Determination of Surface and Thickness Characteristics of Textured Geomembranes Using Image Analysis

Nazli Yesiller

Associate Professor, Department of Civil and Environmental Engineering,
Wayne State University, Detroit, MI 48202

Arif Cekic

Graduate Assistant, Department of Civil and Environmental Engineering,
Wayne State University, Detroit, MI 48202.

ABSTRACT: Image analysis was used to determine surface topography and thickness of textured geomembranes. Images of cross sections (specimen length x thickness) of geomembranes were obtained at 50x magnification using a digital optical microscope. Thickness was determined as the distance between the top and bottom surfaces along an entire cross section. For surface analysis, profiles of top and bottom surfaces were extracted from the cross section images. Amplitude, spatial, hybrid, and functional texture parameters were determined. Tests were conducted on eleven samples of HDPE and LLDPE geomembranes manufactured by co-extrusion and embossing at varying thicknesses. The geomembranes were classified into three texture categories: high, medium, and low. Anisotropy and directionality were observed for all samples to varying degrees between and within manufacturing directions, respectively. Statistical analysis of the results indicated that surface topography of geomembranes could be determined by analyzing one surface of five specimens with 50mm length. Comparisons were made between image analysis and mechanical tests for core thickness and asperity height. Image analysis and mechanical measurements were significantly different. Recommendations were made for the redesign of the mechanical devices by sizing the components in relation to the size and spacing of geomembrane texture features.

Introduction

Geomembrane surfaces are textured to provide improved interface performance against other geosynthetics or soils in various applications. Interface shear strength is a fundamental property in designing with geomembranes. Mechanical stability of various systems containing geomembranes depends on interface shear strength. Interface strength and shear resistance of geomembrane/geosynthetic and geomembrane/soil systems are significantly affected by surface texture characteristics of geomembranes. Thickness is a basic property of geomembranes that is used for general identification and classification of these materials. Mechanical and hydraulic performance of geomembranes are affected by thickness. Thickness is used for manufacturing quality control as well as for conformance and acceptance in the field.

This study was conducted to evaluate surface characteristics and thickness of textured geomembranes using image analysis and standard mechanical test procedures. Variation of surface texture and thickness characteristics for specific geomembranes were determined, and comparisons of texture and thickness were made between geomembranes manufactured using varying texturing processes. In addition, comparisons were made between surface and thickness characteristics determined using image analysis and mechanical procedures.

Background

Surface texture characteristics of materials can be analyzed using 2-D or 3-D analysis. Determination of 2-D parameters requires measurement of a profile along a surface of interest, whereas 3-D parameters require measurement of an entire surface. Some 3-D surface parameters may be estimated using 2-D profile measurements. Analyses may be conducted on a measured profile directly or at roughness, waviness, or form scales extracted from the measured (raw) profile using filtering methods (Fig. 1). Existing quantitative data for characterization of surface topography of textured geomembranes were obtained using 2-D profile measurements on HDPE samples. An optical technique was used to obtain profiles of textured geomembranes by Dove and Frost (1996), Dove et al. (1997), and Lee et al. (1998). Digital images of geomembrane cross sections were obtained using an optical microscope equipped with a CCD camera. Image analysis techniques were used to obtain profiles along top and bottom surfaces of the geomembranes from the cross section images. A stylus profilometer was used to directly obtain profiles of textured geomembranes by Dove and Harpring (1999) and Dove et al. (2001).

Dove and Frost (1996) determined profile roughness parameter (RL) and surface roughness parameter (RS) for geomembranes. RL is the quotient of the actual length of a profile to the projected length of a profile. RS is the quotient of the actual area of a surface to the projected area of a surface. RS was determined from measured 2-D profiles using the method described by Gokhale and Underwood (1990) and Gokhale and Drury (1990). Tests were conducted on two to five specimens with lengths of approximately 42 mm obtained from four textured geomembranes. The samples were determined to be oriented partially (not all surface features lie in a plane) and nonrandom (not all surface element orientations have an equal probability of occurrence). A textural classification system based on RS was proposed that included four categories (smooth to heavily textured). It was determined that cross sections with a minimum length of 35 mm were required to obtain a steady measurement of RS (Dove and Frost 1996). RS was determined on several additional specimens with lengths of 50 mm obtained from the same four textured geomembranes (Dove et al. 1997; Lee et al. 1998). Overall, it is

believed that on the order of twenty specimens were tested for each geomembrane type. However, systematic analyses of variation of *RS* (or *RL*) for a single specimen or for specimens of the same type of geomembrane were not conducted. While Dove and Frost (1996) indicated that the variation of *RS* was low, the reported values from this and the later studies indicated variations over 20%.

Dove and Harpring (1999) and Dove et al. (2001) provided parameters including amplitude (average roughness, maximum peak-to-valley height), spatial (average peak spacing), and hybrid (average slope, RMS slope, average wavelength) parameters. Dove and Harpring (1999) used a total of four profiles each with a length of 40 mm to determine texture parameters for a geomembrane specimen in the machine direction. An extensive analysis of variation of texture parameters for a specific geomembrane specimen or a specific type of geomembrane was not included in the study. Dove et al. (2001) determined the manufacturing variability of surface characteristics of a textured geomembrane. Specimens (300 mm × 300 mm) were obtained from a manufacturing facility every week over an approximately 8-month period. Texture parameters were determined using four 40-mm-profile lengths on each specimen collected from the production line. The variation in the texture parameters during the study period was between 14 and 29% with no discernable increasing or decreasing trends with time. The variation of the texture parameters at a given sample collection time was not determined. The manufacturing variability of the texturing process for a particular time was not distinguished from the time-dependent variability of the texturing process.

Triplett and Fox (2001) provided qualitative assessment of surface characteristics of textured geomembranes in their study of shear strength of geomembrane/geosynthetic clay liner interfaces. Asperities were observed to be removed due to the shearing process from the geomembranes manufactured using lamination, whereas, the co-extruded geomembranes were intact subsequent to shearing. Also, variations were observed in the peak shear strength of the interfaces due to in-plane differences in the surface characteristics of the geomembranes along the same manufacturing direction (“forward” and “backward” test directions).

Thickness characteristics of textured geomembranes are determined using two mechanical tests: core thickness and asperity height. Core thickness measurement is used to determine average minimum thickness for a textured geomembrane (ASTM D 5994, Test Method for Measuring Core Thickness of Textured Geomembrane). A specimen is placed horizontally in a thickness gage between two measurement points (tips). The rounded conical tips are constructed with an apex of $60^\circ \pm 2^\circ$ and a radius of $0.8 \text{ mm} \pm 0.1 \text{ mm}$ at the tip. The specimen is placed such that the locations of the tips coincide with the lowest points (valleys) on the surfaces of the specimen to result in a low (core) thickness measurement. A constant average load of 0.56 N is used. Even though asperity height is

generally classified under thickness determination (Koerner 1998), it is used to obtain the maximum variation in elevation between the highest points (peaks) and the lowest points (valleys) on one surface of a textured geomembrane. Determination of asperity height is described in GRI Test Method GM12. In this method, a setting block with dimensions of 50 mm (length) × 20 mm (width) × 15 mm (height) is placed on a textured geomembrane. The setting block has a hole at the center of it, and a measurement probe with a diameter of 1.3 mm that is tapered to a contact “point” protrudes through this central hole in the block. The block is placed on a specimen such that it rests on the high points (peaks) on the specimen and the contact point rests on the lowest point (valley) on the surface of the specimen, providing a measurement of the localized “maximum” elevation difference on the geomembrane. While specimens that are 75 mm in diameter are used for core thickness measurements, asperity height may be determined by placing the measurement device directly on a geomembrane roll without removing specimens. A total number of 10 specimens is used for core thickness measurements of a sample, and 10 measurements are made on a sample for asperity height determination. Manual adjustments are made in test locations to capture peaks and valleys for both measurement types based on visual observation of a test material. Currently, standardized procedures are not available for determining surface characteristics of textured geomembranes.

Surface characteristics of textured geomembranes have been evaluated in a limited number of studies without comprehensive variability analyses. Published data are not commonly available for thickness and asperity height of textured geomembranes. Some of the geomembranes that were tested in previous studies are no longer manufactured, and data related to these are no longer relevant. This study was conducted to provide an extensive analysis of surface and thickness characteristics of textured geomembranes. Initially, in-depth descriptions of texture parameters that can be used for geomembranes are provided. For experimental analyses, image analysis and standard mechanical test procedures were used in the study. Variability of surface texture and thickness characteristics for specific geomembranes and variability between geomembranes produced by different manufacturers were determined. Comparisons were made between image analysis and standard mechanical measurements. Recommendations for determination of surface and thickness characteristics are provided based on the results of the study.

Texture Parameters

The purpose of this section is to provide a concise description of surface topography analysis that may be used for textured geomembranes. The texture analysis is adapted from the surface metrology discipline. Texture parameters that are commonly used in surface metrology analysis include amplitude, spatial, hybrid, and functional

parameters (Whitehouse 2002, 2003). These parameters may be determined on raw (unfiltered) profiles (referred to as preliminary profiles) directly or at roughness, waviness, or form scales on filtered profiles (Fig. 1). Use of notation R_i describes parameter “ i ” determined at the roughness scale. R_i has been used in various publications to describe texture parameters, since roughness scale is used commonly in surface metrology (Whitehouse 2002, 2003). This notation will be used in this section to define texture parameters. The preliminary (unfiltered) parameters are shown using the notation P_i and the waviness parameters are shown using the notation W_i . Existing quantitative data on textured geomembranes have been determined using preliminary profiles; however, notation R_i has been used to describe the measured parameters in some cases. This causes confusion regarding the scale of analysis and should be avoided.

Equations for 2-D parameters are provided in this section for ease of representation. The common amplitude parameters include average roughness (R_a); RMS roughness (R_q); second and third moments of height distribution, skewness (R_{sk}) and kurtosis (R_{ku}), respectively; maximum peak-to-valley height (R_t); and average peak-to-valley height (R_z). Average roughness is determined as:

$$R_a = \frac{1}{L_x} \int_0^{L_x} |Z(x)| dx$$

where L_x is the length of a profile along a horizontal direction, x , and $Z(x)$ is the function representing the vertical height of the profile with respect to a horizontal best-fit line (with a mean height of zero). R_a is a common surface parameter that is included in most texture specifications used in the manufacturing industry. R_a quantifies the absolute magnitude of profile heights. R_q is the root mean square amplitude parameter. It has been shown to be better correlated to engineering function than R_a for various surfaces and Whitehouse (2002) states that R_q is “gradually superseding R_a ” in practical use. These parameters are not sensitive to the distribution, magnitude, or directional variations of peaks and valleys in a profile. The polarity of a profile is maintained in the skewness analysis and, therefore, R_{sk} may be used to assess the similarity of a surface (around a mean line). R_{ku} may be used to determine the deviation of amplitude distribution for a surface from a normal distribution (Gaussian or bell curve distribution), which may be used to detect anomalies on a surface (Cohen 2002). A surface with normally distributed textures is expected to have an R_{ku} of 3. The parameter may also be used to estimate the sharpness/bluntness of peaks or valleys in a profile (Whitehouse 2003). Softer features result in R_{ku} less than 3 and sharper features result in R_{ku} that are higher than 3.

R_t is the maximum peak-to-valley height (difference between the height of the highest peak and depth of the deepest valley), which needs to be determined on a high number of profiles to obtain statistically significant results. R_t is a divergent parameter (i.e., it increases as a greater profile length is investigated). R_t is the parameter intended to be measured using the mechanical asperity height measurement. An averaged peak-to-valley height (R_z) is used to provide a stable peak-to-valley amplitude parameter for a given profile. This parameter is calculated as the average of the five highest measured peak-to-valley distances on the profile. Overall, the amplitude parameters provide little information about spatial distribution of texture features on a surface. Nevertheless, they are commonly used in the manufacturing industry as quality control measures.

The two additional less common amplitude parameters are the profile roughness parameter (R_L) and the surface roughness parameter (R_S). The 3-D R_S parameter can be determined from 2-D profiles using measurements on three cross sections oriented at 120° to each other with an error less than 6% (Gokhale and Underwood 1990; Gokhale and Drury 1990). Both R_L and R_S are general index parameters that provide overall measures of the magnitude of roughness of a surface. R_L is not as effective as R_a for characterizing the amplitude of a profile since R_L does not provide an average magnitude for profile heights. A similar comparison applies for 3-D analysis. R_L and R_S do not allow for determination of polarity of surfaces, spatial distribution of surface features, or variation of these features within or between manufacturing directions. It is believed that these parameters were used in the earlier studies of textured geomembranes (Dove and Frost 1996; Dove et al. 1997; Lee et al. 1998), since they are relatively easily determined index parameters. These parameters are not commonly used in surface metrology studies.

The spatial texture parameters are related to the spacing of surface features. R_{SS} is the average distance between local peaks and R_{Sm} is the mean width of texture features. R_{Sm} represents the average distance between the positive/upward crossings of the profile over the meanline. R_{SS} and R_{Sm} are equivalent for simple periodic profiles. Counts of local peaks or valleys (with respect to the mean line of a profile or a specific percentage of the meanline) may also be provided. For example, R_{Pcc} is the number of peaks above the mean line for a given profile. These spatial parameters do not provide information related to the amplitude characteristics of a profile (Whitehouse 2002).

The hybrid parameters combine amplitude and spatial analysis. These parameters include average slope (RA_a); RMS slope (RA_q); and average wavelength ($R\lambda_q$). The average slope is calculated as:

$$R_{\Delta a} = \frac{1}{L_x} \int_0^{L_x} \left| \frac{d(z)}{d(x)} \right| dx \quad (2)$$

The RMS slope ($R_{\Delta q}$) is the standard deviation of the average slope and is calculated as:

$$R_{\Delta q} = \left[\frac{1}{L_x} \int_0^{L_x} \left(\frac{dZ(x)}{dx} - \left\langle \frac{dZ(x)}{dx} \right\rangle \right)^2 dx \right]^{1/2} \quad (3)$$

where the term in the brackets, $\langle \rangle$, represents the average value of all slopes along the profile direction. Analysis of distribution of slopes can be used to differentiate between peaks and valleys along varying directions (e.g., machine and cross-machine directions). Analysis of orientation of slopes can be used to distinguish forward and backward (i.e., 180° apart—left to right and right to left along a profile) texture characteristics for a specific manufacturing direction. The variation of texturing in a given manufacturing direction can also be determined by investigating the differences in the cumulative length of the positive or negative slopes with respect to the projected horizontal length of the profile.

The average wavelength ($R_{\lambda q}$) provides a measure of the dominant spatial wavelength for a profile weighted by the amplitude of the components at varying wavelengths that comprise the profile. $R_{\lambda q}$ can be used to differentiate between dominant long wavelength and short wavelength profile structures. $R_{\lambda q}$ is calculated as:

$$R_{\lambda q} = 2\pi \frac{R_q}{R_{\Delta q}} \quad (4)$$

The functional parameters have generally been developed in relation to an intended use of a material. A set of functional parameters that can be used for textured geomembranes is material ratio (also referred to as bearing ratio) parameters. A material ratio curve is generated by assuming that a horizontal line is moving through a profile from the highest peak to the lowest valley (Fig. 2). The percentage of contact the horizontal line would make with the profile is quantified at each level. The curve provides the material-to-air (or other material) ratio at any given depth. The y-axis is the total height of the profile (from the lowest valley to the highest peak), and the x-axis is the percent material above a corresponding height in a material ratio graph (Fig. 2b). R_k is the core roughness depth. The cutoff values used to determine R_k are based on the intersection points of the straight

line that pass through the lowest slope portion of the material ratio curve and the vertical boundary lines corresponding to 0 and 100 % on the x-axis. Mr_1 and Mr_2 closely approximate the upper and lower boundaries of the core roughness, respectively. Rpk represents the average height of the peaks above the core roughness. Rvk represents the average depth of the valleys below the core roughness. Material ratio parameters can be used for progressive determination of contact area (and thus contact stresses) with depth. The amount of material removed from the profile under applied load may be estimated, as well as interlocking of adjacent materials in the profile may be determined, using material ratio analysis. Special filtering methods that are originally developed for certain manufactured parts are used to obtain material ratio parameters (Whitehouse 2002, 2003). Profile section height (Pdc) is the core profile depth between fixed cutoff values of 20 and 80 % determined on a material ratio curve developed using a preliminary profile.

Testing Program

The testing program consisted of determination of surface and thickness characteristics of textured geomembranes using image analysis and standard mechanical methods. Various surface and thickness characteristics were obtained and variations in these parameters were determined using statistical analysis. Comparisons were made between image analysis and standard mechanical measurements.

Materials

Tests were conducted on eleven geomembrane samples that represent two polymer types, HDPE and LLDPE, with nominal thicknesses ranging from 1 to 2.5mm (Table 1). The geomembranes were manufactured using two primary texturing methods: co-extrusion and embossing. The materials labeled HG, HM, HP, LG, and LP are currently available (Fig. 3). The manufacturing methods for textured geomembranes have matured, and these products tested in the study have widespread use. The materials labeled HS were manufactured by a now defunct company and these (Fig. 3) are not currently available. These geomembranes were used in the test program, since they have been used in various applications and also since these materials have distinct texturing features in comparison with the other materials. This provided additional data for determining the effectiveness of the various texture parameters in differentiating between various types of textured geomembranes.

Tests were conducted on specimens with a length of 75 mm and width of 25 mm. The 75-mm length was selected, since this is the size recommended for diameter of specimens for mechanical core thickness measurements. Rectangular specimens were used in the test program to allow for the use of same specimens in both image analysis and mechanical tests without any modifications to the specimens. This allows for direct comparison of the results obtained using the two test methods. A total of 20 specimens (10

in the machine direction and 10 in the cross machine direction) were obtained from each geomembrane sample for testing the currently available materials. A total of 10 specimens (5 in the machine direction and 5 in the cross machine direction) were obtained from each geomembrane sample for testing the materials labeled HS, which are not currently available. Additional specimens were used to determine R_s for samples HG12, HM12, HP11, HS12, and LG11. These specimens were oriented 0, 120, and 240° to the machine direction. In these tests, 3 specimens were obtained for each direction for each sample. Overall, a total of 235 specimens was used in the test program.

Mechanical Thickness Tests

Thickness characteristics of the specimens were initially determined using the core thickness and asperity height mechanical tests. Thickness and surface texture of the same specimens were then determined using image analysis. The core thickness was determined in accordance with ASTM D 5994, and the asperity height was determined in accordance with GRI GM-12. The specimens were traced extensively in attempts to obtain the “lowest” core thickness and the “highest” asperity height for a specimen. A total of 5 core thickness and 2 asperity height measurements were made on each specimen. Overall, 100 core thickness and 40 asperity height measurements were obtained for each of the HG, HM, HP, LG, and LP samples and 50 core thickness and 20 asperity height measurements were obtained for each of the HS samples.

Image Analysis

Image analysis tests were conducted subsequent to core thickness and asperity height determinations. Specimens were inserted vertically into specimen holders. The specimen holders consisted of a base plate and a circular ring attached to the base. Specimen holders with diameters of 150 mm were used to contain 2 or 3 specimens simultaneously (Fig. 4). Specimens were secured in place in narrow grooves that were machined into the base plate of the specimen holders. This configuration was used to ensure verticality of the specimens. The holders were then filled with Plaster of Paris mixtures prepared at a ratio of 2.5 parts Plaster of Paris: 1 part water to surround the specimens. The surrounding medium both aided in keeping the sample vertical as well as providing color contrast for image analysis. Upon hardening of the Plaster of Paris, the disk of hardened material was removed from the sample holder. The top surface of the disk was ground and polished using initially an electric sander and then by hand sanding to prepare the specimens for microscopy analysis. A 120-grit-sand paper was used to provide a smooth and level surface for the subsequent image analysis step. This specimen

preparation approach is similar to the method used by Dove and Frost (1996). In this arrangement, a specimen is available for obtaining an image with the cross section of the material (thickness by specimen length) surrounded by the support/contrast medium.

The equipment used for image analysis consisted of an optical microscope equipped with a digital camera. The microscope had a magnification range of 25× to 300×. Images with a resolution of 1280×1024 pixels were obtained with the camera. Preliminary images were obtained using magnifications of 25× to 100×. Images of the specimens could not be obtained at magnifications higher than or equal to 100×, as the field of view did not include the entire thickness of the specimen. A magnification of 50× was selected as this magnification provided both a high resolution (8 μm and 9 μm along the length and thickness axes, respectively), and also allowed for a practical number of segments to be recorded along the length of a specimen. Approximately 9 segments were obtained for each specimen. These segments were then stitched to obtain the entire cross section of a specimen for further analysis. The entire recorded image of the cross section (75-mm length by thickness) was used to obtain the thickness for a specimen. Thickness was determined as the straight-line distance between the top and bottom sides of a specimen at a given measurement location. For each specimen, a total of 9600 thickness measurements were recorded across the entire length of the specimen. The cross-sectional images obtained were further processed to extract surface profiles along the top and bottom sides of the specimens (Fig. 5). Various texture parameters were then determined on the extracted profiles of the test specimens using a commercially available surface topography software.

Results and Discussion

Initially, surface analyses for the geomembranes are presented. Then, thicknesses of the geomembranes determined using the image analysis and mechanical methods are presented. Finally, comparisons of the measurements obtained using the two methods are provided. Comments about performance and general use of the methods are also included.

Surface Texture Analysis

Overall Trends—A total of 13 preliminary profile texture parameters is determined for the geomembranes (Table 2). Parameters determined along the machine and cross machine directions along the top surfaces of the specimens are provided for each geomembrane sample. For a geomembrane roll, top surface represents the surface that is

“inside” a roll. The average (AVG), standard deviation (STD), and the coefficient of variation (COV) are provided for all of the parameters.

Positive skewnesses for all of the geomembranes indicated that the surface features tended to be more in the form of peaks than valleys. The kurtosis values were generally close to 3 indicating that the profile asperities (peaks and valleys) had near normal distributions. The average amplitude (Pa), maximum peak-to-valley height (Pt), slope ($P\Delta a$), and section height (Pdc) of the raw profiles ranged between 0.13 and 0.22 mm, 0.61 and 0.91 mm, 23.4 and 35.3 degrees, and 0.25 and 0.39 mm, respectively. The low values were generally associated with HG and LG samples, and the high values were generally associated with the HP and LP samples. The HM and HS samples generally had intermediate values. The RMS parameters (Pq and $P\Delta q$) indicated similar trends as the average parameters (Pa and $P\Delta a$). The number of peaks (PPc) varied between 1.5/mm and 3.1/mm. The low values were for HS samples. The surfaces of these materials consisted of alternating “bands” of textured and smooth regions. The low average values reflected the overall low amount of texturing on these samples compared to the other geomembranes. The high values were generally for HP samples. The average wavelength ($P\lambda q$) varied between 1.38 and 3.46 mm. The low values indicate short wavelengths and, thus, close spacing of texture features, and in contrast the high values indicate long wavelengths and distant spacing of texture features. The low values were measured for HP and LP samples, and the high values were measured for HS samples. The HM samples also had moderately high wavelengths. The texturing on these materials consists of more distinct and separated features compared to the more uniform texturing on HP, LP, HG, and LG samples. The peak spacing (PS) and mean crossing (PSm) also indicated similar trends. Textured geomembranes were classified into three categories: low texture, moderate texture, and high texture using amplitude, spatial, and hybrid parameters. The recommended ranges are provided in Table 3. The data indicate that the HP and LP samples have the highest overall texturing due to texture features that have high amplitude, low spacing, and high slope. The HG and LG samples have low texturing due to the low amplitude and slope. The HS samples also have low texturing due to high spacing and low slope. The HM samples were determined to have moderate texturing due to moderate amplitude, spacing, and slope characteristics.

Analysis of the variation of the texture parameters indicated that high variations (multiple COVs > 20 %) were observed for high moments of amplitude distribution (skewness and kurtosis), spatial parameters, and hybrid parameters (wavelength). Low variations were observed for slope parameters (majority of COVs < 10 %). Low order amplitude parameters generally had moderate variations. The HS samples generally had somewhat lower variability compared to the other samples, even though the number of specimens tested (five specimens) for each sample of these geomembranes was lower than

the number of specimens tested (ten specimens) for currently available geomembranes. This comparison was based on the count of COVs<10% and COVs>20% for each geomembrane sample (Table 2).

The texture parameters were also determined at the roughness and waviness scales (Cekic 2005). The profiles at these scales were obtained using filtering schemes that are commonly used in manufacturing industry. The material ratio parameters were also determined using common filtering options. These filtering options were available in the surface metrology software used in the test program. It was observed that the roughness profile had very small amplitudes, on the order of few tens of μm . The material ratio parameters also had very small amplitudes that were not representative of the overall texturing of the geomembranes. The parameters determined at the waviness scale were somewhat similar to the parameters determined using the preliminary profile. The trends observed at these two scales were not significantly different from the trends obtained

using the preliminary profile analysis. The distinct spacing of the texture features on the HS samples were more pronounced for the waviness scale analysis compared to the preliminary profile analysis. The waviness spacing and wavelength parameters were very high for these samples compared to the other samples.

Further analysis was conducted to determine the surface roughness parameter (RS). The results were: 1.31 for HG12, 1.48 for HM12, 1.61 for HP11, 1.42 for HS12, and 1.28 for LG11. HG11 and LG11 were classified as “slightly textured,” HM12 and HS12 were classified as “moderately textured,” and finally HP11 was classified as “heavily textured” according to the classification system proposed by Dove and Frost (1996). Similar classifications were made for the HG, LG, HM, and HP geomembranes using the surface texture parameters provided in Table 2 and recommended ranges provided in Table 3. However, the Dove and Frost (1996) classification for the HS geomembrane did not agree with the classification of the sample in the current study. RS parameter was not effective in capturing the low texture of the HS geomembrane that results from the unique texture characteristics of this sample. Surface roughness provides only an overall indication of the amplitude of the texture features on a geomembrane with no indication of spacing, slope, or wavelength characteristics of surface features. Since the data obtained from the RS analysis are rather simplistic and not fully effective in capturing texturing on a specimen, the authors believe that determination of this parameter is not warranted for texture analysis of geomembranes.

The predictive significance of the various parameters and measurement scales can be determined by establishing correlations to performance parameters, such as interface shear behavior. While preliminary profile analysis provides representative assessment of surface texture characteristics of geomembranes, the common filtering schemes that are

used in the manufacturing industry may not be appropriate for textured geomembranes. Studies need to be conducted to develop filtering methods and additional analysis scales that are applicable to textured geomembranes as well as functional parameters that are related to the performance of these materials.

Isotropy and Directionality—Isotropy of textured surfaces is quantified by determining the relative proportions of representative parameters, Pa , PPc , P_a , and $P\lambda q$, in machine and cross machine directions (Table 4). Anisotropy was observed in the geomembranes based on all the measured parameters. The degree of anisotropy for the amplitude parameter (Pa) was higher than the spatial (PPc) and hybrid parameters ($P\Delta a$ and $P\lambda q$). The amplitude (Pa) and wavelength ($P\lambda q$) parameters were generally lower in the machine direction than in the cross machine direction. The slope ($P\Delta a$) and spatial (PPc) parameters were generally higher in the machine direction than in the cross machine direction. Anisotropy of HM and HS samples was somewhat higher than the anisotropy of HG, LG, HP, and LP samples.

Directional characteristics of the geomembranes were further investigated by determining the cumulative length of the positive slopes (sections where the profile is inclined to the “right”) and the cumulative length of the negative slopes (sections where the profile is inclined to the “left”) for each manufacturing direction. These analyses were conducted from the “left” to the “right” side of the profiles obtained for all of the specimens. The directionality ratio (DR) was calculated as the quotient of positive slopes to the negative slopes for each profile (Table 5). Directionality was observed for all of the geomembrane samples to varying degrees (DR between 0.7 and 1.6). DR and variation between positive and negative slopes were lower for the machine direction than the cross machine direction for all of the samples except for the HP and LP samples, which demonstrated the opposite trend. The directionality as well as isotropy of geomembrane textures may be used in selection of the appropriate placement direction of geomembranes in the field for optimal interface shear strength.

Test Conditions—The test data were further investigated to determine the required test conditions for surface texture analysis of geomembranes. All of the texture parameters were determined for the bottom surfaces of the geomembranes subsequent to the determination of the parameters for the top surfaces (presented above). The variation of the parameters was determined between the top and bottom surfaces. The variation between the two surfaces was less than 10% for 77% of the texture data, and the variation was less than 15% for 90% of the texture data. It was observed that the highest variations (up to 27 %) were obtained for the HS geomembranes. The top/bottom variation analysis

was repeated for the texture data, excluding these samples. For the currently available geomembranes, the variation between the two surfaces was less than 10% for 82% of the data, and the variation was less than 15% for 95% of the texture data, with no variations over 19%. Overall, 85% of the top and bottom surface data were statistically similar based on t-tests conducted at 95% significance level.

The amplitude parameters Pa and Pq and the slope parameters $P\Delta a$, and $P\Delta q$ were higher for the top surfaces than for the bottom surfaces of all of the geomembranes. There were no significant, consistently lower or higher trends for the other texture parameters. In addition, the trends observed in the numerical values and variations of the texture parameters for the bottom surface of the geomembranes were similar to the trends observed for the top surface of the geomembranes. In fact, the variability of the texture parameters was somewhat lower for the bottom surface than the top surface. The textural classification of the geomembranes based on the bottom surface measurements was the same as the classification based on top surface measurements. Further analysis was conducted by averaging the top and bottom surface measurements. The trends in the averaged data were similar to the trends in the individual surface data. Therefore, it was concluded that surface texture analysis could be conducted using only top or bottom surface measurements or using the average of the top and bottom surface measurements for geomembranes. Detailed statistical parameters for the bottom surface texture analysis and averaged top and bottom surface texture analysis are provided in Cekic (2005). In cases with significant differences in manufacturing conditions (e.g., die settings, extruder settings, type of resin, etc.) between the top and bottom surfaces of a geomembrane, both surfaces may need to be tested for surface characteristics.

The size and number of specimens required for surface texture analysis were also investigated. The texture parameters were determined using randomly selected sections along the full length of the 75-mm-long specimens. The sections evaluated had lengths of 10 mm, 20 mm, 30 mm, 40 mm, and 50 mm. The analysis was conducted using the data obtained for the top surface of the specimens of the eight currently available geomembranes. Selected amplitude, spacing, and hybrid texture parameters, Pa , Pt , PS , $P\Delta a$, $P\Delta q$, and $P\lambda q$, determined using the shorter lengths, were compared with the parameters determined on the full-length specimens. The comparisons were made using t-tests. The results indicated that 0, 5, 26, and 54% of the data obtained on 10-mm, 20-mm, 30-mm, and 40-mm sections, respectively, were similar to parameters determined on the 75-mm-long specimens. For 50-mm sections, 91% of the texture data were statistically similar to parameters determined on the 75-mm-long specimens. Data from the currently available geomembranes were also used for analyzing the number of specimens required for surface texture analysis. Texture parameters were determined using five randomly selected specimens out of the ten total specimens obtained for a specific manufacturing

direction. The analysis indicated that 99% of the texture parameters determined using five specimens were statistically similar to the parameters determined using ten specimens for a given geomembrane sample. Detailed statistical parameters for the size and number of specimen analyses are provided in Cekic (2005). All of the comparisons were made using t-tests at 95% significance level. It was concluded that representative surface texture analysis for geomembranes can be conducted using five specimens with 50-mm length.

Thickness Characteristics

The thicknesses determined using image analysis are presented in Fig. 6. For each type of geomembrane, the thickness distributions obtained for all of the specimens of the particular type of geomembrane were averaged and are presented in the figure. Statistical parameters for the thickness data are provided in Table 6. The variations of the average thicknesses were low (COVs range between 1 and 4%) for a particular geomembrane. The variability of average thickness of textured geomembranes is similar to the variability of average thickness of smooth geomembranes determined in previous study (Yesiller and Cekic 2001). Variation of the thickness data for each thickness interval presented in Fig. 6 was also determined for each geomembrane sample. The variation in the frequency of occurrence of the majority of the data in the central histogram columns was approximately 20 %. The variations for the low and high thickness ends were higher (details of this extensive analysis are provided in Cekic (2005)). While the variations of average thicknesses were low, the variations of the distributions of thicknesses were high for a particular geomembrane. These values represent the expected variability of thickness for textured geomembranes.

The thickness distributions for all of the geomembranes are similar with significant skew in the data towards the tail end (high thicknesses above the average thickness), as indicated by the positive skewness values. The kurtosis values that are higher than 3 for all samples also indicate the non-normal distribution (skewed distribution) of the thickness data. The majority (80 %) of the thickness data is within the range of nominal thickness to 25 to 50% higher than the nominal thickness. The range for the majority of data decreases as the thickness of geomembrane samples increases. This indicates that the manufacturing processes generate texturing that is independent of the thickness of the geomembranes. A relatively low amount of data (1 to 8%) lies below the nominal thickness of the geomembranes. The lowest percentages for data below nominal thickness were obtained for embossed HM samples, whereas the highest percentages were obtained for the coextruded HP samples. Thickness histograms such as the examples presented in Fig. 6 can be used as quality control tools for textured geomembranes. Representative target

thickness distributions can be developed for a given manufacturing process, and the compliance of the manufactured products to the target distributions can be determined.

The average (AVG), standard deviation (STD), and the coefficient of variation (COV) are provided for image analysis “core thickness” and mechanical core thickness measurements in Table 7. Results from all machine and cross machine direction specimens are provided for each type of geomembrane. For image analysis, the lowest thickness measured on each specimen of a particular sample of geomembrane is used in the analysis. This thickness represents the ultimate lowest value that is targeted to be determined using the mechanical core thickness measurements. An analysis was also conducted using the five lowest thicknesses determined on each specimen using image analysis. However, this analysis (the thickness values and associated statistics) was essentially the same as the analysis using the single lowest thickness value and, thus, is not presented herein.

Analyses of the test results indicate that the mechanical core thicknesses are 6 to 22% higher than the image analysis core thicknesses for the geomembranes (Table 7). The core thicknesses determined using mechanical analysis are higher than the nominal thicknesses of geomembrane samples, whereas the image analysis core thicknesses are lower than the nominal thicknesses of the geomembrane samples (Table 7). A t-test was conducted to determine the similarity of core thicknesses determined using the two methods for each geomembrane sample at 95% significance level. Results of these tests indicated that mechanical and image analysis core thicknesses were statistically dissimilar. The reasons for the low image analysis and high mechanical core thickness measurements are twofold. The most important reason is the configuration (size and shape) of the mechanical probe tips. Even though the measurement tips are tapered to have small radii, they still do not fit into the valleys that are present on the surface of the textured geomembranes. The combination of the diameter of the probe and taper length in comparison to the average peak spacing (PS) and the average peak-to-valley height (Pz), respectively, prevents the probe from reaching the lowest valleys. The probe used in this study had a diameter of 5 mm, which was tapered to the rounded probe tip with a radius of 0.8mm over a distance of approximately 3 mm. The diameter of the probe at a distance of 0.59mm from the probe tip (corresponding to average peak-to-valley height for all of the samples) is 1.61 mm. This diameter is larger than the average localized peak spacing (PS) for all of the currently manufactured geomembranes (Table 2). For HS geomembranes, this diameter is smaller than the average PS ; however, the surface features on these materials occur in bands and it is believed that the average spacings within the textured regions are smaller than 1.61 mm. In summary, the probe tips could not physically fit into the valleys between the peaks on the surface of the geomembranes tested in the study. In addition, the location of the lowest thickness in a geomembrane is not readily available. While the ASTM standard recommends adjusting a specimen in a thickness measurement device until

valleys are located to obtain a core thickness measurement, it is not possible to estimate visually the location with the lowest thickness. The roaming procedure does not guarantee finding the location with the lowest thickness.

The average (AVG), standard deviation (STD), and the coefficient of variation (COV) are provided for image analysis “asperity height” and mechanical asperity height measurements in Table 8. Similar to core thickness analysis, results from all machine and cross machine direction specimens are provided for each type of geomembrane. For image analysis, the maximum peak-to-valley heights (Pt) measured on each specimen of a particular sample of geomembrane are provided. This height represents the ultimate asperity height value that is targeted to be determined using the mechanical measurements. Image analysis and mechanical measurements were both made on the top surface of the specimens.

Analyses of the test results indicate that the image analysis asperity heights are 17 to 42% higher than the mechanical asperity heights for the geomembranes (Table 8). A t-test was conducted to determine the similarity of asperity heights determined using the two methods for each geomembrane sample at 95% significance level. Results of these tests indicated that mechanical and image analysis asperity heights were statistically dissimilar. The combination of the diameter of the probe and taper length in comparison to the average peak spacing (PS) and the maximum peak-to-valley height (Pt), respectively, prevents the probe from reaching the lowest valleys. The probe has a diameter of 1.3mm that is tapered to a contact “point” over an approximately 0.76-mm length (length not specified in the GRI GM12 standard). The 0.76-mm length is shorter than the majority of the maximum peak-to-valley heights (Pt) and the diameter of the probe (1.3 mm) is larger than all of the localized peak spacings for the currently available geomembranes. In summary, similar to core thickness device, the asperity height probe tip could not physically fit into the valleys between the peaks on the surface of the geomembranes tested in the study. In addition, the setting block rests on the highest peaks under its area along a plane that may or may not be in the horizontal plane. This arrangement results in the potential deviation of the measurement probe from the vertical, which also prevents the probe from fully reaching the low valleys. Similar to core thickness determination, the location of the setting block is adjusted during a measurement to locate the highest peaks and deepest valley. However, this procedure does not guarantee finding such locations.

Overall, it was observed that the mechanical measurements are not entirely effective in capturing the thickness and surface texture properties of textured geomembranes. The dimensional properties and configuration of the mechanical devices are not conducive to capturing the lowest thickness and highest peak-to-valley heights for geomembranes. The setups used in the mechanical tests have simplistic designs that have been developed without considering the surface texture characteristics of the

geomembranes. In addition, the discrete nature of these measurements prevents capturing the desired limiting values for these materials. While the mechanical tests are easy to conduct, their effectiveness in determining the thickness and texture properties of geomembranes is limited. The core thickness and asperity height devices can be improved by adjusting the size and the shape of the measurement probes and tips based on the peak spacing and peak-to-valley height of the geomembranes. A diameter of less than 0.6mm over a probe length of more than 0.9mm at the tip of a probe is recommended for mechanical devices. Another consideration is related to the overall need for determination of asperity height of textured geomembranes. Additional texture parameters may be better correlated to engineering properties and response of textured geomembranes than asperity height, and therefore, there may be need to develop methods to determine these parameters.

The image analysis method described in this paper provides representative measurements for thickness and surface texture properties of geomembranes; however, the method is not highly practical for routine use. It is believed that the image analysis method used in the study allows for capturing all of the texture features on a geomembrane. Nondestructive test methods that use laser, ultrasonic, magnetic, or profilometry techniques may present effective alternatives that provide continuous measurements for thickness and surface characteristics. These alternative methods may not be as effective as the imaging method in capturing intricate features (e.g., features with hidden air pockets) on geomembrane surfaces.

Summary and Conclusions

Surface texture and thickness characteristics of textured geomembranes were evaluated using image analysis and standard mechanical test procedures. Images of cross sections (length by thickness) of textured HDPE and LLDPE geomembranes were obtained using a digital optical microscope. Texture characteristics of the geomembranes were determined using a commercially available surface metrology software. Variation of surface texture and thickness characteristics for specific geomembranes was determined and comparisons were made for surface and thickness characteristics between geomembranes manufactured using varying texturing processes. Comparisons were also made between surface and thickness characteristics determined using mechanical and image analysis procedures.

Analyses of raw (unfiltered preliminary) profiles were used to determine surface texture properties of the geomembranes. The texture parameters for the various geomembranes tested were statistically dissimilar. Geomembranes were classified into three categories based on amplitude, spatial, and hybrid texture parameters: low,

moderate, and high surface texture. Anisotropy and directionality were observed for all samples to varying degrees between manufacturing directions and within a particular manufacturing direction, respectively. These parameters can be used in the placement of geomembranes in the field for optimum interface shear resistance. Statistical analysis of the test results indicated that surface topography of textured geomembranes could be determined by analyzing one surface of five specimens with 50-mm length.

Image analysis allows for determination of texture and thickness characteristics of geomembranes along the entire surface and cross section of the geomembranes, respectively. Thickness histograms can be generated for a manufacturing process and can be used as quality control tools for textured geomembranes. The limiting thickness values (maxima or minima) and average thicknesses can be determined using image analysis. Mechanical test methods provide discrete measurements and limiting values are not effectively captured using these tests. The measured core thicknesses were higher and measured asperity heights were lower in mechanical tests than in image analysis tests. Mechanical measurements are simpler than the image analysis measurements; however, the representativeness of the data obtained in these tests is low due to the size and shape limitations of the devices. The configuration of the mechanical devices can be adjusted using surface characteristics of textured geomembranes. A diameter of less than 0.6mm over a probe length of more than 0.9mm at the tip of a probe is recommended for the devices.

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FIG. 1—Scales of measurement (adapted from Whitehouse 2002).

FIG. 2—Material ratio parameters.

TABLE 1—Materials used in the test program.

Sample	Polymer	Nominal Thickness, mm	Manufacturing Method
HG11	HDPE ^a	1.0	Co-extrusion
HG12	HDPE	1.5	Co-extrusion
HM11	HDPE	1.0	Embossing
HM12	HDPE	1.5	Embossing
HP11	HDPE	1.5	Co-extrusion
HP12	HDPE	2.0	Co-extrusion
HS11	HDPE	1.0	Co-extrusion
HS12	HDPE	1.5	Co-extrusion
HS13	HDPE	2.5	Co-extrusion
LG11	LLDPE ^b	1.0	Co-extrusion
LP11	LLDPE	1.0	Co-extrusion

^a High Density Polyethylene.

^b Linear Low Density Polyethylene.

a) HG Geomembrane

b) HM Geomembrane

c) HP Geomembrane

d) HS Geomembrane

FIG. 3—*Geomembrane samples.*

FIG. 4—Geomembrane specimen and specimen holder.

FIG. 5—Image analysis of specimens.

TABLE 2—Texture parameters.

GM	Statistic	P_a^a	P_q^a	P_{sk}^a	P_{ku}^a	P_l^a	P_z^a	PS_m^a	PS^a	$P_{\Delta a}^b$	$P_{\Delta q}^b$	PP_c^c	$P_{\lambda q}^a$	P_{dc}^a
HG11 ^d	AVG	0.135	0.177	0.654	3.475	0.641	0.505	1.698	0.833	25.750	37.650	2.816	1.782	0.265
	STD	0.019	0.016	0.154	0.431	0.083	0.069	0.572	0.144	2.927	2.901	0.384	0.262	0.039
	COV (%)	14.0	9.2	23.6	12.4	13.0	13.6	33.7	17.3	11.4	7.7	13.6	14.7	14.9
HG11 ^e	AVG	0.128	0.164	0.571	2.904	0.613	0.511	1.795	0.854	24.790	36.830	2.423	1.822	0.245
	STD	0.020	0.024	0.180	0.526	0.059	0.061	0.210	0.123	2.422	2.251	0.515	0.202	0.033
	COV (%)	15.4	14.4	31.5	18.1	9.6	11.9	11.7	14.4	9.8	6.1	21.2	11.1	13.6
HG12	AVG	0.125	0.165	0.811	3.608	0.827	0.602	1.735	0.910	25.090	37.320	2.470	1.952	0.257
	STD	0.019	0.017	0.240	0.739	0.073	0.068	0.301	0.178	1.936	2.122	0.373	0.299	0.045
	COV (%)	15.2	10.5	29.5	20.5	8.9	11.3	17.3	19.6	7.7	5.7	15.1	15.3	17.5
HG12	AVG	0.125	0.166	0.735	3.645	0.726	0.545	1.794	0.988	27.690	39.670	2.547	2.015	0.250
	STD	0.017	0.018	0.213	0.651	0.086	0.062	0.281	0.253	3.303	3.270	0.537	0.449	0.044
	COV (%)	13.6	11.0	29.0	17.9	11.8	11.4	15.6	25.6	11.9	8.2	21.1	22.3	17.5
HM11	AVG	0.135	0.183	0.694	3.490	0.790	0.576	2.503	1.563	28.980	40.320	2.289	2.813	0.272
	STD	0.021	0.020	0.254	0.767	0.060	0.047	0.568	0.514	2.564	2.841	0.378	0.671	0.038
	COV (%)	15.2	11.1	36.6	22.0	7.6	8.2	22.7	32.9	8.8	7.0	16.5	23.9	13.9
HM11	AVG	0.156	0.199	0.877	3.588	0.791	0.580	2.232	1.363	26.320	37.310	2.121	2.738	0.319
	STD	0.021	0.022	0.184	0.553	0.102	0.093	0.558	0.431	3.238	2.777	0.306	0.703	0.039
	COV (%)	13.3	11.1	21.0	15.4	12.9	16.0	25.0	31.7	12.3	7.4	14.4	25.7	12.4
HM12	AVG	0.149	0.200	0.737	3.454	0.758	0.584	1.865	1.117	29.800	41.310	2.147	2.065	0.302
	STD	0.028	0.026	0.191	0.672	0.125	0.099	0.218	0.231	2.553	2.342	0.266	0.212	0.049
	COV (%)	18.6	13.1	25.9	19.5	16.5	17.0	11.7	20.7	8.6	5.7	12.4	10.3	16.3
HM12	AVG	0.173	0.222	0.863	3.740	0.818	0.624	2.049	1.315	29.440	41.490	2.153	2.313	0.344
	STD	0.037	0.037	0.200	0.728	0.093	0.063	0.413	0.351	2.775	3.341	0.223	0.489	0.075
	COV (%)	21.4	16.9	23.2	19.5	11.3	10.0	20.2	26.7	9.4	8.1	10.4	21.2	21.8
HP11	AVG	0.170	0.230	0.627	3.310	0.832	0.619	1.321	0.743	33.710	46.020	3.128	1.616	0.336
	STD	0.023	0.024	0.136	0.503	0.036	0.046	0.263	0.094	2.366	1.991	0.284	0.201	0.033
	COV (%)	13.4	10.5	21.6	15.2	4.4	7.4	19.9	12.7	7.0	4.3	9.1	12.5	9.8
HP11	AVG	0.216	0.275	0.748	3.521	0.883	0.647	1.201	0.622	33.590	45.740	3.050	1.375	0.387
	STD	0.030	0.029	0.220	0.831	0.056	0.057	0.364	0.185	2.505	2.307	0.283	0.359	0.026
	COV (%)	14.0	10.5	29.4	23.6	6.3	8.8	30.3	29.7	7.5	5.0	9.3	26.1	6.7
HP12	AVG	0.200	0.258	0.852	3.876	0.896	0.677	1.393	0.807	34.730	47.130	3.046	1.576	0.378
	STD	0.029	0.026	0.157	0.589	0.106	0.075	0.346	0.281	3.312	2.821	0.277	0.372	0.039
	COV (%)	14.4	10.0	18.4	15.2	11.8	11.1	24.8	34.8	9.5	6.0	9.1	23.6	10.3
HP12	AVG	0.197	0.254	0.930	3.856	0.906	0.640	1.243	0.651	33.340	45.160	2.907	1.444	0.378
	STD	0.032	0.032	0.156	1.283	0.091	0.058	0.279	0.159	2.017	2.031	0.343	0.299	0.049
	COV (%)	16.2	12.8	16.8	33.3	10.0	9.1	22.4	24.4	6.0	4.5	11.8	20.7	13.0
HS11	AVG	0.132	0.170	0.659	3.136	0.861	0.653	2.420	2.080	24.520	37.360	1.662	3.150	0.270
	STD	0.009	0.010	0.169	0.234	0.095	0.080	0.359	0.717	1.436	1.159	0.228	0.891	0.013
	COV (%)	7.2	5.9	25.6	7.5	11.0	12.3	14.8	34.5	5.9	3.1	13.7	28.3	4.8
HS11	AVG	0.174	0.214	0.682	3.032	0.895	0.666	2.290	2.172	23.860	35.700	1.648	3.462	0.326
	STD	0.017	0.019	0.173	0.297	0.055	0.045	0.285	0.529	2.110	1.828	0.139	0.420	0.023
	COV (%)	9.7	8.7	25.3	9.8	6.2	6.8	12.4	24.3	8.8	5.1	8.4	12.1	7.1
HS12	AVG	0.145	0.185	0.582	2.928	0.859	0.643	2.644	2.066	24.840	36.120	1.720	3.160	0.298
	STD	0.006	0.008	0.105	0.233	0.076	0.093	0.515	0.710	1.936	2.306	0.169	0.837	0.016
	COV (%)	4.5	4.1	18.1	8.0	8.9	14.4	19.5	34.4	7.8	6.4	9.8	26.5	5.3
HS12	AVG	0.164	0.205	0.728	3.044	0.847	0.644	2.292	1.684	23.380	35.580	1.538	2.932	0.334
	STD	0.017	0.018	0.143	0.351	0.085	0.079	0.221	0.349	2.956	2.376	0.136	0.403	0.027
	COV (%)	10.3	9.0	19.6	11.5	10.0	12.3	9.6	20.7	12.6	6.7	8.9	13.8	8.0
HS13	AVG	0.139	0.181	0.577	2.860	0.834	0.657	2.502	1.841	24.640	36.600	1.646	3.072	0.292
	STD	0.010	0.012	0.073	0.231	0.042	0.051	0.383	0.449	1.613	1.723	0.163	0.697	0.025
	COV (%)	6.9	6.4	12.6	8.1	5.0	7.7	15.3	24.4	6.5	4.7	9.9	22.7	8.5
HS13	AVG	0.150	0.192	0.593	3.002	0.883	0.646	2.814	2.334	23.840	36.360	1.666	3.296	0.315
	STD	0.033	0.037	0.113	0.364	0.082	0.087	0.339	0.807	1.460	1.916	0.146	0.480	0.065
	COV (%)	21.9	19.5	19.0	12.1	9.3	13.4	12.1	34.6	6.1	5.3	8.8	14.6	20.7
LG11	AVG	0.142	0.188	0.737	3.583	0.691	0.499	1.491	0.841	24.880	37.360	2.464	1.641	0.287
	STD	0.023	0.026	0.187	0.659	0.066	0.051	0.159	0.142	2.542	2.225	0.260	0.191	0.040
	COV (%)	16.1	13.7	25.4	18.4	9.6	10.2	10.7	16.8	10.2	6.0	10.6	11.6	14.0
LG11	AVG	0.147	0.192	0.632	3.219	0.698	0.505	1.495	0.849	27.060	39.230	2.390	1.660	0.296
	STD	0.024	0.025	0.144	0.510	0.094	0.069	0.364	0.259	2.546	2.520	0.353	0.394	0.042
	COV (%)	16.6	12.8	22.9	15.8	13.4	13.6	24.4	30.5	9.4	6.4	14.8	23.7	14.1
LP11	AVG	0.183	0.240	0.852	3.665	0.660	0.503	1.268	0.761	35.280	47.810	2.775	1.451	0.340
	STD	0.018	0.018	0.116	0.540	0.065	0.050	0.273	0.163	2.518	2.417	0.461	0.287	0.024
	COV (%)	10.1	7.5	13.6	14.7	9.9	9.9	21.5	21.4	7.1	5.1	16.6	19.8	7.2
LP11	AVG	0.180	0.238	0.940	4.143	0.633	0.469	1.312	0.731	34.470	46.990	2.893	1.455	0.354
	STD	0.024	0.025	0.112	0.453	0.058	0.045	0.283	0.153	2.275	2.524	0.417	0.277	0.046
	COV (%)	13.5	10.4	11.9	10.9	9.1	9.6	21.6	20.9	6.6	5.4	14.4	19.0	13.0

^a mm.^b degree.^c mm⁻¹.^d Machine Direction.^e Cross Machine Direction.

TABLE 3—Texture classification for geomembranes.

Texture Level	P_a , mm	P_{S_m} , mm	$P_{\Delta a}$, Degree	$P_{\lambda q}$, mm
Low	<0.14	>1.9	<26	>2.7
Moderate	0.14–0.18	1.4–1.9	26–32	1.7–2.7
High	>0.18	<1.4	>32	<1.7

TABLE 4—Isotropy analysis.

Sample	P_a (MD/CM) ^a	$P_{\Delta a}$ (MD/CM)	$P_{\lambda q}$ (MD/CM)	PP_c (MD/CM)
HG11	1.062	1.039	0.978	1.162
HG12	1.001	0.906	0.969	0.970
HM11	0.867	1.101	1.027	1.079
HM12	0.864	1.012	0.893	0.997
HP11	0.785	1.004	1.175	1.026
HP12	1.015	1.042	1.091	1.048
HS11	0.763	1.028	0.910	1.008
HS12	0.880	1.062	1.078	1.118
HS13	0.927	1.034	0.932	0.988
LG11	0.967	0.919	0.988	1.031
LP11	1.017	1.023	0.998	0.959

^aMachine Direction/Cross Machine Direction.

TABLE 5—Directionality analysis.

Sample	Positive Slopes, %	Negative Slopes, %	Directionality Ratio	Variation, %
HG11 (MD)	50.12	49.88	1.01	0.48
HG11 (CM)	57.45	42.55	1.35	25.94
HG12 (MD)	47.82	52.18	0.92	–8.36
HG12 (CM)	61.83	38.17	1.62	38.27
HM11 (MD)	51.89	48.11	1.08	7.28
HM11 (CM)	59.81	40.19	1.49	32.80
HM12 (MD)	46.55	53.45	0.87	–12.91
HM12 (CM)	61.86	38.14	1.62	38.34
HP11 (MD)	55.55	44.45	1.25	19.98
HP11 (CM)	46.35	53.65	0.86	–13.61
HP12 (MD)	57.84	42.16	1.37	27.11
HP12 (CM)	42.56	57.44	0.74	–25.91
HS11 (MD)	48.70	51.30	0.95	–5.07
HS11 (CM)	60.60	39.40	1.54	34.98
HS12 (MD)	57.06	42.94	1.33	24.75
HS12 (CM)	62.10	37.90	1.64	38.97
HS13 (MD)	45.34	54.66	0.83	–17.05
HS13 (CM)	55.70	44.30	1.26	20.47
LG11 (MD)	44.83	55.17	0.81	–18.74
LG11 (CM)	55.88	44.12	1.27	21.05
LP11 (MD)	58.06	41.94	1.38	27.76
LP11 (CM)	43.88	56.12	0.78	–21.81

TABLE 6—Thicknesses determined using image analysis.

Statistic	HG11	HG12	HM11	HM12	HP11	HP12	HS11	HS12	HS13	LG11	LP11
AVG (mm)	1.220	1.727	1.225	1.747	1.795	2.267	1.201	1.700	2.702	1.200	1.249
STD (mm)	0.029	0.026	0.035	0.037	0.032	0.025	0.052	0.047	0.057	0.037	0.038
COV (%)	2.4	1.5	2.9	2.1	1.8	1.1	4.3	2.8	2.1	3.1	3.0
Skewness	1.141	1.070	0.881	1.217	1.296	1.232	1.332	1.203	1.234	1.121	1.309
Kurtosis	5.179	4.795	4.550	5.137	5.839	6.184	6.049	5.537	5.698	5.100	5.702
Range (mm)	0.9–2.0	1.4–2.6	0.9–2.2	1.5–2.6	1.4–2.5	1.9–3.1	0.9–2.1	1.4–2.5	2.4–3.6	0.9–2.0	0.9–2.0
Percent < NT ^a	4.85	3.11	1.28	1.65	7.13	7.53	7.14	5.86	5.49	3.02	4.04
80 % Range (mm)	1.0–1.4	1.5–1.9	1.0–1.5	1.5–1.9	1.5–2.0	2.0–2.5	1.0–1.5	1.5–2.0	2.5–3.1	1.0–1.4	1.0–1.4

^a Nominal Thickness.

FIG. 6—Thicknesses determined using image analysis.

TABLE 7—Core thickness measurements.

Statistic	HG11	HG12	HM11	HM12	HP11	HP12	HS11	HS12	HS13	LG11	LP11
AVG _{mech} (mm)	1.066	1.579	1.178	1.656	1.501	1.974	1.035	1.534	2.526	1.116	1.099
STD _{mech} (mm)	0.082	0.060	0.061	0.050	0.048	0.047	0.056	0.055	0.056	0.056	0.064
COV _{mech} (%)	7.7	3.8	5.2	3.0	3.2	2.4	5.4	3.6	2.2	5.1	5.8
AVG _{image} (mm)	0.865	1.396	0.943	1.459	1.385	1.859	0.900	1.410	2.411	0.874	0.889
STD _{image} (mm)	0.030	0.038	0.021	0.016	0.035	0.032	0.018	0.007	0.006	0.034	0.035
COV _{image} (%)	3.5	2.7	2.2	1.1	2.5	1.7	2.0	0.5	0.3	3.8	4.0
Variation (%)	18.83	11.58	19.99	11.94	7.71	5.83	13.01	8.10	4.56	21.69	19.15

TABLE 8—Asperity height measurements.

Statistic	HG11	HG12	HM11	HM12	HP11	HP12	HS11	HS12	HS13	LG11	LP11
AVG _{Mech} (mm)	0.377	0.454	0.599	0.599	0.597	0.695	0.630	0.704	0.646	0.534	0.480
STD _{Mech} (mm)	0.074	0.061	0.041	0.032	0.041	0.060	0.098	0.074	0.087	0.052	0.030
COV _{Mech} (%)	19.7	13.5	6.9	5.4	6.9	8.7	15.5	10.6	13.4	9.8	6.2
AVG _{image} (mm)	0.627	0.777	0.790	0.788	0.858	0.901	0.878	0.853	0.859	0.695	0.646
STD _{image} (mm)	0.075	0.097	0.086	0.117	0.055	0.101	0.084	0.085	0.073	0.083	0.065
COV _{image} (%)	12.0	12.5	10.9	14.8	6.4	11.3	9.5	10.0	8.5	12.0	10.0
Variation (%)	39.80	41.51	24.18	23.98	30.37	22.84	28.27	17.44	24.75	23.10	25.70