INTERACTIONS BETWEEN PVC GEOMEMBRANES AND COMPACTED CLAYS

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ABSTRACT: The interactions between plastic soils and polyvinyl chloride (PVC) geomembranes were studied using a direct shear device under as-compacted conditions. The PVC geomembranes had smooth or textured surfaces, and the soils were of plasticity index (PI) ranging from 35 to 100%. The peak and residual failure envelopes were expressed using Coulomb failure criteria. The adhesion and angle of friction increased for PIs up to 70% and subsequently recorded a decrease. The adhesion is larger for the peak strength compared to the residual strength, but it was the reverse for the angle of friction. The efficiency in terms of adhesion appeared more relevant than that of the angle of friction in expressing the interactions between geomembrane and cohesive soils. The smooth and textured geomembranes showed little difference in results at the residual state.

INTRODUCTION

High-density polyethylene (HDPE) and polyvinyl chloride (PVC) geomembranes are widely used in the modern municipal solid waste containment system (Koerner and Daniel 1997). They are installed in the side and bottom liners to inhibit flow of leachates and thus prevent the contamination of groundwater. As part of the cover liner, geomembranes stop infiltration and serve to control the gas following the closure of landfills. PVC geomembranes are increasingly used in the cover liner, because they tolerate large deformation.

The hydraulic property has been one of the main issues for selecting geomembrane used in the waste containment system. But the permeability of geomembrane is typically as low as 10^{-12} to 10^{-15} m/s, which meets the requirements. It has been recognized recently that soil-geosynthetic interaction is another important requirement. That is, geomembranes may possess very low shear strength when interacting with soils or other geosynthetics. Such an inadequate interface shear strength had been identified as the cause of the Kettleman Hills Landfill failure (Seed et al. 1990; Byrne et al. 1992). Some geomembranes are textured to provide improved friction with soils or other materials in which they are in contact. There are many factors affecting the direct shear strength between soil-geomembrane interfaces, such as the types of soil and geomembrane, and moisture content, among others. The interaction between soil and geomembrane is site specific, material specific, and warrants laboratory testing for an individual project.

Clay used for the landfill liners are low in permeability, cohesive and plastic in nature, and usually have a plasticity index greater than 10%. A wealth of literature is available for the interface strength between sands and geomembranes (Martin et al. 1984; Druschel and O'Rourke 1991; Takasumi et al. 1991) but only limited results are reported for the interaction between cohesive soils and geomembranes, although they are used routinely in design (Koerner et al. 1986; Williams and Houlihan 1987). Fishman and Pal (1994) provided a review of the interaction behavior between cohesive soils and geomembranes.

Koerner (1998) pointed out that most results reported for the soil-geosynthetic interaction are based on the peak strength. In reaching the residual state, a large shear displacement may be required. Therefore, a shear box larger than that used in the conventional direct shear testing of soil is recommended. ASTM D 5321 specifies a shear box with plan area 30 cm by 30 cm. The specimen size 10 cm by 10 cm has also been used (Fishman and Pal 1994; Martin et al. 1984; Koerner et al. 1986), while many other studies were conducted using a shear box of 5 to 6 cm. To accommodate for large displacement required in reaching residual state, rotation shear devices have also been developed (Stark and Poeppel 1994; Evans and Fennick 1995; Vaid and Rinne 1995; Negussey et al. 1989). The advantages of rotation shear devices include continuous shear displacement in a single direction, use of the same shear surface, and a constant shear area during shearing.

In this study, slight modifications were made on a conventional direct shear device (10 cm × 10 cm). The modified device was used to conduct a series of direct shear tests among soils, soils and smooth geomembranes, and soils and textured geomembranes. The soils were prepared at different plasticity indices. The results of direct shear tests are presented and discussed.

TESTING PROGRAM AND MATERIALS

Modified Direct Shear Device

A conventional displacement-control direct shear device for soil testing was modified and used to conduct the soil-geomembrane direct shear tests. This device, composed of lower and upper shear boxes, is capable of housing a soil specimen of plan area 10 cm × 10 cm and 5 cm in height. In the direct shear tests between the soils and geomembranes, the lower half of the box was mounted with an acrylic plate on which the geomembrane sheet was glued using Permabond adhesive (Fig. 1).

The direct shear device had plan dimensions less than those specified by ASTM D 5321 but the use of which could be justified, because geomembranes have a homogeneous surface structure compared to other geosynthetic materials, such as geogrid and geonet. That is, the scale effect could be minimal, because the issues such as the effects of aperture and rib size do not exist in geomembranes. For geomembranes with a preferred surface texture, the shear stress-displacement relationships could be different for different directions (Mitchell et al. 1990). Thus, the use of a modified direct shear device, instead

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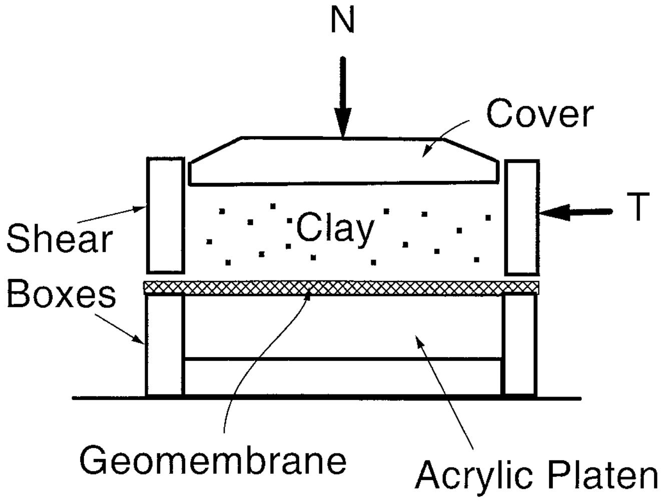

FIG. 1. Modified Direct Shear Device

of a ring shear device, would give a more representative interaction behavior in the preferred direction. The modification of the conventional direct shear device is considered more economical than the acquisition of a special device for soil-geomembrane interaction tests in this study.

Soils and Geomembranes

The variation of properties in natural soil is usually large, and thus, artificial soils are used for research purpose. The soils with different values of plasticity index (PI = 35%, 50%, 70%, and 100%) were prepared by mixing kaolinite, calcium bentonite, sodium bentonite powder, and water in various proportions a mechanical mixer. The index properties of clays are given in Table 1. The mixing proportions, optimum water content w_{opt} and maximum dry unit weight $\gamma_{d,\max}$ are summarized in Table 2, where w_{opt} and $\gamma_{d,\max}$ were determined following ASTM D 698 (Shulley et al. 1997).

The soil specimen used in each test was prepared in the shear box by compacting it to a unit weight of 11.4–13.3 kN/m^3, which was at the maximum unit weight (Table 2). A rammer was manufactured to fit the shear box with the compaction simulating the proctor energy. For the tests with geomembranes, the soil (2.5 cm high) was prepared directly in the upper shear box, sitting on top of the geomembrane layer. The specimen was not exposed or submerged in water, i.e., unsaturated, so that it resembled the field conditions. The settlement of the specimen was monitored for several hours until it stabilized before shearing. The testing setup is covered with plastic sheeting to prevent desiccation.

TABLE 1. Atterberg Limits of Kaolinite, Calcium Bentonite and Sodium Bentonite

	Liquid limit (LL) (%)	Plastic limit (PL) (%)	Plasticity index (PI) (%)
Kaolinite	56	32	24
Calcium bentonite	103	42	61
Sodium bentonite	433	43	390

Geomembranes with both smooth and textured surfaces were used. Both geomembranes were manufactured from PVC with a specific gravity of 1.2. Their thicknesses and tensile strengths were similar, 30 mil and 402 kN/m, respectively. The geomembrane sample was cut into specimens of plan dimensions 12.5 cm × 12.5 cm to include the outer dimensions of the shear box. The specimen was then glued to the acrylic platen in the lower shear box. Thus, the upper box rested on the geomembrane during shearing. The area of shearing between the soil and geomembrane remained constant during the test. The shear box allowed a maximum displacement of 1.5 cm.

The direct shear device was calibrated to determine the inherent friction that existed because of the box-box, box-smooth geomembrane and box-textured geomembrane interactions. The measured interfacial frictional force was constant during shearing: 2.22 N, 17.79 N, and 26.69 N, respectively, for the friction between the boxes, the box with a smooth geomembrane layer and the box with a textured geomembrane layer. The true shear force between the soils and soil with geomembranes were obtained by subtracting the inherent friction from the measured force.

Three different normal stresses (σ_n = 10, 25, and 50 kPa) were used for each soil in the three kinds of interface testing (soil-soil, soil-smooth geomembrane and soil-textured geomembrane). Relatively small normal stresses were used to simulate the loading in the cover liner. All tests were controlled by displacement at a rate of 0.117 mm/min to simulate ‘‘undrained’’ conditions for rapid loading. The tests were conducted at room temperature of 20°C.

Limitations

Some limitations exist in the direct shear device. The principal stresses are not defined, and the results are reported for total stress conditions. The device is not capable of measuring pore water pressure as well as controlling its dissipation. The direct shear device also induces nonuniform stress along the length of the specimen as a result of the rotation of the shear box during shearing. Therefore, the test results may be affected by the dimensions and configuration of the shear box. Nevertheless, the strength parameters obtained from direct shear tests are widely used for design because the setup resembles that of the field conditions.

The effect of geomembrane extensibility was not included in this study, which focused only on the interaction along soil-geomembrane interface. The effect of extensibility could be studied numerically after separately establishing numerical models that consider soil-geomembrane interaction and constitutive relations of geomembranes.

TEST RESULTS AND DISCUSSIONS

Fig. 2 shows typical shear stress versus displacement relationships for the interaction between soil and geomembranes at PI = 35% and 50%, respectively. The peak strength was

TABLE 2. Mixture Proportions, Maximum Density, and Optimum Water Content of Cohesive Soils

Plasticity index (PI) (%)	Plastic limit (PL) (%)	Liquid limit (LL) (%)	Percent kaolinite (%)	Percent calcium bentonite (%)	Percent sodium bentonite (%)	Maximum dry unit weight $\gamma_{d,\max}$ (kN/m^3)	Optimum water content w_{opt} (%)	Unconfined strength, q_u (kPa)
35	35	70	58	42	—	13.3	35	315
50	39	89	23	77	—	12.1	39	416
70	40	110	15	71	14	11.6	35	425
100	40	140	15	61	24	11.4	41	176

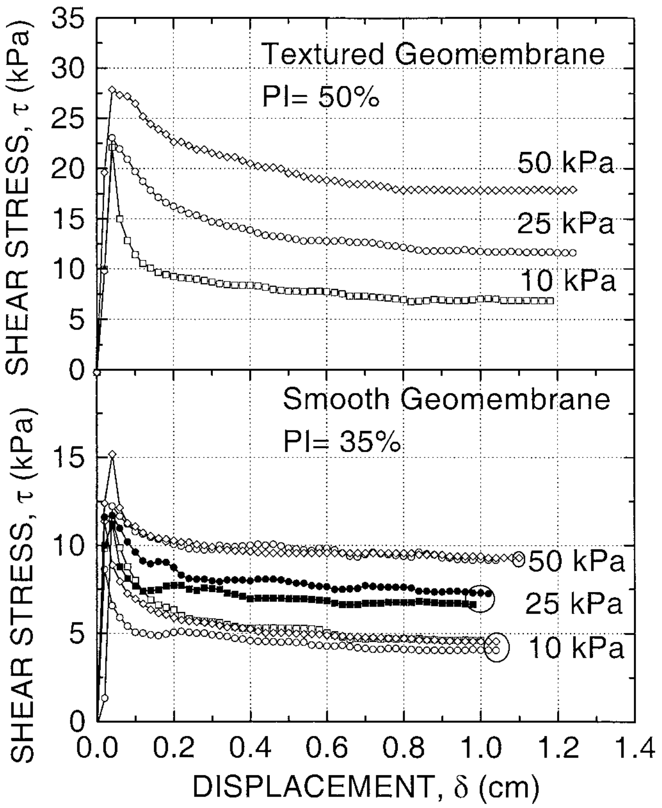

FIG. 2. Typical Shear Stress—Displacement Relationships between Soil and Smooth Geomembrane (PI = 35%) and Soil and Textured Geomembranes (PI = 50%)

mobilized at a very small displacement of less than 1 mm. Such a brittle nature of deformation is typical behavior for compacted clay. The tests were terminated after they reached the residual state. There was variation in the peak strength in each test, but the results for residual stress were consistent. For the tests that had been repeated twice or more, the averaged value of peak and residual strengths were reported.

The peak and residual strength envelopes are expressed using Coulomb failure criteria for the range of normal stress. For the direct shear test of soils and soil-geomembrane, these equations are used

$$\tau_f = c_a + \sigma_n \tan \delta \text{ or } \tau_f = c + \sigma_n \tan \phi \qquad (1)$$

where c and ϕ = the cohesion and angle of friction for the soil; and c_a and δ = the adhesion and angle of friction for the interface, respectively. The efficiency, which is the ratio of adhesion to cohesion or the ratio of angle of friction of the interface to that of the soil, is also used. That is, $E_c = c_a/c$ and $E_\phi = \tan \delta / \tan \phi$. Note that a failure envelope may be nonlinear if a wide range of stress levels is considered (Byrne et al. 1992). Figs. 3(a,b) show the peak and residual failure envelopes for the soils and interfaces conducted at PI = 35, 50, 70, and 100%, respectively.

The friction angle for soil is known to reduce with the increase in plasticity (Skempton 1985; Mesri and Cepeda-Diaz 1986). Meanwhile, the normalized undrained strength is shown to be independent of PI for normally consolidated clays (Jamiolowski et al. 1985). Fig. 4 shows the relationships for the normalized cohesion/adhesion, c/q_u or c_a/q_u, and the angle of friction ϕ or δ versus plasticity index, respectively, for the peak and residual strengths. The strength of clays q_u (Table 2) was determined using unconfined compression test for soils of different PI with the same unit weight and water content corresponding to the direct shear specimens. The results are shown. It is seen that the angle of friction is larger for the residual strength compared to the peak strength. However, it is the reverse for the adhesion. The normalized cohesion increased with PI, and the ratio c/q_u and c_a/q_u were smaller in the residual state compared to the peak state; ϕ increased with PI for the range of PI = 35% ~ 70% but reduced for PI greater than 70%, except for the peak value of soil-smooth geomembrane interaction.

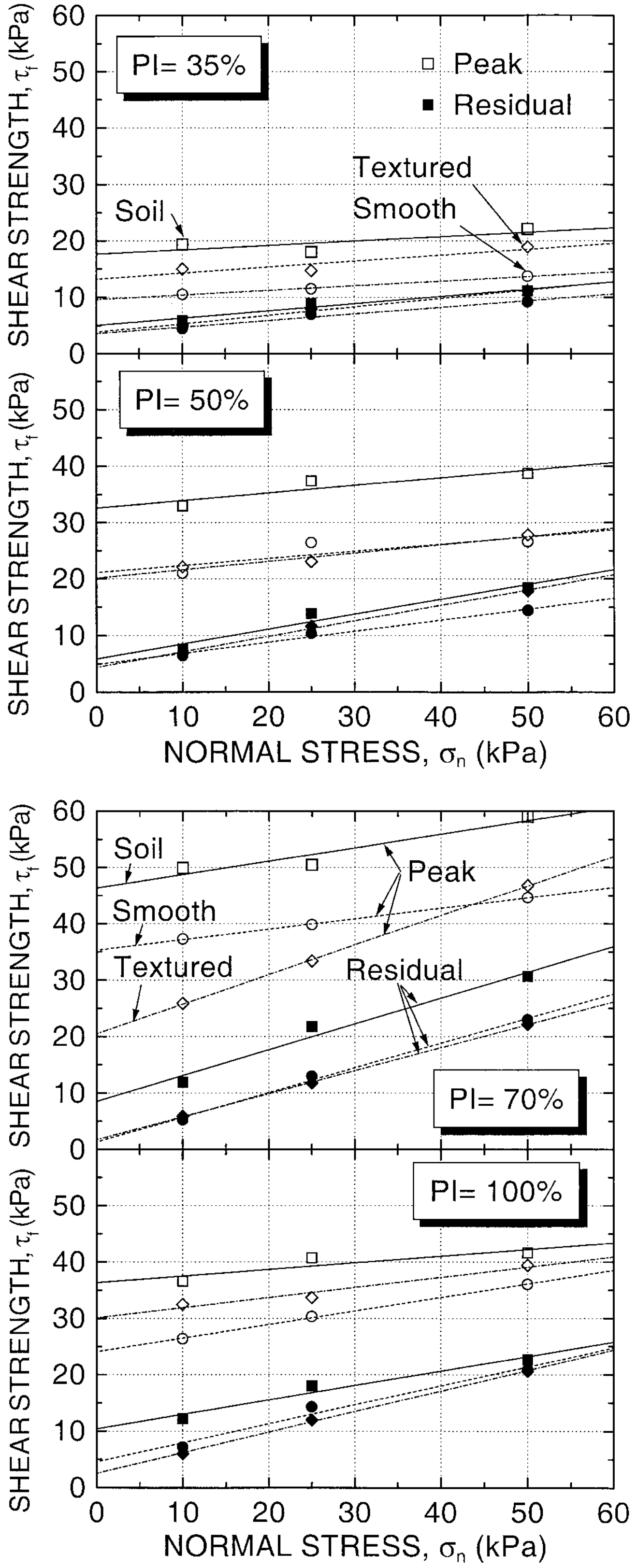

FIG. 3. Peak and Residual Failure Envelopes: (a) PI = 35% and 50%; (b) PI = 70% and 100%

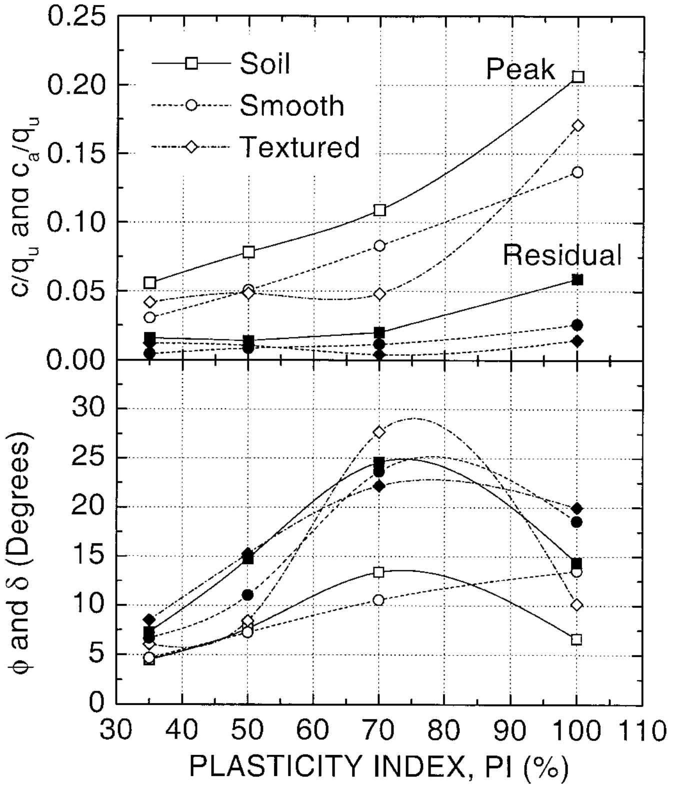

FIG. 4. Relationships between Cohesion/Adhesion, Angle of Friction, and Plasticity Index

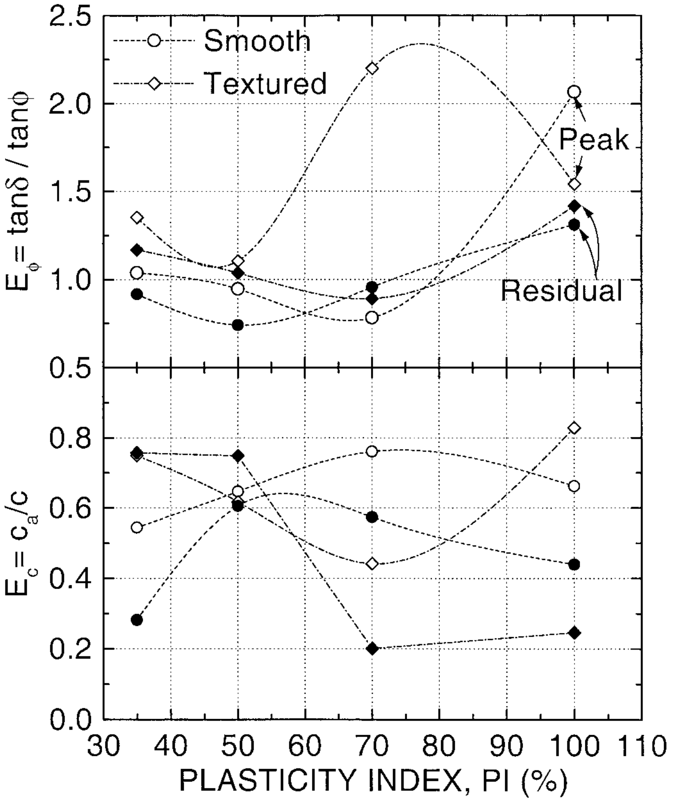

FIG. 5. Efficiencies for Soil-Geomembrane Interaction

The test results showed that soil exhibited the largest cohesion, followed by its interaction with the textured geomembrane and then the smooth geomembrane. The difference in strength between the smooth and textured geomembranes at residual state was very small. It is interesting to note that the friction angle for the interface between soil and textured geomembrane may be larger than the angle of friction of soil. Similar results had been reported by Fishman and Pal (1994). The behavior could be related to the spacing between the upper and lower shear boxes used in testing and/or penetration of soil particles into the geomembrane. However, the shear strength of soil was the largest followed by the interaction between textured and smooth geomembranes.

The efficiency calculated for the angle of friction and adhesion is shown in Fig. 5. It is seen that E_ϕ may be greater or less than unity for the tests; E_c indicated that the efficiency is less than unity for all the tests. The shear strength of soil alone was larger than that of the soil-geomembrane interface. Using E_ϕ to express soil-geomembrane interaction could be misleading for plastic soils. However, a general trend of relationships between efficiencies and PI was not observed.

CONCLUSIONS

A series of direct shear tests were conducted on the cohesive soils of different plasticity, as well as on their interfaces with the smooth and textured PVC geomembranes. The results indicated a larger value of adhesion for the peak strength compared to the residual strength. For the angle of friction, the residual value was larger than the peak value. The normalized adhesion increased with the plasticity index (PI) whereas the angle of friction showed an increase followed by a decrease. The normalized cohesion/adhesion was the largest for the soil, followed by its interaction with the textured and smooth geomembranes. For the interactions between the geomembranes and cohesive soils, efficiency expressed using the angle of friction alone could be misleading. There was very little difference in the shear strength between soils and the smooth and textured geomembranes at the residual states.

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