Evaluation of the shear strength properties of expanded polystyrene geofoam using direct shear test

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ABSTRACT: Expanded polystyrene (EPS) geofoam is a rigid cellular plastic foamed polymeric geosynthetic material that has been used in a wide range of geotechnical engineering applications. Due to very low density compared to other conventional fill materials, it can be used as a lightweight fill like higher and steeper embankments, highways, airfields, railroads and so forth. Meanwhile, the behavior of EPS geofoam is so complex and unavailability of all its physical and mechanical properties from lower to higher densities is also another problem. Thereby, the investigation of the shear strength behaviors of EPS geofoam are useful parameters for researchers who are involved in the design and application of EPS geofoam products. In this study, the shear strength behaviors of EPS geofoam using modified direct shear tests at dry and wet conditions were examined thoroughly. The effect of normal stress, density and water submergence on the EPS geofoam shear strength behavior were focused. The tests have been performed on EPS geofoam specimens of three different densities, 12, 15 and 20 kg/m^3. The stress-strain response of EPS geofoam under uniaxial unconfined compression loading is found to be nonlinear and a function of specimen size, strain rate, and density. The direct shear test results indicated that the cohesion and angle of internal friction of EPS geofoam increase with an increase in density. However, the cohesion is found to be the major parameter which contributes the shear strength of EPS geofoam. The shear stress and normal stress relationship in direct shear failure envelopes found to be linear. The submergence deceased the internal friction angle of EPS geofoam compared to the dry condition for the same density and under same applied normal stress levels, whereas, the cohesion was slightly increased.

*Keywords: EPS geofoam, density, shear strength, direct shear te*st

1 INTRODUCTION

Expanded polystyrene (EPS) geofoam is ultra-lightweight material can effectively be used in various geotechnical engineering applications like as a lightweight fills, compressible inclusion, thermal insulation, drainage, noise barrier and a structural or facing panels in the area of highways, embankments, slope stabilization, retaining walls, tunnels, pipelines, culverts and all that. Geofoam has the scientific name of expanded polystyrene (EPS). It is a super light material which is available in the form of blocks or cellular honeycomb form and geofoams are cellular (generally closed cell) in structure (Horvath 1994). The extensive popularity of EPS geofoam material is due to its many outstanding characteristics, e.g. moisture resistant, possesses negligible capillary, non-biodegradable, eco-friendly, easy to transport and molded into any shapes, and easy to assemble without special equipment and so on (Horvath 1997, Ikizler et al. 2008). However, some of its drawbacks are vulnerable to organic solvents, combustible, ultraviolet degradation and the rest (Elragi 2000). The very low density and high strength to density ratio behaviors of EPS geofoam can be used as a backfill material for construction of embankments and pavements over poor soils (Duškov 1997, Farnsworth et al. 2008, Wang and Miao 2009). Besides, the compressible behavior of EPS geofoam can be used as a compressible inclusion behind earth retaining structures, beneath a grade beam, above pipelines or culverts (McAffee and Valsangkar 2004, Kim et al. 2010, Bartlett et al. 2015). The main significance of EPS geofoam using as a compressible inclusions material: the stress-strain behavior is predictable and controllable, slightly compressible and non-biodegradable (Horvath 1997). Different researchers have been studied about the material behavior of EPS geofoam under various loading conditions: tensile strength and elastic modulus (Gnip et al. 2007); compression creep behavior (Gnip et al. 2010, Mei et al. 2012, Beju and Mandal 2016); uniaxial compression behavior (Chun et al. 2004, Hazarika 2006, Ossa and Romo 2009). The influence of confining stress on EPS geofoam plastic strain behavior has been reported by (Trandafir et al. 2011). The Compressive strength and modulus of EPS geofoam decreases with increasing of confining stress that is equivalent to embedment depth in the field (Sun 1997). The mechanical behavior of EPS geofoam affected by density, strain rate, confining stress and temperature (Birhan and Negussey 2014). The shear strength behaviors of EPS geofoam are considered as a governing factor to perform analyses and designs. Some researchers in the paste have been conducted unconsolidated undrained (UU) triaxial tests to investigate the shear strength behaviors of EPS geofoam (Padade and Mandal 2012, Beju and Mandal 2017). The authors reported that the cohesion is a major parameter which contributes the shear strength of EPS geofoam and it is a function of density. Also, the EPS geofoam displayed nonlinear major principal stress-strain behavior, as a function of confining stress and density. The increase EPS geofoam density showed increase the value of cohesion, but marginal increase in the angle of internal friction. The influence of confining stress on EPS geofoam water absorption capability checked by some authors (Duškov 1997, Ossa and Romo 2012). The result revealed that absorbed water has negligible influence on the strength and stress-strain behavior of EPS geofoam and water absorption depends on the applied stress magnitude. As EPS geofoam has a closed cell structure, it does not absorb water. Also, many researchers in the past (Xenaki and Athanasopoulos 2001, Barrett and Valsangkar 2009, Padade and Mandal 2014, AbdelSalam and Azzam 2016) conducted direct shear tests to study the interface between EPS geofoam and other materials under various normal stresses. The test results indicated that the interface behaviors of EPS geofoam were not affected by density. Whereas, the normal stress has a direct effect on its interface strength especially on interface adhesion.

The properties of EPS geofoam have been investigated experimentally for many years by several researchers who are involved in the design and application of geofoam product. However, no studies have been carried out so far for shear strength parameters on low densities of EPS geofoam at dry and wet conditions. The aim of the present study is to investigate the shear strength behaviors of different low densities of EPS geofoam using the direct shear test method at dry and submerged in water conditions. The effect of density and applied normal stress on the shear strength behaviors of EPS geofoam are reported.

2 EXPERIMENTAL INVESTIGATION

A series of direct shear tests at dry and wet conditions were performed to investigate the shear strength behaviors of EPS geofoam. The EPS geofoams of varying densities 12, 15, and 20 kg/m^3 with squared in sections were used in the experimental test studies. The EPS geofoam specimens used in this study have been prepared at Packshield Industry, which is a manufacturer and supplier of EPS geofoam in Mumbai, India. The influence of density and applied normal stresses on the stress-strain and shear strength behaviors EPS geofoam are investigated. Also, the shear factors were determined to demonstrate the relation between shear stress and normal stress. A relationship between the cohesion, friction angle, and density and normal stress are determined to understand influential parameters on the EPS geofoam material.

Prior to the direct shear test, uniaxial unconfined compressive strength tests were performed for all densities of geofoam using 50, 100 and 150 mm cubic specimens as per ASTM D1621-10 (ASTM 2010). According to ASTM D1621-10, the compressive strength of EPS geofoam specimen measurements are taken at 1, 5, 10% strain per minute are common reference strain levels, at which the stress is considered as the strength of the material. The stress-strain curves shows that the behavior of EPS geofoam under compression loading system depends on its densities; the higher density of EPS geofoam develops high compressive strength. The nature of the stress-strain curves are similar for all densities tested. The stress-strain behaviors of EPS geofoam are found to be nonlinear. Meanwhile, it is directly proportional or linear-elastic response is limited to 1 to 2% of the strain level, and the slope of this portion defines the initial tangent modulus of the material, and between 2 to 4% of strain level the yield points were developed. Beyond the yield point the compressive stress increases slightly with increase strain with linear variation. The stress-strain behavior of EPS geofoam under compressive loading condition for 150 mm cubic specimen size is shown in Figure 1. Moreover, some other physical and mechanical properties of the EPS geofoam such as density, water absorption and flexural strength are determined according to standard test methods and the results are depicted in Table 1. The test results obtained in the laboratory are agreed well with the value given by ASTM D6817-13 (ASTM 2013).

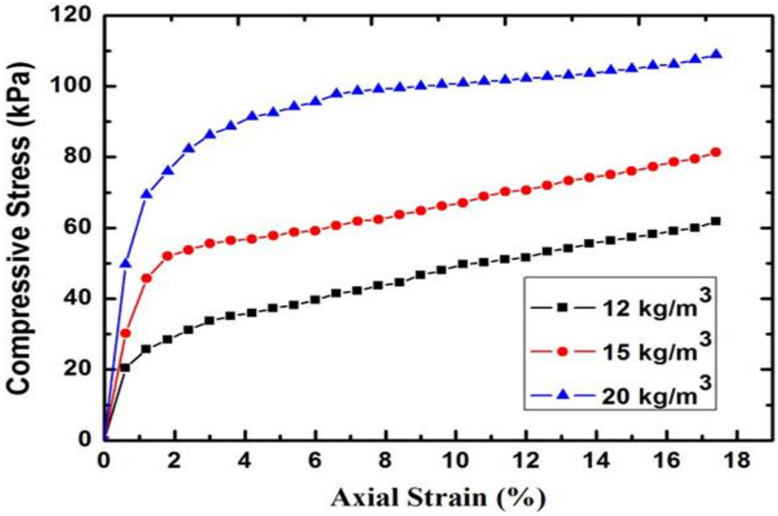


Figure 1. Stress-strain behaviors of EPS geofoam for different densities.

Table 1. Physical and mechanical characteristics of EPS geofoam.

EPS designation	Sample type and size (mm)	Compressive strength, σ_c (kPa)			Yield Strength, σ_y, (kPa)	Initial tangent Modulus, E_i, (kPa)	Density, ρ_g (kg/m^3)	Water absorption, W_g (%)	Flexural strength, σ_f (kPa)
		at 1%	at 5%	at 10%					
EPS12	Cubic (50)	8.00	28.00	39.70	22.42	1134.23	11.88	4.41	88
	100x100x100	14.00	30.50	48.6	25.13	1453.41			
	150x150x150	20.44	34.44	53.82	24.25	2246.22			
EPS15	50x50x50	20.00	55.20	63.79	52.24	1654.53	14.81	3.6	169
	100x100x100	29.00	55.75	69.80	52.16	3123.12			
	150x150x150	30.22	56.00	76.89	50.86	3328.78			
EPS20	50x50x50	68.00	88.00	106.20	81.85	4231.23	19.79	2.88	219
	100x100x100	52.00	91.50	110.60	84.21	5658.43			
	150x150x150	49.78	86.44	117.67	80.87	5569.54			

Note: EPS12, EPS15 and EPS20 denote nominal densities of 12, 15 and 20 kg/m^3, respectively.

3 TEST PROCEDURE

The tests were conducted on EPS geofoam specimens with different densities under three different normal stresses. The EPS geofoam specimens with dimensions 100 mm x 100 mm x 50 mm (length, width and thickness) were cut from each density EPS geofoam block. Figure 2 depicts the schematic view and photograph of sample used for performing the direct shear test. Direct shear test setup was used with modified shear box which can accommodate the test specimen of 100 mm x100 mm x 75 mm. The 5 mm thick grid plates having slots were provided at the top and bottom to hold the specimen in direct shear box. The grid plates were placed with slots in direction perpendicular to the direction of shear. The loading pad was then placed over grid plate and normal stress was applied through lever arm arrangement. Direct shear tests were conducted as per ASTM D3080-11 (ASTM 2011). The tests were carried out under the normal stresses of 10, 30 and 50 kPa for each density of EPS geofoam specimen and each test was conducted up to a maximum axial stain of 10.5% to cover potential phases of shear failure within each loading stage. The shear load was applied with a constant strain rate of 1.25 mm/min. Shear load and horizontal displacement were measured by means of load cell and dial gauge respectively. To ensure an accurate reading, the measuring devices were calibrated before use. The tests were performed in dry conditions (D) and repeated in wet conditions (W) for the same density but new test specimen. In other words, the direct shear test was performed for the same materials in wet conditions. For the wet condition test, the EPS geofoam specimen was immersed in water for 24 hours before testing and then placed inside the shear box, which was kept filled with water during the entire test duration. Tests were identified so as to an EPS12 (EPS geofoam specimen with 12 kg/m^3 density) tested in dry condition under normal stress of 50 kPa is represented as G12-D (50 kPa) and in wet conditions as G12-W (50 kPa).The complete test assembly and placement of EPS geofoam test specimen is displayed in the Figure 3. The ultimate shear load from direct shear tests were not obtained, but the shear loads corresponding to 10% horizontal strain were determined. According to ASTM D3080-11 (ASTM 2011), as the shear stress-strain curves do not show any marked sign of peak shear stress, the shear stress at 10% horizontal strain can be adopted as the peak shear stress. Thereby, the shear stress obtained by shear load corresponding to 10% horizontal strain divided by area.

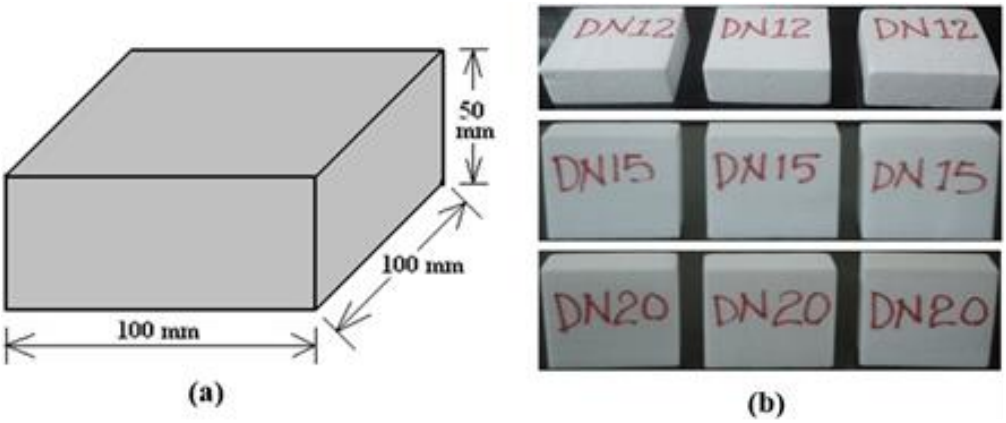


Figure 2. Test specimen of EPS geofoam for direct shear tests: (a) schematic representation and (b) photograph of various density test specimens.

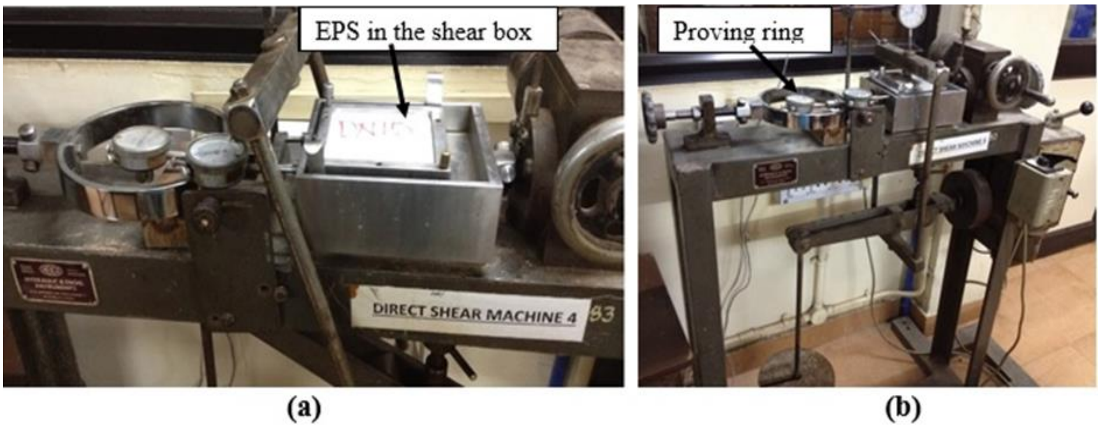


Figure 3. Modified direct shear test: (a) EPS geofoam specimen in the shear box (b) test setup.

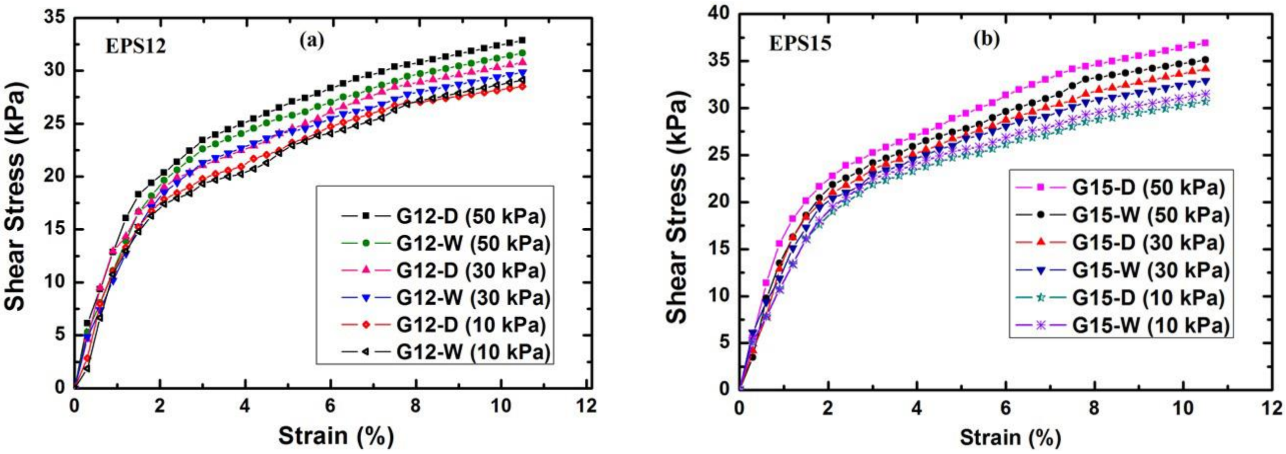
4 RESULTS AND DISCUSIONS

The compression tests were showed different results for different specimen sizes. The small size specimens tended to underestimate compression strengths of EPS geofoam because of end effects and more pronounced seating error. Thereby, large specimen size should be considered in the design process. This paper aims at characterizing the EPS geofoam in a laboratory by conducting the direct shear test in dry and wet conditions. Because the shear strength properties of EPS geofoam as part of the design process of any structures containing EPS geofoam and these tests were not conducted before on low densities of EPS geofoam at different test conditions.

4.1 *Stress-strain and shear strength properties*

The nature of stress-strain curves is found to be almost the same for all densities of EPS geofoam. The density of EPS geofoam and applied normal stress are finds to be affected the stress-strain behavior of EPS geofoam. Figure 4 shows different densities of EPS geofoam specimens after the test. Figure 5 (a-c) shows the measured shear stress-strain behaviors for different densities of EPS geofoam under various normal stresses in dry and wet conditions. From these figures, it can be seen that there is continuously increased in the value of shear stress with increased in normal stress for all densities of EPS geofoams in both dry and wet conditions, which follows the typical properties of medium dense soils. The stress-strain behavior of EPS geofoam is considerably affected by its density but the effect of normal stress is very less. Higher density EPS geofoam displayed higher shear stress value. For a particular density, no significant increase in shear stress was observed with increase in normal stress. Therefore, the shear stress-strain behavior of EPS geofoam is affected by density but, the effect of normal stress was not more noticeable. It is obvious from the figure that the submergence reduced the shear stress induced compared to the dry condition under same applied normal stress levels. The shear strength parameters of EPS geofoam for different densities in dry and wet conditions are plotted in the form of shear stress against normal stress in direct shear failure envelope as shown in Figure 5(d-f). The failure envelopes for all densities are found to be almost linear. The test results showed that no maximum value of shear strength were observed in both dry and wet conditions and in all the densities of EPS geofoam. The cohesion and angle of friction of EPS geofoam were increased with increases in its density. As can be seen from Figure 5 (d), the value of effective cohesion of the EPS12 marginally increased from 27.93 to 29.1 kPa in case of dry and wet conditions, respectively. Whereas, the effective internal friction angle of the EPS12 considerably reduced from 4.67° (dry) to 2.87° (wet). Thereby, water reduced the EPS12 effective internal angle of friction more than 35% and it increased the effective cohesion by around 4.02% as compared with the dry condition under the same applied normal stress. In general, the average effective internal friction angle of EPS12, EPS15, and EPS20 in dry and wet conditions reduced from 5.63° to 3.13°, respectively, whereas, the average effective cohesion is slightly increased from 32 kPa to 33.53 kPa for dry and wet conditions respectively.

Figure 4. The observed shear of EPS geofoam test specimens for different densities.



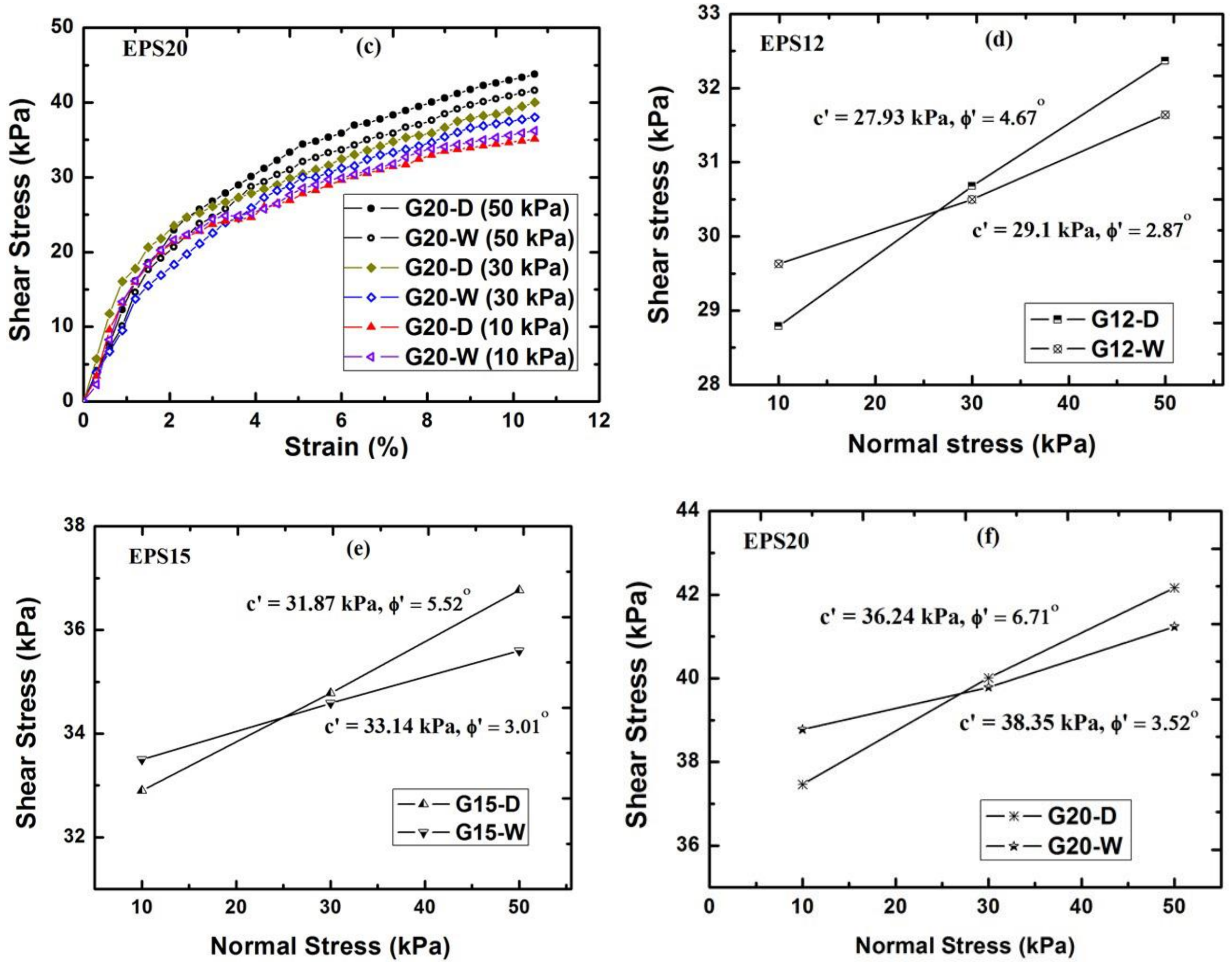


Figure 5. Direct shear test under various normal stresses, and dry and wet conditions: (a–c) shear stress-strain responses (d–f) shear failure envelope [Note: (a and d) EPS12, (b and e) EPS15, (c and f) EPS20].

The test result indicated that the cohesion and angle of internal friction of EPS geofoam increases with an increase in density. However, cohesion is found to be the major parameter which contributes the shear strength of EPS geofoam. Cohesion value increases significantly whereas a marginal increase in the angle of internal friction was observed with increase in the density of EPs geofoam for both test conditions. Cohesion and angle of internal friction values are achieved maximum for 20 kg/m^3 density of EPS geofoam. The value of 36.24 kPa and 6.71° in cohesion and internal angle of friction, respectively were obtained at dry state test condition. The values of cohesion and angle of internal friction obtained for different densities in dry and wet conditions of EPS geofoam are summarized given in Table 2.

Table 2. Direct shear test results for dry and wet conditions.

Geofoam designations	Parameter	Test condition	
		Dry case	Wet case
EPS12	Cohesion, c' (kPa)	27.93	29.1
	Friction angle, ϕ' (°)	4.67	2.87
EPS15	Cohesion, c' (kPa)	31.87	33.14
	Friction angle, ϕ' (°)	5.52	3.01
EPS20	Cohesion, c' (kPa)	36.24	38.35
	Friction angle, ϕ' (°)	6.71	3.52

4.2 *Correlation of Shear Factor and Normal Stress*

The shear factor in shear stress at failure for the case of the dry and wet conditions direct shear test results at different densities of EPS geofoam are depicted in Table 3. The shear stress at failure was normalized by the applied normal stress to determine the shear factor in this table. From this table, it is noticed that for all EPS geofoam densities with an increase in applied normal stress, the value of shear factor decrease, for the same EPS geofoam density in both test conditions. The magnitude of shear factor reduction was relatively higher from 10 to 30 kPa normal stress afterward the reduction was less.

Table 3. Shear factors for different densities of EPS geofoam at different normal stress and test conditions.

Applied normal stress (kPa)	EPS geofoam density (kg/m^3)					
	G12-D	G12-W	G15-D	G15-W	G20-D	G20-W
	Shear factor					
10	2.88	2.96	3.29	3.35	3.74	3.85
30	1.02	1.00	1.16	1.13	1.33	1.26
50	0.65	0.63	0.74	0.71	0.84	0.82

4.3 *Correlation of shear strength and density*

The test results indicated that the cohesion of the EPS geofoam is a major factor contributing to the shear strength. The obtained value of effective cohesion and angle of internal friction were plotted against the density of EPS geofoam to show the relationship between the cohesion and internal friction angle with density (Figure 7). The found correlation between effective cohesion, friction angle and density of EPS geofoam is very beneficial for estimating the approximate value of the effective cohesion and friction angle. The regression analysis is performed for different densities of EPS geofoam and best fitted to a straight line expressed as an equation: $y = m\gamma_g + c$. Where 'y' is the cohesion (in kPa) for c-line and the friction angle (in degree) for Phi-line of EPS geofoam, 'm' is the gradient of the line, 'γ_g' is the unit weight of EPS geofoam (in kN/m^3) and 'c' is constant.

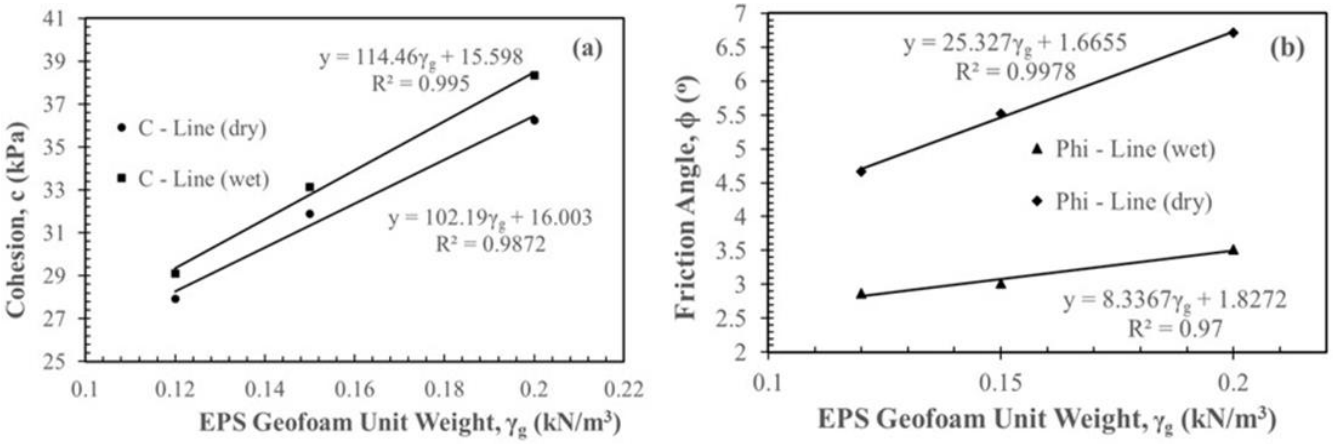


Figure 7. Correlation of shear strength against density of EPS geofoam at dry and wet conditions: (a) cohesion-density (b) friction angle-density.

Knowing the fact that property of the EPS geofoam may vary from one company to another. One of the main problems with manufacturing low-density EPS geofoam is making material that has an inadequate fusion between the individual beads. The EPS geofoam insufficient fusion between beads will simply break apart and have poor strength in geotechnical applications. Thus, it is necessary to use EPS geofoam that has a density marginally above the minimum attainable but with consistent durability. Consequently, these measured shear strength properties of EPS geofoam may not use in design for EPS geofoam manufactured by other companies.

5 CONCLUSIONS

According to the available literature, nowadays, there is a dynamic move towards utilizing geofoam as an option for soils in most geotechnical engineering applications. Be that as it may, the lack of exact material properties are considered as a disadvantage. In this study, a series of laboratory experiments were performed to investigate the shear strength behavior of different densities of EPS geofoam using modified direct shear test method. The study examined the effect of EPS geofoam density, the effect of normal stress and the effect of test conditions (dry and wet). The following conclusions can be drawn from the study.

1. The stress-strain behaviors of EPS geofoam are found to be nonlinear. Meanwhile, it is linear-elastic response is limited to 1 to 2% of the strain level.

2. Density is a good index property for classification of EPS geofoam. The quality and durability of EPS geofoam material influenced by its density because Young’s modulus and compressive strength reduce with reducing density.
3. The shear stress-strain behavior of EPS geofoam is affected by its density, whereas, the effect of normal stress was not more noticeable.
4. It is observed that the cohesion is a major parameter which contributes the shear strength of EPS geofoam and it is a function of density. Meanwhile, the value of angle of internal friction increases very less with increase in density of EPS geofoam.
5. Water submergence reduced the shear stress induced compared to the dry condition under same applied normal stress levels.

REFERENCES

AbdelSalam, S.S. & Azzam, S.A. 2016. Reduction of lateral pressures on retaining walls using geofoam inclusion. Geosynthetics International, Vol. 23(6), pp. 395-407.

ASTM D1621-10, 2010. Standard test method for compressive properties of rigid cellular plastics. ASTM International, West Conshohocken, Pennsylvania, USA.

ASTM D3080-11, 2011. Standard test method for direct shear test of soils under consolidated drained conditions. ASTM International, West Conshohocken, Pennsylvania, USA.

ASTM D6817-13, 2013. Standard specification for rigid cellular polystyrene geofoam. ASTM International, West Conshohocken, Pennsylvania, USA.

Barrett, J.C. & Valsangkar, A.J. 2009. Effectiveness of connectors in geofoam block construction. Geotextiles and Geomembranes, Vol. 27(3), pp. 211-216.

Bartlett, S.F., Lingwall, B.N. & Vaslestad, J. 2015. Methods of protecting buried pipelines and culverts in transportation infrastructure using EPS geofoam. Geotextiles and Geomembranes, Vol. 43(5), pp. 450-461.

Beju, Y.Z. & Mandal, J.N. 2016. Compression creep test on expanded polystyrene (EPS) geofoam. International Journal of Geotechnical Engineering, Vol. 10(4): pp. 401-408.

Beju, Y.Z. & Mandal, J. N. 2017. Expanded polystyrene (EPS) geofoam: preliminary characteristic evaluation. Procedia Engineering, Transportation Geotechnics and Geoecology (TGG 2017), Saint Petersburg, Russia, Vol. 189, pp. 239-246.

Birhan, A.G. & Negussey D. 2014. Effect of confinement on creep behaviour of EPS geofoam. Geotechnical Testing Journal, Vol. 37(6), pp. 1-8.

Chun, B.S., Lim, H.S., Sagong, M. & Kim, K. 2004. Development of a hyperbolic constitutive model for expanded polystyrene (EPS) geofoam under triaxial compression tests. Geotextiles and Geomembranes, Vol. 22(4), pp. 223-237.

Duškov M. 1997. Measurements on a Flexible Pavement Structure with an EPS Geofoam Sub-Base. Geotextiles and Geomembranes, Vol. 15(1-3), pp. 5-27.

Elragi, A.F. 2000. Selected engineering properties and applications of EPS geofoam. PhD Dissertation, State University of New York College of Environmental Science and Forestry Syracuse, New York, USA, 296.

Fransworth, C. B., Bartlett, S. F., Negussey, D. & Stuedlein, A. W. 2008. Rapid construction and settlement behavior of embankment systems on soft foundation soils. Journal of Geotechnical and Geoenvironmental Engineering, Vol. 134(3), pp. 289-301.

Gnip, I.Y., Vaitkus, S., Kersulis, V. & Vejelis, S. 2010. Experiments for the long-term prediction of creep strain of expanded polystyrene under compressive stress. Polymer Testing, Vol. 30(5), pp. 493–500.

Gnip, I.Y., Vejelis, S., Kersulis, V. & Vaitkus, S. 2007. Deformability and tensile strength of expanded polystyrene (EPS) under short term loading. Polymer Testing, Vol. 26(7), pp. 886-895.

Hazarika, H. 2006. Stress-strain modeling of EPS geofoam for large strain applications. Geotextiles and Geomembranes, Vol. 24(2), pp. 79-90.

Horvath, J.S. 1994. Expanded polystyrene (EPS) geofoam: An introduction to material behavior. Geotextiles and Geomembranes, Vol. 13(4), pp. 263-280.

Horvath, J.S. 1997. The compressible inclusion function of EPS geofoam. Geotextile and Geomembranes, Vol. 15(1-3), pp. 77–120.

Ikizler, .S.B., Aytekin, M. & Nas, E. 2008. Laboratory study of expanded polystyrene (EPS) geofoam used with expansive soils. Geotextiles and Geomembranes, Vol. 26(2), 189–195.

Kim, H., Choi, B., & Kim, J. 2010. Reduction of earth pressure on buried pipes by EPS geofoam inclusions. Geotechnical Testing Journal, Vol. 33(4), pp. 1-9.

McAffee, R.P. & Valsangkar, A.J. 2004. Geotechnical properties of compressible materials used for induced trench construction. Journal of Testing and Evaluation, Vol. 32(2), pp. 1–10.

Mei, G.H, Min, C.Y., Long, L.H, Yuan, L.J. & Jian, C. 2012. Creep behavior of EPS composite soil. Science China Technological Sciences, Vol. 55 (1), pp. 1-11.

Ossa, A. & Romo, M.P. 2009. Micro- and macro-mechanical study of compressive behavior of expanded polystyrene (EPS) geofoam. Geosynthetics International, Vol. 16(5), pp. 327-338.

Ossa, A. & Romo, M.P. 2012. Confining stress influence on EPS water absorption capability. Geotextiles and Geomembranes, Vol. 35, pp.132-137.

Padade, A.H. & Mandal, J.N. 2012. Behavior of expended polystyrene (EPS) geofoam under triaxial loading condition. Electronic Journal of Geotechnical Engineering, Vol.17, pp. 2543-2553.

Padade, A.H. & Mandal, J.N. 2014. Interface strength behavior of expanded polystyrene (EPS) geofoam. International Journal of Geotechnical Engineering, Vol. 8(1), pp. 66-77.

Sun, M. 1997. Engineering Behavior of Geofoam (Expanded Polystyrene) and Lateral Pressure Reduction in Substructures. Master's Thesis, Syracuse University, Syracuse, New York, USA.

Trandafir, A.C., Erickson, B.A., Moyles, J.F. & Bartlett, S.F. 2011. Confining stress effects on the stress-strain response of EPS geofoam in cyclic triaxial tests. Geo-Frontiers 2011, Advances in Geotechnical Engineering, Dallas, Texas, USA, pp. 2084-2091.

Wang, F. & Miao, L. 2009. A proposed lightweight fill for embankments using cement-treated yangzi river sand and expanded polystyrene (EPS) beads. Bulletin of Engineering Geology and the Environment, Vol. 68(4), pp. 517–524.

Xenaki, V.C. & Athanasopoulos, G.A. 2001. Experimental investigation of the interaction mechanism at the EPS geofoam-sand interface by direct shear testing. Geosynthetics International, Vol. 8(6), pp. 471–499.