Large displacement, constant contact area geosynthetic-soil interface direct shear test device

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ABSTRACT: For testing of gravel-geosynthetic interface the use of large size direct shear testing devices are needed. The horizontal displacements that can be applied by classical large size direct shear interface test devices are limited due to the change in the contact area and the development of a moment couple during the application of the normal load at large displacements. A new device is developed which allows large horizontal displacements up to two times the size of the sample with no contact area change. The direct shear device is composed of a 0.3 m square upper box travelling over a lower box three times longer. The normal force on the upper box is applied by a set of pneumatic muscles connected to a sliding car on the rails along the side of the lower box travelling together with the upper box. This way the normality of the force is sustained even in large displacements. The long lower box provides constant contact area even at large displacements. The maximum horizontal displacement capability of the equipment is 0.6 meters. The residual interface properties of geosynthetics-soil can be easily determined with the developed equipment. To demonstrate the potential use of the box a smooth and a textured geomembrane are used and the interface properties are determined for number 2 crushed stone to model drainage material overlying geomembrane at the cover of a waste disposal site. The tests are conducted up to 150 mm horizontal displacement at which the textured geomembrane showed a thirty per cent decrease in interface shear trength which cannot be determined by using conventional testing equipment.

Keywords: Geosynthetics interface properties, direct interface shear test, residual shear properties

1 INTRODUCTION

Large size direct/interface shear equipment development studies date back to more than twenty years at Bogazici University (Baykal, 2015). A large size dual purpose direct shear test device, a cylindrical interface test device for geosynthetics and finally a large displacement constant area multipurpose direct shear test device are developed which is the subject of this paper. The previously developed equipments will be briefly explained and a representative data set for each device will be presented.

1.1 *Large size direct shear and pull out testing device*

The first designed large size direct shear testing device is capable of conducting shear tests, interface tests and pullout tests with changing one wall of the lower box (Baykal and Doven 2000), (Doven 1996). The dimensions of the box are 0.30 m by 0.30 m. The normal load is applied by using an airbag placed on top of the upper box. The horizontal displacement is applied via an electric motor, reduction gear and electronic speed control and the bottom box is pulled and a load cell is attached to the drive shaft. The large size direct shear test device is shown in Figure 1.

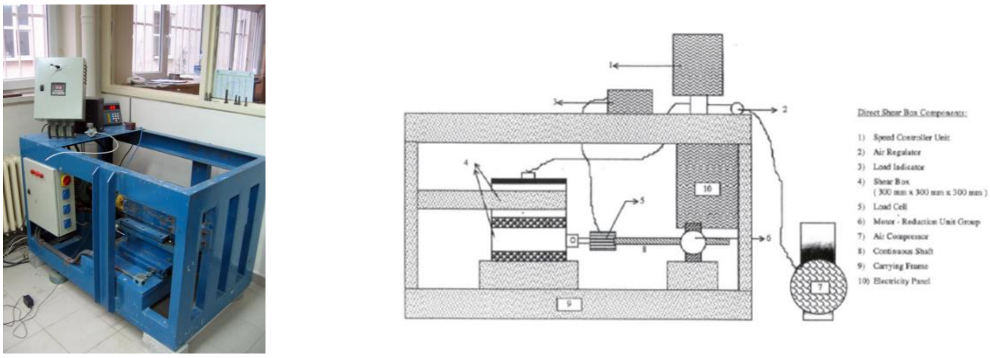


Figure 1: Multipurpose (shear, interface, pullout) large size direct shear testing device

The maximum horizontal displacement used for this equipment is 60 mm corresponding to 20 per cent of the length of the sample. Residual tests may be conducted only by moving the box back and forth till the residual interface shear values are reached. The test system has been successfully used for several commercial projects as well as research. Some examples are given below. The data sets presented are to give a feeling about the use of the equipment and the data given are part of more comprehensive studies which are cited in the references.

1.1.1 *Interface study between geocomposite drainage material and textured geomembrane for dry and wet conditions*

Six sets of experiments were conducted to determine the interface friction angle values for a geocomposite –geomembrane, geocomposite-top soil, geocomposite-fill soil under saturated and unsaturated conditions (Baykal and Danyıldız, 1996). The large size direct shear tests are conducted according to the suggested ASTM D 5321-92 method. The testing speed was selected as 1 mm/ minute and normal stresses of 10, 20 and 40 kPa were applied. The geocomposite drainage material, textured geomembrane and the placement of the geocomposite into the shear box is shown in Figure 2.

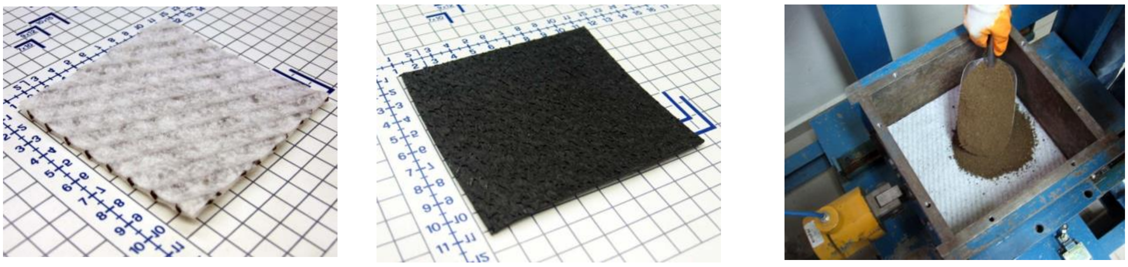
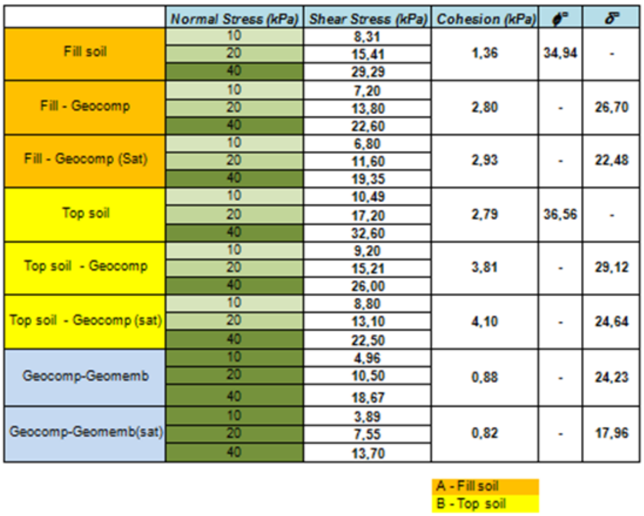


Figure 2: The geocomposite, textured geomembrane and placement of fill soil on geocomposite

The results of the conducted tests are presented in Table 1. The geomembrane was a textured type geomembrane; the geocomposite was used as drainage material.

Table 1. Large size direct shear test results for geocomposite and geomembrane used



	Normal Stress (kPa)	Shear Stress (kPa)	Cohesion (kPa)	φ°	δ°
Fill soil	10	8,31	1,36	34,94	-
	20	15,41			
	40	29,29			
Fill - Geocomp	10	7,20	2,80	-	26,70
	20	13,80			
	40	22,60			
Fill - Geocomp (Sat)	10	6,80	2,93	-	22,48
	20	11,60			
	40	19,35			
Top soil	10	10,49	2,79	36,56	-
	20	17,20			
	40	32,60			
Top soil - Geocomp	10	9,20	3,81	-	29,12
	20	15,21			
	40	26,00			
Top soil - Geocomp (sat)	10	8,80	4,10	-	24,64
	20	13,10			
	40	22,50			
Geocomp-Geomemb	10	4,96	0,88	-	24,23
	20	10,50			
	40	18,67			
Geocomp-Geomemb(sat)	10	3,89	0,82	-	17,96
	20	7,55			
	40	13,70			

🟧 A - Fill soil
🟨 B - Top soil

The lowest interface fri geomembrane interface under saturated conditions. With this interface shear parameters the waste disposal site construction was completed with adequate safety and is under operation for more than seven and a half years with no stability problems.

1.1.2 *Pullout tests for geogrid and crushed rock*

Pullout study for geogrid and crushed gravel is conducted using the dual purpose large direct shear box (Baykal and Dadaşbilge, 2008; Dadaşbilge, 1999). The front panel of the bottom shear box is designed in such a way that it can easily be replaced with a panel having a groove. Due to the relatively small space available in the shear box, the geosynthetic to be tested is taken out from this groove and clamped at the outside of the box which is connected to the load cell. The load cell is fixed to the moving shaft. The clamp is designed according to ASTM D4595. The geogrid shown in Figure 3 is cut into two widths of 0.10 m and 0.20 m and is placed into the shear box as shown. The tensile strength of the geogrid was 55 kN/m. Limestone crushed stone with 20-30 mm diameter is used.

Figure 3: The geogrid used and its placement into the box

The tests have been performed under different displacement rates and normal stresses. The pullout force and displacements in the front and rear nodes are recorded. Pullout occurs when the front and rear nodes make equal displacement under constant or decreasing pullout load. Coefficient of interaction (COI) value was obtained by dividing the pullout force by two times the geogrid width, the mobilized anchor length (L_a), normal vertical stress, and internal friction angle of the soil (**ϕ**). **δ** Value is calculated by using the COI value and internal friction angle. Representative test results are presented in Table 2. Two horizontal displacement rates of 3mm/min and 5 mm/ minute were used. The tests are conducted for 0.1 m and 0.2 m geogrid widths. 50, 100 and 150 kPa normal stresses were applied.

Table 2. Geogrid pullout test results for 0.10 m and 0.20 m sample widths

Test No	Displacement rate mm/min	σ_v kN/m^2	B m	$F_{pullout}$ kN	L_a m	ϕ °	COI	δ °
33	3 mm/min	50	0.1	4.69	0.27	53	**1.31**	**60**
46	3	100	0.1	5.62	0.27	53	**0.78**	**46**
43	3	150	0.1	4.94	0.27	53	**0.46**	**31**
55	5 mm/min	50	0.1	3.96	0.27	53	**1.11**	**56**
29	5	100	0.1	5.36	0.27	53	**0.75**	**45**
28	5	150	0.1	5.51	0.27	53	**0.51**	**34**

TABLE 5.2. Tests with 20 cm specimen width:

Test No	Displacement rate mm/min	σ_v kN/m^2	B m	$F_{pullout}$ kN	L_a m	ϕ °	COI	δ °
19	3 mm/min	50	0.2	7.43	0.27	53	**1.04**	**54**
17	3	100	0.2	9.51	0.27	53	**0.66**	**41**
4	3	150	0.2	9.89	0.27	53	**0.46**	**31**
13	5 mm/min	50	0.2	7.49	0.27	53	**1.05**	**54**
10	5	100	0.2	10.03	0.27	53	**0.70**	**43**
11	5	150	0.2	10.37	0.27	53	**0.48**	**33**

Although the large size direct shear box is relatively small for geogrid pullout tests, the results show that a 0.20 m width of geogrid was adequate to obtain some valuable information about the interface behavior of the crushed stone and the geogrid used.

1.2 *Geosynthetic-soil cylindrical interface testing device*

A cylindrical interface testing device is developed for geosynthetics interface testing (GICT) (Baykal, 1997; Akkol, 1997; Akkol and Baykal, 2001) The geosynthetic to be tested is wrapped over a kestamide cylinder with three boundary conditions; free, one end fixed and two ends fixed. The typical testing set up is given in Figure 4. The cylinder which is wrapped with goesynthetic is placed in the special container and the soil is filled around it at the target relative density. The normal force on the cylinder is applied by a special rubber balloon wrapping the sand at the periphery. By applying air pressure to the peripheral balloon the required normal load is applied to the geosynthetic. The cylinder is turned by an electric motor with a reduction gear. A torque transducer is placed between the kestamide block holding the goesynthetic and the drive shaft of the motor. This way it is possible to measure the torque applied on the interface of geosynthetic and the sand at specified relative density. Using the measured torque value, the shear stress is calculated. The mechanism of the testing system is different than that of the torsional shear test device. Here, the interface around the cylinder is measured where in torsional shear device the interface at the top of the cylinder is measured. This test has many advantages over conventional tests. The displacement that can be applied to at the interface is infinite. The cylinder can be turned as many times as required to reach residual values. There is no need to shear the sample back and forth as it is done in conventional tests.

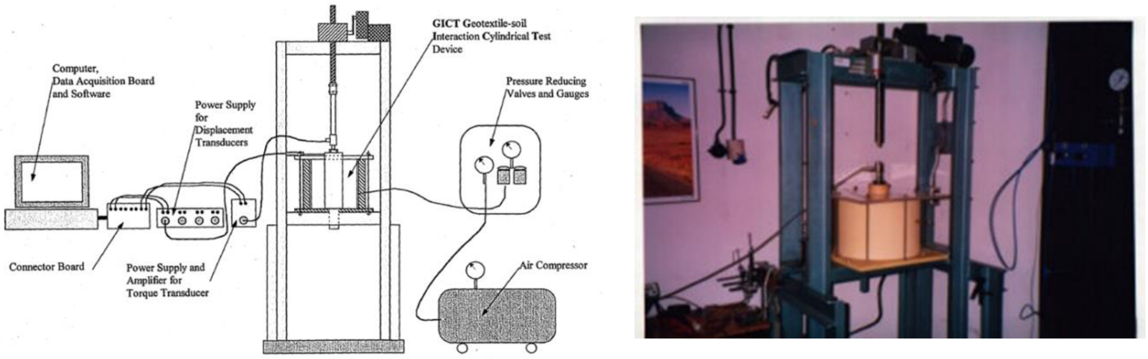


Figure 4: Test setup for cylindrical geosynthetic shear interface device

As a representative test result the interface efficiency values are presented for loose and dense Ottawa sand against spun bonded nonwoven geotextile (A), needle punched nonwoven geotextile (C) and woven geotextile (D) in Figure 5.

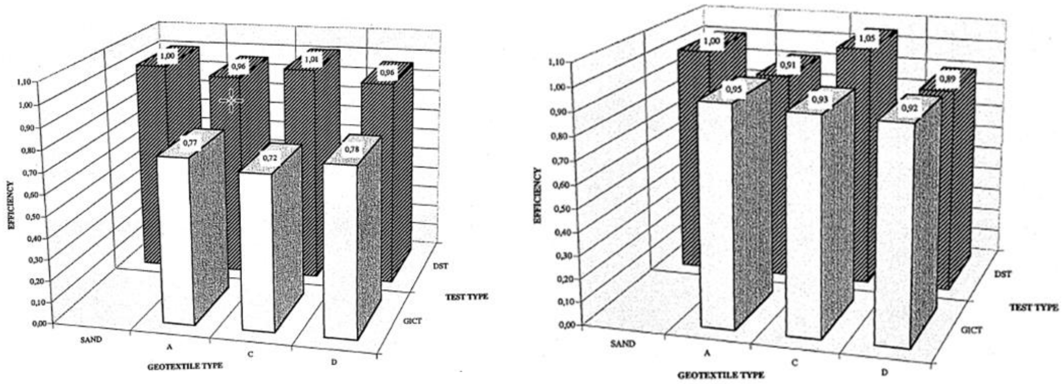


Figure 5: Comparison of interface efficiency for direct shear interface test (dark color) and geosynthetic cylindrical interface test for loose (left) and dense Ottawa sand

2 LARGE DISPLACEMENT CONSTANT CONTACT AREA SHEAR DEVICE

With the experience gained from previous equipment development a complete new large size, large displacement interface testing system is designed and manufactured (Baykal 2015, Baykal 2016). Pneumatic muscles are used for the application of the normal load, a step motor with reduction gear driven linear actuator is used to apply the horizontal load (strain controlled). An antagonistic loading mechanism is also developed by using pneumatic muscles (stress controlled)(Figure 6).The upper box is 0.30 m by by 0.30 m moving on the lower box with 0.90 m length and 0.30 m width. The height of top box is 0.20 m and the height of bottom box can be adjusted between 0.20 m and 0.40 m. The normal load is applied with pneumatic muscle actuators. These actuators contract upon application of air pressure and apply forces up to 6.5 KN for a 40 mm diameter muscle. The pneumatic actuators can contract up to 20 per cent of their lengths. The rubber muscles are attached to a rail near the lower box and can travel together with the upper box (Figure 6). The muscles are connected to a beam in twin order on the top box, exerting compression to the soil in the upper box. The normal stress can be applied by the help of up to six pneumatic artificial muscles, which have a diameter of 40 mm, a nominal length of 250 mm and radial air inlet valves at both end fittings.The bottom part of the muscles, which are connected to rod eyes, are fastened to a linear guide. The top parts, which are connected to rod clevises are fastened to an aluminum beam in order to transmit the tensile load of the muscles to the loading platen. The muscles can operate efficiently up to 25% contraction and the generated force output decreases with increasing contraction ratio. Keeping the contraction at a minimum level, is prefererred to obtain large force output. Typical force magnitudes produced corresponding to varying contraction levels are presented in Figure 7 (Yıldız, 2010). Up to three beams with six rubber muscles can be attached providing a theoretical total of 39000 N normal force. Considering the fact that a ten story high building exerts 100 kPa to the underlying soil, for a 0.09 m2 contact area, the force generated by artificial muscles will be adequate. This can be achieved even using two 40 mm pneumatic artificial muscles.

Figure 6: General view of the large displacement direct interface test device and the linear actuator driven by the step motor and reduction gear mechanism (right)

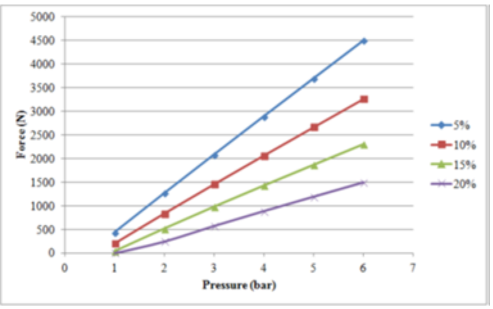


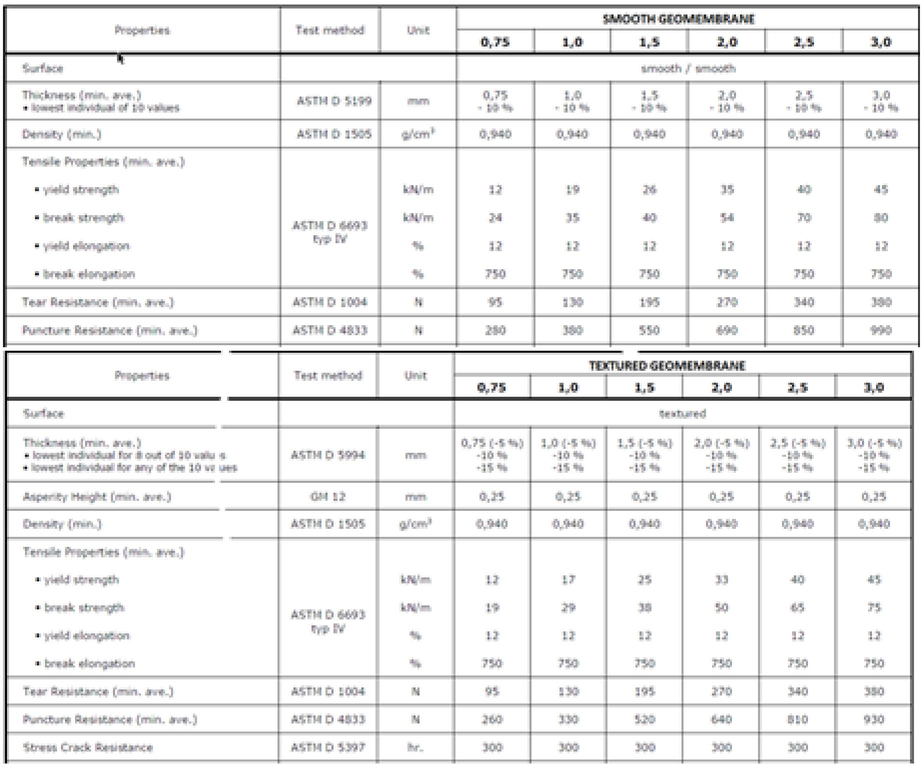
Figure 7: The load capacity of 40 mm muscle at various air pressure and changing contraction

As shown in Figure 6, the small size upper box is pulled or pushed over the fixed larger bottom box. A stepper motor with reduction gear is used to move the linear activator (Figure 6). The step motor is controlled by PLC software by the control box shown towards the right end of the equipment. The capacity of the linear actuator is 15 KN capable of applying 170 kPa shear force for the 0.09 m^2 upper box. The PLC software is capable of applying monotonic and cyclic horizontal loads with strain control. The control unit at the left part of the shear box uses PLC software to control the antagonistic loading system. The antagonistic system is composed of two opposing artificial muscle actuators pulling and pushing against each other to apply cyclic load to the upper box. This provides a stress controlled interface test execution.

2.1 *Large displacement direct shear interface tests with crushed stone drainage material on a smooth and a textured geomembrane*

To demonstrate the capability of the developed direct shear interface test device a smooth and a textured geomembrane’s interface behavior with crushed stone is investigated at large horizontal displacement. The model represents typical drainage material underlain by geomembrane on a slope. A small normal stress of 7.5 kPa is used. The sloped interface is typical for final cover layer of a waste disposal site. The number two size crushed stone is standard for concrete applications. The stone diameter between 16 mm and 23 mm range. The technical specifications of the smooth and textured geomembranes are presented in Table 3. Two mm geomembrane thickness is selected for smooth and textured geomembrane samples.

Table 3. Properties of smooth and textured geomembrane



Properties	Test method	Unit	SMOOTH GEOMEMBRANE					
			0,75	**1,0**	**1,5**	**2,0**	**2,5**	**3,0**
Surface			smooth / smooth					
Thickness (min. ave.) • lowest individual of 10 values	ASTM D 5199	mm	0,75 - 10 %	1,0 - 10 %	1,5 - 10 %	2,0 - 10 %	2,5 - 10 %	3,0 - 10 %
Density (min.)	ASTM D 1505	g/cm³	0,940	0,940	0,940	0,940	0,940	0,940
Tensile Properties (min. ave.)								
• yield strength	ASTM D 6693 typ IV	kN/m	12	19	26	35	40	45
• break strength		kN/m	24	35	40	54	70	80
• yield elongation		%	12	12	12	12	12	12
• break elongation		%	750	750	750	750	750	750
Tear Resistance (min. ave.)	ASTM D 1004	N	95	130	195	270	340	380
Puncture Resistance (min. ave.)	ASTM D 4833	N	280	380	550	690	850	990

Properties	Test method	Unit	TEXTURED GEOMEMBRANE					
			0,75	**1,0**	**1,5**	**2,0**	**2,5**	**3,0**
Surface			textured					
Thickness (min. ave.) • lowest individual for 8 out of 10 values • lowest individual for any of the 10 values	ASTM D 5994	mm	0,75 (-5 %) -10 % -15 %	1,0 (-5 %) -10 % -15 %	1,5 (-5 %) -10 % -15 %	2,0 (-5 %) -10 % -15 %	2,5 (-5 %) -10 % -15 %	3,0 (-5 %) -10 % -15 %
Asperity Height (min. ave.)	GM 12	mm	0,25	0,25	0,25	0,25	0,25	0,25
Density (min.)	ASTM D 1505	g/cm³	0,940	0,940	0,940	0,940	0,940	0,940
Tensile Properties (min. ave.)								
• yield strength	ASTM D 6693 typ IV	kN/m	12	17	25	33	40	45
• break strength		kN/m	19	29	38	50	65	75
• yield elongation		%	12	12	12	12	12	12
• break elongation		%	750	750	750	750	750	750
Tear Resistance (min. ave.)	ASTM D 1004	N	95	130	195	270	340	380
Puncture Resistance (min. ave.)	ASTM D 4833	N	260	330	520	640	810	930
Stress Crack Resistance	ASTM D 5397	hr.	300	300	300	300	300	300

The advantage of the large size box is to allow the in situ aggregate to be tested its real construction size. The equipment is capable of testing up to 40 mm size aggregates or soil clumps which is the maximum size allowed in the field for controlled compaction. The yield strengths of smooth and textured geomembranes are 35 kN/m and 33 kN/m respectively. The yield elongation values for both geomembranes are 12 percent. The asperity height of the textured geomembrane is 0.25 mm. The geomembrane samples are cut to a size of 0.29 m by 0.89 m to fit in the lower box with dimensions 0.30 m and 0.90 m. Wood square beams with 100 mm cross section are placed side by side and on top of each other to fill the lower shear box. The height of the wood beams is adjusted in such a way that the 2 mm thick geomembrane surface is flush with the upper side of the lower shear box. This way it is ensured that the shear force is applied to the interface of the geomembrane and the crushed stone. The back part of the geomembrane is fixed on the wood beams by a Velcro tape. After the geomembrane is tightly placed in the lower box, the crushed stone is placed on top of it at a relative density of fifty per cent. On top of the crushed stone steel weights are placed to apply a normal stress of 7.5 kPa at the interface.

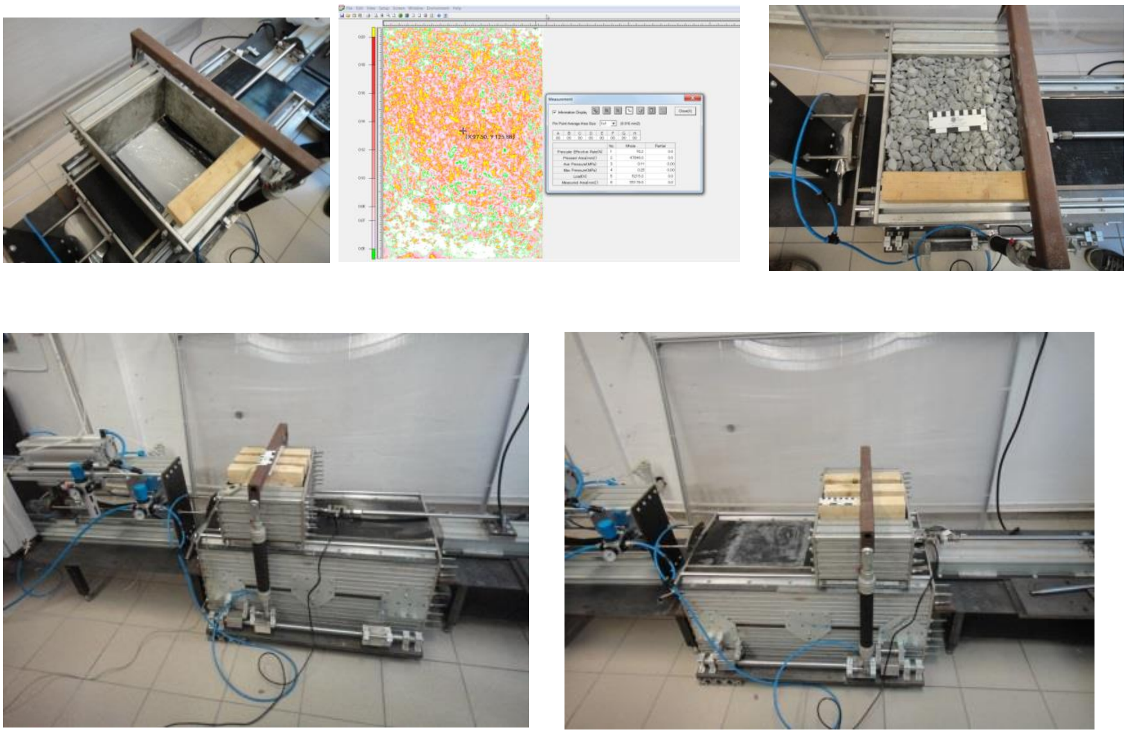


Figure 8: The empty upper box with sensitive film (top left); Typical contact stress map between crushed stone and smooth geomembrane (top middle)`; top box with crushed rock (top right); beginning of the test (bottom left); end of the test (bottom right)

Some scenes from the test are presented in Figure 8. In the top left figure the empty upper box is seen with the sensitive film at the bottom. This is a special film which is used to map the contact stress distribution. The details and use of these films are presented by Baykal (2014). This special film is composed of paint microcapsules which explode upon application of load. The color intensity of the paints released from microcapsules is correlated to contact stress by the use of a dedicated scanner and commercial software. A typical output of the software is presented at the top center figure after the application of the load (Baykal, 2016). Each sensitive film has a certain range of stress. The yellow color corresponds to stresses above maximum range and green color corresponds to below minimum measuring range of the specific sensitive film. As it is clearly seen in the figure, the contact area between the crushed stone and the smooth geomembrane is quantified. The software gives the contact area. Although in this test it is used only at the contact area, the film can easily be use at the walls of the box and at the bottom of the loading mechanism to clearly see the load applied and the corresponding stress distribution. The minimum capacity of the film is 50 kPa which may be a drawback for smaller stress values. The top box with crushed stone filled in is shown in the top right section of the figure. The left bottom figure clearly shows the location of the upper box at the beginning of the test. Notice the inclination of the pneumatic muscle actuators; they are normal to the horizontal plane. In the right bottom figure the end of the test is shown and the normality of the pneumatic muscle activators is perfectly sustained even under this large horizontal displacement. The sliding car mechanism holding the bottom section of the pneumatic muscles worked satisfactorily to sustain the normality of the vertical load throughout the test even at large horizontal displacements reaching up to 200 per cent of the sample size.

The shear stress versus horizontal displacement relationship of the crushed stone and smooth or textured geomembrane are given in Figure 9. The two geomembranes are from the same company. Both of them are 2 mm thick with close physical properties except the 0.25 mm asperity size of the textured geomembrane. The interface shear strength of the smooth geomembrane is mobilized immediately and it is sustained even at large horizontal displacement. The low magnitude of the interface shear stress is due to the application of low vertical stress of 7.5 kPa to model the upper cover layer of a typical waste disposal site. The interface shear strength mobilization is different for the textured geomembrane. The full mobilization is achieved at 30 mm; the peak value is reached at 50 mm horizontal displacement. A decrease is observed in the interface shear strength after the first peak. A second peak is reached at 60 mm horizontal displacement. A sharp loss of interface shear strength is observed after 70 mm horizontal displacement. Typically in large size direct shear testing device a 20 per cent sample size corresponds to 60 mm horizontal displacement. If a conventional large size direct shear device was used, the interface shear parameter would have been given as a peak value. The residual value of the interface shear strength is 30 percent lower than the peak value.

Although the intention of conducing the above mentioned tests was not to jump into conclusions related to the performance of smooth and textured geomembranes (more tests are required), the data obtained clearly demonstrates the potential use of the developed equipment with large horizontal displacement. Due to practicality of the developed equipment the test can be suggested as a standard test for residual geosynthetic-soil interface testing.

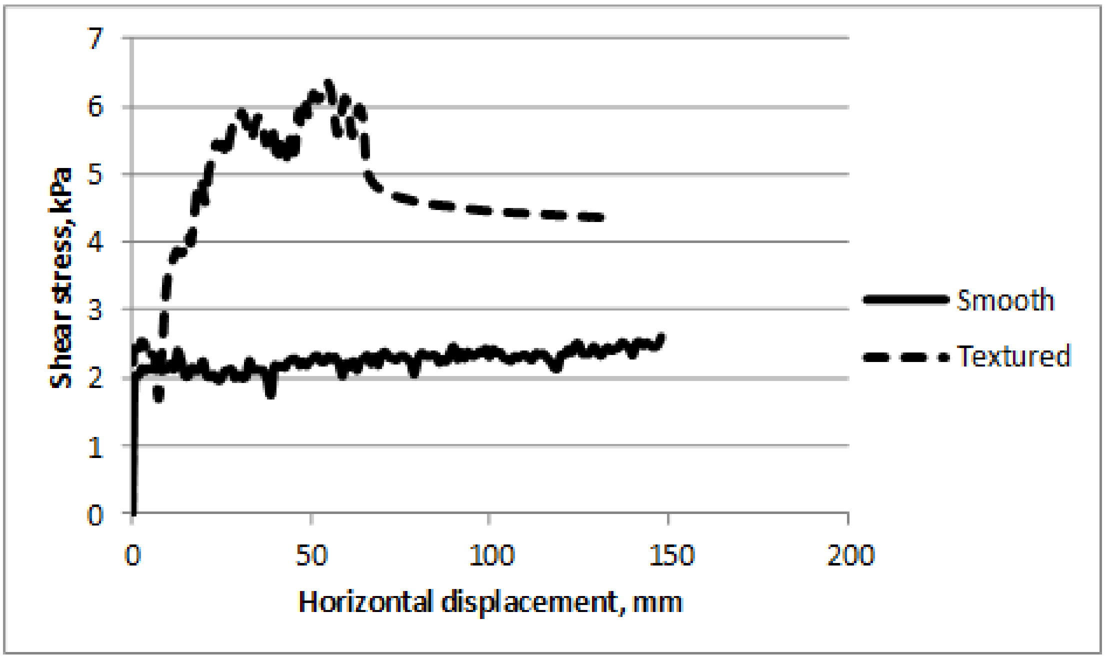


Figure 9: Shear stress vs horizontal displacement of smoot and textured geomembrane and crushed stone

3 CONCLUSIONS

New testing equipment is developed and is suggested as standard equipment for geosynthetic-soil interface testing. The new equipment is capable of reaching horizontal displacements up to 600 mm (200 per cent of the sample size). The normality of the vertical load is sustained throughout the test even at large horizontal displacements. The following conclusions are limited to the test results obtained.

Interface tests are valuable for the determination of the design parameters for geosynthetic-soil interfaces. The interface shear parameters should not be obtained from internal friction angle of the soil at the interface. An appropriate interface experiment should be conducted for each case

For sands and clays many studies show that conventional direct shear test devices can be used to obtain the interface shear parameters. However when larger size particles are of concern like crushed stone or larger soil lumps, large size testing devices are required. The interface between crushed stone and geosynthetics is a frequently encountered case for geotechnical projects.

For large size particles large size equipment is not by itself adequate but large horizontal displacement capability is also required.

The large horizontal displacement creates moment couple at the shear interface which is solved by a sliding vertical load mechanism. The vertical load which is applied via pneumatic muscle actuators with a sliding car mechanism, sustained the normality of the vertical load even at large horizontal displacement.

The constant contact area is achieved by having a three times longer bottom box. This is big advantage because this way the horizontal displacement is not limited to the sample size. For this device the horizontal displacement can be as large as 2 times the sample size. Another advantage of the larger lower box is the elimination of the soil loss during the test.

Although it is not intended to jump to major conclusions about the performance of textured versus smooth geomembranes with crushed stone with this limited number of tests, the data obtained and presented clearly demonstrate the potential use of the developed equipment.

The interface shear strength of the smooth geomembrane is mobilized instantaneously and is sustained even at large horizontal displacements. The mobilization of interface shear for the textured geomembrane occurred at a larger horizontal displacement of 30 mm with a double peak at 50 and 60 mm. A sharp decrease is observed after 70 mm horizontal displacemen. A conventional large size direct shear test device is capable of applying typically maximum 60 mm horizontal displacement. With the given example if a conventional large size direct shear device had been used, the peak interface shear strength rather than the residual interface shear strength would have been reported. This will risk the safety of the project. However with the new large displacement direct shear interface device, the residual value for the textured geomembrane is successfully determined. The use of the reported interface shear strength will be safe to implement in the field application.

The practicality and versatility of the design of the equipment developed, may lead to suggestion of it as a standard testing tool for geosynthetics-soil interface testing.

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