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CONFERENCE PAPER

Comparative analysis on practical implications and evaluation of PVC geomembrane interfaces against particulate materials

Tanay Karademir[1]

[1] Istanbul Bilgi University, Civil Engineering Department, Santral Campus, 34060 Eyup, Istanbul, TURKIYE

ABSTRACT

An experimental research study including a series of laboratory large displacement interface shear tests between different particulate materials (rounded, angular sands) and smooth PVC geomembranes, and additionally, a series of Shore D Hardness measurements were conducted. The aim of this study is to investigate an easy and quick means of predicting shear resistance/strength of sand-polymer interfaces indirectly from the hardness of the continuum material (i.e. PVC geomembrane) at the interface to establish a comparative analysis between direct test results and indirect practical evaluation through hardness property based on an important interface shear property; friction angle, (δ) at peak and residual states measured directly from interface shear tests performed in the laboratory as well as computed indirectly from empirical models developed in the study for the case of different normal loading conditions (i.e. normal stress levels:25, 100, 400 kPa). The results and analysis will be presented throughout the paper demonstrate that the mobilized shear response and the resulting frictional resistance of sand (rounded, angular) – PVC geomembrane interface systems are highly dependent on a combination of loading conditions, geomembrane physical material properties (i.e. hardness) and particulate shape (i.e. angularity/roundness). For direct and indirect assessment of the resultant [δ_{Peak}] and [$\delta_{Residual}$] values, the comparative analysis showed that a reasonable similarity between the laboratory test results and the indirect analytical assessment analysis is evident from the analogicalness of the experimentally measured values at the predetermined normal stress levels (25, 100 and 400 kPa) to the computed values from the proposed empirical correlation equations proposed in the paper.

Keywords: Geosynthetic layereds, landfill design, particulate materials, PVC geomembranes

1. INTRODUCTION AND LITERATURE REVIEW

The design and development of geoenvironmental systems (i.e: composite structural systems at landfill base liners and side slopes) where soil (i.e. sand) is in contact with construction materials such as polymer (i.e. geosynthetics) is widespread. The placement of these dis-similar materials adjacent to one another creates interfaces which can lead to relatively weak shear strengths compared to the frictional strength of the soil mass itself. As such, particulate versus continuum interfaces (e.g. soil-geomembrane) governs the behavior of many geoenviroenmental structures including synthetic impervious liners in municipal waste containment facilities. They are generally used as composite systems rather than as stand-alone solutions in practice due to their complimentary advantages. The resisting forces at soil versus these construction material interfaces are mobilized due to relative movements between counterface materials [1]. As such, the interaction between these materials and soil plays a critical role in governing the integrity of such critical structures. To this end, numerous research efforts have been undertaken to evaluate the interface shear properties of polymers with the intention of establishing a general range for interface shear characteristics for these materials. The experimental studies of [1-5] amongst others, can be considered as important research work on the interface shear resistance of polymeric materials. These experimental studies, in addition to developing a database, also provide designers and engineering agencies with information

Corresponding Author: tanay.karademir@bilgi.edu.tr (Tanay Karademir)

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for estimating the likely range of frictional performance of geosynthetic interfaces in geoenvironmental applications.

Moreover, geomembranes are continuum materials and produced from polymeric material resins (i.e. Polyvinylchloride - PVC) for which the mechanical engineering properties (i.e. shear, tension, compression) are dependent on an important physical property such as hardness. The magnitude of surface hardness of the geomembrane liners, in general, can be associated and linked with the alteration of the material stiffness that is one of the most important visco-elastic and plastic properties of polymeric materials. A change in hardness such that a reduction in surface resistance of polymeric geomembrane liner sheet against indentation can be reflected by the alteration in Shore hardness index value. Furthermore, the stiffness of a polymer principally defines its state on the “softness” through “rigidity” scale as well as governs and is related to its surface hardness. In light of this, it is noted that the primary influence of surface hardness on sand – geomembrane interface shear response and resistance is thought to be related to the alteration of physical and mechanical properties of the geomembrane liner and are not necessarily due to changes in the sand properties. In this perspective, the use of surface hardness to indirectly evaluate the frictional performance of geosynthetic interfaces could be of importance. In this regard, the surface hardness tests of which the purpose is to measure the “resistance” of these polymeric materials developed through their physical properties to withstand an indentation force generated by a sharp object attempting to penetrate into their surfaces could provide a quick and practical mean of indirect evaluaition of frictional properties of those geosynthetics. Since the indentation hardness is inversely related to the penetration and dependent on elasticity, ductility, plasticity, strain, strength, stiffness, toughness, viscoelasticity, and viscosity properties of the polymeric materials that also could govern their interface frictional shear response and strength [6]. To this end, this study has been intended to extend the understanding on shear displacement behavior of granular material (sand) – geomembrane interfaces as numerous man-made polymer-based construction materials (i.e. geomembranes) are being routinely used in conjunction with particulate soils (i.e. sand) in various geoenvironmetal applications (i.e. landfills) and the demand for such composite soil – synthetic material systems has continuously been increasing owing to recent advancements in infrastructural construction technology. In this regard, the effects of distinct geo-material combinations at the interface on the friction properties of particulate versus geomembrane interfaces, investigated based on surface hardness measurements, will be presented. The goal of this experimental research study is to examine: i) the detection of geomembrane hardness; and, ii) develop empirical correlations between hardness and an engineering interface strength property (δ); and iii) compare results of empirically predicted interface frictional strength at peak as well as residual states based on hardness measurements with those of direct evaluation for sand – geomembrane interfaces obtained through direct interface shear tests in the laboratory.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1. Granular Material

Granular materials including Ottawa 20-30 sand and Blasting sand were selected to be used to investigate the frictional properties of sand – PVC geomembrane interfaces. Both sand is poorly graded and has a similar mean grain size (D_{50} = 0.72 mm) while Ottawa 20-30 is composed of rounded quartz sand grains; however Blasting sand is comprised of angular quartz sand particles.

2.2. PVC Geomembrane

Geomembranes, in general, are used in a wide variety of waste containment related applications such as landfill liners (primary and secondary containment), landfill caps/closures. The PVC geomembranes produced with polyvinylchloride as the principal polymer resin are selected for use in infrastructure projects which require more flexibility in three dimensional performance as well as having less hardness of the geomembrane itself which can lead to enhancement of interfacial properties for combined and layered applications consisting of different material types. The benefits of PVC geomembranes are as follows: (i) Flexibility for three dimensional performance; (ii) larger panels (up to 80% less field seams); (iii) long-term survivability.

2.3. Characterization of Surface Hardness of Geomembranes

Shore Hardness is one of the most common methods of determining surface hardness of rubber and plastic materials (i.e. polymeric materials such as geomembranes). In particular, two types of Shore hardness scales are specifically utilized for polymeric/plastic materials: Shore A (H_A) scale is generally preferred for relatively “softer” plastics; while Shore D (H_D) is used for relatively “harder” plastics (e.g. geosynthetics) to obtain an index value of surface hardness.

2.4. Shore D Hardness Measurements: Testing Equipment and Procedure

The geomembrane continuum sheets produced from a base polymer PVC are categorized in the class of relatively hard plastics. Shore D hardness scale, (H_D) ranging from 1 to 100 on Type D durometer gauge was an appropriate technique to attain a scale for surface hardness of the PVC geomembranes in a consistent manner for the purpose of quantitatively assessing such important physical property of those geomembrane liners employed in geoenvironmental applications (landfills). Shore D Hardness, (H_D) measurements, which are conducted in accordance with [7] using a durometer with constant loader test stand (Fig 1), provide an index value of the material surface hardness which can then be used in evaluating the interface frictional characteristics of geosynthetic materials counterfaced by granular soils.

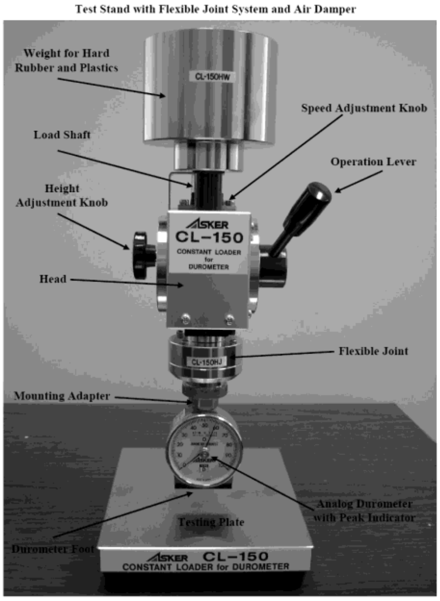

Fig 1. Durometer with constant loader test setup: Flexible joint system and air damper

The continuum material (polyvinylchloride (PVC) geomembrane liner) used throughout this study were neither corrugated nor textured and had clean smooth surfaces. The PVC geomembrane specimens were composed of plied pieces to obtain the minimum thickness with the intention of accurate determination of hardness with the durometer as required by [7]. Hardness measurements were taken at various locations of each specimen to reduce error in measurements by following a random pattern, to observe the variability in surface hardness of intact solid continua (geomembrane) and to investigate the variation in readings across the bulk. Further, for precise surface hardness measurements of polymeric plastic materials, there is a fundamental and important criteria required to be in consideration primarily which is the repeatability/steadiness and consistency of the implementation of durometer measurements. To this end, the constant loader test stand with an adjustable damping system as shown in Fig 1 was selected to ensure a constant speed of downward movement of the load shaft provided reliable and dependable results. This type of constant load stand maximizes repeatability of hardness tests by providing a variable speed control and a flexible joint on the load shaft to ensure complete contact with the sample material as well as to ensure consistent measurements by applying a consistent force throughout all the measurements.

2.5. Detection and Determination of Frictional Properties of PVC Geomembrane Interfaces

The frictional properties of geomembrane interfaces counterfaced with granular materials (i.e. sand) can physically be simulated (modeled) and assessed by performing interface shear tests in the laboratory environment. In this type of performance tests preferred by the engineers for evaluating one of the most important mechanical property (i.e. shear strength) of composite layered systems such that one component of counterface is maintained stationary (no motion) by fixing onto an immobile compartment; and other component of counterface is allowed for displacement relative to the stationary counterface component.

2.6. Interface Shear Strength Measurements: Testing Device and Methodolgy

The interface shear tests involving the particulate material (i.e. sand) and a continuum planar surface material (i.e. geomembrane) were performed by utilizing a Teflon shear box connected to the large displacement interface direct shear device. The box was laterally displaced on the upper surface of the geomembrane specimen that was fastened by clamping metal strips with bolts on a heavy metal block testing platform (Fig 2).

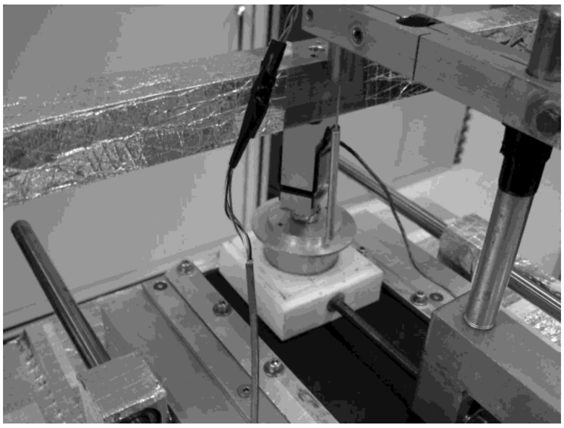

Fig 2. Sand – Geomembrane Interface Shear Testing Equipment

The normal load was applied on the sand specimen contained in the Teflon shear box through a metal cross beam by pressurizing the pneumatic cylinder. A metal round top cap was placed on top of the specimen and at the bottom of the load cell used to measure normal force. In addition, a steel ball was placed in between the normal load cell and the round top cap to prevent moment or eccentric forces from occurring during the test. Lateral and vertical displacements were measured by using a horizontally mounted LVDT attached on a moving metal frame connected to the lateral loading shaft and a vertically located LVDT on the round top cap over the sand specimen, respectively. The normal force and shear force were monitored by the normal load cell located under the loading cross beam and the shear load cell mounted on the lateral loading shaft that moved horizontally during the experiments.

3. RESULTS AND DISCUSSIONS

The shear resistance with respect to slope stability along various geosynthetic component interfaces (i.e. sand – geomembrane) is an important design issue for multi-layered composite systems. A number of case histories by [8-10] revealed that a geomembrane can create a problematic interface due to low frictional resistance between it and soil or another geosynthetic component. To this end, the experimental results of this study that will be presented will enable deeper insight and further understanding on mutual mechanical performance (strength) of composite layered systems employed in various geoenvironmental applications. Since the mobilized frictional strength and the developed interface shear behavior at particulate material (sand) – continua (geomembrane) interfaces are strongly influenced by the surface hardness of the geomembranes. Therefore, the measured index value of hardness of the geomembrane based on a particular scale (i.e. Shore D) will provide a useful quantitative value to indirectly evaluate the magnitude of shear resistance being generated at the interface between granular soil and geosynthetic. Therefore, it is noted that the amount of shear resistance developed at the interface is mainly attributed to geomembrane surface pliability governed by the material hardness.

3.1. PVC Geomembrane Surface Hardness and the Variability in Measurement Data

A total of 30 measurements (Fig 3) were performed on PVC geomembrane plied samples stacked on top of each other making sure there was no air between the layers. In order to maintain consistency in measurements and to obtain accurate test results, it is required to conduct all the hardness measurements with the same speed for all the materials tested. It is recommended as good practice to take several readings and average the results by showing the variability in measurement data. The readings, in general, indicated that the variability in measurements was consistent for all the samples tested and the 30 repeat measurements were more than sufficient to constitute a sample population to evaluate the surface hardness of PVC geomembrane liners. Additionally, the variability in the measurement data and some statistical results on the Shore D surface hardness measurements are listed in Table 1.

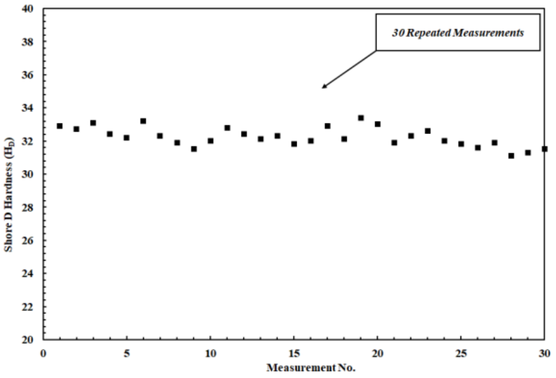

Fig 3. The overall shore D, (H_D) hardness measurements on the material surface of PVC geomembrane samples

As evident from Fig 3 and Table 1, the consistency in measurements on relatively soft and flexible geomembranes produced from PVC could be a beneficial advantage of this polymeric material in the field because of it possessing more consistent global material properties in terms of predicting a general index value by performing measurements on a limited portion of the material over a restricted region for estimating the durability properties of this polymeric geomembrane liner employed in situ over a very large area where probable variations in ambient conditions influencing material endurance characteristics may exist in large areal extent geoenvironmental projects.

Table 1. Variability in measurement data and some statistical results for PVC geomembrane

Specimen Material	Mean	Standard Deviation	Range
PVC	32.2	0.582	2.3

3.2. Interface Friction Angle and Hardness

The general model previously proposed by [5] for predicting frictional resistance of granular soil-polymeric material interfaces is as follows (Equation 1):

$$\frac{\delta}{\varphi'_{ds}} = -0.0088 \times H_D + 1.15 \qquad (1)$$

Where;
δ: Interface Friction Angle
φ'_{ds}: Soil Direct Shear Friction Angle
H_D: Polymeric Material Shore D Hardness

This general model was based on a correlation by assessing interface peak friction angle with the knowledge of soil internal friction angle whereby the ratio of interface angle of shear resistance, (δ) to direct shear angle of soil friction (φ'_{ds}) was related to Shore D Hardness (H_D) index of the polymeric materials. The results of experimental data from laboratory testing programs conducted to explore direct shear angles of Ottawa 20/30 and Blasting sands as tabulated in Table 2 were utilized and a new model has been developed in this study by substituting direct shear angle of soil friction (φ'_{ds}) into the interface property (δ/φ'_{ds}) – hardness relationship to establish a direct correlation between interface friction angle (i.e. peak and residual states of interface shear response) and surface hardness for Ottawa 20-30 Sand – PVC Geomembrane and Blasting Sand – PVC Geomembrane interfaces as given in Equations 2 and 3, respectively. In this way, interface friction angle (i.e. either peak or residual) of sand-geomembrane interfaces can be evaluated with respect to hardness change.

Table 2. Peak and residual direct shear angles for ottawa 20/30 and blasting sands

	φ'ds [Peak]	φ'ds [Residual]
Ottawa 20-30 Sand	39°	28°
Blasting Sand	43°	35°

$$\delta_{\text{peak}} = -0.3432\text{x}\text{H}_\text{D} + 44.85 \qquad (2a)$$

$$\delta_{\text{residual}} = -0.2464\text{x}\text{H}_\text{D} + 32.20 \qquad (2b)$$

$$\delta_{\text{peak}} = -0.3784\text{x}\text{H}_\text{D} + 49.45 \qquad (3a)$$

$$\delta_{\text{residual}} = -0.3080\text{x}\text{H}_\text{D} + 40.25 \qquad (3b)$$

Using the developed empirical relationships (Equations 2 and 3), the peak and residual friction angles (δ_{peak}, $\delta_{residual}$) for Ottawa 20-30 Sand – PVC Geomembrane and Blasting Sand – PVC Geomembrane interfaces have indirectly been calculated based on Shore D surface hardness measurements as presented in the previous section and the computed values of δ_{peak} and $\delta_{residual}$ for those two interface systems are listed in Table 3.

Table 3. The Indirectly Computed Peak and Residual Interface Friction Angles for Ottawa 20/30 Sand – PVC Geomembrane and Blasting Sand – PVC Geomembrane Interfaces

	δpeak	δresidual
Ottawa 20-30 Sand – PVC Geomembrane	33.8°	24.3°
Blasting Sand – PVC Geomembrane	37.3°	30.3°

The preceding empirical models (Equations 2 and 3) between peak or residual interface friction angles (δ_{peak}, $\delta_{residual}$) and surface hardness were developed by interrelating/linking the corresponding frictional resistance parameters for engineering design in the relationships described based on the results of durometer hardness measurements on PVC geomembrane samples. They could be utilized as a mathematical correlation to rapidly evaluate the effects of the change in hardness of the materials at the interface in which both δ_{peak} and $\delta_{residual}$ values follows a inverse linear pattern with increasing hardness for only the geomembrane liners manufactured from PVC base polymer resins. For the other geomembrane types produced from different resins (i.e. HDPE, MDPE, LLDPE or VFPE), the mathematical relation and variational trend between δ and HD will likely be different.

3.3. Results of Interface Shear Tests on Particulate versus Smooth Continua

Ottawa 20-30 Sand – Smooth PVC Geomembrane Interface Systems

A series of interface shear tests involving Ottawa 20-30 sand (rounded grains) and smooth PVC geomembranes were performed at a range of normal stress levels from 25 kPa up to 400 kPa. Stress – displacement curves are presented in Fig 4. A rapid increase in shear stress up to peak stage within 1–2 mm of displacement was observed. This was followed by a reduction to some lower residual shear stress condition with continued loss in frictional resistance as shearing displacement progressed until the termination of the test at 60 mm horizontal displacement. Further, the increase in normal stress from 25 kPa up to 400 kPa resulted in an increase in the displacement to peak.

Blasting Sand – Smooth PVC Geomembrane Interface Systems

Shear stress – horizontal displacement failure curves at different normal stresses ranging from 25 kPa to 400 kPa for smooth PVC geomembrane sheared against Blasting sand (angular grains) are presented in Fig 5. The interface direct shear tests performed using angular sand resulted in higher peak and residual (post-peak) strengths at all loading conditions as compared to rounded Ottawa 20-30 sand. One interesting aspect of the plots is the relative shape of the different curves such that the stress-displacement curves corresponding to the low normal stress condition (25 kPa) resulted in an initial rise immediately in stress at very small displacements with a slight reduction in frictional resistance after the peak strength state was mobilized. However, as the magnitude of applied normal stress increased to higher stress levels (100 kPa and 400 kPa), the stress-displacement curves for the angular sand exhibited well-defined peak state that was followed by a decrease to a residual state.

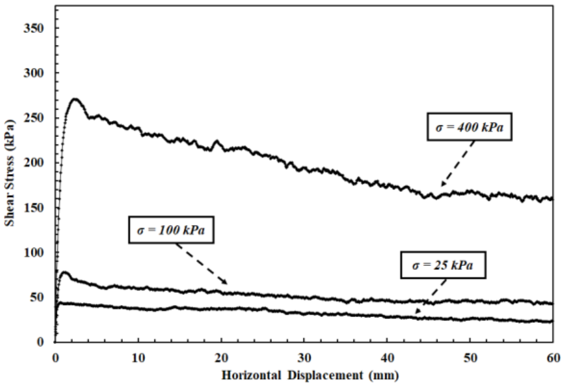

Fig 4. Shear stress – displacement curves at various normal loading conditions including: 25, 100, 400 kPa for ottawa 20-30 sand – smooth PVC geomembrane interface

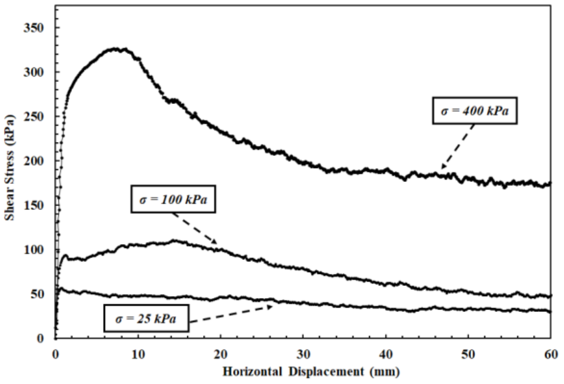

Fig 5. Shear stress–displacement curves at various normal loading conditions including: 25, 100, 400 kPa for blasting sand – smooth PVC geomembrane interface

4. FURTHER DISCUSSIONS ON THE EXPERIMENTAL FINDINGS

In light of the results of the experimental program, it was found that the mobilized frictional strength at granular material – geomembrane interfaces at different normal loading conditions is primarily influenced by the surface hardness of the counterface geomembrane. On this aspect, the measured index value of hardness of the geomembrane surface based on a standard scale (i.e. Shore D in this case) provided a useful quantitative value to evaluate and gauge the magnitude of shear resistance generating at the interface of granular soil – geosynthetic material.

Therefore, it was accomplished that the influence of a physical property of a polymeric geomembrane liners (i.e. hardness) on the mobilized interface shear strength at different loading conditions can indirectly be assessed through the use of the proportional value of δ/φ'ds which applies both for particulate material characteristics and continuum material surface properties. This normalized quantity provides a more comprehensive approach for evaluating shear properties of granular versus polymeric continuum material interfaces.

The peak and residual strengths increased with the use of angular sand instead of rounded sand at all loading conditions, the direct shear tests were performed, such that the angular sand system showed substantially higher interface strength characteristics regardless of normal stress level, and required larger horizontal displacements to reach both peak and residual state. This phenomenon is principally attributed to the amount of sand particle rearrangement occurring during shearing process as the Blasting sand is an angular material and possesses higher internal friction as being more interlocked and hence, more resistant to shear displacement. As a result, the particles on the interface surface are less likely to be rearranged during the course of shear displacement unless the applied shear stress on the interface is sufficiently large to overcome the internal friction of the particulate material itself compared to the Ottawa 20-30 sand consisting of rounded particles in which the rounded particles can easily rolling over each other and rearranging during shearing. As such, the rearrangement of the particles near the contact surface occurs with ease as the smoother rounded nature of Ottawa 20-30 sand grains. Additionally, owing to Blasting sand grains possessing relatively rough surface characteristics as compared to Ottawa 20-30 grains, angular sand – smooth PVC geomembrane system mobilized significantly higher peak and substantially larger residual shear strengths than rounded sands with increasing normal load.

5. COMPARATIVE ANALYSIS BETWEEN DIRECT TEST RESULTS AND INDIRECT PRACTICAL EVALUATION

Fig 6 shows peak interface friction angle (δ_{peak}) and residual interface friction angle ($\delta_{residual}$) plotted as a function of normal stress level for smooth PVC geomembrane interfaces sheared against rounded Ottawa 20-30 sand and angular Blasting sand, respectively, to make a comparative analysis between direct measurement test results (i.e. experimentally evaluated) and indirect assessment values (i.e. computationally evaluated) analytically calculated using empirical correlations. Reasonable similarity between the laboratory test results and the indirect analytical assessment analysis is evident from the proximity of the experimentally measured values at the predetermined normal loading conditions to the empirically computed values. The indirect assessment values from empirical equations generally concur with the direct measurement results from interface shear tests performed in the laboratory with particularly an exception of the 25 kPa normal stress level for the rounded Ottawa 20-30 sand and the angular Blasting sand granular material interfaces both of which counterfaced by the PVC geomembrane liners that shows a notable substantial difference. This is attributed to the occurrence of sand dilation during the course of shear displacement. As such the sand structure dilated which resulted in the development of higher frictional resistances and obtaining greater magnitude of the interface strength values in terms of δ at low normal loading condition of 25 kPa stress level owing to smaller magnitude of confinement applied on the interface.

Furthermore, it is noted that the dilation initiates from the sand grains existing at the contact surface and adjacent to the interface and progresses through the other sand grains beyond the contact surface and positioned within the volume of the sand sample [1]. These particles are relatively free to rearrange their contacts (interlocking between the grains), and thus dilate. As seen in the comparison plots for both δpeak and δresidual frictional properties presented in Figure 6, the response of the two different interface systems (Ottawa 20-30, Blasting) at other loading conditions including 100 kPa and 400 kPa normal stress levels, the test results from experimental direct measurements are similar to the resultant indirectly computed values using the proposed empirical relationships previously presented in the paper.

Additionally, the experimental data in Figure 6 show that both the peak and the post-peak interface friction angle (δpeak, δresidual) decreased with an increase in the normal stress. This relationship concurs with Archard's Theory on elastic deformation friction [11]. The rate of this reduction depends on the shape (i.e.: angularity) of the sand particles, and most importantly, the hardness of the counterface geomembrane which is strongly influenced by the geomembrane liner core material type (i.e. PVC). As such, the friction angle for the tested sand (rounded, angular) – smooth geomembrane (PVC) interfaces decreased with normal stress at low normal stress levels up to ~100 that is consistent with Hertzian contact theory [12]. Under higher normal stresses, the coefficient of friction became constant or continued to decrease slightly with normal stress. This is considered to be the influence of the plowing effect that often occurs at a granular material/planar surface interface as previously noted by [1].

Moreover, the indirect assessment results predicted through the developed empirical equations are marginally higher than that of the direct shear tests for particularly the greatest normal stress level of 400 kPa (Fig 6) in which the sand specimen exhibited larger amount of contraction during shearing. This is further demonstrated in Fig 7 that the percentage error in indirectly evaluated peak and residual friction angles obtained through the developed empirical relationships with respect to the direct measurement test results are negative and notable, in particular, for angular Blastind sand interface system. Two compensating effects occur simultaneously during shear displacement. The sand specimen tends to dilate in order to generate a larger internal frictional strength due to the increased shear resistance mobilized at the interface resulting from the deeper sand particle penetration. At the same time, the sand specimen is subject to volumetric contraction due to highly increased confinement effect of loading at the magnitude of 400 kPa. As such, the dilation in the sand structure was significantly prevented due to compressing and contracting impact of the larger loading conditions (400 kPa) applied on the sand specimen in such a way that a larger volumetric contraction compared to that at low normal stresses was exhibited as a result of the higher confinement of the interface.

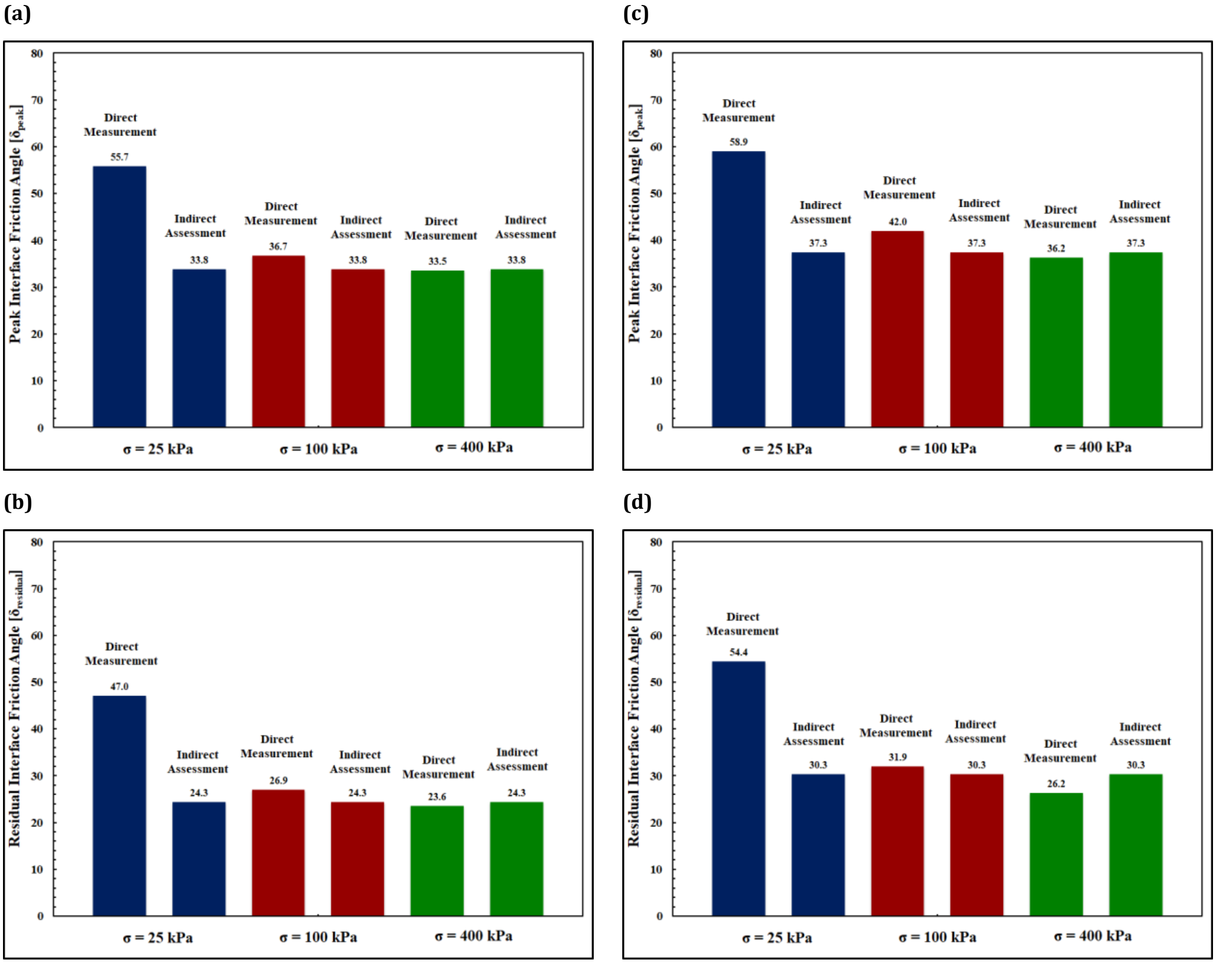

Fig 6. Comparison between direct test results of interface shear tests and indirect evaluation using the developed empirical relationships: Ottawa 20-30 sand–PVC geomembrane (a), (b) and blasting sand–PVC geomembrane (c), (d)

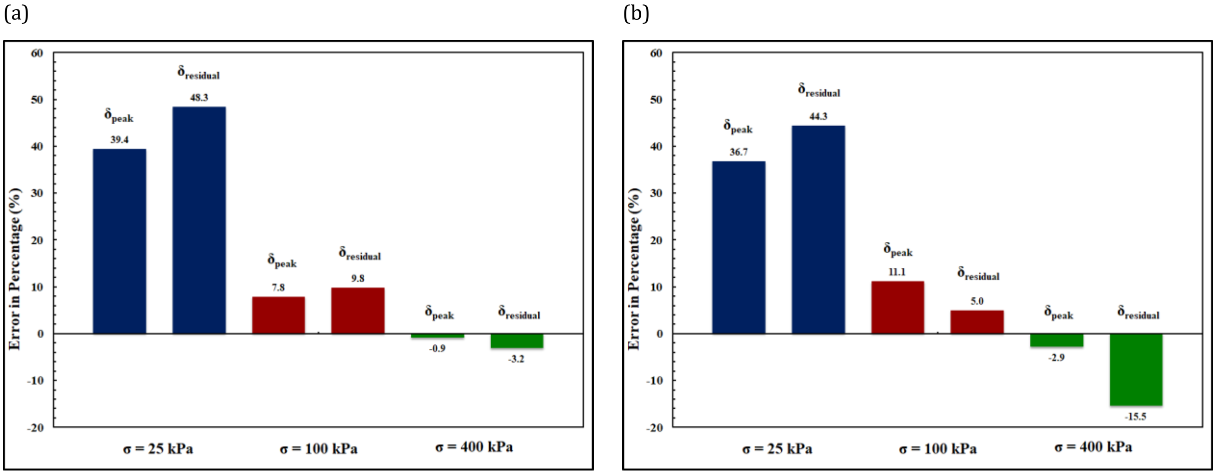

Fig 7. Percentage error in indirectly evaluated peak and residual friction angles computed using the developed empirical equations with respect to direct measurement test results: Ottawa 20-30 sand–PVC geomembrane (a); blasting sand–PVC geomembrane (b)

6. CONCLUSION

The results and analysis presented herein demonstrate that the mobilized shear response and the resulting frictional resistance of sand (rounded, angular) – PVC geomembrane interface combinations are highly dependent on a combination of loading conditions, geomembrane physical material properties (i.e. hardness) and particulate shape (i.e. angularity/roundness). For direct and indirect assessment of the resultant [δPeak] and [δResidual] values, the comparative analysis plots were presented in Fig 6 and Fig 7 and a reasonable similarity between the laboratory test results and the indirect analytical assessment analysis is evident from the proximity of the experimentally measured values at the predetermined normal stress levels (25, 100 and 400 kPa) to the computed values from the proposed empirical correlation equations proposed in the paper. Consequently, the practical implication of this study is that the empirical relationships proposed in light of experimental findings as a result of the laboratory testing program could be utilized for quick, indirect evaluation of frictional properties and shear characteristics of granular soil – geomembrane interfaces.

Moreover, the magnitude of the change in geosynthetic interface response and resistance is, in particular, critical and important when short-term perspectives of the structure are in consideration during design. For example, the design considerations for landfill side slopes for which interface shear resistance between geosynthetic components is crucial and designates the performance and stability of the entire infrastructure application. The practical significance of the results presented in the paper provide a rapid and simple means of estimating the interface design engineering parameters simply from measuring Shore D Hardness, HD of the geosynthetic materials practically in situ; thus, the indirect assessment of the expected mobilized frictional resistance of particulate material – geosynthetic interfaces could be rendered possible quickly in the field in place without laboratory testing by creating the necessary ambience in the lab to imitate real field conditions; or, through a developed numerical simulation analysis. As such, the findings and results of this experimental research study showed the importance of counterface material surface hardness on interface shear response of geosynthetic layered composite systems in addition to providing a rapid and simple evaluation analysis methodology for interface friction properties. Based on the correlations and experimental data on a geosynthetic liner produced from PVC core material, the Shore D Hardness, HD was found to be one of the fundamental factors in controlling frictional resistance. Finally, to sum up, as the frictional shear resistance of geosynthetic interfaces is product dependent and project specific, the discussions on the test results herein are aimed to provide comparative analyses on overall interface shear behavior and relative change (i.e. increment versus decrement) of strength parameters (δ_{peak}, δ_{residual}) as a function of normal loading rather than providing specific shear strength values for use in design applications.

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