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Long-Term Permeability Monitoring of an FGD-Lined Pond Facility

Tarunjit S. Butalia[1], William E. Wolfe[1], and Harold Walker[1]

[1]Department of Civil and Environmental Engineering and Geodetic Science, The Ohio State University, 470 Hitchcock Hall, 2070 Neil Avenue, Columbus, Ohio 43210

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ABSTRACT

The technical feasibility of using stabilized Flue Gas Desulfurization (FGD) product as a raw material for the construction of low permeability liners is presented. To demonstrate the practicality of using FGD material as a hydraulic barrier, a full-scale pond (capacity of one million gallons) was designed and built on property owned by The Ohio State University. The facility, using lime-enriched stabilized FGD material as the primary liner, was constructed in the summer of 1997 at the Western Branch of the Ohio Agricultural Research and Development Center near South Charleston in Clark County. Water was contained within the facility during the first year and subsequently swine manure was added to the facility. The full-scale pond was monitored for a period of approximately four years to study the permeability characteristics of the FGD liner. An evaluation of the performance of the facility is presented in terms of measurements of the permeability of the field-compacted FGD liner. FGD materials can be compacted in the field using traditional construction equipment and the hydraulic barrier can be made comparable to one made from clay. The construction and monitoring of the full-scale FGD lined facility shows that stabilized FGD materials can be used as low permeability liners in the construction of water and manure holding ponds. Actual permeability coefficients in the range of 10^{-7} cm/sec can be obtained in the field by properly compacting lime and fly ash enriched stabilized FGD materials.

INTRODUCTION

In the past two decades, restrictions on the emission of sulfur dioxide from coal-fired power plants have been increasingly stringent in the United States. In response to these developments, power plants have had to remove increasing amounts of SO_2 from the flue gases before releasing them to the atmosphere. This process typically involves the injection of a reagent into the flue gases to form a solid by-product, which can then be collected. This solid by-product is commonly referred to as Flue Gas Desulfurization (FGD) material. Its principal constituents are varying amounts of sulfates and / or sulfites of the reagent, unreacted lime and fly ash. The FGD material may be dry or wet depending on the desulfurization process. The wet scrubbing process, which is commonly used by large electric utilities in Ohio, involves the injection of a reagent (typically hydrated quicklime) into the flue gases. The wet product generated (commonly referred to as FGD filter cake) is a dewatered mixture of sulfites and sulfates of the reagent, unreacted reagent, and some water. Calcium sulfite content is typically greater than 70% while the calcium sulfate content is approximately 13%. Fly ash and additional quicklime are added to stabilize the FGD filter cake. This stabilized (fixated) FGD material is gray in color and looks like silty clay.

Laboratory evaluation of the hydraulic conductivity and strength characteristics of lime enriched stabilized FGD materials have been presented by Butalia and Wolfe.[1] In that study, it was observed that plant mixed stabilized FGD material samples exhibited permeability values in the 10^{-7} to 10^{-8} cm/sec range at 28 days of curing. Samples with higher lime contents resulted in lower coefficients of permeability as well as higher unconfined compressive strengths. It was concluded that FGD material can be compacted in the laboratory using standard soil testing procedures to obtain permeability coefficients that are in the 10^{-7} to 10^{-8} cm/sec range, which can be lower than the $1x10^{-7}$ cm/sec value typically recommended by US Environmental Protection Agency for constructing liners for waste containment facilities.[2]

Permeability of a field compacted FGD structure is likely to be a function of the construction process, and hence field validation of the properties obtained in the laboratory is an important part of the documentation process. The design and construction of the full-scale FGD lined testing facility was presented by Wolfe, Butalia, Mitsch, and Whitlach[3] and is summarized in this paper. The full-scale facility was constructed to address two critical questions about the behavior of stabilized FGD products constructed in the field, i.e. what is the permeability of a compacted engineered liner of known thickness and density, and what is the quality of the water that flows through the FGD liner. This paper presents the permeability monitoring results from the FGD-lined facility.

DESIGN

The full-scale facility was designed and constructed at The Ohio State University's Ohio Agricultural Research and Development Center (OARDC) Western Branch in South Charleston (Clark County), Ohio. This site was chosen over other university sites because it had an abundance of clay onsite that was suitable for use as a secondary or outer liner to contain the primary FGD liner. The OARDC Western Branch facility is a swine and agronomic research facility and, hence, it was decided to build a livestock manure storage facility that could be used by the center for storing swine manure after the completion of this research. The facility was designed for a capacity of approximately one million gallons (150,000 ft^3) to provide six months storage for all liquid wastes from the swine onsite. A double-layered design was chosen with compacted stabilized FGD as the primary inner liner and the onsite clay (about 80 feet of grey glacial till) as the secondary outer liner. A leachate system was designed to be placed between the primary FGD liner and secondary clay liner to collect in a sump any water passing through the FGD fill. The sump was designed so that it could be used to collect leachate samples with ease and for conducting field permeability tests on the pond liner.

The facility is essentially rectangular in shape with overall dimensions of approximately 150 feet by 250 feet (including 8-foot wide berms). Three sides of the pond were constructed at 3:1 slope and the fourth (east) side slope at 7:1. The east side slope was designed to be less steep so as to allow for easy access to the pond bottom during and after construction. The pond is 9 feet deep with a liquid freeboard of 2 feet. A berm of minimum 8-foot top width was added around the periphery of the pond to minimize the inflow of surface water. The natural clay at the site provided an outer liner that was at least 5 feet thick. The leachate collection system, which consisted of corrugated high-density polyethylene (HDPE) perforated pipes (with socks) and protected against crushing using #57 washed river gravel, was placed over the re-compacted clay. The bottom of the pond was then covered with 9 inches of sand. On top of the sand layer, an 18-inch thick layer of compacted FGD material was placed. The proposed design of the facility was submitted to Ohio EPA for review and approval. Prior to project construction, a Permit to Install was issued by Ohio EPA for the installation of the demonstration facility.[4]

CONSTRUCTION

Excavation of the site began on July 30, 1997. The top layer of soil containing organic matter was removed and hauled away from the site. The re-compaction of onsite glacial till to form the secondary clay liner was completed on August 7, 1997. The onsite glacial till clay had an average moisture content of 11.6% and maximum proctor dry density of 18.6 KN/m^3. A sheepsfoot roller (with vibration) was used to compact the onsite clay to 99.4% of the proctor density. The laboratory permeability of the onsite compacted clay was measured to range between 3.04×10^{-7} and 7.24×10^{-8} cm/sec. The locations of the leachate collection system pipes were marked and excavated to a trench depth of 6 to 8 inches. A geofabric (to separate the secondary clay liner and sand particles) was spread over the clay with at least one foot of overlap at the geofabric joints. The leachate system pipes were then placed over the geofabric. The leachate collection system was connected to an 18-inch diameter vertical sump (20 feet height). About 50 tons of crushed #57 washed river gravel was then placed around and on top of the leachate collection system pipes to avoid crushing due to later compaction of FGD on top of it. The bottom of the facility was then covered with approximately 300 tons of silicious round natural fine sand. The average permeability of the sand used in the drainage layer was evaluated in the laboratory to be 3.12×10^{-3} cm/sec. A layer of geofabric was laid over the sand layer.

Lime and fly ash enriched stabilized FGD material was delivered by truck (starting August 11, 1997) from American Electric Power's Conesville Station near Coshocton, Ohio to the site (refer to Figure 1). Placement and compaction of FGD in 4-6 inch lifts on top of the geofabric layer were accomplished using two dozers and one sheepsfoot roller (see Figures 2 and 3). Approximately 2,700 tons of lime-enriched stabilized FGD material was used in the construction of the primary liner. The fly ash to filter cake ratio of the FGD material ranged from 1.48:1 to 2.40:1 with an average ratio of 1.81:1. The lime content varied from 6.79% to 8.44% with an average lime content of 7.98%. The moisture content of the FGD material received at the site during construction ranged from 49% to 62%, while the proctor dry density varied between 9.6 and 11.6 kN/m^3. Wet weather during the liner placement resulted in several delays but construction at the site was completed by August 26, 1997. The site was smooth rolled before completion of the project. Filling of the pond with water from an existing nearby pond began on September 12, 1997 and was completed on September 23, 1997. The pond was filled with water up to a depth of approximately 9 feet as shown in Figure 4.

To avoid coring holes in the full-scale FGD liner for obtaining permeability samples, several FGD test pads were constructed in vicinity of the full-scale facility. Four rectangular test pads (approximately 15 feet wide, 25-30 feet long and 3-4 feet deep) were installed. Each test pad was initially backfilled with 6 inches of sand to provide a permeable layer for drainage. The remainder of the excavation was filled with stabilized compacted FGD material. Due to the small size of the test pads compared to the large dimensions of the sheepsfoot roller, adequate compaction of the FGD material in the test pads could not be obtained. Three of the test pads (TP1, TP2, and TP3) were constructed using the 1.25:1 (FA:FC) and 8% lime mix, which was the typical mix used in the construction of the full-scale facility. TP4 was constructed using a 0.8:1 (FA:FC) and 4% lime FGD mix, which is the typical material generated at the power plant. This weaker mix was not used in the construction of the full-scale facility. An outline of the test pads constructed is shown in Table 1. Each of the test pad was instrumented for Boutwell field permeability testing apparatuses.[5] The instrumentation and monitoring of the test pads was conducted by BBC & M Engineering of Columbus, Ohio.

The actual cash cost of constructing the full-scale facility was estimated to be \$46,623.50. The FGD material was made available at the site free of charge by American Electric Power’s Conesville power plant. Thus the actual cash cost does not include the cost of adding additional lime to the material (approximately \$13,500) and the associated transportation costs (estimated to be \$25,000) for transporting the FGD material from Coshocton to the South Charleston project site. The cash cost of sand, gravel, drainage pipes, geofabric, and other miscellaneous materials was \$4,567.50. The cash cost of construction of the facility was \$42,056. The construction cost included equipment and operator costs for a backhoe (Kebelco 300), two bull dozers (Kamatsu D-6 and John Deere J 450), roller (sheepsfoot / smooth), trenching machine, Bobcat loader, two dump trucks, rotovator with farm tractor, and a farm tractor with front end loader.

MONITORING OF FACILITY

The facility was used to store water for the first year. In early September of 1998, some of the water was replaced with swine manure. Since then swine manure has continued to be added and removed from the facility on a regular basis depending on the manure storage vs. field spreading needs of the research farm. Monitoring of the site for field permeability and water quality was carried out for a period of about four years (September 1997 through July 2001). The average monitoring frequency was about three months. The monitoring program consisted of two main activities:

1) *Field Permeability Testing:* Full-scale falling head permeability tests on the facility were conducted by lowering the water level in the sump to create a head difference across the FGD liner. The amount of time taken to increase the water in the sump to specific levels was observed. Knowing the thickness of the FGD liner and its plan view area, the effective permeability of the field compacted FGD-lined facility was calculated (refer Figure 5).
2) *Water Quality Monitoring Program:* Testing of water samples from the pond, the sump, and a well about 1,000 feet from the site was carried out on a regular basis. The water quality analysis was performed by the Star Laboratory of The Ohio State University's School of Natural Resources at OARDC, Wooster. Tests conducted on the water samples included pH, electrical conductivity, alkalinity, acidity, total dissolved solids, 24 elements by Inductively Coupled Plasma (ICP) Emission Spectrometry Mineral Analysis, 4 anions using Ion Chromatography (IC) Analysis, and ammonia as well as nitrogen by Micro-Kjeldahl Distillation. Although the vicinity well was about 1,000 feet from the site and not necessarily hydrologically connected to the site, the well samples were investigated so that potential contamination of the farm water supply from the FGD lined facility could be detected.

In this paper, we present the results of the permeability monitoring program. Due to the limited length of the paper, the water quality monitoring results are not included. Analysis of the water quality data shows that the leachate from the FGD material meets Ohio's non-toxic criteria for coal combustion by-products[6], and for most potential contaminants the national primary and secondary drinking water standards are also met.[3]

Permeability

After filling the full-scale facility with water, the actual field permeability of the FGD liner was measured by lowering the water level in the sump and taking readings of the water level rising in the sump at various time intervals (refer to Figure 5). The permeability coefficients were calculated using the bottom area of the pond as the effective leaching area for the FGD-liner. Table 2 shows the effective coefficients of permeability obtained from full-scale permeability tests conducted on the pond facility. The permeability coefficient values listed in Table 2 are the average of several test readings that were measured at each curing time. The full-scale permeability of the facility was evaluated to be 9.1×10^{-7} cm/sec at a curing time of one month. The permeability coefficient continued to reduce over time (due to curing of FGD) and has stabilized at approximately 4×10^{-7}cm/sec. The FGD permeability coefficient data range obtained from the full-scale tests is comparable to typical clays used in the construction of compacted liners. The data presented in Table 2 includes the effect of freeze-thaw cycling on the actual permeability of the FGD liner. The actual area over which water flows through the FGD liner is greater than the bottom area of the pond (i.e., a significant amount of water may flow through the sides of the pond). Hence the full-scale permeability values presented in Table 2 should be taken to be an upper bound to the actual permeability of the field-compacted FGD liner. The addition of swine manure to the facility (at 370 days of curing and thereafter) did not affect the actual permeability of the liner.

The specific seepage rate (seepage volume below liner per unit liner area per unit time) for the full-scale facility can be obtained by multiplying the actual average coefficient of permeability with the hydraulic gradient across the liner. If no secondary liner were present at the site, the specific seepage rate for the 9 feet deep manure storage pond having an 18-inch thick FGD liner was calculated to be 0.0952 $in^3/in^2/day$. Although currently Ohio does not provide guidance on maximum design seepage rate from lagoons, many states do specify maximum seepage rate values. For example, Kansas state regulations[7-9] allow for a maximum seepage rate of 0.25 $in^3/in^2/day$. Specific seepage rates less than 0.1 $in^3/in^2/day$ are considered to be very low seepage values. The value for the full-scale FGD lined pond facility is 0.0952 $in^3/in^2/day$. Hence, it can be concluded that if there was no secondary clay liner constructed for the facility (as would be the norm for typical FGD-lined pond and manure storage facilities), the seepage rate loss from such FGD facilities would be very low.

The actual field permeability data obtained from the full-scale pond tests was compared with a) laboratory tests conducted on several laboratory compacted samples collected during pond construction, b) laboratory tests conducted on field compacted samples cored from test pads installed at the site, and c) field permeability tests (Boutwell) conducted on the test pads TP1, TP2, and TP3. TP4 was not considered for comparison because this test pad was constructed using FGD material that was lower in lime content and fly ash to filter cake ratio compared to the material used in the construction of the full-scale facility. Figure 6 shows the time history comparison of the full-scale permeability test values with averaged permeability coefficients obtained from a) laboratory tests on laboratory compacted samples, b) field tests (Boutwell) conducted on test pads, and c) laboratory tests conducted on samples cored from test pads. All the test procedures showed decreasing permeability coefficient with increasing curing time. It was observed that the laboratory compacted samples had permeability coefficients which were an order of magnitude lower than the full-scale testing values. Permeability values obtained from Boutwell tests and cored samples tested in the laboratory were in close agreement with each other but were one to three orders of magnitude higher than the full-scale tests. The test pad sample permeability values (Boutwell tests and cored sample testing) indicated a large scatter in the data. The permeability coefficients varied from 10^{-4} to 10^{-7} cm/sec with average permeability value in range of 10^{-5} cm/sec. This may be due to the unsuitable compaction achieved for the test pads. Furthermore, the Boutwell test procedure relates infiltration rate with permeability coefficient by assuming certain direction and boundary conditions of flow, which are nearly impossible to control in the field. However, it is important to note that the actual measured field permeability values of the full-scale FGD liner are an order of magnitude higher than laboratory measured values.

CONCLUSIONS

A full-scale FGD lined facility (capacity of one million gallons) was constructed, in Summer of 1997 at the Ohio Agricultural Research and Development Center (OARDC) Western Branch, South Charleston, to evaluate the performance of a field-compacted FGD liner. Water was contained within the facility during the first year and subsequently swine manure was added to the facility. The full-scale pond was monitored for a period of approximately four years to study the permeability characteristics of the FGD liner. FGD materials can be compacted in the field using traditional construction equipment and the hydraulic barrier can be made comparable to one made from clay. The construction and monitoring of the full-scale FGD lined facility (capacity of one million gallons) shows that stabilized FGD materials can be used as low permeability liners in the construction of water and manure holding ponds. Actual permeability coefficients in the range of 10^{-7} cm/sec can be obtained in the field by properly compacting lime and fly ash enriched stabilized FGD materials.

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An electronic copy of the detailed technical report published for this study can be accessed at **http://ccpohio.eng.ohio-state.edu/ccpohio/**.

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Figure 1. Truck Unloading FGD Material

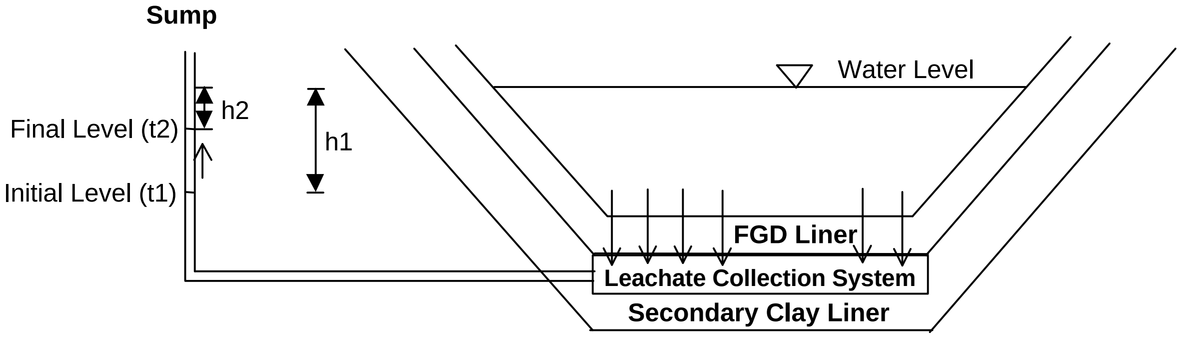
Figure 2. Spreading the FGD Material

Figure 3. Compacting FGD Material on a Side Slope

Figure 4 Facility Filled With Water

Table 1. FGD Test Pads Constructed

Pad Number	Thickness of Sand (inches)	Stabilized FGD			
		Thickness (inches)	Approx. FA:FC ratio	Approx. Lime content (%)	Moisture content (%)
TP1	6	27	1.25:1	8	62
TP2	6	36	1.25:1	8	69
TP3	6	30	1.25:1	8	58
TP4	6	36	0.8:1	4	84



$$k = \frac{L}{(t2 - t1)} \frac{a}{A} \ln\left(\frac{h1}{h2} \right)$$

L = Thickness of FGD liner
a = Area of sump
A = Effective area of FGD liner

Figure 5 Full Scale Permeability Test (not to scale)

Table 2. Full Scale Permeability Test Results

Curing Time (days)	Coefficient of Permeability * (cm/sec)
31	9.1×10^{-7}
63	6.8×10^{-7}
153	4.1×10^{-7}
202	4.3×10^{-7}
317	3.8×10^{-7}
402	4.2×10^{-7}
456	3.9×10^{-7}
567	4.0×10^{-7}
693	3.8×10^{-7}
869	4.3×10^{-7}
1035	4.4×10^{-7}
1141	4.5×10^{-7}
1274	4.2×10^{-7}
1416	4.1×10^{-7}

* Effective area of FGD liner = Bottom area of pond

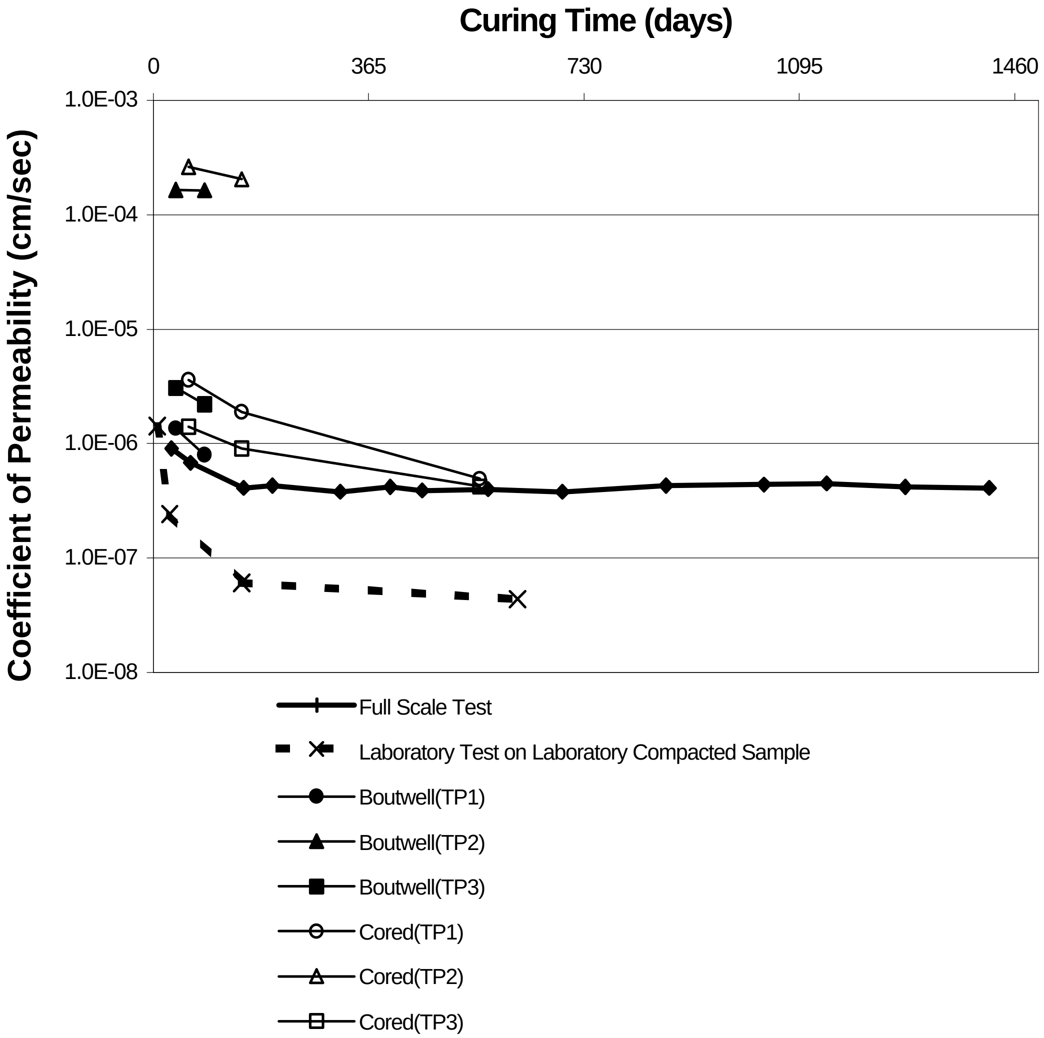


Figure 6. Comparison of Permeability Test Methods