CONTRIBUTIONS TO THE ADVANCEMENT OF GCLS

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ABSTRACT

Geosynthetic clay liners (GCLs) became commonly used about the same time that Robert M. Koerner and his students and colleagues began studying them. Koerner's impact is noticeable in at least seven demonstrable ways: (1) Koerner thought of and coined the name "Goesynthetic Clay Liner," which received instantaneous industry acceptance; (2) Koerner has brought the GCL industry together to advance knowledge of GCLs and to develop testing and evaluative methods for GCLs, and was a critical factor in driving the industry toward consensus ASTM standards for GCLs; (3) Koerner wrote the first guidance document for construction quality control and assurance related to GCLs and their installation, thus advancing the industry's construction protocols; (4) Koerner personally directed many of the early, pioneering studies that defined the performance characteristics of GCLs; (5) Koerner's work on interface friction of GCLs at the EPA test plots in Cincinnati changed the way that GCLs are used on slopes and drove the industry toward using needle-punched geotextiles on both surfaces of GCLs that are deployed on relatively steep slopes; (6) Koerner developed criteria to compare and contrast GCLs with compacted clay liners, thus illuminating the criteria for selecting GCLs in waste containment systems; and (7) Koerner and his colleagues at the Geosynthetic Institute have provided invaluable leadership in disseminating information to manufacturers, practicing engineers, and regulators concerning the properties, use, design, and installation of GCLs.

INTRODUCTION

Robert M. Koerner has been a driving force and the premier leader in advancing technology related to Geosynthetic Clay Liners (GCLs). His contributions include developing the term "Geosynthetic Clay Liner," bringing the industry together to collaborate on developing industry standards, defining practices for construction quality control and construction quality assurance for GCLs, conducting pioneering research on the properties and characteristics of GCLs, leading a pioneering field study of slope stability at test plots in Cincinnati, developing criteria for comparing GCLs to compacted clay liners (CCLs), and providing leadership for continuing education. This paper will provide information about his contributions in these seven arenas.

THE GCL NAME

Robert Koerner first began to investigate GCLs in about 1990. At the time, there was no industry consensus on what these materials should be called. The terms in use included “bentonite mat,” “bentonite panel,” “prefabricated clay blanket,” “clay mat,” and others. In 1991, Koerner was struggling to identify a suitable name that was acceptable to all the GCL manufacturers and key organizations such as the U.S. Environmental Protection Agency. Consensus agreement could not be reached. Although some terms were acceptable to some or most, no term satisfied all. For example, the term “prefabricated clay blanket” is descriptive but was judged unsuitable because of the acronym “PCB.” Other terms, like “bentonite blanket,” failed to capture the essence of the material.

Koerner developed and coined the term “geosynthetic clay liner” (GCL) in October, 1991. The moment of realization was actually in Koerner’s automobile (the author was present), while Koerner was driving from Harrisburg, Pennsylvania, to Philadelphia. The term “geosynthetic clay liner” was descriptive because a GCL is a type of clay liner (compared to, say, a compacted clay liner). And the fact that the term starts with “geo-“ made the term a natural, fitting nicely with other materials whose names begin with “geo,” such as “geomembrane” and “geotextile.” And the acronym “GCL” was problematic in no known way.

The next day, Koerner (then director of the Geosynthetic Research Institute) faxed the proposed term to all key stakeholders, and no one objected. Almost immediately, within weeks, virtually everyone started using the term “geosynthetic clay liner.” The name stuck and replaced the other soon-to-be extinct terms for this material. That the entire industry could almost instantaneously change the name of their class of products to adapt to the term coined by Koerner speaks volumes to the range of his influence and respect for his views.

Within several years, especially as GCLs were compared with compacted clay liners, the phase “CCL” began to be used for compacted clay liner. The similarity in the terms, in a sense, is an accident, and in a sense is not because in creating the term “GCL,” one of the underlying thoughts was to view GCL as simply another type of clay liner. That acronyms for other types of clay liners, like CCLs, would ultimately be developed for their similarity to the term “geosynthetic clay liner” simply reflects the wisdom and good judgment of Koerner for selecting the GCL term in the first place.

BRINGING THE INDUSTRY TOGETHER TO DEVELOP STANDARDS

One of the many critical functions served by the Geosynthetic Research Institute (GRI), and now the Geosynthetic Institute, is to develop industry standards for testing and use of geosynthetic products, based on sound principles of science and engineering. In the early days of GCLS (i.e., late 1980s and early 1990s), there were no industry standards whatsoever for testing of GCLs, although there were some procedures from other industries for testing bentonite, such as the fluid loss test from the bentonite drilling fluid industry or the plate water absorption test for bentonite from the foundry industry. Without standard testing procedures, there was no way for users of products to specify materials or to ensure quality conformance. The industry simply could not advance without such standards. But at the time, the manufacturers were locked in battles with one another over the relative advantages of each manufacturer's products over other manufacturer's products. Progress was slow, if existent at all.

Robert Koerner's arrival on the GCL scene changed all that. He was able to convince the industry of the need to develop standards, and developed the first industry standards for tests such as free swell through GRI. With a remarkable intensity, the industry quickly developed numerous standards for GCLs. Among the more significant ones are:

- D5887, "Test Method for Measurement of Index Flux through Saturated Geosynthetic Clay Liner Specimens using Flexible Wall Permeameter"
- D5888, "Guide for Storage and Handling of Geosynthetic Clay Liners"
- D5889, "Practice for Quality Control of Geosynthetic Clay Liners"
- D5890, "Test Method for Swell Index of Clay Mineral Component of Geosynthetic Clay Liners"
- D5891, "Test Method for Fluid Loss of Clay Component of Geosynthetic Clay Liners"
- D5993, "Test Method for Measuring the Mass per Unit Area of Geosynthetic Clay Liners"
- D6072, "Guide for Obtaining Samples of Geosynthetic Clay Liners"
- D6102, "Guide for Installation of Geosynthetic Clay Liners"
- D6141, "Guide for Screening the Clay Portion of a Geosynthetic Clay Liner (GCL) for Chemical Compatibility to Liquids"
- D6243, "Test Method for Determining the Internal and Interface Shear Resistance of Geosynthetic Clay Liner by Direct Shear Method"

- D6495, “Guide for Acceptance Testing Requirements for Geosynthetic Clay Liners”

- D6496, “Test Method for Determining Average Bonding Peel Strength between the Top and Bottom Layers of Needle-Punched Geosynthetic Clay Liners”

- D6766, “Test Method for Evaluation of Hydraulic Properties of Geosynthetic Clay Liners Permeated with Potentially Incompatible Liquids”

- D6768, “Test Method for Tensile Strength of Geosynthetic Clay Liner”

Koerner also played a crucial role in the industry coming together by through his numerous talks and presentations at conferences, dissemination of information at short courses, and perhaps most importantly, informal but structured discussions with stakeholders (manufacturers, engineers, and regulators) that had the sole purpose of advancing the knowledge of GCLs, proper use of GCLs, and general advancement of the industry. Conferences such as the GCL conference for which the proceedings were edited by Koerner et al. (1995) proved invaluable in advancing the industry.

CONSTRUCTION QUALITY ASSURANCE AND CONTROL

A landmark contribution of Koerner is the EPA construction quality control/construction quality assurance document, first published as an EPA report (Daniel and Koerner, 1993) and later as an ASCE book (Daniel and Koerner, 1995). Koerner wrote the chapter on GCLs and was the driving force for the effort and the publications.

In this body of work, GCLs were defined as follows:

> “Geosynthetic clay liners (GCLs) are factory manufactured, hydraulic barriers typically consisting of bentonite clay or other very low permeability clay materials, supported by geotextiles and/or geomembranes which are held together by needling, stitching and/or chemical adhesives”

The guidance document covered the following topics:

- Types and composition of GCLs
- Manufacturing
- Handling
- Installation
- Backfilling, or covering

PIONEERING RESEARCH

Robert Koerner directed pioneering research that helped to define some of the critical parameters related to GCLs. The earliest of these studies was published by Harpur, Wilson-Fahmy, and Koerner (1992) and involved evaluation of the transmissivity of the contact zone between GCLs and geomembranes. The issue that was of concern was lateral spreading of liquid that passes through a small defect in a geomembrane, and then permeates through the bentonite within the GCL. The desired situation is excellent contact, limited lateral spreading (i.e., very small transmissivity in the interface zone), and minimal permeation through the bentonite. Koerner and his team found that relative behavior of different types of GCLs was about as expected, provided the first quantitative information on interface transmissivity between a geomembrane and GCL. These data have been used by many others to estimate leakage rates through geomembrane/GCL composite liners.

Koerner and Narejo (1995), which was also one of the very first articles of any kind published on the subject of GCLs in an archival journal. In this work Koerner and his student Narejo explored the question of how much soil cover was needed to protect a GCL from “squeezing” of hydrated bentonite from beneath the wheels of construction equipment. If inadequate cover was provided, the passing vehicle could leave a “rut” of thinned bentonite in the GCL, which could compromise the integrity of the material as a hydraulic barrier in the area of thinning.

To study the problem, Koerner and Narejo set up a laboratory “bearing capacity” test using the apparatus shown schematically in Figure 1. A 50-mm-diameter circular cylinder was loaded on a layer of sand, overlying a hydrated GCL. The condition of the GCLs was later observed and correlated with the thickness of sand separating the GCL from the loaded area. The key question was: how much thickness of sand (relative to the width of the loaded area) is needed to distribute the stresses to the point of minimal bentonite thinning? Typical results for one GCL are shown in Figure 2. The investigators found that once the thickness of sand equaled or exceeded about 50 mm (i.e., the diameter of the loaded area), no significant thinning of the bentonite occurred. This, when extrapolated to the field, would indicate that the thickness of protective sand should equal or exceed the width of the loaded area, e.g., the width of the tire of a large construction vehicle. The industry typically requires a soil thickness on the order of 300 to 450 mm (12 to 18 inches), depending on the specific site and anticipated equipment on the site. This study was one of the first examples of application of sound geotechnical engineering principles to the resolution of an issue involving GCLs.

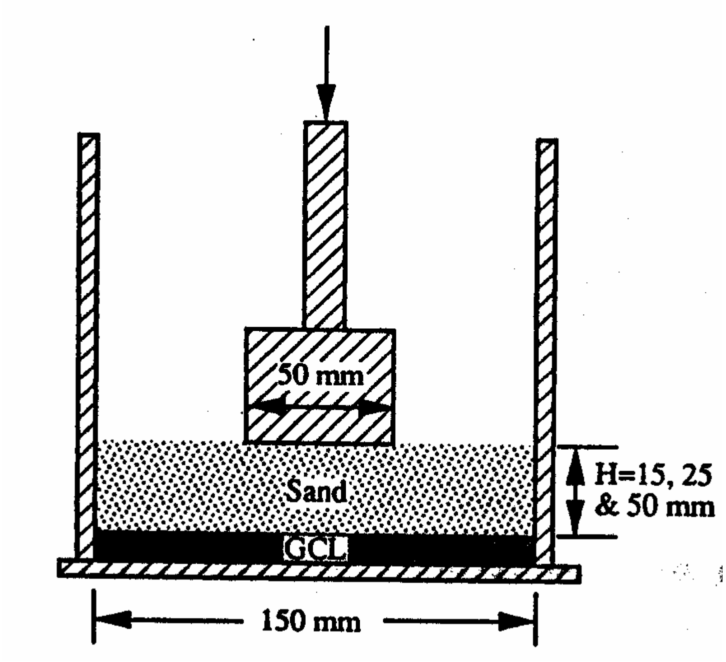


Figure 1. Test Arrangement to Study the Thinning of Bentonite beneath a Loaded Area (Koerner and Narejo, 1995)

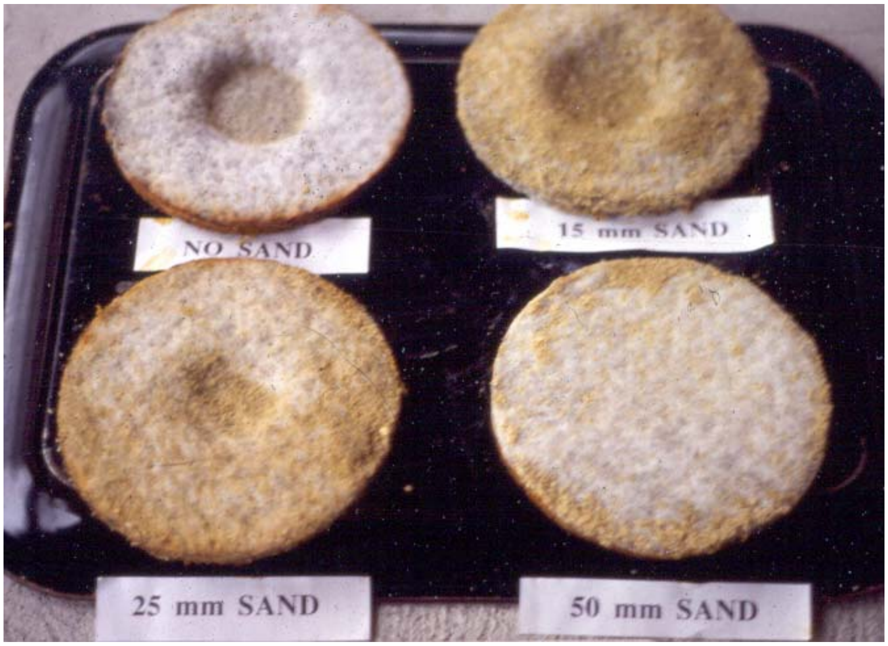


Figure 2. Results of Tests on Thinning of Bentonite beneath a Loaded Area for a Geotextile-Encased GCL (Koerner and Narejo, 1995)

Another example of an important research finding was the work on out-of-plane tension performed by Koerner, Koerner, and Eberle (1996). The work was an extension of a series of research projects employing a chamber for three dimensional straining of geosynthetics (primarily geomembranes), but in this case applied to GCLs. The test set-up is shown in Figure 3. As the pressure is increased, the GCL deforms. When the GCL ruptures, the flow rate increases dramatically, and failure occurs. The strain is calculated at failure from volume-strain relationships. Failure occurred at tensile strains of 10 to 22% (average = 16%). These results correlated extremely well with results that the author obtained with a very different testing method (LaGatta et al., 1997).

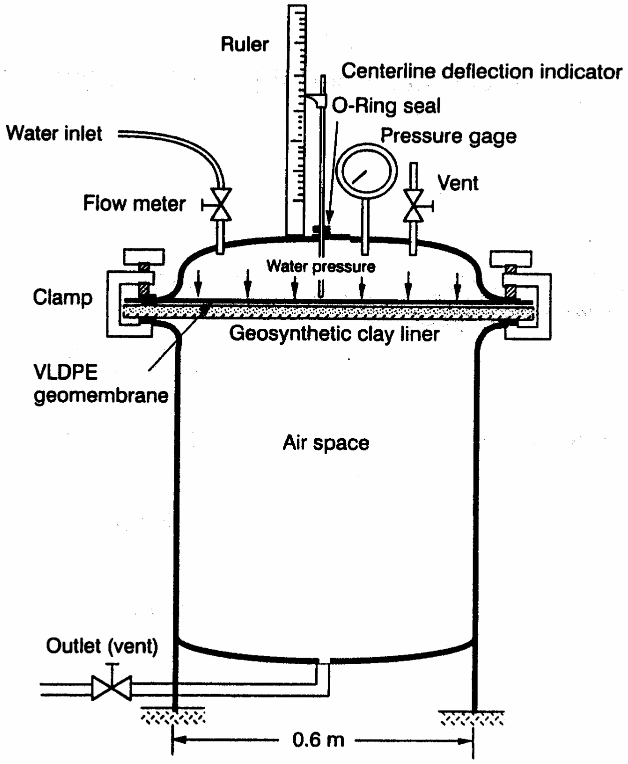
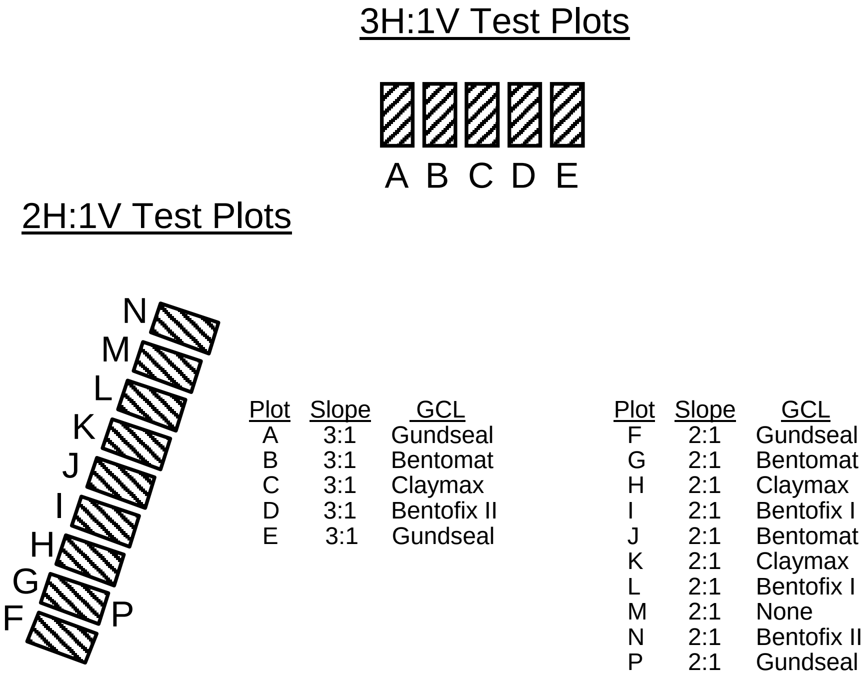


Figure 3. Out-of-Plane Testing Apparatus for GCL (Koerner et al., 1996).

CINCINNATI TEST PLOTS

Perhaps Robert Koerner's single largest project involving GCLs was associated with field test plots constructed in Cincinnati, Ohio, under sponsorship of the U.S. EPA. The study team was headed by Robert Koerner, who was the principal investigator for the project. Results from the multi-year project were described in several publications but are documented in detail in an EPA report (Bonaparte, Daniel, and Koerner, 2002).

Fourteen field test plots were constructed on 2H:1V and 3H:1V slopes, using different GCLs. The layout of the test plots is shown in Figure 4. A typical cross section is shown in Figure 5.



Plot	Slope	GCL
A	3:1	Gundseal
B	3:1	Bentomat
C	3:1	Claymax
D	3:1	Bentofix II
E	3:1	Gundseal

Plot	Slope	GCL
F	2:1	Gundseal
G	2:1	Bentomat
H	2:1	Claymax
I	2:1	Bentofix I
J	2:1	Bentomat
K	2:1	Claymax
L	2:1	Bentofix I
M	2:1	None
N	2:1	Bentofix II
P	2:1	Gundseal

Figure 4. GCL Test Plots at Cincinnati.

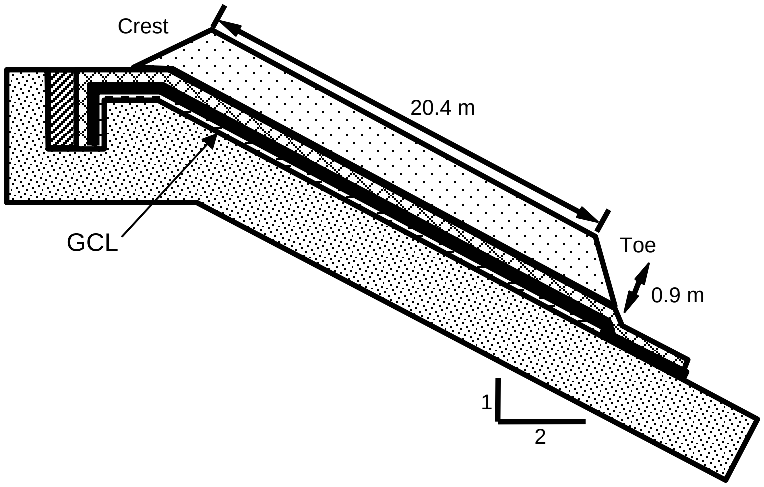


Figure 5. Typical Cross Section of a Test Plot at Cincinnati.

The rationale for selecting the 2H:1V and 3H:1V slope inclinations was as follows. The 3H:1V slope was selected to be representative of typical final cover systems for landfills in use today. In order to confirm that GCLs are safe against internal failure on 3H:1V slopes, it must be shown that they are not only stable, but are stable with an adequate factor of safety. For an infinite slope consisting of cohesionless interfaces with no seepage, the factor of safety (F) is:

$$F = \frac{\tan \phi}{\tan \beta} \qquad (1)$$

where ϕ is the angle of internal friction of the material (or the angle of interfacial friction, if failure occurs along an interface rather than internally within a material) and β is the slope angle. Many engineers design permanent slopes to have a minimum factor of safety for static loading of 1.5. The ratio of tan β for a 2H:1V slope to tan β of a 3H:1V slope is 1.5. Subject to the assumptions listed above, if a GCL is demonstrated to be stable on a 2H:1V slope (i.e., $F > 1.0$), the same GCL is demonstrated to be stable on a 3H:1V slope with $F > 1.5$. Therefore, the 2H:1V slopes were chosen to demonstrate internal stability of GCLs on 3H:1V slopes with $F > 1.5$. However, it was recognized that constructing 2H:1V slopes was pushing the GCLs to (and possibly beyond) their limits of stability, if not with respect to the internal shear strength the GCLs, certainly with respect to the various interfaces within the system and perhaps the subsoils, as well.

Three types of GCLs were used: geotextile-encased, needle-punched GCLs (several different manufactured GCLs of this type were used); a geotextile-encased, stitch-bonded GCL; a geomembrane-supported GCL. Table 1 summarizes the type of GCL installed in each plot, the targeted and actual inclinations of the slopes, and the dimensions and cross section of each test plot.

The test plots were observed for over 4+ years. All test plots were initially stable, but over time as the bentonite in the GCLs became hydrated, three slides (all on 2H:1V slopes) involving GCLs have occurred. Two examples are shown in Figure 6. One slide involved an unreinforced GCL in which bentonite that was encased between two geomembranes unexpectedly became hydrated. The other two slides (Figure 6) occurred on 2H:1V slopes at the interface between the woven geotextile components of the GCLs and the overlying textured HDPE geomembranes.

The experience from these test plots led to several conclusions of practical significance to engineers. At the low normal stresses associated with landfill cover systems, the interface shear strength is generally lower than the internal shear strength of internally-reinforced GCLs. The key (weakest) interface, should it exist, will typically be between a woven geotextile component of the GCL and the adjacent material, which in this case was a textured HDPE geomembrane. The interface strength may be low in part because of the tendency of bentonite to extrude through the openings in the relatively thin, woven geotextile and then into the interface as the GCL hydrates. Design engineers were encouraged to consider GCLs with relatively thick, nonwoven geotextile components in critical situations where high interface shear strength is required. Indeed, the industry shifted its emphasis to these types of materials for GCLs on slopes as a result of these field test results.

Figure 6. Examples of Slides at Cincinnati Test Plots.

Current engineering practice for evaluating the stability of GCLs on slopes is to conduct direct shear tests and then to use limit-equilibrium methods of slope stability analysis to calculate factors of safety based on the results of those tests. The experience from the test plots has validated this process. All three test plots that slid had calculated factors of safety of less than 1.0. All remaining (stable) test plots had factors of safety greater than 1.0. It is a testament to the technology of GCL testing, and the fundamentals of slope analysis and engineering, that the documented field performance substantiates the current design process. Based on the experience from this study, the investigators concluded that 2H:1V slopes are too steep to be stable with a factor of safety normally considered adequate, but 3H:1V slopes (depending on materials) can be constructed with factors of safety of at least 1.5 for the conditions existing in this project, and probably many others, as well.

Koerner's contributions to the industry from this project were: (1) the need for needle-punched textiles as components to GCLs on steep slopes became readily apparent, and GCL manufacturers placed greater emphasis on this fact; (2) the consequences of bentonite becoming hydrated in unreinforced GCLs placed on steep slopes was clearly demonstrated; (3) the testing and analysis methodology in use by the engineering profession was validated; and (4) a confidence level was established for GCLs used on slopes inclined at 3H:1V or flatter. This project was unusually large and significant, and represents one of Robert Koerner's most significant professional contributions.

COMPARING GCLS TO CCLS

Landfill regulations typically require composite liners containing both geomembranes and compacted clay liners, in one or more composite liner systems. There are many potential advantages and some disadvantages associated with substituting a GCL for a CCL. In order to provide a rational basis for making such evaluations, Robert Koerner let the development of so-called "GCL equivalency criteria," which provided a framework for comparing GCLs with CCLs. The recommendations were published in several venues, e.g., Koerner and Daniel (1995), and have been widely used throughout the world.

CONTINUING EDUCATION

Robert Koerner is one of the most prolific individuals in the world in terms of disseminating information related to civil engineering. He is the one person who has done the most to educate professionals about geosynthetics and about GCLs. The output includes publication of articles relating to technology advances aimed at a broad audience (e.g., Koerner and Daniel, 1992, Koerner, 1996; and Koerner, 1997). He has taught in hundreds of short courses, is author of the popular book *Designing with Geosynthetics*, and had created comprehensive, web-based instructional units within the Geosynthetic Institute. He has been remarkably focused and determined professional who has sought to education the profession. And more than anyone else, he has contributed toward this goal. By the author's estimate, he has personally educated and instructed 50,000 to 100,000 professionals on the proper use of GCLs. His reach and impact are unique among all civil engineers known to this author.

CONCLUSIONS

Robert M. Koerner has been instrumental in some of the most significant developments related to GCLs. His impact is noticeable in at least seven demonstrable ways: (1) Koerner thought of and coined the name “Goesynthetic Clay Liner”; (2) Koerner has brought the GCL industry together to advance knowledge of GCLs, and led industry toward consensus ASTM standards for GCLs; (3) Koerner wrote the first guidance document for construction quality control and assurance related to GCLs; (4) Koerner personally directed many of the early, pioneering studies that defined the performance characteristics of GCLs; (5) Koerner’s work on interface friction of GCLs at the EPA test plots in Cincinnati changed the way that GCLs are used on slopes and drove the industry toward using needle-punched geotextiles and needle-punched GCLs on relatively steep slopes; (6) Koerner developed criteria to compare and contrast GCLs with compacted clay liners; and (7) Koerner has been the single most significant person in disseminating information to the industry. In summary, Robert M. Koerner is the most important leaders in the early development and evolution of the GCL industry. The GCL industry is demonstrably better as a result of the leadership of and contributions by Robert M. Koerner.

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