PROPERTIES OF DIFFERENT SIZE SCRAP TIRE SHREDS: IMPLICATIONS ON USING AS DRAINAGE MATERIAL IN LANDFILL COVER SYSTEMS*

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Abstract

Various engineering properties must be known to assess the feasibility of using shredded scrap tires as drainage material in landfill cover systems. These properties include unit weight, hydraulic conductivity, compressibility, shear strength, and interface shear strength. This paper summarizes the engineering properties of tire shreds based reported studies and evaluates the variation of these properties with the size of tire shreds. It is shown that a wide range of values was reported for each property due to differences in the size and composition of tire shreds and the testing methods employed. Despite having a wide range of values, the properties of shredded scrap tires meet the specific requirements to serve as an effective drainage material in landfill cover systems.

Introduction

The tire composition varies by manufacturer and type. Automobile tires are made of natural rubber, synthetic rubber elastomers, polymers, and other additives. Steel reinforcing is also provided to improve strength. Tires are designed to withstand the rigors of the environment so that they are durable and safe when used on a vehicle. Even the discarded tires maintain their chemical composition, requiring hundreds of years to fully decompose (Hoffman, 1974).

Over 280 million scrap tires are generated annually in the United States. In addition, 2 to 4 billion scrap tires are stock-piled across the country, and these stock piles pose health and fire hazards, and they are aesthetically unpleasing. Therefore, the reuse of large amounts of scrap tires is beneficial, and several researchers have devoted their attention to the use of scrap tires for civil and environmental engineering applications (Reddy and Saichek, 1998). One of these applications is the use of shredded scrap tires as drainage material in landfill cover systems. Landfill cover design generally consists of three layers: the barrier layer, the drainage layer, and the cover soil layer. The purpose of the drainage layer is to allow any infiltrated water to drain from the overlying cover soil layer so that it is prevented from seeping into the underlying barrier layer and the waste. The drainage layer minimizes the generation of leachate in the landfill and also prevents build-up of a hydraulic head within the cover. This is critical because a large

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hydraulic head may cause the slopes to become unstable. Thus, the most important engineering property for the use of shredded scrap tires as the drainage material in landfill cover is the hydraulic conductivity, and the hydraulic conductivity must be high to allow the water to drain easily. In addition to the hydraulic conductivity, many other properties are needed to compute settlement and slope stability. These properties include unit weight, compressibility, shear strength, and interface shear strength. These properties for conventional drainage materials such as sand can be easily determined using standard testing techniques. However, finding these properties for large tire shreds is not practical.

An extensive literature survey was conducted using library databases, and it was found that many studies have been performed to determine the properties of shredded scrap tires for various purposes. In addition, these studies utilized different tire shred sizes. Using large tire shreds is cost-effective due to low-cost shredding operations, but none of the reported studies investigated the effects of tire shred size on engineering properties such as hydraulic conductivity.

In this study, an attempt is made to assess the effect of the tire shred size on engineering properties. Particular attention was paid to the properties of large-size tire shreds (larger than 4 inches), which are economical to use as drainage material in landfill covers. The properties analyzed in this study included unit weight, specific gravity, hydraulic conductivity, compressibility, shear strength, and interface shear strength. These property values were helpful in evaluating the potential use of shredded tires as the drainage material in landfill covers.

Unit Weight and Specific Gravity

The unit weight is the ratio of the weight of a substance to the volume of a substance, whereas specific gravity is the ratio of the unit weight of solids divided by the unit weight of water. A material whose unit weight of solids equals the unit weight of water has a specific gravity of 1.0. The specific gravity of tire shreds ranges from 1.02 to 1.36, depending on the amount of glass belting or steel wire in the tire (Edil and Bosscher, 1994; Zimmerman, 1997; ASTM, 1998). Tire shreds that have high specific gravity generally possess a greater proportion of shreds with steel belts. The specific gravity of soils typically ranges from 2.6 to 2.8, which is more than twice that of tire shreds.

The reported data on the dry unit weight of shredded scrap tires is summarized in Table 1. As seen in the table, the investigators used different testing conditions to determine the unit weight of scrap tires. These testing conditions included using shreds with different sizes, size mixtures, and different compositions. The tire shreds tested ranged in size from 0.08 inches to 5.5 inches. Based on these tests, the dry unit weight of tire shreds was found to vary from 15 pcf (pounds per cubic feet) for a loose tire shred mix containing shreds of 0.08 to 1 inches in size to 53 pcf for compacted tire shreds of 1 to 3 inches in size. Figure 1 shows graphically the variation of unit weight with maximum, minimum, and average size of tire shreds, and this data shows that there is not a good correlation between the unit weight and the tire shred size.

Table 1 Unit weight of different size tire shreds

Reference	Tire Shred Size (inch)	Dry Unit Weight (pcf)	Specific Test Conditions
Bressette, 1984 ASTM, 1998	0.2-2.5	25-38	-
Humphrey et al., 1992 Humphrey and Manion, 1992 Manion and Humphrey, 1992 Humphrey and Sandford, 1993 ASTM, 1998	0.08-3	21.4	No compaction
	0.08-2	25.5-30.3	
	0.08-1	31.1	
Ahmed, 1993 Ahmed and Lovell, 1993 ASTM, 1998	0.5-2	29.3	No compaction
	0.5-1	30.8	No compaction
	0.5-1	31.2	ASTM D 4253
	0.5	29.7	ASTM D 4253
	0.5-2	38.6	50% standard – compaction energy
	0.5-1	40.0	
Humphrey et al., 1992 Humphrey and Manion, 1992 Manion and Humphrey, 1992 Humphrey and Sandford, 1993 ASTM, 1998	0.08-3	39	60% standard – compaction energy
	0.08-2	39.3-40.4	
	0.08-1	15.3	
Ahmed, 1993 Ahmed and Lovell, 1993 ASTM, 1998	0.4-2	40	Standard – compaction energy
	0.5-1.5	40.6	
	0.5-1	41	
	0.5	39.8	
Edil and Bosscher, 1992 Edil and Bosscher, 1994 ASTM, 1998	0.75-3	37.0	6 inch-diameter mold compacted by 10 lb-rammer falling 12 inches
	0.75-3	35.0	12 inch-diameter mold compacted by 60 lb- rammer falling 18 inches
Humphrey and Manion, 1992 Manion and Humphrey, 1992 ASTM, 1998	0.08-2	41.5	Modified – compaction energy
Ahmed, 1993 Ahmed and Lovell, 1993 ASTM, 1998	0.5-2	41.7	
	0.5-1	42.7	
Upton and Machan, 1993	2	24-33	Loose
		45	Compacted
		52-53	Surcharged with 3 feet soil, pavement & highway traffic
Newcomb and Drescher, 1994	0.78-1.8	31.2-35.2	
Black and Shakoor, 1994	<0.04-0.27	33	-
Duffy, 1995	2.0	30-50	-
Masad et al., 1996	0.18	39.4	
Cecich et al., 1996	0.2-0.6	35.1-37.3	ASTM D1557
Andrews and Guay, 1996	1-2	40	-
Wu et al., 1997	<0.08	33.3	Tested tire shreds without steel in them
	<0.37	31.5-37.5	
	<0.74	35.8	
	<1.5	37.4	
Tweedie et al., 1998	1.5	44.3	Full scale field tests
	3	43.1	
Chu, 1998	0.25-1.5	43.2-43.6	-
Reddy and Saichek, 1998	0.5-5.5	26	No compaction

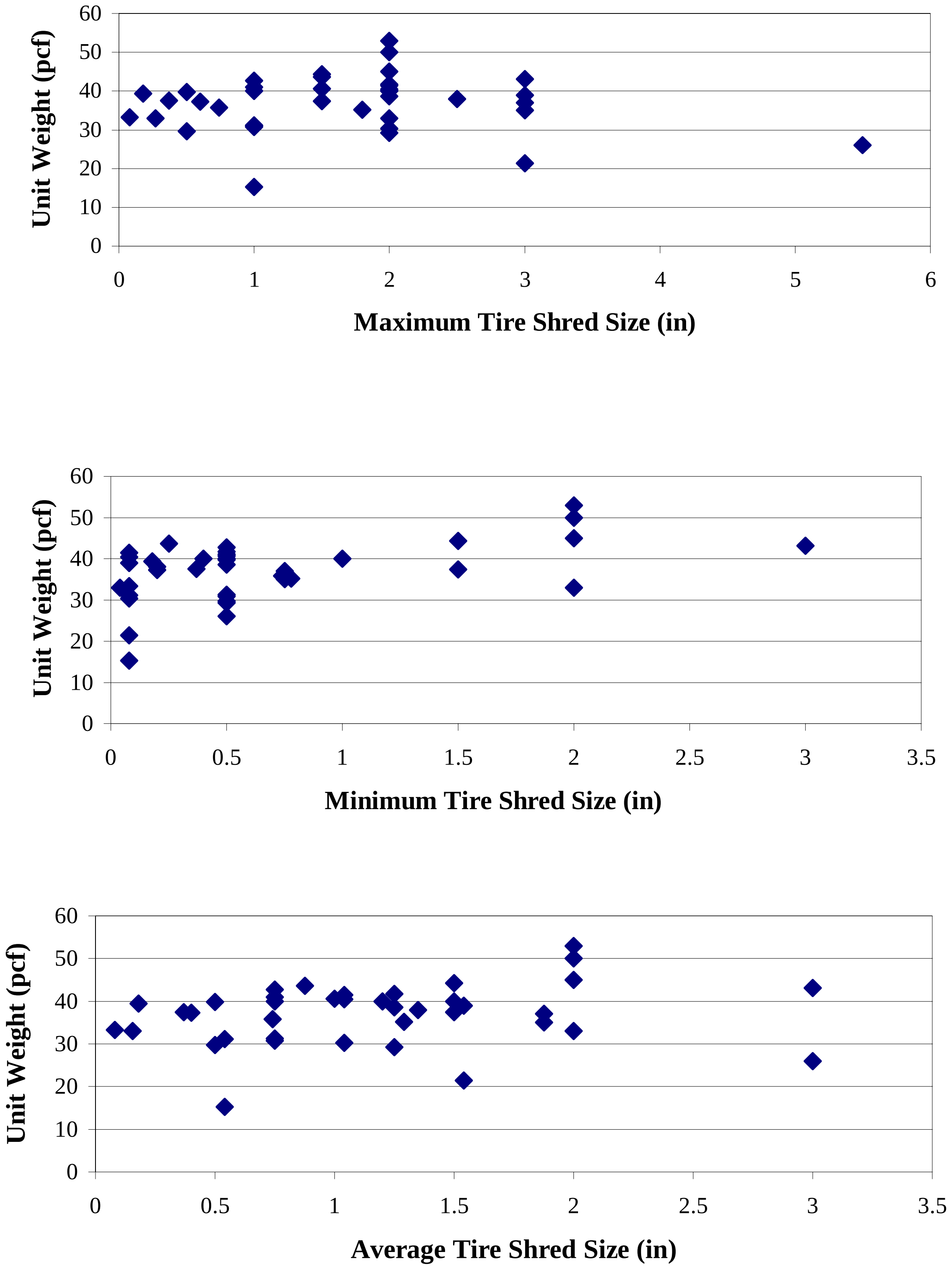

Figure 1 Unit weight of different size tire shreds based on reported studies

Hydraulic Conductivity

Hydraulic conductivity is defined as the rate of water flow under laminar flow conditions through a unit cross-sectional area of porous medium under unit hydraulic gradient and standard temperature conditions. As stated earlier, hydraulic conductivity is of primary importance when assessing the feasibility of using tire shreds as a drainage material. Several investigators have measured the hydraulic conductivity of tire shreds using permeameters with diameters ranging from 8 to 12 inches. Some permeameters had provisions to apply a vertical stress to the sample in order to simulate the compression that would occur under the weight of an overlying soil cover.

Table 2 summarizes the hydraulic conductivity of tire shreds based on previous investigations. It can be seen from this table that the maximum size of the tire shreds ranged 0.18 to 5.5 inches, and the hydraulic conductivity of the tire shreds was found to range from 0.0005 to 59.3 cm/s. The wide range of hydraulic conductivity values is attributed to the differences in shred size and composition, compaction level (initial density/void ratio), and normal stress.

The lowest hydraulic conductivity was 0.002 to 0.0005 cm/s, and this was measured by Masad et al. (1996) when the tire shreds were less than 0.18 inches in size. Such a small tire shred size is not suitable due to the low hydraulic conductivity and high shredding cost. Reddy and Saichek (1998) also found a low hydraulic conductivity of 0.01 cm/s for larger tire shreds that were 0.5 to 5.5 inches in size, but these tire shreds were under a very high vertical stress of 21,000 psf (pounds per square foot). For tire shreds greater than one inch in size and under a normal stress of 100-400 psf, which is expected in a final cover systems, the hydraulic conductivity of tire shreds is always found to be higher than 1.0 cm/s.

It is important that the tire shreds used for drainage material are tested under the stress conditions anticipated at a landfill. ASTM D6270 discusses some of the difficulties in accurately measuring the high hydraulic conductivity of tire shreds as well as the influence of tire shred compression (ASTM, 1998). The hydraulic conductivity of tire shreds measured under a very high normal stress (typical for the drainage layer in a landfill base liner) was significantly less than that measured under a low normal stress (typical for the drainage layer in a landfill final cover). Reddy and Saichek (1998) found that the hydraulic conductivity of tire shreds is reduced to 0.01 cm/sec under a normal stress of 21,000 psf. The tire shreds were compressed by 65% under this high normal stress, but even under this extreme stress condition, the shredded scrap tires met the minimum hydraulic conductivity requirement for drainage materials in landfill covers, which is 0.001 cm/s.

Figure 2 shows the hydraulic conductivity versus maximum, minimum, and average tire shred size, and these results show no definite relationship between hydraulic conductivity and tire shred size. Nevertheless, the results clearly show that larger size tire shreds possess a high enough hydraulic conductivity to serve as effective drainage material in landfill covers.

Table 2 Hydraulic conductivity of different size tire shreds

Reference	**Tire Shred Size (inch)**	**Hydraulic Conductivity (cm/s)**	**Specific Test Conditions**
Bressette, 1984 ASTM, 1998	1-2.5	2.9-23.5	-
	0.2-2.0	3.8-59.3	-
Hall, 1991	1.5	1.43-2.64	Simulated overburden of 0 to 35 feet of MSW
	0.75	0.79-2.74	Simulated overburden of 0 to 25 feet of MSW
Humphrey et al., 1992, Humphrey and Sandford, 1993 ASTM, 1998	0.4-2	7.7	Void ratio=0.925
	0.4-2	2.1	0.488
	0.75-3	15.4	1.114
	0.75-3	4.8	0.583
	0.4-1.5	6.9	0.833
	0.4-1.5	1.5	0.414
Edil et al., 1992 Edil and Bosscher, 1994	2-3	0.6	Stress (psf): 0
		0.45	1440
		0.4	2881
Ahmed and Lovell, 1993	0.5-1.5	0.58	-
Duffy, 1995	2	0.7	2500 psf (40 feet MSW)
		0.53	5000 psf (80 feet MSW)
		0.25	10000 psf (160 feet MSW)
		0.12	15000 psf (240 feet MSW)
Narejo and Shettima, 1995	2.4-4.0	55.0	1879
		20.0	3132
		10.0	7308
		6.0	11484
Andrews and Guay, 1996	1-2	1.0	-
Masad et al., 1996	0.18	0.002	3132
		5×10^{-4}	7308
Cecich et al., 1996	0.2-0.6	0.03	ASTM D2434
Bernal et al., 1996	2	1.2	-
Zimmerman, 1997	8-16	9.0	Void ratio=2.77
		3.2	1.53
		1.8	0.78
Lawrence et al., 1998	0.5-1.5	7.6	Void ratio=0.693
	0.5-1.5	1.5	0.328
	0.5-3	16.3	0.857
	0.5-3	5.6	0.546
Chu, 1998	0.25-0.5	0.16	-
	0.5-1.0	0.18	-
	1.0-1.5	0.18	-
Reddy and Saichek, 1998	0.5-5.5	0.65	3400 psf, Compression - 50%
	0.5-5.5	0.01	21000 psf Compression - 65%

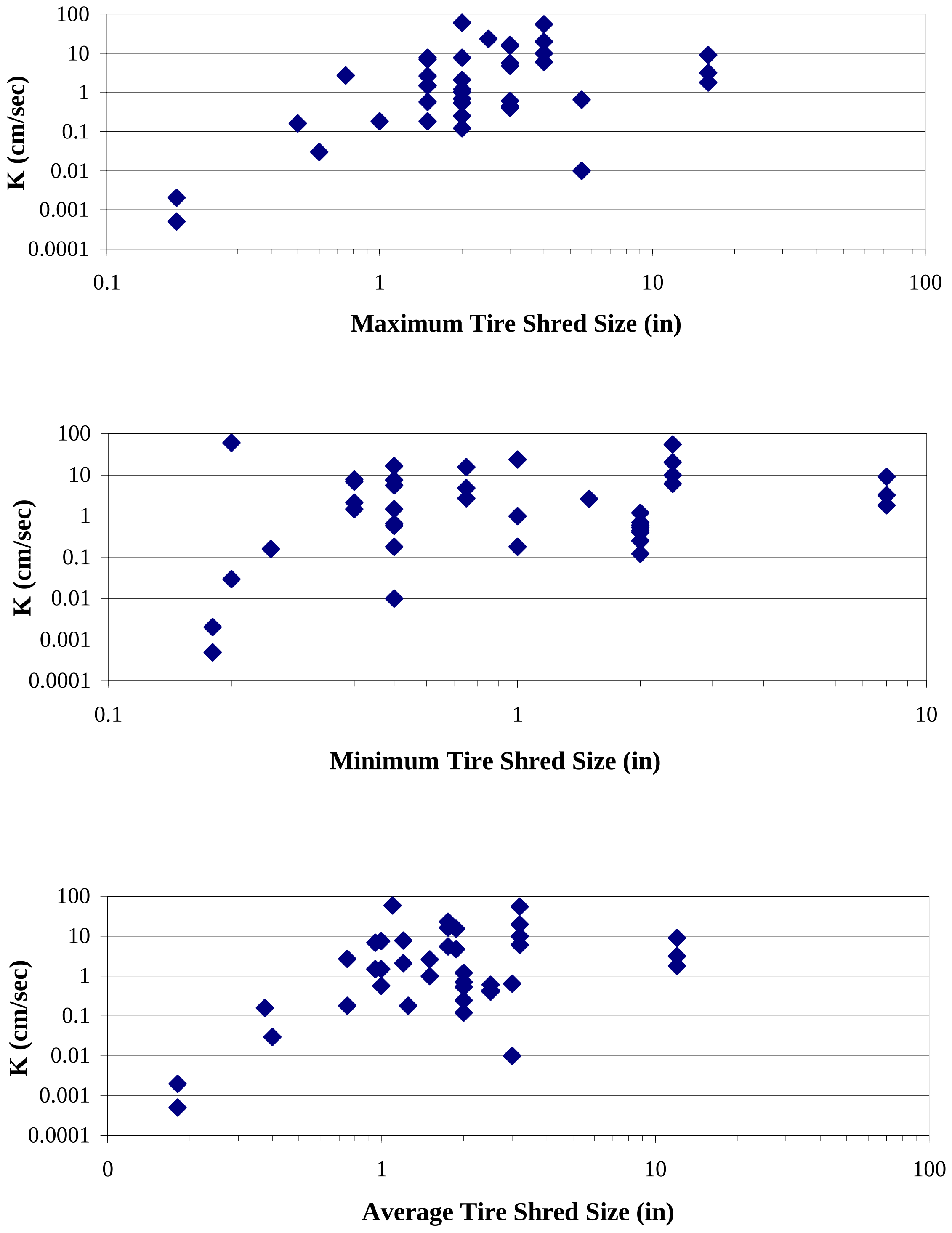

Figure 2 Hydraulic conductivity of different size tire shreds based on reported studies

Compressibility

The property of a material pertaining to its susceptibility to volume change due to changes in stress is called compressibility. Tire shreds are highly compressible because of their high porosity and high rubber content. Tire shreds compress when a load is applied primarily due to two mechanisms: (a) bending and orientation of the shreds into a more compact packing arrangement, and (b) the compression of individual tire shreds under stress. The compressibility of tire shreds is important in the design of landfill final covers in order to assess:

- the settlement that occurs during construction and the settlement that occurs due to the overlying protective vegetative layer, and
- the in-place unit weight and hydraulic conductivity of compressed tire shreds.

The compressibility of tire shreds is generally measured by placing the tire shreds in containers that have diameters ranging from 6 to 29 inches, and then measuring the vertical compression (or strain) caused by an increasing vertical stress. The compressibility values of tire shreds measured in experiments by various investigators are summarized in Table 3. Figure 3 shows the compressibility of different size tire shreds under various normal stresses. These results show that the compressibility increases with an increase in normal stress; however, compressibility appears to have no correlation with the size of the tire shreds.

From experiments conducted by many researchers, it is found that initially loosely placed tire shreds are compressed more than that of slightly compacted tire shreds, and it appears that larger tire shreds are compressed more than smaller tire shreds. In addition, from these experiments, it is found that for stresses expected under landfill cover conditions (100-400 psf), the compressibility of the tire shreds should range from 30 to 50%. Moreover, the compression of tire shreds under construction loading should be taken into account to determine the post construction compression (the compression after the placement of the final cover soil).

Shear Strength

The shear strength between two particles is the force that must be applied to cause a relative movement between the particles (Lambe and Whitman, 1969), and it is a fundamental mechanical property that governs bearing capacity and slope stability. The shear strength of different tire shred sizes based on several reported studies is summarized in Table 4.

Bresette (1984) tested two scrap tire samples. One sample was termed “2-inch square” and it had a cohesion intercept of 540 psf and $\phi = 21^o$, whereas the other sample was termed as “2-inch shredded” and it had cohesion intercept of 660 psf and $\phi = 14^o$. Ahmed and Lovell (1993) conducted different tests on tire shreds with a maximum size of 0.5 inch and 1 inch. Using a 20% axial strain as failure criteria, they found that cohesion intercepts ranged from 694 to 818 psf and friction angles ranged from 20^0 to 25^0 degrees.

Table 3 Compressibility of different size tire shreds

Reference	Tire Shred Size (inch)	Compressibility (%)	Specific Test Conditions (Stress in psf)
Hall, 1991	0.75-1.5	30	1440
Humphrey et al., 1992 ASTM, 1998	0.08-2	33-37	4176 (compacted)
	0.08-2	52	4176 (loose)
	0.08-1	33-35	4176 (compacted)
	0.08-1	45	4176 (loose)
Manion and Humphrey, 1992 ASTM, 1998	0.08-3	38-41	4176 (compacted)
	0.08-2	29-37	4176 (compacted)
Ahmed and Lovell, 1993	0.5-1.5	27	-
Newcomb and Drescher, 1994	1.18	25	104
		40	8532
Edil and Bosscher, 1994	2- 3	37	14400
Zimmerman, 1997	8-16	55	793
Nickels and Humphery, 1997 ASTM, 1998	3	18-28	522
Reddy and Saichek, 1998	0.5-5.5	31	665
	0.5-5.5	50	3400
	0.5-5.5	65	21000

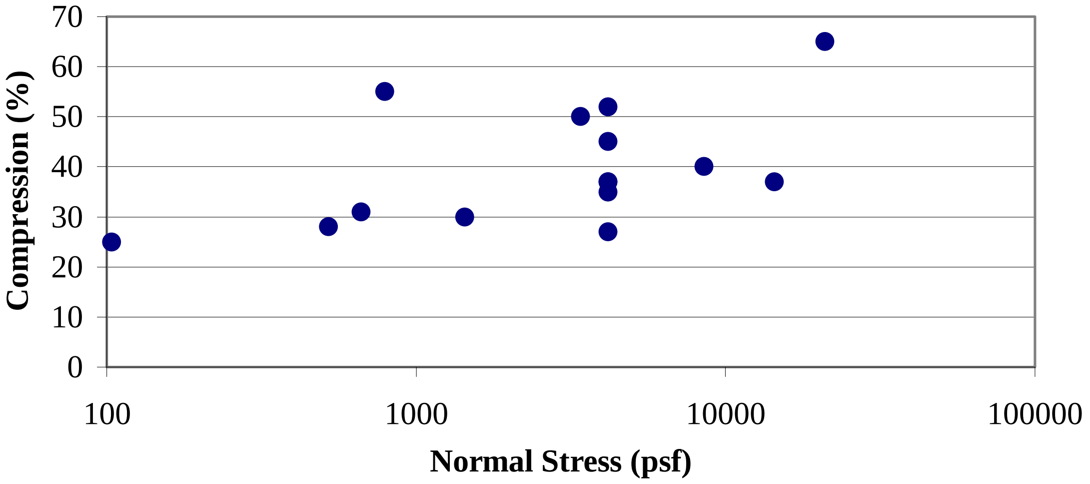

Figure 3 Compressibility of different size tire shreds based on reported studies

Humphery et al. (1993) investigated the shear strength of three separate tire shred sizes that had maximum sizes of 1.5 inches, 2 inches and 3 inches. These experiments were performed under different normal stress conditions, and they found that these shreds possess frictional angle values of 19^{o} to 26^{o} and cohesion values of 90 to 240 psf. Foose (1993) and Foose et al. (1996) performed tests to investigate the shear strength characteristics of a tire shred mixture (sizes ranging from 2 to 6 inches). Several factors, including normal stress, tire shred size, and orientation of tire shreds were considered in their study, and they found angle of friction of 30^{o} and cohesion of 0-62.6 psf.

Edil and Bosscher (1994) conducted tests on 2 to 3 inch size tire shreds and found that the angle of repose or internal friction angle was in the range of 37^{o} to 43^{o}; however, it was as high as 85^{o} under compacted conditions. Black and Shakoor (1994), Duffy (1995), Cosgrove (1995), Bernal et al. (1996), Cecich et al. (1996), and Andrews and Guay (1996) also performed tests under different initial density and normal stress conditions. These investigators found that 0.04 to 3-inch size tire shreds had angle of internal friction values ranged from 17^{o} to 38^{o} and cohesion values ranged from 0 to 150 psf. Gebhardt (1997) investigated the shear strength properties of large tire shreds containing 1.6 to 55 inches in size using the two failure criteria: peak failure and 10% failure. This investigation showed that the shear strength of the shredded tires does not depend on the shred size and $\phi = 38^{o}$ was found for all the tire shreds.

All of the above studies were conducted using the direct shear testing apparatus and procedures. But, Masad et al (1996) and Wu et al. (1997) conducted tests using triaxial testing apparatus and procedures to determine shear strength of tire shreds. Masad et al. (1996) conducted tests on tire shreds smaller than 0.18 inches, and they found that the angle of internal friction ranged from 6^{o} to 15^{o} and the cohesion ranged from 1462 psf to 1712 psf. Wu et al. (1997) conducted tests using four different tire shreds with different maximum tire shred sizes of 0.08, 0.37, 0.74, and 1.5 inches, respectively, and they found that all of these tire shreds possess angle of internal friction of 45^{o} to 60^{o} with cohesion value of zero. It should be noted here that Masad et al. (1996) showed very low friction angles and very high cohesion values as compared to those reported by other investigators, even in studies involving comparable tire shred sizes, but the reasons for such large differences were not explained. Nevertheless, it is uneconomical to use very small size tire shreds (<1 inch), so the results of the study conducted by Masad et al. (1996) are of limited use in evaluating the feasibility of using tire shreds as drainage material in landfill covers.

Figure 4 shows the variation of shear strength parameters (C and ϕ) as a function of minimum, maximum and average size of tire shreds based on all of the reported studies. Based on these results, no correlation between the tire shred size and shear strength was observed. However, these results do indicate that larger tire shred sizes possess shear strengths that are comparable to conventional drainage materials such as sand.

Table 4 Shear strength of different size tire shreds

Reference	Tire Shred Size (inch)	C (psf)	ϕ^{o}	Specific Test Conditions/Normal Stress (psf)
Bresette, 1984	2-inch square	540	21	-
	2-inch shredded	660	14	
Ahmed and Lovell, 1993	0.5	747	20.5	Standard compaction & 20% strain as failure
	1.0	818	24.6	Modified compaction energy & 20% strain as failure
		694	25.3	Standard compaction energy & 20% strain as failure
		779	22.6	50% standard compaction energy & 20% strain as failure
Humphery et al., 1993	<1.5	180	25	Normal stress range: 400-1500 psf
	<2.0	90-160	21-26	
	<3.0	240	19	
Foose, 1993 Foose et al., 1996	<2 2-4 4-6	0-62.6	30	146-1460 psf
Edil and Bosscher, 1994	2-3	-	37-43	0
		-	85	Compacted Condition
Black and Shakoor, 1994	<0.04	100	30	Tested at dry unit weight of 33 pcf
	0.04-0.16	70	31	
	0.16-0.27	130	27	
Duffy, 1995	2	150	27	-
Cosgrove, 1995	1.5	69	38	Saturated
	3	90	32	
Bernal et al., 1996	2	0	17-35	17^{o} at 5% strain 35^{o} at 20% strain
Masad et al., 1996	0.18	1462	6	10% strain
		1482	11	15% strain
		1712	15	20% strain
Cecich et al., 1996	0.2-0.6	147	27	ASTM D3080
Andrews and Guay, 1996	1-2	80	27.5	-
Wu et al., 1997	<0.08	0	45	Tire shreds with out steel-triaxial tests under confining pressure of 720-1148 psf
	<0.37	0	47-60	
	<0.74	0	54	
	<1.5	0	57	
Gebhardt, 1997	1.5-55.1	65	38	115-585 psf Peak failure criterion
	1.5-55.1	0	38	115-585 psf 10% failure criterion

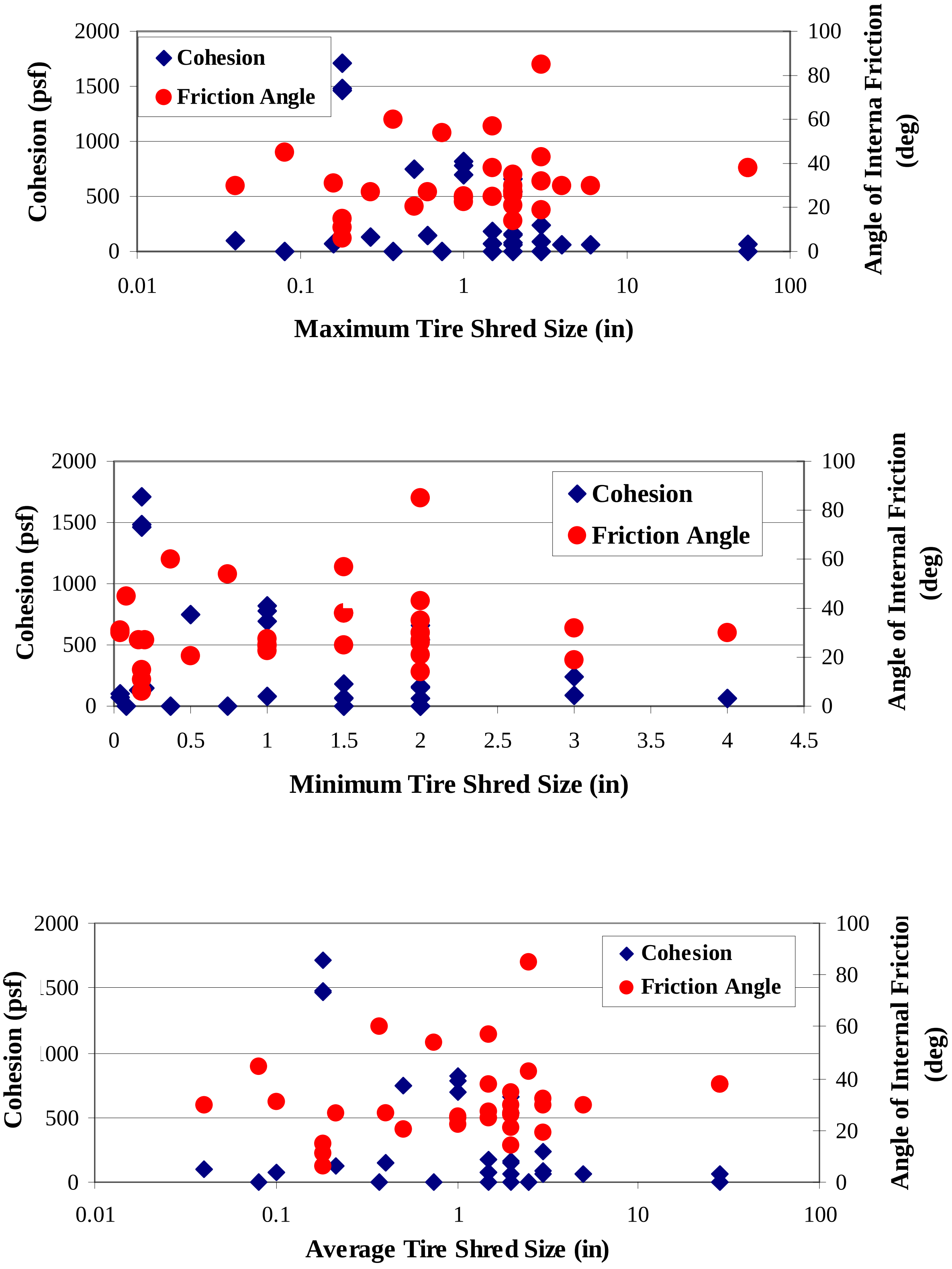

Figure 4 Shear strength of different size tire shreds based on reported studies

Interface Shear Strength

The interface shear strength between the shredded tires and the other materials such as the soils and geosynthetics that they come contact within landfill cover systems is necessary to ensure slope stability. Tables 5(a) and 5(b) summarize the reported interface shear strengths between the shredded tires and the soils and geosynthetics, respectively. Figure 5 shows the variation of interface shear strength parameters, adhesion (c_a) and interface friction (δ), as a function of tire shred size with soils and geosynthetics under different testing conditions. Only limited amount of data is available for the interface strengths of tire shreds.

Foose (1993) and Foose et al. (1996) reported interface friction angles between tire shreds and Portage sand. They conducted different experiments using 2, 4, and 6 inch size tire shreds. During the testing, the surface of the tire shreds was set level with the shear plane by mounting the tire shreds on a piece of plywood. The average interface friction angle was 34^{o} with unit weight of soil of 97– 100 pcf, and the average interface friction angle was 39^{o} for a unit weight of soil of 107 pcf. This study reported an adhesion of zero.

Table 5(a) Interface shear strength of tire shreds with soils

Reference	Tire Shred Size (inch)	Soil			C_a(psf) and δ
		Type	Dry Unit Weight (pcf)	Moisture Content (%)	
Foose, 1993 Foose et al., 1996	2,4,6	Portage Sand	97-100	Dry	C_a= 0, δ= 34^{o}
	2,4,6	Portage Sand	107	Dry	C_a= 0, δ= 39^{o}
Gebhardt, 1997 (Peak failure criterion)	1.5-55.2	Glacial Till	92	8	C_a= 12.5, δ=39^{o}
Gebhardt, 1997 (10% failure criterion)	1.5-55.2	Glacial Till	92	8	C_a=0, δ=37^{o}
Gebhardt, 1997 (Peak failure criterion)	1.5-55.2	Glacial Till	92	18-22	C_a=43.8, δ=33^{o}
Gebhardt, 1997 (10% failure criterion)	1.5-55.2	Glacial Till	92	18-22	C_a=14.6, δ=33^{o}

Gebhardt (1997) investigated the interface shear strength of large tire shreds (1.5 inches to 55.2 inches in size) in contact with glacial till (a clayey soil). Direct shear tests were conducted under five different normal loading conditions with the soil at moisture contents that were dry and wet of optimum (Table 5a). Moreover, two different failure criteria of maximum stress and 10% failure were considered. For the failure criterion defined at maximum shear stress, a friction angle of 39^{o} with adhesion of 12.5 psf was found for all tire shreds with the soil at dry of optimum condition. However, for the same soil and tire shred conditions, but using the 10% failure criterion, a friction angle of 37^{o} with zero adhesion was found.

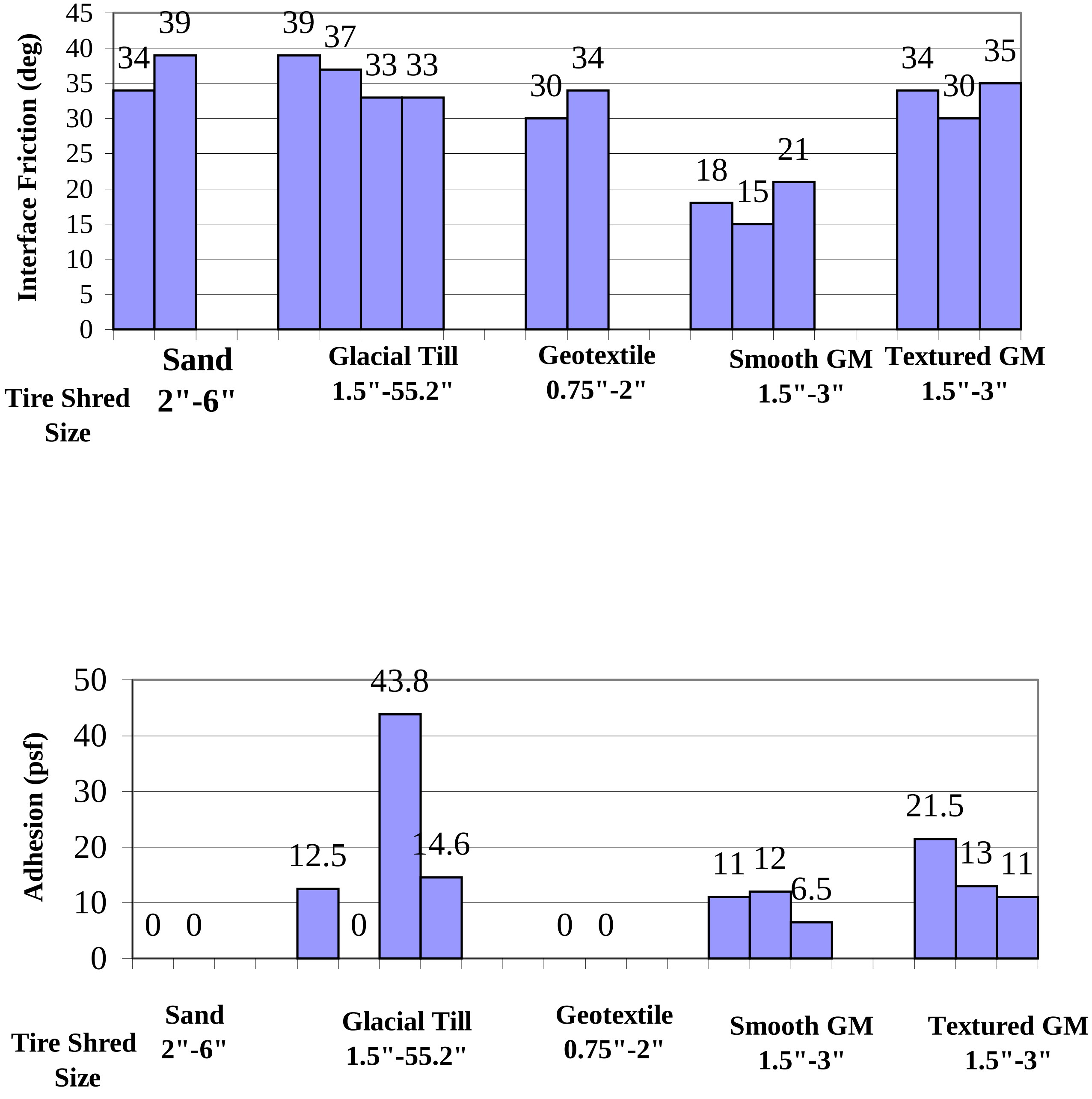

Figure 5 Interface shear strength of tire shreds based on reported studies

For the wet of optimum soil conditions, the same friction angle of 33 ° was found for both failure criteria (maximum stress and 10% failure); however, adhesion values of 44 psf and 15 psf were found using the maximum shear stress and the 10% failure criteria, respectively.

Table 5(b) Interface shear strength of tire shreds with geosynthetics

Reference	Tire Shred Size (inch)	Material	Test Condition	C_a (psf) and δ
Cosgrove, 1995	1.5	Textured GM	Dry	C_a=21.5, δ=34°
	1.5	Smooth GM	Dry	C_a=11, δ=18°
	1.5	Textured GM	Saturated	C_a =13, δ=30°
	1.5	Smooth GM	Saturated	C_a =12, δ=15°
	3	Textured GM	Saturated	C_a =11, δ=35°
	3	Smooth GM	Saturated	C_a =6.5, δ=21°
Bernal et al., 1996	<2	Woven Geotextile	-	C_a =0, δ= 30°
Andrews and Guay, 1996	<2	Geotextile	Max. normal stress=600 psf	C_a =0, δ= 34°
		Textured GM		C_a =0, δ= 34°

Cosgrove (1995) conducted interface shear strength tests between tire shreds and different geomembranes (smooth and textured) under three normal stresses simulating landfill cover conditions. Tests were conducted using both 1.5 inch and 3 inch size tire shreds and under dry as well as saturated conditions. The interface shear strengths under saturated conditions were less than the interface strengths under dry conditions, and the interface friction angle was higher for a textured geomembrane than a smooth geomembrane. Larger size tire shreds exhibited a higher interface shear strength. This study showed that the interface friction values range from 18° to 35° and the adhesion values range from 6.5 to 21.5 psf. Andrews and Guay (1996) reported an interface friction angle of 34° for a 2 inch tire shred and textured geomembrane.

Bernal et al. (1996) and Andrews and Guay (1976) performed interface shear strength tests for the tire shred and geotextile interface, and found the interface friction angle to range from 30° to 34° for tire shreds less than 2 inches in size.

Based on the reported studies, the most critical interface is the tire shreds and the smooth geomembrane, especially for saturated conditions and small tire shred sizes. However, all potential interfaces and conditions in a landfill cover system must be evaluated in order to determine slope stability during and after construction.

Summary and Conclusion

Table 6 presents a statistical summary of unit weight, hydraulic conductivity, compressibility, shear strength, and interface shear strength of shredded tires under the typical conditions expected in a landfill cover system. Based on the statistical analysis of the reported results, the shredded scrap tires exhibit the following properties: unit weight is 36.3 ± 7.6 pcf, hydraulic conductivity is 6.8 ± 12.8 cm/sec, compressibility is 37.3± 11.1%, cohesion is 255 ± 284 psf, and internal friction angle is 33.7° ± 15°. The interface friction angle value of tire shreds with soil is 35.8° ± 2.9°, with a smooth geomembrane it is 18° ± 3°, with a textured geomembrane it is 33° ± 2.6°, and with a geotextile it is 32° ± 2.8°. Adhesion values for the interfaces are generally low and range widely, and they may be assumed to be zero in most designs in order to be conservative. The discrepancy between the values within a particular parameter can be attributed to the differences in the testing procedures adopted and due to the different material characteristics of the scrap tires that were used.

Table 6 Statistical representation of tire shred properties

Property		Units	Minimum	Maximum	Mean	Standard Deviation
Unit Weight		pcf	15.3	53	36.3	7.6
Hydraulic Conductivity*		cm/s	0.01	59.3	6.8	12.6
Shear Strength*	C	psf	0	818	255	284
	ϕ	degree	14	85	33.7	15
Compressibility		%	18	65	37.3	11.1
Interface Shear Strength with Soils	C_a	psf	0	43.8	17.5	17.9
	δ	degree	33	39	35.8	2.9
Interface Shear Strength with Geotextile	C_a	psf	0	0	0	0
	δ	degree	30	34	32	2.82
Interface Shear Strength with Smooth Geomembrane	C_a	psf	6.5	12	9.8	2.9
	δ	degree	15	21	18	3.0
Interface Shear Strength with Textured Geomembrane	C_a	psf	11	21.5	15.2	5.6
	δ	degree	30	35	33	2.6

*Masad et al. (1996) is not included.

In spite of the wide variation in engineering properties, shredded scrap tire properties meet or exceed the minimum requirements for a drainage material in landfill covers. The effect of the size of tire shred on the properties of shredded tires is not clear; however, the shred size ranging from 0.5 inches to 5.5 inches can possess satisfactory properties to serve as the drainage material in landfill covers. However, site-specific testing using the actual tire shreds is recommended to accurately determine the engineering properties and to design an effective and inexpensive tire shred drainage layer for a landfill cover system.

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