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# Farklı Geomembran Astarlarının 2B Yüzey Topografyası Değişimleri: Danecik Şekli, Bağıl Yoğunluk ve Yükleme Perspektifleri

**Tanay KARADEMİR**[1*]

[1]İstanbul Bilgi Üniversitesi, Mühendislik ve Doğa Bilimleri Fakültesi, İnşaat Mühendisliği Bölümü, 34060, İstanbul

[1]https://orcid.org/0000-0002-9689-2140
*Sorumlu yazar: tanay.karademir@bilgi.edu.tr

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## ÖZ

Farklı geomembranların, 2 boyutlu yüzey topografisi değişiklikleri, daha önce farklı bağıl yoğunluklarda ($D_r$) ve farklı danecik şekillerinde (yuvarlak veya köşeli) ve ayrıca çeşitli yükleme koşullarında granüler kumun aşındırıcı etkisine maruz bırakılmış değişik polimerik reçinelerden (HDPE, LLDPE, PVC) üretilen farklı geomembran astar tabakalarının 2 boyutlu yüzey topografyası karakteristik özelliklerini tespit etmek ve belirlemek için profil kabarma ölçümleri gerçekleştirilerek deneysel olarak incelenmiştir. Topografyalardaki tepe ve vadilerden oluşan malzeme dislokasyonlarının boyutu, şekli ve aralıkları gibi pürüzlülük özellikleri de dahil olmak üzere tespit edilen profillerde açıkça görülen yüzey topoğrafik özellikleri farklı ve geomembran tipine özgüdür. Bu nedenle, HDPE, LLDPE, PVC sırasına göre geomembran astar tabakası ne kadar yumuşak ve esnek olursa, yüzey topoğrafyasının daha şiddetli tepeler ve vadiler göstermesi nedeniyle aşınma o kadar fazla gelişir. Ayrıca, kum danelerinin şekilsel özellikleri, köşeli-sivri parçacıkların geomembran astarının yüzeyine nüfuz edebilmesi ve dolayısıyla yüzey boyunca bir yörünge çizebilmesi nedeniyle daha şiddetli aşındırıcı etkinin harekete geçmesine yol açmıştır. Geomembranların ölçülen yüzey topoğrafyaları için belirlenen ortalama pürüzlülüğün ($R_a$) hesaplanan değerleri aracılığıyla farklı geomembrane astarların yüzey topoğrafyası değişiminin niceliği, $R_a$'nın (yani, yüzeysel topografik çeşitliliğin) yük, bağıl yoğunluk, dane şeklinin parçacık sivriliği, ve geomembran astar tabakasının yumuşaklığının artışıyla arttığını ortaya çıkardı. Yuvarlak daneli kum sistemi için, bağıl yoğunluk %45'ten %85'e ve normal stres 75 kPa'dan 150 kPa'a çıktığında, $R_a$ değeri HDPE, LLDPE, PVC geomembran astarları için sırasıyla %129, %133, %137 arttı. Köşeli daneli kum sistemi için, bağıl yoğunluk %45'ten %85'e ve normal stres 75 kPa'dan 150 kPa'a çıktığında, $R_a$ değeri HDPE, LLDPE, PVC geomembran astarları için sırasıyla %234, %242, %262 arttı.

# 2D Surface Topography Alterations of Different Geomembrane Liners: Grain Shape, Relative Density and Loading Perspectives

**Research Article**

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## ABSTRACT

The 2D surface topography alterations of different geomembranes were experimentally be studied by performing profile relief measurements for detecting and determining 2D surface topographical characteristics of different geomembrane liner sheets produced from distinctive polymeric resins (HDPE, LLDPE, PVC) previously subjected to abrasive action of granular sand grains at different relative densities ($D_r$) and dissimilar particle shape (rounded or angular), and additionally at various loading conditions. The surface topographical characteristics as evident on the detected profiles including asperity features such as size, shape, and spacing of material dislocations

Grain shape
Relative density

comprised of peaks and valleys in the topographies were different and unique to geomembrane type. As such, the softer and the more flexible the geomembrane liner sheet in an order of HDPE, LLDPE, PVC becomes, the greater the abrasion has developed in that the surface topography demonstrated more severe peaks and valleys. Further, the angular features of sand grains led to the mobilization of more violent abrasive action in that angular particles were able to penetrate into the surface of geomembrane liner, and thus, gouge on a trajectory along the surface. The quantification of surface topography alterations of different geomembranes by means of the computed values of average roughness ($R_a$) determined for the measured surface topographies of the liners unveiled that the $R_a$ (i.e. surficial topographical changes) increases with an increase in load, relative density, particle angularity of grain shape, and softness of geomembrane liner sheet. For the rounded sand system, the value of $R_a$ increased 129%, 133%, 137% for HDPE, LLDPE, PVC geomembrane liners, respectively when the relative density arised from 45% to 85% as well as the normal stress raised up from 75 kPa up to 150 kPa. For the angular sand system, the value of $R_a$ increased 234%, 242%, 262% for HDPE, LLDPE, PVC geomembrane liners, respectively when the relative density arised from 45% to 85% as well as the normal stress raised up from 75 kPa up to 150 kPa.

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## 1. Introduction

Surface topography is of importance in playing a major role for the mobilized mechanical behavior, and hence, the strength-stability performance of composite layered systems containing synthetic geomembrane liner and natural granular sand. The interaction of one material with the other one is investigated within the scope of contact mechanics. The interaction of synthetic geotechnical materials (e.g. geomembranes) with a natural construction material (e.g. sand) result in alteration of surface topography of synthetic geomembranes produced from different base polymers (e.g. high-density polyethylene (HDPE), linear-low-density polyethylene (LLDPE), polyvinylchloride (PVC)). This is due to inherent softness nature of polymeric geomembrane liner sheets as well as the abrasive texture (i.e. micro-structure) of natural granular material sand. For this reason, the index and physical properties of sand (e.g. relative density, grain shape) and their role as well as the capability in altering surface topography of counterface geomembrane when employed as a composite layer system, adjacent to each other, in infrastructural applications for geotechnical projects including embankments, landfills, dams should be examined in detail and determined in relative terms. In this way, the mechanical behavior of those geo-materials can be engineered by capturing the degree for the importance of manufacturing material characteristics of synthetic geomembrane liners as per core polymer type (HDPE, LLDPE, PVC) and/or the degree for the influence of physical and index properties of natural granular material sand as per relative density and grain shape. Since this interaction and contact behavior can impact the performance and constructability of the aforementioned infrastructural applications in which the geosynthetic liners, comprised of geomembrane layers, interact and contact with granular sands. To this end, a comprehensive experimental study was conducted to investigate and evaluate the resultant surficial wear quantitatively induced on the geomembrane liner surfaces due to abrasive action of granular sand particles based on diversifying boundary conditions (i.e. loading conditions), geomembrane core material properties (i.e. HDPE, LLDPE, PVC), counterface particulate material physical properties (i.e. sand grain shape (rounded or angular), relative density). This current study is unique in terms of the type of base/core material of the selected geomembranes such as LLDPE, PVC to detect surface topographical alterations as well as in terms of the relatively large range of relative densities from 45% up to 85% examined throughout the laboratory testing program. Additionally, the tested sand specimens were intentionally selected with different morphologies including distinct morphological properties such as roundness, sphericity, angularity, and regularity. In earlier research studies, the HDPE geomembrane type was generally preferred to be a liner material as well as similar granular materials possessing identical morphological characteristics were in general selected to be utilized in the laboratory experimental programs. On the other hand, the geomembrane liners produced from the base polymeric materials such as LLDPE and PVC have recently utilized widely in both geotechnical and geoenvironmental projects including infrastructural facilities (e.g. embankments, dams) and environmental applications (e.g. landfills). Further, the influence of grain shape of counterface particulate materials being roundness or angularity of soil particles is necessarily required to be analyzed in detail by varying or preserving the other physical characteristics of the selected sand test specimens such as mean grain size, specific gravity in order to discern the effect of sand morphological properties.

## 2. Surface Topography Characterization and The Relevant Previous Research

Surface topography is of importance in playing a major role for the mobilized mechanical behavior, and hence, the strength-stability performance of composite layered systems containing synthetic geomembrane liner and natural granular sand that are placed as a counterface to each other. Among various surface topography determination parameters developed to characterize topographical alterations, the most commonly utilized parameter to quantify and quantize those alterations in surficial topography is the average roughness parameter ($R_a$) (Ward, 1982) that could be computed as follows:

$$R_a = \frac{\left(\int_0^L |z(x)| dx\right)}{L} \tag{1}$$

Where:

L: Assessment Length

z(x): Height of the Profile from the mean line

Moreover, a different concept, called normalized roughness ($R_n$) to characterize surface topographical characteristics of continuum materials such as geomembranes, was proposed by Uesugi and Kishida (1986). The $R_n$ parameter accounts also for the relative aspect of the roughness such that the ratio of maximum roughness ($R_{max}$) with respect to the mean grain size ($D_{50}$) of counterface granular material (sand). Furthermore, DeJong and Frost (2002) conducted a comprehensive research study and unveiled the relevance of the relative aspect of surface roughness. As such, when a spherical particle is travelling on a simplified rough surface consisting of simple surficial topographical features of peaks and valleys, the influence of peaks and valleys on the trajectory of the spherical particle is not the same (dissimilar) with the path over which the centroid trace of that individual particle. Further, the vertical deviation from the centroid trace is distinct for different sizes of particles.

The alterations in surface topography of such a soft, flexible synthetic material geomembrane is caused by the penetration of relatively harder counterface granular sand particles into the softer surface of geomembrane liners, and thus, ploughing on a trajectory along the surface. This incident and/or this observed mechanism results in abrasion in geomembrane, and hence, decreases the durability leading to deterioration of endurance properties due to induced damage by sand particles. The severity and the significance of the abrasion produced on the surface of the liner is attributed to the material properties of core polymer of the geomembrane (i.e. HDPE, LLDPE, PVC) as well as the particulate characteristics and index properties of the granular sand (i.e. relative density, particle shape). Related research by Frost et al. (2002) numerically investigated that the hardness/softness properties of the geomembrane liners can be linked and coupled to the alterations in surficial topographical features generated by counterface sand grains. In order to demonstrate this, they performed discrete element modeling (DEM) for the distinct particulate versus continuum material interfaces such that the DEM provided insight on the behavior at global level (i.e. macro level), and additionally, extend the understanding on the mechanism regarding local particle response at micro level in penetrating and ploughing along the surface of counterface geomembrane leading to the changes in topography.

Furthermore, another research study on the quantitative measurement of induced surface changes in the geomembranes due to shearing effect by Vangla and Gali (2016) revealed that the shearing mechanism at the interface governed by critical normal stress level dependent on both granular material and geomembrane characteristics plays a vital role on the resultant mutual interaction developed between soil and synthetic polymeric materials. Moreover, Araujo et al. (2022) published the result of a specific study concerned with the geomembrane inherent surface roughness at production stage instead of induced abrasive wear at post-production stage or in-application (in-employment) phase. Their findings showed that the mean height of profile elements on the geomembrane liner surface and the liner core (base) material volume presented stronger correlations with the resultant generated mutual interaction along with counterface materials. Further, the change pattern of geomembrane surface roughness for textured geomembranes was examined by Xu et al. (2023). It was shown that the application of texture on the geomembrane surface improves frictional performance. On the other hand, the variation in the roughness of textured surface affects the surface deformation characteristics of geomembrane liner, and thus, induced wear on the liner surface controlled by the asperity height of the textural elements on the geomembrane surface.

A different study on the geomembrane mutual interaction along with a dissimilar counterface material being geosynthetic clay liners (GCL) was carried out by Feng et al. (2022) to observe the topographical alterations on the surface of geomembrane liners when being in direct contact with GCLs employing multi-functional laboratory apparatus. It was investigated that the surface roughness of geomembrane liners and the hydration condition of geosynthetic clay liners prominently influence the mechanical interaction between the geomembrane and the GCL as well as the resulting surficial topographical changes at the contact surface. Furthermore, Adeleke et al. (2021) published the influence of the resulting asperities located on the geomembrane surface based on roughness and topographical alterations on the surficial features of the liners. It was detected that as the surface texturing was increased, a more pronounced wear/abrasion occurred that resulted in observing deeper mechanical interaction.

Xia et al. (2024) reported the experimental and numerical results of a geoenvironmental study concerned with the geomembrane liners subjected to mutual interaction with municipal solid waste (MSW) samples of different ages in landfill applications. It was shown that the sliding surface of geomembrane-lined landfills is discontinuous at the lining interface, which can delay the penetration of slip surfaces and block the formation of slip, and thus, prevent substantial abrasive wear induced on the geomembrane liners. Although they revealed the mutual interaction between geomembranes and MSW of different ages, and the resulting wear on the liner surface, they didn't either measure the occurrence of surficial wear or quantify the degree and severity of this induced abrasive action and the resultant surface topographical changes developed on the liner surface of geomembranes produced from distinct base/core polymer resins such as HDPE, LLDPE, and PVC. In this regard, the current study presented in this paper could supplement the previous study of Xia et al. (2024) by extending understanding in terms of the detection and the quantification of surface topographical alterations on the geomembrane liners manufactured from various base polymeric materials including HDPE, LLDPE, PVC due to induced abrasive action, and hence, the generated surficial wear.

Using micro computed tomography and shear band analysis; soil and geosynthetic material interaction was studied to extend multi-scale understanding by Khan and Latha (2023). They were interested in shape parameters of sand particles including convexity, aspect ratio, and roughness that were quantified at different scales. The current study presented in this paper that deals with sand particle roundness or angularity and their quantification will complement the earlier study of Khan and Latha (2023) in this origin. Besides, one-dimensional surface profile measurements performed in this current study will aid the readers in comprehending the developed form and the generated pattern of surface topographical changes along with further engineering quantification by means of quantitative parameters such average roughness ($R_a$).

As evidently seen from the relevant studies published in the literature and discussed earlier, an experimental study is necessarily required to fill the gap in terms of the assessment of 2D surface topography alterations of different geomembrane liners produced from distinct base polymeric materials including HDPE, LLDPE, PVC due to abrasive action (i.e. wear) induced by granular counterface materials (i.e. sandy soils) at different grain shapes (i.e. rounded or angular), at various relative densities ($D_r$: 45%, 65%, 85%), and at a range of loading conditions from 75 kPa up to 150 kPa. Further, the detected surficial topographical changes on the geomembrane liners are required to be quantitatively evaluated by means of roughness parameters such as average roughness ($R_a$) in order to comprehend the degree, magnitude and significance of surficial wear induced on the geomembrane liners due to abrasive action of granular particulate materials (i.e. sand) that are in direct contact and interaction with geomembranes employed in geotechnical and geoenvironmental projects in the infrastructural field applications including embankments, landfills, artificial ponds. The engineering quantification and the comparative analysis conducted in the current study and presented in this paper as well as the test results and the experimental findings of the laboratory program not only fill the gap in the literature regarding the detection and the quantitative evaluation of the resultant polymeric material condition due to abrasive wear but also will provide a comprehensive understanding for the engineers in design and the contractor practitioners in construction sites in terms of material selection, the resulting mutual compatibility of the preferred materials, and the consequential changes exhibited on the physical characteristics, mechanical properties of the selected materials in construction as well as operation stages. In this way, the design engineers and the contractor practitioners would be able to estimate stable durability and secure lifespan of the utilized polymeric geomembranes and particulate granular soils as well as their safe and secure mutual interaction in the multi-layered composite systems typically applied in infrastructural facilities including embankments, landfills and artificial ponds.

## 3. Geomembrane Liner Types and Granular Materials

### *3.1. Types of Geomembrane Liners*

The geomembrane liner sheets utilized throughout the testing program consist of three different types produced from distinct base polymer resins including high-density-polyethylene (HDPE), linear-low-density-polyethylene (LLDPE) and polyvinylchloride (PVC) to investigate the influence of base polymer type, and hence, the softness/hardness characteristics of the lining sheets on the alterations of surficial topographical features. All the selected geomembrane liners possess thickness of 1 mm (40 Mil). The specific gravity ($G_s$) of HDPE, LLDPE, and PVC geomembranes are 0.94, 093, and 1.20, respectively. Those three types of liner sheets are widely preferred, commonly utilized geomembranes in geotechnical infrastructural applications and geoenvironmental projects owing to the enhanced strength properties particularly for the geomembranes produced from HDPE base polymer and owing to the superior flexibility characteristics especially for the liners manufactured from LLDPE as well as PVC base polymeric materials.

### *3.2. Granular Materials*

In the experimental program, two different types of sand were used to examine the influence of particle shape such that the one comprised of rounded grains whereas the other composed of angular grains. Additionally, the sand specimens were prepared at three different relative densities ($D_r$) including $D_r$: 45%, 65%, and 85% to evaluate the effect of an important physical index property of granular materials on the resulting abrasion induced into counterfaced geomembrane liner sheets. In order to evaluate the principal role of only the shape (i.e. angularity versus roundness) of sand grains (i.e. particles), the testing materials were purposefully selected in such a way that they possess similar index properties including average particle size, identical soil particle gradation with an only exception of grain shape. The index properties are presented in Table 1 below. The mean particle sizes of the two sand specimens tested in the comprehensive experimental program were selected to be similarly identical in an intention to examine the predominant influence of sand grain shape (i.e. rounded or angular) on the resultant abrasion observed on the polymeric liner surfaces. The sand specimens prepared at different relative densities ranging from 45% up to 85% are expected to be exhibiting different mutual interaction with the counterface continuum materials being geomembrane liners possessing distinctive core polymeric resins and having different softness or hardness characteristics as well as having distinct flexibility or stiffness.

**Table 1.** Index Properties of Granular Materials Used In Experimental Program

| Granular Material | $D_{50}$ (mm) | $C_u$ | $C_c$ | $G_s$ |
|---|---|---|---|---|
| ***Rounded Sand*** | 0.72 | 1.39 | 0.88 | 2.67 |
| ***Angular Sand*** | 0.75 | 1.34 | 0.71 | 2.67 |

## 4. 2D Surface Topography and Profile Relieves

The relevance in between surface topography of continuum materials as well as alterations in surficial topographical characteristics and frictional mechanism, mechanical behavior as well as strength properties has been emphasized by various researchers including Potyondy (1961), Brumund and Leonards (1973), Uesugi and Kishida (1986), Paikowski et al. (1995), Frost et al. (2002), Vangla and Gali (2016), Araujo et al. (2022), Khan and Latha (2023), Xu et al. (2023), and Xia et al. (2024). To this end, the two dimensional (2D) surface topography alterations of a synthetic geo-material (geomembrane) and its different types manufactured from distinct base polymers that are commonly utilized in typical geotechnical applications including the infrastructural projects such as embankments, landfills, dams was intended to experimentally be studied by the author. This was achieved by performing profile relief measurements for detecting and determining 2D surface topographical characteristics of different geomembrane liner sheets produced from distinctive polymeric resins (HDPE, LLDPE, PVC) previously subjected to abrasive action of granular sand grains at different relative density and dissimilar particle shape (rounded or angular), and additionally at various loading conditions. In this way, the degree of influence of geomembrane polymeric material characteristics and sand physical index properties as well as the state of the composite system – comprised of sand and geomembrane – due to diverse loading situations on the resulting alterations in surface topography as per surficial profile variations in terms of generated peaks and valleys as a result of material dislocations will be investigated by means of a testing program conducted in the laboratory using stylus profilometer (Figure 1).

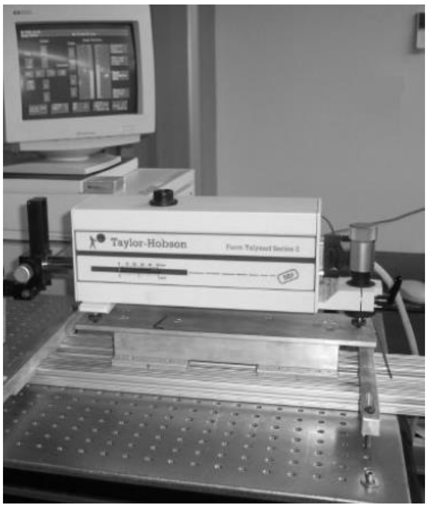



**Figure 1.** Stylus Profilometer to Quantify Surface Topography

In light of experimental surfacial topographical detections of geomembrane specimens through profilometer measurements, the characteristics of 2D surface topography alterations of the specimens were quantified and quantized using a universally recognized surface topography parameter being average roughness ($R_a$) (Equation 1). As such, this quantification based on an important roughness parameter will evidently aid the researchers to obtain a comparative analysis for the resultant wear generated on the surface of polymeric geomembrane liners due to sand abrasion.

*4.1. 2D Surface Topographies*

The performed comprehensive testing program in the laboratory by means of stylus profilometer consists of 36 surface topography quantification measurements to detect one-dimensional surface topographies of geomembrane liners manufactured from three different core polymers including high-density polyethylene (HDPE), linear-low-density polyethylene (LLDPE) and polyvinylchloride (PVC) and subjected to various loading conditions ranging from 75 kPa up to 150 kPa and subsequent shearing against different granular sands having dissimilar grain shape (rounded or angular) and distinct relative densities ranging from 45% up to 85% (Table 2). In this way, it was intended to investigate the influence of base polymer of geomembrane liner and relative density, and grain shape of sand particles as well as the effect of loading conditions on the resultant abrasive wear induced on geomembrane surface. The profilometer device utilized in the experimental program to measure and evaluate geomembrane surficial topographical variations is a computer-automated and controlled testing system as well as connected to a data acquisition system in order to log measurement data during the tests.

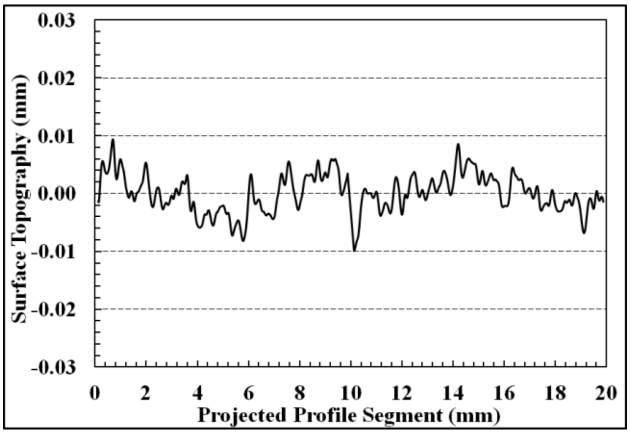
The quantification of 36 surface topographical alterations were evidently sufficient in order to comprehend the behavioral changes, the generated patterns, and the developed forms of surficial wears mobilized due to abrasive action of sand particles being in direct contact with the surface of geomembrane liners manufactured from various core material polymer resins being relatively hard, and stiff (e.g. HDPE) or contrarily being relatively soft, and flexible (e.g. PVC).

**Table 2.** Laboratory Testing Program

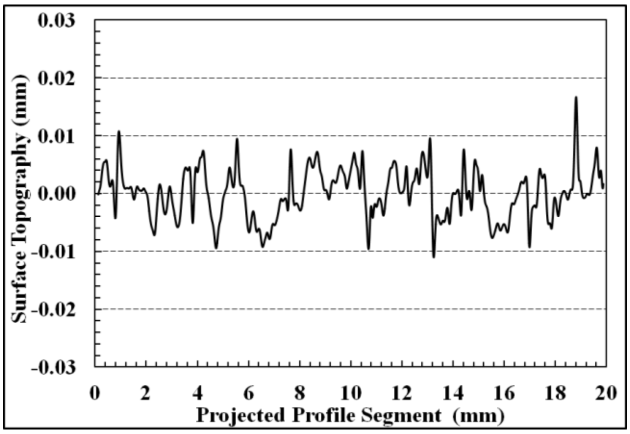
| Geomembrane Type | σ = 75 kPa | | | | | | σ = 150 kPa | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **HDPE** | ***Rounded Sand*** | | | ***Angular Sand*** | | | ***Rounded Sand*** | | | ***Angular Sand*** | | |
| | $D_r$: 45 | $D_r$: 65 | $D_r$: 85 | $D_r$: 45 | $D_r$: 65 | $D_r$: 85 | $D_r$: 45 | $D_r$: 65 | $D_r$: 85 | $D_r$: 45 | $D_r$: 65 | $D_r$: 85 |
| **LLDPE** | ***Rounded Sand*** | | | ***Angular Sand*** | | | ***Rounded Sand*** | | | ***Angular Sand*** | | |
| | $D_r$: 45 | $D_r$: 65 | $D_r$: 85 | $D_r$: 45 | $D_r$: 65 | $D_r$: 85 | $D_r$: 45 | $D_r$: 65 | $D_r$: 85 | $D_r$: 45 | $D_r$: 65 | $D_r$: 85 |
| **PVC** | ***Rounded Sand*** | | | ***Angular Sand*** | | | ***Rounded Sand*** | | | ***Angular Sand*** | | |
| | $D_r$: 45 | $D_r$: 65 | $D_r$: 85 | $D_r$: 45 | $D_r$: 65 | $D_r$: 85 | $D_r$: 45 | $D_r$: 65 | $D_r$: 85 | $D_r$: 45 | $D_r$: 65 | $D_r$: 85 |

In addition to qualitative distinctions, quantitative differences as well as visual variations were investigated from surficial topographical profiles of different geomembranes. The surface topographies of HDPE, LLDPE and PVC geomembrane liner sheets, quantified for the loading condition of 75 kPa normal stress level and relative density of 45%, and subjected to abrasive action of rounded or angular sands, are shown in Figure 2 for clear presentation of experimental data and explicit clarification of surficial topographical profiles.

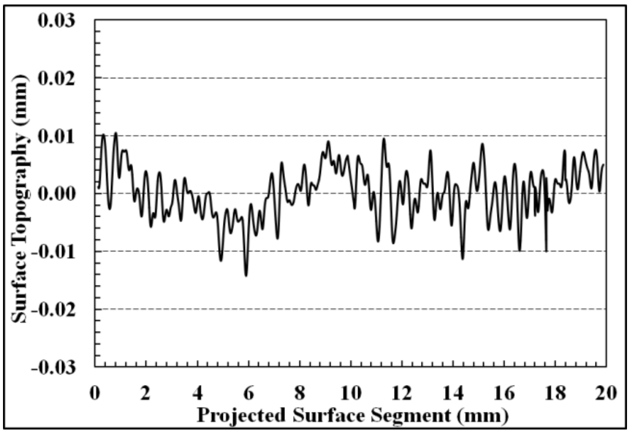
As per Figure 2, the surface topographies detected over a projected profile segment of 20 mm on three different types of geomembranes produced from distinct polymeric resins including HDPE, LLDPE, PVC subjected to abrasive action of rounded or angular sand particles are evidently demonstrate the influence of the grain shape of sandy soil. The higher the angularity of sand particles the larger and severer abrasion and wear induced on the geomembrane liners regardless of base polymer type of the geomembrane that could be either HDPE, LLDPE, or PVC. Furthermore, the effect of geomembrane base polymer is evidently observed from the resultant surface topographies developed as a result of particulate material (i.e. sand) abrasive action such that as the geomembrane becomes relatively harder and less flexible in an order from PVC to LLDPE, and then to HDPE, the abrasive wear induced on the geomembrane liner decreases. As such, the lower the abrasion generated in which the surface topography demonstrated smaller ups and downs in terms of minor peaks and valleys. In this regard, the most intense (i.e. violent) surficial abrasion was exhibited in the softest and the most flexible geomembrane manufactured from PVC and subjected to the abrasive action of angular sand, while the most mild (i.e. gentle) abrasive wear was displayed in the hardest and the most stiff (inflexible) geomembrane produced from HDPE and exposed to the abrasive action of rounded sand.



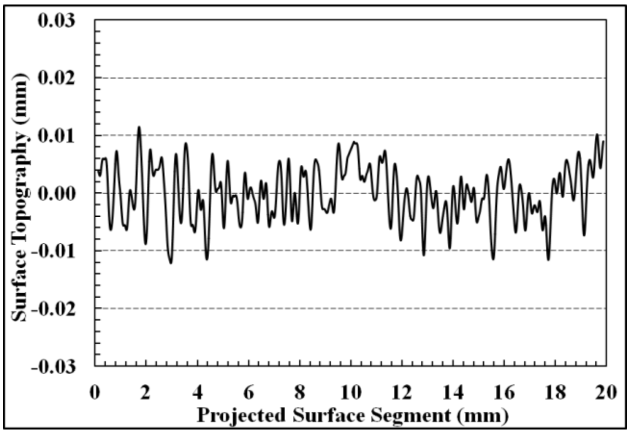

**(a)** HDPE Geomembrane: Rounded Sand Abrasion



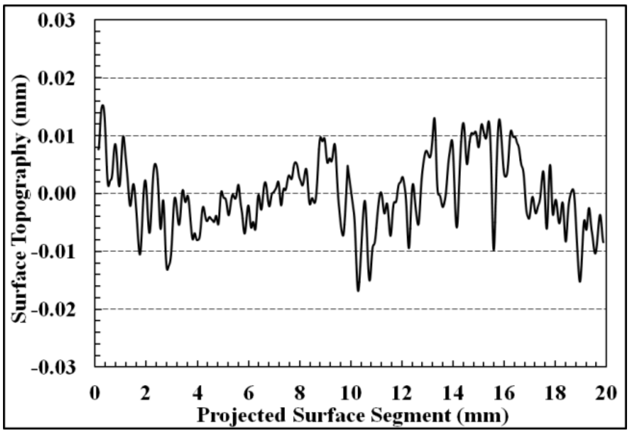

**(b)** HDPE Geomembrane: Angular Sand Abrasion



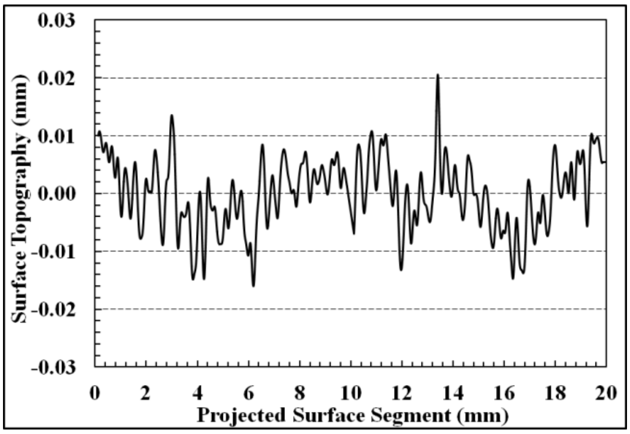

**(c)** LLDPE Geomembrane: Rounded Sand Abrasion




**(d)** LLDPE Geomembrane: Angular Sand Abrasion




**(e)** PVC Geomembrane: Rounded Sand Abrasion




**(f)** PVC Geomembrane: Angular Sand Abrasion

**Figure 2.** Surface Topographies of HDPE, LLDPE, PVC Geomembrane Liners (σ: 75 kPa and $D_r$: 45%)

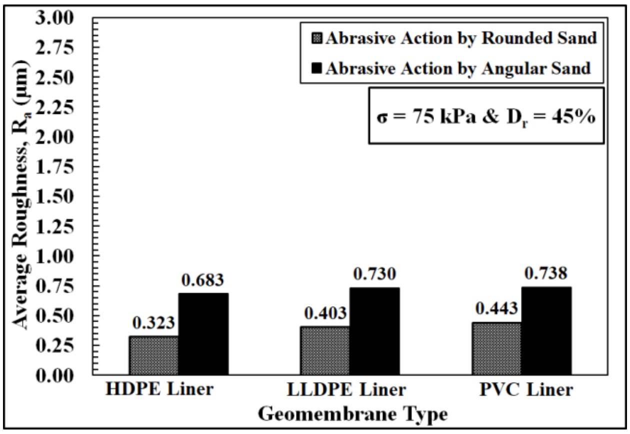
Furthemore, in addition to the effect of granular soil particle shape, it was seen that the softness, hardness characteristics of the geomembrane liners based on the flexibility, stiffness properties also strongly influence and prominently control the degree, magnitude and significance of surficial wear induced due to abrasive action of granular soils (i.e. sandy soils). When the hardness of geomembranes used in the study including HDPE, LLDPE, PVC liners are compared with that of sandy soils utilized in the testing program, the geomembranes possess relatively softer nature. On the other hand, the three distinct types of geomembranes were selected intentionally to investigate the effect of liner flexibility such that the PVC geomembranes serve relatively higher flexibility while the HDPE geomembranes show relatively larger stiff nature and the flexibility properties of LLDPE is being in between those two geomembrane types aforementioned.

The fluctuations in the data in Figure 2 are attributed to the variations in surface topographical characteristics of the geomembrane liners. Considering surface topographies as demonstrated in Figure 2 where the traverses are evident on the profiles, asperity features such as size, shape, and spacing of material dislocations including peaks and valleys in the topographies were different and unique to geomembrane type. As such, the softer the geomembrane liner sheet (HDPE ➔ LLDPE ➔ PVC) becomes, the greater the abrasion has developed in that the surface topography demonstrated more severe peaks and valleys (i.e.  ups and downs). Furthermore, the angular features of sand grains led to the mobilization of more violent (i.e. aggressive) abrasive action in that angular particles were able to invade and penetrate into the surface geomembrane liner, and thus, gouge and plough on a trajectory along the surface. This resulted in observing material dislocations at greater intensities such that the surface topography exhibited both the peaks and the valleys not only at higher amplitudes but also displaying the traverses at larger size as well as spacing. That is to say, the dimensions and spacing of peaks and valleys were small-scale in relatively stiffer (harder) geomembrane liner sheet of HDPE in which the surface topography did not possess sharp corners such that the transitions from peaks to valleys to peaks were smooth and rounded as compared to that of LLDPE as well as PVC geomembranes where sharp and rough transitions from peaks to valleys to peaks exhibited. Consequently, the surface topography of inherently harder HDPE liner sheet depicted fewer ups and downs as well as smoother and unsharpened returns from peaks and valleys. The fluctuations in the surface topography data were considerably less owing to relatively firm and intensified core material characteristics of HDPE liner in comparison to that of LLDPE and PVC geomembranes. To sum up, the dimensions and spacing of peaks and valleys for the surface topography were small-scale in relatively stiffer geomembrane liner sheet of HDPE in which the surface topography did not possess sharp corners such that the transitions from peaks to valleys to peaks were smooth and rounded as compared to that of LLDPE as well as PVC geomembranes where sharp and rough transitions from peaks to valleys to peaks exhibited.

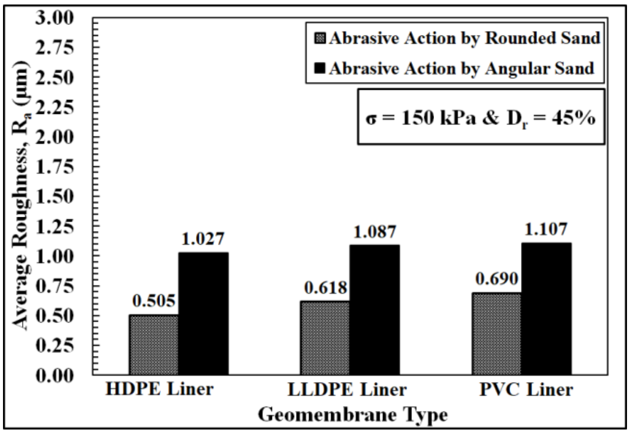
### *4.2. Quantification of Surface Topography Alterations*

A proper engineering analysis of surface topography involves in accurate quantification of topographical alterations on the geo-material surface. Thereafter, the detected surface profiles require to be numerically quantified to be able to perform further comparative analysis among the distinct characteristic surfaces of different geo-materials. To this end, the quantification of alterations in topography on the surfaces of geomembranes were determined in a quantitative manner by means of the average roughness parameter ($R_a$) so as that the topographical changes were quantized to characterize and to compare the alterations in surficial topography of different geomembranes manufactured from distinct core polymeric materials including HDPE, LLDPE and PVC. The changes in the values of $R_a$ with respect to several essential factors involved in the testing program such as the grain shape and/or the density of granular material, loading condition and geomembrane base polymer are presented in Figure 3.

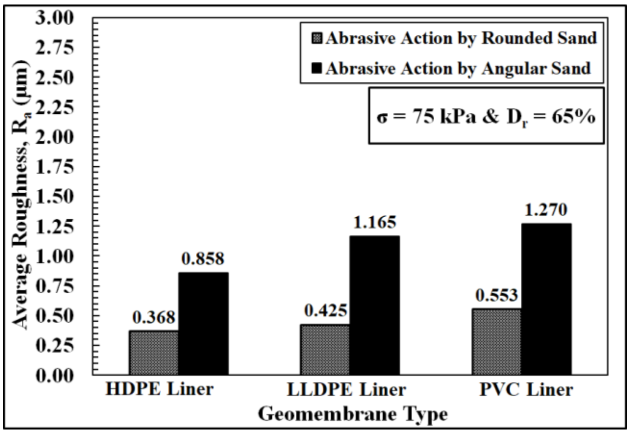
The comparative analysis in Figure 3 exhibits that the average roughness ($R_a$) increases with an increase in normal load from 75 kPa up to 150 kPa as well as with an increase in relative density ($D_r$) of granular sand. The larger the loading the higher the contact stresses will develop at the contact surface in between sand grains and continuum geomembrane leading to severe and harsh indentation of grains into the liner material that causes significant alterations in surface topographical characteristics. Likewise, as the density of granular material ($D_r$) becomes larger, the number of particles that exist at the contact surface in between sand and geomembrane increases resulting in greater amount of grains to penetrate into counterfaced polymeric material, and thus, plough on a trajectory along the surface by inducing and triggering considerably major variations in surface topography. This is associated with larger magnitude of topographical changes such that the polymeric-material dislocations mobilized on the surface of geomembrane develops at higher intensities. Additionally, the higher values of average roughness ($R_a$) were attained for the angular sand regardless of geomembrane type which demonstrates that the greater aggressive abrasion is induced into the surface of geomembrane resulting in the substantial alteration of surface topography. This is attributed to the angular features of sand grains having sharp corners such that the invasion and penetration of angular particles into the surface of geomembrane liner at greater extremity, and thus, gouging surface resulting in exceptional surficial topographical changes. Further, the greatest abrasion – regardless of the grain shape of sand particles (rounded or angular) – has been induced to the softest PVC geomembrane liner such that the softer the geomembrane liner becomes in an order of HDPE, LLDPE, PVC, the significance of abrasive action of granular material on the liner sheet has happened to be evident and vital as demonstrated from the detected increase in the values of average roughness ($R_a$). This shows that the base polymer type from which the geomembrane has been manufactured plays a crucial role such that the physical material characteristics of polymeric continuum liner sheet are of importance regarding the resultant surficial topographical changes.



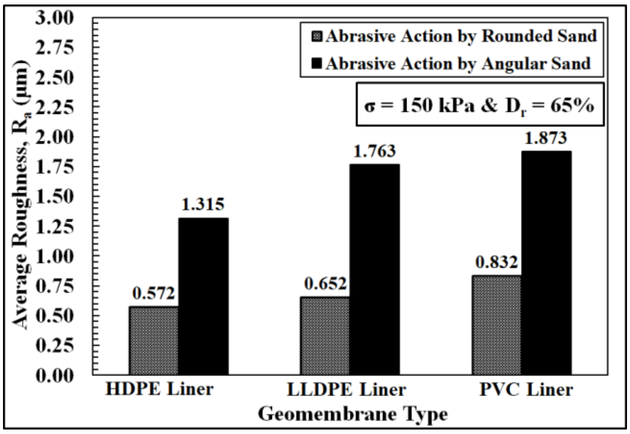

**(a)** σ = 75 kPa & $D_r$ = 45%



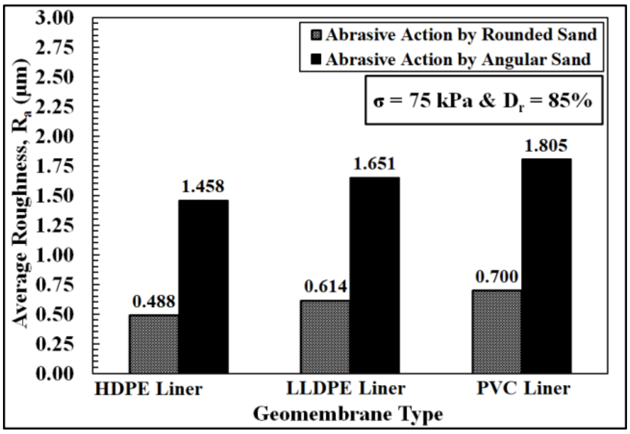

**(b)** σ = 150 kPa & $D_r$ = 45%



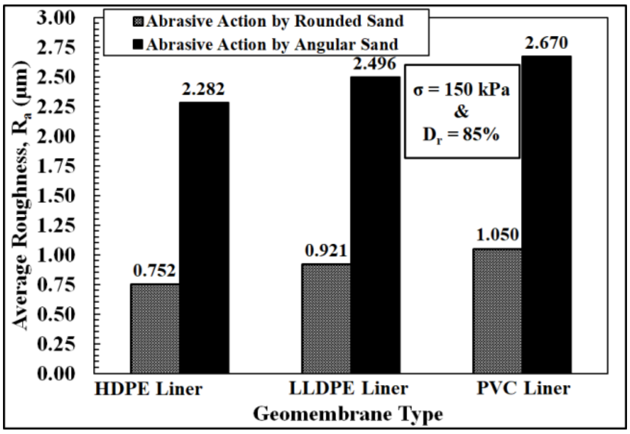

**(c)** σ = 75 kPa & $D_r$ = 65%




**(d)** σ = 150 kPa & $D_r$ = 65%




**(e)** σ = 75 kPa & $D_r$ = 85%




**(f)** σ = 150 kPa & $D_r$ = 85%

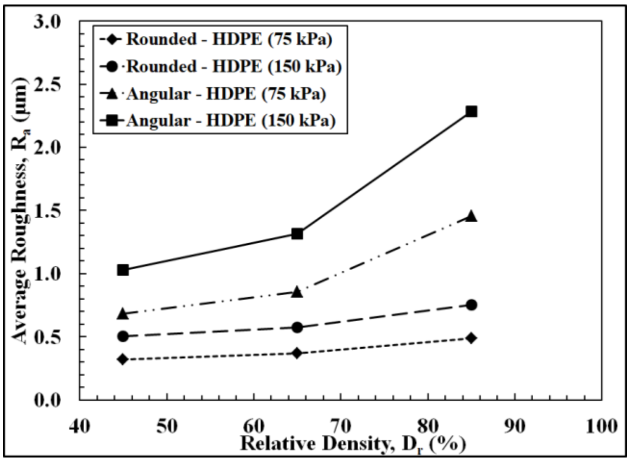
**Figure 3.** Comparison of Average Roughness ($R_a$) of Different Geomembrane Liners for Different Relative Density and Loading Conditions

The variation of average roughness ($R_a$) with respect to the change in relative density ($D_r$) as well as normal stress (σ) and grain shape (particle angularity/roundness) for the geomembrane liners produced from HDPE, LLDPE, and PVC base polymeric materials are presented in Figures 4a, 4b, and 4c, respectively. Regardless of the type of base polymer, the $R_a$ increased with an increase in $D_r$ and/or σ. In addition, when the counterface soil particle shape turns into more angular, the increase in the resultant measured value of $R_a$ becomes relatively larger for the same identical geomembrane liner as compared to the counterface soils having more roundness features in grain shape. Further, the largest increment in the magnitude of $R_a$ was detected for the PVC geomembrane, whereas the smallest rise in the value of $R_a$ was observed in the HDPE geomembrane. The increase in the $R_a$ was medium by the value for the LLDPE geomembrane.

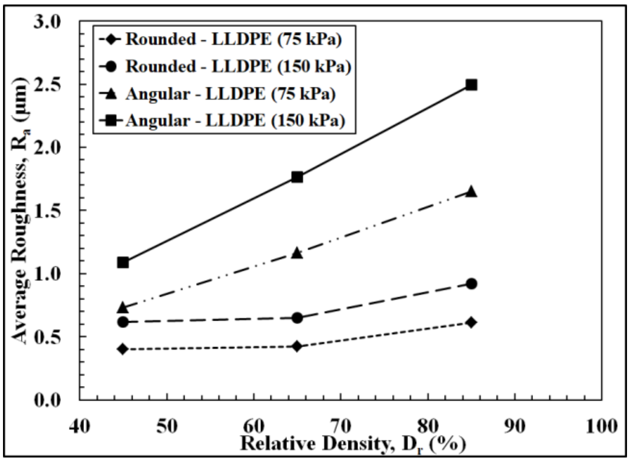
Furthermore, the rate (i.e. slope) of increase in $R_a$ was lower from Dr = 45% to 65%, and then, beyond the relative density of 65%, the rate of increase became larger particularly for the HDPE geomembrane in all loading conditions (i.e. 75 kPa, 150 kPa) for both rounded and angular sand systems; as well as for the LLDPE geomembrane in all loading conditions (i.e. 75 kPa, 150 kPa) but for only rounded sand system. On the other hand, the LLDPE geomembrane for angular sand system didn't exhibit a change in the rate of increase throughout the entire range of relative density tested from 45% up to 85%. Moreover, the PVC geomembrane didn't display a discernable and noteworthy change in the rate of increase regardless of loading condition or granular soil grain shape such as sand particle angularity or roundness.

In light of comparative analysis presented in Figure 4, it is further noted that the softer and the more flexible the geomembrane liner becomes, the higher the increase in the detected magnitude of $R_a$ is explored. Therefore, the hardness/softness of the geomembrane plays an important role for the resultant alterations in surface topography of the liners, and thus, for the resulting surficial abrasion or wear mobilized on the geomembrane counterfaced with granular materials including sandy soils possessing different grain shape features such as distinct particle angularity/roundness. Moreover, the rate of increase in the detected value of $R_a$ becomes higher for the counterface soils possessing angular grain properties, while the rate of that increase is displayed relatively lower for the counterface soils having rounded particle features. Consequently, it is further highlighted that the angular soil grains lead to the development of more abrasive wear, and thus, greater alterations in surface topographical features of geomembrane liners that are in direct contact with soil particles under imposed loads/forces, and hence, under induced stresses at different modes and directions.

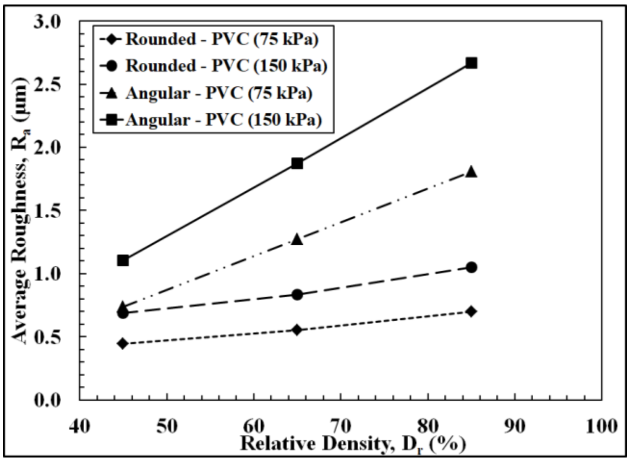
To sum up, surficial topographical alterations of geomembranes are controlled by the liner hardness/softness characteristics as per polymeric core material flexibility/stiffness properties as well as granular soil particle shape such as roundness, angularity, relative density and loading conditions. In this regard, the greatest increase in the value/magnitude of $R_a$ was observed for angular sand systems in largest loading case (i.e. 150 kPa) whereas the smallest increase in the value/magnitude of $R_a$ was seen for rounded sand systems in lowest loading situation (i.e. 75 kPa) regardless of the type of the geomembrane liner. Consequently, the surficial wear induced on the liner surface due to abrasion is strongly governed by the morphology/shape of the sand particles (i.e. rounded, angular). Further, sufficient magnitude of loading is necessarily required for the sand particles to implement and excite abrasive action in order to penetrate and generate abrasion on the liner surface. Therefore, it is evident that different surface topographical changes could be observed depending on geomembrane or sand material selection as well as based on their mutual interaction over the entire extent of the contact area.




(a) HDPE Geomembrane




(b) LLDPE Geomembrane




(c) PVC Geomembrane

**Figure 4.** The variation of Average Roughness ($R_a$) with respect to the change in Relative Density ($D_r$) as well as Normal Stress (σ) and Grain Shape (Particle Angularity/Roundness)

## 5. Conclusions

In light of experimental findings/results of the current research study presented in the paper, the surface topographical characteristics as evident on the detected profiles including asperity features such as size, shape, and spacing of material dislocations comprised of peaks and valleys in the topographies were different and unique to geomembrane type. As such, the softer the geomembrane liner sheet (from HDPE to LLDPE then to PVC) becomes, the greater the abrasion has developed in that the surface topography demonstrated more severe peaks and valleys. Further, the angular features of sand grains led to the mobilization of more violent abrasive action in that angular particles were able to penetrate into the surface geomembrane liner, and thus, gouge on a trajectory along the surface. The dimensions and spacing of peaks and valleys for the surface topography were small-scale in relatively stiffer geomembrane liner sheet of HDPE in which the surface topography did not possess sharp corners such that the transitions from peaks to valleys to peaks were smooth and rounded as compared to that of LLDPE as well as PVC geomembranes where sharp and rough transitions from peaks to valleys to peaks exhibited. As such, the fluctuations in the surface topography data were considerably less owing to relatively firm and intensified core material characteristics of HDPE liner in comparison to that of LLDPE and PVC geomembranes. Consequently, the quantification of surface topography alterations of different geomembranes by means of the computed values of average roughness ($R_a$) determined for the measured surface topographies of the liners unveiled that the $R_a$ (i.e. surficial topographical changes) increases with an increase in load, relative density, particle angularity of grain shape and softness of geomembrane liner sheet. As such, for the rounded sand system, the value of $R_a$ increased 129%, 133%, 137% for HDPE, LLDPE, PVC geomembrane liners, respectively when the relative density arised from 45% to 85% as well as the normal stress raised up from 75 kPa up to 150 kPa. For the angular sand system, the value of $R_a$ increased 234%, 242%, 262% for HDPE, LLDPE, PVC geomembrane liners, respectively when the relative density arised from 45% to 85% as well as the normal stress raised up from 75 kPa up to 150 kPa. Therefore, it is evidently seen that the grain shape (roundedness versus angularity) of particulate materials (i.e. sand) plays a significant role for the induced surface wear onto geomembrane liner regardless of its type or its core polymer (i.e. HDPE, LLDPE, PVC) due to greater magnitude of abrasive action mobilized by the sharp features of angular sand particles. For this reason, a higher increase in the value of $R_a$ was displayed for the angular sand system as compared to that of the rounded sand system. Furthermore, when the increase in the value of $R_a$ as the $D_r$ arised from 65% to 85% is compared with the increase in the value of $R_a$ as the $D_r$ arised from 45% to 65%, it was obviously realized that a greater rise was identified beyond $D_r$ = 65% up until $D_r$ = 85% substantially in particular for the HDPE geomembrane, considerably for the LLDPE geomembrane, and marginally for the PVC geomembrane system.

To sum up, the alteration of surface topography is not only a function of geomembrane material properties including softness/hardness characteristics but also controlled by counterface material physical properties, shape features as well as boundary conditions including the magnitude of loading, the severity of external forces, and induced stresses. For this reason, the selection of materials and the design of multi-layered infrastructural application plays an important and critical role for the sake of safety and stability in a typical composite system designed and constructed for a geotechnical or geoenvironmental facility including more than one distinct materials which are counterfacing each other through a contact surface along with a direct interaction due to imposed external loads/forces and induced resultant stresses. Consequently, the design engineers shall necessarily pay special attention to mutual interactive behavior and engineering properties of materials in construction including strength and durability characteristics in addition to single/unique material strength and durability response against imposed loads and forces in any mode of application such as compression, tension or shear induced singly of jointly/collectively.

In conclusion, the detected surficial topographical changes on the geomembrane liners were quantitatively evaluated by means of a common roughness parameter (i.e. average roughness, $R_a$) in order to comprehend the degree, magnitude and significance of surficial wear induced on the geomembrane liners due to abrasive action of granular particulate materials (i.e. sand) that are in direct contact and interaction with geomembranes employed in geotechnical and geoenvironmental projects in the infrastructural field applications including embankments, landfills, artificial ponds. The engineering quantification and the comparative analysis conducted in the current study and presented in this paper as well as the test results and the experimental findings of the laboratory program not only filled the gap in the literature regarding the detection and the quantitative evaluation of the resultant polymeric material condition due to abrasive wear but also provided a comprehensive understanding for the engineers in design and the contractor practitioners in construction sites in terms of material selection, the resulting mutual compatibility of the preferred materials, and the consequential changes exhibited on the physical characteristics, mechanical properties of the selected materials in construction as well as operation stages. In this way, the design engineers and the contractor practitioners would be able to estimate stable durability and secure lifespan of the utilized polymeric geomembranes and particulate granular soils as well as their safe and secure mutual interaction in the multi-layered composite systems typically applied in infrastructural facilities including embankments, landfills and artificial ponds.

**Statement of Conflict of Interest**

No conflict of interest is declared such that no known competing financial interests or personal relationships exist which could have appeared to influence the work reported in this paper.

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