Damage Analysis of Geomembranes through a 3D Optical Profilometer

Prashanth Vangla[1]; Ishan Boro[2]; and Madhavi Latha Gali[3]

[1]Ph.D. Student, Dept. of Civil Engineering, Indian Institute of Science, Bangalore 560012, India. E-mail: pvangla@civil.iisc.ernet.in
[2]Dept. of Civil Engineering, Indian Institute of Science, Bangalore 560012, India. E-mail: 1989ishanboro@gmail.com
[3]Professor, Dept. of Civil Engineering, Indian Institute of Science, Bangalore 560012, India. E-mail: madhavi@civil.iisc.ernet.in

Abstract

The mechanisms governing the shear behaviour of sand and sand-geomembrane interfaces is studied by carrying out large scale symmetric loading direct shear tests on three sands of different sizes with similar morphological characteristics and a smooth high density polyethylene geomembrane. To focus on the effect of particle size on the shear behaviour, the morphological properties of sand particles, measured from microscopic images, were kept same. Surface topographical profiling of the geomembranes before and after interface shear tests was carried out to understand the extent of indentation due to shearing along the interface. The representative samples of smooth geomembranes after tests with three sands of different sizes at one particular normal stress were selected for damage analysis/surface roughness measurements through 3D optical profilometer. 3D contours of surface roughness of the geomembrane before and after the tests are presented and compared. Interface shear strength was observed to hugely depend upon the effective contacts formed on the surface of the geomembrane, which are a function of the number of particles in contact and the depth of the grooves formed by these particles on the surface of the geomembrane.

1. INTRODUCTION

The behaviour of geosynthetic reinforced soil structures can be of two types - dilative and non-dilative. The mechanism involved in these two types of behaviour is different because the dilatancy at the interface depends upon the relative size of soil particles compared to the surface asperities of the geosynthetic material. The shearing resistance offered in case of dilative interface systems (sand-textured geosynthetics) is mainly due to interlocking between the soil particles and surface asperities of the geosynthetic material. Therefore, the surface roughness due to the asperities of the geosynthetic significantly influences the magnitude of interface shear strength in this interface system (Paikowsky et al, 1995; Lings and Dietz 2005). Whereas in the case of non-dilative interface system, particularly sand-smooth geomembrane interface, fundamental mechanism that mainly contributes to the shearing resistance is plowing of softer material (geomembrane) by the harder material (sand particles). Particle size (Uesugi and Kishida, 1986; Williams and Houlihan 1987) and morphology of the particulate material as well as surface hardness (O'Rourke et al. 1990) of the smooth continuum material plays important role in plowing mechanism and associated shearing resistance. Thus the mechanism involved in the non-dilative interface systems cannot be explained by traditional soil mechanics principles unlike the case of dilative interface systems. To understand the plowing mechanism, more accurate quantification of the size and morphological properties of particulate materials as well as shear induced surface changes of the geomembrane becomes necessary. Recent developments in digital image techniques enabled easy and more accurate quantification of the morphological properties of the sand particles compared to conventional techniques (Vangla and Latha, 2015). Similarly, the advancement in non-contact optical techniques provided more accurate and easier way of quantification of the surface changes on the geomembrane. The present study is aimed at understanding the interface shear behaviour of sand-geomembrane interfaces, with a specific focus towards the effect of particle size by adopting latest techniques for the material characterization and measurements.

2. MATERIALS

2.1 *Sand*

Three different types of sands were used in this study, namely, coarse sand (CS: particle size 4.75 mm-2 mm), medium sand (MS: particle size 2 mm-0.425 mm) and fine sand (FS: particle size 0.425 mm-0.075 mm). All these sands are classified as poorly graded sands (SP) as per Unified Soil Classification System. These sands were obtained by scalping specific size fractions from river sand of same origin. Table 1 presents the properties of sands. Photographs showing the physical appearance of sands and Scanning Electron Microscopic (SEM) images showing the variation in grain sizes of the three sands are shown in Fig. 1.

Table 1. Properties of sands used in this study

Property Grain size parameters	Coarse Sand (CS)	Medium Sand (MS)	Fine Sand (FS)
D_{10} (mm)	2.18	0.5	0.16
D_{30} (mm)	2.57	0.68	0.19
D_{50} (mm)	3	0.87	0.22
Coefficient of uniformity, C_u	1.49	1.96	1.51
Coefficient of curvature, C_c	0.93	0.97	0.93
Maximum unit weight, γ_{max} (kN/m^3)	15.88	16.09	16.05
Minimum unit weight, γ_{min} (kN/m^3)	13.96	13.59	13.1
Maximum void ratio, e_{max}	0.82	0.87	0.95
Maximum void ratio, e_{min}	0.6	0.58	0.6

Literature suggests that the morphology of sands, which represents the geometry and shape of sand grains plays important role on the shear behaviour (Santamarina and Cho, 2004; Göktepe and Sezer, 2010). To eliminate the effects of sand morphology while studying the effect of particle size, sands of similar morphology with varying particle size are selected for this study. The morphological characteristics of sand grains were quantified through image analysis on 50 particles. The image analysis on the particles involves conversion of SEM images into binary images and extracting the pixels information to obtain the geometrical information of the sand particles to compute the morphology as per the formulae given in Table 2. A special algorithm is written in MATLAB to carry out the image analysis. It is observed from Table 2 that CS, MS, and FS have similar roundness, sphericity and regularity, indicating that these sands have similar morphology.

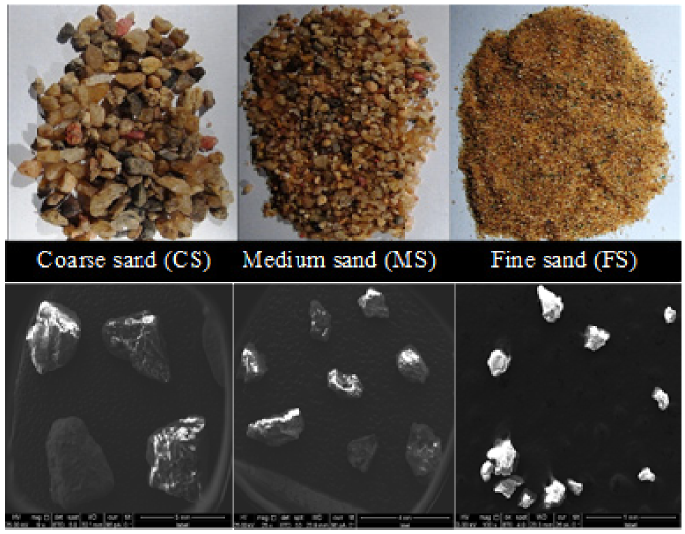
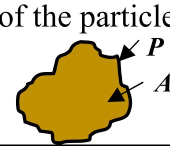


FIG. 1. Photographs and Scanning Electron Microscopic (SEM) images of sands

Table 2. Morphological characteristics of sands

Morphological Descriptor	Formula	Reference	CS	MS	FS
Roundness ($\boldsymbol{R}$)	$\frac{4\pi \boldsymbol{A}}{\boldsymbol{P}^2}$	Janoo (1998)	0.74	0.73	0.74
Sphericity ($\boldsymbol{S}$)	$\frac{2\sqrt{\pi \boldsymbol{A}}}{\boldsymbol{P}}$	Sympatec (2008)	0.86	0.85	0.86
Regularity ($\boldsymbol{\rho}$)	$\frac{(\boldsymbol{R}+\boldsymbol{S})}{2}$	Cho et al. (2006)	0.80	0.80	0.80
Pictorial representation ofat rest notation and description	$\boldsymbol{P}$ is the perimeter of any horizontal projected section of the particle $\boldsymbol{A}$ is the area of the profile of the particle projection				

2.2 *Geomembrane*

A smooth High Density Polyethylene (HDPE) geomembrane, which is commercially available and more often used in engineering applications due to its more favorable properties like high tensile strength at low strains is used in this study. The properties of this geomembrane given by manufacturer are: thickness - 1.5 mm, mass per unit area - 1326 g /m2, tensile strength - 45 kN/m, and failure strain - 700 %.

3. INTERFACE DIRECT SHEAR TESTS

3.1 *Test Setup*

A large size symmetric loading direct shear test setup enhanced with digital imaging capabilities was developed and used for the determination of shear strength parameters of sands used in this study. The test setup is in accordance with ASTM D 3080 for sand alone tests and ASTM D 5321 for interface shear tests. The detailed description of this test setup is presented in Vangla and Latha (2014) and Vangla and Latha (2015). The same test setup is further modified into interface symmetric loading direct shear test setup as shown in Fig. 2 to conduct the interface shear tests with sands and planar continuum material like geomembrane. Additionally, this test set-up has a facility to shear the sample up to a larger displacement (75 mm) to understand the post peak behaviour in interface shear tests. The shear box of this test setup can hold a sample size of 300 mm× 300 mm× 80.5 mm. The bottom half of the setup is made up of rigid base to which the planar continuum materials like geomembrane can be fixed with the help of specially designed clamps on all four sides of the platform. This way of fixing the planar continuum materials can avoid sagging and wrinkling and restricts the shearing plane to the interface during the test. The setup is integrated with an automatic data acquisition system and graphical display so as to acquire the data continuously and to monitor the test response respectively during the test.

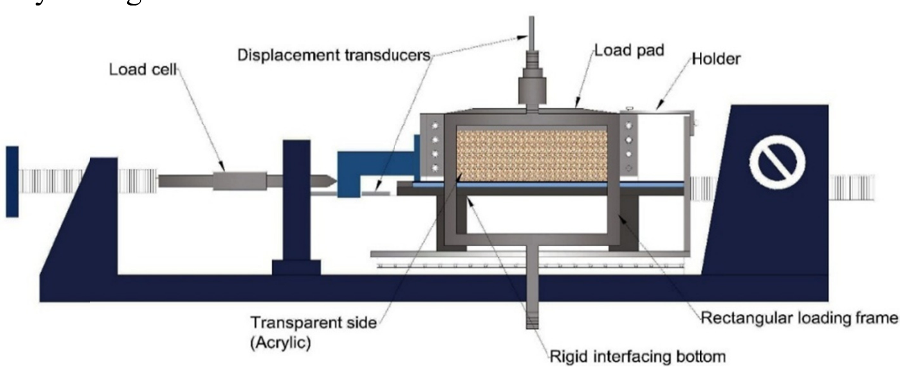


FIG. 2. Schematic diagram of symmetric loading interface direct shear test setup

3.2 *Sample Preparation and Testing*

Prior to placing shear box over the bottom rigid base, a geomembrane of size equal to the bottom base platform of 465 mm length × 433 mm width is placed over the rigid base and fixed with clamps on four sides. Later the shear box is placed over the geomembrane and filled with sand. In all tests the sand samples were prepared at a relative density of 70% by layerwise hand compaction technique. Number of blows were gradually increased from bottom layer to top layer of the sample to ensure uniform compaction. During the sample preparation the shear box was fixed firmly to the vertical side of the platform with a holder (refer Fig. 2) to ensure no effect of lateral movement of shear box on the sample. All tests were carried out at a constant displacement rate of 1 mm/min under three normal stresses (22, 37 and 53 kPa).

4. RESULTS AND DISCUSSIONS

4.1 *Direct shear tests*

Initially a series of symmetric loading direct shear tests were performed on all three sands at relative density of 70 % under three normal stresses to determine the internal friction angle. A representative shear stress-shear displacement response of all three sands under a normal stress of 53 kPa is shown in Fig 3a. Fig 3b, 3c and 3d present peak and post peak normal stress vs. shear stress plots for CS, MS and FS respectively. Irrespective of the large variations in the particle sizes of all three sands, the shear stress-shear displacement response have shown almost same peak shear stress.

The peak and post peak friction angles obtained for these sands are presented in Table 3. From this table it is evident that CS, MS and FS have almost same friction angle and have different post peak friction angles. Literature suggests that morphology of the sands have major role on peak friction angle (Santamarina and Cho, 2001; Holtz and Kovacs, 1981) and also suggested that particle size does not have any effect on the peak friction angle if the shear tests are carried out at same void ratio (Holtz and Kovacs, 1981). Thus, the similar peak friction angles obtained for sands used in this study can be attributed to the fact that these sands have similar morphological characteristics and all the tests were performed at almost same void ratio as shown in Table 3.

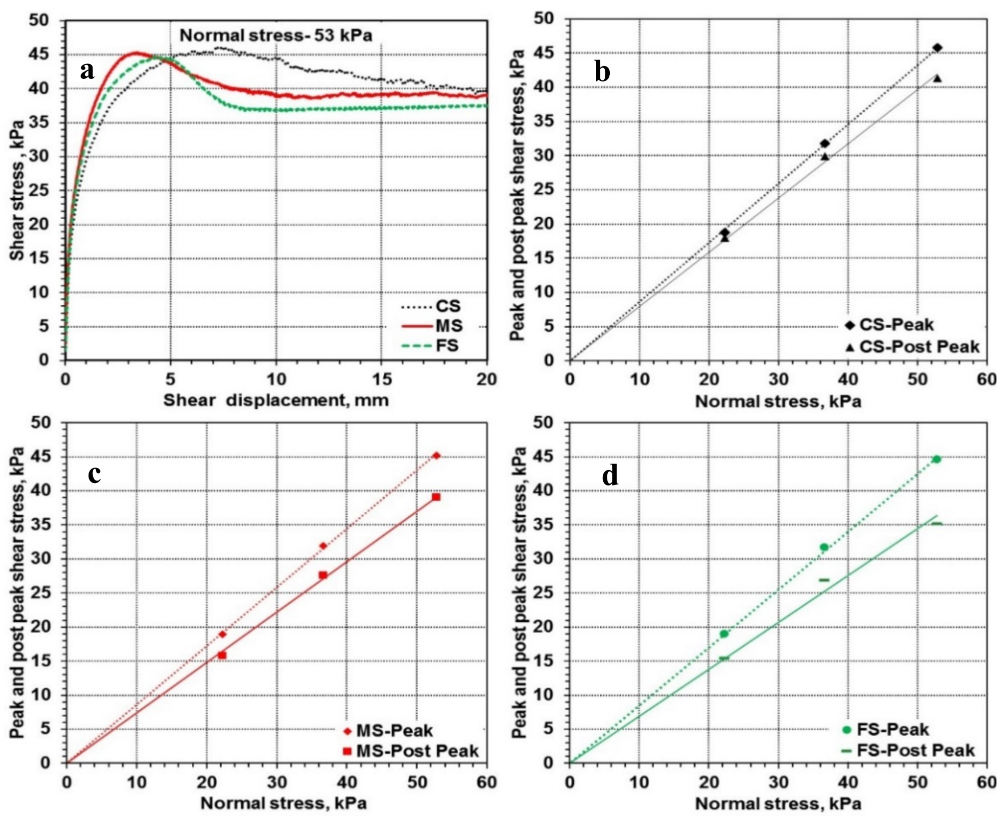


FIG. 3. A representative shear stress-shear displacement and the failure envelopes of the CS, MS and FS

Table 3. Peak and post peak friction angles for CS, MS and FS

Type of sand	Internal peak friction angle	Internal post peak friction angle	Void ratio 'e' at RD 70%
CS	40.8	38.9	0.67
MS	40.7	37.2	0.67
FS	40.4	35.9	0.70

The drop of the peak shear stress is increasing with decrease in particle size, which is clearly visible in the comparison plots (Fig 3b, 3c and 3d) of peak and post peak shear stress envelopes. Further, the influence of the particle size on the post peak shear response and post peak friction angle can be seen in Fig 3a and Table 3 respectively. The drop of the peak friction angle or peak shear stress with shear displacements is more in fine sand with respect to medium and coarse sands. The reason for this behaviour is that the interlocks between sand particles get slowly released while the sand is sheared after the peak shear stress is reached, which reflects as the drop in peak shear stress. The post peak release of interlocks between the sand particles is comparatively slower for bigger size particles and hence the drop is minimal.

4.2 *Interface shear tests*

The effect of particle size on the interface shear behaviour was investigated by conducting a series of shear tests on sand-geomembrane interfaces. A representative shear stress-shear displacement plot at a normal tress of 53 kPa is shown in Fig 4a. Figs 4b, 4c and 4d present of peak and post peak shear stress envelopes for CS-GM, MS-GM and FS-GM interfaces respectively. Table 4 presents the peak and post peak friction angles for all three interfaces. Results from interface shear tests show that CS with mean particle size (D_{50}) of 3 mm has yielded lesser interface peak friction angle than MS and FS which have obtained almost same interface peak friction angles. The reason for higher interfacial strength in case of medium and fine sands compared to coarse sand can be attributed to the higher number of effective contacts, which will be explained in later sections. Also, there is a considerable drop of peak shear stress in case of fine sand, unlike coarse and medium sands where the peak shear stress is sustained for large deformations. The comparative plots of peak and post peak shear stress envelopes presented in Figs. 4b, 4c and 4d show more clearly that the drop of peak shear stress is higher in case of FS and it decreased with the increase in particle size, from MS to CS. This result is similar to the behaviour observed in sand alone tests.

Table 4. Peak and post peak friction angles of CS-GM, MS-GM and FS-GM interfaces

Interface	Peak friction angle	Post peak friction angle	Void ratio 'e' at RD 70%
CS-GM	18.2	17.9	0.67
MS-GM	22.6	21.6	0.67
FS-GM	22.5	17.4	0.70

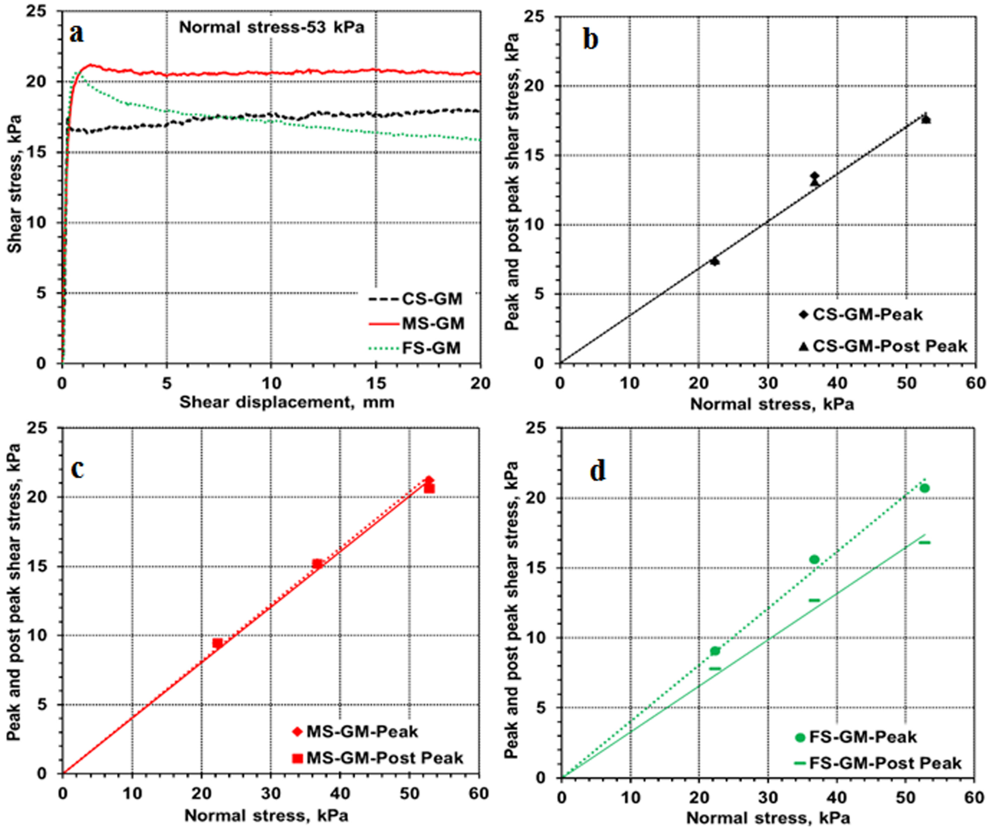


FIG. 4. Shear stress-shear displacement plots and the failure envelopes for the sand-geomembrane interfaces

While the shearing in sand alone tests involves rolling and sliding of sand particles on each other, shearing in interface shear tests involves plowing and sliding along the indents formed. The major contribution for the shearing resistance in the sand-geomembrane interfaces (non-dilative interface systems) is plowing of the geomembrane surface by sand particles. The plowing of geomembrane material happens when sand particles are hard enough and the normal stress applied on the sand particles is adequate to indent the geomembrane. The plowing of the softer material like GM can induce surface changes and these surface changes depends upon factors like particle size, morphology and normal stress applied during the tests. The quantitative understanding of these surface changes of geomembrane can provide a clear insights into the mechanisms involved in interface shear. Therefore, in this study a sophisticated 3D optical profilometer is adopted for the quantification of the surface changes induced by the sand particles on GM during the shear.

5. SURFACE ROUGHNESS STUDIES

The shear induced surface changes of the geomembrane is very often measured by traditional stylus profilometer and image based Optical Profile Microscopy (OPM) technique (Dove, 1996; Dove and Frost, 1996) in geotechnical community. In the present study, more accurate and advanced non-contact 3D optical profilometer is used for surface roughness measurements, which offers several advantages over the above mentioned methods, including the elimination of surface damage, increase in accuracy and increased measurement speed.

The surface roughness studies were carried out on the geomembrane samples of size 14 mm length × 3.5 mm width. Samples of geomembrane were tested for their surface roughness prior to the shear test and after shear test at 20 mm shear displacement. Surface roughness for the samples is characterized by amplitude parameters, namely, average roughness (R_a), maximum height of the profile (R_t) and summation of average peaks and average valleys (R_v). Average roughness (R_a) is defined as the arithmetic average of the absolute values of profile height deviations recorded within the evaluation length and measured from the mean line. R_a of untested geomembrane is measured as 0.05 µm. Figs. 5a, 5b and 5c show the 3D topographical images of the surface changes induced by the coarse sand, medium sand and fine sand respectively. The amplitude parameters determined for all samples are listed in Table 5.

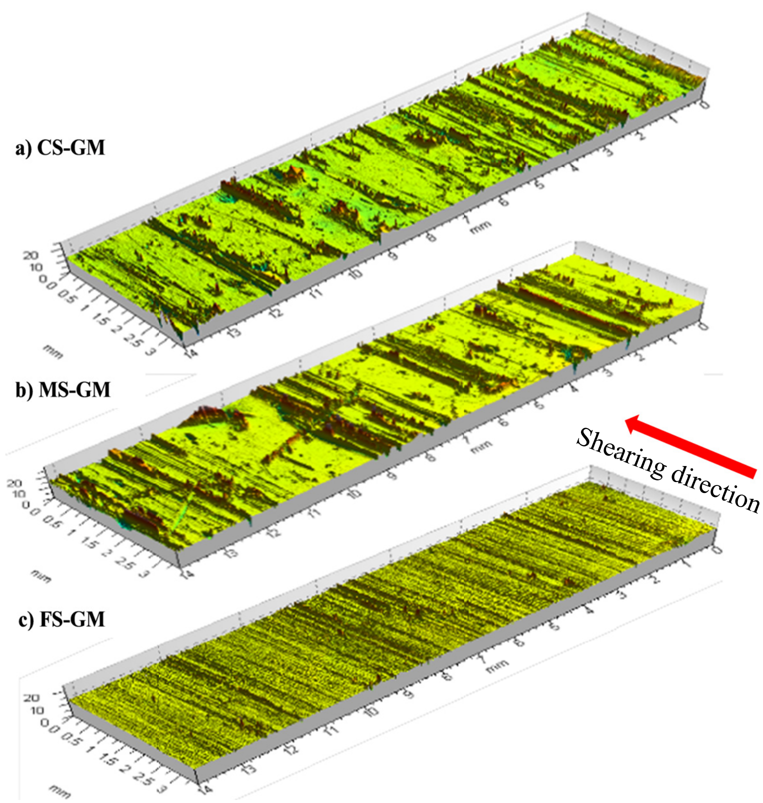


FIG. 5. Shear induced surface changes on geomembrane by a) Coarse sand b) Medium sand c) Fine sand

Surface profile analysis after shearing showed that the number of grooves formed on CS-GM interface are very less compared to the grooves formed on MS-GM and FS-GM interfaces. Table 5 shows that the average roughness (R_a) of the sheared surface is in the decreasing order for MS-GM, CS-GM and FS-GM interfaces. Also, when the depth of grooves is compared in terms of R_t, grooves were deeper for MS-GM interface. Fig.5 also shows that the grooves formed by coarse sand are wider but less deep compared to medium sand because of their bigger particle size. In case of fine sand, the grooves were more but the depth and width of these grooves is relatively small, because of which the sand could easily slide along the grooves, which is the reason for post-peak shear stress drop in this case. These observations lead to the fact that medium sand used in this study was able to make more effective contacts with the geomembrane compared to other two sands, which was measured through more number of deeper grooves formed.

Table 5. Amplitude parameters of post shear profiles of geomembrane sheared by CS, MS and FS

	Amplitude Parameters		
Interface	R_a (μm)	R_z (μm)	R_t (μm)
CS-GM	0.636	6.375	15.000
MS-GM	0.782	6.471	15.176
FS-GM	0.395	4.176	9.325

Results from the interface shear tests reveal that the effect of particle size on the interface shear behaviour is more evident on the post peak behaviour, which can be correlated to the surface changes on the geomembrane. It is the effective contacts, which can cause deeper grooves that govern the interface shear behaviour than the particle size alone.

6. CONCLUSIONS

A systematic series of symmetric loading direct shear tests were performed on three sands having different mean sizes and similar morphological properties. It was observed that sands having different mean particle size (D_{50}) exhibit similar peak friction angles if the morphology and initial void ratio remain same. However the effect of particle size can be seen in post peak behaviour, the post peak friction angle increasing in the order of increase in particle size. Further, interface direct shear tests were performed on these sands interfacing with a smooth geomembrane. Test results showed that the shear behaviour of sand-geomembrane interfaces is mainly governed more by the effective contacts than the particle size. Surface change measurements showed that the medium sand could make more number of effective contacts with deeper grooves, resulting in highest interface friction. The number of grooves were less in case of coarse sand and the depth of grooves was less in case of fine sand, resulting in lesser interface friction for these two sands compared to medium sand, supporting the results of interface shear tests

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