Comparison of Direct and Indirect Assessments of Temperature Effects on Interface Shear Strength between Sand and HDPE Geomembranes

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ABSTRACT
The shear strength of granular soil-geomembrane interfaces is controlled by the mechanisms of friction including sliding, rolling and plowing acting during shearing which in turn, depend primarily on the relative hardness of the counterface materials and the angularity of the soil particles. The interfaces between sands and geomembranes in landfill applications are subject to elevated temperatures due to exothermic reactions occurring in the waste body. An experimental research study was undertaken to investigate temperature effects on the mobilized interface shear strength between sands and geomembranes. The laboratory testing program consisted of direct interface shear tests at temperatures ranging from 21°C up to 50°C. For this purpose, a temperature controlled chamber (TCC) was developed to evaluate shear displacement–failure mechanisms at elevated temperatures. Moreover, complementary surface hardness measurements on geomembrane samples were performed at various temperatures and then correlated to the change in temperature. A general relationship for interface frictional strength as a function of temperature was developed using a new empirical relationship developed between temperature and surface hardness and the relationship between hardness and normalized interface friction proposed earlier by others. Predictions made with this new empirical relationship were compared with direct measurements of the mobilized frictional shear strengths at elevated temperatures using an interface shear device enclosed by the TCC.

RÉSUMÉ
Cet article présente les résultats des essais de cisaillement direct effectués sur des interfaces de sable et de géomembrane à différentes températures allant de 21 ° C à 50 ° C dans la chambre à température contrôlée. Des mesures complémentaires dureté de surface sur des échantillons de géomembrane ont été effectuées à différentes températures élevées pour établir des corrélations empiriques pour évaluer indirectement les effets de température sur la résistance au cisaillement d'interface entre le sable et géomembrane PEHD, ainsi que de comparer avec les données expérimentales acquises grâce à des mesures en laboratoire direct (à savoir: l'interface de cisaillement tests) à des températures élevées.

1 INTRODUCTION

An interface is the zone of interaction between different counterface components created by placement of materials having distinct properties adjacent to one another. Relative movement is likely to occur at an interface which makes it the potentially weakest zone of the overall system in terms of strength and durability. Therefore, the frictional resistance of interfaces can control the performance of designed composite structures consisting of more than one material. To this end, the operational frictional resistance and response mechanisms of geosynthetic interfaces should remain within acceptable limits during the required service life as they are critical factors controlling the stability of the entire system composed of composite material side slopes, covers and liners.

2 BACKGROUND

The variation in physical properties, such as extensibility, flexibility and hardness of counterface materials influences the frictional shear strength mobilized at planar material interfaces. As such, geomembranes are continuum sheet materials which depend on properties such as tensile strength, modulus, hardness, surface roughness, and chemical constitution. Temperature has a significant influence on these physical and mechanical properties. However, limited understanding exists as to the influence of elevated temperatures on the mobilized interface shear strength of composite systems containing these materials. For example, after the waste is deposited and the landfill is closed, the ambient conditions inside the landfill change and can have a critical impact on the mechanical and durability properties of the geosynthetics employed in the landfill base as well as their interactions with the surrounding materials. The functional engineering properties of these composite geosynthetic layered systems must remain within established reliability margins to retain the quality and endurance properties during the required service life of the complete structure as well as the stability of the constructed project. Despite these considerations, most geosynthetic interface testing to date has been performed at room temperature and information today is emerging that confirms and indicates how temperatures in the bottom liner systems of landfills can be significantly higher.

In response to this potential influence of elevated temperature conditions on interfacial strength and shear behaviour of geosynthetic layered systems, a research study was performed to investigate temperature effects on interface frictional resistance and shear response between sands and smooth HDPE geomembranes. Additionally, to expand the understanding and application of the experimental findings, a parallel indirect assessment analytical approach was implemented for both practical field application and comparison purposes.

3 DIRECT MEASUREMENTS

3.1 Temperature Controlled Chamber (TCC)

To simulate the higher temperature field conditions in the laboratory, a unique temperature controlled chamber (TCC) (Figure 1) was designed to be utilized throughout the entire testing program involving interface shear tests on geosynthetic layered systems with the opportunity of imitating the developed shear-displacement-failure mechanism at elevated temperatures and evaluating the temperature dependency of the frictional resistance.

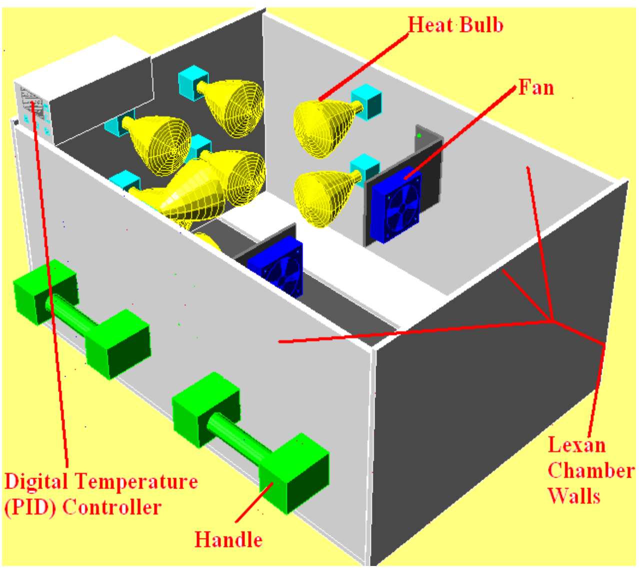


Figure 1. Solid Model Sketch of Temperature Controlled Chamber (TCC)

3.2 Tested Materials and Apparatus

3.2.1 Continuum Material Characteristics

A smooth geomembrane lining material produced from high density polyethylene (HDPE) used commonly in practice in both landfill bases and covers was selected for the interface testing with sands reported in this paper.

3.2.2 Particulate Materials Properties

Ottawa 20-30 sand and Blasting sand were used to study sand versus smooth geomembrane contact behaviour at elevated temperatures. The Ottawa 20/30 sand is composed of rounded to sub-rounded quartz sand grains whereas, the blasting sand is comprised of angular quartz sand particles. These two sands which have similar mean grain sizes (D_{50} = 0.72 mm) were used to study the role of grain shape/particle angularity on shear response at different test temperatures.

3.2.3 Interface Direct Shear Apparatus Enclosed by TCC

The assessment of interface frictional resistance at different ambient test temperature levels was performed by utilizing a Teflon block with a cylindrical opening having dimensions of 62.5 mm in diameter and 37.5 mm in height located in the center and connected to a platform which travels along a set of linear bearings. The shear box is displaced relative to the upper surface of the lining material specimen to be tested and is fastened to a metal platform with metal strips and bolts (Figure 2).

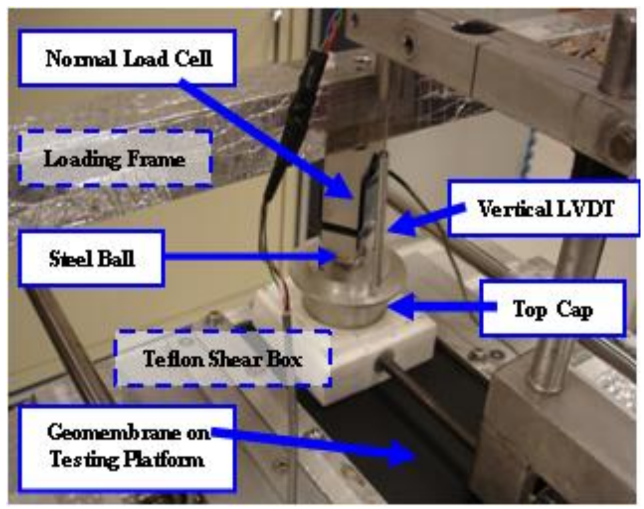


Figure 2. Sand – Geosynthetic Interface Direct Shear Testing Module

3.3 Interface Shear Experimental Program and Laboratory Measurements

The laboratory testing program consisted of a series of conventional macro-scale direct shear frictional resistance tests between sands (rounded, angular) and smooth HDPE geomembranes at different test temperatures ranging from 21°C to 50°C to investigate how shear strength of particulate versus continua interfaces changes with increasing temperature. Normal stresses ranging from 100 to 400 kPa were applied in tests presented in this paper. All specimens were sheared at a constant rate of displacement of 1 mm per minute over a distance of 60 mm.

3.4 Sand – Geomembrane Direct Shear Test Results

There are two primary fundamental frictional mechanisms mobilized at particulate versus smooth planar material contact surfaces during shearing – sliding and plowing. Minimal work is required for the sand particles to slide along a planar interface. However, if the sand grains plow into and displace the counterface geomembrane material at the interface, significant effort which manifests as a larger shearing resistance is observed. As the ambient temperature increases, the relative hardness of the geomembrane sheet compared to that of the sand particles decreases and this reduction in the counterface material surface hardness increases the amount of plowing of the sand grains into the geomembrane surface that occurs.

3.4.1 Rounded Sand versus Smooth HDPE Liner Interface

The primary controlling mechanism of the mobilized frictional resistance of rounded sand versus smooth relatively stiff HDPE geomembrane interface systems at room temperature condition (21 °C) is sliding of the sand particles along the surface of the lining sheet (Dove and Frost 1999). The combination of moderate relative hardness, rounder particle shape and moderate stress level used in the present study at standard temperature levels leads to a predominantly sliding mechanism. As temperature is increased, the geomembrane which is produced from a polymeric material became softer and the degree of material surface hardness decreases which results in a greater ability of the sand particles to penetrate into the malleable and softer geomembrane surface and is observed as an increase in interface shear strength with increasing temperatures (Figure 3) as more effort is necessary to move the particles as they plow against the geomembrane surface. Therefore, the relative contribution of the plowing component to the developed friction mechanism increased for the interfaces at elevated temperature conditions.

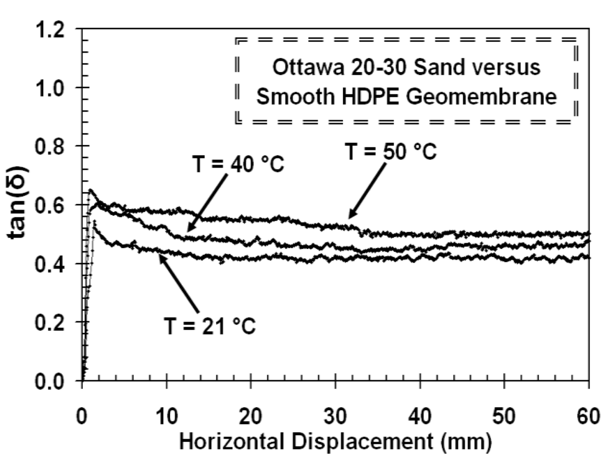


Figure 3. Shear Stress Normalized by Normal Stress and Displacement Curves at Different Test Temperatures for Rounded Sand – Smooth HDPE Geomembrane Interface

Plowing also results in increased wear on the smooth surface of geomembrane samples tested at higher temperature levels. The amount of this surficial damage on the lining material surface can be directly related to the magnitude of the surface hardness of the liner relative to the counterface sand material. In contrast the surficial damage incurred by the geomembrane specimens at lower test temperatures is minimal when the particles merely slide along the planar surface. As discussed later in the paper, both peak and post-peak interface shear strength values defined in terms of coefficient of friction, increase with increasing temperature. The measured shear stress values were normalized by stress level and presented in terms of friction coefficient [$\tan(\delta) = \tau/\sigma$].

3.4.2 Angular Sand versus Smooth HDPE Liner Interface

In contrast to the behaviour of rounded sand interface systems noted above, the principal controlling mechanism for shear strength of angular sand versus smooth HDPE geomembrane interface composite systems is plowing of the sand particles into the surface of geomembrane liner (Dove and Frost 1999). The more angular sand particles, even at the same moderate relative hardness and stress levels used in the present study increase the role of plowing in the overall shearing response significantly. Under elevated temperature conditions, the degree of this destructive plowing mechanism was increased even further and resulted in a substantially larger magnitude of frictional shear resistance between angular sands and planar geomembrane surfaces. Comparing the behaviour at higher temperature conditions with those at lower temperatures, the angular sand grains could more easily penetrate into and plow through the lining sheet surface with less effort resulting from the geomembrane liner becoming softer and more malleable with a concomitant reduction in surface hardness (Figure 4). Since angular sand particles were more readily capable of penetrating into the geomembrane surface at higher elevated temperatures, the rate of increase in the resultant interfacial shear strength increased significantly.

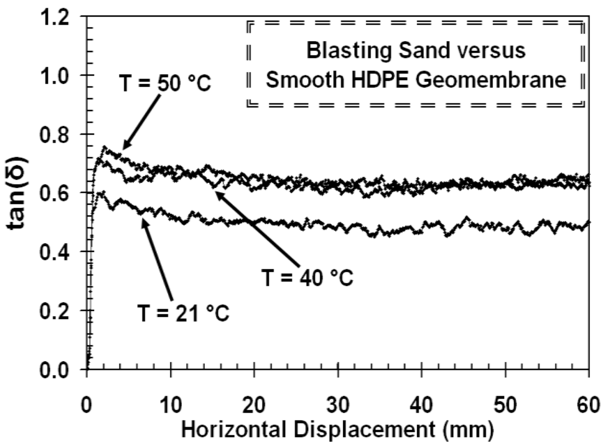


Figure 4. Shear Stress Normalized by Normal Stress and Displacement Curves at Different Test Temperatures for Angular Sand – Smooth HDPE Geomembrane Interface

4 INDIRECT ASSESSMENT

4.1 Concept on Hardness of Continuum Materials

Hardness primarily depends on stiffness and viscoelastic properties of the material and is defined as the resistance of a plastic or rubbery material to indentation. As previously discussed, surface hardness is one of the fundamental engineering properties of geomembranes in controlling the mobilized interfacial friction and shear transfer. For example, relatively hard smooth polymer surfaces tend to promote sliding of sand grains, while relatively soft surfaces tend to induce sand particle rolling and plowing at the interface. Consequently, the magnitude of surface hardness of polymeric materials is a good index for estimating the shear strength properties of geosynthetics at different temperature conditions. An empirical correlation between interface shear strength and temperature can be developed by using a relationship (O'Rourke et al. 1990) between hardness and normalized interface friction (δ/φ'_{ds}) and hardness and temperature as described below. In this manner, a general empirical model can be developed for evaluating the variation in interface frictional shear strength properties of sand versus geomembrane layered systems with changing temperature. The resultant trends from computational analyses were compared to the experimental findings of direct laboratory measurements at various temperatures.

4.2 Hardness and Normalized Interface Friction Angle

The ratios of peak interface friction angles to soil direct shear friction angles (δ/φ'_{ds}) as a function of the Shore D Hardness for several different sand versus polymer interfaces are shown in Figure 5 (O'Rourke et al. 1990). It is evident that the interface friction property, (δ/φ'_{ds}) decreases with increasing Shore D Hardness, (H_D).

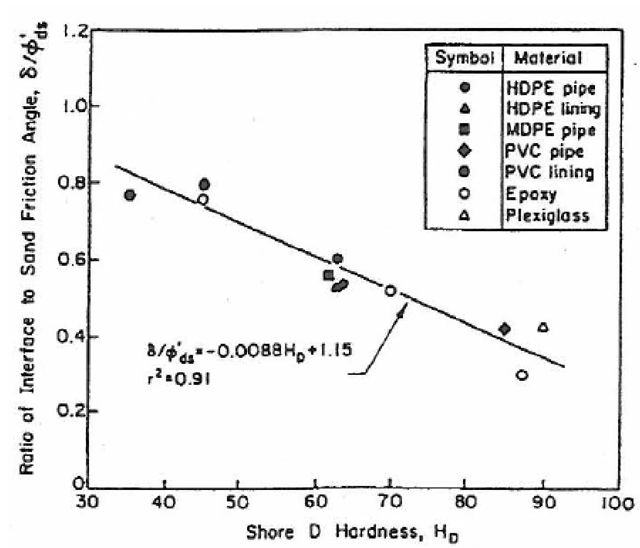


Figure 5. Ratio of Interface Friction Angle to Soil Friction Angle and Shore D Hardness, (H_D) (O'Rourke et al. 1990)

The linear regression on the data exhibits a straight line fit with a relatively high coefficient of determination, (r^2 = 0.91). Therefore, Shore D Hardness can be taken as an appropriate index for indirectly evaluating the frictional shear strength characteristics, (δ/φ'_{ds}) of a broad range of polymers in contact with granular soils (Equation 1).

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

4.3 Surface Hardness of Geomembranes at Different Temperatures

Surface hardness of a plastic material is a measure of its resistance to an indentation force. The indentation hardness is inversely related to the penetration which means that the deeper/further the indenter penetrates, the lower the surface hardness of the material. A durometer with a constant loader test setup composed of a flexible joint system and air damper to facilitate repeatable and consistent readings was utilized in the present study. The device was enclosed by the TCC to allow surface hardness measurements to be performed on geomembrane specimens (Figure 6) at various elevated temperatures.

The geomembrane continuum sheets are typically produced using base polymers such as HDPE and are categorized in the class of relatively hard plastics. Accordingly, the Shore D hardness scale, (H_D) ranging from 1 to 100 with a Type D durometer gauge is an appropriate scale to provide an index value regarding the degree of surface hardness. Shore D measurements were performed according to ASTM D 2240-05 (2005) in the insulated and uniform temperature environment of the TCC at various ambient temperature conditions ranging from 21 °C up to 50 °C. As recommended in the ASTM standard, hardness readings were obtained at various locations on each specimen surface to reduce error in measurements by using a random sampling process. A total of 120 measurements were taken on HDPE lining samples, with 30 readings at each test temperature. The readings indicated that the scatter in measurement values was uniform through all the samples tested. Over the entire test temperature range, the measurements were consistent at each test temperature and confirmed that the surface hardness of HDPE geomembranes is dependent on temperature change.

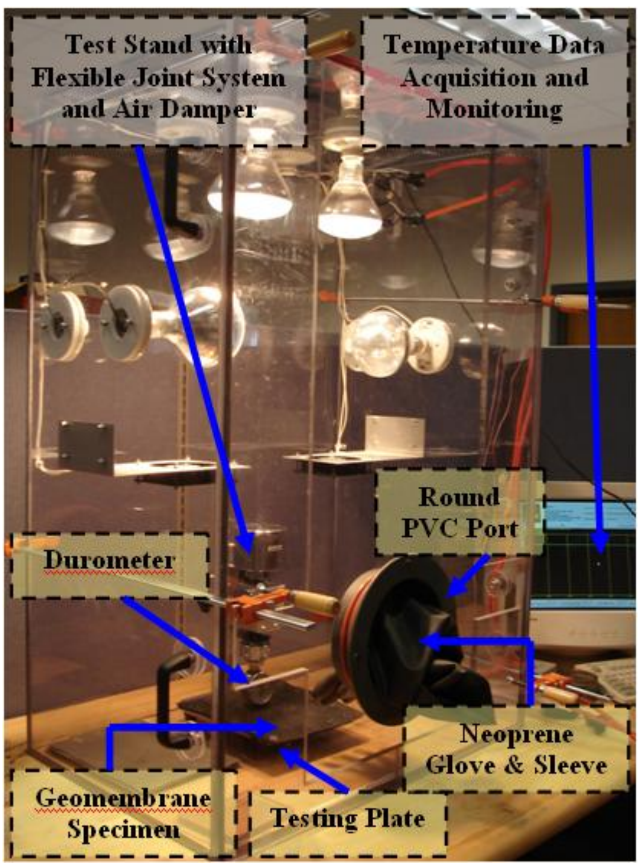


Figure 6. Durometer Affixed on Constant Loader Test Setup and placed in the Insulated Ambience of the TCC

4.4 Shore D Hardness (H_D) and Temperature

The Shore D, (H_D) hardness values decreased from ~ 60 down to ~ 40 in the test temperature range from 21 °C to 50 °C. The error bars at each measurement temperature level were computed and designated based on the variational range and scatter of the readings from the calculated average value (Figure 7). The rate of decrease in the H_D values diminished at higher temperatures (~ >40 °C) for the HDPE geomembrane. Accordingly, it can be expected that the reduction in H_D may reach a saturation threshold (i.e. likelihood of existence of a lower bound at further excessive temperatures ~ > 60 °C).

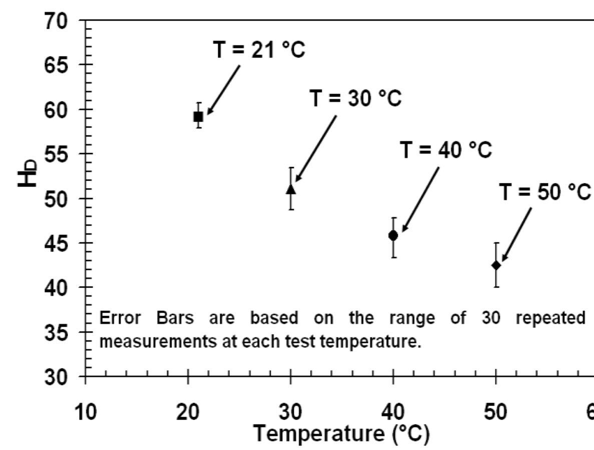


Figure 7. Change in Surface Hardness, (H_D) with Temperature for Smooth HDPE Geomembrane

4.5 Correlation between HDPE Geomembrane Hardness and Temperature

Several different regression analyses including linear, exponential and polynomial were applied to the measured Shore D hardness readings at the various ambient temperature levels. An exponential decaying regression analysis provided the best correlation between H_D and temperature (Figure 8) with a relatively high coefficient of determination (CoD = 0.972) compared to that of the other regression methods. A variably decreasing trend in the magnitude of H_D values with increasing temperature (especially above 40 °C) can also be observed.

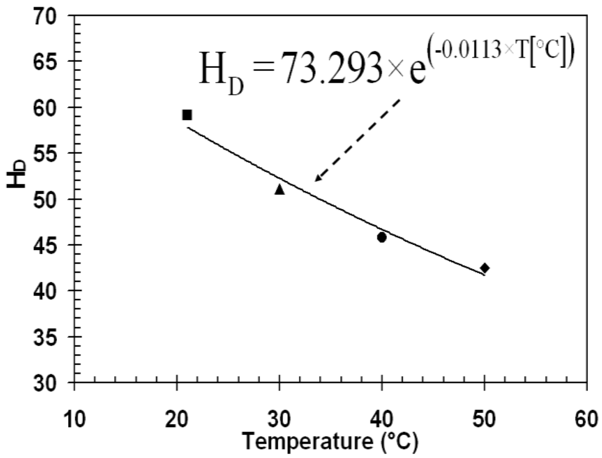


Figure 8. Correlation between Smooth HDPE Geomembrane Surface Hardness Values and Temperature

For the smooth HDPE geomembrane, the proposed empirical relationship correlating the magnitude of Shore D Hardness, (H_D) to the degree of ambient temperature, (T) level is given in Equation 2 in which T is in degree Celsius.

$$H_D = 73.293 \times e^{-0.0113 \times T\ °C} \qquad [2]$$

4.6 Frictional Property for Sand – Smooth HDPE Geomembrane Interface

The general model proposed earlier by O'Rourke et al. (1990) to predict the frictional resistances of granular soil–polymeric material interfaces as discussed in Section 4.2 with the soil internal friction angle, [(δ/φ'_{ds})] was related to the measured Shore D Hardness (H_D) index values measured on smooth HDPE geomembrane samples at different temperatures. Based on this, a new empirical correlation model is proposed by substituting the hardness versus temperature relationship (Equation 2) developed in this study into the interface property, [(δ/φ'_{ds})] versus Shore D hardness relationship (Equation 1) to establish a mathematical correlation (Equation 3) to further investigate the behaviour in the resultant trend between interface property, [(δ/φ'_{ds})] and the change in temperature, (T [°C]). The resulting natural logarithmic regression analysis provided the best correlation between the discontinuous test data and continuous regression curve with a high coefficient of determination (CoD = 0.994). The [(δ/φ'_{ds})] ratio was then plotted as a function of temperature as shown in Figure 9 to demonstrate the trend between frictional strength properties of HDPE liners in contact with particulates at elevated temperature conditions. The apparent influence of temperature on sand and HDPE geomembrane interface shear resistance is seen in the plot in which a reduction in the rate of increase is observed at higher temperatures for the interface tested.

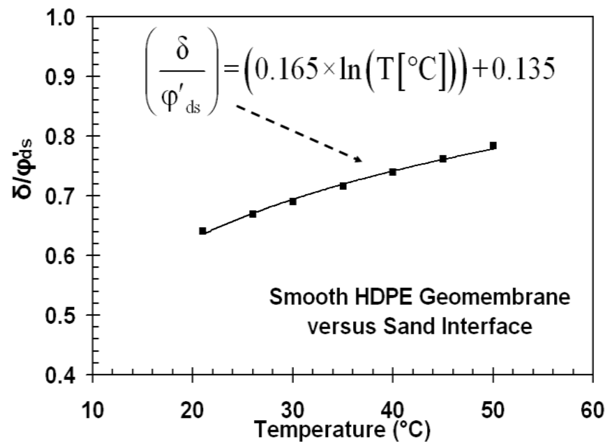


Figure 9. Frictional Property and Temperature for Sand – HDPE Geomembrane Interface

$$\left(\frac{\delta}{\varphi'_{ds}}\right) = 0.165 \times \ln\ T\ °C \quad + 0.135 \qquad [3]$$

4.7 Interface Shear Strength (Peak State & Residual Phase) and Temperature

Based on this proposed empirical model (Equation 3), the coefficient of friction for sand–geomembrane interfaces can be evaluated as a function of the change in temperature using direct shear test results from laboratory experimental programs previously conducted by Frost et al. (2002) and Iscimen (2004) (Table 1) for direct shear frictional resistance angles, [(φ'_{ds})] of Ottawa 20/30 rounded and Blasting angular sands used in this study.

Table 1. Used Peak and Residual Soil Friction Angles

	φ'ds [Peak]	**φ'ds [Residual]**	**Reference**
Ottawa 20-30 Sand	38.9°	28°	Frost et al. (2002)
Blasting Sand	43.1°	34.6°	Iscimen (2004)

4.7.1 Ottawa 20/30 Sand – Smooth HDPE Geomembrane

Using the direct shear angles of soil resistance for the case of peak and/or residual states as tabulated in Table 1, for rounded Ottawa 20/30 sand versus smooth planar HDPE geomembrane interface systems, the empirical equations correlating peak and residual friction coefficients, [tan(δ_P) & tan(δ_R)] to temperature, (T [°C]) are presented in Equations 4 and 5, respectively:

$$\tan(\delta_P) = 0.143 \times \ln(T\ [°C]) + 0.026 \qquad [4]$$

$$\tan(\delta_R) = 0.091 \times \ln(T\ [°C]) + 0.044 \qquad [5]$$

4.7.2 Blasting Sand – Smooth HDPE Geomembrane

Similarly, based on the direct shear angles of soil resistance for the case of peak and/or residual conditions as tabulated in Table 1 for angular Blasting sand versus smooth planar HDPE geomembrane liner interface systems, the empirical equation model correlating peak and residual friction coefficients, [tan(δ_P) & tan(δ_R)] to temperature, (T [°C]) are presented in Equations 6 and 7, respectively:

$$\tan(\delta_P) = 0.168 \times \ln(T\ [°C]) + 0.007 \qquad [6]$$

$$\tan(\delta_R) = 0.121 \times \ln(T\ [°C]) + 0.037 \qquad [7]$$

The friction coefficient is a critical interface property generally used for design purposes as a key parameter throughout the computation steps and analyses. To this end, the preceding four empirical algebraic correlations involving the change in temperature and the resultant variation in the magnitude of tan(δ_P) and tan(δ_R) values mobilized at the interface during shearing can be utilized for indirect evaluation of the influence of elevated temperatures as well as for practical and rapid estimate of interfacial frictional strength properties for the particulate–continua systems at different temperatures by simply measuring the value of geomembrane surface hardness at that current ambient condition in the field. To avoid the need for numerical simulations which can be costly and/or the experimental imitations of laboratory modelling of field situations which can be time consuming, the proposed relationships can be used to assess whether designs are conservative and to what degree.

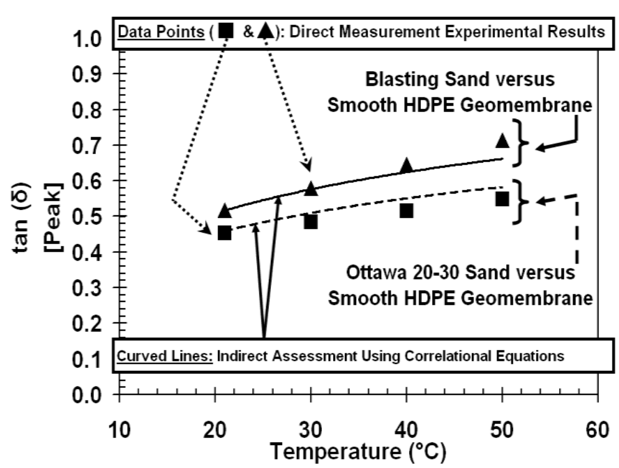
5 COMPARATIVE ANALYSES AND DISCUSSIONS

In general, a reduction in the magnitude of surface hardness of the polymeric geomembrane liner can be associated and linked with the alteration of the polymer material stiffness since the elasticity modulus as well as visco-elastic and plastic properties are strongly temperature dependent. A decrease in hardness is observed with increasing ambient temperature level and hence, a reduction in surface resistance of polymeric lining sheet against indentation as reflected by Shore D hardness index value is seen. 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. It is noted that the primary influence of elevated temperature conditions on sand–geomembrane interface shear response and resistance results from the temperature dependency of physical and mechanical properties of the geomembrane liner and are not necessarily due to changes in the sand properties.

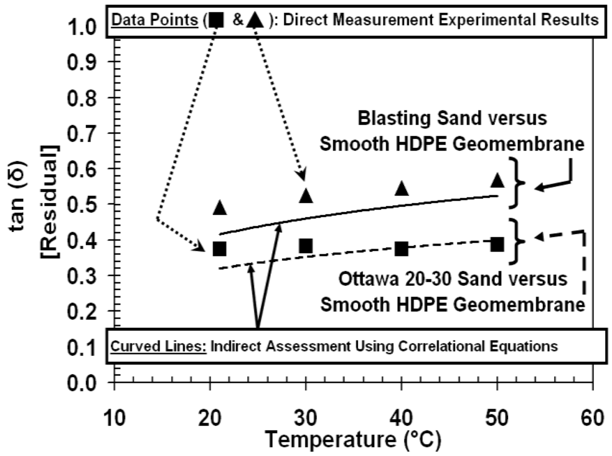
As seen in Figure 10a and 10b, the geomembrane lining sheet softened and the degree of material surface hardness decreased with increase in temperature that resulted in plowing becoming the more dominant interface shearing mechanism acting during the course of shear displacement. The increased plowing of the sand particles into the surface of the geomembrane liner impacts and correlates directly to the increase of interface frictional resistance at elevated temperatures as more effort is extended in penetrating and plowing the particles into and through the geomembrane surface. As a result, except the residual state of the rounded sand interface, the friction coefficient exhibits an incremental increasing trend with rising ambient temperature conditions in the range from 21 °C to 50 °C.

The comparison plots for [tan(δ_{Peak})] and [tan($\delta_{Residual}$)] are presented in Figure 10a and 10b, respectively, in which the test results from experimental direct measurements at different test temperatures can be compared to the resultant correlational trends generated through indirect evaluations using the proposed empirical relationships previously presented.

The discontinuous data points from interface shear tests performed at elevated temperatures in the TCC generally concur with the proposed correlation curves. The proposed natural logarithmic behaviour trend provided the best relationship for the variation of interfacial shear strength properties of the sand (rounded, angular) versus the smooth HDPE geomembrane interface systems with increasing temperature.



(a)



(b)

Figure 10. Comparison between Direct and Indirect Assessments: (a) *Peak State;* (b) *Residual State*

The slight difference observed between the direct and indirect assessments, in particular, for the case of residual state of the angular blasting sand interface system reflects the importance of the shape of soil particles (i.e. rounded versus angular) in contact with a smooth geomembrane material surface. It illustrates the significance of particle shape in governing the resultant frictional strength as well as in defining the relative role of the various interface shearing mechanisms including sliding, rolling and plowing during shear displacement. Based on post-test inspections, it was determined that wear observed in the post-test geomembrane specimens as scarring or striations was greatest for tests involving angular sand grains. The grooves after shearing were deeper for the case of angular sand as compared to that of rounded sand. As shearing progressed at displacements to post-peak residual stage, the magnitude of plowing and scarring along the interface and hence, the depth of indentation and/or penetration of angular sand grains through/into plastic lining sheet surface resulted in larger frictional resistances generated at the interface in comparison to that of indirectly assessed and computed values using empirical correlations. Additional work and energy is required for deeper indentations to scratch the geomembrane surface. Furthermore, as was noted by Dove and Frost (1999), the main component of the friction force is plowing for interface shear tests performed with angular blasting sand as opposed to rounded Ottawa 20-30 sand. Additionally, they indicated that the increased amount of wear on geomembrane surface after shearing directly corresponds to improved shearing frictional resistance due to plowing; and thereby, the resultant increased value of interface strength property, [tan(δ)] at the contact surface.

6 CONCLUSION

The effects of temperature on the friction properties of particulate versus geomembrane interfaces were investigated based on surface hardness measurements at different temperatures. The goal of this experimental work was to examine: i) the change in geomembrane hardness with temperature; and, ii) develop empirical correlations between hardness and temperature; and iii) compare results of empirically predicted interface strength based on temperature measurements with those of direct measurements for sand – geomembrane interfaces obtained through direct interface shear measurements at different temperatures in the temperature controlled chamber (TCC). The mobilized frictional strength at granular material – geomembrane interfaces at different temperatures are primarily influenced by the surface hardness of the geomembrane. The measured index value of hardness of the geomembrane surface based on a standard scale (i.e. Shore D in this case) at various temperatures provided a useful quantitative value to evaluate and gauge the magnitude of shear resistance generating at the interface of granular soil-geosynthetic.

The results and analyses presented herein demonstrate that the mobilized shear mechanisms (i.e. sliding and/or plowing) and the resulting frictional resistance (i.e. shear strength behavior) of sand – smooth HDPE geomembrane interface combinations are highly dependent on a combination of temperature, geomembrane physical material properties (i.e. hardness) and particulate shape (i.e. angularity/roundness). Therefore, the degree to which plowing influences and contributes the mobilized interface strength is directly dependent on particulate material grain shape, temperature and continuum material surface hardness properties. The plowing effect is minimal for hard counterface material surfaces that resist indentation of the sand particles where the shear mechanism is dominated by sliding. As temperature increases, the polymeric geomembrane becomes softer and exhibits a reduction in the degree of its surface hardness by showing less surface resistance to the counterface component which results in the increased plowing of the soil particles along the interface into geomembrane sheet surface during the course of shear displacement that correlates directly to the increased interface strength at elevated temperatures as additional work is required to indent and plow the particles through the geomembrane surface at initial shear displacements and to penetrate the sand grains deeper into the counterface geomembrane with further progression of the shearing process.

In light of the experimental tests performed and the analyses and discussion presented herein, it is important to consider the significant influence of ambient temperature conditions on the mobilized interface shear strength at sand–geomembrane composite layered systems widely designed and employed in common geotechnical applications. The frictional shear capacity of granular soil and continuum geomembrane sheet interface is dependent strongly on the current degree of surface hardness of the polymeric geosynthetic lining material. Therefore, the measured index value of hardness for the geomembrane samples based on a particular scale at various ambient temperature levels provided a useful quantitative parameter to indirectly assess and gauge the resultant magnitude of interface shear strength.

REFERENCES

ASTM D2240-05 2005. Standard Test Method for Rubber Property – Durometer Hardness. ASTM International. West Conshohocken, PA, USA.

Dove, J.E., and Frost, J.D. 1999. Peak Friction Behaviour of Smooth Geomembrane – Particle Interfaces. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 125 (7): 544-555.

Frost, J. D., Evans, T.M., Hebeler, G.L., and Giroud, J.P. 2002. Influence of Wear Mechanisms on Geosynthetic Interface Strengths, *Proceedings of the Seventh International Conference on Geosynthetics*, Nice, France, pp.1325-1328.

Iscimen, M. 2004. Shearing Behaviour of Curved Interfaces. *M.S. Thesis*, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA, USA, 130p.

O'Rourke, T.D., Druschel, S.J., and Netravali, A.N. 1990. Shear Strength Characteristics of Sand – Polymer Interfaces. *Journal of Geotechnical Engineering*, ASCE, 116 (3): 451-469.