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Journal of Hazardous Materials 76 (2000) 193–216

**Journal of
Hazardous
Materials**

www.elsevier.nl/locate/jhazmat

Liners for waste containment constructed with class F and C fly ashes

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Received 8 June 1999; received in revised form 25 December 1999; accepted 4 January 2000

Abstract

Hydraulic conductivity of a Class F fly ash containing residual organic carbon was evaluated in this study using laboratory and field tests. Compacted specimens of the Class F fly ash mixed with various materials (sand, Class C fly ash, and bottom ash) were prepared in the laboratory at various water contents and different compactive efforts. Hydraulic conductivity of the compacted specimens was measured using flexible-wall permeameters. A test pad was constructed to determine whether a low hydraulic conductivity liner could be constructed with Class F fly ash mixtures. Sealed double-ring infiltrometers and two-stage borehole permeameters were used to measure the field hydraulic conductivity of the test pad. Specimens were also removed from the test pad for hydraulic conductivity testing in the laboratory. Results of the study showed that mixtures of Class F and Class C fly ashes along with coarse aggregate can be compacted to hydraulic conductivities needed for landfill liners provided compaction is wet of optimum water content. The field tests showed that constructing a fly ash liner with hydraulic conductivities similar to those found in the laboratory is challenging, and requires careful attention to factors that result in cracks and permeable interlift regions that result in high field hydraulic conductivity. Leachate collected from the base of the test pad also showed that metal leaching must be considered when designing a liner with fly ash. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Fly ash; Hydraulic conductivity; Liner; Reactive barrier; Waste containment; Beneficial re-use; Industrial by-product

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1. Introduction

Lining systems for waste containment facilities can be enhanced if they are constructed with reactive materials, that is, materials that retard the movement of solutes, promote biodegradation, or induce chemical conversion. In many facilities, volatile organic chemicals (VOCs) are the primary contaminants of concern because of their mobility and the low concentrations at which they are toxic. Thus, reactive materials that adsorb VOCs and retard their movement can make liners more effective.

One potential material for constructing reactive liners is fly ash from coal-fired power plants that contains a modest amount of residual organic carbon, which is a sorbent of VOCs (Briggs [1], Karickhoff et al. [2], Gray et al. [3]). Such residual organic carbon could result in significant sorptive capacity for VOCs when compared to inorganic clays typically used in liner construction. For example, for the Class F fly ash used in this study (total organic carbon content = 5.9%), batch adsorption tests conducted with toluene, ethyl benzene, and *m*-xylene yielded partition coefficients of 199, 367, and 483 l/kg, respectively (Edil and Benson [4]). Coal fly ash also is a fine-grained material that previous research has shown to have potential for constructing hydraulic barriers (Edil et al. [5,6], Bowders et al. [7], Creek and Shackelford [8]). In addition, Class F fly ashes, which usually contain modest amounts of carbon, currently are being disposed in ponds and landfills. Using Class F fly ash for a reactive liner provides a means to build a more effective liner and also is a beneficial use of a waste material.

The objective of this study was to evaluate the hydraulic properties of a Class F fly ash that contains residual organic carbon. Hydraulic conductivity of the fly ash, as well as adsorption and diffusion of VOCs through the fly ash, were studied. This paper describes the portion of the study focused on hydraulic conductivity, which included laboratory and field components. The transport portion of the study is described in Erkinheimo [9].

2. Background

Large quantities of coal fly ash are generated each year by the electric power industry. In 1993 alone, 43 million Mg of fly ash was produced in the US. Twenty two percent of the fly ash was reused as a construction material or in other miscellaneous jobs. The remaining 78% were disposed in landfills and holding ponds (ACAA [10]). In Wisconsin, USA, fly ashes that are not reused must be disposed in engineered waste containment facilities.

Coal fly ash is the portion of unburned coal that is collected from flue gas by electrostatic precipitators and filter bag houses. Fly ash consists of unburned coal particles and spherical agglomerates that form during cooling of droplets of inorganic coal residue. Proportions and the size distribution of the unburned coal and agglomerate particles vary among different coals and burning processes (Roy et al. [11]).

Coal fly ash is a pozzolanic material and has been divided into two classes, F and C, by ASTM C 618. A pozzolan is defined in C 618 as a siliceous material that chemically reacts with calcium hydroxide (CaO) in the presence of moisture to form a material that

exhibits cementitious properties. Class F fly ash is produced from burning anthracite and bituminous coals. Class C fly ash is produced from lignite and sub-bituminous coals. Class C fly ashes can contain significant amounts of calcium hydroxide and, as a result, can be self-cementing. Construction applications typically use Class C fly ash because of its cementitious properties. Both Class C and Class F fly ashes are added to cement and lime for use as a pozzolan in construction.

2.1. Hydraulic conductivity of compacted Class F fly ash

Bowders et al. [7] evaluated the potential for using Harrison and Amos Class F fly ashes from West Virginia in hydraulic barriers. Varying amounts of lime or cement were mixed with the fly ashes and test specimens were compacted at optimum water content according to procedures in ASTM D 698 (standard Proctor). Hydraulic conductivities were measured using single- and double-ring rigid-wall compaction mold permeameters at a hydraulic gradient of 100. Distilled-deionized water (DDIW) was used as the permeant liquid. The specimens were tested after 7 and 28 days of curing in 100% relative humidity.

The hydraulic conductivity tests showed that unstabilized Harrison and Amos fly ashes had hydraulic conductivities of 7.2×10^{-6} and 5×10^{-5} cm/s, respectively, when compacted at optimum water content. Increasing the amount of lime or cement decreased the hydraulic conductivity. For example, the hydraulic conductivity of Harrison ash dropped about an order of magnitude when 15% lime was added. Bowders et al. [7] also found that increasing the curing time from 7 to 28 days did not significantly decrease the hydraulic conductivity.

Bowders et al. [12] examined how bentonite content, permeant, and curing conditions affect the hydraulic conductivity of fly ash mixtures using methods similar to those in Bowders et al. [7]. DDIW, methanol, and acetic acid were used as permeant liquids. Addition of bentonite to mixtures containing cement and lime did not reduce the hydraulic conductivity of the mixtures and, in some cases, actually increased the hydraulic conductivity. Permeation with a 5% methanol solution yielded a decrease in hydraulic conductivity for specimens containing lime and lime–bentonite, whereas an increase in hydraulic conductivity occurred in the specimens containing cement and cement–bentonite. Permeation with 3.2% acetic acid solution lowered the hydraulic conductivity of all specimens, except those with 10% bentonite.

Bowders et al. [12] conducted long-term curing tests on mixtures containing Class F Harrison ash with 9% cement or lime. Hydraulic conductivity tests were run after 7, 28, 56, 128, and 256 days. The lime-stabilized mixture showed steady decreases in hydraulic conductivity over time. Hydraulic conductivity of the specimen cured for 256 days decreased three orders of magnitude compared to the value at 7 days (1.7×10^{-5} to 2.7×10^{-8} cm/s). Hydraulic conductivity of the cement-stabilized mixture cured for 256 days dropped an order of magnitude. Another series of tests was run to examine how dry curing affected the hydraulic conductivity. In this series of tests, the specimens were removed from the wet curing conditions after 7 or 28 days and allowed to cure under room conditions with varying humidity for up to 270 days. Although no shrinkage cracks were observed, the hydraulic conductivity increased slightly.

Creek and Shackelford [8] investigated the hydraulic conductivity of a Class F fly ash from Colorado mixed with varying amounts of sand, bentonite, and cement. Specimens of pure fly ash had a hydraulic conductivity of 1.0×10^{-7} to 2.4×10^{-6} cm/s, while adding various admixtures produced hydraulic conductivities ranging from 1.2×10^{-4} to 4.5×10^{-7} cm/s. An optimum percentage of fines existed that minimized the hydraulic conductivity and maximized the dry unit weight.

Shackelford and Glade [13] evaluated the hydraulic conductivity of sand bentonite fly ash mixtures. A specimen containing no bentonite had the largest hydraulic conductivity. Increasing the bentonite content generally lowered the hydraulic conductivity up to a bentonite content of 18%, beyond which the hydraulic conductivity increased. Shackelford and Glade [13] also found that the hydraulic conductivity typically decreased an order or magnitude as the hydraulic gradient was increased from approximately 5 to 100.

2.2. Hydraulic conductivity of compacted Class C fly ash

Vesperman et al. [14] investigated the hydraulic conductivity of Belle Ayre and Colstrip Class C fly ashes from Wisconsin and mixtures of these ashes with sand. Belle Ayre fly ash was mixed with varying percentages of sand (0% to 90%). The lowest hydraulic conductivity was less than 10^{-7} cm/s and was obtained for mixtures containing 40% and 100% fly ash compacted at optimum water content with standard compactive effort. Belle Ayre fly ash had lower hydraulic conductivity than the Colstrip fly ash, due to the greater pozzolanic properties of the Belle Ayre ash. All the mixtures showed a decrease in hydraulic conductivity during testing due to clogging of voids as pozzolanic reactions occurred.

Edil et al. [5] evaluated how addition of sand and bentonite affected the hydraulic conductivity of Black Thunder and Pleasant Prairie Class C fly ashes. Some of the specimens were subjected to freeze–thaw cycles. The hydraulic conductivities ranged from 2.8×10^{-7} to 7.5×10^{-10} cm/s. Statistical analysis of the data indicated that type of fly ash, percent fly ash, and freeze–thaw had a significant effect on hydraulic conductivity. Addition of bentonite did not affect hydraulic conductivity or resistance for freeze–thaw damage, although it did improve workability and quality of the specimens.

Edil and Berthouex [15] investigated methods of controlling set-up time of fly ash mixtures, including varying the water content, changing the compactive effort, and adding retarders. Increasing the water content and compactive effort decreased the hydraulic conductivity and increased the dry unit weight. Use of a retarder (a lignin solution mixed at 0.1% by dry weight of the mixture) delayed hardening so that compaction was possible for nearly an hour, increased the dry unit weight, and decreased the hydraulic conductivity.

2.3. Hydraulic conductivity of other compacted fly ashes

Sachdev and Amdurer [16] studied the hydraulic conductivity of New York and West Virginia fly ashes. The fly ashes were mixed with various amounts of lime, cement, and bentonite. Lime and cement were ineffective in reducing the hydraulic conductivity of the New York ash, as were granular and powdered bentonites. A finely powdered bentonite was successful in reducing the hydraulic conductivity of the New York ash.

However, hydraulic conductivities less than or equal to 10^{-7} cm/s could not be obtained, even with 12% bentonite.

Quant [17] presents information regarding a mixture of fly ash, soluble silicate (water–glass solution), and lime that had hydraulic conductivities ranging from 10^{-7} to 10^{-8} cm/s, and decreased with time. Quant [17] reports that increasing the calcium oxide and colloidal silica content reduce the hydraulic conductivity.

2.4. Leaching

Edil and Berthouex [15] examined how inorganic permeant liquids affected leaching from fly ash–sand mixtures. A synthetic permeant liquid was used that simulated leachate in a fly ash landfill. The leachate contained calcium, sulfate, cadmium, zinc, and boron with sodium and chloride added to achieve consistent ionic strength. Two fly ashes were mixed as 50:50 mixtures with coarse Portage sand. Concentrations of cadmium, sodium, and chloride in the effluent were not affected by any of the test variables. Sulfate, boron, and zinc concentrations in the effluent were affected by the type of fly ash used in the mix. Calcium concentrations in the synthetic leachate affected the pH and the calcium and sulfur concentrations in the effluent.

Bowders et al. [12] examined factors affecting leaching of copper, cadmium, chromium, and lead from Harrison ash. Increased curing time and addition of cement or lime reduced leachate concentrations, while addition of bentonite increased leaching by inhibiting fixation by cement and lime. The initial effluent also had higher metal concentrations than leachate sampled after one or two pore volumes of flow.

Creek and Shackelford [8] report that metals leached from their fly ashes exhibited two types of behavior: early and delayed leaching. Early leaching is characterized by high initial concentrations that decrease after one pore volume of flow. Delayed leaching corresponds to low initial concentrations that increase with additional pore volumes of flow. Most metals exhibited the early leaching behavior. Barium, calcium, and strontium exhibited delayed leaching. Creek and Shackelford [8] also report that iron and manganese did not leach from mixtures having 0.1% or less of the initial mass available in the mix. Addition of cement significantly reduced leaching of aluminum, boron, cadmium, chromium, molybdenum, lead, and zinc. As little as 2.5% cement reduced leaching of molybdenum from nearly 100% to less than 8% of the mass available and chromium from 50% to about 1% of the mass available.

Edil et al. [6] examined effluent characteristics from fly ash specimens permeated with a synthetic leachate similar to the one described by Edil and Berthouex [15]. Four distinct effluent responses were observed. Sodium and chloride concentrations decreased until they equaled the concentration in the synthetic leachate. Cadmium and zinc concentrations decreased to an equilibrium concentration below the concentration in the synthetic leachate. There were also two “breakthrough” type curves, with one leveling at the influent concentration and the other equilibrating above the influent concentration. Boron and sulfate displayed a breakthrough curve with the equilibrium concentration equaling the influent concentration. Calcium also displayed a breakthrough curve, but the equilibrium concentration was higher than the influent concentration suggesting leaching of calcium from the fly ash.

Edil et al. [6] also report that the fly ash–sand mixture leached aluminum, arsenic, chromium, strontium, and selenium. Leaching of these metals exhibited the early and delayed leaching patterns described by Creek and Shackelford [8]. As in Creek and Shackelford [8], Edil et al. [6] also found that most of the leached metals showed the early leaching pattern. The exceptions were strontium and chromium for one test specimen having low hydraulic conductivity. Leaching tests by Sachdev and Amdurer [16] conducted on the New York and West Virginia fly also showed the same early and delayed leaching patterns observed by Creek and Shackelford [8] and Edil et al. [6]. Most constituents such as calcium, chloride, and sulfate showed the early leaching pattern, while arsenic, fluoride, and selenium showed the delayed leaching pattern. Aluminum, mercury, and silver did not consistently show either leaching pattern.

3. Materials

Five materials were used in the testing program: Class F ash, Class C ash, sand, bottom ash, and bentonite. Two Class F ashes and two Class C ashes were used because the process used at the plants producing the ashes changed during the course of the testing program.

3.1. Class F fly ash

Two Class F fly ashes were used that were obtained from two different coal mixtures. One was from burning a 50:50 mixture of Wyoming and Illinois coals and the other from an 80:20 mixture of the same coals. Both mixtures were burned at the Edgewater

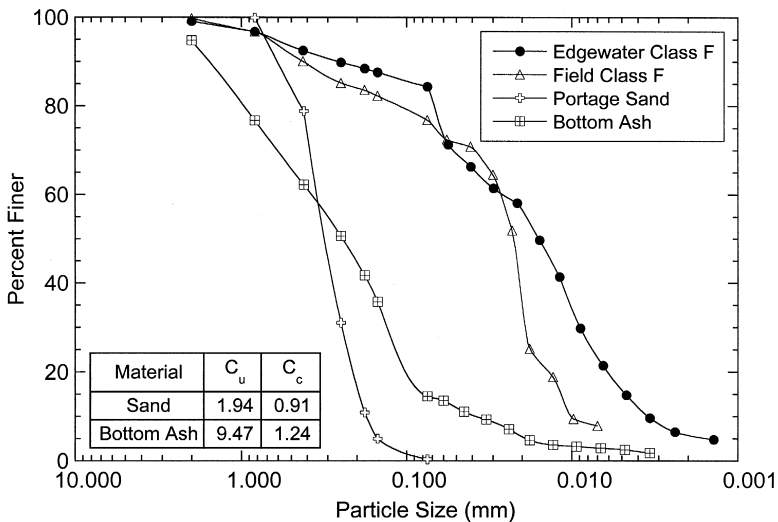


Fig. 1. Particle size distribution curves for Edgewater and Field Class F fly ashes, Portage sand, and bottom ash.

Generating Station in Sheboygan, Wisconsin. Fly ash from the 50:50 mixture was initially used for laboratory testing and is referred to as Edgewater Class F fly ash. During field testing, the power plant was burning the 80:20 coal mixture. Fly ash from the 80:20 mixture is referred to as the Field Class F fly ash.

Both Class F fly ashes classify as ML in the Unified Soil Classification System (USCS). Particle size distributions for the Class F ashes are shown in Fig. 1. Edgewater Class F fly ash contains 85% fines ($< 75 \mu\text{m}$), whereas Field Class F fly ash contains 76% fines. Clay size particles ($< 2 \mu\text{m}$) comprise less than 5% of both fly ashes. The specific gravity (G_s) of Edgewater Class F fly ash is 2.66 and for the field Class F fly ash it is 2.54. The liquid limit of both fly ashes could not to be determined.

The ash supplier provided the composition of the fly ashes, as shown in Table 1. The main constituents of the fly ash are calcium, magnesium, sulfur, aluminum, sodium, and iron. Field Class F fly ash has twice as much calcium as the Edgewater Class F fly ash used initially in the laboratory tests. The Edgewater Class F fly ash has five times as much organic carbon as the Field Class F fly ash.

3.2. Class C fly ash

Black Thunder Class C fly ash generated by Columbia Generating Station Unit II in Portage, Wisconsin was initially used in the laboratory test program. This is the same fly

Table 1
Chemical constituents in fly ashes

Chemical	Edgewater Class F fly ash	Field Class F fly ash	Columbia Class C fly ash	Field Class C fly ash	Bottom ash
P	1666	2753	2280	2689	1330
K	3859	2368	991.7	1065	558.9
Ca	52,286	139,328	195,032	170,295	85,141
Mg	8562	23,880	27,011	23,108	12,550
S	12,819	18,405	10,065	9081	1749
Zn	2557	3240	86.77	144.0	18.15
B	1243	934.0	690.4	547.4	245.9
Mn	62.48	122.2	123.6	168.3	358.6
Fe	65,326	39,062	35,086	32,765	20,181
Cu	170.3	213.6	169.8	186.3	53.07
Al	44,036	64,772	79,479	75,585	55,016
Na	2842	12,077	9515	8260	2942
Cd	< 1.00	< 1.00	< 1.00	< 1.00	< 1.00
Cr	31.57	24.05	7.48	9.69	< 1.80
Co	107.0	57.88	42.93	54.38	10.24
Mo	62.84	38.11	26.26	25.86	37.33
Ni	16.5	3.36	< 2.10	3.51	< 2.10
Li	170.1	31.11	26.80	37.66	< 3.66
Pb	146.4	< 11.1	< 11.1	< 11.1	< 11.1
As	< 27.9	< 27.9	< 27.9	< 27.9	< 27.9
TOC (%)	5.9	1.0	0.3	0.2	0.2

Note: All constituents except organic carbon are in ppm. Total organic carbon (TOC) is a percentage.

ash used by Edil and Berthouex [15]. The other ash, which was also obtained at Columbia Generating Station during field testing, is referred to as Field Class C fly ash. Thus, both ashes are from the same source, but were obtained at different times. Only percent fines ($< 75 \mu\text{m}$) was determined for the Class C ashes because of their cementing characteristics when moistened. Columbia Class C fly ash contained 97% fines and Field Class C fly ash contained 90% fines. Chemical composition of the Class C fly ashes is shown in Table 1. Both Class C fly ashes have more calcium and less organic carbon than the Class F fly ashes.

3.3. Sand and bottom ash

Fine Portage sand was used in the laboratory mixtures. The particle size distribution of fine Portage sand is shown in Fig. 1. This clean sand is uniformly graded, classifies as SP in the USCS, has sub-rounded grains, and $G_s = 2.66$.

Bottom ash from the Columbia Generating Station was used as an alternative to sand in the field test and as a beneficial use of the ash. The bottom ash has sub-angular grains and is classified as a SM in the USCS. The particle size distribution of the bottom ash is shown in Fig. 1. The bottom ash contains approximately 15% fines and has $G_s = 2.69$.

4. Laboratory methods

Specimens were compacted in the laboratory using standard and modified Proctor methods (ASTM D 698 and D 1557). Mixtures were blended while dry until appearing uniform and then were moistened to pre-determined water contents by spraying with tap water. The moistened mixtures were compacted immediately due to the pozzolanic property of the fly ashes.

4.1. Hydraulic conductivity testing

Hydraulic conductivity tests were performed using flexible-wall permeameters in accordance with ASTM D 5084 using the falling headwater-rising tailwater method. Tap water was used as the permeant liquid. The hydraulic gradient was between 10 and 15 and the average effective stress ranged between 10 and 12 kPa. No backpressure was used.

Tests were conducted on specimens prepared and compacted in the laboratory, specimens compacted in the field using laboratory compaction hammers, and on cores removed from a test pad. Specimens prepared in the laboratory or compacted in the field using laboratory compaction hammers were cured before permeation typically for 7 days in a 100% humidity room. All of the specimens had a diameter of 100 mm, except the cores, which had a diameter of 150 mm. The aspect ratio was approximately one.

4.2. Freeze–thaw and wet–dry testing

Testing was conducted to evaluate whether freeze–thaw and wet–dry cycling would affect hydraulic conductivity of compacted ash. Freeze–thaw testing used the freestand-

ing closed-system procedure in ASTM D 6035. Wet–dry cycling involved placing specimens in a low-temperature oven (60°C) for 24 h. Although oven drying likely caused more severe conditions than would exist in the field, the oven drying procedure was necessary to permit assessment of wet–dry effects in a reasonable time frame. Dried specimens were placed back in permeameters to be re-saturated at room temperature and tested using a hydraulic gradient of 10–15.

Flexible-wall permeameters were used to saturate and determine the initial hydraulic conductivity of the specimens. Five freeze–thaw and five wet–dry cycles were conducted based on recommendations by Othman et al. [18]. They show that changes in hydraulic conductivity after five freeze–thaw or wet–dry cycles are usually negligible.

5. Field measurements on test pad

A test pad was constructed using a mixture of Class F fly ash, Class C fly ash, and bottom ash. Various methods were used to evaluate the hydraulic conductivity of the test pad. In the field, sealed double-ring infiltrometers (SDRI) and two-stage borehole permeameters (TSB) were used to measure the field hydraulic conductivity. Laboratory tests were conducted on 150-mm-diameter cores and on specimens of the field mixture compacted in Proctor molds during construction using modified Proctor effort. Lysimeters were also placed underneath the test pad to collect leachate for analysis.

5.1. Sealed double-ring infiltrometers (SDRIs)

Two SDRI tests were performed following procedures described in ASTM D 5093. The inner and outer rings were square. The outer rings had a width of 3.65 m while the inner rings had a width of 1.52 m. Bentonite paste was used to seal the rings in the trenches.

Hydraulic conductivity, K , was calculated from the infiltration rate, I , using (Daniel [19]):

$$K = \frac{I}{i} \quad (1)$$

where i is the hydraulic gradient:

$$i = \frac{D_p + L}{L} \quad (2)$$

In Eq. 2, D_p is the depth of water in the outer ring and L is the thickness of the test pad. Eq. 2 underestimates the hydraulic gradient unless the wetting front reaches the bottom of the test pad (Wang and Benson [20]). By the end of testing, the wetting front had reached the base of the test pad, as evinced by collection of leachate from the lysimeters. Thus, in this case Eq. 2 provides a good estimate of the hydraulic gradient, which averaged 1.3 in both SDRIs.

5.2. Two-stage borehole permeameters (TSBs)

Two-stage borehole tests were also conducted to measure the hydraulic conductivity following methods in ASTM D 6893. Because the test pad was extremely hard, the borehole extension could not be advanced for the second stage. Thus, only the first stage of the test was run. Boutwell [21] shows that the apparent hydraulic conductivity obtained from the first stage (K_1) is an upper bound for the vertical hydraulic conductivity (K_v).

The TSBs consisted of a 100-mm inside-diameter casing with a 25-mm-diameter clear standpipe. A core drill was used to drill 150-mm-diameter holes for the casing. Cores that were removed were saved for hydraulic conductivity testing in the laboratory. A hand chisel and a shop vacuum were used to clean the holes and to extend them to a final depth of 200 mm. The base of the casing was placed flush with the bottom of the borehole and a bentonite grout was used to seal the casing-fly ash annulus.

Head in the permeameter was recorded periodically and used to calculate the apparent hydraulic conductivity, K_1 (Daniel [19]):

$$K_1 = \frac{\pi d^2}{11 D \Delta t} \ln \left(\frac{H_1}{H_2} \right) \quad (3)$$

where d is the inside diameter of the standpipe, D is the inside diameter of the casing, Δt is the time interval ($t_1 - t_2$), H_1 is the head at time t_1 , and H_2 is the head at time t_2 . The head is defined as the distance from bottom of the borehole to the meniscus in the standpipe (Daniel [19]).

5.3. Lysimeters

High-density polyethylene lysimeter pans were installed underneath the test pad to collect leachate that percolated through the test pad. The lysimeter pans were 0.6 m wide, 0.9 m long, and 50 mm deep. A 25-mm-diameter PVC pipe ran from each lysimeter to the edge of the test area for sample collection. Several layers of geonet were placed in the lysimeters to prevent collapse and clogging during construction. After the lysimeters were installed, they were cleaned and de-contaminated following procedures in to ASTM D 5088 and covered with a non-woven needle-punched geotextile.

Leachate samples were collected regularly from the lysimeters 30 days after the field hydraulic conductivity tests began. Water samples were also collected from the SDRIs to define background levels. The samples were analyzed using ICP spectrophotometry.

6. Results of laboratory study

6.1. Edgewater Class F fly ash

Compaction curves are shown in Fig. 2a for Edgewater Class F fly ash with no admixtures. The compacted specimens were allowed to cure for at least 7 days while

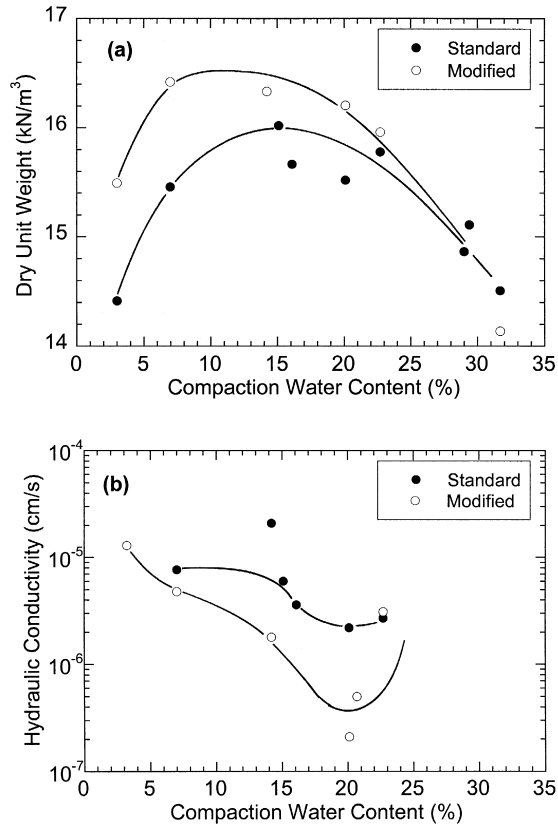


Fig. 2. Compaction curves (a) and hydraulic conductivity versus compaction water content (b) for Edgewater Class F fly ash.

sealed in plastic wrap and stored in a sealed plastic container. Optimum water content is 10% for modified effort and 15% for standard effort.

The relationship between hydraulic conductivity, water content, and compactive effort is shown in Fig. 2b. The hydraulic conductivity is lower for modified effort and the minimum occurs wet of optimum at about 20% water content, but none of the hydraulic conductivities are less than the typically required maximum for liners, 10^{-7} cm/s. The sensitivity of hydraulic conductivity of the fly ash to water content is attributed to cementation reactions that reduce the porosity of the fly ash. These reactions should be more prevalent at higher compaction water contents.

6.2. Edgewater Class F ash with columbia Class C fly ash

Several hydraulic conductivity tests were performed with varying amounts of Class C fly ash added to Class F fly ash to see if the hydraulic conductivity could be reduced below 1×10^{-7} cm/s. One series of tests involved adding 1 and 6% Class C fly ash by

Table 2
Hydraulic conductivities for Class F and C fly ash mixtures

Class C fly ash (%)	w (%)	γ_d (kN/m ³)	Hydraulic conductivity (cm/s)
1	3.5	15.25	1.3×10^{-5}
6	4.0	14.57	1.0×10^{-5}
6	10.0	15.63	6.0×10^{-6}
10	15.8	16.17	1.4×10^{-7}
10	15.8	16.49	2.5×10^{-7}
20	15.5	16.11	4.0×10^{-7}
20	15.5	16.25	1.4×10^{-7}

weight to the Class F fly ash. These specimens were compacted with standard effort at molding water contents below 10% and were cured for one day before hydraulic conductivity testing began. Low water contents were initially used to ensure that addition of Class C fly ash did not affect the workability of the Class F fly ash mixture.

Another series of tests involved adding 10 and 20% Class C fly ash by weight to the Class F ash. The specimens were compacted using modified Proctor compactive effort at higher water contents (15–16%). Curing occurred in a 100% humidity room for 7 days with the specimens open to the atmosphere. Higher water content and open curing were used with the larger Class C admixtures to ensure that adequate water was present for pozzolanic reactions.

Results of these tests are summarized in Table 2. Addition of small amounts of Class C fly ash (1 and 6%) at low water contents (< 10%) resulted in hydraulic conductivities between 6.0×10^{-6} and 1.5×10^{-5} cm/s. Increasing the amount of Class C fly ash (10% or 20%) and using higher water content (~ 15.5%) decreased hydraulic conductivity to between 1.4×10^{-7} and 4×10^{-7} cm/s.

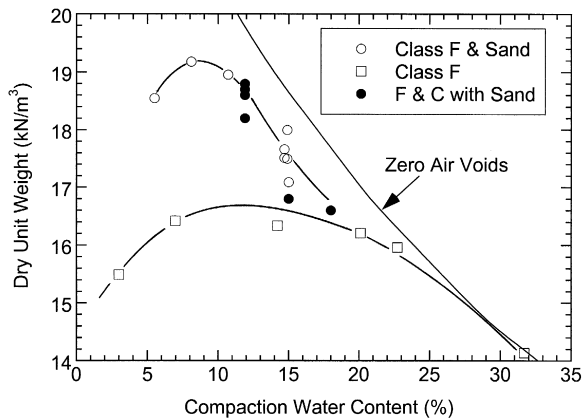


Fig. 3. Compaction curves for Edgewater Class F fly ash mixed with sand and with Class C fly ash and sand.

Table 3

Hydraulic conductivities of 50:50 Class F fly ash–sand mixture amended with Class C fly ash

Class C fly ash (%)	w (%)	γ_d (kN/m ³)	Hydraulic conductivity (cm/s)
0	14.9	17.50	2.3×10^{-6}
0	14.9	18.00	1.7×10^{-6}
10	11.9	18.20	2.2×10^{-7}
10	11.9	18.79	2.7×10^{-7}
20	11.9	18.74	2.8×10^{-7}
20	11.9	18.64	1.7×10^{-7}
10	15.0	16.84	2.4×10^{-7}
28	18.0	16.60	3.1×10^{-8}

6.3. Edgewater Class F fly ash and sand

Tests were also conducted to investigate how addition of sand would affect the hydraulic conductivity of Class F fly ash mixtures. A sand admixture was considered because Edil and Berthouex [15] and Burkhalter [22] found that lower hydraulic conductivities of Class C fly ash can be achieved with higher sand contents. An equal (50:50) mixture of Class F fly ash and Portage sand was prepared and this mixture was amended with various percentages of Class C fly ash.

All specimens were compacted using modified effort at water contents of 11 to 18%. The compaction curve for these mixes and the modified Proctor curve for pure Edgewater Class F fly ash are shown in Fig. 3. The specimens were cured in the compaction mold for 7 days in a 100% humidity room.

Addition of sand resulted in a denser material at a given water content and generally lower hydraulic conductivities, as summarized in Table 3. This decrease in hydraulic conductivity may be due to better packing obtained by adding sand as well as enhanced pozzolanic activity due to Class C fly ash. Also, when the mixture contained 28% Class C fly ash, hydraulic conductivity less than 10^{-7} cm/s was obtained.

Table 4

Hydraulic conductivities of 50:50 Field Class F fly ash–bottom ash mixtures amended with field Class C fly ash (preliminary field design mix)

Class C fly ash (%)	w (%)	γ_d (kN/m ³)	Hydraulic conductivity (cm/sec)
20	9.3	15.13	4.1×10^{-6}
20	14.0	15.69	9.2×10^{-7}
20	18.5	15.73	1.1×10^{-7}
20	18.3	15.52	3.1×10^{-7}
30	8.9	15.07	6.5×10^{-6}
30	13.1	15.63	2.2×10^{-6}
30	18.6	15.46	2.0×10^{-7}
30	18.4	15.69	1.2×10^{-7}
30	18.2	15.59	1.2×10^{-7}
30	22.6	14.27	2.7×10^{-7}

6.4. Preliminary field design mix

Results of the aforementioned tests were used to develop a preliminary field design mix for the test pad. The design mix was required to provide consistent results in the laboratory and be cost-effective. A mixture was designed using field Class F ash, coarse aggregate, and field Class C fly ash. While sand was used in the laboratory as coarse aggregate in the preliminary mix design, ultimately a sand-like material (bottom ash) was used in the field mix. Bottom ash produced at Columbia Generating Station was substituted for the coarse aggregate instead of sand to enhance the beneficial reuse aspect of the project.

Mixtures were prepared consisting of a 50:50 blend of Field Class F fly ash and bottom ash to which 20 or 30% Field Class C fly ash was added. Specimens of both mixtures were compacted with modified effort over a range of water contents (9% to 23%) and cured for 7 days in a 100% humidity room. Hydraulic conductivities of the specimens are summarized in Table 4. As with the other mixtures, the hydraulic

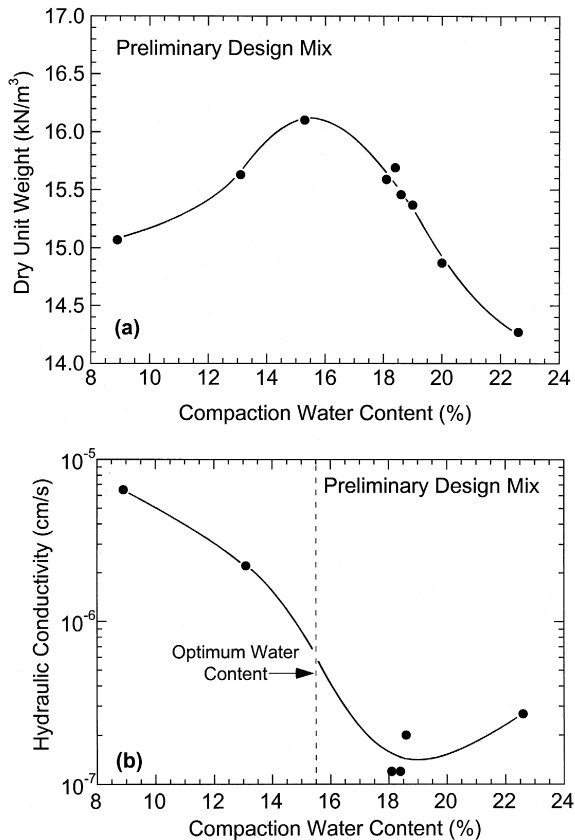


Fig. 4. Compaction curve (a) and hydraulic conductivity versus compaction water content (b) for preliminary design mixture.

conductivity decreases with increasing compaction water content. Slightly lower hydraulic conductivities were also obtained with the 30% amendment of Class C ash. However, none of the hydraulic conductivities were less than 10^{-7} cm/s.

Because of time constraints, the Class F-bottom ash mixture with 30% Class C fly ash was used as the “design mixture” even though hydraulic conductivities below 10^{-7} cm/s were not achieved. The compaction curve for the design mixture is shown in Fig. 4 along with the relationship between hydraulic conductivity and molding water content. The hydraulic conductivity is lowest at about 18% water content. Water contents less than 18% yield significantly higher hydraulic conductivities (Fig. 4). Slight increases in hydraulic conductivity occur as the water content is increased above 18%.

6.5. Freeze–thaw and wet–dry tests

Freeze–thaw and wet–dry tests were conducted on the design mixture using test specimens compacted near 18% water content that were cured in a 100% humidity room for 7 days. After curing, the specimens were placed in permeameters for saturation and to determine their initial hydraulic conductivity. After the initial hydraulic conductivity was determined, five specimens were subjected to cycles of freezing and thawing and two were subjected to cycles of wetting and drying. Results of the durability tests are summarized in Table 5.

The hydraulic conductivity increased slightly (2 to 3 times the initial hydraulic conductivity) when the specimens were subjected to freeze–thaw or wet–dry cycles. For comparative purposes, this increase is significantly less than the increase found in compacted clays, which is commonly over an order of magnitude (e.g., Othman et al. [18]). No cracks or other visible defects were apparent in the specimens after freeze–thaw

Table 5
Results of freeze–thaw and wet–dry tests

No. cycles (n)	Freeze–thaw or wet–dry	K_n ($\times 10^{-7}$ cm/s)	K_n/K_0
0	freeze–thaw	1.1–1.7	1.0
1	freeze–thaw	3.1	2.2
2	freeze–thaw	3.6	2.1
3	freeze–thaw	2.7	2.5
4	freeze–thaw	2.4	1.5
5	freeze–thaw	3.1	2.1
0	wet–dry	2.1	1.0
1	wet–dry	2.5	1.2
2	wet–dry	6.8	3.2
3	wet–dry	5.7	2.7
4	wet–dry	4.9	2.3
5	wet–dry	7.0	3.4
0	wet–dry	1.1	1.0
1	wet–dry	1.7	1.5
2	wet–dry	2.4	2.2
3	wet–dry	3.2	2.9
4	wet–dry	3.6	3.3
5	wet–dry	3.2	2.9

or wet–dry cycling. Also, because the specimens were rigid due to the cementitious ash, no measurable volume change occurred during freeze–thaw or wet–dry cycling. The cementitious characteristic of the ash probably minimizes cracking caused by the formation of ice crystals or by drying, and consequently little change in hydraulic conductivity occurs.

7. Results from test pad

7.1. Construction of test pad

The test pad was constructed at Columbia Generating Station in Portage, Wisconsin using a variation of the preliminary design mixture, which was mixed in a concrete batch truck. Constituents of the mixture were belt-fed from bins in the truck into an auger where water was added and mixing occurred. Prior to start up, the batch truck was calibrated by adjusting gates from the bins so the design mixture could be achieved. However, the auger could not handle the material output required to achieve the design mixture developed in the laboratory. Therefore, adjustments were made until a mixture was obtained that the auger could handle. This mixture was an equal blend of Field Class F fly ash and bottom ash (both 31% by weight), with Field Class C fly ash as 38% of the mix.

The base area of the test pad was approximately 260 m × 140 m. A non-woven needle-punched geotextile (mass per unit area of 544 g/m²) was placed on top of a prepared subgrade and the lysimeters. The test pad was constructed on top of the geotextile in four 150-mm-thick lifts. Since the mixture was soft when it exited the batch truck, compaction was performed by repeated back-blading and trafficking with a John Deere 644D front-end loader.

Several problems were experienced during construction. One was build-up of material in the auger, which required that construction stop for 30–45 min while the auger was cleaned. To alleviate clogging, the water content of the mixture was increased, which yielded a mixture having a wet, uncured concrete-like texture when placed. The greater fraction of Class C fly ash also caused the mixture to set-up in 20–30 min, which is faster than originally planned. The rapid set-up limited the amount of time for compaction. Cracking was also observed in the compacted material as the test pad was constructed. The cracks were attributed to two factors: shrinkage during curing and loading (i.e., compaction or traffic) after the material had begun to harden.

7.2. Compaction assessment

Compaction of the test pad was assessed using a nuclear density gauge (ASTM D 2922) provided by the Wisconsin Department of Transportation and by the drive-cylinder method (ASTM D 2937). The nuclear density gauge provided a total unit weight, but could not be used to reliably measure water content. Drive cylinders (diameter = 75 mm, length = 94 mm) were driven into the fly ash with a metal plate and a claw hammer.

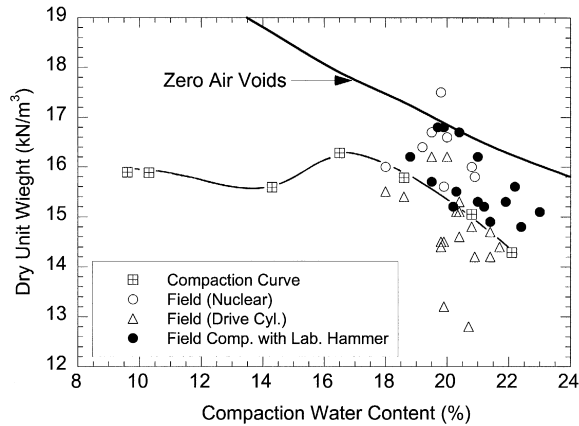


Fig. 5. Compaction curve for field mixture along with water contents and dry unit weights of the field compacted specimens (laboratory hammer) and the field measurements of water content and dry unit weight made using the nuclear gauge and drive cylinders.

The measurements of water content and dry unit weight are shown in Fig. 5. A wide range of dry unit weights was measured (12.8 to 17.5 kN/m^3). Higher dry unit weights were measured with the nuclear density gauge than the drive-cylinder method (16.3 vs. 14.7 kN/m^3 on average, respectively). Some dry unit weights were similar for the two methods, whereas others differed by as much as 3 kN/m^3 . These differences were probably caused by disturbance during driving the drive-cylinder into a stiff mixture. Variations in the composition of the mix may also have led to this discrepancy. All water contents were measured using a microwave oven following ASTM D 4643. The average water content was 20.2% .

Since the field mix varied from the design mix, specimens were compacted at the field site using a laboratory hammer and modified effort (ASTM D 1557). A compaction curve was also developed in the laboratory using a sample of the mixture collected from the batch truck before water was added. The laboratory compaction curve for the field mix is shown in Fig. 5 with the field compaction data. All the water contents measured in the field are wet of optimum water content (16.5%). Many of the dry unit weights measured on the test pad and on the specimens compacted in the field using a laboratory hammer fall above the compaction curve and in some cases exceed the maximum dry unit weight. The high dry unit weights may be related to curing of the mixture in the field; as the mixture cured it became stiff which allowed greater compaction than when it was soft.

7.3. Hydraulic conductivities

Hydraulic conductivity tests were conducted in the laboratory and in the field. Hydraulic conductivities were measured in the laboratory after construction of the test pad on a variety of different specimens. The test specimens included specimens prepared to develop a compaction curve for the mix actually used to construct the test pad,

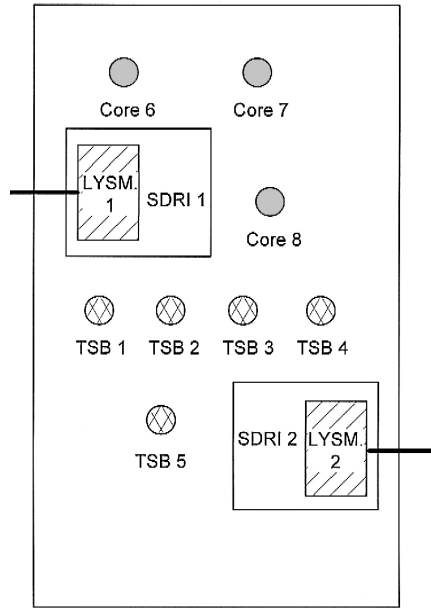


Fig. 6. Layout of field hydraulic conductivity tests.

specimens compacted in the field using a laboratory compaction hammer, and cores removed from the test pad. Field hydraulic conductivities were measured using two SDRIs and five TSBs. Locations of field hydraulic conductivity tests on the test pad are shown in Fig. 6 along with locations for three additional cores (Cores 6–8). Cores 1–5 were obtained when installing the TSBs.

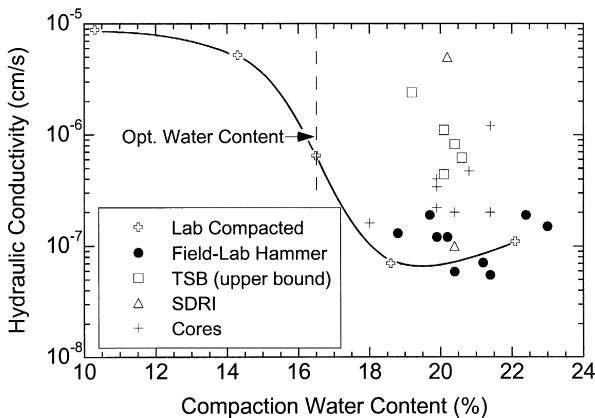


Fig. 7. Hydraulic conductivity versus molding water content for field mix along with hydraulic conductivities measured in the field with the SDRIs and TSBs and the hydraulic conductivities measured in the laboratory on cores and field compacted specimens (laboratory hammer).

7.3.1. Laboratory-compacted specimens of test pad mix

Hydraulic conductivities of laboratory-compacted specimens of the field mixture are shown in Fig. 7 along with the other hydraulic conductivity measurements. The hydraulic conductivity of the field mix decreases as the molding water content increases, with a minimum hydraulic conductivity of 7.0×10^{-8} cm/s near 18% water content. A slight increase in hydraulic conductivity occurs as the water content increases above 18%. As was shown for the other mixtures, the hydraulic conductivity of the field mix drops over an order of magnitude as the water content increases from 16.5% (optimum) to 18%. The additional Class C ash used in the test pad probably resulted in the field mixture having slightly lower hydraulic conductivities than the preliminary design mixture.

7.3.2. Specimens compacted in the field with laboratory compaction hammer

Hydraulic conductivity tests were conducted in the laboratory on nine specimens compacted in the field using a laboratory (modified Proctor) hammer. These specimens were selected to represent the range in dry unit weights and compaction water contents measured in the field. Results of these tests are also shown in Fig. 7. The hydraulic conductivity of the field compacted specimens ranged from 1.9×10^{-7} to 5.5×10^{-7} cm/s, with an average of 1.8×10^{-7} cm/s. These hydraulic conductivities compare reasonably to those measured on the laboratory-compacted specimens, which suggests that the mixture used to prepare the compaction curve was representative of the field mixture.

7.3.3. Cores from test pad

Laboratory hydraulic conductivity tests were performed on one specimen from each core. Hydraulic conductivities of the cores are shown in Fig. 7. The nearest water content measured during construction was assigned to each core when preparing Fig. 7.

The hydraulic conductivities range between 1×10^{-7} and 5×10^{-7} cm/s, with exception of Core 7, which had a hydraulic conductivity of 1.2×10^{-6} cm/s (Fig. 7). The average hydraulic conductivity of the cores (excluding Core 7) is 4.0×10^{-7} cm/s. Examination of Core 7 revealed no insight concerning its higher hydraulic conductivity.

When Core 7 is excluded, the cores have hydraulic conductivities similar to those of the laboratory-compacted specimens and the specimens compacted in the field with the laboratory hammer, which also suggests that the mixture used for the compaction test was representative of the field condition. In addition, the similarity of these hydraulic conductivities suggests that mixture was reasonably homogeneous in the field.

7.3.4. Field tests on test pad

The SDRI and TSB tests were used as the basis to estimate the field-scale hydraulic conductivity of the test pad. The average water content measured during construction in the vicinity of the field test was used when plotting these hydraulic conductivities on the graph in Fig. 7. SDRI 1 yielded a hydraulic conductivity of 1×10^{-7} cm/s and SDRI 2 yielded 5×10^{-6} cm/s. Apparent hydraulic conductivities from the TSBs ranged between 4.4×10^{-7} cm/s and 2.4×10^{-6} cm/s.

With the exception of SDRI 1, the hydraulic conductivities measured in the field are larger than those measured in the laboratory. Macroscopic defects were responsible for

the difference between the laboratory-scale and field-scale hydraulic conductivities. The laboratory specimens are representative of the matrix of the test pad, whereas hydraulic conductivities measured with the SDRI and TSBs are influenced by the matrix and macroscopic defects such as cracks and lift interfaces. The region near SDRI 1 (where the field and laboratory measurements of hydraulic conductivity are comparable) was free of cracks and permeable lift interfaces, resulting in low field hydraulic conductivity. In other regions, these macroscopic features controlled flow. Photographs of the macroscopic features, including cracks and lift interfaces, are in Palmer [23].

In an actual field application, regions containing macroscopic defects will control the overall performance of the liner. Thus, practical application of fly ash liners requires development of methods to minimize or eliminate defects in the cured fly ash.

7.4. Post-winter testing

Frost penetration into the test pad was not measured. However, measurements were made nearby as part of a separate project (Jong et al. [24]). These measurements indicated that frost penetrated 1.8 m during the winter after construction, suggesting that the entire test pad underwent at least one cycle of freeze–thaw cycle.

Field hydraulic conductivity testing was conducted with the SDRI and TSBs after the winter period to determine if frost had damaged the test pad. Hydraulic conductivities from the post-winter tests are summarized in Table 6. All but one of the hydraulic conductivities measured after winter (K_A) are lower than the hydraulic conductivities measured before winter (K_B). The geometric mean of the ratio K_A/K_B is 0.26 for the SDRI and 0.32 for the TSBs, indicating that the hydraulic conductivity of the test pad decreased by about 70% due to additional curing of the mixture. The absence of frost damage is consistent with the results of freeze–thaw and wet–dry tests conducted in the laboratory, as summarized in Table 5.

7.5. Leachate

Leachate collected from the lysimeters was sampled for chemical analysis during hydraulic conductivity testing before and after winter. Samples were also collected from the SDRI rings to define the initial concentrations of the permeant. However, the

Table 6
Post-winter field hydraulic conductivities

Test	Hydraulic conductivity (cm/s)		K_A / K_B
	Before winter, K_B	After winter, K_A	
SDRI-1	1×10^{-7}	4.2×10^{-8}	0.42
SDRI-2	5×10^{-6}	4.9×10^{-7}	0.10
TSP-1	$< 8.2 \times 10^{-7}$	$< 6.6 \times 10^{-8}$	0.08
TSB-2	$< 4.4 \times 10^{-7}$	$< 1.3 \times 10^{-7}$	0.30
TSB-3	$< 1.1 \times 10^{-6}$	$< 6.5 \times 10^{-8}$	0.59
TSB-4	$< 2.4 \times 10^{-7}$	$< 6.7 \times 10^{-7}$	2.8
TSB-5	$< 6.2 \times 10^{-7}$	$< 5.8 \times 10^{-8}$	0.09

Note: K_A and K_B for borehole tests are apparent hydraulic conductivity, K_1 .

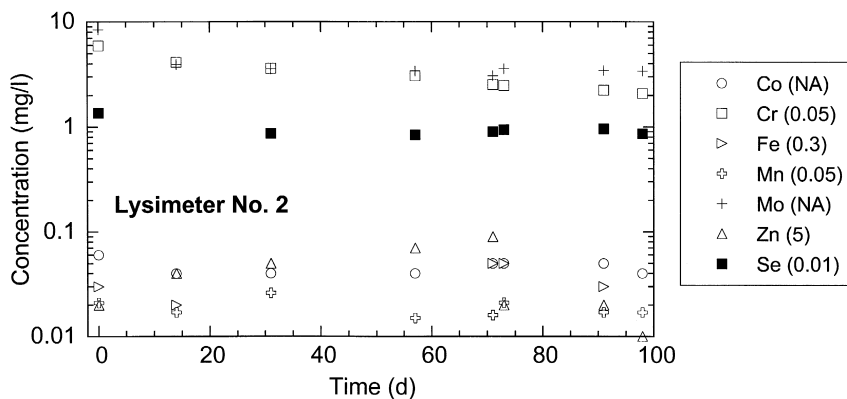


Fig. 8. Concentration of metals in water collected in Lysimeter 2.

composition of the ring water does not necessarily represent background conditions at the site, since the ring water was in contact with the surface of the test pad and thus mixed with dust and debris. Analyses were conducted for As, Cd, Co, Cr, Cu, Fe, Li, Mn, Ni, Pb, Se, and Zn as required in Section NR 140 of the Wisconsin Administrative Code.

Concentrations measured in Lysimeter 2 are shown in Fig. 8. Similar concentrations were measured in both lysimeters (Palmer [23]), and thus concentrations from Lysimeter 1 are not presented. Measurements made before winter are shown in Fig 8 as the 0-day samples. All other measurements were made on samples obtained after winter, and the times correspond to when the water was sampled relative to initiation of the post-winter field hydraulic conductivity tests. As, Cd, Cu, Li, Ni, and Pb were below their respective detection limits (0.01, 0.03, 0.02, 0.04, 0.1, and 0.28 mg/l).

Cr, Mo, and Se leached in the largest concentrations, and Wisconsin groundwater quality standards (in parentheses in the legend of Fig. 8, units are mg/l) were exceeded for Cr and Se. Concentrations of these metals were typically one to two orders of magnitude higher than the other metals that were detected (Fe, Mn, Zn, and Co), none of which exceeded Wisconsin groundwater quality standards. The concentrations remained fairly constant or decreased slightly during the sampling period. Only Mo (0.04 mg/l, on average) and Li (0.03 mg/l, on average) were detected in the ring-water, and only in the post-winter tests.

8. Summary

Hydraulic conductivity tests were conducted in the laboratory and field in this study to determine if mixtures of Class F fly ash and other materials (Class C ash, sand, and bottom ash) could be compacted to hydraulic conductivities less than 10^{-7} cm/s, the typical maximum permissible hydraulic conductivity for landfill liners. A test pad was constructed and tested to determine if the hydraulic conductivities found in the laboratory could be replicated in the field.

Hydraulic conductivities less than 10^{-7} cm/s were not easily achieved in the laboratory. Various amounts of sand and Class C fly ash were added to reduce the hydraulic conductivity. Addition of 20–30% Class C fly ash reduced the hydraulic conductivity to near, but not below 10^{-7} cm/s, provided the compaction water content was greater than optimum water content. The design mixture and the mixture ultimately used in the field included a blend of Class C fly ash (38%) and equal parts (31% each) of bottom ash (as a substitute for sand) and Class F fly ash. Laboratory tests on these mixtures showed that hydraulic conductivities near or less than 10^{-7} cm/s could be obtained for compaction water contents wet of optimum.

Construction of a test pad proved difficult. Hardening of the mixture made mixing and compaction difficult, and hampered compaction control. Hardening of the mixture also resulted in distinct interlift zones, and in some cases cracks. The field hydraulic conductivity of the test pad varied considerably, from 1×10^{-7} cm/s to 5×10^{-6} cm/s, and half of the field hydraulic conductivities were greater 10^{-6} cm/s. Cores from the test pad tested in the laboratory had lower ($\sim 10^{-7}$ cm/s) hydraulic conductivities that were comparable to hydraulic conductivities of laboratory-compacted specimens and specimens compacted in the field with a laboratory hammer. The similarity of these laboratory measurements of hydraulic conductivity indicated that the fly ash matrix was consistent and could be compacted to achieve low hydraulic conductivity. Thus, the higher hydraulic conductivities measured in the field were most likely the result of macroscopic flow through cracks and interlift zones.

Hydraulic conductivity testing after winter showed that freezing did not adversely affect the test pad. In fact, the post-winter hydraulic conductivity was lower than that before winter, suggesting that the test pad was still curing over winter. Tests conducted in the laboratory also showed that changes in hydraulic conductivity caused by freeze-thaw or wet–dry cycling were small.

Leachate collected from the base of the test pad showed that a variety of metals leached from the compacted ash mixture. However, only Cr, Se, and Mo had concentrations exceeding 1 mg/l, and none of the concentrations were greater than 10 mg/l. Only Cr and Se had concentrations in excess of Wisconsin groundwater quality standards.

In summary, this study showed that mixtures of Class F and C ashes combined with a coarse aggregate (e.g., bottom ash) can be compacted to achieve hydraulic conductivity near or below 10^{-7} cm/s at compaction water contents above optimum water content. However, constructing a fly ash liner with hydraulic conductivities similar to those found in the laboratory was difficult. Careful consideration must be given to mixing, compaction, and lift interfaces so that macroscopic defects leading to high field hydraulic conductivity are avoided. Metal leaching (Cr and Se, in particular) must also be considered when designing a liner with fly ash.

Acknowledgements

The State of Wisconsin's Solid Waste Research Program provided financial support for this study. The Wisconsin Dept. of Transportation provided the nuclear density

gauge and a technician. Hoechst-Celanese Corporation provided the geotextile placed under the test pad. Wisconsin Power and Light (now Alliant Energy) provided the ashes, as well as equipment and personnel for construction of the test pad. Mr. Randy Polleck and Mr. Edward Hallet of Alliant were particularly helpful. Todd Hill conducted the post-winter hydraulic conductivity tests and collected water samples from the rings and lysimeters.

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