However, it should be practical to test most residuals at hydraulic gradients between 1 and 10. Gradients higher than 10 should not be used. Similar effects of hydraulic gradient on hydraulic conductivity have been reported by Taylor et al. 1999.

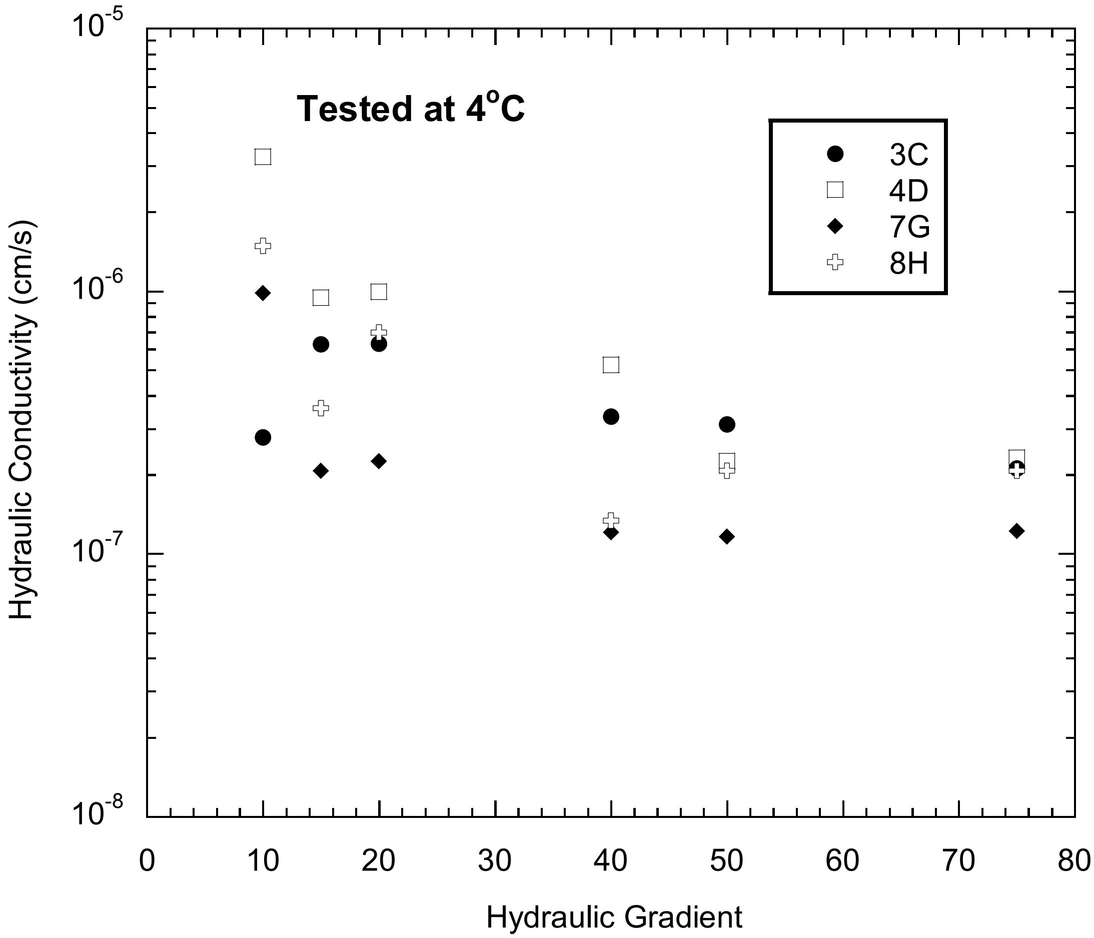

Figure 3.1 Hydraulic Conductivity vs. Hydraulic Gradient for Residuals 3C, 4D, 7G, and 8H

3.1.2 *Effective Stress*

Using effective stresses that do not correspond to field conditions can result in incorrect hydraulic conductivities, particularly for soft and compressible materials such as paper mill residuals. One specimen each of Residuals 3C, 4D, 7G, and 8H was tested at various effective stresses to evaluate how effective stress affects the hydraulic conductivity of residuals. Each specimen was initially permeated at an effective stress of 15 kPa. After equilibrium was established, the effective stress was increased to 25, 40, 80, and ultimately 120 kPa by increasing the cell pressure. Permeation continued until equilibrium was established before the effective stress was increased. Specimens were tested at 4°C.

An average effective stress of 15 kPa was used with a backpressure of 275 kPa for two days before applying a hydraulic gradient of 10. After equilibrium was reached according to the termination criteria in D5084, the average effective stress was stepped up to 25, 40, 80, and 120 kPa by increasing the cell pressure. Equilibrium was established at each effective stress before the cell pressure was increased.

Results of the tests conducted at various effective stresses are shown in Figure 3.2. The hydraulic conductivity decreases by almost an order of magnitude as the effective stress is increased from 15 to 120 kPa. Zimmie and Moo-Young (1995) and Kraus et al. (1997) report similar results. Residuals 3C and 4D, and Residuals 7G and 8H essentially have the same hydraulic conductivity and exhibit the same decrease in hydraulic conductivity with increasing effective stress. However, the rate of decrease in hydraulic conductivity is slightly larger for Residuals 3C and 4D. Additional data on the effects of effective stress are presented in Appendix D and G of Technical Bulletin No. 848 (NCASI 2002).

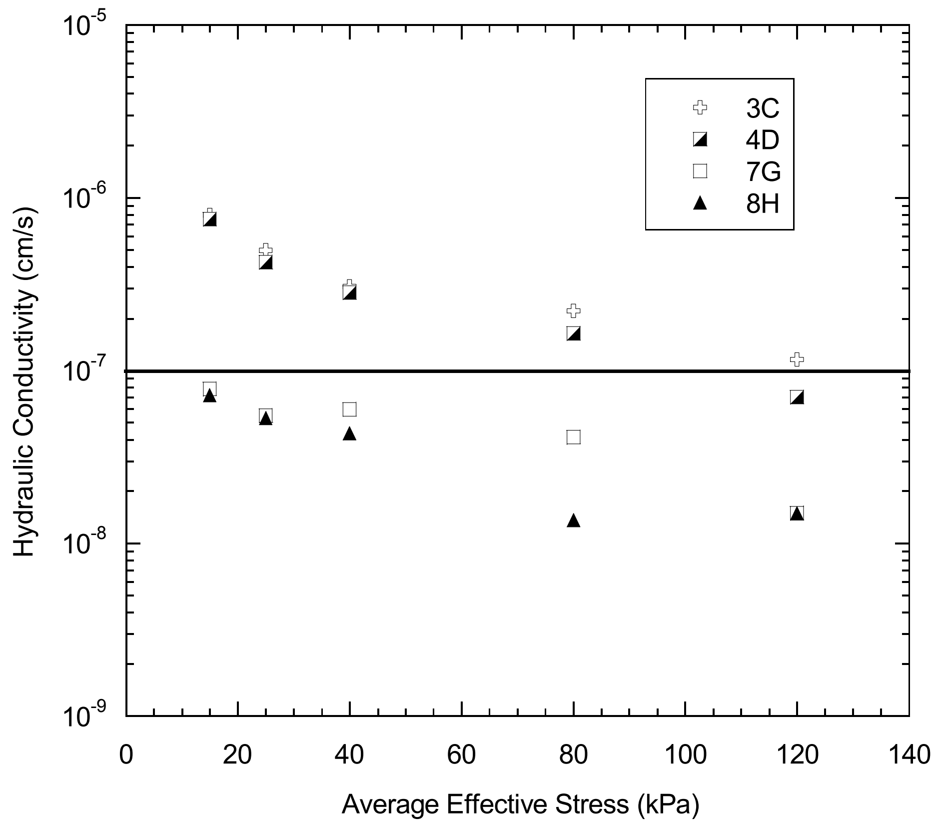

Figure 3.2 Hydraulic Conductivity vs. Effective Stress for Residuals 3C, 4D, 7G, and 8H

The hydraulic conductivity decreases with increasing effective stress because of consolidation of the residuals, which causes a reduction in void ratio. This effect is shown in Figure 3.3 in terms of hydraulic conductivity vs. void ratio. The larger decrease in hydraulic conductivity observed for Residuals 3C and 4D is consistent with their larger change in void ratio for the range of effective stresses that were applied.

These results suggest that field effective stresses must be accurately estimated and implemented during laboratory testing to obtain representative hydraulic conductivity results.

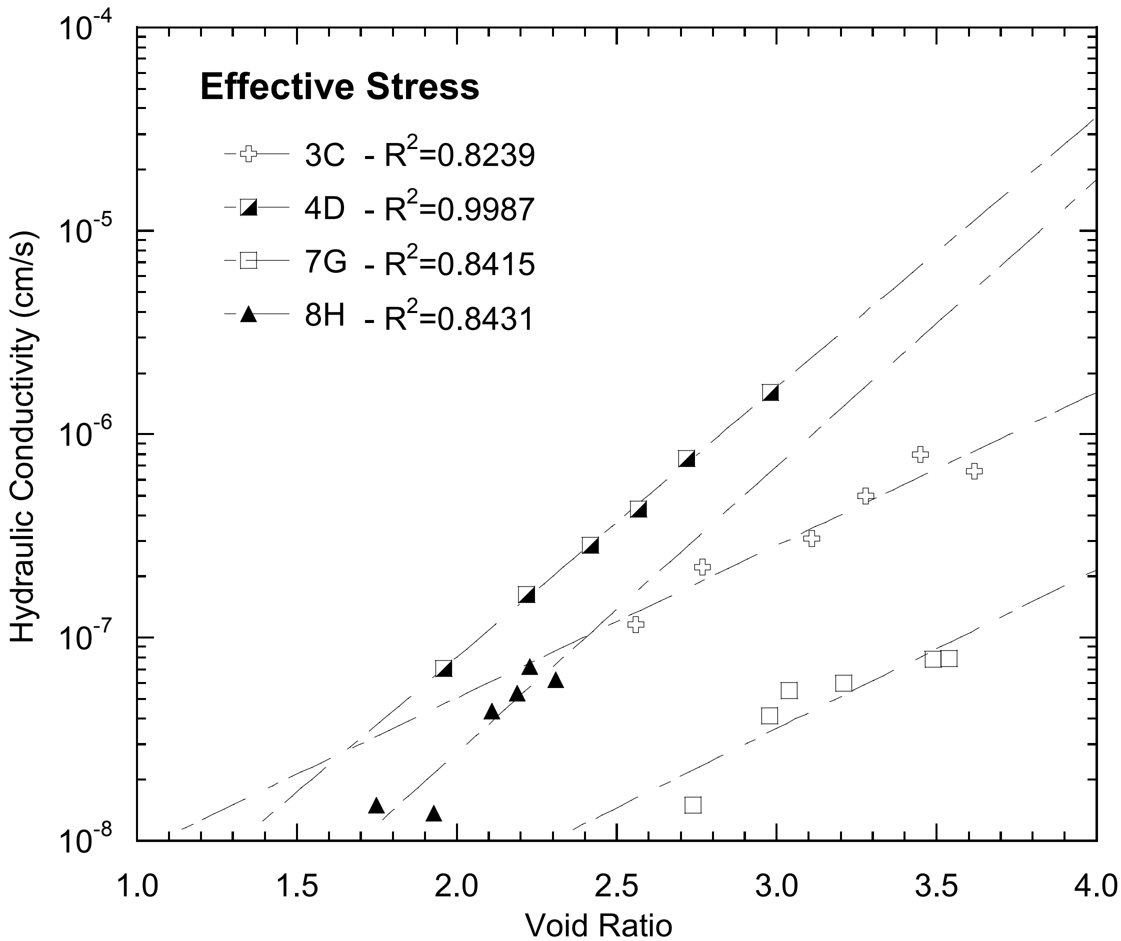

Figure 3.3 Hydraulic Conductivity vs. Void Ratio for Residuals 3C, 4D, 7G, and 8H Subjected to Increasing Effective Stress

3.1.3 *Composition of Permeant Water*

There is no standard permeant water for hydraulic conductivity testing. ASTM D5084 states that tap water should be used if the requestor does not specify the permeant water. Where permeant water makeup is specified, the latest version of ASTM D5084 (2003) states that 0.01 M $CaCl_2$ can be used. The state of Michigan requires that a 0.005 M $CaSO_4$ solution be used. However, no data existed prior to publication of Technical Bulletin No. 848 regarding how the hydraulic conductivity of paper residuals is affected by the type of permeant water.

Two residuals (4D and 7G) were sequentially tested with tap water and deionized water (at 0.05 M $CaCl_2$, and 0.1 M $CaCl_2$) to determine if the hydraulic conductivity of paper residuals is sensitive to composition of the permeant water. $CaCl_2$ was used instead of $CaSO_4$ to eliminate difficulties associated with sulfates. Specimens were initially permeated with tap water. Then the permeant water was changed, and permeation was continued until equilibrium was established again. This process was continued until specimens were permeated with each permeant liquid. An effective stress of 15 kPa was applied with a backpressure of 275 kPa for two days before a hydraulic gradient of 10 was applied to initiate permeation. Specimens were initially tested at room temperature with tap water. When the termination criteria were reached, the specimens were placed in refrigerators at 4°C. After equilibrium was established, the bladders were attached to the permeameters and tested at 4°C with deionized (DI) water, 0.05 M $CaCl_2$, and 0.1 M $CaCl_2$.

Results of these tests are shown in Figure 3.4. The hydraulic conductivity for tap water at 22°C is one-half order of magnitude lower than the hydraulic conductivity of Residuals 4D with tap water at 22°C as determined earlier in baseline tests and more than an order of magnitude lower than the baseline conductivity with tap water at 4°C as the permeant liquid. In contrast, the hydraulic conductivity of Residuals 7G decreases by almost an order of magnitude when DI water was used as the permeant water instead of tap water. Permeation with 0.05 M $CaCl_2$ and 0.1 M $CaCl_2$ resulted in similar hydraulic conductivity as the hydraulic conductivity to DI water for Residuals 4D and 7G.

These results suggest that the hydraulic conductivity of paper residuals are not affected in a consistent manner by changes in the permeant liquid. However, for all tests but one, using tap water as the permeant liquid resulted in the highest hydraulic conductivity. Thus, because it gives conservative results and also from a practical perspective, testing with tap water is reasonable.

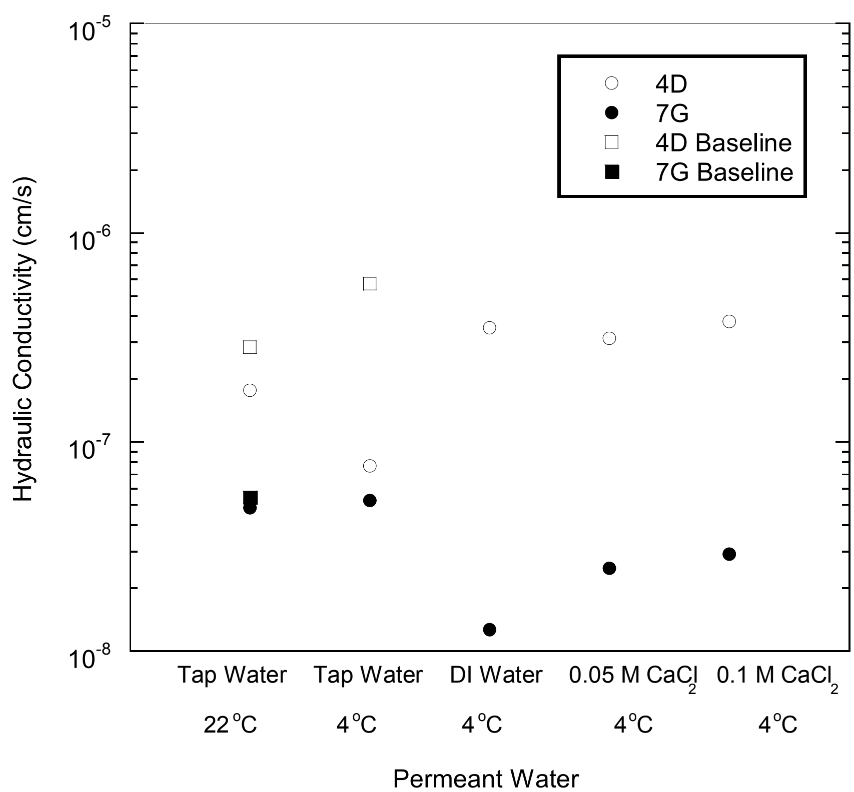

Figure 3.4 Hydraulic Conductivity of Residuals 4D with Different Permeants

3.1.4 *Summary and Conclusions of Standardized Test Procedures*

The objectives of this research were to determine how testing parameters affect the hydraulic conductivity of paper residuals and to create testing guidelines specific to paper mill residuals used for landfill covers. These objectives were met by conducting a laboratory testing program using ten paper mill residuals, four of which were tested extensively. These residuals were obtained from different mills throughout the U.S. and had varying index properties and hydraulic conductivity.

All residuals were characterized by determining their index properties and their baseline hydraulic conductivity under typical testing conditions. Four residuals were then selected for parametric testing. These four residuals were selected based on their index properties and baseline hydraulic conductivity, which indicated that the residuals were representative of materials used for constructing barrier layers in landfills. A series of tests were then conducted on these fours residuals to evaluate how gas production, hydraulic gradient, effective stress, and permeant liquid affect the hydraulic conductivity. Based on the results of these tests, recommendations for testing conditions were developed. In addition, the termination criteria in ASTM D5084 were re-evaluated to determine if they were appropriate for hydraulic conductivity testing of paper residuals.

Based on these tests, the following recommendations are made regarding testing of paper mill residuals.

- Backpressure should be applied for 12-24 hours to saturate specimens.
- The B-coefficient may be used to indicate whether the specimen is saturated.
- Measures to control gas should be used when testing residuals that produce gas. Gas production can be controlled effectively by a) testing at 4°C, b) spiking permeant with DBNPA biocide at maximum recommended concentration, and c) applying high backpressure (> 330 kPa) while testing. Flushing lines also works but is labor intensive.
- The hydraulic gradient should be as low as practical to simulate field conditions. Hydraulic gradients more than 10 should not be used.
- Residuals specimens should be tested at the effective stress likely to exist in the field.
- Testing residuals with tap water as the permeant liquid is acceptable.
- The termination criteria of ASTM D5084 are reasonable for paper mill residuals except that the range of acceptable outflow-inflow ratio should be increased to 0.70 to 1.3.

A draft test method is has been proposed as a standard guide that is being balloted by ASTM through Subcommittee D18.04.

3.2 Moisture Density/Hydraulic Conductivity Relationship

Several states have expressed interest in residuals as a substitute for clay in covers as long as residuals can meet the same geotechnical test criteria specified for compacted clay. Typically this involves a specification for compaction at a particular moisture content that corresponds to a minimum hydraulic conductivity. For compacted clay soils, this is a well-accepted procedure that has been standardized by ASTM D698 and is commonly referred to as the “Proctor” test (ASTM 2000a). While compaction curves can be developed for residuals using this procedure, they are strikingly different from the compaction curves for clay soils. For clay soils, there is a well-established relationship between molding moisture content[1] and hydraulic conductivity. The minimum hydraulic conductivity occurs slightly wet of the optimum moisture content[2] (Daniel and Benson 1990; Daniel 1984). A typical example of this relationship is shown in Figure 3.5.

Research conducted by others documents that this relationship is substantially different for paper industry residuals (Zimmie, Moo-Young, and LaPlante 1993; Moo-Young and Zimmie 1996; Kraus et al. 1997). It was observed that the minimum hydraulic conductivity for paper mill residuals used for a landfill cover occurred 50 percentage points wet of the optimum moisture content. Drying this residual to the optimum moisture content resulted in approximately a two order of magnitude increase in hydraulic conductivity. Research conducted on three paper industry residuals by Kraus et al. (1997) indicated that the lowest hydraulic conductivity for these residuals occurred about 55 percentage points wet of optimum moisture content. As shown in Figure 3.6, drying these residuals to the optimum moisture content resulted in approximately a three order of magnitude increase in hydraulic conductivity. An attempt to field-adjust the moisture content to that which corresponds to maximum dry density may increase the hydraulic conductivity of the barrier layer several orders of magnitude as well as potentially create material handling difficulties in the field.

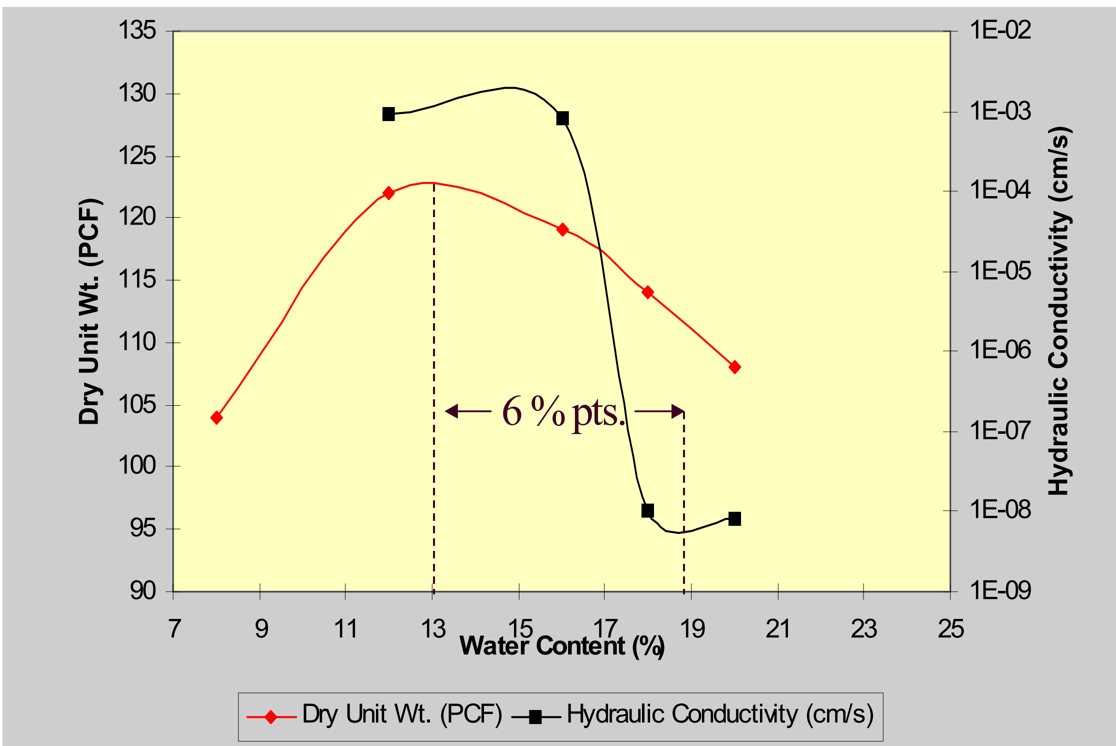

Figure 3.5 Moisture Density Relationship – Compacted Clay

[1] Molding moisture content is the water content at which the material is place in the testing device and compacted.

[2] Optimum moisture content is the water content which yields the maximum dry density after standard compaction effort.

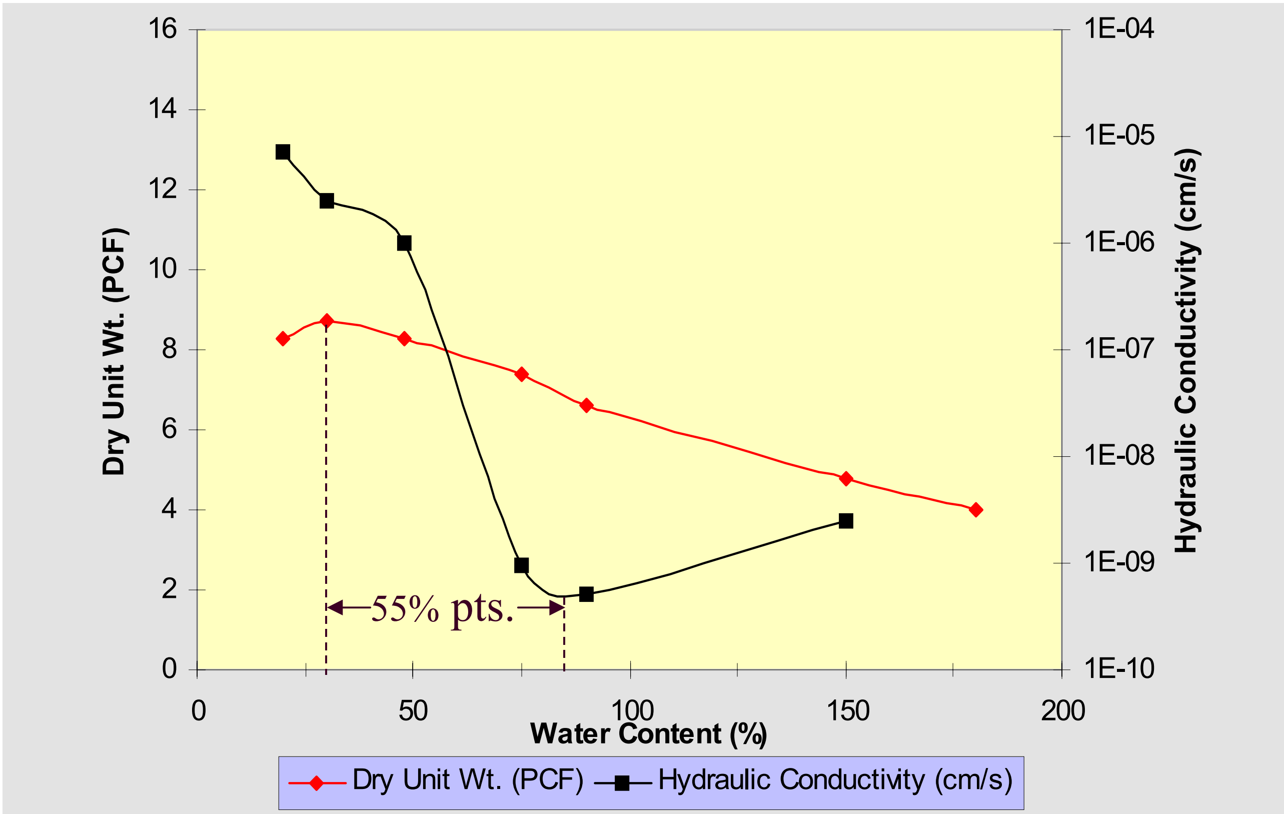

Figure 3.6 Moisture Density Relationship – Residuals

3.3 Consolidation

Because of the low strength and highly plastic nature of paper industry residuals, it is reasonable to assume that a barrier layer constructed from such a material will consolidate to some degree in response to overburden stress from the protective layer above. NCASI's experience with paper mill residuals consolidation is based on direct observations made during laboratory hydraulic conductivity testing and consolidation of residuals barriers in the field (Figure 2.4). Consolidation values for residuals reported in the literature ranges from 20 to 35% whereas compacted clays only consolidate 2 to 3% of their original thickness.

Additional researchers have described consolidation of paper mill residuals (Charlie, Wardwell, and Andersland 1979; Wardwell and Charlie 1981; and Zimmie, Moo-Young, and LaPlante 1993). They report that, similar to organic soils, three types of consolidation are observed: immediate consolidation, primary consolidation, and secondary compression. Immediate consolidation is usually attributed to compression or expression of gas pockets initially entrapped in the residuals, elastic compression of solids, shear deformation, or all three. If residuals are saturated, the immediate consolidation is usually insignificant when compared to the total consolidation. Primary consolidation occurs as water in the residuals drains due to the hydraulic gradient produced by the excess pore water pressures as a result of overburden. Secondary compression may occur in residuals due to migration of fines or decomposition of the organics, or both.

During primary consolidation, as the water moves out of the matrix and the solid particles move closer together, there is a reduction in the void ratio that is usually accompanied by a significant reduction in hydraulic conductivity and an increase in shear strength. Moo-Young and Zimmie (1996) showed that the hydraulic conductivity of a landfill cover constructed from residuals decreased by an order of magnitude due to consolidation. Quiroz and Zimmie (1998) concluded that the increase in undrained shear strength of a residuals cover was the direct result of consolidation.

Simulation of long-term performance including consolidation of residuals used in landfill covers was examined in a geotechnical centrifuge (Zimmie, Mahmud, and De 1994a, 1994b; Zimmie and Moo-Young 1995). The use of a geotechnical centrifuge (105g-ton, 24 hours) permitted simulation of about 30 years of cover behavior related to settlement, consolidation, and leachate transport. Results indicated that the degree of consolidation of residuals was about an order of magnitude greater than compacted clay, and a decrease in void ratio accompanied the consolidation, which resulted in a significant reduction in hydraulic conductivity.

The practical effect of consolidation in the field on the performance of residuals in a landfill cover is a long-term reduction in hydraulic conductivity when compared to the hydraulic conductivity of the residuals at the time of placement. In conclusion, in designing a full-scale cover using residuals, it is necessary to anticipate consolidation to ensure that adequate thickness is maintained after consolidation has occurred and to avoid problems associated with movement downward of the materials above the hydraulic barrier.

3.4 Liquid and Plastic Limits

Liquid and plastic limits (historically referred to as Atterberg Limits) are used to define the moisture content of cohesive soils (clays and silts) as they transition from one rheological state to another in response to a changing moisture content (ASTM 2000b). The liquid limit is the moisture content at which the soil has such a low shear strength that a sample divided in two by a grooving tool will flow together upon application of a standardized mechanical energy input. The plastic limit is the moisture content at which a 3.2mm rolled thread of the sample begins to crack upon a continuous rolling motion. The plasticity index is the liquid limit minus the plastic limit. While these limits remain the primary form of engineering classification for cohesive soils, the presence of cellulose fibers in residuals can severely hamper the accurate determination of liquid and plastic limits.

NCASI encountered considerable difficulties with residuals during plasticity index testing (NCASI 1989). In highly fibrous residuals, the interlocking nature of the fibers resulted in relatively little change in liquid limit over large changes in water content. During application of the liquid limit test, the two halves of the residuals sample were observed to move together while maintaining their integrity rather than flowing together to close the groove. The presence of fibers also interfered with the plastic limit determinations. The water content of the 3.2mm diameter thread was reduced to well below that required for cohesion of the fines; however, the presence of fiber continued to hold the thread together. Similar difficulties have been reported by others (Zimmie, Moo-Young, and LaPlante 1993; Moo-Young and Zimmie 1996; Kraus et al. 1997; Brown 1998; Genth 1993; LaPLante 1993).

3.5 Slope Stability

Due to the relatively low shear strengths associated with most residuals, landfill sidewall slope is an important design consideration when using residuals in landfill covers. Comprehensive information on slope stability factors for residuals utilized as covers is presented by NCASI (1971); Quiroz and Zimmie (1999); and LaPlante, Callahan, and Quiroz (1999). Additional shear strength information of residuals using triaxial compression tests (ASTM 2003b) and vane shear tests (ASTM 1994) has been reported by several researchers (Moo-Young and Zimmie 1996; Zimmie, Moo-Young, and LaPlante 1993; Kraus et al. 1997; Quiroz and Zimmie 1998; Taylor et al. 1999). All researchers reported a significant increase in the shear strength in response to post placement consolidation. Zimmie, Moo-Young, and LaPlante (1993) noted, however, that failure is difficult to determine from stress-strain curves, which are typical of soft compressible material, in that they exhibit no sharp yield point and that failure has to be arbitrarily selected at some reasonable strain. Variation in residuals shear strength is thought to be from the wide range of water contents and the relatively high organic content. Researchers commonly report that side slopes of residuals utilized as covers should not exceed 25% (1:4).

Taylor et al. (1999) reported that field observations indicate that shear strength properties of residuals covers change significantly with time. Attempts to replicate observed failures with models have led to the following conclusions.

- Residuals covers are most vulnerable to failure shortly after placement, prior to significant consolidation.
- Failures occur within the residuals layer, not at the interface between layers in the final cover system.
- Low unit weight of the residuals and lack of confining pressure are the primary factors leading to failure.

While relatively rare, some downward movement of residuals on side slopes has been observed, especially prior to the placement of the overburden layer. NCASI is aware of three instances where such slumping occurred during construction and in all three occurrences, increased moisture content of the residuals was responsible. Aloisi and Atkinson (1992) reported that during the placement of residuals on a municipal solid waste (MSW) landfill, Hurricane Bob dumped eight inches of rain on the residuals layer on two separate occasions causing several sections to slide downward approximately one to two feet. Topographic irregularities in the residuals layer appeared to act as miniature retention ponds, allowing rainwater to soak into the residuals and reduce cohesion. It was observed that areas that had been rolled smooth with a weighted roller were not subject to slumping. During closure of a nine-acre industrial landfill in Michigan, Malmstead, Bonistall, and Maltby (1999) reported that at times throughout construction of the cover, some slumping of the residuals layer was observed if the overlying 12-in. sand layer was not placed quickly enough to prevent damage from precipitation. The affected areas were removed and replaced using new residuals material. During closure of a New Hampshire MSW landfill, a small area of the residuals layer slumped downward approximately three to four feet because a small quantity of residuals with a higher than usual water content was used. The residuals were removed and replaced with residuals with a more typical water content. Figure 3.7 shows the area where slumping occurred.

Figure 3.7 Slumped Area Due to High Moisture Content

3.6 Biological Activity

One concern sometimes expressed about the use of residuals as barrier materials is the potential for biodegradation to affect the integrity of residuals layer. At this time, all studies of the use of residuals as landfill hydraulic barrier material and all full-scale applications have been restricted to either primary or combined residuals. These materials are generally low in nutrients and not likely to support significant biological activity. While secondary residuals may have higher nutrient levels due to the high concentration of biomass, they also generally have physical properties that make them entirely unsuitable for landfill construction material. Such materials are typically very difficult to dewater, very low in structural strength, have high moisture contents, and are difficult to handle.

It is common to see some gas generation in both field studies and laboratory studies of residuals utilized as barriers. This gas is the result of decomposition of organic matter. One study that evaluated whether decomposition affected long-term laboratory hydraulic conductivity for three different residuals at different water contents concluded that the hydraulic conductivity remained essentially unchanged or decreased slightly during permeation (Kraus et al. 1997).

During NCASI's long-term field evaluation of residuals as hydraulic conductivity materials, both of the residuals studied showed a slight increase in ash content and a slight decrease in moisture content over a period of eight years (NCASI 1997a). The increase in ash content is likely associated with a small amount of biodegradation and the decrease in moisture content is most likely a function of continued consolidation in the barrier layer. To visually assess whether any degradation of the cellulose fibers occurred, electron microscopy was performed on the eight-year old samples and compared to fresh samples collected from the two original paper companies (Maltby and Eppstein 1996). Production categories for these two companies remained essentially unchanged since the initiation of the field project. Electron microscope images (Figures 3.8–3.11) show little visual evidence of biodegradation of the cellulosic portion of the barriers occurred during the study. While these photographs are not conclusive, they do suggest that the rapid biodegradation of cellulose in landfill covers constructed from residuals is not occurring.

In an earlier NCASI study that examined the application of conventional soil engineering tests to characterize paper industry residuals, core samples were taken from a primary residuals landfill in which placement records allowed for accurate determination of residuals age. Samples were collected from areas of the landfill that corresponded to residuals ages of 1 and 12 years after placement and were photographed using an optical microscope. Visual examination of the Figures 3.12 and 3.13 indicate the presence of cellulose fiber in both residuals samples extracted from the landfill (NCASI 1969). The absence of degradation was attributed to such factors as fines concentration, lignin content of the fiber, hydrophilic nature of the cellulose, inhibition to degradation of microbial substances bound to clay, and the deficiency of nitrogen in residuals. The residuals examined in the study contained 0.002 to 0.005% available nitrogen. The study referenced an earlier study that stated that if the available nitrogen content of soils is below 1.2% cellulose, decomposition ceases (Imshenetsky 1968).

Comprehensive descriptions of the microbial degradation mechanisms of cellulose in paper residuals are presented by Wardwell (1980), and Barlaz, Schaefer, and Ham (1989). Laboratory decomposition tests conducted on primary residuals found little decomposition because of the lack of available nutrients (Wardwell 1980). In a study to assess refuse decomposition in a simulated sanitary landfill, conditions necessary for rapid cellulose decomposition included leachate recirculation, leachate pH adjustment, very high water content, incubation at 41ºC, and nutrient addition (Barlaz, Schaefer, and Ham 1989).

Other studies designed to specifically address the effects of biological activity on residual physical parameters such as compressibility and shear strength, could not be completed without optimization of conditions to accelerate biological activity to the extent that effects could be observed (Al-Khafaji and Andersland 1981; Lowe and Andersland 1981). Decomposition was accelerated by the addition of nutrients, microbial seed, increased moisture content, recirculation of leachate, and storage of residuals at 35ºC.

In a long-term study that described the effects of fiber decomposition of combined or secondary residuals on geotechnical properties, Wardwell and Charlie (1981) determined that secondary residuals had sufficient nutrients in the form of nitrogen and phosphorus when combined with primary residuals to support fiber decomposition. Long-term laboratory tests revealed that organic breakdown of fiber significantly decreased the hydraulic conductivity and increased the compressibility of paper residuals.

A study supported by NCASI to evaluate the EPA-recommended approach to predicting air emissions from pulp and paper industry landfills assessed the characteristics of solid wastes placed in industry landfills (NCASI 1999a). Data in Table 3.2 summarize the type and proportions of waste materials recently placed in industry landfills. While MSW landfills contain a high proportion of yard wastes which are rich in nitrogen and support vigorous anaerobic biodegradation of organics, pulp and paper industry landfills do not normally contain these materials. While secondary wastewater treatment residuals from pulp and paper mills may have carbon to nitrogen ratios that favor biodegradation of organic material, only 1% of the residuals sent to company landfills are such biosolids alone. Table 3.2 indicates that 56% of landfilled wastewater treatment residuals are a combination of residuals from primary and secondary wastewater treatment, with the majority of the combination usually being from primary treatment; 38% of landfilled residuals are primary residuals alone. Primary residuals contain only 0.27% nitrogen and even combined primary and secondary residuals contain only 0.85% nitrogen (median values; see NCASI 1984). These data show that wastewater treatment residuals placed in pulp and paper industry landfills tend to be deficient in the nitrogen needed to support anaerobic degradation and, therefore, covers constructed from the same materials will be deficient too.

Table 3.2 Wastewater Treatment Residual Types Sent to Pulp and Paper Industry Landfills

Residual Type	Percent by Dry Weight (NCASI 1999b)	Nitrogen Percent (NCASI 1984)	C:N Ratio (NCASI 1984)
Primary	38	0.27	32-930:1
Secondary	1	2.33	6-115:1
Combined	56	0.85	13-81:1
Dredged	5	na	na

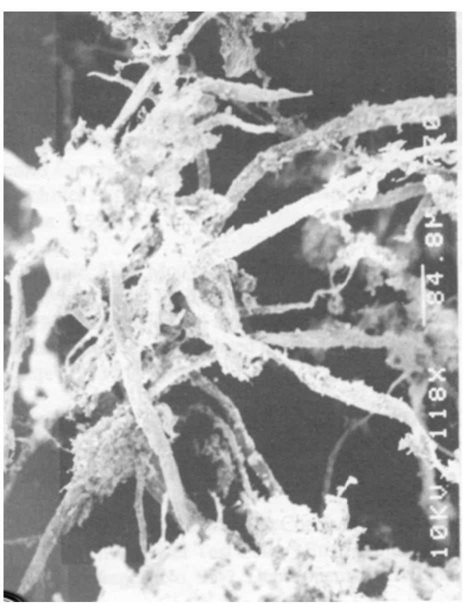

Figure 3.8 Primary Residuals, 8 Years Old

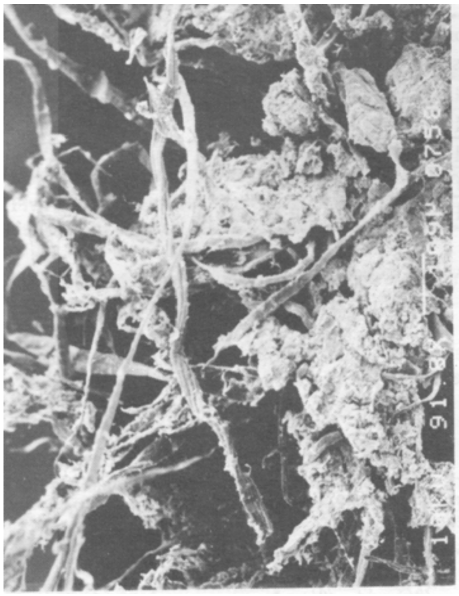

Figure 3.9 Primary Residuals, Fresh

Figure 3.10 Combined Residuals, 8 Years Old

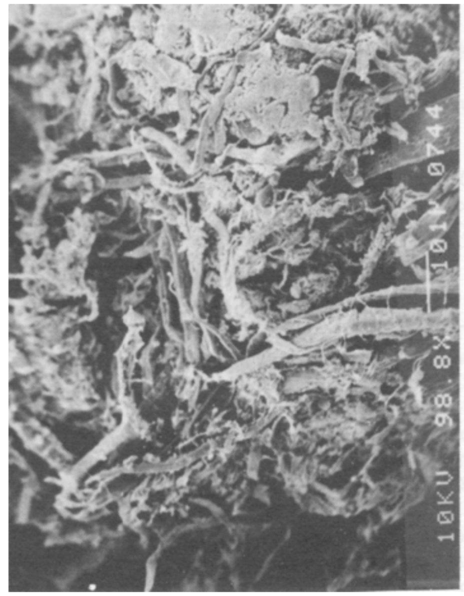

Figure 3.11 Combined Residuals, Fresh

Figure 3.12 Residuals – 1 Year Old

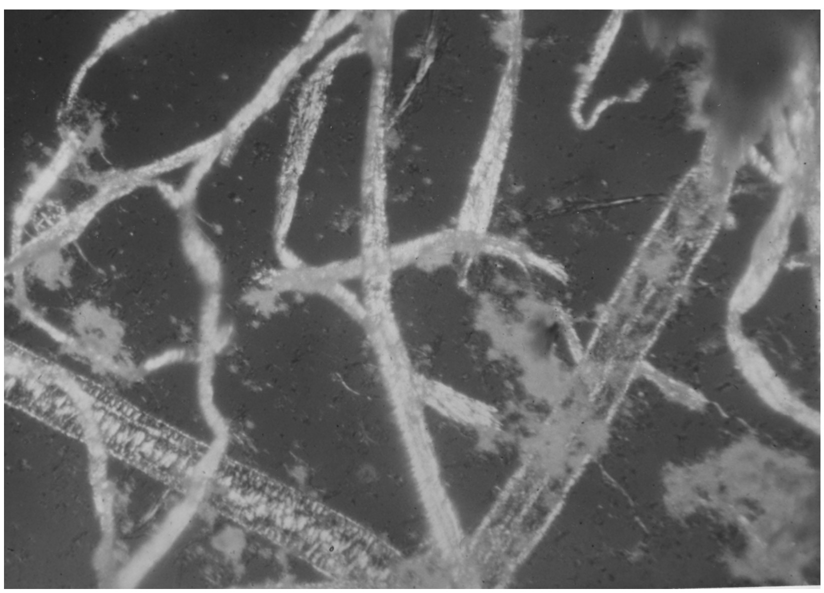

Figure 3.13 Residuals – 12 Years Old

3.7 Freeze-Thaw Effects

The deleterious effects of freezing and thawing conditions on the hydraulic conductivity of compacted clay are well documented (Benson and Othman 1993; Chamberlain, Erickson, and Benson 1995; Kim and Daniel 1992; Erickson, Chamberlain, and Benson 1994; Wong and Haug 1991). When the temperature of compacted clay is reduced sufficiently, water present in the clay freezes and ice lenses form. Concurrently, soil below the freezing front desiccates as water is pulled toward the growing ice lenses. As the temperature of the clay later rises above freezing, the ice lenses thaw, leaving behind a network of cracks that allows a rapid transmission of water, generally resulting in a one to four order of magnitude increase in hydraulic conductivity.

In 1996, the state of Maine evaluated the long-term performance of compacted clay covers utilizing sealed dual-ring infiltrometers (SDRIs) at four MSW landfills where the covers had been in place between four and six years (Maine DEP 1997). The study concluded that all four barriers were undergoing degradation with an associated loss of hydraulic performance. Drying trends appear to be the most significant factor increasing the infiltration rate and freezing and thawing is suspected to be one of the primary factors in the hydraulic degradation. A final report stated that most clay cover system barrier soils will eventually degrade to a hydraulic performance in the range of 1×10^{-5} cm/sec where they will remain (Maine DEP 2001).

As discussed in Section 2.2.3, NCASI coordinated laboratory and field tests at the University of Wisconsin to assess the impact of freeze-thaw on the hydraulic conductivity of two compacted clays and three paper mill residuals (NCASI 1998). Increases in hydraulic conductivity of two orders of magnitude were observed for the clay specimens that were subjected to freeze-thaw cycles. Two of the three residuals had one order of magnitude increases in hydraulic conductivity after multiple freeze-thaw cycles. The third residual sample had no change in hydraulic conductivity after exposure to multiple freeze-thaw cycles. Based on these results, the study concluded that residuals incorporated into barrier layers would perform as well as or better than compacted clay when subjected to freeze-thaw cycles.

During the 1992-93 winter, the depth of frost penetration into a residuals cap at an MSW landfill in Massachusetts was measured using soil resistivity (Zimmie et al. 1994). Results indicated that frost did not penetrate into the residuals barrier layer. Heavy snowfall throughout the winter covered the landfill and acted as an insulation blanket which reduced the frost penetration. The high water content of the residuals also inhibited frost penetration into the landfill cover, since the high water content requires more energy loss to freeze the water in the residuals matrix as compared to drier matrices.

A similar study was conducted on the residual barrier layer at a municipal landfill in New York (Moo-Young and Zimmie 1997). Because protection from freezing was a major design consideration at this landfill, a 19-in frost protection layer composed of residuals was placed directly over the 36-in residuals hydraulic barrier layer. Thermistor probes and soil resistivity blocks were embedded throughout the layers and data were recorded on a data logger. During the winter of 1994-95, probe readings indicated that while frost penetrated through the vegetation and overburden layers, it did not reach the frost protection layer. Researchers assumed that the lack of frost penetration may have resulted from the increase in the effective overburden layer (i.e., the increased height of the sand drainage layer and the addition of a frost protection layer).

3.8 HELP Modeling

The Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al. 1984a, 1984b) is a quasi-two-dimensional hydrologic model for conducting water balance analysis of landfills, cover systems, and other solid waste containment facilities. The model accepts weather, soil, and landfill design data, and uses solution techniques that account for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane, or composite liners. Landfill systems including various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and synthetic geomembrane liners may be modeled. The model facilitates rapid estimation of the amounts of runoff, evapotranspiration, drainage, leachate collection, and liner leakage that may be expected to result from the operation of a wide variety of landfill designs. The primary purpose of the model is to assist in the comparison of design alternatives and is commonly used by both designers and permit writers.

The most recent release of the HELP model (Version 3, HELP 3) is of greater utility to the paper industry than earlier versions because the default waste characteristics and soil layers have been greatly expanded and include default values for high-ash paper mill residuals (USEPA 1994a, 1994b). User-defined barrier layer characteristics may also be entered to allow for simulations of landfills with residual barrier layers. An extensive study by NCASI indicated that HELP 3 evaluation of landfill designs should be done for long-term (greater than 10 years) water balances only (NCASI 1997b, 1997c, 1997d).

4.0 REVIEW OF FULL-SCALE ALTERNATIVE CLOSURE PROJECTS

At least 29 full-scale landfill closure projects have included final covers incorporating paper mill residuals as the hydraulic barrier construction material. Table 4.1 presents summary information on these closure projects. The data presented in Table 4.1 are from a variety of sources that include published material, engineering and consultant reports, state records, and NCASI visits. Examination of the data presented indicates that the amount of available information for each location varies.

Landfills closed with residuals in North America range in size from a 1.6-acre municipal landfill to a 30-acre industrial landfill. Three closures reported using primary residuals and the balance (where information was available) used combined residuals. The combined residuals were reported as containing approximately 5 to 15% secondary residuals. Barrier thickness layer ranged from 18 to 49 inches with a median value of 30 inches. In some cases, residuals were placed up to 25% thicker than the target thickness to account for consolidation. Overburden thickness ranged from 3 to 24 inches with a median value of 12 inches.

Table 4.1 Full-Scale Closures Using Residuals as Hydraulic Barrier Material

State	Location	Landfill Type	Size (acres)	Residuals Type	Barrier Thickness (inches)	Cubic Yards Utilized	Hydraulic Conductivity (cm/sec)	Overburden Thickness (inches)	Placement Year(s)	Hydraulic Conductivity Testing	Other Testing
AL	Courtland	Industrial	22	Combined	36		$<10^{-6}$	6	1997	Yes	Yes
AL	Mahrt	Industrial	19	Combined	36		10^{-5}	6-12	In progress	Yes	
Al		Industrial	1+	Primary	36		10^{-7}	6-12	2003		
ME	Solon	Municipal	3	Combined	30	12,800	$10^{-6} – 10^{-7}$	6	1994	Yes	Yes
ME		Municipal	3.2	Combined	30		10^{-7}	6	1996	Yes	No
ME	Somerville	Municipal	1.5	Combined	30	8,000	10^{-5}	6	1995	Yes	No
ME	Warren	Municipal	25			35,000			1998-1999		
MA	Hubbardston	Municipal	8	Combined	36	24,000	$10^{-8} – 10^{-9}$	12	1990-2002	Yes	Yes
MA	Montague	Municipal	7.5+	Combined	30	58,500	$10^{-8} – 10^{-9}$	12	1993,94,98	Yes	No
MA	Athol	Municipal	16	Combined	30	49,700	10^{-8}	12	1994	Yes	Yes
MA	Colrain	Municipal	3	Combined	30	6,400	$10^{-8} – 10^{-9}$	12	1996	Yes	Yes
MA		Municipal	3	Combined	30		$10^{-8} – 10^{-9}$	12	1995	Yes	Yes
MA		Municipal	16	Combined	30		$10^{-8} – 10^{-9}$	12	1996	Yes	Yes
MI	Escanaba	Industrial	9	Combined	32		$<10^{-7}$	18	1995	Yes	Yes
NH	Marlboro	Municipal	1.6			6,000			1994		
NH		Municipal	3	Combined	30		$10^{-8} – 10^{-9}$	12	1995	Yes	Yes
NH	Goshen	Municipal	2		24	8,600					

(Continued on next page.)

Table 4.1 Continued

State	Location	Landfill Type	Size (acres)	Residuals Type	Barrier Thickness (inches)	Cubic Yards Utilized	Hydraulic Conductivity (cm/sec)	Overburden Thickness (inches)	Placement Year(s)	Hydraulic Conductivity Testing	Other Testing
NH	Lisbon	Municipal	4		24	20,100					
NH	Gilmanton	Municipal	3.5		28	17,600					
NH	Loudon	Municipal	4		28	20,100					
NH	Tuftonburo	Municipal	6		24	2000			2002		
NH	Littleton	Municipal	12			15,600			2002-2003		
NH	New Ipswich	Municipal	12	Combined	18	30,100		18	2002-2003	Yes	
NH	Nottingham	Municipal	2.5			9,300			2003		
NH	Berlin	Municipal	9.5			29,700			2003		
NH	Tuftonboro	Municipal	0.9			2,500			2002		
NH	Wakefield	Municipal	10			28,400			2002		
NY	Corinth	Municipal	10	Primary	36		10^{-7}	24	1995	Yes	Yes
NY		Industrial	12	Primary	24		10^{-7}	18	1996	Yes	Yes
Other Regions											
Nova Scotia	Point Tupper	Industrial	1.5	Combined/ash	49	8070	10^{-6}		2001	Yes	Yes
South Africa	Springs, Gauteng	Industrial	0.2	Combined	24		10^{-6}	8	1997	Yes	

4.1 Residuals Placement Techniques

The most common method described for the hydraulic barrier placement is spreading the residuals from the toe of the landfill toward the top using a low ground pressure bulldozer. Typically, residuals are trucked to a landfill site and placed near the base of the landfill onto pads constructed of clay. These clay pads are constructed at several locations around landfill perimeters and serve as centralized locations where bulldozer operators push residuals up the landfill sides. These pads are often constructed of clay to minimize any concerns associated with infiltration and/or runoff of stormwater that may have contacted the residuals. Residuals are spread using low ground pressure bulldozers in multiple lifts to a predetermined thickness. Grade stakes are often used to control lift thickness and guide the bulldozer operators during installation of each lift. While residuals are rarely compacted after placement, they are usually "smoothed" or rolled with a smooth, weighted roller (see Figure 4.1). Rolling the residuals serves to promote consolidation of each lift and creates an exposed residuals surface that promotes runoff and limits absorption of water. Based on field observations from multiple projects, significant absorption of precipitation can increase the moisture content of the placed residuals such that loss of shear strength and the exhibition of liquid properties (i.e., slumping of the residuals) may occur (see Section 3.5). Both NCASI's field-scale experience and experience from full-scale landfill closures indicate that barrier layers constructed from residuals should be placed at solids contents typically achieved by mechanical dewatering.

Figure 4.1 Residuals Placement with Low Track Pressure Dozer and Smooth Roller

One company reported the results of a material workability study in which different types of equipment were used to place both clay and residuals used as construction materials. The highest degree of compaction was achieved for clay using conventional equipment such as a vibratory compactor; however, this equipment did not perform well on residuals. The best method reported for the placement of both primary and combined residuals was a roller towed by a low track pressure dozer. This placement method was successful in removing virtually all voids from the residuals materials (Aloisi and Atkinson 1992).

NCASI has anecdotal information from several landfill operators with full-scale residual closures of both industrial and MSW landfills that indicated that equipment operators quickly learn any nuances associated with using residuals as construction material. The most significant differences between clay and residuals handling techniques was attributed to the residuals' low shear strength, the tendency to remold itself (deform), and the potential to slump after placement if the residuals had too high a water content. One location reported that the dozer operators quickly learned to visually identify (based on color) residual loads that were too wet for proper spreading. These loads were rejected at the landfill toe because of the potential for slope failure.

As stated earlier in this report, due to shear strength limitations, side slopes typically do not exceed 25%. However, in some situations with significantly steeper side slopes, special handling and spreading techniques may be needed. Figure 4.2 shows a relatively large MSW landfill in New England that is sequentially being closed using residuals as the hydraulic barrier layer. The MSW refuse is steep enough that dozers were unable to push residuals from the toe of the landfill upward in the conventional manner. Instead, residuals were trucked to the top of the landfill via a service road and pushed downward over the sand gas venting layer using a trackhoe with a 6-ft cleanup bucket attached (Figure 4.3).

Figure 4.2 Sequential Closure of MSW Landfill with Residuals

Figure 4.3 Trackhoe with 6-ft Cleanup Bucket

4.2 Test Pad Construction and Operation

To evaluate practical construction issues and document initial hydraulic conductivity of placed residuals, some full-scale applications construct relatively small test pads to simulate the placement of a full-scale residuals barrier. In some instances, state regulators have made test pads, sometimes called "demonstration projects," a required component of the permit for full scale closure.

The test pads model the construction of the full-scale cover to verify that the residuals can be used as construction materials for an engineered cover and that the methods will provide the desired in-situ hydraulic conductivity.

These test pads vary in size up to 25 x 25 feet in area. Grade stakes are sometimes used to insure that slopes and lift thicknesses are accurate. To evaluate the in-situ hydraulic conductivity of the residuals, most facilities collect an undisturbed Shelby tube (thin wall sampler) sample that is sent to a contract laboratory for hydraulic conductivity testing. Sometimes hydraulic conductivity is evaluated with a sealed dual-ring infiltrometer (ASTM 2002) because of its ability to measure infiltration over a larger surface area that includes potential defects and preferential flow paths.

Multiple test pads are sometimes constructed to evaluate differences in construction practices, construction materials, varying thicknesses of overburden, etc. Test pad hydraulic performance is monitored for a period of several months to as long as two years. At one location, in lieu of test pads, prototype caps were installed as a portion of the landfill cover. Each of the six prototype caps was built with a separate drain pipe to collect and quantify any moisture that penetrated the residual layer. These prototypes will remain in place as part of a long-term assessment of residuals as cover material.

4.3 Gas Collection Layers

There is nothing unique about the design of alternative landfill covers utilizing residuals that requires any modifications to typical landfill gas collection systems. Compared to MSW landfills, however, pulp and paper industry landfills are expected to decompose at lower rates, and ultimately to release lower amounts of methane and other gases; as a result, not all paper industry landfills have gas collection systems (NCASI 1999a). However, the majority of the full-scale closure applications identified in Table 4.1 are at municipal landfills, and therefore, will likely have some type of collection system in place.

Where described, the collection system consists of a layer of sand or gravel (most common) underneath the hydraulic barrier. With these materials, a filter or geotextile fabric may be needed to prevent infiltration of materials from the barrier layer. Geotextile drain and filter materials have additionally been used in construction of gas collection layers (McGee, Taylor, and Nilsson 1997; Malmstead, Bonistall, and Maltby 1999; SENA 2001).

5.0 SYNTHETIC SOIL USE

A significant number of the full-scale closure applications utilized a blend of residuals and local soils to construct the overburden, frost protection, and vegetative layers. These synthetic soils, sometimes referred to as engineered soils, while not designed for low hydraulic conductivity, often have other desirable properties that exceed those found in local soils used as capping materials. These properties include increased moisture holding capacity, increased strength, reduced erosion, and increased evapotranspiration rates. Table A1 in Appendix A identifies by state some of the sites where synthetic soils have been utilized as topsoil or cover construction materials.

Agronomic testing of synthetic soils has been described by Laubenstein and Field (1994) and Kanasaki, Ishii, and Takhashi (1994). The most important parameter reported was the carbon to nitrogen (C:N) ratio. The design value for the synthetic soils used in vegetative layers is a 40:1 ratio. To achieve this, it is typically necessary to add relatively large amounts of nitrogen to the blend.

Another related use of residuals is the use of synthetic soils as a capping material for mine refuse piles where water quality issues are of concern. These soils are used as an infiltration barrier to minimize the volume of acid mine drainage (AMD) and as an oxygen barrier to minimize the formation of acidic AMD. Additional information on the use of residuals to control AMD is presented by Laubenstein (2001) and Lawson (1996).

An extensive study evaluated the use of uncomposted residuals as the organic matter component in a manufactured topsoil (Carpenter and Fernandez 2000). Seven manufactured topsoils, containing 5.1, 8.8, 9.6, 10.9, or 13.8% residuals and 0, 8.4, or 20.7% flume grit on a dry weight basis, were applied to an abandoned gravel pit. Manufactured topsoils and a control topsoil were evaluated for a) impacts on soil and soil chemistry, and b) effectiveness as a growing medium for a grass conservation medium mix and hybrid poplars. Significant nitrogen mineralization was evident for all the manufactured topsoils within the first season. Soil cation exchange capacity, pH, and phosphorus availability were positively correlated to the residuals loading rate. Cumulative grass yields during the 15-month study were greater than those in the control topsoil, and tree height, diameter, and foliar nutrient concentration corresponded positively to the manufactured topsoils.

Additional information on the physical characteristics, erosion resistance, C:N ratios and macronutrients, cation balance, vegetative qualities, aesthetic considerations, and economics of manufactured topsoils was presented by Carpenter 2004.

Table A2 in Appendix A identifies by state some of the full-scale mile reclamation sites.

6.0 FULL-SCALE CASE HISTORIES

Several full-scale alternative closures are reviewed below. They were selected for review because of either a unique application of residuals or a particularly comprehensive amount of available information for the project.

6.1 Hubbardston, Massachusetts

In July, 1991, Erving Paper (Erving, Massachusetts) petitioned the Central Region of the Massachusetts Department of Environmental Protection (DEP) to conduct a full-scale demonstration project at the Hubbardston, MA municipal landfill and ultimately became the first paper company in the United States to utilize residuals as hydraulic barrier material (Figure 6.1).

Erving conducted a significant amount of research on its own residuals prior to the petition. Six test plots simulating typical landfill final capping designs were constructed. The six test plots allowed comparison of two types of compacted sludge to a clay control cap and comparison of different sludge cap thicknesses. Additionally, two plots of the same type and thickness of sludge were constructed at different times to assess reproducibility of results. Test plots were 25 feet x 25 feet in area. A smooth base with a 6% bottom slope and containment berms was prepared using fine soil. The base of each test plot was covered with a layer of protective geotextile filter fabric. A double layer of 6-mil agricultural plastic was used as the test plot liner. The base of each test plot was shaped to facilitate drainage of liquid to a sump area. A leachate collection system, consisting of PVC piping and two plastic drums in series, was installed for each test plot. Clay and residuals were compacted in lifts. Various placement techniques were explored to achieve the optimum compaction for each material. Equipment used included smooth drum and padded drum vibratory rollers, a small reversible plate compactor, and a low pressure track dozer. The top surface of the low permeability layer was leveled at a 6% slope at an elevation slightly above the top of the containment berms.

Hydraulic conductivities of fresh samples of primary and combined residuals were determined under standard laboratory conditions. Hydraulic conductivity varied with the degree of compaction and dry density of the sample. The measured hydraulic conductivity of fresh primary residuals and blended residual samples, at the highest dry density tested for each, were 1.50×10^{-7} and 5.68×10^{-7} cm/sec, respectively. Other residuals testing included chemical analysis, material workability, core permeability, leachate generation rates, and additional field permeabilities.

The initial calculated hydraulic conductivities of the residuals test plots was higher than the average values over time. This was likely due to consolidation and/or in situ dewatering of the residuals over time. After the initial period of higher values, the calculated permeability of the 18-in thick primary residuals test plot decreased and fluctuated in a pattern similar to the clay control test plot but within a narrower range of values. The clay control cap apparently suffered significant deterioration of cap integrity over the first freeze-thaw cycle.

Figure 6.1 Hubbardston, MA MSW Landfill - 2003

Spreading of the residuals layer on the landfill began on July 1, 1991 and was completed on May 8, 1992. The cover was seeded on May 29, 1992. The closure required about 24,000 cubic yards of residuals (five months of mill production). The residuals cap on the landfill is approximately three feet of residuals, topped by a 6-in sand drainage layer and 12 inches of vegetative supporting overburden.

The sequence for placing materials and constructing the landfill cap began with careful final grading of the landfill surface. Paper mill residuals were brought directly from the wastewater treatment plant to the landfill. The residuals were spread and compacted in layers to a final thickness of 3 feet using a low ground pressure track dozer. A customized water filled roller approximately 18 inches in diameter and weighing between 1000 and 3000 lbs (depending on amount of water added) was determined to be effective in compacting the residuals and eliminating all voids. The maximum manageable slope was determined to be 1:3.3 (about 30%). The level of effort required to place the residuals layer, as opposed to placing clay, was reported to be very small. After the residuals were compacted and grades rechecked, a 6-in layer of sand was placed, and then a 12-in layer of soil to support vegetation was added. The construction of the landfill cap was completed in sections. Minimal erosion of sediment was observed and no odor problems associated with the sludge were reported by workers, neighbors, or DEP inspectors either during or after construction of the cap. Once one area was completely capped with residuals, the sand layer and the soil layer were added to that area.

In late August 1991, Hurricane Bob passed over the area of the landfill, depositing approximately 9 inches of rain in a two-day period. Two weeks later, a second heavy rainstorm deposited approximately 8 inches of rain in two days. Following the abundant precipitation, residuals that had been spread but not yet rolled smooth lost cohesion and slid several feet downslope. Uncovered residuals that had been rolled smooth did not lose cohesion. Attempts to push the mobilized residuals back into position failed, and they were excavated and removed from the cover and placed into a landfill. Fresh residuals were brought in for replacement.

Moo-Young and Zimmie (1996) monitored post-closure hydraulic performance of the residuals and showed that the hydraulic conductivity of the cover decreased by an order of magnitude due to consolidation. Eight Shelby tube samples of the residuals were collected and hydraulic conductivities were determined to be between 1.9×10^{-8} and 8.9×10^{-8} cm/sec.

Following the completion of the demonstration project, Erving applied for, and received, a Beneficial Use Determination (BUD) from the DEP for the use of their residuals as a landfill capping material. The BUD was issued in February 1993, allowing Erving to submit bids to cap landfills with their residuals without performing any additional testing (Quiroz and Zimmie 1998; Smith and Smith 1993; Aloisi and Atkinson 1992).

6.2 Courtland, Alabama

In October 1997, International Paper (IP) Company's Courtland, Alabama facility (then owned by Champion International Corporation) completed the closure of a 22-acre industrial landfill using residuals as the hydraulic barrier layer. The residuals consisted of both primary clarifier residuals and secondary clarifier residuals from an activated sludge treatment system. Secondary solids comprised between 0 and 70% of the loading to the dewatering system. Dewatering to approximately 30% solids was accomplished using belt filter presses. Preliminary geotechnical testing and extrapolation of NCASI test plot results indicated that the sludge would meet Alabama Department of Environmental Management (ADEM) hydraulic conductivity requirements. The capping project was presented to IP management and ADEM as an experiment with good opportunity for success. Performance monitoring after the completion of the project confirmed the projections.

The original process waste landfill at the Courtland Mill had been abandoned in the early 1980s, but had not been "closed." IP committed to ADEM to cap the site in an environmentally sound manner, but had not specified the cap design. ADEM solid waste regulations required a landfill cap to be at least as impermeable as the subgrade. To meet this standard, a design that incorporated a barrier layer with a maximum hydraulic conductivity of $4 \times I0^{-7}$ cm/sec was required. Constructing the barrier layer of the cap using residuals was attractive for several reasons:

- It presented an opportunity to establish a beneficial use for a waste material.
- It would relieve some of the challenge of disposing of the sludge in the active landfill.
- It would extend the useful life of the active landfill.

Prior to preliminary engineering, the concept was reviewed by ADEM staff and a proposal was developed to fit within the regulatory framework. ADEM staff were receptive, in part, for the following reasons.

- Because operation of the landfill was ceased before ADEM regulations required final caps, the closure was voluntary rather than required.
- IP was willing to commit to performance tests on the cap.

- Site grading and drainage improvements required prior to placement of the sludge barrier layer would be suitable for a traditional clay cap if the sludge cap were to fail.

An engineering study and a cost/benefit evaluation were performed prior to presenting the project to mill management for approval. The cost of the residuals cap was very attractive relative to a traditional clay cap. The project team reasoned that the potential to succeed far outweighed the risk of failure. Furthermore, if the residuals barrier layer were to fail, most of the investment in the project (regrading, drainage) would be useful for a traditional cap.

Using residuals in the barrier layer of the cap was considered beneficial in two respects. First, at a relatively low unit weight, the cap would place limited bearing pressure on the waste material. Also, the residuals were considerably more flexible than compacted clay. Samples of residuals were compacted to densities measured on undisturbed samples from the active landfill. At those densities, hydraulic conductivities of less than 4×10^{-7} were measured.

Based on the consolidation observed in the NCASI test cells, lower final hydraulic conductivities for an "aged" cap were predicted. In addition to the final cap, the closure design included regrading the 22-acre site to a central ridge with 5 to 9% slopes falling to a perimeter ditch. Output from the HELP model indicated that the closed site would generate significantly less infiltration through the base than the existing condition. The final closure design included a 3-ft thick residuals layer overlain by a 6-in thick topsoil vegetative layer. Passive gas vents, including 200 feet of lateral collection line were installed on 500-ft centers.

The most significant challenge to construction of the cap was the low shear strength of the residuals layer. Initially, it was thought that moisture content could be successfully used as an indicator of shear strength. After a year of close scrutiny, it was concluded that moisture content and shear strength do not correlate consistently. Courtland mill residuals ranged from 20 to 70 volume percent secondary residuals and it was assumed that secondary residuals would be significantly weaker than primary residuals. In addition, empirical evidence suggested that heavy polymer dosing in the dewatering process would result in uncharacteristically weak residuals.

Wet weather caused problems other than the obvious limitations on spreading the residuals barrier layer during storms. The only slope failure experienced during the construction of the cap occurred after heavy rain. Placement of topsoil on a section of the cap had been completed the evening before a heavy rain. The following day, tension fractures opened near the top of the slope and mud waves developed at the base of the slope as residuals and topsoil slid downslope. It was not determined whether the cause of the failure was the excess load placed on the residuals by the saturated topsoil or infiltration of rainwater into the residuals barrier layer.

Analyses of runoff from the cap met ADEM standards for total dissolved solids and oil and grease, and was below detection for 2,3,7,8 TCDD. Consolidation of the residuals layer was not as great at expected. Residuals were placed at a minimum thickness of three feet. At the few locations where the thickness of the barrier layer has been measured, it ranged from 27 to 30 inches. The residuals barrier layer appears to have gradually consolidated from top to bottom. Stratification of the material was observed in the gas vent trenches, with dry, stiff material overlying moist residuals. Mill personnel expect that the entire barrier layer will consolidate to this condition over time.

Undisturbed samples of the residuals barrier layer have exceeded the performance specification of 4×10^{-7} cm/sec. Test results are shown in Table 6.1.

Table 6.1 Summary of Geotechnical Test Results

Sample Description	Moisture* Content (%)	Dry Unit Weight (pcf)	Hydraulic Conductivity (cm/sec)	Shear Strength (total) (effective)
Bulk residuals (remolded)	147	22	3.3×10^{-6}	29 degrees 55 degrees
Bulk residuals (remolded)	277	18	1.8×10^{-8}	2.2 degrees 4.7 degrees
Residuals cap (undisturbed)	177	24	5.9×10^{-6}	
Residuals cap (undisturbed)	200	22	3.8×10^{-8}	
Residuals cap (undisturbed)	127	30	1.1×10^{-7}	
Residuals cap (undisturbed)	133	34	6.0×10^{-8}	16 degrees 21 degrees

* wt. of water/wt. of dry solids

While the stability of the cap during construction was challenging, once constructed, the stability appeared to increase with time, to the point where the cap could hold vertical walls in trenches. Residuals were spread using a low ground pressure (LGP) bulldozer. Typically, the residuals would support 6 inches of topsoil, also spread with an LGP dozer. Structural geogrid was used in limited areas where the residual layer would not support the weight of the topsoil and dozer.

After a prolonged period of dry weather, a 6-foot long desiccation crack was observed in the topsoil layer. This feature was carefully investigated by digging a two-foot square trench using a straightblade shovel. The crack was clearly evident to the base of the topsoil layer. Faint evidence of the feature could be seen at the top of the residuals barrier, but disappeared completely within the top inch of the material.

Construction of the 22-acre residuals cap was completed in October 1997. Construction proved to be difficult, requiring patience and creative methods to complete the project. To date, stability problems have been experienced in only one area of the cap. This instance appears to have resulted from heavy rainfall on a section of the cap recently completed. The cap has met all performance criteria. Hydraulic conductivities have been lower than initially projected (McGee, Taylor, and Nilsson 1997; McGee et al. 1996).

6.3 Escanaba, Michigan

In 1995, New Page's (formerly MeadWestvaco Paper) Escanaba facility evaluated its wastewater treatment plant (WWTP) residuals as an alternative construction material. Four residuals samples were submitted to an engineering laboratory to characterize hydraulic conductivity (ASTM D5084) and compaction/density properties (ASTM D1557). While residuals samples were assumed to be close to saturation in their as-received state, approximately 50 psi of backpressure was applied to the samples to minimize the effect of incomplete saturation. Hydraulic conductivity testing was conducted at relatively low hydraulic gradients to simulate field conditions. Because residuals coming from belt presses had varying ratios of primary and secondary residuals solids, samples were taken to evaluate the effects of different primary to secondary proportions. Results are summarized in Table 6.2.

Table 6.2 Properties of Whole Residuals at Various Ratios of Primary/Secondary Residuals

Testing Parameter	Ratio of Primary/Secondary Residuals*			
	60/40	65/35	70/30	75/25
Moisture %	130	132	135	186
Solids %	44	43	43	35
Hydraulic conductivity, 10^{-8} cm/sec	1.8	1.6	1.6	2.3
Dry Density, lb/ft^3	34	34	33	28
Max Dry Density, lb/ft^3	53	54	53	48
Optimum Moisture content, %	76	63	66	70

*weight basis

Table 6.2 indicates that all residuals samples had hydraulic conductivity values less than the 1.0×10^{-7} cm/sec required for hydraulic barriers constructed of soil. Additionally, data in Table 6.2 demonstrates that these low hydraulic conductivity values were achieved when the moisture content of the residuals (off the presses) was significantly higher than the "optimum" value.

To evaluate practical construction issues, a small test pad was constructed to simulate the placement of a full-scale residuals hydraulic barrier layer. The test pad residuals layer was placed on a 20% slope in three lifts to a total depth of about 32 inches. Grade stakes were used to ensure that lift thicknesses were accurate. Each lift was placed with low ground pressure bulldozers. Although no compaction specification was required, the bulldozer operators used the cleated bulldozer tracks to compact/consolidate each lift. Spreading and placement of the residuals was found to be fairly simple using the existing landfill equipment and no limiting construction issues were observed.

To evaluate the in-place hydraulic conductivity of the completed test pad, an undisturbed Shelby tube sample of the residuals layer was collected and submitted to a contract laboratory for hydraulic conductivity analysis (ASTM D5084). Results of the test indicated an in-place hydraulic conductivity value less than 1.0×10^{-7} cm/sec.

Results of the feasibility evaluation indicated that the mill's residuals would be a viable option for construction of a hydraulic barrier layer in the Phase 2 landfill cover system. To get the Michigan Department of Environmental Quality's (MDEQ) approval of this concept and their ultimate approval of a residuals cover project for the Phase 2 cell, extensive amounts of information were shared with MDEQ personnel. This information included research work completed by NCASI and others; details associated with completed full-scale projects; and data characterizing the properties of these residuals. In addition to written correspondence, several meetings and many telephone conversations were held to discuss the information. Throughout these discussions, the mill's goal was to demonstrate that, in accordance with the state's rules, a hydraulic barrier constructed of residuals could provide protection equivalent to that of a conventional clay cover.

After receiving conceptual agreement from MDEQ, detailed closure design plans were prepared for the final Phase 2 landfill cover system design. There are several general components of the cover system. These include

- a 12-in gas venting layer consisting of sand;
- a 32-in residuals hydraulic barrier layer;
- an 18-in vegetative rooting layer consisting of a lower sand erosion layer and an upper topsoil layer; and
- a drainage ditch consisting of a compacted sand-bentonite mixture.

A 30% consolidation was factored into the design of the barrier layer to allow for a long-term thickness of at least two feet.

To address concerns associated with the potential for water that may infiltrate through the residuals barrier layer and into the groundwater, the outer edges of the barrier layer do not extend beyond the landfill's solid waste boundary. With this design, any water that does infiltrate the residuals layer will be contained within the landfill's leachate collection system. In addition, to address concerns associated with the potential for impacted stormwater runoff, a sand-bentonite (material specified to have hydraulic conductivities less than 1.0×10^{-7} cm/sec) stormwater control channel was designed to surround the landfill cell and divert stormwater to the facility WWTP. This approach protects the groundwater in the unlikely event that the residuals layer adversely impacts stormwater quality.

Landfill design features, which include a double liner system with leak detection capabilities, also served to minimize concerns associated with potential groundwater impacts from the use of residuals as barrier materials.

During construction, residuals produced at the WWTP were trucked to the landfill site and placed near the base of the landfill onto constructed clay pads. These clay pads were constructed at several locations around the landfill perimeter and served as centralized locations where bulldozer operators would push residuals up the landfill slopes on top of the geotextile. These pads were constructed of clay to minimize any concerns associated with infiltration and/or runoff of stormwater that may have contacted residuals. The clay roadway pads were graded to drain toward the landfill's sand drainage layer. Residuals were spread using low ground pressure bulldozers in three distinct lifts to a thickness of 32 inches. Grade stakes were used to control lift thicknesses and guide the bulldozer operators during installation of each lift. Although there were no compaction specifications for the residuals barrier layer, each lift was compacted with the cleated tracks of the bulldozer and also rolled (minimum of three passes) with a smooth, weighted roller. Rolling the residuals served to promote compaction/consolidation of each lift and also created an exposed residuals surface that would promote runoff and limit absorption of water. Based on field observation at the site, significant absorption of precipitation could increase the moisture content of the placed residuals such that loss of shear strength and the exhibition of liquid properties (i.e., slumping of the residuals) would occur.

As part of the overall quality assurance and quality control plan, thin wall (Shelby tube) samples (ASTM D1587) were collected at a frequency of 2 per lift per acre to evaluate the in-place hydraulic conductivity of the hydraulic barrier layer. A total of 47 samples were taken and tested for hydraulic conductivity (ASTM D5084-90, flexible wall permeameter). Most results were in the range of 1.0×10^{-8} cm/sec and all the samples passed the maximum hydraulic conductivity specification of 1.0×10^{-7} cm/sec.

Several months of residuals production were required to generate the amount needed for completion of the hydraulic barrier layer. Consequently, construction of the hydraulic barrier layer extended through the summer and into the fall months of 1995. Upon completing the residuals hydraulic barrier layer and receiving test results that confirmed the in-place hydraulic conductivity specification had been achieved, sections of the hydraulic barrier were covered with the 12-in sand layer portion of the rooting layer. At times throughout construction of the cover, some slumping of the residuals barrier layer was observed if the overlying 12-in sand layer was not placed quickly enough to prevent damage from precipitation. The affected areas were removed and replaced using new residuals material. Each replaced section was constructed in lifts, compacted/consolidated, and tested for hydraulic conductivity.

After the 12-in sand layer over the hydraulic barrier layer was completed, the existing sand that was on top of the landfill liner and anchor trench (placed there during construction of the landfill) was carefully removed and the sand-bentonite drainage ditch was installed. The sand-bentonite mixture had been produced using a pug mill operation and was tested for hydraulic conductivity conformance prior to placement. The sand-bentonite material was placed in 9 to 12 inch lifts and was compacted by the bulldozer during placement. Horizontal and vertical grade stakes were used to facilitate construction of the sand-bentonite drainage ditch. The drainage ditch was designed and constructed to drain to the south end of the landfill, into a lined (PVC) stormwater channel and ultimately, to the facility WWTP.

Topsoil was spread in a 6-in layer over the entire surface of the cover and was seeded, fertilized and mulched. To prevent erosion, the mulch was crimped into the soil using an agricultural disk. In addition, erosion control matting (mulch blankets) was installed in portions of the drainage ditches and windbreak fencing was installed in accordance with the project soil erosion and sedimentation control plans. As the last steps of the closure construction project, six gas vent wells and five residuals barrier layer consolidation gauges were installed. The gas vent wells, which were installed using a drill rig, consisted of 4-in diameter PVC pipe. The vents were 20 feet in total length with the bottom 10 feet of pipe having perforations. The upper section of the perforated pipe was installed so that it intersected the sand gas vent layer. The consolidation gauges were installed to allow for long-term post-closure monitoring of residuals barrier layer consolidation/thickness.

After submitting construction documentation to the MDEQ and receiving concurrence that the cover system was constructed in accordance with the approved design plans and specifications, the thirty-year post-closure care period began (April 1996). Similar to post-closure work that would be conducted for conventional landfill cover systems, mill personnel have monitored and maintained vegetative growth on the landfill. Because the landfill cover was not seeded until fairly late in the fall season of 1995, almost all the vegetative growth began in the spring of 1996. During initial monitoring work, some additional seeding and mulching was completed in areas that appeared to have limited growth and additional erosion control matting was installed on areas that appeared susceptible to runoff and soil loss. The facility has and will continue to perform other conventional monitoring/maintenance tasks, including

- monitoring for landfill settling and ensuring that the landfill slopes are maintained at proper grades;
- maintaining transfer pumps and piping systems to ensure that landfill leachate is removed and properly treated;
- monitoring and maintaining the landfill's secondary leachate collection system (leak detection system) to document the integrity of the landfill's primary liner system;

- conducting semi-annual groundwater monitoring in up-gradient and down-gradient wells to document that the landfill is not adversely impacting local groundwater quality.

Post-closure monitoring of leachate production rates in the landfill has shown that the cover system effectively limits infiltration into the landfill. Although the landfill will likely produce leachate for many years (because of long-term consolidation), external rainwater and snowmelt no longer promote additional leachate formation.

After vegetation was established at the landfill, five stormwater samples were collected from the Phase 2 drainage ditches after rainfall events. These samples were analyzed for several metals (arsenic, barium, boron, iron, manganese, potassium, sodium, and vanadium) and general indicator parameters [ammonia, nitrates, nitrites, total Kjedahl nitrogen (TKN), bicarbonate, chemical oxygen demand (COD), chloride, pH, specific conductance, and total organic compounds (TOC)] to determine if utilization of residuals has any adverse impacts on stormwater quality. Control samples were also collected from the stormwater sedimentation pond of a nearby, on-site landfill that had been closed with a PVC membrane barrier. The Phase 2 stormwater data were compared against the control stormwater data in addition to available surface water protection standards. Results of these comparisons indicated that no significant difference between the Phase 2 stormwater data and the control stormwater data and no adverse impacts caused by the residuals barrier layer. This finding was not surprising since stormwater at the site results from surface runoff rather than lateral drainage within the cover system profile.

Several environmental and cost benefits were achieved through implementation of the residuals cover project. Most importantly, an effective landfill cover system was constructed to minimize the amount of rainwater and snowmelt that can enter the closed Phase 2 Landfill. Limiting the amount of water that can infiltrate through a landfill cover system reduced the long-term risk for groundwater contamination because a minimal amount of leachate is contained in the landfill at any given time.

Approximately 1,000,000 cubic feet of landfill space was also conserved by diverting residuals to the closure project. This resulted in significant cost savings due to the value of landfill space that is affected by high landfill permitting, construction, and operating costs. Because of the nature of the residuals cover project, it was not necessary to hire specialized construction contractors to complete the landfill closure work. The mill’s own personnel, who are familiar with residuals handling, were used as equipment operators and laborers (with contracted engineering oversight). Taking into account the estimated costs for landfill space that would have been consumed and conventional construction work that would have been required for closure of the landfill, implementation of the project resulted in a savings of approximately $1 million.

In 1998, a study was conducted that compared the effectiveness of the mill’s alternative cover design to that of a prescriptive design for the landfill (Benson 1998). The prescriptive design consisted of a vegetated surface layer 6 inches thick underlain by a drainage layer 12 inches thick, and a compacted clay layer 24 inches thick. The alternative design was identical to the prescriptive design except that residuals were used in place of the clay. The study was conducted because the residuals layer consolidated after construction, and in some locations may have had a thickness less than 24 inches. Two types of calculations were made: hand calculations and HELP model simulations.

The hand calculations and HELP model simulations both showed that percolation from the alternative cover using a residuals barrier layer was significantly less than percolation from the prescriptive cover employing 24 inches of compacted clay and having a saturated hydraulic conductivity of 1 x 10^{-7} cm/sec. Less percolation was transmitted from the alternative cover because the residuals have low hydraulic conductivity (geometric mean = 3.1 x 10^{-8} cm/sec), even when the thickness of the residuals layer is less than 24 inches. The ultimate thickness of the residuals layer should be approximately 18.5 inches. At this thickness, percolation from the residuals layer should be about four times less than percolation from the prescriptive cover (NCASI 1995; Malmstead, Bonistall, and Maltby 1999; Benson 1998).

6.4 Corinth, New York

In 1994, the Corinth municipal landfill located in Corinth, New York, became the first landfill in New York state to utilize paper industry residuals as the hydraulic barrier system. International Paper Company's Hudson River facility, in conjunction with the municipality, Rensselaer Polytechnic Institute (RPI), New York State Department of Environmental Conservation (NYSDEC), and a consultant, conducted research to assess the mill's residuals as barrier materials. While hydraulic conductivity testing using triaxial permeameters (performed at various confining pressures) indicated that the residuals were capable of meeting the state required 1 x 10^{-7} cm/sec, there was concern regarding the long-term consolidation behavior and leachate generation of the residuals.

To address long-term consolidation behavior and leachate generation, RPI conducted geotechnical centrifuge experiments that permitted the simulation of 30 years of behavior related to consolidation, settlement, and leachate generation in about 24 hours. The results indicated that long-term settlement could approach 17%. Leachate generated during the test was analyzed chemically and met the toxicity requirement for use as impermeable barrier material. This proved to be an important consideration in obtaining regulatory approval.

Based on the study, NYSDEC approved the use of the residuals as barrier layer material for the Corinth landfill. Construction began in August 1994, and was completed in July 1995. A 36-in layer of residuals was used as the barrier layer. Because freezing and thawing was a major consideration in the design of the cover system, a 19-in layer of residuals was used as a frost protection layer overlying the barrier layer. A 7-in vegetative layer and a 25-in drainage layer were placed above the frost protection layer. Residuals were placed at their dewatered solids content with a low ground pressure dozer pulling a smooth roller. Thermistor probes placed at various depths in the cover system indicated that depth of freezing did not penetrate the frost protection layer (Moo-Young and Zimmie 1997; Floess 1996; Floess, Smith, and Hitchcock 1995; Zimmie, Mahmud, and De 1994b).

6.5 Port Hawkesbury, Nova Scotia

In mid-April 2001, the Nova Scotia Department of Environment (NSDOE) granted Stora Enso Port Hawkesbury Limited approval to construct a "prototype" alternative hydraulic barrier using a blend of residuals and fly ash over a portion of a closed industrial landfill. The landfill, which was closed in 1998, contained primarily wet bottom ash from a hog fuel boiler, fly ash from an electrostatic precipitator, wood waste from yard cleanup, and wastewater treatment plant primary and secondary residuals.

While the hydraulic conductivity of the fly ash alone (3 x 10^{-3} cm/sec) was unsuitable as barrier material, the ash had other desirable geotechnical properties which rendered it suitable for contouring the surface of the landfill to create the base grades needed both to support the barrier layer and to create slopes sufficient to shed water. A series of tests on the residuals established an optimum blend of one-third ash (bottom and fly ash as delivered) and two-thirds residuals on a weight basis, for a hydraulic conductivity of 6 x 10^{-6} cm/sec. The advantage of the residuals/ash mixture was reduced hydraulic conductivity. A disadvantage was the need to provide a consistent mixture prior to placement and decreased workability of the material on the landfill surface. The materials were mixed by a screener which produced a well mixed product. All of the capping materials were mixed during a two week period.

An 11.8-in (300-mm) ash layer was placed on top of the graded waste material in the landfill to act as a gas collection layer. Once this layer was in place, a layer of polyethylene film was placed over the ash in vertical strips running from top to bottom. The film was for testing only and was to collect any moisture that penetrated the barrier and direct it to collection containers. Immediately above this plastic is a geotextile which, after the plastic layer degrades, keeps the vent layer and the residuals separate. The barrier layer was placed on top of the geotextile layer to a depth of 49 inches (1250 mm); the barrier layer is assumed to compact over time to a thickness of 39 inches (1000 mm). The material was placed and compacted in place with an excavator. The total area of the cap is 1.51 acres (6120 m^2), divided into six contiguous cells consisting of two “steep” sections and a “flatter” section. Each cell is equipped with a bottom drain pipe to collect moisture which penetrates the cover. Separate barrels collect moisture from each cell.

Some difficulties encountered during construction were related to very wet weather and consisted of the barrier layer sliding downslope because of a lack of friction between the geotextile layer and the plastic underneath. This did not prevent the barrier layer from being placed.

Testing carried out between August and October, 2001, indicated that the cap appears to be relatively impermeable and is effective in directing the precipitation as runoff. Daily monitoring of precipitation indicated that less than 2% of the precipitation was penetrating the barrier layer.

7.0 SUMMARY AND CONCLUSIONS

The following conclusions are made from the research described here.

- An ASTM Standard Guide is being developed to define appropriate hydraulic conductivity testing protocols for paper industry residuals utilized as barrier material in landfill covers. The Standard Guide will proscribe the following.
    - Measures to control gas should be used when testing residuals that produce gas. Gas production can be controlled effectively by a) testing at 4°C, b) spiking permeant with DBNPA biocide at maximum recommended concentration, and c) applying high backpressure (> 330 kPa) while testing. Flushing lines also works but is labor-intensive.
    - The hydraulic gradient should be as low as practical to simulate field conditions. Hydraulic gradients more than 10 should not be used.
    - Residuals specimens should be tested at the effective stress likely to exist in the field.
    - Testing residuals with tap water is acceptable; however, some states may have regulations that specify other permeants.

  - The termination criteria of ASTM D5084 are reasonable for residuals except that the range of acceptable outflow-inflow ratio should be increased to 0.70 to 1.3.

- Use of ASTM D698 "Proctor test" is completely inappropriate when determining a moisture density relationship/hydraulic conductivity relationship for residuals. An attempt to field-adjust the moisture content to that which corresponds to maximum dry density may increase the hydraulic conductivity of the barrier layer several orders of magnitude and potentially create material handling difficulties in the field.

- Full-scale covers using residuals should be designed to anticipate consolidation to ensure that adequate thickness is maintained after consolidation has occurred and to avoid problems associated with downward movement of the materials above the hydraulic barrier. The practical effect of consolidation in the field on the performance of residuals in a landfill cover is a long-term reduction in hydraulic conductivity when compared to the hydraulic conductivity of the residuals at the time of placement.

- The presence of cellulose fibers in residuals can severely hamper the accurate determination of liquid and plastic limits. While these limits remain the primary form of engineering classification for cohesive soils, they are of little use in describing the behavior of residuals because of the presence of fiber.

- Variation in slope stability (function of shear strength) is assumed to result from a wide range of water contents and relatively high organic content. Side slopes of residual covers are typically 25% (1:4) or less. Downward movement (failure) of residuals is relatively rare and is usually a function of unusually heavy precipitation. Residuals that had been rolled smooth with a weighted roller during construction were not prone to failure.

- Numerous studies concluded that there is little evidence of biodegradation in residuals used as construction materials. Residuals are generally assumed to be deficient in the nitrogen needed to support anaerobic degradation. There is no evidence of any deleterious effect on hydraulic conductivity due to biodegradation.

- The deleterious effect of multiple freeze-thaw cycles on residuals is similar to that same effect observed on compacted clay covers, although some residuals were demonstrated to be more resistant to freezing. Studies conducted on the depth of frost penetration concluded that the high water content of residuals contributed to the lack of frost penetration when compared to clay covers.

- Since 1990, at least 29 full-scale landfills have been closed with residuals incorporated as the hydraulic barrier layer. Landfill size ranged from a 1.6-acre municipal landfill to a 30-acre industrial landfill. Combined residuals were reported to contain approximately 5 to 15% secondary sludge. Barrier thickness ranged from 18 to 49 inches with a median value of 30 inches.

- The most common method of residuals placement was from the toe of the landfill toward the top using a low ground pressure bulldozer.

- Practical construction issues and initial hydraulic conductivity are commonly evaluated using one or more test pads.

- Because the majority of full-scale landfill closures utilizing residuals are at municipal landfills, gas collection systems are common. There is nothing unique about the design of such covers that requires any modifications to typical gas collection systems.

- A significant number of the full-scale closure applications used a blend of residuals and local soils to construct the overburden, frost protection, and vegetative layers. These synthetic soils (sometimes referred to as engineered soils), while not designed for low hydraulic conductivity, were determined to have other desirable properties, making them superior to local soils for use as capping materials.

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APPENDIX A

CLOSURES UTILIZING RESIDUALS/SOIL ADMIXTURES

Table A1 Full-Scale Closures Using Residuals/Soil Admixtures as Topsoil

State	Location	Landfill Type	Placement Year	Size (acres)	Thickness (inches)	Cubic Yards
GA	Camden	MSW	1997	15		In progress
MA	Ayer	MSW	Na	5	8	7,200
ME	Buxton	MSW	1987	7		5,650
ME	Brunswick	MSW	1988	2		1,610
ME	Yarmouth	MSW	1990	6.5		5,250
ME	Falmouth	MSW	1990	8.25		6,660
ME	Freeport	MSW	1990	3.8		3,070
ME	Vassalboro	MSW	1990	4.5		3,630
ME	Harrison	MSW	1991	3.2		2,580
ME	Cumberland	MSW	1991	8.9		7,180
ME	Waldoboro	MSW	1991	6.5		5,250
ME	Stonington	MSW	1992	3.5		2,830
ME	Friendship	MSW	1992	3.5		2,830
ME	Dexter	MSW	1992	11		8,880
ME	Sawyer (Hamden)	MSW	1992	11		8,880
ME	Brewer	MSW	1992	20		16,140
ME	Bowdoinham	MSW	1992	2.5		2,020
ME	Fairfield	MSW	1993	18.4		14,850
ME	Lewiston (Phase 1)	MSW	1993	25		20,180
ME	St. Albans	MSW	1993	1.5		1,210
ME	Abbott	MSW	1993	2		1,615
ME	Lewiston (Phase II)	MSW	1994	28		22,600

(Continued on next page.)

Table A1 Continued

State	Location	Landfill Type	Placement Year	Size (acres)	Thickness (inches)	Cubic Yards
ME	Topsham	MSW	1994	13.1		10,570
ME	Unity	MSW	1994	3.5		2,830
ME	Waterville (Phase I)	MSW	1994	3.5		2,830
ME	Waterville (Phase II)	MSW	1995	9		7,270
ME	Wayne	MSW	1995	4		3,230
ME	Bristol (Phase I)	MSW	1995	3		2,420
ME	Woolrich	MSW	1995	4.5		3,630
ME	Sabbatus	MSW	1995	2.5		2,020
ME	Alna	MSW	1995	3		2,420
ME	Somerville	MSW	1995	1.5		1,210
ME	Searsport	MSW	1996	10.5		8,470
ME	Warren	MSW	1996	3.8		3,070
ME	Waterford	MSW	1996	2.8		2,260
ME	Waterville (Phase III)	MSW	1996	8		6,460
ME	Bristol (Phase II)	MSW	1996	3		2,420
ME	Augusta	MSW	1996	2		1,610
ME	Freeport (Phase II)	MSW	1996	1.8		1,450
NH	Wolfeboro	MSW		8	12	17,280
NH	Hooksett	MSW		6	9	9720
NH	Keene	MSW		20	9	32,400
NH	Walpole	MSW		9	9	14,580
NH	Gilmanton	MSW		3.5	28	17,640
NH	Claremont	MSW		24	9	38,880
NH	Meredith	MSW		4	6	4,320
NH	Manchester	MSW		40	4	27,000

(Continued on next page.)

Table A1 Continued

State	Location	Landfill Type	Placement Year	Size (acres)	Thickness (inches)	Cubic Yards
NH	Hinsdale	MSW		6	9	10,160
NH	Hillsborough	MSW		16	9	29,040
NH	Concord	MSW	1995	17		13,720
NH	Conway	MSW	1995	12		10,000
NH	Madbury	MSW	1995	8		6,460
NH	Berlin	MSW	1996	14		11,280
NH	Pelham	MSW	1997	28		In progress
NH	Littleton	MSW	1997	10		In progress
NY	Hadley	MSW	1992	5		8,070
NY	Wilton	MSW	1992	7		11,300
VT	Hartford	MSW		3	4	2,160
WV	Clarksburg	MSW	1997	17.2		In progress

Table A2 Full-Scale Mine Reclamation Using Residuals/Soil Admixtures as Topsoil

State	Location	Application	Year	Acres	Thickness (inches)	Cubic Yards
AR	Bauxite	Mine	1998	10		15,000
FL	Bartow	Mine	1997	2		5,000
NH	Ambrose	Mine		20	9	32,400
NH	Latulippe	Mine		11	12	18,500
NH	Franklin Farm	Mine		3	6	3,240
NH	Tuftonboro	Mine		3	12	6480
VT	Rockingham	Mine		3	9	4,860
WV	Fairmont	Mine	1996	55		250,000