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Effects of soil and geomembrane types on interface and shear strength behaviour

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Research Paper

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Effects of soil and geomembrane types on interface and shear strength behaviour

The interface shear behaviour between the geomembranes and soils was studied. Sand/bentonite (80/20), crushed sand, river sand, crushed gravel, and river gravel were used in this study. Polyvinyl chlorides were cured in the 0.5 molar saltwater and high-density polyethylene was cured in municipal solid waste leachate for eight months. Direct shear experiments were performed using cured GMs. This study recommends the use of crushed gravel in projects that use polyvinyl chloride and high-density polyethylene. The interface friction angles, which were exposed to the effects of saltwater and municipal solid waste leachate, decreased even after eight months, and this reduction effect should be considered in future projects. When designing projects involving GMs exposed to MSW leachate, particularly in landfills, potential damage over time should be considered, and appropriate design parameters should be selected. Failure to do so can lead to disasters that cause the loss of life and property.

Key words:
geomembrane, interface shear strength, internal friction angle, direct shear test

Prethodno priopćenje

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Utjecaj tipova tla i geomembrana na ponašanje sučelja i posmičnu čvrstoću

U ovom je radu ispitano smicanje sučelja između geomembrana i tla. U istraživanju su primijenjeni pijesak/bentonit (80/20), drobljeni pijesak, riječni pijesak, drobljeni šljunak i riječni šljunak. Polivinil kloridi su njegovani u slanoj vodi molarne mase 0,5, a polietilen visoke gustoće njegovan je u procjednoj vodi krutog komunalnog otpada osam mjeseci. Pokusi izravnog posmika izvedeni su primjenom njegovanih geomembrana. Rad preporučuje upotrebu drobljenog šljunka u projektima koji upotrebljavaju polivinil-klorid i polietilen visoke gustoće. Efektivni kutovi trenja sučelja koja su bili izloženi učincima slane vode i procjednih voda iz komunalnog krutog otpada, smanjili su se čak i nakon osam mjeseci, a navedeni je učinak smanjenja potrebno uzeti u obzir u budućim projektima. Pri realizaciji projekata koji uključuju geomembrane izložene procjednoj vodi od komunalnog otpada, posebno na odlagalištima, treba uzeti u obzir potencijalnu štetu koja će nastati tijekom vremena i odabrati odgovarajuće projektne parametre. U suprotnom može doći do katastrofa koje uzrokuju gubitak života i imovine.

Ključne riječi:
geomembrana, posmična čvrstoća, sučelje, efektivni kut unutarnjeg trenja, ispitivanje izravnim posmikom

1. Introduction

Effective soil reinforcement techniques have revolutionised construction practices [1-2]. In this context, the use of geosynthetics in the construction industry has increased in recent years, and they have become one of the most popular construction materials now [3-11]. Geosynthetics are not only used for reinforcement purposes but also for a large number of engineering functions such as separation, filtration, drainage, and containment. With the possibility of quality control, an active market that is economical and time-efficient makes geosynthetics preferable, even for difficult designs. Geomembranes (GMs) are one of the most widely used geosynthetics in various civil engineering applications, such as solid waste storage areas, ponds (artificial lakes), treatment and irrigation pools, tanks, wastewater pipes, tunnel insulations, channels, and canals [12, 13]. In practical applications, GMs are generally in contact with soil. However, in design, the interface friction behaviour is generally not considered. This has led to several construction failures, such as a shift in the storage facility in Kettleman Hills, California [14]. It was determined that shear failure occurred at the soil-GM interface. Because of limited references, engineers often reduce the internal friction angle (1/2 or 2/3) when determining the interface friction angle, as suggested in textbooks [15-16]. Because some researchers have determined that the reduction factor can be less than 2/3 or even less than 1/2, the interface behaviour between different soils and GMs needs to be studied in detail [17-20].

When the studies with geosynthetics are examined in the literature, it is seen that many studies are investigating the effect of soil type on interface shear strength behaviour of soil – geosynthetic. Fleming et al. [21] examined the interface shear behaviour of unsaturated and smooth GM. The GM type was high-density polyethylene (HDPE) with a thickness of 1.5 mm. Three different soil types were used: silty sand, Ottawa sand, and an Ottawa sand – bentonite mixture. A miniature pore-pressure transducer was placed in the modified direct-shear test device. Thus, excessive pore water pressure was measured, and the results were interpreted in terms of both total and effective stresses. The test results showed that the internal and interface friction angles of silty sand and Ottawa sand were 31.8° to 21.0° and 35.5° to 14.1°, respectively. Higher interface friction angles were obtained at higher placement dry densities, and lower interface friction angles were obtained at higher placement water content. The decrease in the friction angle was explained by the authors as scratching and sliding at a low normal stress and ploughing at a high normal stress. Chai and Saito [22] studied the interface shear strength parameters of GM – clayey soil using a large-scale direct shear test device. The quartz and bentonite powders were mixed with a clayey soil of 30/70. Three types of GMs were used: polyvinyl chloride (PVC), polyethylene (PE), and HDPE. The dimensions of the upper jaw of the large-scale direct shear apparatus was 200 x 450 x 100 mm^3 and those of the lower jaw was 200 x 200 x 70 mm^3. Normal stresses of 50 kPa, 80 kPa, and 100 kPa were used for the experiments. The test results showed that the maximum adhesion value was obtained for the clayey mixture – PVC GM interface. The interface friction angles of the bentonite – GMs were quite small (3° to 4°). Because the water squeezed out of the bentonite and appeared at the interface during the shear test, it was postulated that a water membrane was formed between the GM and bentonite particles; thus, the interface friction angle was low. In all samples, the interface shear strength was approximately 55 % lower than the shear strength of the soil. When studies investigating the effect of both geosynthetic, and soil type are examined; Frost et al. [23] investigated the effect of GM surface roughness, soil angularity, and normal stress on the interface shear strength behaviour. The first series of direct shear tests included the testing of rounded sand with three different GM roughness values at a normal stress of 100 kPa. The second series included angular sand with two different GM roughness values under a normal stress of 100 kPa. Two additional tests were conducted using rounded and angular sands at a normal stress of 300 kPa to determine the effects of normal stress. The tests were performed using a modified direct shear test device (100 x 100 x 38 mm^3) with a shear rate of 0.25 mm/min. The soil sample was placed in a shear box according to the pluvial method with a relative density of 80 %. The displacement required for the rough GM (1.5 mm) to reach the peak shear stress was greater than that required for the smooth GM (0.3 mm). Also, the peak and residual interface friction angles increased significantly with changes in roughness up to a critical roughness value (≈1.35) then remained constant. The interface friction angle increased with increasing roughness. The interface friction angle was positively affected, whereas normal stress did not. Adamska [24] designated the shear strength behaviour of HDPE GMs – fly ash interfaces. A traditional direct shear test apparatus with a cylindrical shear box was used for the tests. Two HDPE GMs, smooth and rough, were used, each with a thickness of 1.5 mm. The fly ash was placed in a box at the maximum dry unit weight and optimum moisture content according to the Standard Proctor energy. Also, in order to determine the water content effect on the interface shear strength, the water content values ($w_{op}t$ ±2.5 and w_{opt} ±5) were changed. The test results showed that the water content had little effect on the interfacial shear strength of smooth GMs. The rough GM has a higher interface friction angle than the smooth GM. The minimum interface shear strength was obtained at the highest water content for the rough GM.

In this study, the shear strength behaviours of interfaces formed between two types of GMs (PVC and HDPE) and five different soils (sand/bentonite mixture, crushed sand, river sand, crushed gravel, and river gravel) were examined. Firstly, the geotechnical properties and internal friction angles (ϕ) of the soils. Then, soil – GM interfaces were formed in the direct shear box and the interface friction angles (δ) were obtained. In addition, PVC GMs were cured in saltwater (SW) and HDPE GMs were cured in municipal solid waste (MSW) leachate in a laboratory environment for eight months to represent the environment formed at solid waste landfills and structures near the coastline. The experiments were conducted using a direct shear apparatus (100 x 100 mm^2). The normal stress values were applied in the direct shear test range between 12.25 and 784 kPa. Based on the test results, the effects of angularity, grain size, pore liquid, and normal stress on the interface shear behaviour were determined. The most important innovations and necessities that distinguish this study from other studies are the use of two different GM types and several different soil types. Thus, findings regarding the relationship between GM type and the five different soils were obtained. The most important gap in previous studies on this subject is the lack of studies on the interface friction angles of cured GM samples. Therefore, the negative effects of groundwater and leachate liquids on the GM were ignored during the project design phase. In this study, the negative effects on GMs of groundwater or waste leachate, to which GMs are exposed during the design of structures close to the coastline or municipal solid waste storage on GMs can were considered.

2. Materials and methods

2.1. Soils

Five different soils were used in this study, namely, sand/bentonite (80/20) mixture (SB: particle size 2.0 – 0.0 mm), crushed sand (CS: particle size 2.0 – 0.075 mm), river sand (RS: particle size 2.0 – 0.075 mm), crushed gravel (CG: particle size 10.0 – 1.0 mm), and river gravel (RG: particle size 10.0 – 1.0 mm). These soils are preferred because they are frequently used in building foundations, waste storage areas, ponds, artificial pools, and GMs. In addition, the effects of grain size (coarse – fine) and angularity (angular – round) were investigated using these soils. The particle size distributions of the five soils are shown in Fig. 1. The geotechnical index properties of the soil samples are listed in Table 1. Figure 2 shows the physical appearance of the soil.

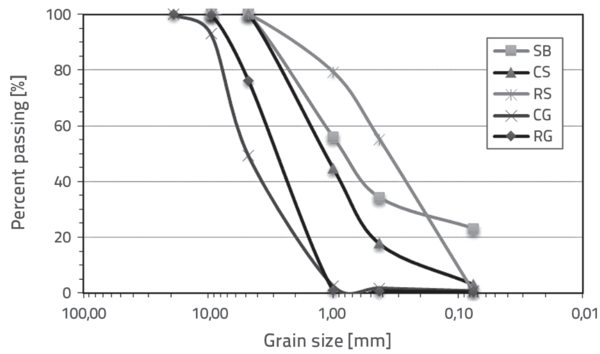

Figure 1. Particle size distributions of soils

2.2. GMs

Commercially available smooth HDPE and PVC GMs were used in this study. The reasons why these GMs are preferred more

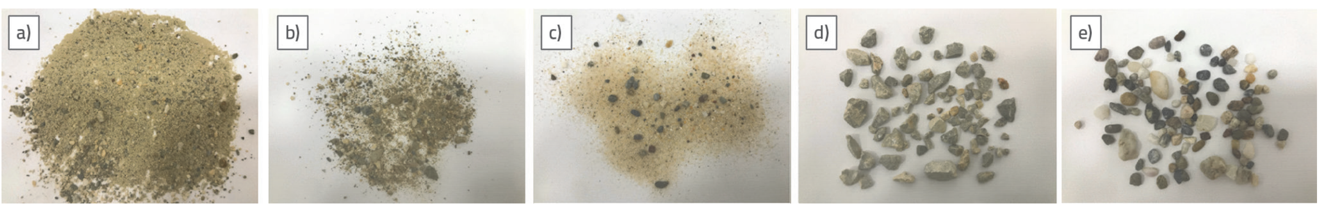

Figure 2. Physical appearance of soils: a) sand/bentonite (SB), b) crushed sand (CS), c) river sand (RS), d) crushed gravel (CG), d) river gravel (RG)

Table 1. Geotechnical index properties of soils

Property	SB	CS	RS	CG	RG
Specific gravity, G_s	2.46	2.68	2.67	2.63	2.62
Liquid limit, LL [%]	60.7	-	-	-	-
Plastic limit, PL [%]	30.2	NP	NP	NP	NP
Max. dry unit weight, $\gamma_{dry.max}$ [kN/m^3]	17.0	17.3	17.1	17.6	17.2
Opt. moisture content w_{opt} [%]	13.2	11.2	11.7	6.5	4.7
D_{10}	-	0.19	0.11	1.29	1.10
D_{30}	0.2	0.69	0.19	2.77	1.90
D_{60}	1.5	1.70	0.50	5.95	3.64
Coefficient of uniformity, C_u	-	8.95	4.55	4.61	3.31
Coefficient of curvature, C_c	-	1.47	0.66	1.00	0.90
USCS	SC	SW	SP	GW	GP

Table 2. Essential characteristics of GMs

PVC			HDPE		
Essential characteristics	**Unit**	**Value**	**Essential characteristics**	**Unit**	**Value**
Thickness	mm	1.5	Thickness	mm	1.5
Resistance to tearing	N	150	Stress crack resistance	h	>200
Shear resistance of joints	N/5 cm	800	Elongation at yield	%	>12
Tensile strength	N/mm^2	15	Tensile stress at break	N/mm^2	>26
Elongation at break	%	250	Elongation at break	%	>700
Water tightness	-	Fully	Water permeability	$m^3/m^2 \cdot d$	$<10^{-6}$
Artificial aging-water tightness	-	Fully	Resistance to weathering	%	<25
Chemical resistance-water tightness	-	Fully	Oxidation strength	%	<25
Resistance to impact	mm	1500	Yield strength	N/mm^2	>16
Resistance to static load	kg	20	Static puncture resistance	N	3700

frequently in engineering applications are some properties such as high tensile strength at low stresses, low-cost assembly, and long-term weather resistance. PVC GM is a protective layer composed of synthetic raw materials and is used for liquid and thermal insulation. PVC is a symbol created from the abbreviation polyvinyl chloride. It is a type of polymer produced from oils and salts in petrochemical plants. They are produced by mixing PVC raw material with softeners, stabilisers, and various additives in a mixer, processing it using an extrusion system at an appropriate temperature, and shaping it homogeneously. PE takes the name of ethylene which is in the form of a monomer. Ethylene is converted into polyethylene using several polymerisation methods. HDPE GM is a geosynthetic liner formed by the extrusion of high-density polyethylene and is shaped homogenously by a calendar system. It is used to ensure impermeability in projects, such as municipal solid waste landfill sites, mine waste landfill sites, acid tanks, ponds, tank fields, and irrigation channels. The properties of the GMs provided by the manufacturers are listed in Table 2.

2.3. Pore liquids

The synthetic waste (MSW) leachate used in this study, with a composition described by Hrapovic (2001), was produced by mixing various chemical compounds in distilled water, as described by Hrapovic (2001). MSW leachate is a suitable medium for the growth and maintenance of acetogenic, methanogenic, and sulphidogenic bacteria involved in the mineralisation stage of anaerobic degradation. In addition, a mixture containing only three fatty acids, adjusted to pH = 3.45, was used as a possible variant in the landfill leachate [25]. The chemical composition of the MSW leachate is presented in Table 3.

PVC GMs are generally used as structural foundations for basement tanking. The PVC GM used in the foundation was exposed to saltwater when the structure was close to the coastline. Therefore, the PVC GM used in the study was cured in 0.5 molar saltwater for 8 months, and the damaging effect of saltwater on the GM was investigated. SW was obtained by mixing 1 L of distilled water with 29.25 g of NaCl.

Table 3. Composition of the MSW leachate [25]

Chemical name	Chemical formula	Amount (per 1 L)
Acetic acid	CH_3COOH	7 mL
Propionic acid	$CH_3CH_2CO_2H$	5 mL
Butyric acid	$C_4H_8O_2$	1 mL
Dipotassium phosphate	K_2HPO_4	30 mg
Potassium bicarbonate	$KHCO_3$	312 mg
Potassium carbonate	K_2CO_3	324 mg
Sodium chloride	NaCl	1440 mg
Sodium nitrate	$NaNO_3$	50 mg
Bicarbonate of Soda	$NaHCO_3$	3012 mg
Calcium chloride	$CaCl_2$	2882 mg
Magnesium chloride hexahydrate	$MgCl_2.6H_2O$	3114 mg
Magnesium sulphate	$MgSO_4$	156 mg
Ammonium bicarbonate	NH_4HCO_3	2439 mg
Urea	$CO(NH_2)_2$	695 mg
Trace metal solution	-	1 mL
Sodium sulphide nonahydrate	$Na_2S.9H_2O$	Titrirati to Eh 120-180 mV
Sodium hydroxide	NaOH	Titrirati to pH 5.8-6.0
Distilled water	H_2O	Za 1 L

2.4. Methods

First, the internal friction angles of the soils were determined according to ASTM D3080 [26] with the traditional direct shear test method, but using a different-sized shear box (100 x 100 x 40 mm^3) [27-30]. The friction angle of the soil – GM interfaces was determined according to ASTM D5321 [31] using a direct shear apparatus. The test setup is illustrated in Fig. 3.

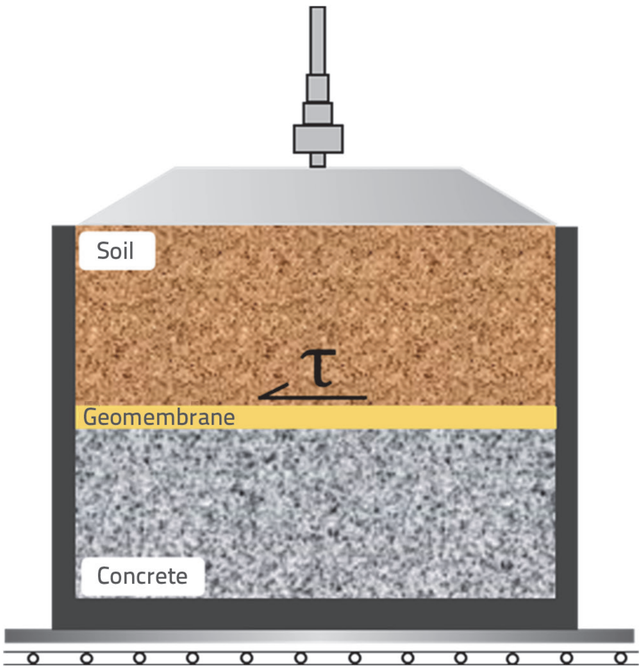

Figure 3. Schematic of direct shear apparatus

To maintain the soil – GM interface fixed during the experiment, concrete blocks with the dimensions of the lower box of the direct shear device were produced. A concrete block was placed at the bottom of the box, the GM was laid on the interface and glued to the concrete block, and the soil was placed at the top. The preparation steps for the specimens are shown in Figure 4. In all the experiments, the soil samples were prepared at the optimum moisture content and placed in a shear box with the maximum dry unit weight. The samples were kept in water for one hour before each experiment to reach 100 % saturation (after the experiments, the degree of saturation of the samples was determined and found to be almost 100 % saturated). Direct shear tests were performed under normal stresses of 12.25, 24.5, 49, 98, 196, 392 and 784 kPa. The experiments were performed at a shear rate of 0.5 mm/min because the permeabilities of CS, CG, RS, and RG were very high, and 0.1 mm/min because the permeability of SB was low [22, 32-33].

3. Results and discussion

3.1 Traditional direct shear test

Initially, a series of soil-soil experiments was performed on five soils (SB, CS, RS, CG, and RG) at the maximum dry unit weight and optimum moisture content under seven normal stresses (12.25, 24.5, 49, 98, 196, 392, and 784) to determine the shear strength behaviour. The reason for testing from very low normal stresses to very high normal stresses was to determine whether the behaviour of the GMs changes under high normal stresses. The initial void ratios and internal friction angles obtained for the soils are presented in Table 4. The interface friction angles of the coarse and angular soils are higher, as listed in Table 4. It has been determined that soils with different morphological properties (roundness and sphericity) can affect the internal friction angle [23-24, 34-37]. The internal friction angle increased as the particle size increased because larger particles required more friction force to roll and reach the sliding state after the lock was released at the peak [36, 38, 39].

Table 4. Initial void ratios and internal friction angles of the soils

Type of soil	Initial void ratio, e	Internal friction angle ϕ [°]
SB	0.339	21.2
CS	0.517	34.9
RS	0.535	28.5
CG	0.471	43.9
RG	0.428	40.6

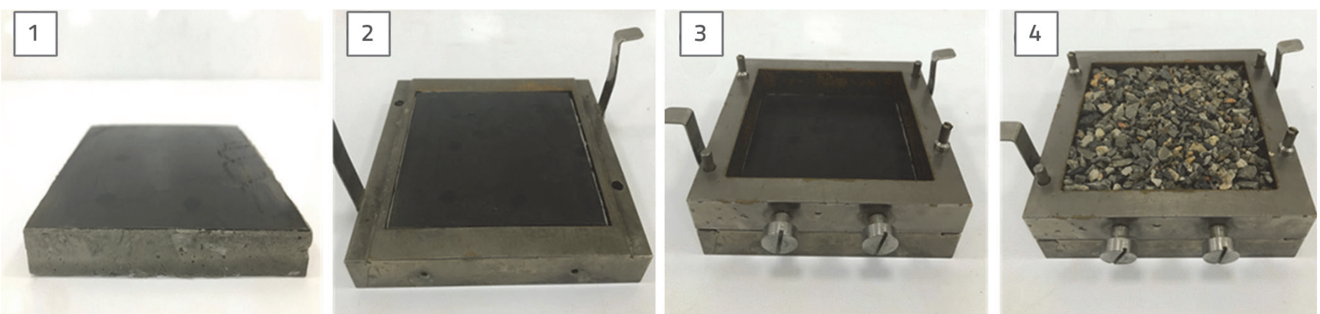

Figure 4. Sample preparation steps for direct interface shear tests

3.2. Interface direct shear tests

Interface direct shear experiments were performed to investigate the effects of particle size, morphology, normal stress, and GM type on the interface shear behaviour between soil-GM. The preparation conditions and normal stresses of the samples were identical to those used in the direct-shear tests. The repeatability of the experimental results of the direct shear and interface direct shear experiments was ensured by repeating the tests twice or even thrice. The shear stress-strain graphs of the soil – PVC GM and soil – HDPE GM are shown in Figures 5 and 6. In Figures 5 and 6, whereas the shear stresses at the HDPE – soil interface became constant at small deformations (≈2 %), the shear stresses at the PVC – soil interface became constant at larger deformations (≈7 %) and even continued to increase in some samples. This situation can be explained as follows: the combined use of soft GM (PVC) and soil containing angular particles (SB, CS, and CG) resulted in the early start of ploughing and significant mobilisation of shear strength due to ploughing. However, the combined use of hard GM (HDPE) and soil can result in little or no ploughing [19, 21, 40].

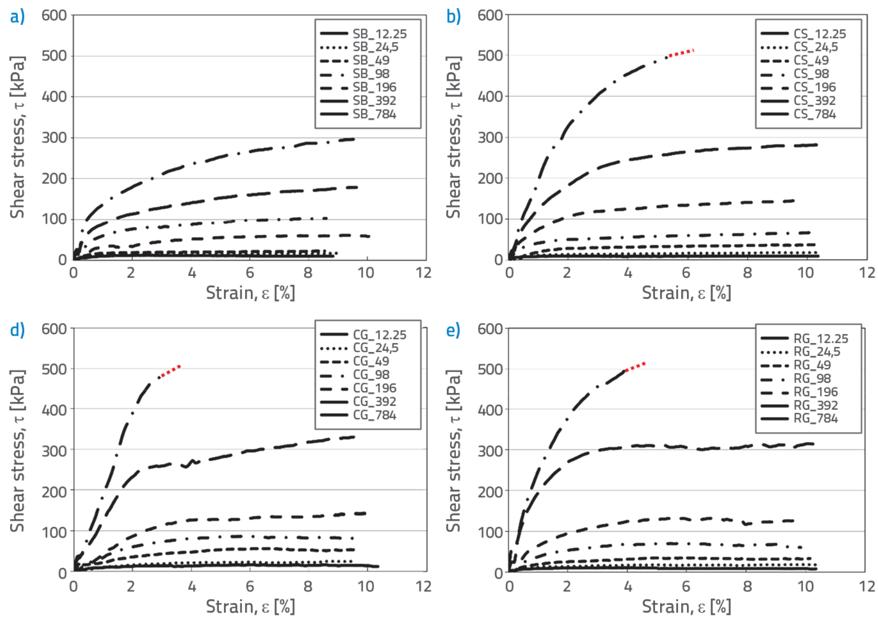

Figure 5. shear stress-strain graphs of soil – PVC interfaces

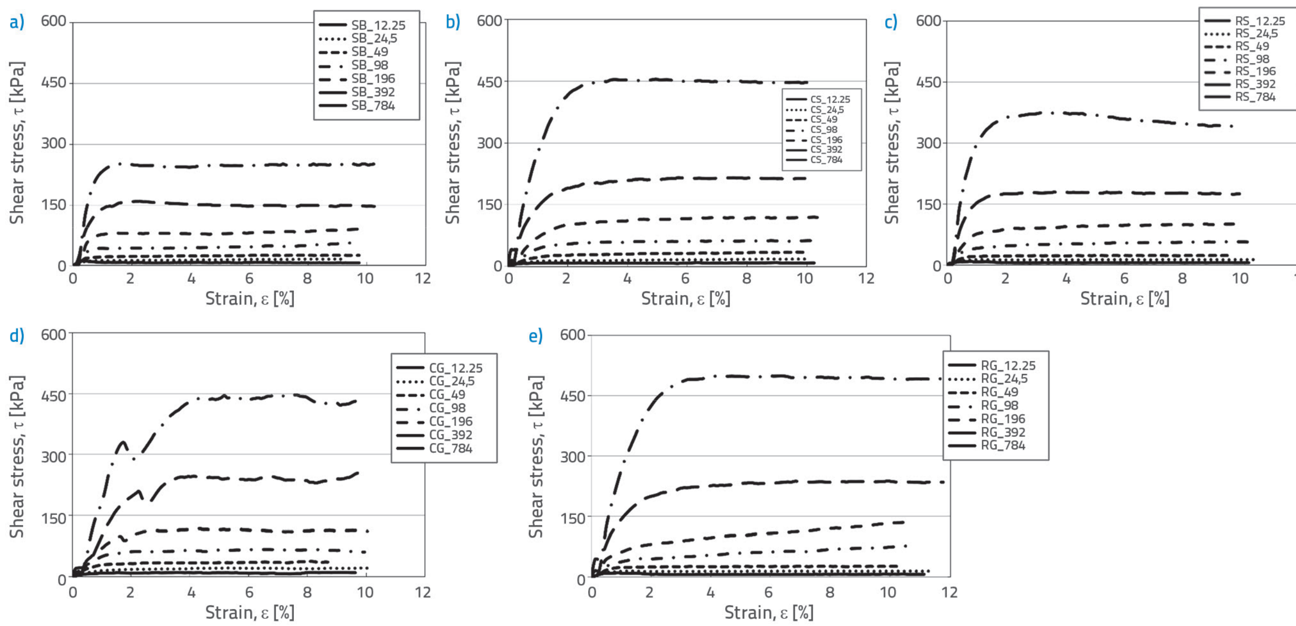

Figure 6. shear stress-strain graphs of soil – HDPE interfaces

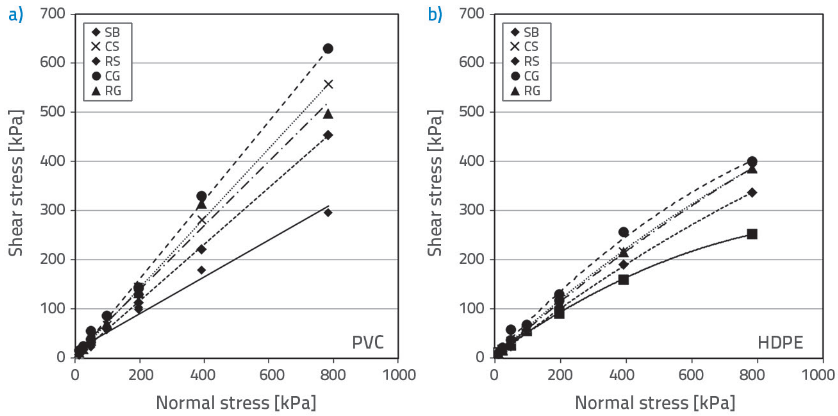

Figure 7. Mohr–Coulomb failure envelopes of soil–GM interfaces: a) PVC and b) HDPE

The Mohr–Coulomb failure envelopes of the soil – PVC and soil – HDPE interfaces obtained from the shear stress-strain graphs are shown in Fig. 7. The soil – PVC interfaces have linear Mohr–Coulomb failure envelopes, whereas the soil – HDPE interfaces have parabolic Mohr–Coulomb envelopes. This is because the particles slide on the GM surface up to a certain value of normal stress and, as a result, the shear stresses increase. After a certain value of normal stress, the particles begin to become embedded in the soft PVC GM surface; thus, there is a decrease in HDPE GM, whereas in PVC GM, there is no such decrease as soil–soil friction occurs [41].

3.3. Effect of normal stress

The shear stress did not reach the residual at high normal stress values at the soil–PVC GM interfaces. However, the same situation was not observed at the soil–HDPE GM interface. The shear stresses increased to a certain point and then remained constant, as shown in Figures 5 and 6. Similar results were obtained by Fleming et al. [21] and explained by the finding that at high normal stresses, the failure mechanism varies from soil particles sliding on the GM surface to soil particles embedded in the GM and ploughing trenches along the shear direction. The ploughing fracture mechanism resulted in significantly higher shear strength at the GM–soil interface. For this mechanism to occur, the GM must be composed of soft polymers. In the HDPE GM, the shear stresses increased with the normal stress values, but no linear increase was observed. The increase in the shear stress decreased as the normal stress increased. However, the same situation was not observed for the PVC GM, and the increase was linear. In some experiments, the test was stopped at a stress of 784 kPa because the shear stress exceeded 500 kPa, which is the capacity of the load cell of the direct shear test device (indicated by the red line in Figure 5).

3.4. Effect of particle size and angularity

The internal friction angles of the soil – PVC and soil – HDPE GMs are shown in Figure 8. When comparing soils with the same angularity, it was found that the interface friction angles of the sandy soils (CS and RS) were lower than those of the gravel soils (CG and RG). Large particles require more frictional force to achieve sliding conditions and roll after the release of interlocking [36]. It was also observed that the sand/bentonite mixture with the highest cohesion had the lowest interface friction angle of the two types of GMs.

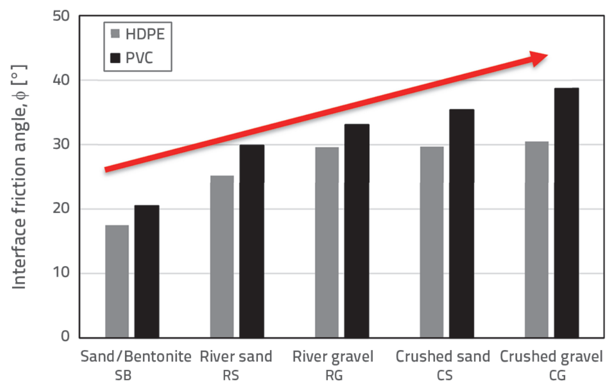

Figure 8. Comparison of interface friction angle values

If the angularity effect is examined, soils with high angularity (CS and CG) have a higher interface friction angle than round-grained (RS and RG) soils. Crush sand and crushed gravel were less spherical, less rounded, and less regular than river sand and gravel, respectively. These angular sand particles can easily plough and form deeper grooves, providing higher interface friction angles [23, 24, 36, 37, 42]. Studies have also reported that higher interfacial friction angle values are obtained at higher dry densities because more soil particles are in contact with the surface of the GM, resulting in an increased contact area, and therefore, increased interface shear strength [21, 24, 43]. The experimental results also showed that the interface friction angles were directly proportional to the dry density.

3.5. Effect of GM type

The thicknesses of both GM types were chosen to be the same (1.5 mm) to examine the effects of the GM type on the interface friction angle. For all soil types, the soil–PVC interface friction angle was greater than the soil–HDPE interface friction angle.

This was because the PVC GM was softer than the HDPE GM. Studies have shown that the friction angles are greater because soil particles are more easily embedded in the surface of soft GMs. The interface friction angles of crushed soils–PVC were 19.2–26.9 % higher than those of crushed soils (HDPE). However, the interface friction angles of river soils–PVC were 11.8–18.7 % higher than those of river soils–HDPE. Because the morphology of river soils was rounded, there was no embedment on the GM surface; therefore, the friction angle was lower [22, 44, 45].

3.6. Effect of aging and liquid composition on GM performance

GMs were stored in MSW leachate and SW for eight months to examine the effects of leachate and groundwater generated in landfills and coastline structures on the shear strength parameters of the GMs. Interface direct shear tests were performed without curing the samples in tap water and 8 months cured samples of MSW and SW. A comparison of the interface friction angles for the different pore liquids is shown in Figure 9.

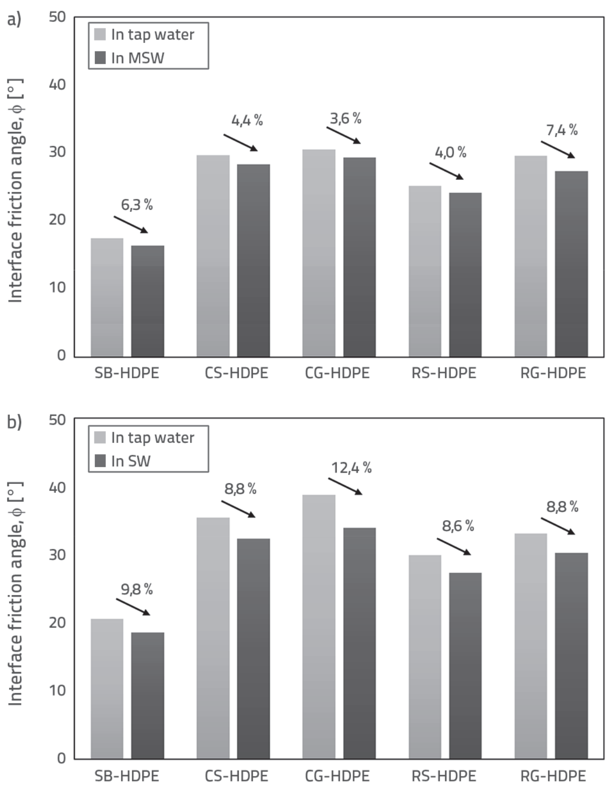

Figure 9. Interface friction angles of cured samples: a) HDPE-soil interface and b) PVC-soil interfaces.

Figure 9 shows that the interface friction angles of the GMs kept in MSW for 8 months decreased by an average of 5.1 %. The reason for MSW damage to GM is that oxidative degradation starts from the 4th month. Viebke et al. [46] and Hsuan and Koerner [47] described oxidative degradation as a three-step process. In stage 1, there was no significant change in the engineering properties. Stage 2 is the induction time for degradation to begin after the antioxidants are depleted. The end of the 2nd stage coincides with the beginning of oxidation. In stage 3, there were significant changes in the physical and mechanical properties owing to oxidation which eventually led to GM failure. Failure in this context refers to the reduction of an engineering property, such as stress–crack resistance and tensile-breaking stress, to a certain value [3]. In this study, it was determined that stage 2 started after a 4-month curing period and continued for four months. Rowe et al. [3] stated in their study that even at 50°C in MSW, the oxidation time decreased by only 25 % after 8 months. Therefore, the decrease in the interface friction angle was low. It was also observed that the interface friction angles of the GMs kept in SW for 8 months decreased by an average of 9.7 %. In the studies conducted in the literature, it has been determined that SW has a negative effect on the stress crack resistance, breaking tensile stress, and elongation of the GM [48, 49]. This is because the presence of salts on the GM surface without diffusion catalyses polymeric degradation.

3.7. Comparison with the interface friction angles in literature

The interface friction angles (uncured) were compared with the results obtained in the literature and are summarised in Table 5. In this study, the friction angles of the GM–soil interfaces were consistent with the results of Fleming et al. [21], Frost et al. [23], Cen et al. [37], and Stark and Santoyo [50]. It was also evident that the friction angle of the coarse-grained soil was greater than that of the fine-grained soil. In addition, the interface friction angles are clustered in Figure 9 according to the interface type. As shown in Figure 10, the interface friction angles of samples with the same interface type are close to each other.

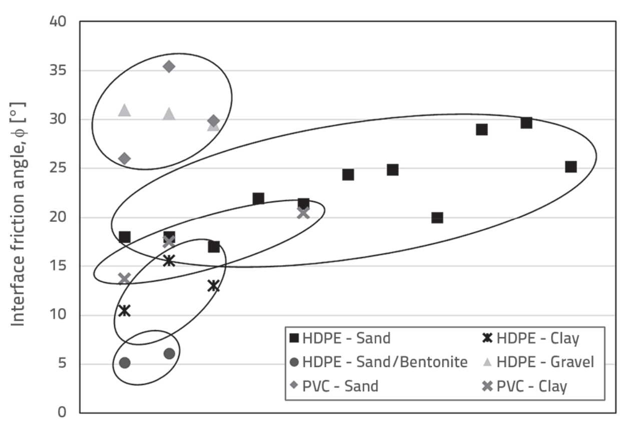

Figure 10. Comparison of the interface friction angles by interface type

Table 5. Summary of GM – soil interface shear strength parameters from previous studies

Study	Normal stress [kPa]	Testing equipment	Interface	Peak Friction angle δ [°]
Williams & Houlihan [51]	-	Direct shear	PVC – rounded sand HDPE – rounded sand PVC – angular sand HDPE – angular sand	26.1 18.8 33.0 27.0
Mitchell & et al. [52]	158, 316, 479	Modified direct shear	HDPE – concrete sand	18.0
			HDPE – Ottawa sand	18.0
			HDPE – Misa Schist sand	17.0
O'Rourke & et al. [18]	-	Direct shear	PVC – rounded sand HDPE – rounded sand	30.1 18.8
Nataraj & et al. [53]	-	Direct shear	PVC – rounded sand HDPE – rounded sand	31.8 20.8
Izgin & Wasti [54]	5 – 50	Inclined board	HDPE – Ottawa sand	22.0
			HDPE – Ottawa stone	31.0
Dove & Frost [34]	-	Large scale direct shear	HDPE – rounded sand HDPE – angular sand	21.3 27.9
Bergado & et al. [55]	150 – 400	Direct Shear	HDPE – compacted clay	10.5
Fleming & et al. [21]	-	Modified direct shear	HDPE – silty sand	21.4 – 23.7
			HDPE – 6% sand/bentonite	19.8 – 21.2
Mariappan & et al. [56]	100, 200, 300	Large scale direct shear	HDPE – native soil	15.6
Mariappan & et al. [57]	100, 200,. 300	Large scale direct shear	HDPE – 10% silt/bentonite	5.2
			HDPE – 10% sand/bentonite	6.1
			HDPE – native soil	19.8
			PVC – 10% silt/bentonite	13.7
			PVC – 10% sand/bentonite	3.5
			PVC– native soil	17.5
Frost & et al. [23]	100, 300	Large scale direct shear	HDPE – Ottawa sand	24.4 – 25.5
			HDPE – Blasting sand	24.9 – 25.5
Stark & Santoyo [50]	17, 50, 100, 200, 400	Modified ring shear	PVC – Urbana glacial till	26.0
			PVC – Ottawa sand	26.0
			HDPE – Urbana glacial till	13.0
			HDPE – Ottawa sand	20.0
Cen & et al. [37]	50, 100, 150, 200	Large scale composite shear	HDPE – fine sand	29.0
			HDPE – sandy gravel	30.6
Markou & Evangelou [41]	100, 200, 400	Large scale direct shear	PVC – rounded sand HDPE – rounded sand PVC – angular sand	30.8 16.7 40.9

Table 5. Summary of GM – soil interface shear strength parameters from previous studies - continuation

Study	Normal stress [kPa]	Testing equipment	Interface	Peak Friction angle δ [°]
Present study	12.25, 24.5, 49, 98, 196, 392, 784	Modified direct shear apparatus	PVC – 20% sand/bentonite	20.5
			HDPE – 20% sand/bentonite	17.5
			PVC – crushed sand	35.4
			HDPE – crushed sand	29.7
			PVC – crushed gravel	38.7
			HDPE – crushed gravel	29.5
			PVC – river sand	29.9
			HDPE – river sand	25.2

4. Conclusion

In this study, the shear strength behaviour of the soil–GM interface was examined. The friction angles of the soil–GM interface were determined using a direct shear apparatus. Five soil types (sand/bentonite mixture, crushed sand, river sand, crushed gravel, and river gravel) were used in the experiments to investigate the effects of particle size and angularity on the interface friction angle. Two different types of GMs with the same thickness were used to determine the effect of the GM type on the interface friction angle. In addition, normal stresses from 12.25 kPa to 784 kPa were applied in the experiments to obtain the effect of the normal stress on the interface friction angle. The experimental test results showed that shear stress increases as horizontal strain increases at high normal stresses in PVC GM interfaces, but at HDPE GM interfaces even at high normal stresses, the shear stress increases to a certain horizontal strain (≈7.0 %) and then remains constant. The HDPE GM carried a smaller load than the PVC GM under high pressures. Therefore, in a real project, it is recommended to use a PVC GM on the foundation of multi-layered buildings, according to the test results obtained from the current study. Soils with larger and angular particles had higher interface friction angles, and the soil–PVC interface had a 10.6–21.2 % higher interface friction angle than the soil–HDPE interface. The smallest difference between the friction angles of both interfaces was in river gravel, whereas the largest difference was in crushed gravel. The critical conclusion drawn from this study is that there is a 9.7 % reduction in the interface friction angle of the PVC GM used in the foundation, even after eight months, in structures built close to the coastline. Another critical result is the 5.1 % reduction in the interface friction angle of the HDPE GM used for impermeability in municipal solid waste landfills, even after eight months.

Another important result obtained from this study is that using specific values such as 2/3 (0.67) as the interface friction coefficient in the codes, regulations, or standards used as a reference in GM projects can carry significant risks. This study revealed that a 2/3 ratio of reduction in the internal friction angle may be insufficient for some interfaces, depending on the environmental conditions. Therefore, when designing projects involving GMs exposed to MSW leachate, particularly in landfills, potential damage over time should be considered, and appropriate design parameters should be selected. Failure to do so can lead to disasters that cause the loss of life and property.

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