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Evaluating Compatibility of CCR with Leachate Collection System to Ensure Rule Compliance

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ABSTRACT

Section 271.71(d)(3) of the Coal Combustion Residuals (CCR) Rule requires that the leachate collection system of a landfill be designed and operated to minimize clogging during the active life and post-closure care period. The attributes of the mix of CCR materials going to the landfill at any given station are unique. Site-specific evaluation of the CCR should be conducted proactively to confirm its compatibility with the proposed leachate collection system, particularly with the filter geotextile. A common method for evaluating compatibility is Hydraulic Conductivity Ratio (HCR) testing (ASTM D5567).

The HCR test is performed using a flexible wall permeameter with a specimen of CCR material mounted on a geosynthetic, and flow is monitored over time. The HCR is the ratio of the hydraulic conductivity of the system at any given point in time during testing to the hydraulic conductivity of the system at the start of testing. The HCR at stability and test termination is reported as the final HCR. The test is can be performed in two phases to model staged consturction. The first phase monitors flow under low effective stress and is indicative of the early conditions of a landfill cell under construction, where and “piping” of CCR is most likely. Blinding of geosynthetic and natural drainage materials commonly occurs under these conditions. Piped material can clog the leachate collection pipes and sumps and also damage pumps. The second phase of the test monitors flow under increasing pressure (which can exceed 27,000 PSF beneath 300 feet of CCR). This is when geotextiles are subject to clogging and geocomposites are subject to compression, reducing their flow capacity.

Interpretation of HCR results as to whether the sample is piping, clogging, or stable is somewhat subjective. The Geosynthetic Research Institute recommends an ideal HCR range of 0.4 to 0.8 for minimal clogging—but the primary goal is to see the hydraulic conductivity stabilize and level off, indicating that a “filter cake” has formed along the critical surface (i.e. filter geotextile). An initial decrease in hydraulic conductivity is optimal as an indicator that the "filter cake" is setting up along the geotextile surface. The final end-of-test HCR hydraulic conductivity values can be used to revisit design calculations to estimate anticipated impingement on the leachate collection system and ensure that the leachate collection system can still meets the Rule requirement to maintain less than 30 cm depth of leachate over the liner system.

INTRODUCTION - DESIGN AND SITE CONDITIONS

The CCR Rule published by U.S. Environmental Protection Agency (EPA) requires that the leachate collection system of a new Coal Combustion Residuals (CCR) landfill must be designed and operated to minimize clogging during the anticipated active life of the landfill and the 30-year post-closure care period. Unlike typical Municipal Solid Waste (MSW) facilities, where the first loosely-placed / “fluff lift” of waste can act as a filter for overlying materials, CCR materials placed in proximity to natural or geosynthetic drainage media has the potential to clog this underlying drainage layer. The filter design is key to the long-term performance of the leachate collection system.

There are several other aspects of a CCR landfill that can be problematic for the leachate collection system, and these should be considered during the design, construction and operational phases. Sand tends to wash away in heavy rain unless covered. Bottom ash may contain pyrites that clog the leachate collection system with ochre formed by ferrous hydroxide. CCR fines in the “contact water” can run off the surface of CCR placed in the landfill and blind the leachate collection system. This can form a “slime” layer that causes mechanical blinding on the surface of the layer. This phenomenon can be minimized through the inclusion of “chimney drains” that facilitate an inward gradient and essentially a “stormwater bypass” directly to the leachate collection pipes. The focus of this paper is not on these acute “turbulent” issues, but rather on the long-term compatibility of the through HCR testing that evaluates the potential for the proper formation of a “filter cake” of CCR along the top of the sand or geotextile that is designed to protect the leachate collection system.

Geotextiles can pose a problem in several manners:

- Piping - If the Apparent Opening Size (AOS) is too large, a stable filter cake is not able to form and CCR particles can pass through the geotextile and clog the leachate pipe and sump area, possibly resulting in damage to the pumps.
- Blinding – If the apparent opening size (AOS) or percent open area (POA) are too small and the geotextile blocks CCR particles but does not form a proper filter cake that allows water to pass through a spatial matrix, then the geotextile may blind, representing a clogged filter that is impractical to replace.

Finding the proper filter mechanism is critical to long-term performance of the leachate collection system. The CCR properties can vary greatly from plant to plant, depending on type of boiler, coal being burned, limestone used in the scrubber and other variables. Therefore it is highly advisable to conduct site-specific testing to confirm compatibility of the proposed filtration media or geotextile with the on-site CCR material.

DESIGN CALCULATIONS

The engineering team performs design calculations to evaluate the performance of the leachate collection system under various conditions at different stages of the facility's life. The results of HCR testing can be used to refine design calculations and/or verify whether the leachate collection system will perform adequately long-term. Reductions in system permeability, due to clogging and (in the case of a geocomposite) creep due to compression from the confining pressure of overlying CCR, are based on the compatibility testing results.

ASTM LABORATORY TESTING METHODS FOR EVALUATING COMPATIBILITY

The two principal ASTM methods that are utilized in the laboratory to evaluate the compatibility of a soil-geotextile system are the Gradient Ratio Test (GR test/GRT, ASTM D5101[3]) and the Hydraulic Conductivity Ratio Test (HCR, ASTM D5567[4]). The GR test measures the gradient across the system for two zones, with Zone 1 measuring headloss across the soil-geotextile interface, and Zone 2 measuring head loss across the soil alone. The ratio of these two gradients (GR=Z1/Z2) generally interpreted as system stability (GR=1), the presence of piping (GR<1), or the occurrence of clogging (GR>1). The GR test is performed in a fixed wall permeameter and head losses are measured through the use of manometers or pressure transducers typically either place along the sidewall of the device or through the use of injection ports. The testing method and permeameter used are similar to those used to perform ASTM D2434[1] - *Standard Test Method for Permeability of Granular Soils (Constant Head*).

The HCR test measures the hydraulic conductivity of the system at the beginning of permeation and at the end of permeation after the system has stabilized. The ratio of the final hydraulic conductivity to the initial hydraulic conductivity generally indicates system performance. The HCR test is performed in a flexible wall permeameter and the head difference across the system is typically controlled through the use of a pressure panel. The testing method and permeameter used are similar to those used to perform ASTM D5084[2] - *Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter.*

The selection criteria for determining the appropriate test to perform are presented in Table 1. The methods utilizing the fixed wall permeameter have requirements based on index properties including percent fines and plasticity index. The methods utilizing the flexible wall permeameter have requirements based on hydraulic conductivity.

Table 1: ASTM Language Describing Test Method Selection Criteria

Evaluated System	**ASTM**	**Description**	**ASTM Language Describing the Appropriate Materials**
Soil	D2434	Constant Head	“disturbed granular soils with not more than 10 percent passing the 75-μm (No. 200) sieve.
	D5084	Flexible Wall	“hydraulic conductivity less than about 1x10-6 m/s (1x10-4 cm/s)” [providing head loss requirements are met]
Soil-Geotextile	D5101	Gradient Ratio (GR)	“plasticity index lower than 5” “For soils with a plasticity index of 5 or more, it is recommended to use ASTM D5567”
	D5567	Hydraulic Conductivity Ratio (HCR)	“hydraulic conductivity less than or equal to $5x10^{-2}$ cm/s”

In addition to differences in the testing apparatus, placement of the soil material varies between each of the test methods (Table 2). The methods of placement for the GR testing include slurry, water pluviation, and the dry method. For HCR testing, either undisturbed samples are utilized or samples are reconstituted/remolded in the laboratory. In some circumstances, CCR waste material may be deposited as slurry in the field. Thus, one would think that a GR test may be more appropriate for testing the material. This is complicated, however, when fine-grained particles often present in CCR materials migrate through the filters utilized in the manometer setup. The clogging of the manometer port filters can cause significant delays in the development of a stabilized response pressure at tap locations. These issues are not generally encountered when evaluating poorly graded and silt (not CCR silt sized particles) in the gradient ratio apparatus[6].

If the stress state and its effects on the hydraulic conductivity of the system are to be evaluated, this cannot be readily accomplished in the ASTM D5101 as the configuration is not intended to be loaded. In an HCR test, however, the effective stress on the sample can be increased following stability at a lower stress

Table 2: ASTM Language Describing Material Placement

ASTM	**ASTM Language Describing the Appropriate Materials**	**Soil Deposition / Installation**
D5101 (GR)	“silty soils, with permeabilities less than 10-3 cm/s”	Slurry
	“sandy soils, with permeabilities greater than 10-3 cm/s”	Water Pluviation
	“well graded soils or unstable soils that easily segregate”	Dry Method
D5567 (HCR)	In-situ Placement of Filter	Undisturbed Tube Sampling
	Compacted Fill	“Prepare specimens using the compaction method, predetermined water content, and unit weight prescribed by the individual assigning the test.

The saturated vertical hydraulic conductivity of coal ash can vary by several orders of magnitude with common values between 1x10^{-3} cm/s and 5x10^{-6} cm/s[5]. Rates of horizontal permeability in the field can vary even more widely. Given the relatively high anticipated head losses in the system, manometer complication issues, and the soil type in the installation, the HCR method is often found to be advantageous over GR testing for the filtration evaluation of CCR.

HCR TEST CONFIGURATION AND TESTING PARAMETERES

The HCR test consists of placing the retained soil atop the geotextile of interest. ASTM D5567 Section 8.1.4 stated to “Place the proposed drainage material (typically pea gravel, coarse sand, or geosynthetic drainage core) on the bottom plate”. In Table 3, several typical configurations for the material underlying the retained soil are presented.

Table 3: Typical Laboratory Configurations for HCR Testing

Configuration	**A**	**B**	**C**	**D**	**E**	**F**
Material Underlying the Retained Soil	Geotextile	Geocomposite	Geonet Component of Geocomposite	Geotextile	Geotextile	Geotextile Component of Geocomposite
Material in Contact with the Bottom Platen	Site-Specific Sand, Pea Gravel, etc.	-	Site-Specific Drainage Core	-	Generic Media – Soil or Plastic Spheres	Generic Media

Opinions regarding the correct means of setting up the profile to be used for HCR testing vary greatly between engineers. Often this selection is left to the discretion of the engineer. In some cases, the objective is to directly model the profile as it will exist in the field. For this case, the underlying soil, geocomposite, or drainage core / geonet component (Table 3, Configurations A through C) is included in the test setup. In other cases, the objective is to isolate and evaluate compatibility without regards to the underlying material (Table 3, Configurations D through E).

In addition to various profile configurations, the effective stress can also be varied in the flexible wall apparatus[5]. This testing is predominantly specified with an effective confining stress of 5 psi following the effective stress that is prescribed for testing GCL index flux and for testing the hydraulic conductivity of compacted clay liners. In other cases, the stresses used for testing can be used to model the anticipated stresses during cell construction and during landfill operation[5]. An additional approach is to perform the test at a low stress, then increase the effective stress and repeat the testing.

HCR MONITORING AND TEST TERMINATION

For low-plasticity retained silts, the hydraulic conductivity of the silt can lead to the use of a flexible wall permeameter and HCR testing procedures. In these cases, the system typically stabilizes relatively rapidly and can typically be evaluated within one to five days. For CCR, the material is fine grained and thus also requires the use of a flexible wall permeameter. Some of these materials undergo long-term secondary consolidation following pore pressure relief, where particle reorientation leads to the continued volume change. The continued volume change results in a system hydraulic conductivity that continues to decrease with time whether or not migration of the CCR material into or through the media occurs. ASTM D5567 termination criteria for HCR testing are presented in Table 4. For HCR testing of CCR, the point of termination is often a function of the hydraulic conductivity falling below a predetermined allowable design per ASTM D5567 - Section 5.8.2).

Table 4: ASTM D5567 Termination Criteria

Section	Language
8.5.1	A graph is generated that shows the hydraulic conductivity values plotted as a function of pore volumes of water passing through the specimen. The test may be terminated when the slope of this curve has become nearly horizontal for more than five consecutive pore volumes and the effluent water is relatively clear, indicating that a stabilized hydraulic conductivity has been achieved. The hydraulic conductivity is considered stable if the hydraulic conductivity values fall within +/-50 % of the mean value and the plot of hydraulic conductivity versus pore volumes shows no significant upward or downward trend during the final five pore volumes. Additionally, the ratio of measured outflow to inflow rate should be between 0.75 and 1.25.
8.5.2	The hydraulic conductivity… falls below a predetermined allowable design value.
8.5.3	The effluent does not become clear within the first 20 pore volumes, indicating that continuous piping of soil is occurring through the geotextile filter.

POST-TEST EXAMINATION

One can determine and report the system hydraulic conductivity over the duration of the test, but outside of suspended solids leaving the evaluated system, one can not readily evaluate the migration of the CCR material into or through the geotextile filter. Several common post-test observations are presented in Table 5.

Table 5: Post-Test Observations

Observed behavior(s)		**Applicable Laboratory Configurations (See Table 3)**
Separation	No filter cake formation / particle migration	A-E
	Filter cake formation at the interface with ready separation / non-observable intrusion	A-E
Intrusion	Into the Geotextile	A-E
	Into the Coarse Media	A, D, & E
	Into the Geosynthetic drainage Layer	B & C
	Full to bottom flatten	A-E
Piping	“Retained” soil through the geotextile and out of the system.	A-E

ACCEPTANCE AND REJECTION OF SYSTEM PERFORMANCE

The initial and final system hydraulic conductivities for individual HCR tests performed on CCR systems are plotted in Figure 1. The majority of these HCR tests that were conducted on CCR systems were taken to completion. Four of the presented tests were terminated prior to equilibrium, as the measured hydraulic conductivities reduced to less than the design hydraulic conductivities. For the tests that were taken to completion(system stabilization), the mean HCR at the end of testing was 0.62 and the median HCR was 0.74 with a minimum value of 0.06 and a maximum value of 1.

The gradient ratio value and the hydraulic conductivity value at the end of testing are often used as the principal criteria for the evaluation of compatibility. It should, however, be noted that, given stabilization, system hydraulic conductivity controls system performance.

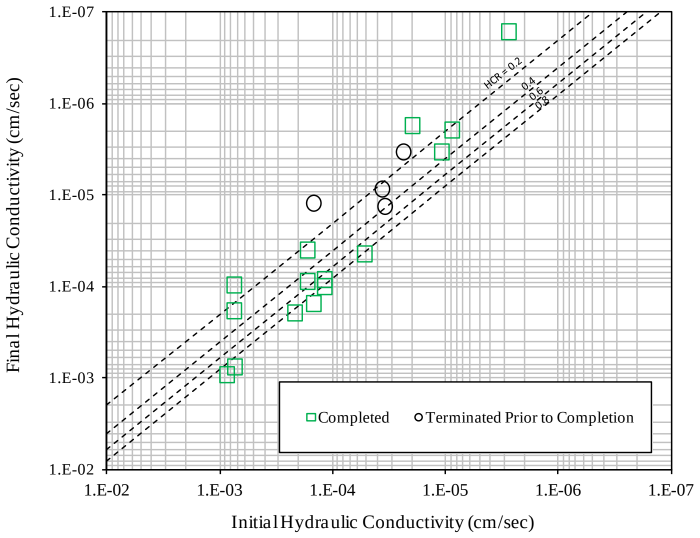


Figure 1: Final versus Initial Hydraulic Conductivity
for Completed and Terminated HCR Testing

HCR TEST DURATION AND PLANNING

The HCR test can take several weeks to complete. Adequate time should be budgeted for testing, accounting for the possibility of testing multiple materials if the initially selected material performs unsatisfactorily.

Testing duration is often discussed in terms of pore volumes of flow. The dry density and void ratio/space within CCR is, however, debatable given the potential for the presence of absorbed water. The expected duration of the test based on the initial system conductivity is a valuable tool in planning laboratory testing. Figures 2a and 2b present the final volume of flow versus the system hydraulic conductivity and the hours of flow versus the system hydraulic conductivity, respectively. Given the difficulty in determining weight-volume relationships for CCR materials, a rough estimate of the testing duration should be derived base on the initial hydraulic conductivity of the system noting that higher gradients are permitted for use in testing at lower hydraulic conductivities. In planning states, the hydraulic conductivity of the CCR itself can alternately be utilized as a tool for estimating the duration of testing. When considering the total duration of testing both index property testing (e.g. moisture-density, particle size analysis, etc.) in addition to back-pressure saturation time should be considered.

Figure 2: a) Pore Volumes of Flow for Stability and b) Hours of Flow for Stability

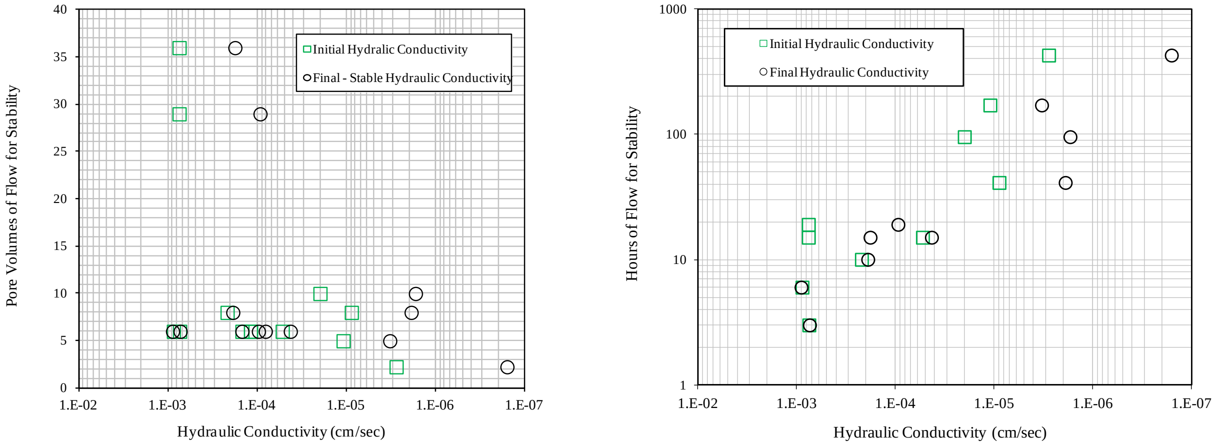


Figure 2: a) Pore Volumes of Flow for Stability and b) Hours of Flow for Stability

MATERIAL PROPERTIES OF CCR

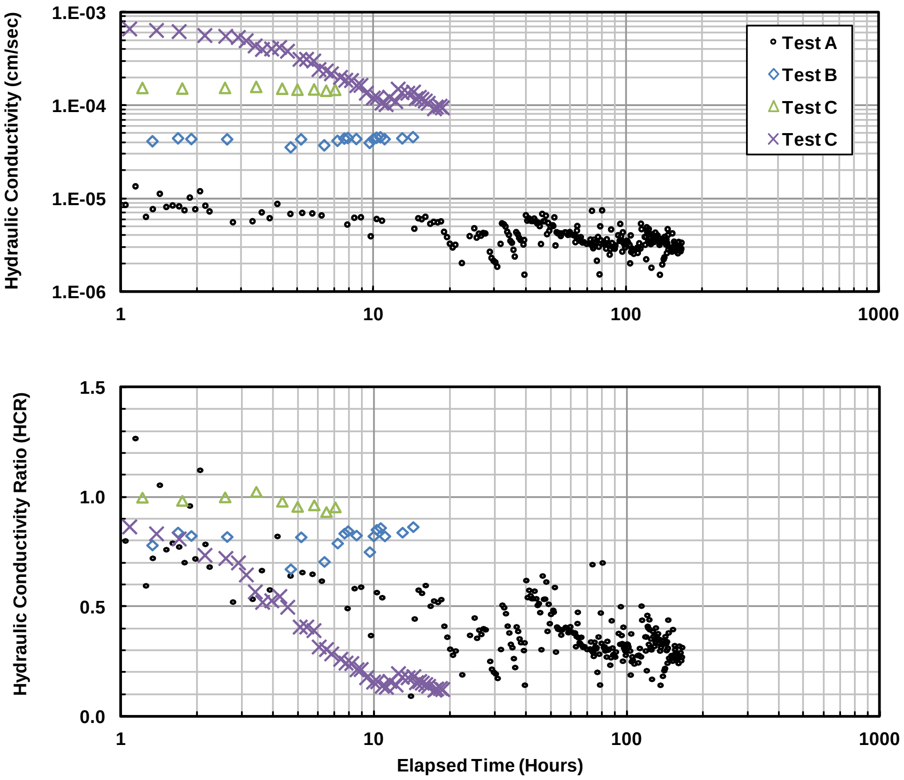
The choice of a testing method to evaluate the filtration compatibility of CCR materials with the leachate collection systems is complicated by the unique material properties of CCR. For the filter compatibility of natural soils, the choice of methods for the evaluation of filter compatibility has been largely dictated by the plasticity and hydraulic conductivity of the retained material. Typically, non-plastic to low plasticity soils (e.g. gravel and sand) have higher hydraulic conductivities, while more plastic, fine grained, materials have lower hydraulic conductivities (e.g. sandy clay, lean clay, fat clay, etc). Silts, however, often exhibit hydraulic conductivities that can require the use of a flexible wall hydraulic conductivity system. Like silts, CCR materials often exhibit hydraulic conductivities that can require the use of a flexible wall permeameter, but unlike silts have significant field capacities / are not freely draining and also exhibit time-dependent consolidation with often quick pore pressure dissipation and often significant and long secondary compression.

The moisture-density relationships for CCR can be difficult to define and testing can be difficult to repeat. In particular, mineral-bound water can lead to erroneous values of moisture content. One particular solution is to utilize a reduced temperature of sixty degrees centigrade (down from the standard 110 degrees) for determining the oven-drying moisture content, as noted in standard and modified Proctor testing (ASTM ASTM D1557). It has, however, been found that reduced temperature and even air-drying processes do not always yield repeatable results. As such, moisture-density testing of the coal ash byproducts should be performed in advance of the GR or HCR testing.

EXAMPLE EXPERIMENTAL FINDING FOR HCR TESTING OF CCR

A series of four different test series performed on four different combinations of CCR and a filter media are presented in Figure 3. These examples were chosen to illustrate the variability of the absolute value of the system hydraulic conductivities and the variability of the time dependent changes in system hydraulic conductivity. For HCR testing on silty soils, the termination criteria presented in Table 4 are often readily achieved. For CCR testing, meeting these termination criteria can be difficult and often testing terminations are client initiated. Given the difficulty in defining a pore volume for CCR given the issues with moisture content determination, it is recommended that various CCR materials are compared in terms of their behavior with time and not in terms of their behavior with pore volumes, noting that higher gradients are permissible when testing lower permeability systems. Appropriate gradients should be determined in advance through hydraulic conductivity testing of CCR alone when practical. With hydraulic conductivities on the order of 1x10^{-4} cm/s, this can be difficult in a flexible wall apparatus due to the presence of filter paper and porous stones in ASTM D54084 testing.

Figure 3 – Example HCR Test Series on CCR



CLOSING

To help ensure that the leachate collection system of a landfill is designed to meet the CCR Rule, laboratory compatibility testing of site specific material is essential. While multiple methods exist for evaluating compatibility within the laboratory, the HCR test is typically found to be the most appropriate.

The hydraulic conductivity of a CCR / filter system can vary over several orders of magnitude. The flow and time dependent performance of these systems can be evaluated via HCR testing. The choice of the profile within the HCR test varies between practitioners and may control the behavior of the system in a laboratory setting. If interpretation and completion of HCR testing is left to the interpretation of the engineer of record, and not specifically dictated, explicit instructions should be established with the laboratory in terms of the test setup. Clear communication of these instructions should be provided to the owner per a timeline. Upon completion of testing, a post-test visual evaluation of the specimen can allow for the observation of phenomena within the CCR / filter system that cannot be otherwise observed.

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REFERENCES

[1] ASTM International, ASTM D2434: Standard Test Method for Permeability of Granular Soils (Constant Head)

[2] ASTM International, ASTM D5084: Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter.

[3] ASTM International, ASTM D5101: Standard Test Method for Measuring the Filtration Compatibility of Soil-Geotextile Systems.

[4] ASTM International, ASTM D5567: Standard Test Method for Hydraulic Conductivity Ratio (HCR) Testing of Soil/Geotextile Systems.

[5] Semach, A.C., Zyche, G, Wolfe, W., and Butalia, T. Laboratory Analysis of Geocomposites for Use in Drainage Systems in CCP Landfills., *World of Coal Ash (WOCA) Conference 2011, Denver, CO..*

[6] Shan, H-Y, Wang, W-L, and Chou, W-L Effects of boundary conditions on the hydraulic behavior of geotextile filtration system, *Geotextile and Geomembranes*19, 2001, pp 509-527.