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Effects of asperities on the geotextile-geomembrane interface shear characteristics

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ABSTRACT: This paper investigates the impact of geomembrane texturing on the peak and post-peak shear strength of high-density-polyethylene (HDPE) geomembranes/nonwoven-geotextiles interface using the large-direct shear. Three HDPE geomembranes with similar manufacturing techniques but different surface textures were utilized to investigate the texturing effect on interface shear resistance. Geomembrane texturing, quantified by asperity heights and/or density, was found to be highly important. Texturing was identified to improve both the peak and post-peak shear strength of geomembranes/nonwoven-geotextiles interface. The textured interfaces with high-density asperity exhibited a large post peak strength loss which was attributed to the pulling out or tearing of filaments from the nonwoven-geotextile and orienting them parallel to shear and polishing of the texturing on the geomembrane. At high normal stresses, the strength loss was caused by micro-damage to the asperities on the geomembrane. The obtained data indicates that for un-hydrated geomembranes/geotextiles interfaces, an efficient asperity parameter can be recommended.

1 INTRODUCTION

Generation of waste is on the rise globally, with South Africa's annual waste statistic approximately at 108 million tonnages. Studies show that about 90% of this waste is absorbed by waste containment facilities such as landfills. This scenario is similar to most developing nations. Therefore, landfills are required to have liner and cover systems with low-permeability, high chemical resistance and high-liquid collection properties to accommodate the high quantity of waste been generated. These lining systems typically contain compacted clay, granular soils, and geosynthetic materials (Stark et al. 1996). Geonets or geo-composite drainage layers, geotextiles (GTX), geosynthetic clay liners (GCL) and geomembranes (GM) liners are examples of the geosynthetic components of landfill lining systems (Stark et al. 1996). Cañizal Berini et al. (2015), identified that there are many possible interfaces in landfill waste facilities and some of these interfaces are critical than others in terms of shear characteristics. For instance, in a typical municipal solid waste landfill, geomembrane/geotextile (GM/GTX), drainage geo-composite/geomembrane and soil/geomembrane are identified as critical interfaces (Cañizal et al. 2015). GM/GTX interface have numerous applications, for instance, the use of geomembranes as hydraulic barriers and the geotextiles protecting it from damage that can be incurred due to high normal stresses and other site conditions.

Geomembranes used in waste containment facilities are manufactured from various polymeric resin. However, medium- or high-density polyethene (HDPE) is the most common geomembrane type deployed to several geotechnical engineering applications, this is due to its durability and high ultra-violet (UV) resistance (Stark et al. 1996). The interaction of HDPE with other geosynthetics such as geotextile results to an interface. The shear resistance along the interface between two geomaterials is a crucial factor in accessing slope and global stability of the landfill. For instance, due to insufficient shear resistance at the interface, Kettleman Hills Class I hazardous waste treatment and storage facility in Kettleman City, Calif failed (Mitchell et al. 1990; Stark et al. 1996). In this scenario, the use of smooth HDPE geomembranes at the critical interface resulted in low interface shear resistance, hence the failure (Stark et al. 1996). The replacement of smooth GM with textured HDPE GM have been historically reported by Cañizal Berini et al. (2015), Chenggang (2004), and Stark et al. (1996) to increase the geosynthetic shear resistance of interfaces used in landfills and other applications. The increase in interface shear resistance for a textured HDPE geomembrane is due to the roughened top and/or bottom surfaces i.e. asperities. The asperities increase the shear resistance between soil or geosynthetics in comparison to the shear resistance developed along smooth HDPE.

The GM/GTX interface was studied by means of the results of fifteen different interfaces using one type of geotextile and three types of geomembranes with different asperity height and density as shown in Table 2. In this study, a methodology based on the ASTM D5321 was applied to carry out direct shear tests at the GM/GTX interfaces. The gripping method employed for the geosynthetics inside the shear box was established based on studies from (Allen and Fox 2007; Sikwanda and Kalumba 2018). This paper describes the results of direct shear tests on geomembrane/nonwoven geotextile interface. The relationships analysed were; interface shear strength against shear displacement, interface shear strength against normal stress, interface friction angle against asperity height and the sensitivity against normal stress.

These results obtained can be used to quantify the efficiency of smooth and textured geomembrane interfaces with respect to landfills slope stability. Also, the outcome would provide designers with insight for selecting the appropriate geomembrane for waste containment facility liner and cover systems that utilizes nonwoven geotextile at the critical interface. In conclusion, higher shear resistance and more reliant interface interaction between geomembrane and adjacent materials will accommodate the construction of steeper, higher and durable geo-structures. Furthermore, improved geosynthetic interface performance will influence the widespread application of these materials in the engineering field (Fowmes et al. 2017).

2 EXPERIMENTAL WORK

2.1 *Materials*

The geosynthetics required for this study are geomembranes and geotextiles. Table 1 below summarizes and describes the characteristics of the geomaterials used for the direct shear tests. Their properties were as follows:

(1) One nonwoven geotextile: GTX (400 g/m^2), manufactured from virgin polypropylene fibres with added UV stabilizer (Fibertex 2017).

The needle-punched filaments geotextile was selected because it is preferred when interfaced with regular textured geomembrane under high normal stress (Cañizal et al. 2015).

(2) Three geomembranes of 1.5 mm thickness. In this study, the following label was used to distinguish the geomembranes; GMx2, GMx8, GMx9. GMx8 is a single textured-smooth surface geomembrane, while GMx2 and GMx9 are double textured geomembranes with evenly spread surface asperities smaller than 1 mm and larger than 1 mm respectively.

The regular textured geomembrane is produced by the flat-die extrusion manufacturing process, this was selected because of its asperities consistency and negligible complexity of its texturing. While for irregular textured geomembrane produced by the blown film manufacturing process, the asperities are highly variable.

2.2 *Testing equipment*

The large direct shear machine was used to carry out the direct shear tests on the HDPE geomembrane sheared against needle-punched non-woven geotextile.

Throughout the batch of tests, a non-woven needle punched geotextile, typically employed as a protection layer, was used to maintain consistency. The properties of the geosynthetics are outlined in Table 1. The geomembrane was a flat die extruded 1.5 mm thick HPDE with structured texturing. However, the texture properties such as asperity height and density are different. The surface properties of the geomembrane are presented in Table 2.

According to testing standards, 300 mm long, 300 mm wide and 100 mm depth shear box was used. The tests were performed with a constant shear rate of 1 mm/min and a range of applied normal stress of 50 - 400 kPa. The shear box used consist of two compartments; the static upper part and the moving lower part. The geosynthetics are placed in the experiment set up depending on the intended design and field application. The geomembrane was fastened to the lower box, whereas the geotextile was fastened to the upper box. The gripping system used for different geosynthetics depends on various factors such as physical properties and site-specific conditions. In this study, the gripping system employed for both the geotextiles and the geomembrane was the adhesive tape.

Table 1. Type of geosynthetics.

Geosynthetics	Label	Fiber-type	Density (g/m^2 / g/cc)	Thickness mm
Geotextiles	GTX	Nonwoven	400	3.4
Geomembranes	GMx2	Textured HDPE	0.94	1.5
	GMx8	Smooth HDPE	0.94	1.5
	GMx9	Textured HDPE	0.94	1.5

Textured geomembrane was quantified by measuring asperity parameters such as asperity height and density. Test method GRI GM13 was used to measure the asperity heights (Koerner and Koerner 2015). The test includes placing of a dial gauge at the tip of asperity spike and measuring the difference in depth from the peak to the lowest surface of the geomembrane. This step was repeated at about ten locations across the interested geomembrane interface (McCartney et al 2005). In addition, asperity density, which is related to asperity spacing, was measured by counting spikes pec cm^2. This was repeated in at least two different locations to obtain an average.

Table 2. Summary of geomembrane properties.

Property	GMx2	GMx8	GMx9
Polymer	HDPE	HDPE	HDPE
Thickness (mm)	1.5	1.5	1.5
Asperity height (mm)	0.9	-	1.9
Spacing mm (MD/XMD)	5/5	-	11/5
Density (g/cm^3)	0.942	0.942	0.942
Asperity density (per cm^2)	3.42	-	2.11

2.3 *Procedures*

The procedure for the direct shear test was according to ASTM D5321 (2014).

The GM/GTX interfaces were tested under dry conditions with consolidation time as 10 min and a constant shear rate of 1 mm/min. Dry conditioning was selected due to the relatively impermeable nature of geomembrane and the less significant effect of water on GM/GTX interface as compared with other critical interfaces. This was proven by Bergado et al (2006). Surprisingly, studies by Stark et al. (1996) and Triplett and Fox (2001) shows that the shear rate does not majorly affect the peak and post-peak strengths for geomembrane/geotextile interface.

The experiment was set-up as shown in Figure 1 and specified normal stress was applied to the loading platen above the upper metal support. The lower shear box moves in a parallel direction to the shear force at a constant shear rate after the consolidation period of 10 min was elapsed. The equipment maximum shear displacement is 75 mm. Records of shear displacement, shear force and vertical displacement were taken during the test. Shear and vertical displacements are measured with linear variable differential transformers (LVDTs).

3 DIRECT SHEAR TESTS

3.1 *Interface shear strength behaviour*

The geomembrane/geotextile interfaces tested exhibit frictional behaviour, this behaviour was modelled by Coulomb's equation $\tau = c_a + \sigma_n tan\delta$, where τ and σ_n are interface shear strength and normal stresses acting on the failure plane, c_a is the interface adhesion and δ is the interface friction angle. The best-fit interface shear strength characteristics was represented by the linear regression of the plot of τ against σ_n (Cañizal et al. 2015). Approximately all interfaces tested in this investigation have shear strength with characteristics friction angles and relatively negligible adhesion.

Within the normal stress range of 50 – 400 kPa, about fifteen direct shear tests from three different geomembrane/geotextile interface were performed under dry conditions. The post-peak shear strength was obtained at 65-70 mm and the peak interface shear strength was attained at 4-10 mm. A typical shear strength behaviour of nonwoven geotextile/geomembrane interfaces is represented in Figure 2 below. The shear strength displacement curves, shows strain softening behaviour, i.e. the interface shear strength reduction with increasing shear displacement. According to Bacas et al (2011), an increase in strain softening behaviour is proportional to increased normal stress.

Previous studies by (Hebeler et al 2005; McCartney et al. 2009; Stark et al. 1996), identified that during shearing of textured geomembrane/geotextile interface at low normal stress (<100 kPa), the interaction mechanism can be presented in two main components; namely, interlock (hook and loop) interaction and frictional interaction. In addition, as the normal stress increases (> 100 kPa), asperities penetrate into the geotextile fabric and result to their

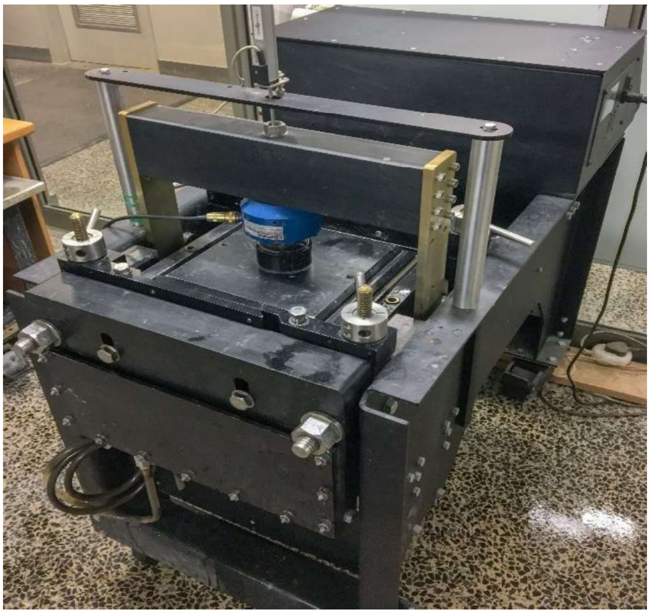

Figure 1. Large direct shear device set up for geomembrane/nonwoven geotextile interfaces.

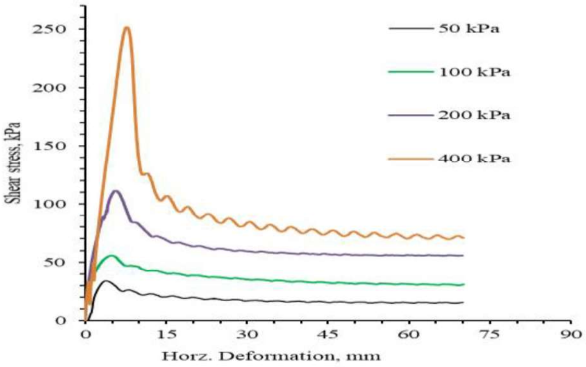

Figure 2. Typical geomembrane/nonwoven geotextile interface shear strength.

compression, this is known as the interbedding factor (Hebeler et al 2005). However, for the smooth geomembrane interface tested, it can be stated that it has little or no interlock interaction and friction is solely responsible for the interaction mechanism (Bacas et al 2015).

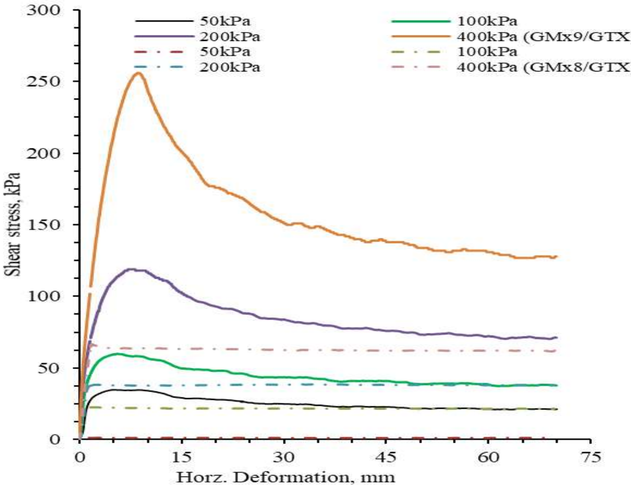

Figure 3. Comparison of smooth GMx8 with textured GMx9 interface shear strength.

3.2 *Effects of geomembrane roughness*

In this study, geomembrane roughness is described in terms of textures and asperity parameters. Its roughness patterns were analyzed through the plot of interface shear strength against displacement when sheared with nonwoven needle-punched geotextile. The asperity parameter investigated are asperity height and density. Figure 3 above illustrates the shear stress against horizontal deformation curves of two geomembrane/geotextile interfaces; which are smooth and textured geomembranes. They have different roughness patterns and asperity height. The interface shear strengths observed for the smooth geomembrane was generally the smaller value. This could be because of the absence of interlock interaction at the interface. However, textured geomembrane GMx9, with asperity height greater than 1 mm showed greater peak shear strength values.

For textured geomembrane, roughness directly affects interlocking mechanism, peak interface shear strength and strain softening behaviour, especially at high normal stress. It is generally accepted by the geosynthetics community, that peak interface shear strength would increase if the asperity height and density are increased (McCartney et al 2005). Interestingly, interface shear strength for the textured geomembranes (GMx2 & GMx9) at 50 kPa normal stress, presents quite close values (see Figure 4). The difference in asperity parameters for the interfaces did not result in significant change to the shear strength at low normal stress. From Table 2, GMx9 and GMx2 have asperities spaced at 11 mm and 5 mm in staggered rows, respectively. Therefore, GMx2 is expected to present larger peak and post-peak interface shear strength than GMx9. However, this was not the case, instead, the interface peak shear strength was relatively constant. A possible explanation for this could be the corresponding reduction in asperity height of GMx2 when compared with GMx9. Remarkably, both GMx2 and GMx9 showed an increase in frictional interaction performance when compared with GMx8 smooth geomembrane. In other words, textured geomembranes provide a substantial increase in interface shear strength over smooth geomembrane (Stark et al. 1996). Also, varying asperity height and density caused a corresponding change in the interface friction angles, see Figure 5. In addition, increase in normal stress lead to increased interlocking for the textured geomembrane (Bacas et al. 2011).

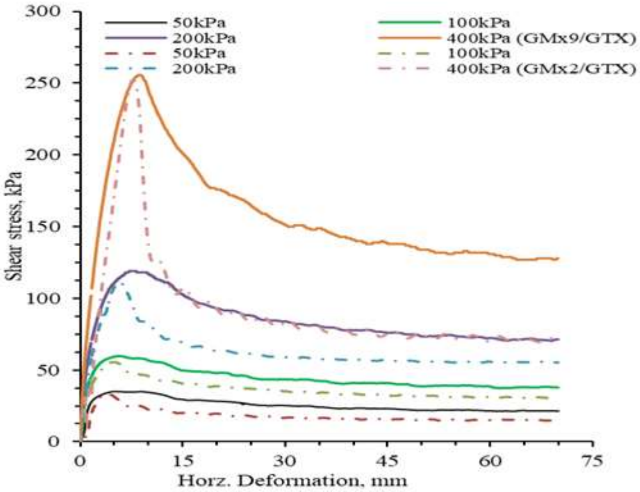

Figure 4. Comparison of textured geomembranes with different asperity parameter.

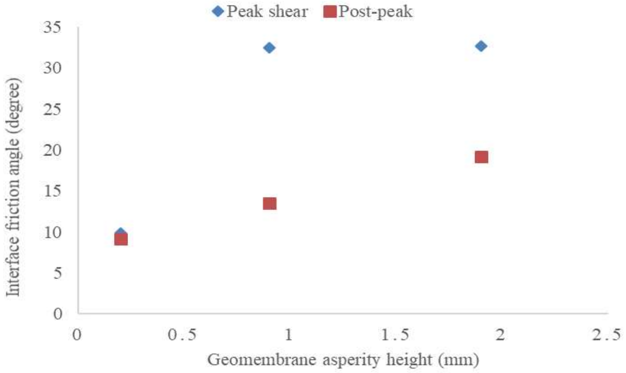

Figure 5. Friction angles of GM/GTX interface against geomembrane asperity height.

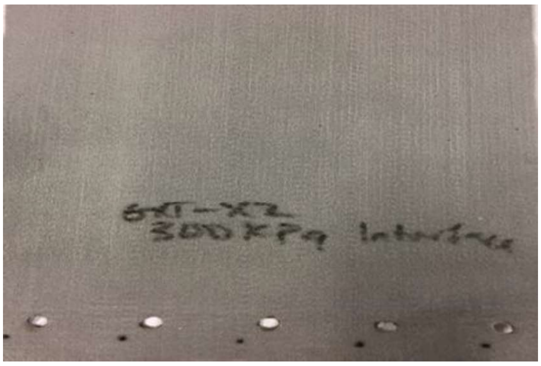

Figure 6. Fiber-stretch of geotextile interfaced with high density geomembrane.

3.3 *Effect of asperity height and density*

Figure 6 presents the geotextile stretch caused by textured geomembrane asperities. GMx9 and GMx2 have asperities height > 1 mm and < 1mm respectively. In agreement with Fowmes et al (2017), GMx9 (high asperity) exhibited higher post peak shear strength than GMx2 (low asperity) (see Figure 8). It was observed that for GMx9/GTX interface there was a steady rise to peak shear strength at most normal stress level. In the same vein, the transition of peak strength to post-peak shear strength was quite uniform. However, GMx2/GTX interface displays a non-uniform transition from peak to post-peak shear strength, especially at high normal stresses. This can be attributed to the high-capacity damage of the geotextile fibre by the relatively clustered geomembrane asperity spikes; i.e. high-density asperity. At low normal stress, i.e. 50 kPa, and in agreement with Bacas et al (2015), the asperities could not fully penetrate the geotextile matrix, hence the gentle stress curve displayed.

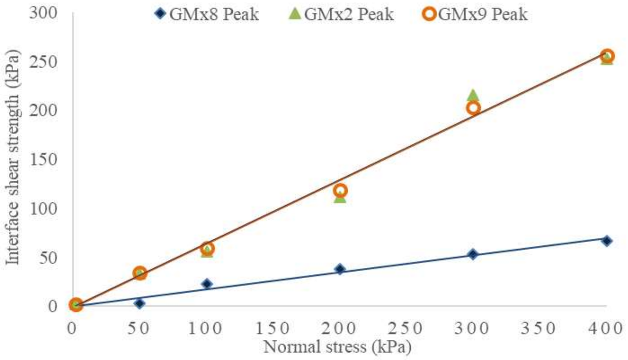

Figure 7. Peak shear strength interface envelope.

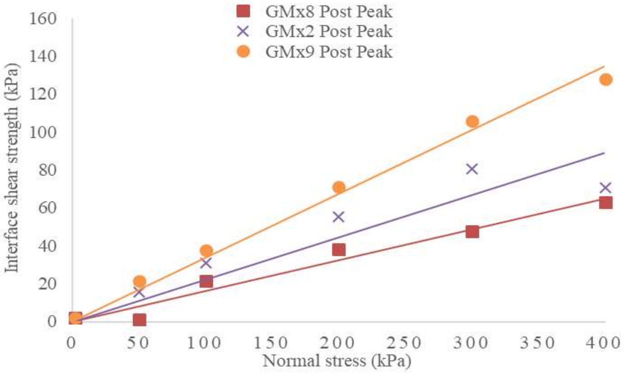

Figure 8. Post peak shear strength interface envelope.

3.4 *Effect of applied normal stress*

The stress range of 50 – 400 kPa was selected for this investigation because it represented the stimulated field conditions for baselining and cover lining system. In addition, it allowed asperities effects on the interface to be evaluated across the stress range. The influence of the normal stress on the peak interface shear was observed by comparing the smooth geomembrane (GMx8) interface and the textured geomembranes (GMx9 and GMx2) interfaces as shown in Figure 7. At 50 kPa normal stress, there was little difference in the peak shear strength value for the two textured interfaces. A possible reason for this could be that the stress was just sufficient to establish contact at the interface and not contribute meaningfully to the interface shear strength. Also, GMx8 presents, in general, the smaller peak and post-peak interface shear strength. The smooth geomembrane does not develop interbedding mechanism as much as the textured geomembrane even at higher stress level.

The peak shear values for GMx9 and GMx2 at normal stresses higher than 100 kPa were close. In contrast, there were differences in the post-peak shear values for GMx9 and GMx2, with the lower post-peak shear values belonging to the GMx2. In agreement with Eid (2011), this is possible because the asperity spikes closeness of GMx2 caused a concentrated fibre-stretch in the geotextile and this resulted to an excessive reduction in post-peak shear strength.

3.5 *Sensitivity of interface shear result to asperity*

The interplay of peak and post-peak shear strength describes to a certain extent the sensitivity of an interface. Sensitivity is a measure used to highlight the difference in peak and post-peak responses of geomembrane/geotextile interface. Hebeler et al (2005) conducted a study to explain the difference in the sensitivity of two geomembranes manufactured differently; coextruded and structured geomembrane. However, the effect of asperity parameters on the sensitivity of geomembrane with the same manufacturing process was not considered. As shown in Figure 9, GMx2 displays the highest sensitivity as a function of applied normal stress, when compared with other interfaces. A possible explanation for this could be the presence of highly dense asperity per cm^2 and significant hook and loop interaction. In other words, interface sensitivity is directly dependent on asperities and/or surface roughness (Frost & Lee, 1990). Also, as shown above, all interfaces exhibited an initial decrease in sensitivity with increasing normal stress. The decrease is due to the absence of sufficient engagement at the interface. After the initial decrease,

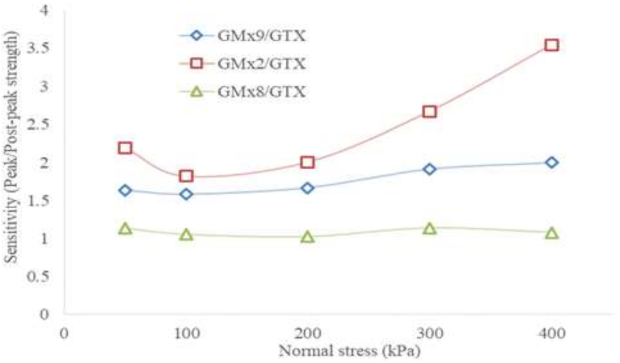

Figure 9. Sensitivity against normal stress for tested geomembrane /geotextile interface.

there was an average increase in sensitivity across all interface.

3.6 *Conclusions*

The following conclusions are premised on the foregoing experimental investigation of asperity effects on geomembrane/geotextile (GM/GTX) interface, where the nonwoven geotextile acts as the protective layer;

1. Textured HDPE geomembranes (GM) provide improved peak and post-peak interface shear strength when compared with smooth GM.
2. For landfill designed with post-peak shear strength, it is preferred to use a textured geomembrane with relatively less asperity density at the (GM/GTX) interface. The reason for this is the possible risk of 50 -60% reduction in post-peak shear strength when high-density geomembrane is used.
3. For cover lining systems of landfills usually subjected to low normal stress (< 50 kPa), it is recommended that using textured geomembrane with relatively low asperity height can help mobilize interlocking mechanism at lower normal stress. Also, this has an economic advantage from a manufacturing viewpoint.
4. For base & slope lining systems of landfills subjects to high normal stresses (> 100 kPa), it can be advised that the use of high-asperity height textured geomembrane would help develop interlocking and friction mechanism at the matrix level.
5. When asperity height was increased by 60%, and asperity density reduced with approximately the same percentage, the peak shear strength would be nearly constant. In addition, there would be a significant increase to the post-peak shear strength.
6. Furthermore, if the asperity height was reduced, coupled with increased in asperity density. This was found to result in a notable decrease in post-peak shear strength for the geomembrane/geotextile interface.

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