# Quantification of Surface Topography Using Digital Image Analysis

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## 요 지

여러 연구들을 통하여 표면 거칠음 정도가 접촉면 전단력에 매우 중요함이 밝혀졌으며, 따라서 그 역할을 충분히 이해하기 위해서는 표면 거칠음 정도가 정확히 정량화 되어야 한다. 이 연구에서는 표면 형상을 정량화하기 위하여 일반적으로 사용되는 표면 거칠기 매개변수와 측정방법에 대하여 여러 참고문헌들을 검토하였다. 이것을 바탕으로 Normalized Roughness Parameter, $R_n$ (Uesugi and Kishida, 1986), Profile Roughness Parameter, $R_L$, 그리고 Surface Roughness Parameter, $R_S$(Dove and Frost, 1996)가 적합한 표면 거칠기 매개변수로 선택되었으며, 디지털 이미지 분석 시스템을 이용한 Optical Profile Microscopy(OPM) 방법을 표면 거칠음 측정방법으로 선택하였다. 이 실험장비를 이용하여 일반적으로 사용되는 지오멤브레인의 표면과 표면 패턴을 대표하는, 표면이 매끄러운 것과 3가지 종류의 돌기형 HDPE 지오멤브레인을 사용하여, 전단 시험에 사용되지 않았던 지오멤브레인과 전단시험후의 지오멤브레인에 대한 표면 거칠음 정도의 정량화 작업을 수행하였다. 그 결과, $R_L$과 $R_S$값은 이 연구에 사용된 지오멤브레인의 거칠음 정도를 충분한 측정범위로 표현할 수 있는 매개변수로 밝혀졌으나, $R_n$값은 충분히 표면 거칠음 정도의 차이를 표현하기에는 부족하게 매우 좁은 변화 범위를 나타내었다. 이 연구는 접촉면에서 표면 거칠음 정도가 접촉면 전단력에 미치는 영향을 조사하고자 우선적으로 표면 거칠음 정도의 정량화 작업을 연구한 것이다.

## Abstract

It was found that surface roughness has a first-order effect on the interface shear strength and accordingly it should be accurately quantified if its role is to be properly understood. To quantify the surface topography, first of all, a variety of commonly used surface roughness parameters and profiling methods were reviewed in this study. Based on this review, the normalized roughness parameter, $R_n$(Uesugi and Kishida, 1986), the profile roughness parameter, $R_L$, and the surface roughness parameter, $R_S$(Dove and Frost, 1996), were selected to be appropriate candidates of roughness parameters and the digital image analysis based Optical Profile Microscopy(OPM) method(Dove and Frost, 1996) to be an appropriate profiling method for this study. Using a smooth and three textured HDPE geomembranes which encompass the range of textures and

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texture patterns commonly used, a series of roughness measurements on virgin and previously used geomembranes were performed. The results showed that both $R_L$ and $R_S$ values appropriately reflect the degree of texturing for the geomembranes used in this study, however, $R_n$ value showed limited ranges of variation which may not be sufficient to permit distinction between roughness values for certain conditions. The results of this study will be extended to the investigation of the influence of surface roughness on interface strength in future study.

**Keywords** : Surface roughness, Geomembrane, Interface, Shear strength

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## 1. Introduction

The interface is generally defined as the common boundary between two materials. In some cases, this interface may exist when soil is placed in contact with a man-made material such as a geomembrane which results in a soil/continuous material interface while in other cases both materials at the interface may be continuous such as when a geotextile and geomembrane are placed in contact with each other although it could be argued that a geotextile is only a semi-continuous surface. Discontinuities in rock masses such as bedding planes, faults, fissures, fractures, joints and other mechanical defects can also be characterized as the interface.

It was found that surface roughness has a first-order effect on the interface shear strength and accordingly it should be accurately quantified if its role is to be properly understood. An appropriate roughness parameter and test equipment(profiling method) should be selected based on the specific application being considered and indeed, a review of previous research indicates that surface roughness parameters have generally been developed/used for specific applications(e.g. Barton and Choubey, 1977; Yoshimi and Kishida, 1982; Uesugi and Kishida, 1986; Vallejo and Zhou, 1995; Dove and Frost, 1996; Lee et al., 1999).

Focusing on a geomembrane surface as a material to be quantified, a variety of commonly used surface roughness parameters were reviewed within the context of interface shear strength. Profiling methods were also reviewed recognizing the characteristics of the commonly used textures and texture patterns of geomembranes. Based on this review, the normalized roughness parameter, $R_n$ (Uesugi and Kishida, 1986), the profile roughness parameter, $R_L$, and the surface roughness parameter, $R_S$(Dove and Frost, 1996), were considered to be appropriate candidates of roughness parameters and the digital image analysis based Optical Profile Microscopy(OPM) method(Dove and Frost, 1996) to be an appropriate profiling method for this study. Using a smooth and three textured HDPE geomembranes which encompass the range of textures and texture patterns commonly used, a series of roughness measurements on virgin and previously used geomembranes were performed.

## 2. Description of Surface Topography

Figure 1 presents a summary of terminology generally used to describe surfaces(Dove et al., 1996). In general, waviness describes long wavelength and high amplitude undulations and frequently results from unexpected sources such as inaccuracies in the machine tool, deformation under unexpected forces, or vibrations of the machine. In contrast, surface roughness, generally reflected as short wavelength irregularities, is the result of specific manufacturing techniques. For example, coextrusion, lamination, and impingement are used for manufacturing textured polyethylene geomembranes and each results in a characteristic pattern of surface roughness. More details of surface terminology is provided by Ward(1982), and Dove et al. (1996).

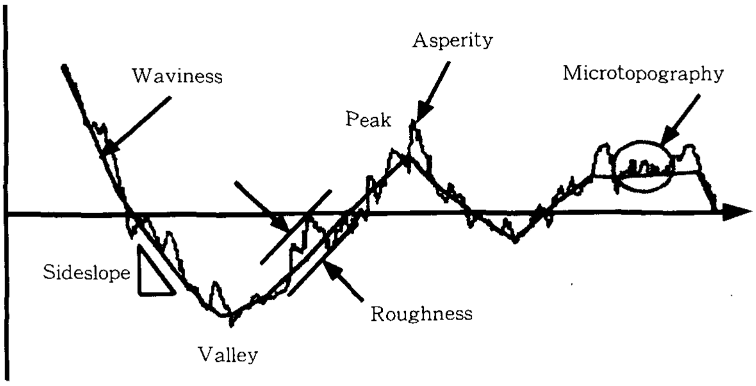


Figure 1. Terminology used to describe surface topography (after Dove et al., 1996)

Geomembranes have an extremely large range of surface roughness. The term macro-texture is often used to refer to the surface texture perceptible to the naked eye, while micro-texture (microtopography) is used to refer to the profiles at localized regions of the surface that do not include the overall surface topography and which typically require some microscope system to allow the surface to be viewed. These different scales can affect interface shear behavior differently depending on the characteristics of other materials at the interface. For example, micro-texture may prove to be important in describing the roughness of surfaces when fine-grained soils are placed in contact with geosynthetics, while macro-texture may be more important when dealing with coarse-grained soils. These different scales also present difficulties in selecting an appropriate instrument (profiling method) for measuring the surface roughness.

## 3. Profiling Method

A variety of profiling methods(instruments) have been developed and used. For example, Dove et al.(1996) summarized the instruments which are of practical use for determining geomembrane surface roughness and their associated approximate vertical measuring ranges with the range of relief for smooth and textured geomembranes.

Among them, Optical Profile Microscopy(OPM) is an image analysis based technique developed by Dove and Frost(1996) which permits profiling of surfaces using optical microscopy. This method is selected in this study for its vertical measuring ranges, and the effectiveness for soft materials such as geomembranes. The technique is described in detail in section 5.

## 4. Surface Roughness Parameters

A variety of surface roughness parameters have been developed and used. For example, Ward (1982) summarized 23 different international standard measurements of roughness. However, each of these parameters was developed for a particular application. Six of these existing surface roughness parameters are reviewed with their advantages and disadvantages in this study.

### 4.1 Maximum Peak to Valley Roughness Parameter, $R_{max}$

Yoshimi and Kishida(1982) used $R_{max}$ as a roughness parameter to quantify the roughness of machined steel surfaces. It was defined as the relative vertical distance between the highest peak and the lowest valley along a surface profile over a gauge length(each measuring length) of 2.5mm. The surface profile was measured with a stylus profilometer. $R_{max}$ was obtained by averaging values measured for 24 to 40 gauge lengths along the steel surface.

The main advantage of using $R_{max}$ is that it is easy to measure. However, the use of $R_{max}$ may not provide a true representation of the surface profile. This is due to the fact that, within a gauge length, a significant amount of small amplitude roughness could be ignored which could affect the interface shear strength when shearing occurs adjacent to a fine-grained soil. This means that $R_{max}$ is an absolute roughness parameter rather than a relative roughness parameter.

### 4.2 Normalized Roughness Parameter, $R_n$

Uesugi and Kishida(1986) found that the interface shear strength between soils and machined steel surfaces was influenced by the surface roughness of the material, the $D_{50}$ of the sand, and the interaction of these factors. Based on this, they concluded that the surface roughness could be better correlated with interface shear strength when normalized by the sand particle size. They suggested that the normalized roughness parameter, $R_n$, be defined as follows:

$$R_n = \frac{R_{max}(L = D_{50})}{D_{50}} \tag{1}$$

where: $R_{max}$ $(L = D_{50})$ = $R_{max}$ when L = $D_{50}$,
$D_{50}$ = mean grain size, and
L = gauge length of $R_{max}$

In their study, $R_n$ ranged from 0.001 to 0.1 for machined steel surfaces.

The main advantage of using $R_n$ over $R_{max}$ is that $R_n$ accounts for the size of soil and produces a relative roughness parameter. In other words, $R_n$ can be correlated with the coefficient of interface friction over a wide range of particle sizes. However, $R_n$ does not consider the roughness contributed by the wavelength profiles greater than the gauge length since all the measurements are based on the gauge length of $D_{50}$.

### 4.3 Fractal Analysis

Fractal theory was first introduced by Mandelbrot(1967) and has been applied to describe the shape of irregular or rough objects(e.g. Kaye, 1978; Carr and Warriner, 1989; Carr et al., 1990; Miller et al., 1990; Turcotte, 1992; McWilliams et al., 1993). The length of a complex profile is measured using different segment lengths(measuring lengths), r. The length of the complex profile (total measured length), L, can be represented by the following relationship:

$$L = c\ r^{1-D} \qquad (2)$$

where: D = fractal dimension,
r = segment length, and
c = constant.

Fractal analysis uses the concept of the fractal dimension, D, to describe the degree of roughness of a complex profile. D is equal to the slope of the linear trend of a log-log plot of L versus r.

Vallejo and Zhou(1995) used fractal analysis to evaluate the roughness of four commercially available geomembranes. They found that the fractal dimension of the geomembrane profiles increased as the roughness increased. The smoothest of the four geomembranes had a fractal dimension equal to 1.001, while the roughest had a fractal dimension of 1.1345.

Based on the results, Vallejo and Zhou suggested that at least four digit precision in the fractal dimension, D, needs to be calculated due to the parameter sensitivity to the roughness of geomembranes. This fact is a main disadvantage of fractal analysis. In addition, fractal analysis does not account for the characteristics of the other materials, resulting in an absolute measurement value of the surface roughness.

### 4.4 Fourier Analysis

A number of researchers have used fourier analysis to measure the irregular shape of, for example, sand particles(Schwarcz and Shane, 1969; Ehrlich and Weinberg, 1970; Anstey and Delmet, 1973; Meloy, 1977; Ehrlich et al., 1980; Czarnecka and Gillott, 1980; Clark, 1981; Luerkens, 1991; Wang, 1998).

Fourier analysis is conducted by unrolling the outline of the soil particle in two dimensional view and a fourier series is fitted to match the unrolled outline. This yields significant information about the shape of particles. However, the analysis approach used by the various researchers to study the information differed and could not be adequately reduced to a sufficiently small number of parameters for purposes of correlation with engineering properties. With respect to the interface shear strength, this approach can not explain the effect of the other materials and the reentrance of the material can not be readily considered.

### 4.5 Profile Roughness Parameter, $R_L$ and Surface Roughness Parameter, $R_S$

Based on the theoretical developments of Gokhale and Underwood(1990) and the experimental work of Gokhale and Drury(1990), Dove and Frost(1996) proposed the Optical Profile Microscopy (OPM) method to quantify the surface roughness of geomembranes.

For a two-dimensional profile of a material surface(Figure 2(a)), the profile roughness parameter, $R_L$ is defined as:

$$R_L = \frac{L}{L_0} \tag{3}$$

where: L = the actual length of the profile, and
$L_0$ = the projected length of the profile.

For a three-dimensional surface of Figure 2(b), the surface roughness parameter, $R_S$ is defined as:

$$R_s = \frac{A_s}{A_0} \tag{4}$$

where: $A_S$ = the actual area of the surface, and
$A_0$ = the projected area of the surface.

For most practical applications, the three-dimensional surface roughness, $R_S$ can be accurately derived from two-dimensional profile roughness, $R_L$ based on stereology(Gokhale and Drury, 1990) as:

$$R_s = \overline{R_L \varphi} \tag{5}$$

where, $\varphi$ is the profile structure factor as defined by Gokhale and Drury (1990) as:

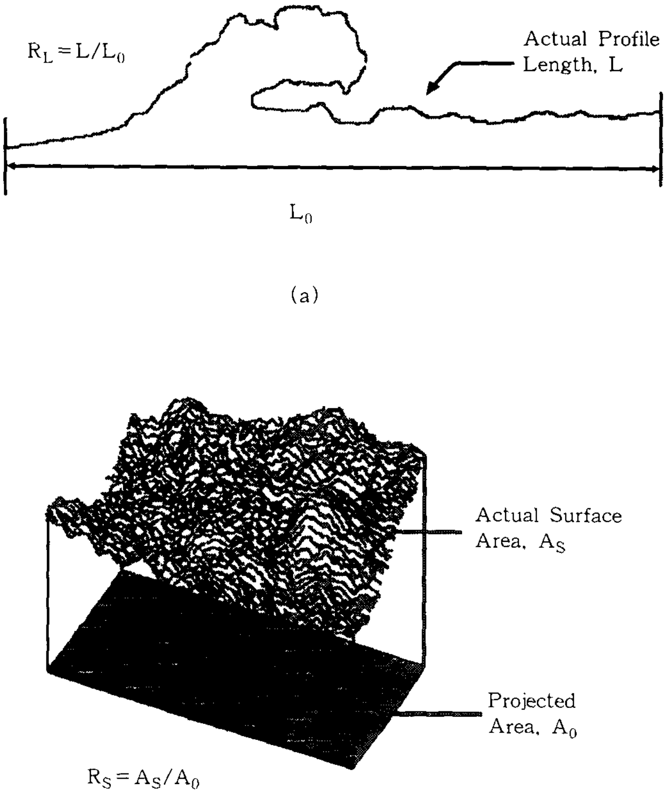
$$\varphi = \int_0^\pi [\sin \alpha + [\frac{\pi}{2} - \alpha] \cos \alpha] f(\alpha, \phi)\ d\alpha \tag{6}$$

where, $\alpha$ is the angle from vertical of a line segment on the profile and $\phi$ is the orientation of the normal to a vertical sectioning plane with respect to a reference axis. The quantity $f(\alpha, \phi)$ is the frequency distribution function of the line segment orientations over all two-dimensional profiles of the surface which provides information on the distribution of surface topography. Further details on the derivation is provided by Gokhale and Drury (1990) and Dove and Frost (1996).

Based on measurements made using OPM method, Dove and Frost(1996) proposed a geomembrane roughness classification scheme based on ranges of $R_S$ values as shown in Table 1.

Table 1. Geomembrane textural classification(after Dove and Frost, 1996)

| Textural Descriptor | $R_s$ Range |
|---|---|
| Smooth | 1.00 to 1.10 |
| Slightly Textured | 1.10 to 1.35 |
| Moderately Textured | 1.35 to 1.60 |
| Heavily Textured | Greater than 1.60 |



(a)

(b)

Figure 2. Definition of roughness parameters: (a) $R_L$: (b) $R_S$ (after Dove and Frost, 1996)

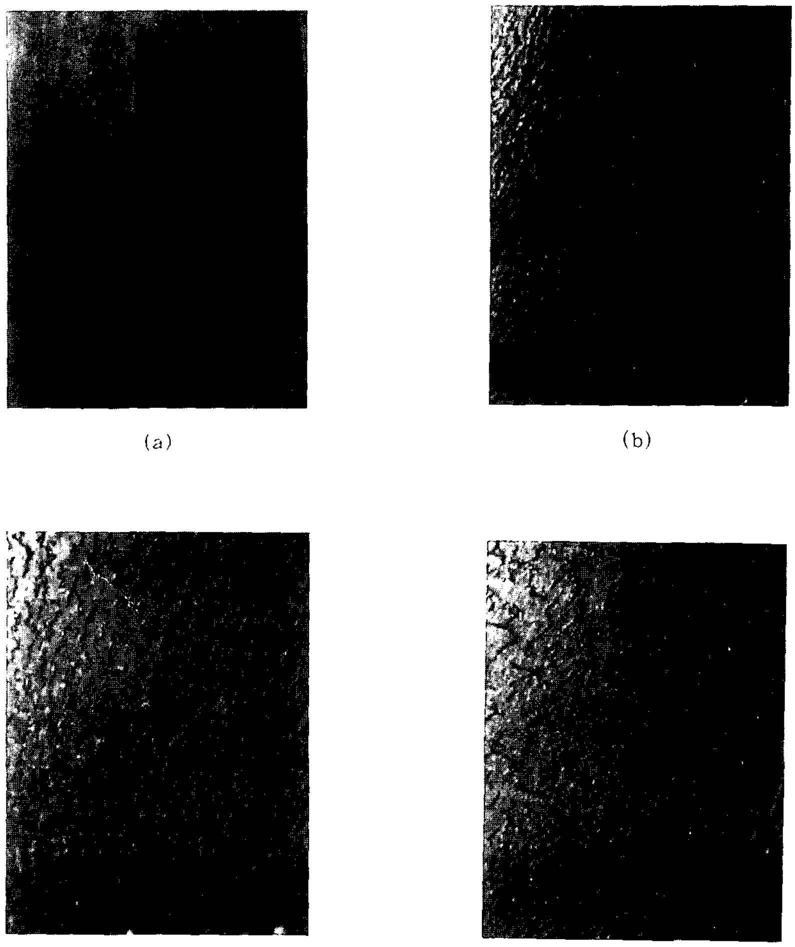
The parameters developed by Dove and Frost (1996) have two main disadvantages. First, the parameters do not necessarily have a directional relationship with shear direction. Second, the parameters do not account for the characteristics of other materials with which they are interacting. However, these two parameters, $R_L$ and $R_S$, have advantage over other roughness parameters in that intermediate amplitude textures which can be ignored, for example, in $R_{max}$ and $R_n$, can be easily incorporated. This means that these two parameters are sensitive to small changes of texture. A three-dimensional roughness parameter, $R_S$, has also advantage over a two-dimensional(single profile-based) parameter in that surface anisotropy can be accounted for.

## 5. Characterization of Geomembrane Surface Topography Using Digital Image Analysis

A series of roughness measurements on virgin and previously used geomembranes were performed using the digital image analysis based Optical Profile Microscopy(OPM) technique. This method permits profiling a wide range of geomembrane surfaces. The used geomembranes were taken from specimens on which interface shear tests between geotextiles and geomembranes had been performed. The virgin geomembranes were taken from the same roll of geomembrane as the used geomembrane specimens were taken from but were not used in any shear testing before their surface were quantified.

### 5.1 Geomembrane Evaluated

One smooth and three textured HDPE geomembranes which encompass the range of textures and texture patterns commonly used were analyzed in this study. Photographs of each geomembrane are shown in Figure 3. Figure 3(a) shows a typical smooth geomembrane surface manufactured by National Seal Co. (Dura Seal HD). This geomembrane has a very glossy surface. Figure 3(b) shows a typical textured geomembrane surface manufactured by GSE(Friction Flex). This has the least relief of the textured samples used in this study. Figure 3(c) is a typical textured surface from National Seal Co. (Friction Seal HD) which is the most highly anisotropic of the samples studied. The texture of this geomembrane is composed of rows of texture elements oriented in the cross machine direction with the surface between the texture elements being relatively smooth. The texture of the geomembrane surface was made by the extrusion coating technique in which a flat sheet coat hanger die is used to extrude a coating onto the surface of a previously made and tested smooth geomembrane(Donaldson, 1994). Figure 3(d) is representative of a highly textured geomembrane manufactured by Poly-Flex, Inc.(Poly-Flex Textured HDPE). This geomembrane has the most relief of the textured samples used in this study. The texture of this geomembrane was made by the blown coextrusion technique(Donaldson, 1994).



(a) (b)

(c) (d)

Figure 3. Images of representative geomembrane samples: (a) National Seal, Smooth: (b) GSE Lining Technology, Slightly Textured; (c) National Seal, Moderately Textured; (d) Poly-Flex, Moderately/Heavily Textured.

### 5.2 Preparation of Coupons for Optical Profile Microscopy(OPM) Method

Procedures for preparing coupons for study using the OPM method were similar to those developed by Dove(1996). Figure 4 shows a plan view of the sectioning planes and their orientations. Three coupons were obtained along three sectioning lines oriented at 120 degrees to each other to represent the three dimensional surface. Typically, the first sectioning line was chosen as the reference axis and was aligned parallel to the machine direction and shear direction. These coupons were embedded in a Plaster of Paris mixture having a cement to water ratio of 2.5:1. Plaster of Paris mixture was used in this study to enhance the contrast between the black geomembranes and the white background material, thereby yielding clearer images for subsequent measurements using image analysis. The sample molds consisted of circular plastic petri dishes with diameters of 90mm and depths of 18mm. The geomembrane specimens had lengths of 60mm and heights of 15mm.

Once a petri dish had been filled with Plaster of Paris, coupons were inserted on their edges through the paste with the cross section of interest placed firmly against the petri dish bottom. The surface of interest was then denoted as side A. Care was taken to insert the coupons as near vertically as possible.

After the Plaster of Paris material containing the coupons had hardened, the plastic petri dish was peeled away leaving a circular disk of material with a smooth base. Consecutive grinding and polishing of the smooth base was conducted to expose the geomembrane coupons using a commercial grinder/polisher apparatus. 120 grit sand paper and then 240 grit sand paper were used during grinding to expose the geomembrane coupons without damaging the specimen. Polishing cloth was then used to sharpen the boundary between the Plaster of Paris and the geomembrane. Figure 5 provides an example schematic of a completed disk showing the three coupons exposed for imaging.

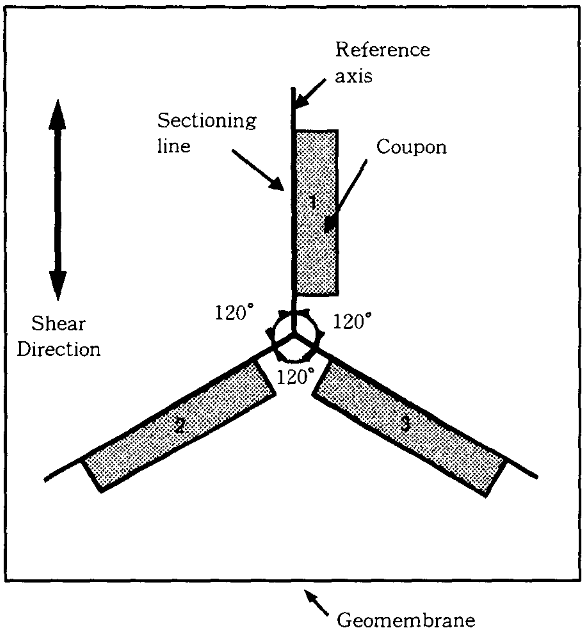


Figure 4. Vertical sectioning planes and orientations (adapted from Dove and Frost, 1996)

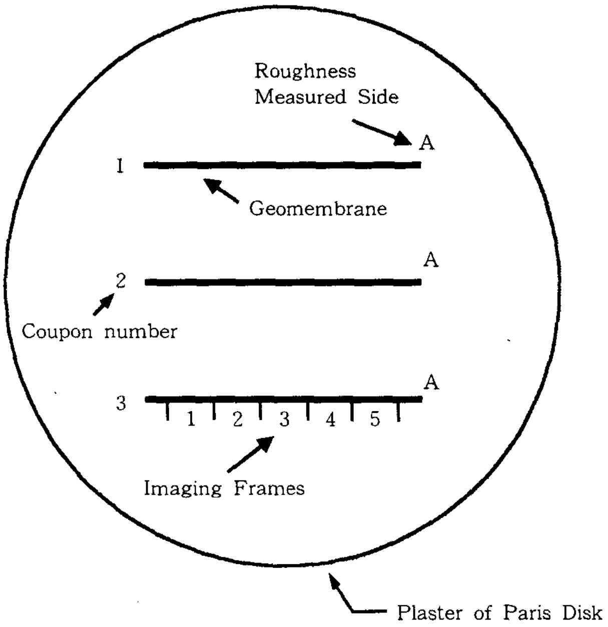


Figure 5. Bottom view of completed disk (adapted from Dove and Frost, 1996)

### 5.3 Digital Image Analysis

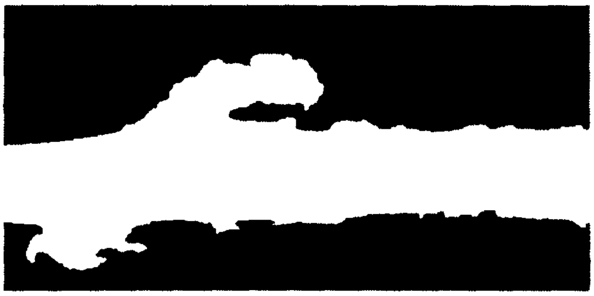
All image analyses in this study were performed on a Cambridge Instruments, Leica Quantimet Q-570 image analyzer. The system has a resolution of 512 pixels horizontally by 480 pixels vertically. Details of the systems and imaging methods used in this study can be found in Frost and Kuo(1996) and Dove and Frost(1996).

An important consideration in profiling is the selection of the appropriate magnification level and sufficient measuring length. As shown by Dove and Frost(1996), the magnification was chosen to represent the 7mm of geomembrane profile by 512 pixels on the computer screen which was considered sufficiently sensitive to the range of roughness used in this study. At this magnification, each imaging frame was 7mm in length, so that each parameter was determined by the profile length of 105mm(7mm × 5 images × 3 coupons) which was shown to be sufficient to obtain an accurate roughness value(Dove and Frost, 1996).

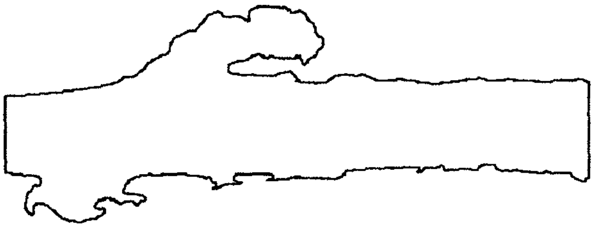
### 5.4 Data Acquisition

Once a gray image was captured by the CCD camera attached to the microscope, the binary image was extracted through the process of Detection which applies thresholds to the gray image. An example of a gray and its companion binary image are shown in Figures 6(a), and 6(b), respectively. The surface profile of the geomembrane was then obtained by using the Outline command which leaves only a single line of pixels representing the common boundary between background and geomembrane, as shown in Figure 6(c). Since the outline of only the side of geomembrane, denoted A, against which the shear strength test was conducted, was needed for determining the roughness value, the pixels making up the outline of the side not being examined and the two image boundaries were erased from the image using the binary image editing functions of the analyzer. The measurements of each parameter were then conducted based on the procedures proposed by Dove and Frost(1996).

(a) Gray Image



(b) Binary Image



(c) Outline Image

Figure 6. Image processing on textured geomembrane:(a) Gray Image; (b) Binary Image; (c) Outline Image

## 6. Results

As noted above, both virgin and used geomembrane roughness values were quantified in this study. Using the procedure described above, the following roughness parameters were measured:

- Profile Roughness Parameter ($R_L$)
- Surface Roughness Parameter ($R_S$)
- Normalized Roughness Parameter ($R_n$)

Table 2 presents the results obtained for virgin geomembranes of various roughness parameters including the means, standard deviations, and coefficients of variation.

Table 2. Results of surface roughness determinations of virgin geomembranes

| Manufacturer | Product | Membrane Number | Statistics | $R_L$ | $R_S$ | $R_n$ |
|---|---|---|---|---|---|---|
| GSE Lining Technology Inc. | Friction Flex | 2.2 | | 1.22 | 1.27 | 0.19 |
| | | 2.6 | | 1.19 | 1.24 | 0.17 |
| | | | Mean | 1.21 | 1.25 | 0.18 |
| National Seal Co. | Friction Seal HD | 3 | | 1.64 | 1.77 | 0.41 |
| | | 5 | | 1.38 | 1.46 | 0.30 |
| | | 9 | | 1.59 | 1.73 | 0.41 |
| | | 11 | | 1.42 | 1.51 | 0.31 |
| | | 17 | | 1.42 | 1.52 | 0.32 |
| | | | Mean | 1.49 | 1.60 | 0.35 |
| | | | Standard Deviation | 0.12 | 0.14 | 0.06 |
| | | | Coefficient of Variation | 0.08 | 0.09 | 0.17 |
| Poly-Flex, Inc. | Textured HDPE | 4 | | 1.49 | 1.59 | 0.34 |
| | | 8 | | 1.61 | 1.73 | 0.40 |
| | | 12 | | 1.55 | 1.67 | 0.39 |
| | | 22 | | 1.61 | 1.74 | 0.42 |
| | | 10 | | 1.63 | 1.77 | 0.44 |
| | | | Mean | 1.58 | 1.70 | 0.40 |
| | | | Standard Deviation | 0.06 | 0.07 | 0.03 |
| | | | Coefficient of Variation | 0.04 | 0.04 | 0.08 |

As shown in Table 2, $R_S$ values for textured virgin geomembranes range from 1.24 to 1.77, and appropriately represent the degree of texturing. The $R_L$ values also reflect the degree of texturing and range from 1.19 to 1.64. It is observed that $R_n$ values for the textured virgin geomembranes, however, show limited variation ranging from 0.17 to 0.44. This small ranges of variation may not be sufficient to permit distinction between roughness values for certain conditions.

The roughness determinations for virgin geomembranes obtained in this study are compared with those previously reported by Dove and Frost(1996) as shown in Table 3. The last column of Table 3 lists the corresponding texture descriptor as proposed by Dove and Frost(1996) and is based on the average value of $R_S$ as shown in Table 1. Roughness values measured in this study are slightly higher than their measurements, but do, however, exhibit similar trends.

Table 3. Comparison of roughness values with Dove and Frost (1996)

| Manufacturer | Product | Specimen Number | $R_s$ by Dove and Frost | $R_s$ Measured in this study | Textured Descriptor |
|---|---|---|---|---|---|
| National Seal Co. | Dura Seal HD (smooth) | 1 | 1.09 | 1.09 | Smooth |
| | | 2 | 1.07 | | |
| | | 3 | 1.08 | | |
| | | 4 | 1.08 | | |
| | | 5 | 1.09 | | |
| | | Mean | 1.08 | N/A | |
| | | Standard Deviation | 0.01 | N/A | |
| | | Coefficient of Variation | 0.01 | N/A | |
| GSE Lining Technology Inc. | Friction Flex | 1 | 1.17 | 1.27 | Slightly Textured |
| | | 2 | 1.20 | 1.24 | |
| | | 3 | 1.23 | | |
| | | 4 | 1.23 | | |
| | | 5 | 1.25 | | |
| | | Mean | 1.22 | 1.25 | |
| | | Standard Deviation | 0.03 | N/A | |
| | | Coefficient of Variation | 0.03 | N/A | |
| National Seal Co. | Friction Seal HD | 1 | 1.42 | 1.77 | Moderately Textured |
| | | 2 | 1.50 | 1.46 | |
| | | 3 | 1.53 | 1.73 | |
| | | 4 | 1.55 | 1.51 | |
| | | 5 | 1.45 | 1.52 | |
| | | Mean | 1.49 | 1.60 | |
| | | Standard Deviation | 0.05 | 0.14 | |
| | | Coefficient of Variation | 0.03 | 0.09 | |
| Poly-Flex, Inc. | Textured HDPE | 1 | 1.76 | 1.59 | Moderately/ Heavily Textured |
| | | 2 | 1.62 | 1.73 | |
| | | 3 | 1.54 | 1.67 | |
| | | 4 | 1.50 | 1.74 | |
| | | 5 | 1.49 | 1.77 | |
| | | Mean | 1.58 | 1.70 | |
| | | Standard Deviation | 0.11 | 0.07 | |
| | | Coefficient of Variation | 0.07 | 0.04 | |

Table 4 presents the results obtained from used geomembranes of various roughness parameters. It is noted that Table 4 includes roughness measurements made after different numbers of shear tests had been conducted, thus, the means, the standard deviations, and the coefficients of variation are not included. A similar trend is found for the used geomembrane surface roughness determinations to those for virgin geomembranes. $R_S$ and $R_L$ represent the degree of texturing appropriately, however, the various $R_n$ value exhibit narrow ranges.

Table 4. Results of surface roughness determinations of used geomembranes

| Manufacturer | Product | Membrane Number | $R_L$ | $R_S$ | $R_n$ |
|---|---|---|---|---|---|
| National Seal Co. | Dura Seal HD (smooth) | 1 | 1.07 | 1.09 | 0.06 |
| GSE Lining Technology Inc. | Friction Flex | 2 | 1.19 | 1.24 | 0.17 |
| | | 2.1 | 1.23 | 1.28 | 0.20 |
| | | 2.2 | 1.20 | 1.24 | 0.18 |
| | | 2.3 | 1.17 | 1.21 | 0.16 |
| | | 2.4 | 1.19 | 1.23 | 0.17 |
| | | 2.5 | 1.23 | 1.28 | 0.20 |
| | | 2.6 | 1.19 | 1.23 | 0.17 |
| National Seal Co. | Friction Seal HD | 3 | 1.38 | 1.45 | 0.27 |
| | | 5 | 1.25 | 1.30 | 0.21 |
| | | 7 | 1.42 | 1.52 | 0.33 |
| | | 9 | 1.32 | 1.39 | 0.25 |
| | | 11 | 1.40 | 1.49 | 0.30 |
| | | 13 | 1.47 | 1.58 | 0.36 |
| | | 15 | 1.38 | 1.45 | 0.25 |
| | | 17 | 1.41 | 1.51 | 0.32 |
| | | 19 | 1.45 | 1.55 | 0.30 |
| | | 21 | 1.38 | 1.46 | 0.30 |
| Poly-Flex, Inc. | Textured HDPE | 4 | 1.40 | 1.49 | 0.30 |
| | | 6 | 1.42 | 1.52 | 0.33 |
| | | 8 | 1.52 | 1.63 | 0.36 |
| | | 10 | 1.56 | 1.68 | 0.37 |
| | | 12 | 1.53 | 1.65 | 0.38 |
| | | 14 | 1.60 | 1.73 | 0.40 |
| | | 16 | 1.42 | 1.51 | 0.31 |
| | | 18 | 1.71 | 1.87 | 0.46 |
| | | 20 | 1.52 | 1.64 | 0.43 |
| | | 22 | 1.48 | 1.60 | 0.39 |
| | | 23 | 1.61 | 1.74 | 0.41 |
| | | 24 | 1.71 | 1.86 | 0.47 |

Roughness values measured after the first shear test are summarized in Table 5 along with their means, the standard deviations, and the coefficients of variation. It is observed that the variations of roughness determinations are strongly dependent on the manufacturing methods of geomembrane surface textures. For example, it is noted that the National Seal Friction Seal HD has a higher standard deviation than the Poly-Flex Textured geomembrane for the virgin geomembrane even though its average roughness value is smaller. However, the roughness values after the first shear

Table 5. Average roughness values after first shear test

| Manufacturer | Product | Statistics | $R_L$ | $R_S$ | $R_n$ |
|---|---|---|---|---|---|
| GSE Lining Technology Inc. | Friction Flex | | 1.23 | 1.28 | 0.20 |
| | | | 1.17 | 1.21 | 0.16 |
| | | | 1.19 | 1.23 | 0.17 |
| | | | 1.23 | 1.28 | 0.20 |
| | | | 1.19 | 1.23 | 0.17 |
| | | Mean | 1.20 | 1.25 | 0.18 |
| | | Standard Deviation | 0.03 | 0.03 | 0.02 |
| | | Coefficient of Variation | 0.02 | 0.02 | 0.12 |
| National Seal Co. | Friction Seal HD | | 1.42 | 1.52 | 0.33 |
| | | | 1.40 | 1.49 | 0.30 |
| | | | 1.47 | 1.58 | 0.36 |
| | | | 1.38 | 1.45 | 0.25 |
| | | | 1.41 | 1.51 | 0.32 |
| | | | 1.45 | 1.55 | 0.30 |
| | | | 1.38 | 1.46 | 0.30 |
| | | Mean | 1.42 | 1.51 | 0.31 |
| | | Standard Deviation | 0.04 | 0.05 | 0.03 |
| | | Coefficient of Variation | 0.02 | 0.03 | 0.10 |
| Poly-Flex, Inc. | Textured HDPE | | 1.56 | 1.68 | 0.37 |
| | | | 1.53 | 1.65 | 0.38 |
| | | | 1.60 | 1.73 | 0.40 |
| | | | 1.42 | 1.51 | 0.31 |
| | | | 1.71 | 1.87 | 0.46 |
| | | | 1.52 | 1.64 | 0.43 |
| | | | 1.61 | 1.74 | 0.41 |
| | | | 1.71 | 1.86 | 0.47 |
| | | Mean | 1.58 | 1.71 | 0.40 |
| | | Standard Deviation | 0.10 | 0.12 | 0.05 |
| | | Coefficient of Variation | 0.06 | 0.07 | 0.13 |

test indicate that the National Seal Friction Seal HD has a lower standard deviation than the Poly-Flex Textured geomembrane. This is due to the differences in the manufacturing of geomembrane surface textures. The National Seal Friction Seal HD has an easily breakable surface texture. Part of the surface texture of this geomembrane might have been damaged during the manufacturing, packing(rolling for transportation), and unpacking of the geomembrane. This may be the cause for the greater variations in roughness values measured for the virgin geomembranes. The remaining easily breakable surface texture can be easily removed during the first shear test, thus consistent surface texture throughout the geomembrane specimen can be achieved. Consequently, smaller standard deviation is achieved than Poly-Flex Textured geomembrane after first shear test. In addition, the National Seal Friction Seal HD has rows of texture elements oriented in the cross machine direction with a relatively smooth zone in between. These variability in the manufacturing process produces the most highly anisotropic structure and results in the largest coefficient of variation of the geomembranes used in this study.

## 7. Conclusions

Focusing on a geomembrane surface which encompasses the range of textures and texture patterns commonly used as a material to be quantified, three surface roughness parameters($R_L$, $R_S$, and $R_n$) were measured and quantified in this study.

Generally, both $R_L$ and $R_S$ values appropriately reflect the degree of texturing for the geomembranes used in this study, however, $R_n$ value showed limited ranges of variation which may not be sufficient to permit distinction between roughness values for certain conditions. However, the general trend of the various surface roughness parameters measured in this study exhibits similar trend of roughness values. It is noted that the general observations found in this study are based on the results of geomembrane textures and texture patterns examined in this study. Geomembranes of other texture patterns should be fully investigated.

This study was mainly focused on the basic research for quantification of surface roughness. This study can be extended for the roughness measurements of joints in rock mass. Further study also will be carried out to investigate the relationship between the interface shear strength and the surface roughness measured in this study.

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