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FIELD PERFORMANCE OF AN ASPHALT BARRIER TEST PAD

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Abstract

A field study of asphalt concrete and fluid applied asphalt - geotextile (FAA/GT) was undertaken to evaluate their suitability as a barrier (liner/cover) material in waste containment applications. A test pad consisting of 2-3 mm thick FAA/GT and 10-15 cm thick asphalt cement concrete was designed, constructed using full-scale asphalt paving equipment and its performance monitored. The in situ hydraulic conductivity of the barrier was measured using sealed, double-ring infiltrometers. Core and large block samples were taken from the test pad and analyzed in the laboratory under several conditions including: immediately after compaction, after aging for up to three years and after deformation. The in situ hydraulic conductivity of the barrier was 1×10^{-9} cm/s to 1×10^{-10} cm/s. The conductivity range represents the lower limit of quantifiable conductivities with the in situ testing equipment. The laboratory-measured hydraulic conductivity of the specimens sampled immediately after compaction was 1×10^{-10} cm to 1×10^{-11} cm/s. The hydraulic conductivities of the same specimens were re-evaluated twice after exposing them to the ambient temperature in the laboratory for a period up to three years. No change in hydraulic conductivity was observed during this period. Beams of aged asphalt concrete were subjected to three point bending to impart distortions in the range from 1/500 to 1/25. Though observable cracks developed in the beam that underwent the maximum distortion of 1/25, there was no appreciable effect on the hydraulic conductivity. The hydraulic conductivity of the asphalt barrier design used in this test pad was uncompromised by aging of 3 years and distortions up to 1/25. Based on the results of the testing performed, asphalt concrete combined with fluid applied asphalt - geotextile proved to be an effective barrier when designed and constructed with low hydraulic conductivity as a goal.

Introduction

Since the promulgation of the United States' Resource Conservation and Recovery Act (RCRA) subtitle - C (1984) and subtitle - D (1993), hazardous and municipal waste containment systems have been dominated by composite liners (and covers) consisting of a compacted soil liner (CCL) in tandem with a polymeric geomembrane liner (GM). The engineering and waste disposal community has singly focused on this containment system and has made quantum leaps in perfecting the containment system. However, the CCL/GM system is not without limitations and our focus solely on this system reduced our consideration and development of alternative containment systems to practically nil. Liners and cover systems other than CCL/GM are used and prescribed in other countries (Manassero et al, 1998). In some cases, asphalt-based barriers are prescribed. In the United States, very-long term containment systems, primarily for the nuclear industry, have evaluated and suggested that asphalt-based covers pose the best solution (Wing and Gee, 1994). In addition asphalt-based barriers have a long history as seepage barriers in dams and other hydraulic structures (Sherard et al., 1963). Given the need for acceptable alternatives to the prescribed CCL/GM barriers it is long past time to re-focus some of our efforts away from CCL/GM and begin examining alternatives that may augment or even replace CCL/GM containment systems while providing a higher level of environmental protection. Our existing knowledge of asphalt-based seepage barriers makes asphalt a logical choice for in-depth study, development and performance assessment.

The United States' RCRA regulations provide for use of alternative liners (or covers) for waste containment provided equivalency is demonstrated. While equivalency is not clearly defined, the intent is taken to mean the alternative must perform as well as, or better than the existing CCL/GM systems (Koerner and Daniel, 1993). One facet of equivalency is the hydraulic barrier function of the liner/cover system. While this is often evaluated in the laboratory using hydraulic conductivity testing procedures, the final demonstration of equivalency is often through construction and performance testing of a full-scale test pad. The results of performance tests of a full-scale test pad demonstrate whether the actual construction process will result in the product, in this case the asphalt-based barrier, meeting the performance specifications or providing an equivalent barrier. To these ends, an asphalt-based barrier system was designed, a full-scale test pad constructed and performance tested. The design of the test pad is summarized followed by a description of the performance monitoring systems. The results are then reported and discussed.

Asphalt-Based Test Pad

Liner Design

The asphalt-based barrier reported herein was developed using the results of an extensive literature review on the use of asphalt barriers in dams and waste containment facilities (Bowders et al., 2000), laboratory testing results (Bowders et al., 2003) and existing design guidance for landfill liners and covers (EPA 1988, 1993). The lessons learned from the literature on asphalt-based barriers are detailed in

(Bowders et al., 2000, 2003) and are summarized here for clarity. Past efforts have shown that:

- air voids must be below 4% (vol. basis) to achieve low hydraulic conductivity,
- asphalt cement content must be above 6% (wt. basis) to achieve low hydraulic conductivity,
- fines content (fraction less than 0.074 mm) must be from 8% - 15% to ensure a dense graded mixture,
- two (or more) layers of asphalt concrete should be used with a minimum thickness of 5 cm/layer to minimize continuity of potential defects and lateral spreading of any seepage,
- asphalt cement tack coat should be applied between layers, and the joints staggered and sloped to permit good compaction,
- any fluid applied asphalt layer should be between 1 and 3 mm thick, and
- the subgrade must be stable and adequately drained.

Considering the above items, an asphalt-based liner system consisting of two components was designed. The lower component consisted of 100 mm to 150 mm of asphalt concrete while the upper or surface layer consisted of a non-woven, needle-punched paving geotextile (125 gm/m^2) impregnated with asphalt cement. The upper layer is referred to as fluid applied asphalt - geotextile (FAA/GT). Together the layers act as a composite barrier with the FAA/GT acting as the primary barrier and the asphalt concrete as the secondary barrier.

The primary barrier was designed to be saturated with asphalt cement. Saturation typically requires 0.9 L/m^2 (0.2 gal/yd^2) of asphalt cement. In traditional paving applications, the asphalt cement is applied to the existing pavement, the geotextile is placed on the freshly sprayed surface, and additional hot mix asphalt is placed on the geotextile. This results in the asphalt cement flowing up through and saturating the geotextile. A low permeability barrier is thus created in the pavement section (Baker and Marienfeld, 1999). However, in the barrier application, no overlying asphalt concrete layer was placed on top of the geotextile, so to ensure saturation of the geotextile, asphalt cement was sprayed on top of the geotextile (0.9 L/m^2) as well as on the upper surface of the underlying asphalt concrete. The secondary barrier, the asphalt concrete was designed to be placed and compacted in two lifts with a total thickness between 100 mm to 150 mm.

Asphalt Concrete Mix Design

Asphalt cement concrete consists of a mixture of graded aggregates, liquid asphalt cement and air-filled voids. The aggregate composition used in this study complied with the suggested mix specifications of the Asphalt Institute (1974) for low hydraulic conductivity asphalt concrete material. The maximum aggregate size was 12.5 mm and the percentage of fines (< 0.074 mm) was 12.9 (dry mass basis).
Construction specifications for asphalt cement content and in place unit weight were based on hydraulic conductivity testing results from laboratory compacted specimens (Bowders et al, 2003). A parametric study was performed to evaluate the effects of

unit weight and asphalt content on the hydraulic conductivity of the resulting asphalt concrete. A *zone of acceptability* was developed for various combinations of unit weight and asphalt cement content that result in hydraulic conductivity less than 1×10^{-9} cm/s. A mix with asphalt cement content greater than seven percent and compacted in-place unit weight greater than 22 kN/m^3 provided acceptable hydraulic conductivities (Figure 1). The zone shown in Figure 1 indicates the general trend of decreasing hydraulic conductivity with increasing unit weight and increasing asphalt cement content. Additional data (Table 2) confirmed the lower limits of seven percent asphalt cement and unit weight of 22 kN/m^3 for maximum hydraulic conductivity of 10^{-9} cm/s.

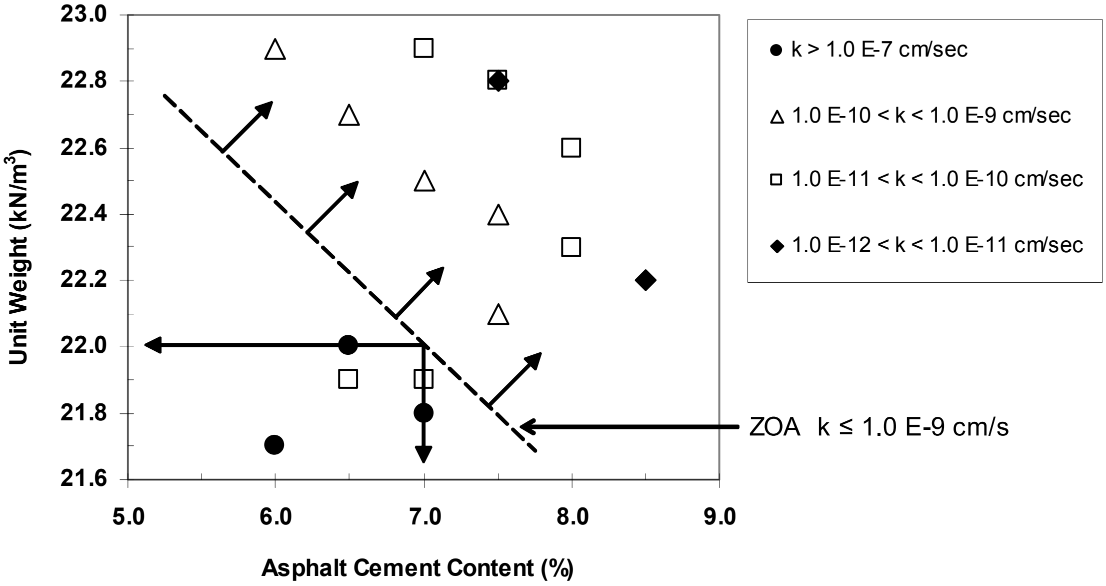

Figure 1 – Hydraulic Conductivity with Respect to Unit Weight and Asphalt Cement Content for Laboratory Compacted Asphalt Concrete Specimens Showing Zone of Acceptability (ZOA) for Hydraulic Conductivity Lower than 10^{-9} cm/s. (Bowders et al, 2003).

Test Pad Construction and Construction Quality Control

The test pad was constructed during April/May 2000 and was located in a former quarry approximately 10 km east of Kansas City, Missouri. The test pad was 60 m x 15 m (180 ft by 50 ft) in plan and consisted of four 4-m (10 ft) wide lanes of asphalt concrete (Figure 2). The asphalt concrete was placed in two lifts. The objective was to have two lanes with a total thickness of 15 cm (6 inch) and two lanes with a total thickness of 10 cm (4 inch). Post-construction coring showed the thickness varied and ranged from 11 cm to 18 cm (4.5 inch to 7 inch).

The sub base for the test pad was cleaned and then leveled using high fines content quarry fill with maximum aggregate size in the range of one inch. The sub base was roller compacted. In order to maintain controlled, known boundary conditions, coarse drainage rock was placed beneath the northern half of the test pad. The drainage rock ensured that the lower flow boundary would be freely draining, i.e., no build up of pore water pressure beneath the liner. Such a layer would not be included in the prototype liner, rather the liner would be placed on a prepared subgrade, i.e., a compacted, rolled surface. Prior to paving, the aggregate layer was relatively loose. There was some concern by the contractor over meeting the required density (unit weight) for the asphalt concrete given the loose condition of the base. The southern half of the test pad was placed on a typical subgrade. This subgrade does not necessarily provide a freely draining lower boundary beneath the asphalt liner. The asphalt concrete was rolled with standard pneumatic and smooth drum asphalt compaction equipment. The top surface of the test pad consisted of hot fluid applied asphalt with a paving geotextile (non-woven, polypropylene, 125 g/m^2). In order to protect the surface, a 5 cm (2 inch) thick layer of sand was placed on the completed surface.

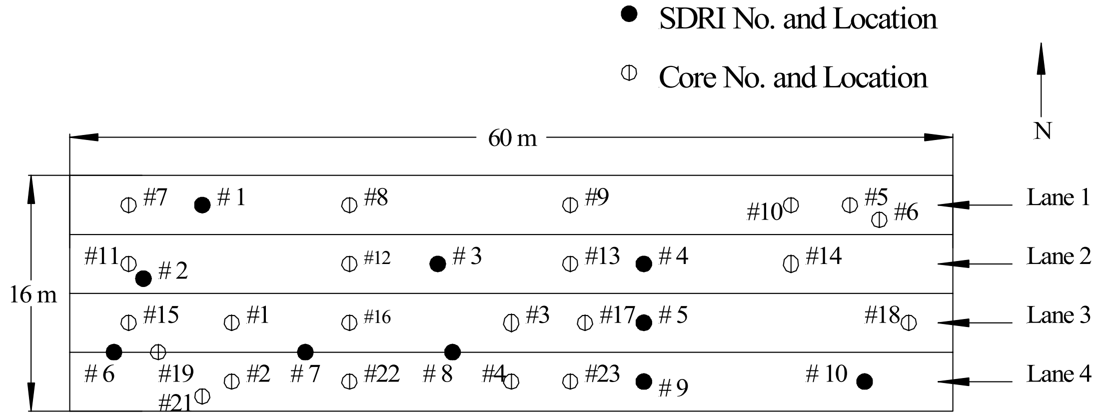

Figure 2 – Plan View of the Layout of the Asphalt-Based Barrier Test Pad Showing Locations of Sealed, Double-Ring Infiltrometers (SDRIs) and Core Samples.

The results of the measurements of percent asphalt content of the mix and the corresponding in situ unit weight and air void content after compaction is given in (Table 1). The specified minimum asphalt cement content was 7.0 percent for the first lift. The first truckload of asphalt concrete was found to have 6.3 percent asphalt content. The mix procedure was revised and the remainder of lift 1 met or exceeded the prescribed 7.0 percent. Although the second (upper lift) was specified at 7.0 percent asphalt cement content, the mix target was increased to 7.5 percent asphalt cement to ensure that the specification would be met. Unit weights were measured in the field using a nuclear density meter. The specified minimum unit weight was 22 kN/m^3 (140 pcf). All of the in situ unit weights exceeded the specified 22 kN/m^3 limit

(Table 1). For this range of unit weights, air void contents in the field were all below 4 percent.

Table 1 – Results of CQA Tests on the Asphalt Concrete Component of the Asphalt-Barrier Test Pad: Percent Asphalt Content, In-Situ Unit Weight, and Percent Air Void Content.

Lift	Lane	Asphalt Cement (%)			In Situ Unit Weight (kN/m^3)			Air Void Content (%)		
		No of Samples	Range	Average	No of Samples	Range	Average	No of Samples	Range	Average
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	1	2	6.3 - 7.1	6.7	4	22.0 - 23.2	22.8	2	2.5 - 3.2	2.9
	2	2	7.0	7.0	4	22.2 - 23.4	22.7	2	3.2 - 3.5	3.4
	3	2	7.0 - 7.1	7.0	4	23.1 - 23.5	23.3	2	2.3 - 3.5	2.9
	4	2	7.0 - 7.1	7.0	4	23.0 - 23.4	23.3	2	3.6 - 3.9	3.8
2	1	1	7.7	7.7	2	23.1 - 23.5	23.3	1	2.1	2.1
	2	1	7.5	7.5	2	22.8 - 23.0	22.9	1	2.3	2.3
	3	-	-	-	5	22.8 - 23.8	23.2	1	2.1	2.1
	4	-	-	-	5	22.8 - 24.5	23.5	1	2.3	2.3

Hydraulic Conductivity Assessment

Hydraulic conductivity of the test pad was measured in situ and in the laboratory on cores taken from the test pad. In situ hydraulic conductivity was measured using sealed, double-ring infiltrometers. Ten SDRIs' were installed over the test pad (Figure 2). The SDRI consisted of a square outer ring (60 cm x 60 cm x 45 cm) embedded about 8-cm into the asphalt concrete and a circular inner ring (11.5 cm effective diameter) glued directly to the surface of the test pad. The SDRI's were operated according to ASTM D5093 with some modifications necessitated by low hydraulic conductivity of the asphalt barrier. A new flow measuring device known as constant head board (CHB) was developed and used along with flexible bag to measure small incremental flow volume and hence the infiltration rate of the liner. The difficult issue was to determine the hydraulic gradient which is needed to calculate the hydraulic conductivity. The hydraulic gradient in the asphalt liner changes with time as the wetting front moves from the surface of the liner down through the liner section. The most conservative method of estimating hydraulic gradient was to assume the full-depth of liner to be saturated. Additionally a more representative method (modified wetting front) of measuring hydraulic gradient was developed and used to report the in situ hydraulic conductivity of the liner. Details regarding design and operation of CHB and the method to estimate hydraulic gradient and subsequently hydraulic conductivity of the liner based on modified wetting front method are detailed in Neupane et al (2003).

Laboratory hydraulic conductivity tests were performed on 10 cm (4 inch) diameter core samples extracted from the test pad. The locations of core samples are shown in Figure 2. These samples included FAA/GT, asphalt concrete and the combination of FAA/GT and asphalt concrete. The hydraulic conductivity was measured according to ASTM D5084.

Field Performance

In Situ Hydraulic Conductivity

The results of the in situ hydraulic conductivity measured using SDRIs are given in Table 2. These values were based on flow during the period of May 2000 and September 2000. The values are reported based on different hydraulic gradients, as it was difficult to determine the exact hydraulic gradient in the field. Column 2 (Table 2) is the measured hydraulic conductivity values based on the most conservative approach for hydraulic gradient where the full-depth of the liner was assumed to be saturated. The resulting conductivities ranged from 3 x 10^{-7} cm/s to 2 x 10^{-9} cm/s. The highest value was recorded for SDRI No. 8 located in the southern most section where the area was observed to be poorly compacting during the asphalt concrete placement operation. Asphalt at this region showed a density of 21.3 kN/m^3, which was below the specified limit and higher conductivities in this area were anticipated. This area was underlain by a water-filled bladder which was intended for later use to induce deformations in the asphalt concrete barrier. However, compaction atop the bladder was difficult. This behavior illustrates the necessity of providing a firm sub base prior to placement of the asphalt concrete liner.

Table 2 – In Situ Hydraulic Conductivity of the Asphalt-Based Barrier Calculated on the Basis of Full Depth Saturation and Modified Wetting Front Methods.

SDRI No	Hydraulic Conductivity (cm/s)		
	Full Depth Saturation	i @ 3.8 % Void Content	i @ 2.1 % Void Content
(1)	(2)	(3)	(4)
1	5.7E-09	6.1E-10	1.1E-09
2	4.8E-09	7.3E-10	1.3E-09
3	5.5E-09	6.8E-10	1.2E-09
4	4.8E-09	7.3E-10	1.3E-09
5	1.4E-08	2.4E-09	4.1E-09
6	3.5E-09	5.2E-09	6.7E-09
7	6.3E-09	1.7E-09	2.9E-09
8	3.1E-07	3.5E-08	6.3E-08
9	1.7E-09	6.3E-10	1.1E-09
10	5.7E-09	6.1E-10	1.1E-09

A more representative value of in situ hydraulic conductivity is reported in columns 3 and 4 (Table 2) based on known volumes of inflow to estimate the depth of the wetting front. The wetting front depth is a direct function of the volume of inflow and volume of air voids in the liner. The extreme cases of air voids (3.8 % and 2.1 %) were used to calculate the smallest and largest wetting depths, which were used to estimate the hydraulic gradients and subsequently the hydraulic conductivity of the liner. Hydraulic conductivities averaged 1 x 10^{-9} cm/s for asphalt concrete with 2.1 percent air void content and 6x10^{-10} cm/s for asphalt concrete with 3.8 percent air void content. In general the conductivities are about half to one order of magnitude lower than those calculated using the full-depth saturation assumption of the liner.

Laboratory Hydraulic Conductivity

A total of 23 (10-cm diameter) core samples were extracted from various locations on the test pad (Figure 2). The cores were extracted within several days after the asphalt concrete was compacted in the field. Except cores 3, 4, 6 and 7 (retained for other testing purposes) the remaining 19 cores were brought to the University of Missouri Geotechnical Engineering laboratory for testing. The cores consisted of both FAA/GT and asphalt concrete. The cores were sawed at the bottom to provide a smooth surface. The tops of the cores were also sawed and this portion consisted of the 1-2 mm thick FAA/GT and a 2-3 cm thickness of asphalt concrete. Hydraulic conductivities of the asphalt concrete and the FAA/GT + asphalt concrete were measured.

The results of the hydraulic conductivity tests performed on the asphalt concrete specimens are summarized in Table 3 (Column 4). The resulting hydraulic conductivity ranged from a minimum of 6.2 x 10^{-11} cm/s to a maximum of 9.4 x 10^{-10} cm/s. Also given in Table 3 (Columns 2 and 3) are the thickness and unit weight of each specimen. The thickness of the specimens varied from 5.3 cm to 10.5 cm. There was no evident impact of specimen thickness on the measured hydraulic conductivity. The unit weights of the specimens were found to be fairly consistent. One of the cores (No. 19) was obtained from the staggered joint between the lanes. Inter-lane bonding was not visible in the core and the measured conductivity of this core was 2.2 x 10^{-10} cm/s. The narrow range of estimated hydraulic conductivity reflected the homogeneity of the finished asphalt barrier. Hydraulic conductivities were also measured on the composite FAA/GT + asphalt concrete specimen. The resulting conductivity ranged from 1.8 x 10^{-11} to 5.6 x 10^{-11} cm/s.

Specimens of FAA/GT were removed from different sections of the test pad several days after placement and were brought to the University of Missouri Geotechnical Engineering laboratory for testing. Prior to performing the hydraulic conductivity tests on 10-cm diameter specimens, the mass per unit area of the specimens was measured. The mass per unit area of the FAA/GT was found to vary from 1500 - 3000 g/m^2. The corresponding asphalt application rate was calculated to be in the range of 1.4 - 2.8 L/m^2. The hydraulic conductivity of the FAA/GT ranged from 1 x10^{-11} cm/s to 5 x 10^{-12} cm/s. These values were comparable to FAA/GT specimens prepared in the laboratory and FAA/GT specimens manufactured in the factory (Bowders et al 2002).

Table 3 – Hydraulic Conductivity Values of Cores from the Asphalt Barrier Test Pad Measured at Different Time Periods After Construction of the Test Pad.

Core No	Height (cm)	Unit Weight (kN/m^3)	Hydraulic Conductivity (cm/s)		
			0 yr	1.5 yrs	3 yrs
(1)	(2)	(3)	(4)	(5)	(6)
1	5.3	22.7	8.8E-11	2.4E-10	4.2E-10
2	8.6	22.4	6.5E-11	4.6E-10	3.9E-11
5	10.1	22.7	2.7E-10	5.2E-10	1.2E-10
8	7.9	22.8	1.9E-10	1.4E-10	2.8E-10
9	7.8	22.6	1.6E-10	3.4E-10	2.5E-10
10	10.1	22.9	1.2E-10	4.6E-10	5.0E-10
11	9.3	22.5	5.0E-10	2.3E-10	2.3E-10
12	9.1	22.7	7.7E-11	2.5E-10	4.6E-10
13	9.2	22.3	2.5E-10	4.8E-11	4.3E-10
14	10.0	22.7	9.4E-10	2.5E-10	7.1E-10
15	6.8	22.7	6.9E-11	3.6E-09	1.7E-09
16	8.2	22.9	8.3E-11	6.9E-10	1.1E-10
17	8.0	22.5	8.8E-11	2.0E-09	3.0E-11
18	8.0	22.3	1.0E-10	3.1E-10	3.1E-11
19	9.6	22.7	2.2E-10	3.8E-10	7.0E-11
20	9.9	22.6	6.2E-11	3.9E-09	1.4E-09
21	12.1	22.6	1.0E-10	1.1E-10	2.6E-10
22	10.5	22.7	2.4E-10	2.0E-10	3.4E-11
23	7.1	22.6	7.9E-11	3.5E-10	2.3E-11

It should be noted that hydraulic conductivities in the 10^{-10} cm/s to 10^{-11} cm/s range approach the lower limit of our capacity to measure this parameter. Small flow rates are easily masked by the combined effect of temperature and barometric pressure changes and simple ability to make very small flow measurements. Given these limitations, the measured hydraulic conductivities represent the upper bound values. Actual hydraulic conductivity values may be significantly lower than those reported especially with respect to the in situ values.

Evaluation of Aging

Twelve asphalt concrete beams (90 cm x 15 cm x 10cm) were extracted from the test pad after being in place for one year. Temperatures ranged from a high of 40 ^{0}C to a low of -20 ^{0}C over this period. There were 12 times when the air temperature dipped below 0 ^{0}C, once for a period of 18 consecutive days. Six of these beams were cut in the paving direction while the other six were cut perpendicular to the paving direction. A 10-cm (4-inch) core was cut from the end of each beam. The cores included the FAA/GT layer and a 10-cm thick layer of asphalt concrete. Hydraulic conductivity tests were performed on each core. No appreciable impact on hydraulic conductivity was observed after a year of exposure to outdoor environment. The minimum and maximum values of conductivity were 7.2 x 10^{-11} cm/s and 3.2 x 10^{-10} cm/s respectively.

Effect of aging under a laboratory environment was also evaluated over a period of 3-years. The original 19 cores were re-tested in the laboratory to determine their hydraulic conductivity after $1^1/_2$ years and 3 years. In order to increase the accuracy and sensitivity of the measurement, the constant volume method (ASTM 5084 C) was used to determine the hydraulic conductivity. The measured conductivities are given in Columns 5 and 6 of Table 3. Again, there are no observable changes in the hydraulic conductivity values from those values measured at several days after barrier construction. Any difference in the measured values is attributed to testing sensitivity.

Evaluation for Deformation

In waste containment applications, liner and covers can be subjected to distortions due to differential movement of underlying media. The distortions are representative of strains in the barrier that could possibly cause cracking and jeopardize the hydraulic barrier function of the liner. In order to examine the impact of differential movements on the conductivity of the asphalt barrier, beams cut from the test pad, were subjected to three point bending. Subsequently, cores were taken from the deformed beams and tested for hydraulic conductivity. The desired deflection of each beam was calculated based on distortions estimated from a settlement analysis for a typical landfill.

The distortions were 1/25, 1/50, 1/75, 1/100, 1/250, 1/500. Initially, five beams cut parallel to the paving direction were subjected to 1/25, 1/50, 1/75, 1/100 and 1/250 distortions. No physical effects on the beams were visually apparent during bending except for the beam that was subjected to the maximum deflection (1/25) where minor cracks developed at the bottom of the beam due to tensile stresses. A core was cut from the middle of each beam at the point of maximum deflection and was set up for hydraulic conductivity testing. The measured conductivity ranged from 5.9 x 10^{-11} cm/s to 1.1 x 10^{-10} cm/s. Similarly, three of the beams that were cut perpendicular to the paving direction were subjected to the three largest deformations (1/25, 1/50 and 1/75). No cracks were observed in the beams with 1/50 and 1/75 distortions. A visible, approximately 2-cm deep, crack developed at the base of the 10-cm thick beam that underwent maximum distortion of 1/25. A core was cut from each of the three beams taking the center as the point of maximum deflection. The hydraulic conductivity of the cores ranged from 1.2 x 10^{-10} cm/s to 4.3 x 10^{-10} cm/s. No observable change in conductivity was measured between the cores retrieved along the paving direction and perpendicular to the paving direction. The core with the visible crack did not show any increase in hydraulic conductivity. There was a variation in the amount of resistance developed during bending for the beams with their long axis in the direction of paving versus those with their long axis perpendicular to the paving direction. In general, the beams in the direction of paving tended to be 100 to 200 percent stronger in flexure than those in the direction perpendicular to the paving.

Evaluation for Deformation without FAA/GT

There was no sign of distress of the FAA/GT layer during the beam bending and the resulting hydraulic conductivity tests indicated that the conductivity of the composite section (FAA/GT + asphalt concrete) was not altered by the distortions imparted to the barrier system. It is possible that the distortion partially compromised the asphalt concrete portion of the barrier but not the FAA/GT layer. In order to evaluate the effects of the distortions on the asphalt concrete alone, the FAA/GT layer (and approximately the top 1-cm of asphalt concrete) were cut from four specimens (2 parallel and 2 perpendicular), which were subjected to the maximum distortions (1/25 and 1/50). The hydraulic conductivity results on these cores indicated no change in the conductivity of the asphalt concrete. In the specimen that experienced the most severe distortion (1/25), the cracks did not extend the full thickness of the beam nor induced any preferential pathway for liquid to flow.

The results of the aging and deformation tests are presented in Figure 3. For sake of comparison, the four specimens from those beams that underwent maximum deflection are plotted (most severe case). It can be seen that there has been no change in hydraulic conductivity among all three cases - aged, aged + deformed, aged + deformed + asphalt concrete only (no FAA/GT). The minor variation in the results can be attributed to testing sensitivity. The hydraulic conductivities are within the

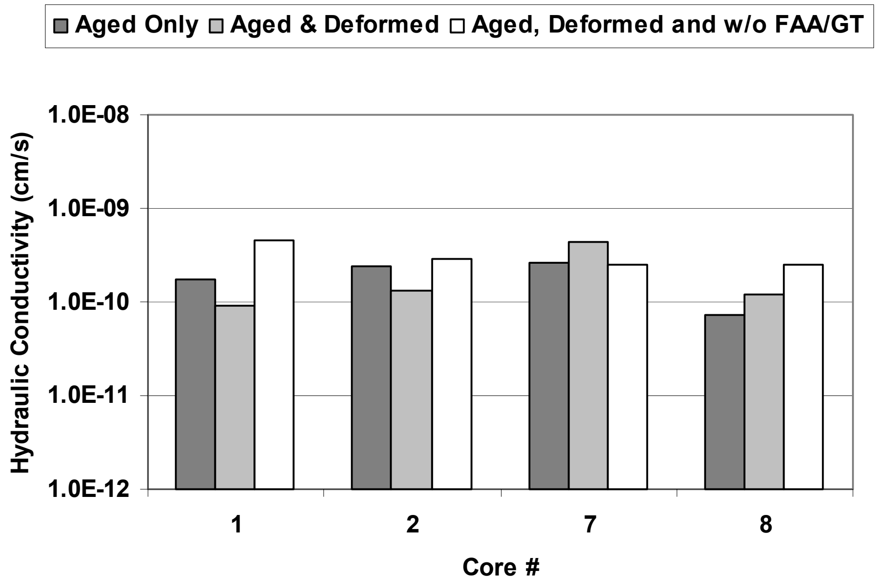

Figure 3 – Hydraulic Conductivity of Asphalt Concrete Cores under Three Different Conditions, i.e., Aged, Aged and Deformed and Aged, Deformed and without FAA/GT Layer.

same range as those measured on cores taken immediately after the test pad was constructed. Based on the results of the testing performed, the asphalt liner system tested should not be susceptible to damage from aging and should be capable of undergoing the maximum anticipated distortion (1/25) without compromising the hydraulic barrier function, i.e., no change in the hydraulic conductivity is expected.

Practical Implications

An acceptable alternative to existing GM/CC liners must demonstrate equivalency in protecting the environment against contamination resulting from migration of leachate to underlying soil. Koerner (1999) stated that issues such as hydraulic, physical/mechanical and construction all need to be addressed for proving equivalency of a barrier. However, the hydraulic issue still remains the most critical.

Giroud and Bonaparte (1989a, 1989b) presented theoretical methods to calculate flow rates based on the defects in geomembrane and the hydraulic conductivity of the soil component of a composite liner. They argued that the higher rates of leakage through GM/CCL were due to construction defects in the GM and inadequate interface contact between the GM and compacted soil. According to them the overall leakage rate varies from 935 l/ha-d for a poorly constructed liner to 10 l/ha-d for a well constructed liner. Othman et al (1996) monitored 44 double-lined landfill facilities with either a sand or geonet leak detection layer. They determined the flow rates corresponding to three different phases of landfill operations and showed that the average flow rate ranged from 64 to 220 l/ha-d with sand leak detection layer and from 65 to 170 l/ha-d with geonet leak detection layer.

Asphalt based barriers consisting of asphalt concrete and a FAA/GT provides low hydraulic conductivity of the asphalt concrete (secondary barrier), intimate contact between the FAA/GT and the asphalt concrete components and the potential for self-healing behavior of the FAA/GT. A leakage rate on the order of 38 l/ha-d would exist based on the average hydraulic conductivity ($1x10^{-9}$ cm/s) estimated in the field which is the upper bound hydraulic conductivity measurable with available testing apparatus. Hydraulic conductivities in the range of 10^{-10} cm/s to 10^{-11} cm/s were observed in the asphalt concrete and FAA/GT components of the barrier in the laboratory (10-cm dia specimens). These conductivities translate into leakage rates of 4 l/ha-d and 0.4 l/ha-d respectively. The greater control in materials, mix design, preparation and placement of asphalt concrete, decrease the size of the specimen required for a representative specimen. For this reason a 10-cm diameter core of the asphalt concrete may very well represent the field hydraulic conductivity of the liner.

Several European researchers have linked aging in asphalt concrete to the air void content of the mix. Investigations by Zenke on asphalt pavement that have been in use for 20 years show that aging effects are much stronger with open (large void content) than dense asphalt (Holzlöhner et al 1995). Given the fact that asphalt concrete in the barrier application will have a lower air void content than typical for pavements, the process of aging can be expected to be minimal. The aging process in the case of a buried liner should be essentially stopped due to a lack of oxygen. Absence of aging is further supported by the asphalt artifacts recovered during excavations showing no appreciable oxidation/aging after 1000's of years (Freeman et al 1994). Based on the results of the tests and available literature, aging of asphalt barriers is not considered to be a critical issue in the long-term performance of a liner. Asphalt based cover systems may be more subject to aging effects simply because of being a surface or near surface application.

The findings from this study demonstrate the hydraulic equivalency of FAA-GT/Asphalt Concrete barriers to that of GM/CCL composites; however, there are other issues that should be addressed. A major concern is chemical compatibility of the barrier. While the solubility of asphalt is well known when immersed in solvents or petroleum-based liquids (Asphalt Institute, 1976), the actual compatibility in waste leachate and chemical reagents is under evaluation (Bowders and Neupane, 2004). A comparison between asphalt barriers and GM/CCL barriers along with a qualitative assessment of other technical equivalency issues are presented in Table 4.

Table 4 – Comparison of FAA/GT-Asphalt concrete barrier and Geomembrane-Compacted Clay barrier.

Characteristics	FAA/GT-Asphalt Concrete Liner	Geomembrane-Compacted Clay Liner
Material	Asphalt cement, aggregates, fillers	Natural or recompacted soil, amended soil
Liner thickness	10 cm – 12 cm	30 cm
Hydraulic conductivity	10^{-10} cm/s (AC), 10^{-11} cm/s (FAA/GT)	$1x10^{-7}$ cm/s (soil), 10^{-12} cm/s (GM)
Speed of construction	More rapid construction	Slow, complicated construction
Interfacial contact	Intimate contact between AC and FAA/GT	Questionable contact between CCL and GM
Vulnerability to dessication cracking	No problem with dessication and produce no consolidaton water	Can dessicate/crack and produce consolidaton water
Experience Level	Limited	Has been in use for 20^{+} years

Conclusion

Asphalt based barriers have been used in hydraulic applications throughout the ages. More recent applications have been as waste containment and isolation barriers. Ensuring the constructability of low hydraulic conductivity asphalt based barriers in these applications is critical to the expanded or even continued use of asphalt barriers for waste containment applications. An asphalt barrier test pad was constructed with full-scale equipment and prototype conditions. The design specification included two lifts of asphalt concrete at 7 percent asphalt cement and unit weight greater than 22 kN/m^3 with an overlying asphalt saturated fluid applied asphalt-geotextile (FAA/GT). In situ hydraulic conductivities were measured on the test pad using sealed, double-ring infiltrometers. The in situ hydraulic conductivity averaged 1×10^{-9} cm/s. These hydraulic conductivities represent the upper bound as they are at the lower limit measurable with the available testing equipment and procedures. Asphalt concrete and FAA/GT samples were sampled from the test pad and taken to the laboratory to measure hydraulic conductivity. The conductivities of the asphalt concrete cores averaged 1 x 10^{-10} cm/s. Tests on FAA/GT and FAA/GT + asphalt concrete yielded conductivities between 1 x 10^{-10} cm/s to 1 x 10^{-11} cm/s. The effects of aging and deformation on the hydraulic conductivity of the asphalt concrete and FAA/GT were evaluated. The results indicated that the neither aging nor deformation due to distortion in the range of 1/25, impacted the hydraulic conductivity of the asphalt barrier.

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References

Asphalt Institute. (1974) *Asphalt Linings for Landfills,* Construction Leaflet No.9, The Asphalt Institute, College Park, Maryland.

Asphalt Institute (1976) *Asphalt in Hydraulics*, Manual Series No. 12 (MS-12), November, College Park Maryland, 67p.

Baker TL and Marienfeld ML (1999) " Paving Fabric Interlayer System as a Pavement Moisture Barrier," *Transportation Research Board Circular*, No. E-C006, March, 13p.

Bowders, J. J., Loehr, J. E., Mooney, D. T., and Bouazza A. (2000). "Asphalt Barriers for Waste Isolation." *Proc*., *GeoEngineering*, Melbourne Australia, November 19-24.

Bowders, J. J., Loehr, J. E., Neupane, D., and Bouazza, A. (2003). "Construction Quality Control for Asphalt Concrete Hydraulic Barriers." *J. of Geotech. and Geoenvir. Engrg*., ASCE, 129 (3), 219-223.

Bowders JJ and Neupane D (2004) "Compatibility and Durability of an Asphalt-Based Barrier System," *Draft Report*, Dept of Civil & Environmental Engineering, University of Missouri-Columbia.

EPA. (1988). "Lining for Waste Containment and Other Impoundment Facilities." EPA / 602 / 2-88 /052, September.

EPA. (1993). "Technical Guidance Document: Quality Assurance and Quality Control for Waste Containment Facilities." EPA / 600 / R-93 /182, September.

Freeman, H. D., and Romine, R. A. (1994). "Hanford Permanent Isolation Barrier Program: Asphalt Technology Development," *Proc.* In-Situ Remediation: Scientific Basis for Current and Future Technologies, Part 1. Thirty-Third Hanford Symposium on Health and the Environment, Pasco, Washington, 491-505.

Neupane et al., *Field Performance of An Asphalt Barrier Test Pad*, Proceedings of GeoFrontiers, Jan, 23-26, 2005, Austin Texas.

Giroud, J. P., and Bonaparte, R. (1989a) "Leakage Through Liners Constructed with Geomembranes – Part I, Geomembrane Liners." *Geotextiles and Geomembrane*, Vol. 8, 27-76.

Giroud, J. P., and Bonaparte, R. (1989b). "Leakage Through Liners Constructed with Geomembranes – Part II, Composite Liners." *Geotextiles and Geomembrane*, Vol. 8, 71-111.

Holzlöhner, U., August, H., Meggyes, T., and Brune, M. (1995). "*Liner Systems*- A state of the Art Report." 42 p

Koerner, R. M., and Daniel, D. E. (1993). "Technical Equivalency Assessment of GCLS to CCLS." *Geosynthetic Liner Systems: Innovations, Concerns and Designs*, Industrial Fabric Association International, 265-285.

Koerner, R. M. (1999). *Designing with Geosynthetic*, Fourth Edition, Prentice Hall, New Jersey, 761 p.

Manassero, M., Parker, R., Pasqualini, E., Szabo, I., Almeida, M. S. S., Bouazza, A., Danial, D. E., and Rowe, R. K. (1998). "Controlled landfill design (Geotechnical aspects)." *Proc., 3rd Int. Conf. on Geosynthetics*, Lisbon, Portugal, Vol, 3, 1001-1038.

Neupane, D., Bowders, J .J., Loehr, J .E., Bouazza, A., and Trautwein, S. J. (2003). "Sealed Double Ring Infiltrometers for Estimating Very Low Hydraulic Conductivity." ASTM, *Geotechnical Testing Journal* accepted for publication.

Othman, M. A., Bonaparte, R., Gross, B. A. (1996). "Preliminary Results of Study of Composite Liner Field Performance." *Proc.*, *of the 10th GRI Conference*, Derxel University, Philadelphia, December, 110-137.

Sherard, J. L., Woodward, R. J., Gizienski, S. F., and Clevenger, W. A.(1963). *Earth and Earth Rock Fill Dams*, John Wiley & Sons, New York, 72 p.

Wing, N. R., and Gee, G. W. (1994). "The Development of Surface Barriers at Hanford Site," *Proc.*, 33rd Hanford Symposium on Health and Environment, In Situ Remediation: Scientific.