Georgia Tech Sponsored Research

Project	E-20-663 a D7684	
Project director	Dove	Joseph 44
Research unit	CEE	
Title	Rational Design of Geomembrane Surface Texture for Infrastructure Applications	
Project date	3/31/2001	

Final Report for Period: 05/1998 - 12/2000

Submitted on: 04/09/2001

Principal Investigator: Dove, Joseph E.

Award ID: 9800291

Organization: GA Tech Res Corp - GIT

Rational Design of Geomembrane Surface Texture for Infrastructure Applications

Project Participants

Senior Personnel

Name: Dove, Joseph
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student

Name: Johnson, Max
Worked for more than 160 Hours: Yes
Contribution to Project:
Max worked as a Graduate Ressearch Assistant on the project and prepared a written thesis for partial fullfillment of his degree requirements.

Undergraduate Student

Name: Booth, Angela
Worked for more than 160 Hours: Yes
Contribution to Project:
Angela worked under an REU to collect surface characterization data for geomembrane products. Her work was instrumental in obtaining the basic data base for analysis of surface texture variation.

Name: Jarrett, James
Worked for more than 160 Hours: Yes
Contribution to Project:
Brad was an Undergraduate Research Assistant supported on this project, an REU, and awards from Georgia Tech.

Organizational Partners

GSE Lining Technology, Inc.
GSE is the GOALI partner for the project. They provided geomembrane products, technical leadership in polymer processing and geomembrane production, and implemented surface characterization techiques.

Other Collaborators or Contacts

Dr. Mark Wayne, Tensar Earth Technology, Inc., Atlanta, GA
- Characterized the surfaces of a new Geogrid product under development

Mr. Jon Luellen, URS Corporation, San Jose, CA and Buffalo, NY
Mr. Rob Swan, GeoSyntec Consultants, Atlanta, GA
- Worked with these engineers to design a 'sacrifical' interface for protecting a landfill liner system against earthquake-induced

deformations.

Activities and Findings

Project Activities and Findings: (See PDF version submitted by PI at the end of the report)
Project Training and Development: (See PDF version submitted by PI at the end of the report)
Research Training:
The project supported one graduate student and two undergraduate students (in addition to REU supplement and funding for one student from the Georgia Tech Materials Council). These students attained primary skills in surface characterization and laboratory interface shear testing.

The students also learned about the area of geosynthetics, and how these materials are manufactured. For instance, the graduate student (Mr. Johnson) and the PI traveled to the industry partner's manufacturing facility and were given training in the various processes used to produce geomembranes. This knowledge is directly transferable to engineering practice, and gives the student a unique set of skills. Mr. Johnson is now in engineering practice.

The undergraduates learned a great deal about how to conduct research. This includes topics such as finding and reading technical papers, experimental design, record keeping and data management, error minimization, and technical presentations (oral and written). Mr. Jarrett worked with the PI on two publications, and gave a technical presentation on his research to the Georgia Tech Materials Council. This required organizing the data, using software to plot the results, and using additional software to make presentation quality figures.

The PI feels that the research experience was instrumental in convincing the undergraduates to pursue graduate studies. Mr. Jarrett was awarded a NSF Graduate Fellowship and elected to pursue his graduate studies at Stanford University. Ms. Booth is a graduate student at Georgia Tech.

Outreach Activities:
The PI introduced small groups of minority students visiting Georgia Tech to this work on two occasions. The students were part of a program to encourage minorities to pursue graduate education. On tours of the geotechnical laboratories, students were shown how surface topography is measured and how the data is useful in practice.

Journal Publications

Dove, J.E. and Jarrett, B.J., "'Application of Geotribology to Systematic Evaluation of Interface Behavior'", *ASCE Journal of Geotechnical Engineering*, p. , vol. , ().) Accepted
Dove, J.E. and Frost, J.D., "'Peak Interface Friction Behavior of Smooth Geomembrane-Particle Interfaces'", *ASCE Journal of Geotechnical Engineering*, p. 544, vol. 125, (1999).) Published
Dove, J.E. and Johnson, M.L., "'Surface Characterization by Stylus Profilometry'", *Geotechnical Testing Journal, ASTM.*, p. , vol. , ().) In advanced preparation

Books or Other One-time Publications

Johnson, M.L., "Characterization of Geotechnical Surfaces by Stylus Profilometry", (2000). *Thesis*, Published
Bibliography: Master of Science Thesis, School of Civil and Environmental Engineering, Georgia Institute of Technology

Web/Internet Sites

URL(s):

Description:

Other Specific Products

Product Type: Data or databases

Product Description:
We have developed a data base of surface topography for co-extruded geomembrane produced by GSE Lining Technology, Inc.

Sharing Information:
This data was published in the conference paper:

Dove, J.E., Adams, M.W., and Johnson, M.L., 2001. 'Manufacturing Variability of Coextruded Geomembrane Surface Texture', Proceedings of Geosynthetics 2001, IFAI, Portland, OR, February 2001, pp. 823-834.

Contributions

Contributions within Discipline:
This project has made contributions in the geosynthetics, soil mechanics, and material characterization sub-disciplinary areas of geotechnical engineering. As discussed below, contributions have been made in advancing basic knowledge and in application to practical problems.

Geosynthetics

The geosynthetics industry is one of the largest segments of the geotechnical economy. It has traditionally been a leader in developing and implementing creative products and ideas. This project has contributed to basic understanding of soil/geomembrane strength and deformation behavior by:

1. Development of surface characterization methods that allow quantitative description of geomembrane surfaces. One key advantage of the profilometry method developed in this project over point measurements of asperity height is that it provides spatial as well as height information.
2. Using surface characterization methods to create a database for the variability of a geomembrane product. With this technology and information, the industry partner can better monitor their production process, develop new products, and find new market areas. This database can also be used by engineers in preparing designs such that variations in interface strength can be anticipated. The sensitivity of interface strength to changes in texture is an urgently needed research topic.

Soil Mechanics

A systematic study of the influence of topography on interface strength is a contribution to the soil mechanics field. It was shown that the optimum topography of a surface is related to the dilation angle of Ottawa sand and glass bead soils (see 'Findings' section). This result suggests that surfaces could be optimized in a plant to meet site conditions or a material selected for a project. Research is needed to further generalize this result to other materials.

Material Surface Characterization

The rock mechanics sub-discipline of geotechnical engineering has utilized surface characterization methods for rock fracture and joint surfaces. However, the use of surface characterization in soil mechanics is new. The 'Findings' section discusses the advances in surface characterization for soil mechanics made during this project.

Contributions to Other Disciplines:

Contributions to Human Resource Development:
As discribed in the 'Project Training and Development' section, two undergraduate students were mentored on this project. Both students have continued in graduate studies. One student received an NSF Graduate Fellowship and is now attending Stanford University.
Contributions to Science and Technology Infrastructure:
See 'Findings' and 'Contributions' (to discipline) sections.
Beyond Science and Engineering:

Categories for which nothing is reported:

Contributions: To Any Other Disciplines
Contributions: Beyond Science or Engineering

Research and Education Activities

The primary goals of this two-year collaborative university-industry research program were to:

Goal 1. Develop methods to characterize the surface topography of geomembranes and other construction materials;
Goal 2. Use the above surface characterization method and the results of laboratory interface shear tests to uncover the mechanisms that control on interface shear behavior. Base on these fundamentals, develop design guidance for selecting optimal combinations of surface texture (roughness) and soil grain size; and
Goal 3. Transfer the results to industry.

The direct benefits to industry from this research include: (1) the ability to rapidly prototype construction materials as new applications arise; (2) improved methods of manufacturing quality control; (3) a method to facilitate quality assurance at the construction site; and, (4) development of techniques for quantifying roughness of geomembrane and other civil construction surfaces.

Activities conducted to achieve these goals are discussed below.

Goal 1.

A comprehensive study was conducted to develop a surface characterization method that is applicable to geomembranes and a wide range of construction materials. This included reviewing literature in the field of surface metrology, using a stylus profilometer to measure the surface topography of a large number of geomembranes and machined surfaces; and, development of normalized parameters that relate physical behavior of interface systems to surface and material geometry.

Surface texture parameters evaluated included Average Roughness, R_a; Peak to Valley height, R_t; Average Slope, Δ_a; Average Wavelength, λ_q; Skew, S_{sk}, Kurtosis, R_{ku}; Average Peak Spacing, S; and, Average Spacing, S_m.

Goal 2.

The fundamental question addressed in this phase of the project was: "how does surface topography control the strength-dilation behavior of a soil/construction material interface system"? Stated another way, this phase of the project sought to determine if steady-state concepts of soil mechanics applied to interface systems. By answering this question, the underlying principles governing behavior could be determined.

A series of surfaces with regular, repeating, anisotropic texture patterns were precision machined from aluminum stock. Approximately 350 interface shear tests were conducted using Ottawa 20/30 sand as the soil material. Test variables included asperity height, spacing, and slope. Other test parameters were held constant.

A second series of interface shear tests were conducted on high density polyethylene surfaces created by press-molding texture patterns against selected ideal surfaces. A third series of tests were conducted to relate the ideal surface data to production geomembrane surfaces. In this series, textured geomembrane products were obtained from the industrial collaborator.

In all tests, surface topography was measured with a stylus profilometer. Surface roughness parameters were normalized with respect to the soil grain diameter.

Goal 3.

The industry Co-PI was actively involved in nearly all phases of the research. Two seminars were given by the academic PI and graduate students at the headquarters of GSE Lining Technology, Inc. in Houston, TX. These seminars were attended by the industry partner's materials engineering, production and sales executives. During these meetings, research results were presented and the assessed in terms of how they met the industry partner's project goals. Detailed discussions regarding the practical significance of the results to industry in general were typical.

The industry Co-PI served as a thesis committee member for a graduate student working on the project. He was also given instruction in the surface characterization technique while visiting in the Georgia Tech Geosystems laboratories.

Major presentations by the academic PI included:

"Tribology in Geotechnical Systems", Poster presented at Tribology on the 300th Anniversary of Amontons' Law, Materials Research Society Workshop, San Jose, CA, June, 1999.

"Geometric and Spatial Parameters for Analysis Of Geomembrane/Soil Interface Behavior", Geosynthetics '99, Boston, Massachusetts, February, 1999.

"Manufacturing Variability of Coextruded Geomembrane Surface Texture", Geosynthetics 2001, Portland, Oregon, February, 2001.

"Workshop on Surface Characterization", Geosynthetics 2001, Portland, Oregon, February, 2001.

"Introduction to Surface Characterization", National Capital Section of ASCE Geotechnical Seminar, Tysons Marriott, Vienna, Virginia, April, 2001.

Research Findings

Surface Characterization

Surface characterization is the process of measuring the topography of a material surface for the purpose of quantifying "roughness" through computation of standardized parameters. In this phase of the project, a practical surface characterization method was developed that is applicable to a range of construction materials.

A literature review and discussions with mechanical engineering researchers was conducted to evaluate available techniques to record surface topography and to determine their suitability for construction material surfaces. It was concluded that stylus profilometry has distinct advantages over other surface analysis methods for construction materials. The stylus profilometer mechanically traces a 2-dimensional surface profile the topography of a surface. Advantages of this system include: 1) rapid measurement and analysis; 2) non-destructive assessment of the surface; 3) measurement of actual physical surface features (contact technique), and (3) use of a standard instrument that is used in other engineering disciplines.

An extensive study was conducted to establish recommendations for the length and number of profiles necessary to provide representative values of roughness parameters with an acceptable degree of variation. It was found that profile length should be a minimum of 3 texture repeat units. Texture repeat units are the fundamental size of one cycle of texture and arise on relatively anisotropic manufactured surfaces due to production processes. The first major peak of the autocorrelation function of a profile (Figure 1a) or the minimum of the structure function (Figure 1b) was shown to provide unbiased estimates of repeat unit length. Repeat unit lengths determined analytically agreed with manual measurements made by 10 different individuals. For purely random, isotropic surfaces, there is no repeat distance and any profile length is theoretically permissible. The repeat unit lengths range from 7 to 13 mm for the textured geomembrane surfaces used in this study.

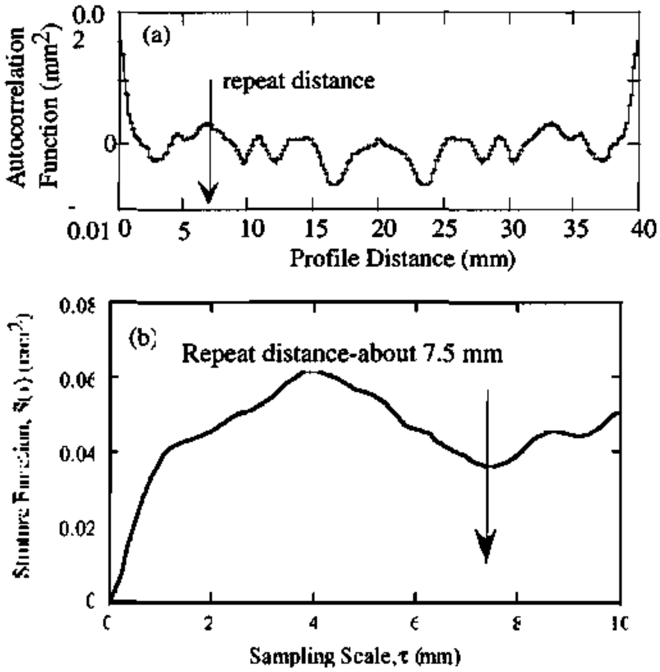

Figure 1. Analysis of Repeat Unit Length for Geomembrane: (a) by Autocorrelation, (b) by Structure Function.

It was concluded that a 40 mm profile length incorporates 3 or more repeat units, depending on the surface. A profile length of 10 mm was found to be adequate for homogeneous, smooth surfaces. The results also suggest that a minimum of four randomly located profiles is necessary to capture the texture variation of most surfaces. However, only one profile is required when the surface is purely homogeneous.

Surfaces can be visualized as a series of superimposed waves of varying wavelengths. As such, signal analysis methods can be used to eliminate unwanted wavelengths and decompose the texture into individual component wavelengths. The results of studies performed using high and low pass filters show that surface parameters and profiles vary according to the type of filter being applied and type of surface being measured. By applying filters with cutoff wavelengths near the median soil grain diameter, only texture that interacts with the opposing material (soil, geotextile) and influences interface behavior remains. Preliminary results suggest a linear relationship exists between a spacing parameter and interface strength (Ottawa 20/30 sand) results. If this proves to be correct and sufficiently general, the influence of topography on interface strength might be easily inserted into geotechnical analysis codes. Additional research is needed to fully explore this important result.

The surfaces used in this study model most construction materials, as they are typically anisotropic. Orientation of the texture with respect to shear direction is extremely important, especially in design of landfills. An investigation to quantify the changes of surface parameters with changes in surface orientation concluded that there was little change in height parameters as the surfaces were rotated from the machine direction to the cross-machine direction. However, the study revealed that spacing increases significantly as the orientation of the surfaces was varied up to 90 degrees from the manufacture direction (machine direction). The influence of spacing on the strength of interfaces will be discussed in the next section.

A procedure for characterizing geomembrane surfaces was developed that accounts for inherent inhomogeneity of the surface texture. For any given material sample, only one set of four profiles is required when the surface of interest is purely homogenous. However, in the event that a texture is pseudo-homogenous or non-homogenous, additional sets of four profiles should be taken in order to account for these areas. The aggregate value of any surface parameter, P_{agg}, may be area-weighed as in the following equation:

$$P_{agg} = \frac{P_1A_1 + P_2A_2 + \ldots + P_nA_n}{A_1 + A_2 + \ldots + A_n}$$

where P_1, P_2 and P_n are the values of the surface parameter over areas A_1, A_2 to A_n. The areas, A_1, A_2 to A_n, are determined to have differing degrees of texture where n represents the n^{th} area of texture on the surface. Values of P_n are averages of a minimum of four, 40 mm long profiles. If the sample is homogenous, then P_{agg} would equal P_1, and only one profile is necessary.

The profile lengths taken in different areas should correspond to the repeat unit length inherent in that particular area on the sample surface. Note that it is possible to have the same repeat length with different texture areas, since the repeat length is a function of the spacing parameters only.

It was found that Average Roughness (R_a), Average Slope (Δ_a), Average Spacing (S_m), and Average Wavelength (λ_q) parameters can be used to relate geomembrane texture and grain size of dense Ottawa 20/30 to interface performance. The stress-dilatancy response observed in interface shear tests was correlated to average slope parameters. Interface shear response is discussed in more detail below.

Interface Shear Behavior

Force transmission between a structural system and surrounding earth material occurs through relative displacement at the interface. An understanding of how surface geometry influences interface behavior is required to develop a comprehensive interface model for soil-structure analyses, and to develop interface design methods. A systematic investigation to quantify the influence of surface to soil particle relative geometry on interface stress and volume change response was conducted. Approximately 350 interface direct shear tests were conducted using Ottawa 20/30 sand and glass beads. Surfaces were machined from aluminum in anisotropic patterns with known root spacing, asperity spacing, asperity height, and asperity slope.

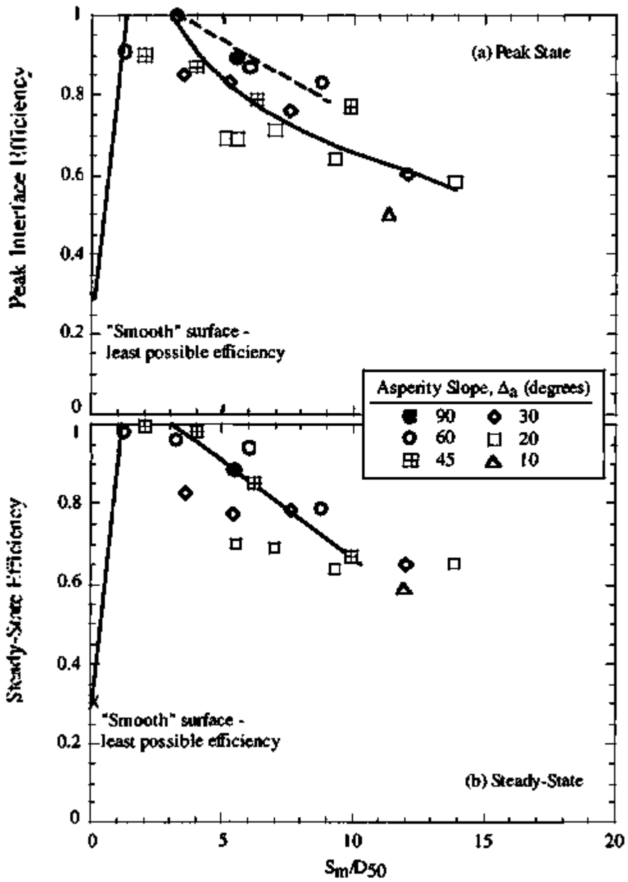

Figure 2. Influence of Surface Geometry on Interface Strength: a) Peak State; b) Steady State

The results shown in Figure 2 suggest that maximum interface efficiency for these materials is achieved for at an asperity spacing to median grain diameter ratio of between 1.0 and 3.0, with a asperity height to median grain diameter ratio greater than about 1.0. An asperity slope of 50 degrees or greater yields maximum efficiency for any given asperity spacing or height. The results suggest that interface behavior is governed by predictable geometric and mechanical relationships. Additional research is needed to verify these relationships for well-graded soil materials and geotextiles, and more complex manufactured surfaces.

The conceptual interlocking models of interface behavior suggest that dilation should be related to asperity slope. Figure 3a shows that interface dilation response is controlled by asperity geometry. Increasing asperity slope causes increased dilation with the upper bound equal to the dilation angle of the granular material tested alone. Figure 3a indicates that, in general, greater interface dilation angles are observed only at lower values of asperity slope for Ottawa 20/30 sand which has greater angularity than the glass beads. Dilation angles become similar at greater asperity slopes. Figure 3b shows measured peak interface friction angles (δ_p) and those predicted using the relationship:

$$\delta_p = \delta_{ss} + \psi,$$

where δ_{ss} is the steady-state interface friction angle and ψ is the interface dilation angle. The good agreement between measured and predicted peak friction angles demonstrates that: (1) critical state concepts apply to interfaces and (2) asperity geometry controls dilation which, in turn, controls strength.

Fundamental Interface Behavior

The above results suggest soil mechanics principles can be used to understand interface behavior when the topography/soil grain relative size promotes dilation. Jewell and Wroth (1987) performed experiments in direct shear on sand to examine the behavior of soil reinforcing with extensible and inextensible elements placed at various orientations to the shear plane. Maximum benefit of the reinforcement was attained when the reinforcing element was parallel to the direction of principal incremental tensile strain. The principal extensional incremental plastic strain is directed at an orientation of 45+ν/2 to the rupture surface, where ν is the dilation angle of the soil tested alone in shear. For the materials used in their experiments, this optimum orientation was found to be approximately 60 degrees to the horizontal.

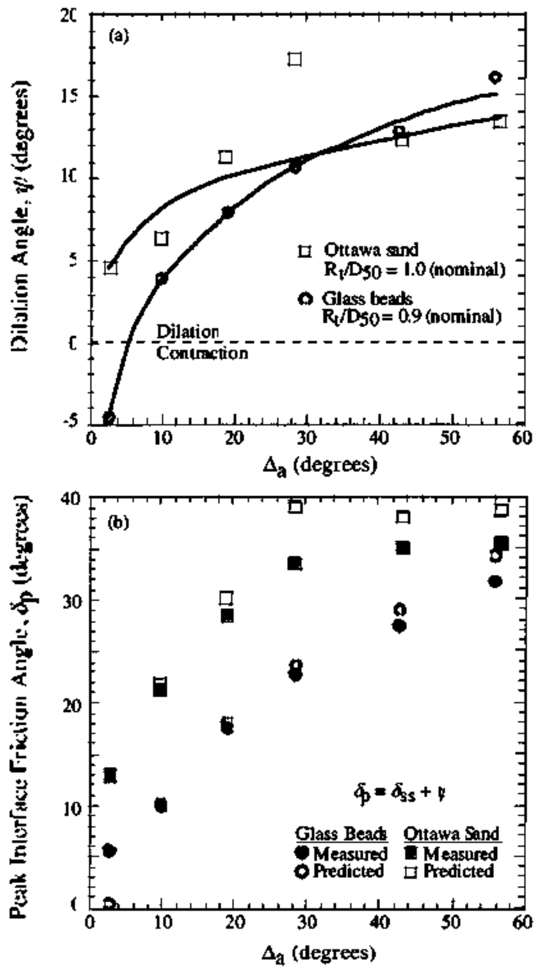

Figure 3. Dilatancy of Ideal Interfaces: (a) Dependence of Dilation Angle on Average Asperity Slope, (b) Measured and Predicted Peak Friction Angles. Root Spacing = 0 for all surfaces.

It was found that the incremental extensional plastic strain is orientated about 50 degrees from the horizontal at peak state for the materials used herein. This value is in agreement with the orientation for greatest efficiency based on findings from the interface shear tests. Surfaces with asperity slopes greater than or equal to 50 degrees restrain lateral translation of particles at the interface thus allowing greater shear stress to be mobilized than surfaces with smaller asperity slope angles. As the shear stress reaches the peak strength of the granular material, the principal stresses have reached their maximum obliquity positions and a shear band forms just above the interface with a corresponding friction coefficient equal to that of the granular material. It is expected that variables controlling soil strength would control interface strength for surfaces having asperity slopes of this orientation.

The critical asperity slope required for maximum efficiency found in this study is slightly less than the optimal angle of reinforcing found by Jewell and Wroth (1987), as it is controlled by dilation angle. It is not known at this time if soil with a greater dilation angle would have a greater critical asperity slope.

Maximum efficiency cannot be developed on these surfaces with asperity slopes less than about 45+v/2. In this case, partial soil strength mobilization occurs simultaneously with translation of grains at the interface as if it were a wavy surface. Particle translation over the surface is impeded if the small-scale relative roughness at the grain level restricts movement. Additional research to determine directions of grain movement during shear would confirm the above expectations.

Industry Uses

The results of this research are directly transferable to the geotechnical engineering industry. Uses include design of optimized interfaces, manufacturing quality control, field quality assurance, product improvement, and development of design tools.

An example of many of these uses is in the design of landfills. One major concern in landfill cell design has to do with how reliably the range of interface shear strengths between a textured co-extruded HDPE geomembrane and a specific type of cushion geotextile could be predicted to occur and be achieved in cells to be constructed over several years. In order to optimize liner system design, the range of friction angles for this interface is relatively narrow (within a few degrees). Until now, designers and contractors have little information regarding the variability of texture in a geomembrane, which has been shown above to control strength. Repeated similar texturing in the membrane will maintain interface strength within the design range. However, variation in texture could result in lower strengths.

The ability to specify and control texture for future designs is desired by practitioners and contractors. One step toward this goal is for producers to establish ranges of texture for their products. This could help ensure that the desired degree of texturing, therefore strength would be obtained during cell construction projects, especially if different contractors are involved who use geomembranes manufactured by different manufacturers. Engineers could verify the texture in the field and have an improved degree of confidence in the constructed facility.

Toward establishing a database on the variability of co-extruded textured geomembrane product, a long-term study was performed in conjunction with the industry partner to ascertain changes in geomembrane surface texture over time and manufacturing line. Specimens of two coextruded textured high density polyethylene geomembrane products were sampled from two manufacturing lines over an eight-month period. Surfaces were characterized using parameters obtained from profilometer traces. An example of the results are shown in Figure 4.

For the materials and manufacturing processes used, the results show that surface texture remained within discernable ranges that have not previously been defined for coextruded geomembranes. Coefficients of variation of the roughness parameters V(x) range from 14.2 to 29.4 percent and are comparable to coefficients of variation for other geotechnical design parameters.

The practical significance to the geotechnical community from this study is in showing that the manufacturing process for the materials used produced coextruded geomembranes with definable bounds of texture over the duration of the project. The profilometry method was shown to have the capability to quantify this variability for quality control purposes. A database of manufacturing data could be used to determine if the texture of a geomembrane sample is within normal ranges of variation for the manufacturing process and manufacturing equipment. This use requires that an acceptable variation from the mean be established (quality limit).

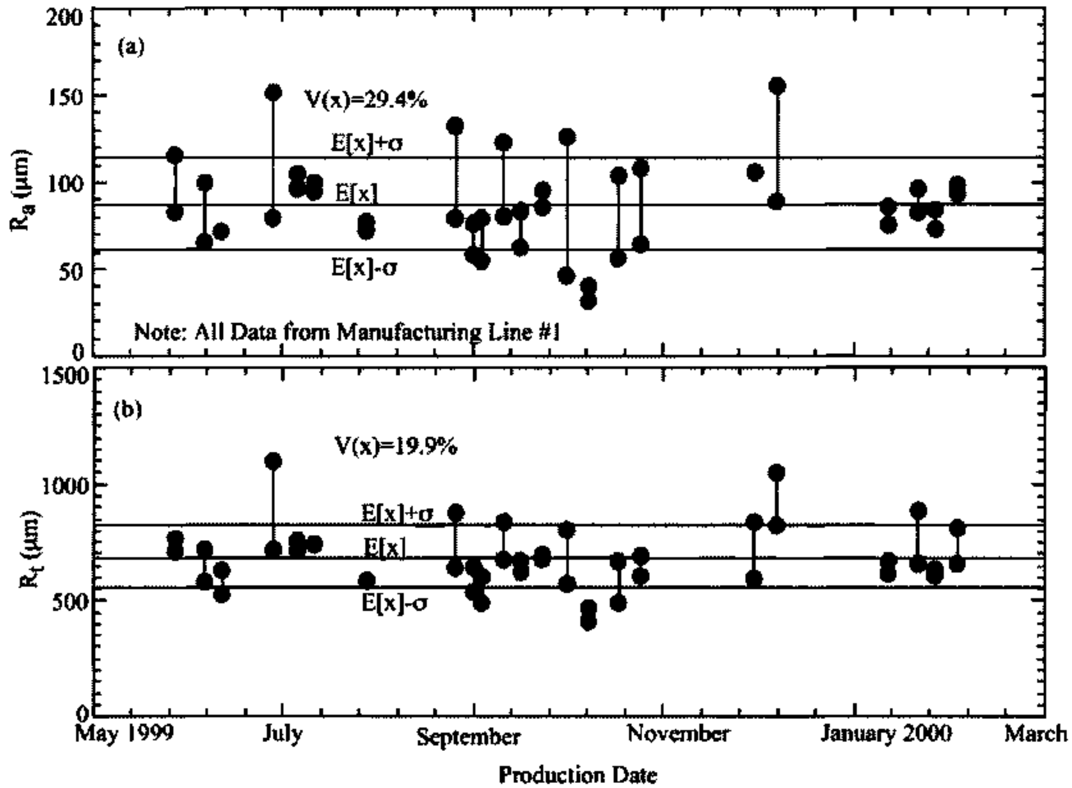

Figure 4. Variation of Height Roughness Parameters
for Coextruded Geoemebrane

Additional data is needed to conclude if variations in the degree of surface texture observed in this study are typical for the coextrusion process. This requires that additional data be collected over a longer time period. It should be noted that variability in these materials has been visually observed in the past with no negative impact on performance. Further research is also needed to determine the sensitivity of interface strength and deformation behavior to texture variations, and how each of the processing variables influences the final product.

Design Tools. A goal of this research program is to implement surface information in soil-structure interaction codes. Currently design analysis tools do not account for the local interaction of earth material and a man-made element. However, research has shown that this interaction is important to the overall behavior of the system.

Research Needs

This project has been groundbreaking in the field of geotechnical engineering. A technique is now established that can provide critical geometric and spatial information for construction material surfaces. The parameters obtained from the profilometry method describe the critical elements of surface geometry that control strength-volume change behavior of interfaces composed of granular soil and anisotropic surfaces. The results are directly applicable to practice. One example, controlling geomembrane texture for landfill design, was shown to have immediate need of this research.

A number of new questions were raised which could not be answered in this project due to the limited scope and budget. Areas where additional research is critically needed and is of significant practical value include:

1. Surface roughness/interface strength relationships for well-graded materials, geomembranes/geotextile interfaces, and other construction material interfaces.
2. Determination of the spatial scales controlling shear behavior.
3. Relation of 2-dimensional profile data to the 3-dimensional surface through application of random field theory.
4. Insertion of surface characterization information into interface models in soil-structure interaction codes.

Reference:

Jewell, R. A. and Wroth, C.P., 1987. "Direct Shear Tests on Reinforced Sand". Geotechnique, Thomas Telford Publishers, Vol. 37 No. 1, pp. 53-68.