Evaluation and Design Considerations of Geocomposite Leachate Collection Layers for Coal Ash Landfills

A. Zhao, S. Mayes & B. Betke
GSE Environmental, LLC, USA

ABSTRACT: The paper presents results of laboratory and field tests evaluating the application of specialty filters and drainage geonet composites as leachate collection layers in landfills containing coal combustion residuals (CCRs). Different types of CCR materials (stabilized FGD, gypsum and fly ash) from coal-fired power facilities were used. Laboratory tests included gradient ratio tests (ASTM D5101) and hydraulic conductivity ratio tests (ASTM D5567). The paper also presents results of field test pads constructed to compare the performance of leachate collection system alternatives; systems including a geocomposite with the specialty filter to the systems using bottom ash as the leachate collection drainage layer. Measurements included field flow rates, leachate total suspended solids (TSS), total dissolved solids (TDS), and PH values. Results from these Laboratory and field performance tests provided the basis for the use of the drainage geocomposites in actual projects. The paper then presents design considerations for a geocomposite leachate collection layer and the proper use of US EPA HELP model for the leachate quantity and hydraulic head calculations. The paper concludes with a recent project case history.

Keywords: specialty filter, geonets and geocomposites, laboratory and field tests, HELP model

1. INTRODUCTION

A drainage geonet composite is composed of a geonet core with a geotextile laminated to one or both sides. The upper geotextile is used to filter out particles from overlying soils. The lower geotextile is used to increase the interface friction against the underlying geomembrane and to provide cushion protection for the geomembrane. The primary function of a geonet composite is DRAINAGE. This function must be preserved over the duration of the geonet composite service life. Important engineering properties of a geonet composite drain include: filtration characteristics of the upper geotextile component, long term transmissivity under field conditions, structural design sufficient to accommodate design loads, and interface friction with adjacent soil and/or other ‘geo’ layers.

The United States Environmental Protection Agency (US EPA) published regulations in October 2015 on the disposal of coal combustion residuals (CCRs). The containment of CCRs in landfills requires the use of a composite liner system and a leachate collection drainage layer. Note that bottom ash is also a CCR, however for the purpose of this paper the term CCR will reference non-cohesive fine grained CCRs such as fly ash, stabilized FGD, and gypsum. Fly ash has a typical particle size range from 0.001 to 0.1 mm; dry flue gas desulfurization (FGD) gypsum ranges from 0.001 to 0.05 mm; and wet FGD gypsum ranges in size from 0.002 to 0.075 mm. Gradation examples of fine CCRs from two electricity power plants are shown in Figure 1.

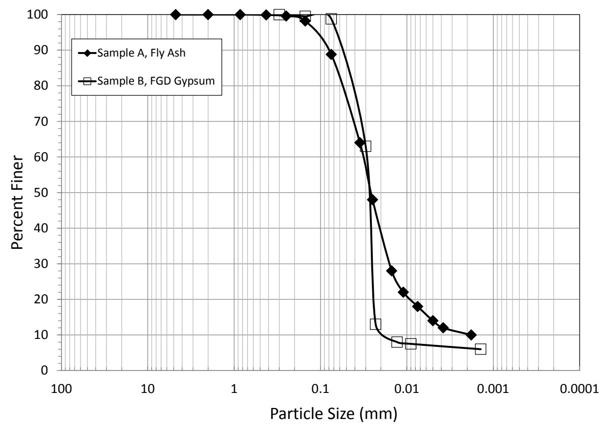

Figure 1: Example gradation of CCRs from two power plants

An effective filter layer is essential between the CCRs and the leachate drainage materials to ensure no clogging of the drainage layer. Historically geotextile filters and design methods have been developed based on sand-sized particles. As a result, the opening size of most geotextiles is in the range of 0.1 to 0.3 mm, making most geotextiles unsuitable for filtering CCRs due to blinding at the geotextile interface, clogging the geotextile filter, or piping of fines through the geotextile filter. Upon extensive laboratory and field performance evaluations, a hybrid geotextile filter that combines a nonwoven and a woven geotextile was developed to filter CCRs, and to be suitable for heat-lamination to a HDPE geonet drainage core (Narejo et al, 2013, Zimmel et al, 2013). Table 1 shows the index properties, and Figure 2 is a photo of a drainage geocomposite with the hybrid specialty filter on the top.

Table 1. Engineering characteristics of the hybrid geotextile filter

Property	Test Method	MARV
Mass per unit area	ASTM D 5261	480 grams/m^2
Apparent opening size (AOS), US sieve	ASTM D 4751	170(0.088 mm)
Permittivity	ASTM D 4491	0.3 sec^{-1}
Water flow rate	ASTM D 4491	814 lpm/m^2
Grab strength	ASTM D 5034	890 N
Puncture strength	ASTM D 6241	3447 N
Tear strength	ASTM D 4533	378 N

Figure 2: Photo of a drainage geocomposite with a hybrid specialty filter at the top

The next section of this paper presents the results of gradient ratio tests (ASTM D5101) and hydraulic conductivity ratio tests (ASTM D5567) conducted using the specialty filter geotextile with three distinct CCR materials. Section 3 discusses the results of intermediate-scale field tests, and Section 4 summarizes results and conclusions drawn from on large-scale field test. Measurements taken during the field tests included field flow rates, leachate total suspended solids (TSS), total dissolved solids (TDS), and PH values. Section Five describes the application of the US EPA HELP model to compare and contrast a geocomposite leachate collection layer with a traditional bottom ash drainage layer as used in the base liner system of a CCR landfill.

Section Six highlights a recent large CCR project that utilized the specialty geocomposite as the leachate collection layer.

2. LABORTORY TESTS WITH COAL COMBUSTION RESIDUALS

Extensive laboratory tests have been performed on the hybrid geotextile. Figure 3(a) presents typical gradient ratio data (ASTM D 5101) obtained using CCR samples obtained from a power plant; two fly ash samples and one FGD gypsum sample. The gradient ratio refers to the ratio of the hydraulic gradient of a soil-geotextile system to that of the soil. A gradient ratio that is much smaller than one represents a soil loss, while a value much greater than one indicates clogging. A geotextile is considered compatible with the base material if the gradient ratio is less than 3 when that value stabilizes over time. The figure shows that the hybrid geotextile forms a stable filter against fly ash and FGD gypsum material within a few pore volumes.

For non-cohesive, fine-grained materials like CCRs, a hydraulic conductivity ratio (HCR) test, performed according to ASTM test method D 5567, offers some advantages over a gradient ratio test. The HCR test includes back-pressure saturation, a better stress control, and the use of higher gradients. HCR is the ratio of the hydraulic conductivity of the soil/geotextile system measured during the test to the initial hydraulic conductivity measured at the beginning of the test. Figure 3(b) shows the results from HCR tests performed on fly ash and FGD gypsum. The HCR value stabilized within two pore volumes with no further decrease. The hybrid geotextile forms a stable filter indicating no further decrease in hydraulic conductivity with time.

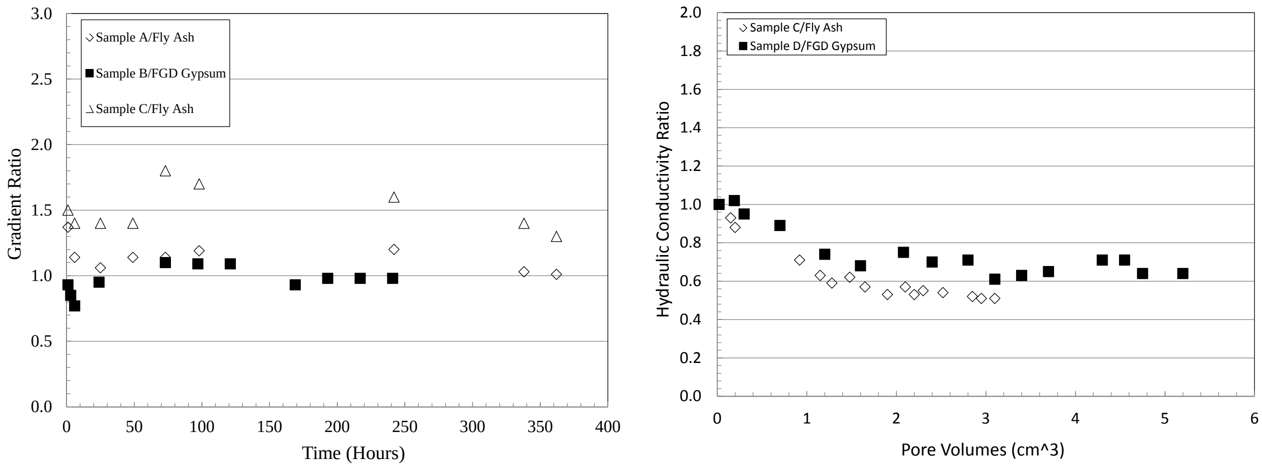

Figure 3: (a) Gradient ratio test results on samples of CCRs from a power plant; (b) HCR test results

3. INTERMEDIATE-SCALE FIELD TESTS WITH COAL COMBUSTION RESIDUALS

Intermediate scale field tests were conducted at the Olentangy River Wetland Research Park of the Ohio State University (Mitsch et al, 2012). Four test basins were constructed for the tests. Each of the test basins was approximately 4.9 meters by 1.5 meters and had a side slope of 2H:1V, as shown in Figure 4(a). A 0.6 meter wide collection trough was placed at one end of each of the basins. The test basins were lined with a geomembrane to ensure that water could exit only through the hybrid geotextile and geonet geocomposite via the collection trough. The geocomposite with the hybrid geotextile facing upwards was installed in the test basins on top of the geomembrane. The test basins were filled with about 0.3 meters of CCR material. Four CCR materials were included in the field tests: test basin 1 - wet fly ash, and test basin 2 - stabilized FGD gypsum, both from one power plant; test basin 3 - dry fly ash, and test basin - 4 unwashed FGD gypsum, both from a second power plant. A 2100 liter water tank was installed at one end of each of the basins to provide water for the testing. To maintain a constant head of water during the testing process, six pore volumes of water were released into each of the test basins at controlled flow rate. A metropolitan water source was used for all test basins.

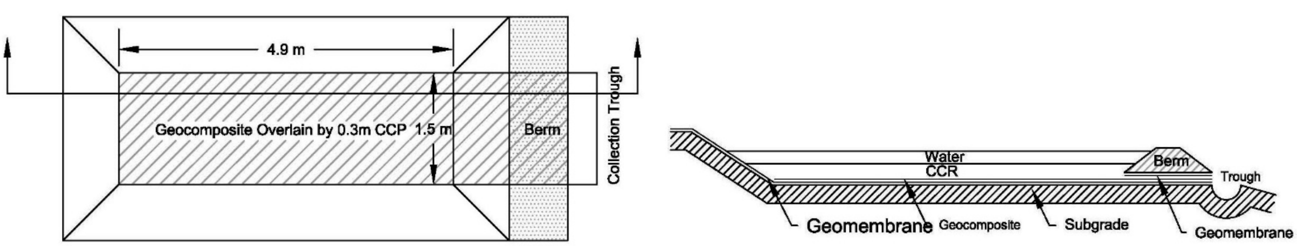

Figure 4: (a) Plan view of the test plot (left), and (b) section along the length of the plot (right)

Measurements of the in-situ temperature, conductivity and pH were taken within the basins. One-liter leachate samples were collected periodically from the open end of the hybrid geotextile geonet composite at the collection trough. These samples were sent to an offsite laboratory, where they were tested for turbidity, total suspended solids (TSS) and total dissolved solid (TDS).

The results for the TSS in terms of the pore volume are presented in Figure 5. The solid concentrations within the first pore volume ranged from 20 to 300 mg/L. The hybrid geotextile formed a stable filter within less than two pore volumes for all the fly ash and FGD gypsum tested. The final pore volume had solid concentrations that were below the detection limit of 18 mg/L.

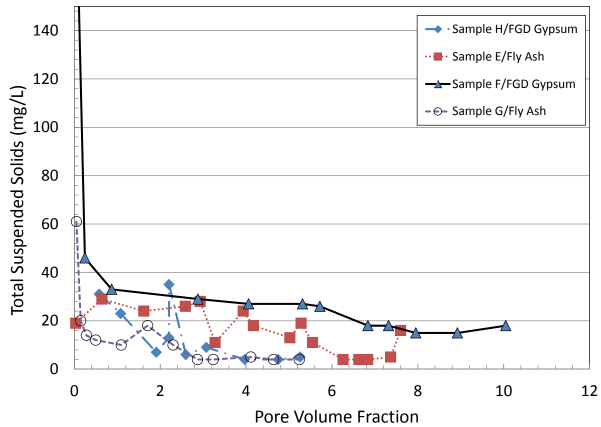

Figure 5: Total suspended solids from the field tests

4. LARGE-SCALE FIELD TESTS WITH COAL COMBUSTION RESIDUALS

Three large test cells, each 12 meters long and 6 meters wide, were constructed side-by-side on a project location with the following configuration from the bottom to top:

- South Cell – 1.5 mm LLDPE liner, specialty geocomposite (the hybrid filter geotextile on top of a geonet and a nonwoven geotextile at bottom), 0.6 meters gypsum protective cover;
- Middle Cell – 1.5 mm LLDPE, specialty geocomposite, 0.3 meters fly ash, 0.6 meters gypsum protective cover; and
- North Cell – 1.5 mm LLDPE, 0.45 meters bottom ash, 0.6 meters gypsum protective cover. In the North Cell, sieved (10% fine content) bottom ash was used as the filtration and drainage layers instead of the geocomposite, since this was a locally available material that could be a cost-effective alternative.

Figure 6(a) shows the test pad plan view and Figure 6(b) is the profile of the Middle Cell. All three ponds were then filled with water. Two full 15,000-liter loads from a water truck were applied daily during the two-month test period. The effluent from the drainage layers was monitored over time. Flow rates collected in the sump and measurement of total suspended solids are presented in Figure 7. The South Cell (gypsum protective soil over the specialty geocomposite) maintained flow rate, with TSS concentration of 1.2 mg/l towards the end of the test. The Middle Cell (fly ash over the specialty geocomposite) had a consistent flow, with TSS concentration of 5 mg/l towards the end of the test. The North Cell (gypsum over bottom ash) indicated low or minimum flow, with TSS concentration 220 g/l towards the end of the test. The hybrid geotextile overlying the geonet performed satisfactorily with its filter function in both South and Middle Cells. The filter-drainage system used in the third cell, in which the specialty geocomposite was not used, showing piping of fines in the effluent and minimum flow or clogging, is not suitable for use as a filter and drainage layer.

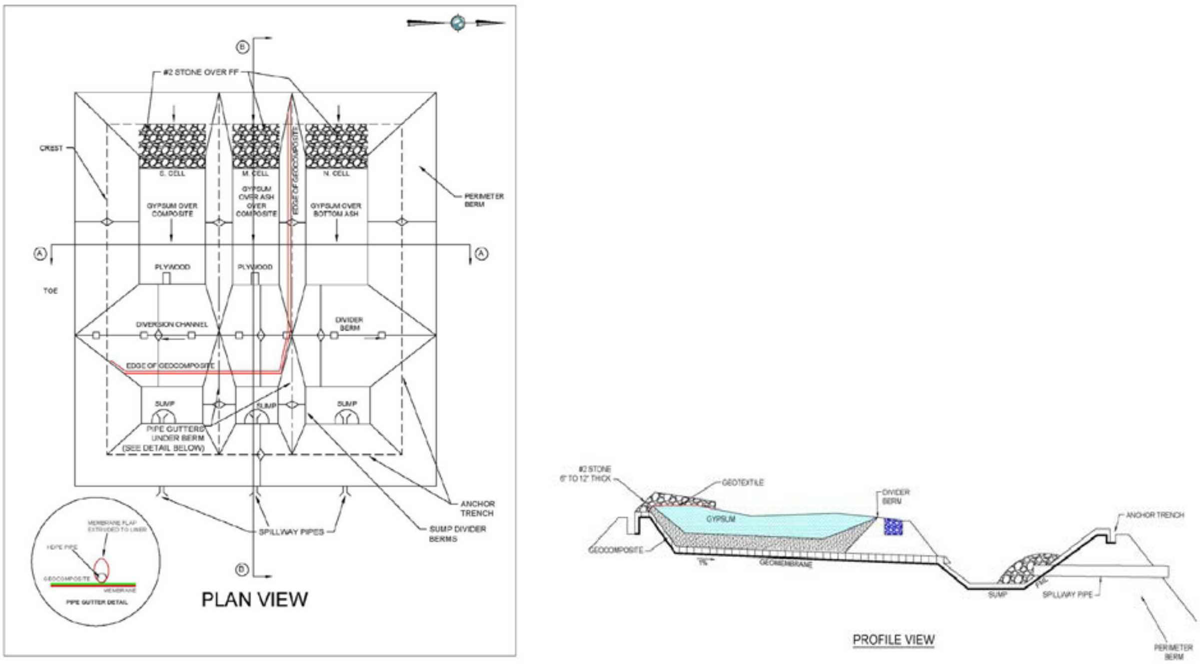

Figure 6: (a) Test pad plan view, and (b) test pad profile (Middle Cell) (Schmitt and Cole, 2012)

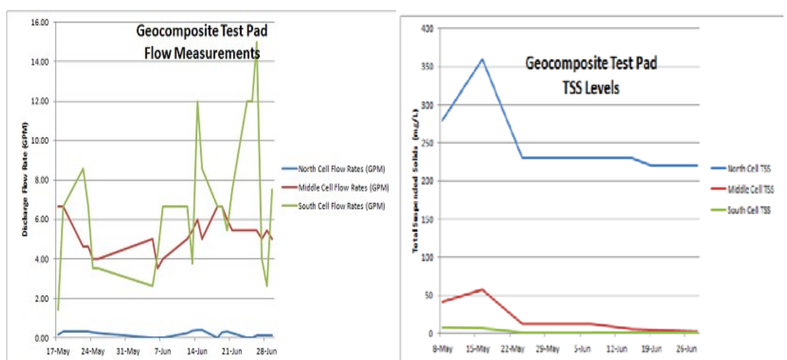

Figure 7: Field and lab results of sump samples, flow measurements (left), and TSS (right) (Schmitt and Cole, 2012)

At the end of the test period, the CCR waste was carefully removed from the test pads in order to visually inspect the condition of the specialty geocomposite. The top hybrid geotextile was cut out in order to expose the geonet core to see if any fines that had accumulated within it. Practically no fines were found within the geonet core, as shown in a photo of the exposed geocomposite after the overlying geotextile was removed (Figure 8). Transmissivity tests performed on the retrieved material indicated that there was no loss of hydraulic performance over the exposure time period.

Figure 8: Condition of the geocomposite after the test (Schmitt and Cole, 2012)

5. DESIGN CONSIDERATION OF GEOCOMPOSITE LEACHATE COLLECTION LAYER

5.1 HELP model analyses and drainage layer input parameters

A properly designed leachate collection layer is an integral part of the liner system for a fly ash landfill. Water balance analyses are required to assess liner and leachate collection systems efficiencies, including leachate generation quantity, liner leakage quantity, and leachate head over the liner, and leachate collection layer flow capacity (transmissivity for a geocomposite collection layer). In the USA, the US EPA HELP (Hydraulic Performance of Landfill Performance) model (Schroeder, et al, 1994) is the most common water balance software used to perform the hydraulic analysis of a proposed landfill. Different stages of the landfill operation, from the time of first lift of waste placement through the installation of a final closure system, can be simulated.

For a geocomposite leachate collection layer design, the greatest quantity of leachate liquid is after the initial placement of waste when the applied pressure on the geocomposite is the least. As the waste height in the cell increases, the quantity of liquid will decrease due to the liquid storage capacity of the waste. Although the quantity of liquid the drainage geocomposite must handle is decreasing with waste height, the applied pressure from the waste is increasing which decreases the transmissivity performance of the geocomposite. Thus both the worst hydraulic and the worst loading conditions should be analyzed. For instance, the Florida Department of Environmental Protection Rule 62-701.400 Subparagraph (3) (d) 8 (Landfill construction requirements, solid waste management facilities, 2015) requires “The testing for the geonet in the liner system shall be conducted using actual boundary materials intended for the geonet at the maximum design normal load for the landfill, and at the design load expected from one lift of waste.”

The following are the input data required by the HELP model to simulate a lateral drainage layer:

- Layer thickness
- Moisture retention parameters: porosity, field capacity, and wilting point.
- Saturated hydraulic conductivity
- Maximum drainage length (m), the horizontal projection of the slope
- Drain slope (%)

All dimensional and hydraulic input data for a geosynthetic drainage layer should simulate the anticipated field conditions, taking into account long-term reduction factors and overall safety factors (GRI-GC8, 2001, Zhao et al, 2012). The HELP model user manual and software provides various default input values for soil, waste, and geosynthetics, as shown in Table 2, in which two geonet textures #20 and #34 are listed. A 5 mm geonet is shown to have a hydraulic conductivity of 10 cm/s. The 6 mm geonet has a hydraulic conductivity of 33 cm/s. Unless one has a clear definition of the product as a geonet core alone or a geocomposite, and has testing conditions (applied loads, boundary conditions, hydraulic gradient, and seating time), these default values are often incorrect, and thus should not be used in the analyses.

5.2 HELP model analyses example

The following example considers a fly ash landfill liner system (from bottom up) comprised of a GCL (texture #17), a 60-mil HDPE geomembrane (texture #35, good installation quality, three defects per acre), a specialty geocomposite, and 30 meters of fly ash waste from a coal-burning plant (texture #30). The leachate collection layer is sloped at 2% and is 122 meters in slope length. The fly ash waste has a unit weight of 10kN/m^3. The design safety factor for loading is 1.5. Geonet reduction factors due to compressive creep RF_{CR} = 1.1, chemical clogging RF_{CC} = 2.0, biological clogging RF_{BC} = 1.1, and overall drainage safety factor FS_D = 2.0

a. Determine design load and geonet thickness
- Design normal load = 1.5 x 30 m x 10 kN/m^3 = 450 kN/m^2
- Design thickness of the geonet under load = 6.8 mm

b. Determine design hydraulic conductivity
- The transmissivity of the geocomposite = 13 cm^2/s, tested with a soil layer on top of the geocomposite and under the design load 450 kPa
- The design transmissivity = 13 cm^2/sec / (FS_D x RF_{CR} x RF_{CC} x RF_{BC}) = 13/(2.0 x 1.1 x 2.0 x 1.1) = 2.7 cm^2/sec
- Design hydraulic conductivity = Design transmissivity / design thickness = 2.7 cm^2/sec /0.68 cm = 4 cm/sec

Table 3 lists the HELP model output . The maximum head over the liner is 2.3mm (0.092 inches), less than the design thickness of the geonet, indicating a valid design scenario. In the event the maximum head is greater than the geonet design thickness, design parameters must be adjusted (either increase the transmissivity of the product, or shorten the drainage length, or steepen the slope).Once the design parameters are adjusted (if required), the designer would re-run the HELP model analysis until the maximum head is within the design thickness of the geonet to ensure an unconfined flow condition.

Table 2. HELP model default soil, waste, and geosynthetic characteristics

Classification			Total Porosity	Field Capacity	Wilting Point	Saturated Hydraulic Conductivity
HELP	USDA	USCS	vol/vol	vol/vol	vol/vol	cm/sec
1	CoS	SP	0.417	0.045	0.018	1.0×10^{-2}
2	S	SW	0.437	0.062	0.024	5.8×10^{-3}
3	FS	SW	0.457	0.083	0.033	3.1×10^{-3}
4	LS	SM	0.437	0.105	0.047	1.7×10^{-3}
5	LFS	SM	0.457	0.131	0.058	1.0×10^{-3}
6	SL	SM	0.453	0.190	0.085	7.2×10^{-4}
7	FSL	SM	0.473	0.222	0.104	5.2×10^{-4}
8	L	ML	0.463	0.232	0.116	3.7×10^{-4}
9	SiL	ML	0.501	0.284	0.135	1.9×10^{-4}
10	SCL	SC	0.398	0.244	0.136	1.2×10^{-4}
11	CL	CL	0.464	0.310	0.187	6.4×10^{-5}
12	SiCL	CL	0.471	0.342	0.210	4.2×10^{-5}
13	SC	SC	0.430	0.321	0.221	3.3×10^{-5}
14	SiC	CH	0.479	0.371	0.251	2.5×10^{-5}
15	C	CH	0.475	0.378	0.265	1.7×10^{-5}
16	Barrier Soil		0.427	0.418	0.367	1.0×10^{-7}
17	Bentonite Mat (0.6 cm)		0.750	0.747	0.400	3.0×10^{-9}
18	Municipal Waste (900 lb/yd^3 or 312 kg/m^3)		0.671	0.292	0.077	1.0×10^{-3}
19	Municipal Waste (channeling and dead zones)		0.168	0.073	0.019	1.0×10^{-3}
20	Drainage Net (0.5 cm)		0.850	0.010	0.005	$1.0 \times 10^{+1}$
21	Gravel		0.397	0.032	0.013	3.0×10^{-1}
22	L*	ML	0.419	0.307	0.180	1.9×10^{-5}
23	SiL*	ML	0.461	0.360	0.203	9.0×10^{-6}
24	SCL*	SC	0.365	0.305	0.202	2.7×10^{-6}
25	CL*	CL	0.437	0.373	0.266	3.6×10^{-6}
26	SiCL*	CL	0.445	0.393	0.277	1.9×10^{-6}
27	SC*	SC	0.400	0.366	0.288	7.8×10^{-7}
28	SiC*	CH	0.452	0.411	0.311	1.2×10^{-6}
29	C*	CH	0.451	0.419	0.332	6.8×10^{-7}
30	Coal-Burning Electric Plant Fly Ash*		0.541	0.187	0.047	5.0×10^{-5}
31	Coal-Burning Electric Plant Bottom Ash*		0.578	0.076	0.025	4.1×10^{-3}
32	Municipal Incinerator Fly Ash*		0.450	0.116	0.049	1.0×10^{-2}
33	Fine Copper Slag*		0.375	0.055	0.020	4.1×10^{-2}
34	Drainage Net (0.6 cm)		0.850	0.010	0.005	$3.3 \times 10^{+1}$

Table 3. HELP model analysis output – geocomposite drainage layer

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                 PEAK DAILY VALUES FOR YEARS     1 THROUGH    20
--------------------------------------------------------------------------
                                                  (INCHES)       (CU. FT.)
                                                 ----------    -------------
  PRECIPITATION                                     3.66          13285.801

  RUNOFF                                            0.000             0.0000

  DRAINAGE COLLECTED FROM LAYER   2                 0.10635         386.03625

  PERCOLATION/LEAKAGE THROUGH LAYER   4             0.000000          0.00006

  AVERAGE HEAD ON TOP OF LAYER   3                  0.047

  MAXIMUM HEAD ON TOP OF LAYER   3                  0.092

  LOCATION OF MAXIMUM HEAD IN LAYER   2
        (DISTANCE FROM DRAIN)                       2.2 FEET

  SNOW WATER                                        6.34          23023.9687


  MAXIMUM VEG. SOIL WATER (VOL/VOL)                        0.5410

  MINIMUM VEG. SOIL WATER (VOL/VOL)                        0.0470


   ***  Maximum heads are computed using McEnroe's equations.   ***

        Reference:  Maximum Saturated Depth over Landfill Liner
                    by Bruce M. McEnroe, University of Kansas
                    ASCE Journal of Environmental Engineering
                    Vol. 119, No. 2, March 1993, pp. 262-270.
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As a comparison, the following HELP model analysis was performed with a bottom ash drainage layer. Holding all other design input data the same as the above, a 60 cm bottom ash texture #31 is used as a drainage layer with a hydraulic conductivity of 4.1×10^{-4} cm/s. Table 4 lists the HELP model analysis output . With the bottom ash drainage layer the maximum head on top of the liner is now increased to 66 cm (25.8 inches), greater than 30 cm maximum head allowed by regulation, indicating the bottom ash layer does not have adequate permeability. A drainage geocomposite is more effective in limiting the hydraulic head on top of the liner, and minimizing the leakage quantity.

Table 4. HELP model analyses results – bottom ash as a drainage layer

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             PEAK DAILY VALUES FOR YEARS    1 THROUGH   20
----------------------------------------------------------------------------
                                              (INCHES)      (CU. FT.)
                                             ----------    -------------
  PRECIPITATION                                 3.66        13285.801

  RUNOFF                                        0.000           0.0000

  DRAINAGE COLLECTED FROM LAYER  2              0.05448       197.77756

  PERCOLATION/LEAKAGE THROUGH LAYER  4          0.000021        0.07553

  AVERAGE HEAD ON TOP OF LAYER  3              21.401

  MAXIMUM HEAD ON TOP OF LAYER  3              25.783

  LOCATION OF MAXIMUM HEAD IN LAYER  2
        (DISTANCE FROM DRAIN)                  90.0 FEET

  SNOW WATER                                    6.34        23023.9687

  MAXIMUM VEG. SOIL WATER (VOL/VOL)                    0.5410

  MINIMUM VEG. SOIL WATER (VOL/VOL)                    0.0470

   ***  Maximum heads are computed using McEnroe's equations.  ***

        Reference:  Maximum Saturated Depth over Landfill Liner
                    by Bruce M. McEnroe, University of Kansas
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6. CASE HISTORY

The project site in Figure 9(a) is a 43- hectare CCR landfill application permitted for construction with the following leachate collection layer alternatives: 1) a 45-cm graded aggregate material and 2) a specialty geocomposite alternative overlain by CCR. The graded aggregate material alternate expected to consist of either a graded sand filter or bottom ash layer. Availability of sufficient bottom ash quantity was a concern for the project design team as was the cost associated with importing a suitable off-site sand or river gravel from a borrow source. Due to these concerns, a specialty geocomposite overlain by CCR was included in the permit as an alternative to the 45-cm graded aggregate material.

Though the plant's gypsum and fly ash gradations were considerably different from each other, both CCRs had a similar permeability of 1×10^{-6} cm/s. Hydraulic Conductivity Ratio (HCR) Tests per ASTM D 5567 were completed at 244 kPa and 488 kPa confining pressures to predict filtration compatibility between the specialty geocomposite and the plant's gypsum and fly ash CCRs. The hydraulic conductivity test results were used in the specialty geocomposite hydraulic calculations as well as the HELP modeling. The hydraulic conductivity test results were plotted versus time and a trend line equation established to allow hydraulic conductivity calculation associated with the time period for each of the development conditions in the HELP modeling.

Figure 9: (a) Aerial view of project site, and (b) Specialty geocomposite installed over a white liner

The Owner awarded the construction contract for the specialty geocomposite alternate because it was more cost-effective and provided a higher level of technical performance as compared to the graded aggregate alternative. The liner system cross-section, from the subgrade up, consisted of GSE Coal Ash Resistant BentoLiner NWL GCL (secondary liner), GSE White 60mil Textured LLDPE Geomembrane (primary liner), GSE CoalDrain Geocomposite (filter and drainage layer for the leachate collection system), and 60-cm of gypsum protective cover. Figure 9(b) illustrates the specialty geocomposite placement over the white geomembrane.

Figure 10: (a) CCR (gypsum) protective cover placement on the geocomposite; (b) The geocomposite being installed over a white geomembrane with CCR (gypsum) protective cover

Generally speaking from initial construction through landfill closure, the calculated liner leakage rate for the specialty geocomposite alternate was two orders of magnitude lower than it was for the 45-cm graded aggregate material. The specialty geocomposite alternative will also save the Owner an estimated $5.6 million in capital expense and provide an estimated 190,000 cubic meters in additional storage capacity. To date, about 18-hectaress of the 43-hectare CCR landfill has been constructed utilizing the specialty geocomposite alternative overlain by a 60-cm protective cover layer of gypsum (see Figure 10(a)). Because the specialty geocomposite alternate is being utilized in lieu of the 45-cm graded aggregate material, there is no need to monitor calcium carbonate content, soundness, gradation, and other variability considerations associated with the aggregate. Figure 10(b) illustrates current installation progress at the site.

7. CONCLUSIONS

Laboratory results from the gradient ratio tests and hydraulic conductivity ratio tests provide performance indications of the hybrid filter with coal combustion residuals. Large-scale field tests, simulating the field conditions, provide measurement of leachate flow rates and analyses of total suspended solids to further prove the effectiveness of the hybrid filter and the geonet geocomposite in filtration, retention and drainage functions. HELP Model water balance analyses are effective tools in designing geocomposite leachate collection layers, however, default geonet properties should not be used without considering field conditions. A properly designed drainage geocomposite provides a more effective means to control the hydraulic head on top of the liner, thereby reducing the leakage rate. The paper entitled "field evaluation of geonet flow rate (transmissivity) under increasing load" (Eith and Koerner, 1991) proved geonet performance under field conditions. Without this milestone work, geonets and geocomposites might never have been accepted as alternatives to granular drainage layers in landfills. For applications of drainage geocomposites in CCRs landfills, field tests are an integral part of the assessment of filter effectiveness and drainage performance due to the very fine grain and non-cohesive nature of CCRs.

8. REFERENCES

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