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Laboratory investigation of the effects of asperity concentration and geotextile-type on geomembrane/geotextile interface shear characteristics

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ABSTRACT: Asperities on textured geomembranes are known to develop high interface shear strength and resist sliding. To date, due to asperity advantages, many textured geomembranes with different asperity heights and concentrations have been manufactured and used in landfill linings together with other geosynthetics such as geotextiles. Previous studies have investigated the effects of asperity height on geomembrane/geotextile interface shear strength and mechanism. However, limited studies have considered the effects of asperity concentration on the geomembrane/geotextile interface. Consequently, the main objective of this study was to investigate the influence of asperity concentration on geomembrane/geotextile interface as asperity concentration was doubled (from 332 to 663 spikes per 10000 mm^2) and geotextile-type changed. Shear tests were conducted with ASTM D5321/D5321M-14 standard and using a 305 mm by 305 mm large direct shear-box. It was observed that a 100% increase of asperity concentration at fixed asperity height led to an increase of 24% and 11% in peak and large displacement (LD) friction angles, respectively, and a 24% increase in the displacement required to mobilize peak shear. Furthermore, doubling the asperity concentration caused the shear mechanism to change from matrix-level ploughing to ploughing assisted with a failure plane, thus, resulting in less frictional resistance.

RÉSUMÉ : Les asperités sur les géomembranes texturées sont connues pour développer une résistance élevée au cisaillement d'interface et résister au glissement. À ce jour, en raison des avantages de l'asperité, de nombreuses géomembranes texturées avec différentes hauteurs et concentrations d'asperité ont été fabriquées et utilisées dans les revêtements de décharge avec d'autres géosynthétiques tels que les géotextiles. Des études antérieures ont étudié les effets de la hauteur d'asperité sur la résistance et le mécanisme de cisaillement de l'interface géomembrane/géotextile. Cependant, des études limitées ont examiné les effets de la concentration d'asperité sur l'interface géomembrane/géotextile. Par conséquent, l'objectif principal de cette étude était d'étudier l'influence de la concentration d'asperité sur l'interface géomembrane/géotextile à mesure que la concentration d'asperité était doublée (de 332 à 663 pics pour 10000 mm2) et que le type de géotextile changeait. Les essais de cisaillement ont été effectués avec la norme ASTM D5321/D5321M-14 et à l'aide d'une grande boîte de cisaillement direct de 305 mm sur 305 mm. Ll a été observé qu'une augmentation de 100 % de la concentration d'asperité à hauteur d'asperité fixe entraînait une augmentation de 24 % et de 11 % des angles de frottement de pointe et de grand déplacement (LD), respectivement, et une augmentation de 24 % du déplacement requis pour mobiliser le cisaillement de pointe. De plus, le doublement de la concentration d'asperité a fait passer le mécanisme de cisaillement d'un labour au niveau de la matrice à un labour assisté par un plan de défaillance, ce qui a entraîné une résistance au frottement moindre.

KEYWORDS: Asperity concentration, friction angle, failure mechanism, geomembrane/geotextile interaction, shear strength.

1 INTRODUCTION.

Geomembranes are used in waste containment facilities as a barrier liner with low permeability to fulfil landfill environmental regulatory requirements. These geomembrane liners, when used at the cover and bottom liner of the landfill, can effectively minimize the percolation of fluids into the engineered system and migration of contaminated liquid into the surrounding soil and water body (Buthelezi, 2017; Cen et. al., 2018). In landfill applications, geomembranes are used with soils or other geosynthetics. Particularly, geotextiles are often placed immediately above geomembranes to form a geomembrane-geotextile composite lining system, where the geotextile protects the geomembrane from puncture and abrasion caused by angular particles and gravitational force (Adeleke, 2020). According to the Geosynthetic Institute (2011), usable geomembranes must be characterised by a set of minimum physical, mechanical, and chemical properties to ensure good quality and acceptable performance. Geomembrane properties such as density, melt index, thickness, surface property (asperity geometry), tensile properties, tear strength and puncture strength may be evaluated using appropriate test method to determine field application suitability. In this study, surface properties were considered crucial among other physical/mechanical properties, because it has a pronounced relationship with interface shear characteristics and can vary depending on manufacturing technique and polymer properties.

With regards to surface properties, geomembranes can either be smooth or textured in features. Depending on their application and project-specific conditions such as an increase in slope angle, smooth geomembranes interfaced against geotextile may develop low shear resistance, and as such could act as a potential failure surface in the liner system; hence, the need for texturing (Cen et. al., 2018; Sikwanda, 2018). A notable benefit of texturing the geomembrane surface is the increased interface shear resistance which can potentially prevent the geomembrane surface from developing a slip surface in the liner structure. The increase in shear resistance can be attributed to either macro-topography, micro-topography, or both, depending on asperity geometry, applied normal stress, and counteracting geomaterial surface. While macro-topography features are visible to the human eye and measurable with dial gauges, micro-topography features are visible only with the aid of an electronic magnifying instrument (Dove & Frost, 1996). In this investigation, macro-topography is synonymous with asperity whereas micro-topography is interrelated with roughness.

Asperities are individual notable projections of polymer that extend above the main surface of a textured geomembrane (ASTM D7466/D7466M-10(2015)E1). They are surface properties used to quantify the degree of roughness of a geomembrane surface and are characterized by their height, concentration, spacing and pattern/configuration (Yesiller, 2005). The average height of the polymeric projection is termed asperity height while asperity concentration is the number of individual polymer projections per given area. Asperity spacing is the distance between adjacent asperities either in the machine direction or the cross-machine direction. Lastly, the asperity pattern is the manner of asperity arrangement on the geomembrane surface. It should be noted that for this investigation, asperity concentration was considered to encompass asperity spacing and pattern; thus, it was the focus of this study. Although previous studies by Yesiller, 2005; Adesokan & Blond, 2018; Robbe-Valloire et. al., 2018; and Adeleke et. al., 2019 have researched the effect of asperity height on the geomembrane-geotextile interface shear parameter, only a few studies by Fowmes et. al., (2017) and Zaharescu (2018) have investigated the significance of asperity concentration. Therefore, this study presented herein seeks to provide further knowledge and a detailed understanding of asperity concentration by conducting direct shear tests with varying asperity concentration while asperity height remained constant. Also, the undertaken study presented in this paper would report the right balance between the desired interface shear performance, material cost, and asperity concentration.

2 EXPERIMENTAL.

2.1 *Materials – Geomembranes*

Textured HDPE geomembranes were tested in addition to the smooth geomembrane (GMB-S) which served as a control test. The textured HDPE had a thickness of 2 mm, asperity height of 0.7 mm, and varying asperity concentrations. The tested geomembranes are illustrated in Figure 1. Also, the asperities geometry and roughness measurement of each geomembrane is presented in Table 1. The asperity height and concentration for both GMB-T1 & GMB-T2 itemized in Table 1 were measured with a digital dial gauge and 100 mm by 100 mm metallic square, respectively. As shown in Table 1, asperity concentration was quantified by the number of spikes per 10000 mm^2. Due to the manufacturing process and probability of asperity variability, asperity concentration quantification methods at three different locations on each textured geomembrane, from which the average measurement was reported as presented in Table 1. Also, line and areal roughness measurements were included for both geomembranes, where line roughness (R_a) determination

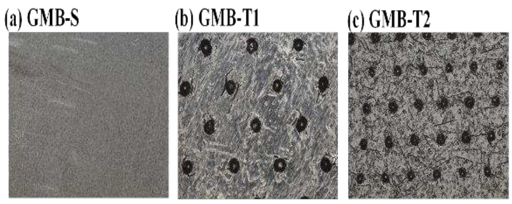

Figure 1. 50X magnified aerial view of geomembrane surface (a) GMB-S (b) GMB-T1 (c) GMB-T2.

Table 1. Tested geomembrane asperity geometry and roughness

GMB	S_a (μm)	R_{a-a} (μm)	R_{a-b} (μm)	Asp. Height (mm)	Asp. Conc. (no/area)
GMB-S	19.77	9.09	6.61	0	0
GMB-T1	60.17	146.83	29.90	0.7	332
GMB-T2	63.99	172.73	30.18	0.7	663

included both roughness profile taken along the asperities and profile taken in between the asperities and areal roughness (S_a) represented the average of along-asperities and between-asperities (Adeleke et. al., 2021a). It is worth mentioning that R_{a-a} and R_{a-b} represent along-asperities line roughness and between-asperities line roughness, respectively.

2.2 *Materials – Geotextiles*

Two staple fibre, needle-punched nonwoven geotextiles – namely polypropylene (GTX-PP) and polyester (GTX-PET) geotextile, each with a mass density of 400 g/m^2, were used in this research. Their selection was premised on their wide acceptance as suitable landfill liner materials, particularly in South Africa. Comparing the shear responses of both geotextiles when interfaced against geomembrane was considered necessary to evaluate their suitability and identify geotextile-polymer behaviour to asperity concentration variation. Photographs and scanning electronic microscope (SEM) images of the geotextiles are given in Figure 2. The geotextiles were hydrated before testing to typify moist field conditions.

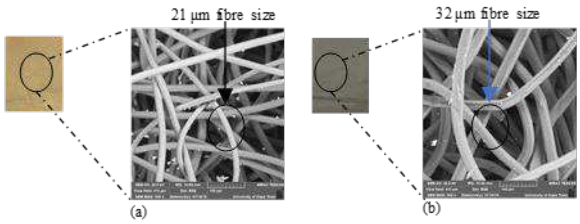

Figure 2. Geotextile surface and 500X microscopic view (a) GTX-PET (b) GTX-PP.

2.3 *Interface shear test procedure*

Shear tests were conducted in accordance with ASTM D5321/D5321M-14, using a large direct shear box with a dimension of 305 mm by 305 mm by 100 mm. For each experimental set-up, the geotextiles and geomembranes were clamped to the upper box and lower box of the direct shear device, respectively. The gripping system consisted of clamps and 3M sandpaper as recommended by Sikwanda et. al., 2018a and Sikwanda et.al., 2018b. Normal stresses ranging from 25 kPa to 400 kPa were applied to each geomembrane-geotextile setup at a constant shear displacement rate of 1 mm/min. The shear displacement of 1 mm/min was considered adequate as no excess pore pressures were expected at the geosynthetic interface.

During the shear test, a linear Variable Differential Transducer (LVDT) was connected to record and store displacements and shear responses. At the end of each setup, peak and large displacement shear strength values were determined from the measured shear forces and displacements. These shear strength values are plotted against the applied normal stress to determine the interface friction angle and apparent cohesion – according to the Mohr-Coulomb criterion.

3 RESULTS AND DISCUSSION.

3.1 *Effect of geomembrane asperity concentration on shear stress-horizontal displacement curve*

Figure 3 & Figure 4 show the shear behaviour of the tested geomembranes-geotextile interfaces. Smooth geomembranes acted as the control test and were represented with “dotted lines” for both polypropylene and polyester interfaces. In contrast, interfaces with relatively smaller asperity concentration and greater asperity concentration were identified with “broken lines” and “solid lines”, respectively.

3.1.1 *GMB-S/GTX interfaces*

For the GMB-S/GTX interfaces shear stress – horizontal displacement plot which is shown in Figure 3, there was an initial gradual increase in shear stress as soon as shear displacement began, followed by a minimal reduction in peak shear stress with further shear displacement. The observed shear reduction increased as applied normal stress was enlarged. Also, for the GMB-S/GTX interfaces, the peak shear stress was mobilized at an average shear displacement of 2.18, 4.30, 5.00, 5.86 and 8.18 mm at applied normal stress of 25, 50, 100, 200, and 400 kPa, respectively. On average, polyester (GTX-PET) interfaces exhibited slightly less displacement required to develop peak shear than polypropylene (GTX-PP) interfaces. This behaviour was attributed to the lesser strain characteristics of the recycled polymer from which is the basic structural unit of PET.

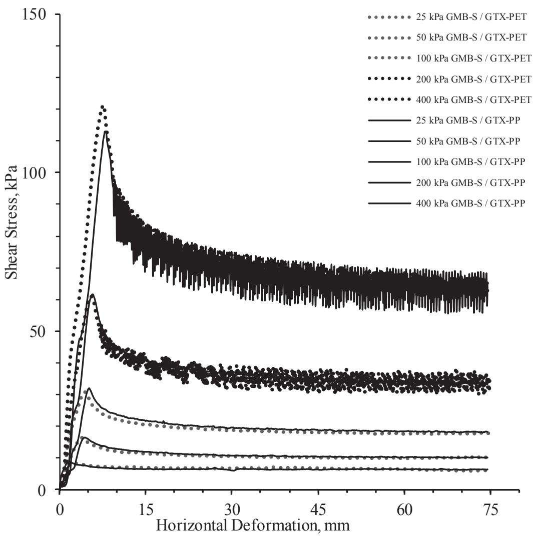

Figure 3. Shear stress versus shear displacement for GMB-S interfaced against GTX-PET and GTX-PP.

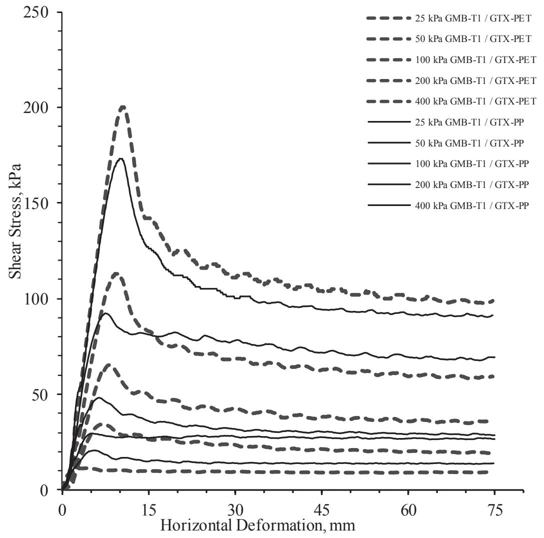

Figure 4. Shear stress versus shear displacement for GMB-T1 interfaced against GTX-PET and GTX-PP.

3.1.2 *GMB-T1/GTX interfaces*

From the GMB-T1/GTX interfaces shear stress – horizontal displacement plot shown in Figure 4, it was evident that with the inclusion of (332 spikes per 10000 mm^2) asperity concentration, the displacement required to develop peak stress was increased by an average of 60 % in relation to the smooth geomembrane. As such, the peak shear stress was mobilized at a shear displacement of 5.00, 6.30, 7.30, 8.90 and 10.85 mm at applied normal stress of 25, 50, 100, 200, and 400 kPa, respectively. Also, the reported shear stress exhibited a significant increase in comparison with the smooth geomembrane interfaces, particularly at greater applied normal stress. Regarding shear reduction after attaining peak shear stress, the inclusion of asperity further triggered more shear reduction accompanied with "undulating behaviour", especially at higher applied normal stresses.

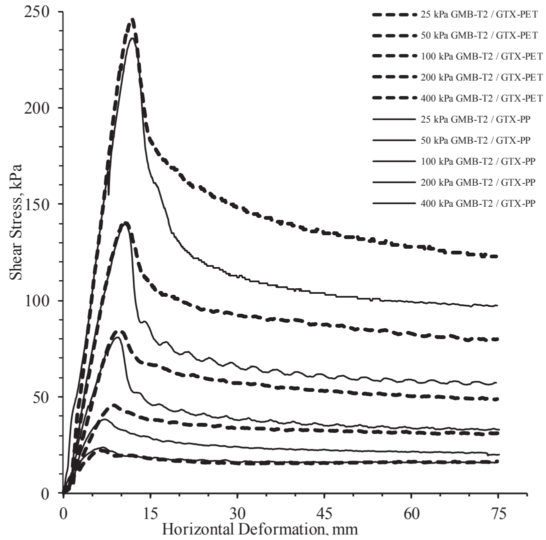

Figure 5. Shear stress versus shear displacement for GMB-T2 interfaced against GTX-PET and GTX-PP.

3.1.3 *GMB-T2/GTX interfaces*

For the GMB-T2/GTX interfaces shear stress – horizontal displacement plot shown in Figure 35, it was observed that subsequent doubling of asperity concentration (from 332 spikes to 663 spikes per 10000 mm^2) at fixed asperity height, caused the displacement needed to mobilize peak stress to increase by 25 %. As such, the peak shear stress was mobilized at a shear displacement of 6.58, 8.01, 9.51, 10.98 and 12.27 mm at applied normal stress of 25, 50, 100, 200, and 400 kPa, respectively. The changes to horizontal displacements required to attain peak stresses were considered to be caused by the resulting fibre-asperities interaction as asperity concentration was increased. A possible explanation for the minimal increase of 25 % in peak displacement even when asperity concentration was increased by 100 %, was the crowded gripping of the asperities into the geotextile's fibres. It was observed from the presented plot that a 100 % increase in asperity concentration at constant asperity height resulted in a minimal increase to the GMB/GTX interface peak displacement at all applied stresses except at 50 kPa and 100 kPa. Therefore, it was considered that doubling of GMB asperity concentration under certain conditions might result in little or no increment to the displacement required to mobilise peak shear.

3.2 *Effect of geomembrane asperity concentration on GMB/GTX failure envelope*

This section presents and discusses the failure envelope behaviour of the GMB/GTX interface as asperity concentration was varied at constant asperity height. For each failure envelope presented herein, the smooth interface was denoted with "dotted lines" for both polypropylene and polyester interfaces, whereas interfaces with relatively smaller asperity concentration and greater asperity concentration were symbolized with "broken lines" and "solid lines", respectively.

From Figure 6(a), for GMB/GTX-PP interfaces, it was evident that a 100 % increase in asperity concentration (from 332 to 663 spikes) resulted in a 16 %, 30 %, 67 %, 51 %, and 37 % increase in peak shear strength at 25, 50, 100, 200, and 400 kPa stress, respectively. Also, considering the recorded GMB/GTX-PP large displacement shear strength from Figure 6(b) as asperity concentration was doubled, an increase of 17 %, 25 %, 15 %, 17 % and 6 % at the respective stress of 25, 50, 100, 200, and 400 kPa was identified. On the other hand, for GMB/GTX-PET interfaces, it was observed from Figure 7(a) that at 25, 50, 100, 200, and 400 kPa stress, respectively, an increase in peak shear strength of 94 %, 33 %, 30 %, 25 %, and 23 % was attained. With regard to the effect of 100 % increase in asperity density on GMB/GTX-PET large displacement shear strength, 77 %, 61 %, 40 %, 35 % and 24 % increase in large displacement shear strength at 25, 50, 100, 200, and 400 kPa stress, respectively, were recorded.

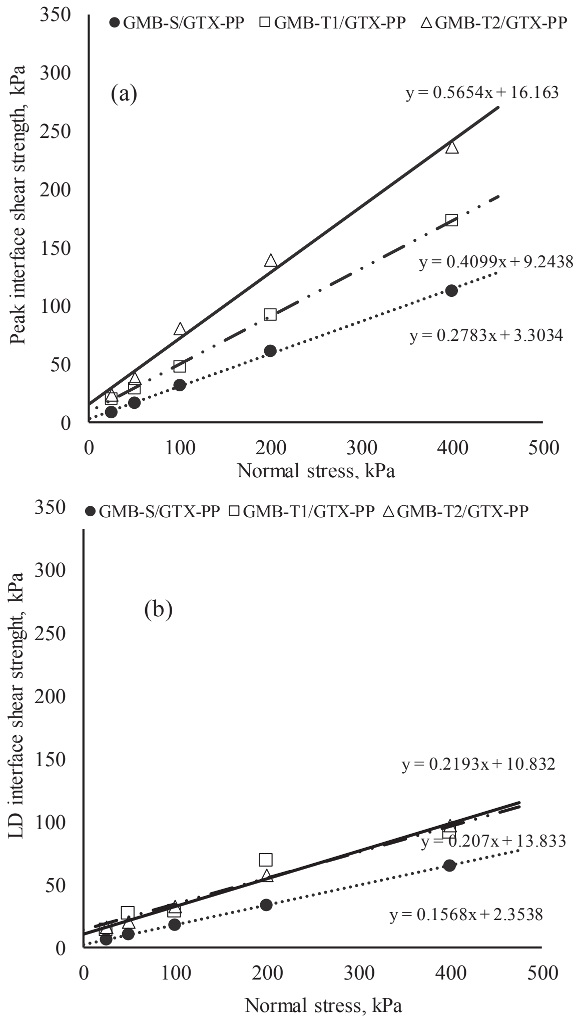

Figure 6. Shear stress versus normal stress for GMB/GTX-PP interfaces with varied asperity concentration (a) Peak (b) LD

This investigation revealed that doubling asperity concentration resulted in improved shear strength characteristics, with GTX-PET interfaces producing higher shear increase than GTX-PP interfaces. GTX-PET interfaces exhibited greater shear resistance because their fibres were thin and tightly clustered and the surface accommodated matrix-level interaction with GMB asperities. Also, the effects of doubling asperity density were observed to reduce as applied stresses increased – this was attributed to excess interlocking and raking of geotextile fibres by asperities at higher applied stresses. Therefore, it can be inferred that a 100 % increase in asperity concentration resulted in minimal changes to the reported failure envelopes.

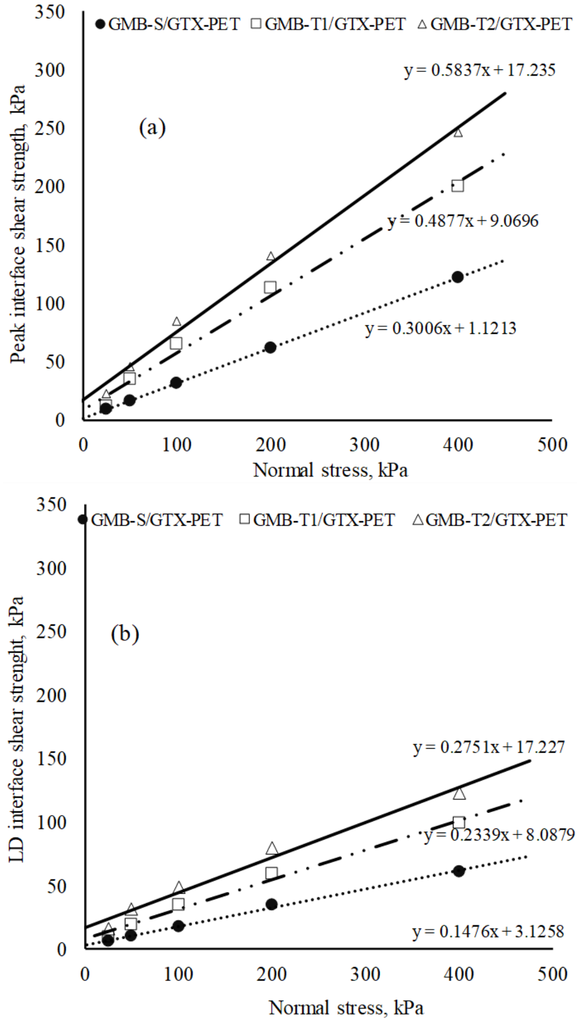

Figure 7. Shear stress versus normal stress for GMB/GTX-PET interfaces with varied asperity concentration (a) Peak (b) LD.

Table 2. GMB/GTX interface shear parameters at varied asperity density.

Interface	*Asp. Conc. (no/area)*	*Peak shear strength*		*LD shear strength*	
		δ_p(°)	$c_{a\text{-}p}$ (kPa)	δ_{ld}(°)	$c_{a\text{-}ld}$ (kPa)
GMB-S/GTX-PP	0	15.55	3.30	8.91	2.35
GMB-S/GTX-PET		16.73	1.12	8.40	3.13
GMB-T1/GTX-PP	332	22.29	9.24	11.70	13.83
GMB-T1/GTX-PET		26.00	9.07	13.17	8.09
GMB-T2/GTX-PP	663	29.48	16.16	12.37	10.83
GMB-T2/GTX-PET		30.27	17.24	15.38	17.23

It was identified from Table 2 that the inclusion of asperities, GMB-T1 (332 spikes) interface relative to GMB-S interface produced an average (both GTX-PP & GTX-PET) increase of 50 % and 44 % in peak and LD friction angle, respectively. Subsequently, a 100 % increase in asperity density (from 332 to 663 spikes) at constant asperity height led to an increase of 24 % and 11 % in peak and LD friction angle, respectively. Similarly, observations from apparent adhesion (c_a) revealed that peak and LD apparent cohesion increased by 80 % and 30 %, respectively. The minimal increase in friction angle even at a 100 % increase in asperity density was considered to be caused by the weakening of the geotextile-fibre strength as the asperities tip mobilized concerted matrix-level interaction and the failure plane shifted from the geomembrane-geotextile interface to the geotextile fabric. Assuming that apparent cohesion is sometimes negligible, it can therefore be stated that provided the GMB asperity height remains fixed, an increase in asperity density produced a correspondingly less effect on the shear characteristic (friction angle), particularly at large displacement (Adeleke, 2020). Generally, considering the observed impact on large displacement friction angle, polyester geotextile (GTX-PET) exhibited greater improvement than polypropylene geotextile (GTX-PET) as asperity concentration was doubled.

4 CONCLUSION

In addition to the details given to the effects of asperity height by previous studies and researchers, this study presents insight into the role of asperity concentration and geotextile-type on geomembrane-geotextile interface shear parameters. The data shows interesting trends and indicate that GMB/GTX interface shear strength are affected by asperity concentration and geotextile-type as well as applied normal stress. For the considered GMB/GTX interfaces, doubling asperity concentration triggered an aggressive shear mechanism as only 11 % and 24 % increase in LD friction angle and LD apparent cohesion, respectively, were recorded. The significance of this data is that asperity concentration effects are not directly proportional as normally anticipated. This may necessitate a further study that would aim at identifying asperity concentration that optimizes GMB/GTX interface shear characteristics. Also, further studies may consider confirming that identified optimized asperity concentration corresponds to a higher slope stability factor of safety using limit equilibrium analysis as assessed in Adeleke et. al., 2021b.

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