Beneficial Use of Shredded Tires as Drainage Material in Cover Systems for Abandoned Landfills

Krishna R. Reddy[1]; Timothy D. Stark[2]; and Aravind Marella[3]

Abstract: Over 280 million tires are discarded each year and over 4 billion tires are stockpiled at numerous locations in the United States. The stockpiled tires represent a public health hazard, an aesthetic nuisance, and waste of a valuable resource. Recently, attention has been given to the use of scrap tires for civil engineering applications such as highway embankments, retaining structures, and lightweight fill material. This paper presents the results of a research study performed to assess the feasibility of using shredded scrap tires as a drainage material in cover systems for abandoned landfills. The research study included extensive laboratory testing and field demonstration at an abandoned landfill in Carlinville, Ill. Laboratory testing was conducted using tire shreds to determine the following: (1) potential for clogging when used in the cover systems; (2) long-term transmissivity when used in cover systems; and (3) interface shear strengths with various other cover materials. Slope stability analyses were performed to determine the stability of final covers incorporating shredded tires as drainage layers. A field demonstration was performed to determine the constructability and assess the performance of tire shreds as a drainage material in the landfill final cover as compared to that of a conventional drainage layer consisting of sand. Overall, the results showed that shredded tires possess the required characteristics and perform well as drainage material. Using shredded tires as a drainage material is a practical solution to scrap tire disposal problems and also for constructing cost-effective final covers for abandoned landfills.

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Introduction

Over 280 million used automobile, truck, and specialty tires are discarded each year nationwide. The state of Illinois alone contributes approximately 12 million scrap tires each year to this figure. Disposal of whole tires in landfills was the common practice for many years. However, whole tires tend to "float" to the surface, breaking the landfill cover and causing increased leachate production, which can contaminate groundwater. Because of this, many states have banned the disposal of whole tires in landfills. The state of Illinois requires tires to be shredded before being placed in landfills. This requirement has caused an increase in scrap tire stockpiling. Currently, 2 to 4 billion tires are stockpiled nationwide and approximately 40 to 50 million scrap tires are stockpiled at numerous locations in Illinois [Illinois Department of Energy and Natural Resources (IDENR) 1994]. These stockpiled tires represent a public health hazard, an aesthetic nuisance, and waste of a valuable resource. A scrap tire stockpile or dump provides an ideal breeding ground for mosquitoes, rats, and other disease-carrying vermin. Mosquito-borne diseases associated with the stockpiling of scrap tires cost approximately $5.5 million per year. Scrap tire stockpiles can self-ignite, which has detrimental effects on air quality, groundwater quality, and public health due to liquid and gaseous emissions produced by burning tires. The annual cost of extinguishing such fires exceeds $2 million.

The best way to reduce the environmental and health hazards associated with used and waste tires is to minimize, and ultimately eliminate stockpiling. Numerous studies have been conducted to investigate and develop alternative methods to landfilling and stockpiling, such as using shredded tires for tire-derived fuel (TDF), the creation of barrier reefs, and crumb rubber asphalt surfaces. Of these, TDF appears to consume the largest quantity of tires in Illinois as well as nationwide. However, such usage has a number of limitations, including: (1) the need to shred tires into small, uniform chips (usually less than 5 cm × 5 cm), which results in high processing costs; (2) a marginal cost advantage as compared to other competing fuels such as coal; (3) the need for major environmental permit modifications to burn tires; (4) high costs of conducting permit required tests for compliance; (5) reliability of supply in remote locations; (6) transportation costs for remote locations; and (7) local community opposition to tire burning. Other uses of shredded tires include retreading, pyrolysis, rubber-modified asphalt, and

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molded rubber products; however, these applications currently consume a very small amount of the stockpile. In addition, or as an alternative to TDF, the State of Illinois is searching for other beneficial uses for waste tires. The state is seeking to develop additional statewide, large-scale, and cost-effective uses for large size (greater than 10 cm) tire shreds (TS). The larger the TS, the lower the processing cost and the more viable the recycling option.

Large-scale uses for shredded tires have been identified by several researchers for civil engineering applications, such as highway embankments, pavements, retaining structures, and lightweight fill material (e.g., Ahmed and Lovell 1993; ASTM 1998a,b; Bernal et al. 1996; Bressette 1984; Cecich et al. 1996; Edil and Bosscher 1992, 1994; Foose et al. 1996; Humphrey and Manion 1992; Humphrey and Sandford 1993; Humphrey et al. 1993; Masad et al. 1996; and Newcomb and Drescher 1994). This study proposes another use for shredded tires in civil engineering: employing them as drainage material in the design of waste containment facilities. The specific focus is to perform a comprehensive study involving both laboratory and field testing to investigate the feasibility of using shredded tires as a drainage material in cover systems for waste containment facilities.

The cover system of a landfill is designed to prevent infiltration of precipitation into the waste; promote good surface drainage; resist erosion; restrict landfill gas migration or enhance recovery; prevent animals, insects, and rodents from contact with the waste; minimize long-term maintenance; and protect human health and the environment (Daniel and Koerner 1992; U.S. Environmental Protection Agency 1994; Sharma and Reddy 2004). Generally, the cover system consists of several layers of different materials. The bottom-most layer that is in contact with the waste is called the gas collection layer. This layer allows easy movement of gas to collection areas, where it is removed. The next required layer is the barrier layer. This layer consists of compacted clay to produce very low hydraulic conductivity. Geomembranes and geosynthetic clay liners may also be used in some combination for the barrier layer. This layer minimizes the infiltration of precipitation into the waste and also prevents gas from escaping. The drainage layer, which overlies the barrier layer, is designed to remove rainwater so that it does not percolate into the waste. It also dissipates porewater/seepage pressures. This layer is required when there is a significant precipitation and/or slope stability concern. If rainwater is not drained, then a greater amount of hazardous leachate will result, which has the potential to break through the bottom liner system and contaminate the surrounding subsurface. Because a drainage layer has high hydraulic conductivity, it easily allows lateral drainage. Above the drainage layer is the protection layer, which must be constructed in a manner that does not allow burrowing animals or penetration by plant roots. This layer protects the barrier layer below and also stores water. The final layer is called the surface layer, which is needed to promote vegetative growth. This layer allows good surface drainage, prevents erosion, and promotes evapotranspiration. The protection layer and the surface layer can be made of the same clayey soil, often known as the cover soil layer. For abandoned landfills, a simple cover system consisting of a barrier (clay) layer, drainage layer, and final cover soil layer may be sufficient.

The drainage layer in cover systems is typically constructed from granular soil such as sand. However, shredded tires have the potential to serve as a replacement material for sand because they possess a higher hydraulic conductivity. This application has significant potential for using large quantities of shredded tires (160,493 to 395,061 tires per hectare) and providing economic advantages over conventionally used materials without compromising engineering performance (Reddy and Saichek 1998a,b). This application also has the potential for immediate field implementation as compared with other civil engineering applications, thus alleviating the growing problem of management and disposal of scrap tires in a timely fashion.

The specific objective of this study was to determine the feasibility of using shredded scrap tires as a drainage layer material in a landfill cover. Specifically, this study addressed the following: (1) evaluation of properties of TSs; (2) evaluation of the clogging potential of TSs under conditions that simulate final cover systems; (3) evaluation of the transmissivity of TSs in final cover systems; (4) evaluation of interface shear strengths and slope stability of TSs in final cover systems; and (5) construction and performance assessment of a landfill cover incorporating a shredded tire drainage layer.

Materials and Methods

Engineering Properties

Several studies have been performed to determine the properties of shredded scrap tires for various purposes. Different sizes of TSs have been used in these studies. Using larger TSs is cost-effective due to the lower cost of shredding operations. We performed an extensive literature review to assess the effect of TS size on engineering properties. Particular attention was paid to the properties of large-size TSs (larger than 10 cm), which we consider to be economical for 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. Although none of the reported studies investigated the effects of TS size on engineering properties, such as hydraulic conductivity, the studies and property values were helpful in evaluating the potential use of different size TSs as drainage material in landfill covers.

Clogging Potential Testing

The abandoned landfill cover systems consist of a cover soil layer, typically a clayey soil layer, overlying a drainage layer. Due to precipitation, there is infiltration of rainwater into the cover layer and the drainage layer allows for lateral drainage of the infiltrated rainwater. If a drainage layer is not provided, the rainwater eventually infiltrates the waste, causing excessive leachate production inside the landfill. In addition, the absence of a drainage layer may cause build-up of pore water pressures in the final cover system, leading to potential slope stability problems. The presence of a drainage layer in a final cover system reduces leachate generation and enhances slope stability.

Along with the infiltrating rainwater, soil particles from the clay soil cover layer may migrate into the TS drainage layer. Such migration of soil particles can clog the drainage layer, leading to inefficient drainage. In conventional drainage layers, where sand and/or gravel is used as drainage material, the initial porosity of these drainage materials is too small to allow significant migration of soil particles from the overlying cover soil layer. However, when TSs are used as drainage material, the porosity of the TSs is very high (approximately 60%), which results in the possibility for a greater amount of soil migration from the overlying cover soil layer. As a consequence, the shredded tire drainage layer may become significantly clogged and its drainage performance may

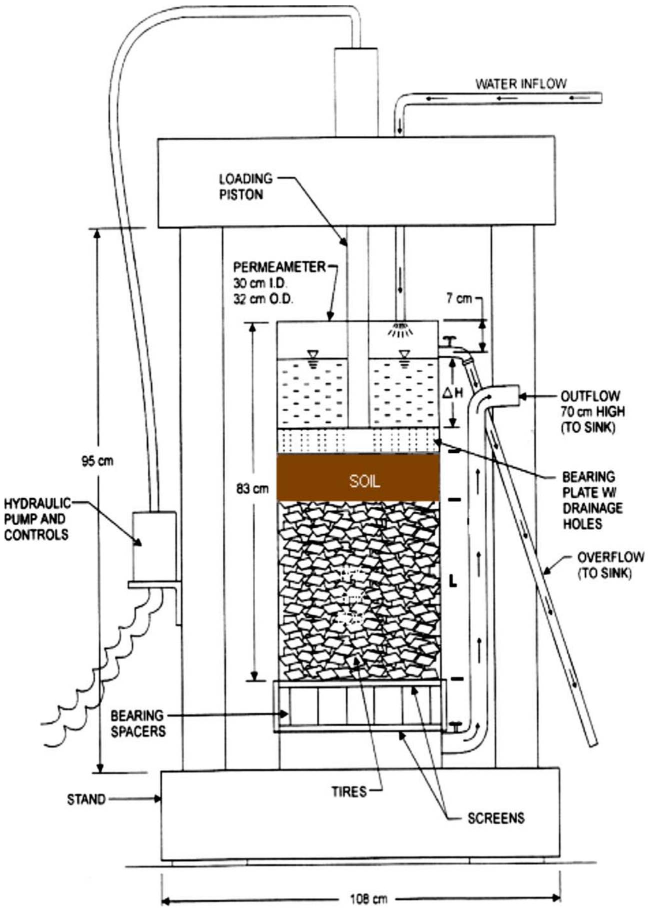


Fig. 1. Schematic of permeameter used to study clogging potential of TSs

be compromised. An experimental laboratory program was undertaken to assess the clogging potential of a shredded tire drainage layer in a landfill cover system.

A large-scale permeameter setup was used to simulate the shredded tire drainage layer and cover soil layer system and to study the clogging potential of TSs. Fig. 1 shows a schematic of this setup. The same permeameter setup was used in a previous study to determine hydraulic conductivity of TSs under different normal stresses (Reddy and Saichek 1998b). The permeameter was made of a rigid PVC cylindrical pipe of 30.5-cm diameter and 83-cm height. An inlet was constructed at the top of the permeameter to allow water inflow. Outlets with control valves were constructed at the top and bottom of the permeameter. The top outlet maintained a constant hydraulic head and was located at a height of 76 cm from the base of the permeameter. The bottom outlet consisted of two openings, 3.8- and 1.9-cm diameter, which were located at a height of 8.1 cm from the base of the permeameter. The purpose of the smaller opening was to measure low outflow volumes. A flow meter was connected to the bottom outlets to record outflow volume. A metal screen was placed at the bottom of the permeameter at a height of 11.43 cm from the base. The screen was supported on a set of bearing spacers that transferred the load uniformly onto the base. The screen was rigid enough to support the TSs, soil, and any additional applied normal stress. Adhesive plastic measuring tape was affixed to the inner wall of the permeameter to measure the depth of the TSs, the thickness of the soil layer, and the hydraulic head over the soil layer.

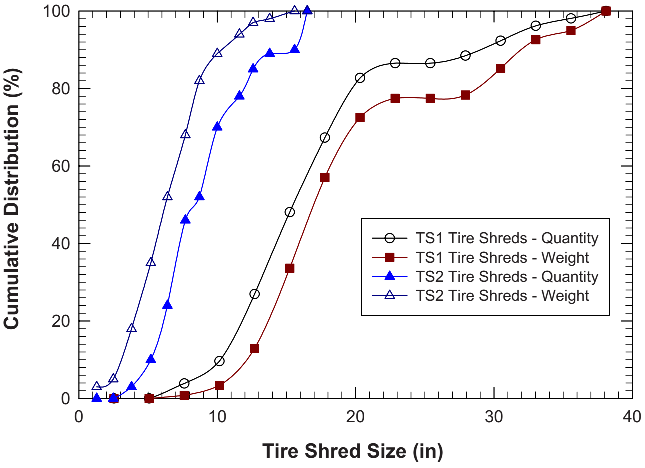


Fig. 2. Size distribution of TSs used in this study

Two different sizes of TSs, obtained from two different sources, were used in this study. These TSs were designated as TS-1 and TS-2 and were tested initially for their size distribution, unit weight, and hydraulic conductivity. A standard sieve analysis could not be performed to determine the size distribution of the tire chips present in the TSs. Instead, the TSs were characterized by randomly selecting samples from a TS pile. Approximately 10 kg of TSs were chosen per sample. The weight and maximum and minimum size of each individual tire chip in the TS sample were measured and recorded. Fig. 2 shows the tire chip size versus cumulative distribution by the individual chip quantity and weight. These measurements indicate that the tire chips TS-1 ranged in size from 1.3 to 22.9 cm with an average tire chip size of approximately 16.5 cm, whereas the size of the tire chips TS-2 ranged from 1.3 to 14.0 cm, with an average size of 7.6 cm. The unit weight of the TSs was determined by placing the TSs in a large cylindrical container and measuring their weight and volume. Using a specific gravity of 1.2 for TSs, the values of void ratio (e) and porosity (n) were calculated. The bulk densities of TS-1 and TS-2 were about 500 and 415 $\mathrm{kg/m^3}$, respectively, and the porosity for both TSs ranged from 50 to 60%. The hydraulic conductivity (K) of the TSs was determined by using the TSs alone in the permeameter shown in Fig. 1. The TSs were placed in the permeameter without any compaction. The initial thickness of the TS layer in the permeameter was 30.5 cm. Hydraulic conductivity was measured in stages under three different stress conditions: (1) 0 normal stress; (2) 5.7-kPa normal stress (30.5-cm soil layer equivalent); and (c) 11.5-kPa normal stress (61-cm soil layer equivalent). For TS-1, the results showed that the hydraulic conductivity of 2.27 and 1.83 cm/s and compression as 23 and 37% under normal stresses of 5.7 and 11.5 kPa, respectively. The results for TS-2 were reported by Reddy and Saicheck (1998a,b) and were found that the hydraulic conductivity of 2.15 cm/s under no normal stress to 1.0 cm/s under normal stress of 66 kPa. Compressibility increases and hydraulic conductivity decreases with an increase in normal pressure. The compression and resulting reduction in compression were higher for the large-size TSs. Both TS-1 and TS-2 possess higher hydraulic conductivity than the standard drainage materials of sand and gravel, making them better suited as drainage material in a landfill final cover system.

A silty clay soil obtained from the Carlinville Landfill in Carlinville, Illinois, was used as cover soil in this study. The soil consisted of 11% sand and 89% fines (<0.075 mm) and possessed hydraulic conductivity of 2.4×10^{-8} cm/s. A nonwoven

Table 1. Clogging Potential of TSs: Testing Program, Soil Infiltration, and Change in Hydraulic Conductivity

Test series	Average TS size (cm)	Cover soil layer thickness (cm)	Test number	Geotextile	Normal stress (kPa)	Cover soil infiltration (% by weight)	TS hydraulic conductivity ratio (final/initial)
I	16.5	7.6	1	None	5.7	27	0.75
			2	None	0	15	0.83
			3	$271\ \text{g/m}^2$	5.7	5	0.85
			4	$271\ \text{g/m}^2$	0	4.5	0.94
II	16.5	15.2	1	None	5.7	23	0.73
			2	None	0	14	0.78
			3	$271\ \text{g/m}^2$	5.7	2	0.76
			4	$271\ \text{g/m}^2$	0	4.8	0.99
III	8.9	7.6	1	None	5.7	25.3	0.79
			2	None	0	13.5	0.88
			3	$271\ \text{g/m}^2$	5.7	2.5	0.78
			4	$271\ \text{g/m}^2$	0	1.5	0.93

geotextile ($271\ \text{g/m}^2$) was used at the interface between the TSs and the cover soil layers in selected experiments to assess its role in minimizing clogging of the TSs.

Table 1 shows the details of the three different series of clogging simulation experiments (designated as Series I, II, and III) that were conducted. Approximately 8.0 kg of tire chips, which created a 30.5-cm thick TS layer, were weighed and placed in the permeameter. The tire chips were placed carefully to ensure that no large void(s) existed in the TS layer. No compaction effort was applied while placing the tire chips. The thickness of the shredded tire layer was measured.

The required amount of dry cover soil to yield a 7.6 or 15.2-cm thickness in the permeameter was weighed. Water was added to the soil so that the water content was equal to the optimum moisture content. The soil was mixed thoroughly until it became uniform in color without any clods. The soil was placed over the TSs in layers and was lightly tamped after each layer. For select experiments, a nonwoven geotextile was placed on top of the shredded tire layer before placing the soil layer. The geotextile was cut into a circular shape with a diameter slightly greater than that of the permeameter cell to avoid direct soil migration from the soil layer into the voids of the tire chip layer along the sides of the permeameter. The dry weight of the geotextile was measured prior to placement in the test setup. Where required, a normal stress of 5.7 kPa was applied to simulate a 30.5-cm thick overlying vegetative soil layer in a landfill cover system.

Water was introduced into the soil layer through the permeameter top inlet. The inflow rate was adjusted in such a way that it did not exceed flow in the outlet; thus a constant head was maintained in the setup during the experiment. The starting time of the experiment was noted. The outflow was collected at regular time intervals and the total outflow volume was recorded. Experiments were conducted generally for a total duration of 150 to 200 h.

At the end of each experiment, the inflow was stopped and the applied normal stress was removed. The soil layer was removed from the permeameter and was allowed to dry. Its dry weight was recorded. If present, the geotextile used at the soil and TS interface was also removed and dried and its dry weight was also recorded. The hydraulic conductivity of the TSs was then measured in the permeameter to assess the reduction in hydraulic conductivity due to the compression of TSs and clogging of TSs with soil. Finally, the TSs were removed from the permeameter and were air dried.

Transmissivity Testing

Transmissivity refers to the lateral drainage capacity, and this hydrologic property must be evaluated for TSs before they can be considered for use as the drainage layer in a landfill cover system. The transmissivity is measured in terms of the flow rate per unit cross sectional area. The main source of water that flows through the drainage layer is the water that infiltrates through the overlying cover soil layer from precipitation. Soil particles from the overlying cover soil layer may migrate along with the infiltrating water into the void spaces of the drainage layer, partially clogging the drainage layer. In addition, as a result of water draining in the lateral direction, soil erosion may occur from the soil layers on either side of the drainage layer; in the present study, this type of erosion was investigated.

A laboratory testing program was developed to assess the transmissivity of TSs, with and without the presence of a geotextile, and to study the migration of soil particles into the void spaces of the TSs from the soil layers above and below the drainage layer. Fig. 3 shows the schematic of the transmissivity test setup that was used in this study. The test setup consisted of a rectangular-shaped Plexiglas open-top box with the dimensions $61\ \text{cm} \times 25\ \text{cm} \times 35.6\ \text{cm}$ ($L \times W \times H$). This box had two open-

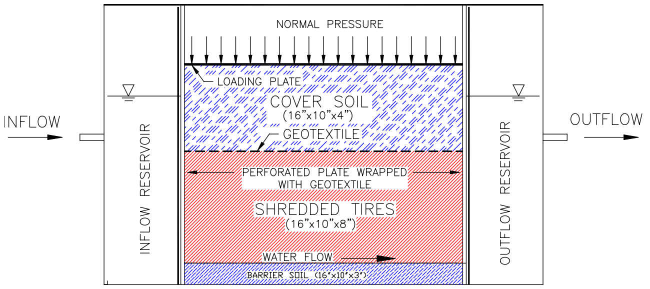


Fig. 3. Transmissivity testing apparatus

Table 2. Transmissivity of TSs: Testing Program and Soil Infiltration Results

Test series	Average TS size (cm)	Test number	Geotextile at the interface between TSs and top cover soil (g/m^2)	Geotextile at the interface between TSs and bottom barrier soil (g/m^2)	Normal stress (kPa)	Soil infiltration/erosion into TSs	
						From top cover soil layer (% weight)	From bottom barrier soil layer (% weight)
I	16.5	1	None	None	0	39.0	4.6
		2	None	271	0	28.7	12.5
		3	271	None	0	2.0	11.5
		4	271	271	0	8.3	9.7
II	16.5	1	None	None	5.7	27.0	1.0
		2	None	271	5.7	35.5	1.6
		3	271	None	5.7	4.4	3.3
		4	271	271	5.7	1.6	1.3
III	8.9	1	None	None	0	23.0	4.7
		2	None	271	0	22.0	1.7
		3	271	None	0	2.2	6.7
		4	271	271	0	1.0	2.3
IV	8.9	1	None	None	5.7	46.2	3.0
		2	None	271	5.7	37.0	1.0
		3	271	None	5.7	1.2	3.4
		4	271	271	5.7	2.8	5.0

ings, one inlet and one outlet, which were both connected to control valves. The two openings were located at a height of 20.3 cm from the base of the test setup. The box was divided into three compartments using two perforated plates that were wrapped with a geotextile and placed 40.6 cm apart. These plates were used as screens to prevent soil from eroding into the inflow and outflow reservoirs and to retain the simulated landfill cover system. The simulated landfill cover system was located in the center compartment. Various configurations were selected for the different experiments with the cover soil layer and the barrier soil layer placed above and below the TS drainage layer. The inlet valve was connected to a water source that provided a constant inflow rate, and the outflow volume was measured at regular time intervals.

The same two types of TSs (TS-1 and T-S2), silty clay soil, and nonwoven geotextile used in the clog experiments were also used in transmissivity testing. Four series of experiments (designated as Series I, II, III, and IV) were conducted to assess the effects of soil erosion from the cover and/or barrier soil layers on the transmissivity of the TSs. Each test series consisted of four separate tests with the variables shown in Table 2.

Initially, the transmissivity test apparatus was placed on a level surface. The inlet was then connected to a constant water supply source using flexible PVC tubing. Another flexible PVC tube was used to connect the outlet control valve to a drain. The amount of soil required to create a 7.6-cm thick barrier soil layer in the test setup was calculated. The soil was then measured and subsequently mixed with water to result in the optimum moisture content. The moist soil was then placed in small layers in the center compartment and each layer was tamped lightly until the layer thickness was 7.6 cm. In select experiments, a geotextile was placed over the barrier soil layer. The dry weight of the geotextile was measured before placing it in the test setup.

Approximately seven kg of TSs, an amount sufficient to create

Table 3. Summary of Engineering Properties of TSs Based on Published Literature

Property		Units	Minimum	Maximum	Mean	Standard deviation
Unit weight		kN/m^3	2.43	8.40	5.75	1.20
Hydraulic conductivity		cm/s	0.01	59.3	6.8	12.6
Shear strength	C	kPa	0	39.2	12.21	13.6
	ϕ	degree	14	85	33.7	15
Compressibility		%	18	65	37.3	11.1
Interface shear strength with soils	C_a	kPa	0	2.1	0.8	0.85
	δ	degree	33	39	35.8	2.9
Interface shear strength with geotextile	C_a	kPa	0	0	0	0
	δ	degree	30	34	32	2.82
Interface shear strength with smooth geomembrane	C_a	kPa	0.31	0.57	0.47	0.14
	δ	degree	15	21	18	3.0
Interface shear strength with textured geomembrane	C_a	kPa	0.53	1.03	0.73	0.27
	δ	degree	30	35	33	2.6

Table 4. Chemical Analysis of Outflow Samples

	Sampling date: November 2001		Sampling date: October 2003	
Analyte	Sand section	Tires section	Sand section	Tires section
(a) Metals per SW 6020 (mg/L)				
Aluminum	<0.004	<0.004	0.25	1.5
Antimony	<0.012	<0.024	<0.012	<0.024
Arsenic	<0.004	<0.004	<0.004	0.031
Barium	<0.004	<0.004	0.029	1.3
Beryllium	<0.002	<0.004	<0.002	<0.004
Cadmium	<0.002	<0.004	<0.002	<0.004
Calcium	72	4.4	92	190
Chromium	<0.004	<0.008	<0.004	<0.008
Cobalt	<0.004	<0.008	<0.004	0.0099
Copper	<0.004	<0.008	0.068	0.91
Iron	0.31	<0.1	2.2	400
Lead	0.031	0.011	0.007	0.34
Magnesium	42	93	62	83
Manganese	<0.02	<0.02	0.11	1.8
Mercury	<0.00025	<0.00025	<0.00025	<0.00025
Nickel	<0.004	<0.004	<0.004	0.017
Potassium	3.7	6.9	7.9	5.1
Selenium	<0.004	<0.008	<0.004	<0.008
Silver	<0.004	<0.008	<0.004	<0.008
Sodium	18	52	26	31
Thallium	<0.004	<0.008	<0.004	<0.008
Vanadium	<0.004	<0.008	<0.004	<0.008
Zinc	0.061	<0.02	<0.02	1.8
(b) Organic compounds per SW8260B and SW8270				
VOCs and SVOCs were not detected in all samples tested.				

a 20.3-cm thick TS layer, were placed randomly over the bottom layer without compaction. Depending on the testing conditions (Table 4), a geotextile was then weighed and placed over the TS layer. Finally, a 7.6-cm thick cover soil layer was placed over the TS layer in the same manner that was used for the barrier soil layer.

After the simulated landfill cover system was configured, water was allowed to enter through the inflow reservoir and the starting time of the experiment was recorded. The water level in the inflow reservoir was maintained at 30.5 cm from the base of the test apparatus. The 30.5-cm water level was provided to saturate the bottom soil layer, the drainage layer, and the bottom half of the cover soil layer. This water level was used to simulate a high amount of infiltration from precipitation and the worst-case scenario erosion conditions for the cover soil layer. The outflow from the outflow reservoir was measured periodically. The measured outflow volume in a specified time period was used to calculate the flow rate. At the end of the experiment, the top cover soil layer was removed and dried. The dry weight of the layer was measured. The geotextile, if used, was also removed, dried, and weighed. The TSs from the drainage layer were then removed and dried as was the soil and/or geotextile from the bottom layer. The dry weights of the individual components were used to calculate the amount of soil erosion that occurred and to determine the amount of soil that clogged in the geotextile interstices.

Interface Shear Testing

One of the major concerns in using shredded tires to replace granular drainage layers in abandoned landfill final cover systems is the stability of the final slopes. In order to evaluate slope stability, interface shear strengths for the materials involved must be known (Stark and Poeppel 1994; Stark et al. 1996; Reddy et al. 1996). A laboratory interface shear testing program was developed to quantify the shear resistance along the various interfaces that are generally present in an abandoned landfill final cover system that utilizes shredded tires as the drainage layer above the barrier layer, i.e., a compacted soil liner. The interface shear strength properties of the various materials involved in a shredded tire final cover system were measured using a 30.5 cm × 30.5 cm direct shear device (ASTM 1998b). In particular, 30.5 cm × 30.5 cm direct shear tests were conducted on the following interfaces: (1) nonwoven filter geotextile/shredded tires; (2) shredded tires/soil; and (3) nonwoven filter geotextile/soil. The materials were prepared and placed in the direct shear apparatus using methods similar to their installation in the field. The tests were conducted at effective normal stresses (σ_n') of 4.8 and 19.2 kPa to simulate the field normal stress applied to a landfill final cover system. The normal stresses were generated using dead weights placed on top of the direct shear box. All three interfaces were sheared at a shear displacement rate of 0.036 cm/min. The direct shear apparatus used for the testing allowed a total of 7.6 to 10.2 cm of shear displacement before the test was stopped. All of the direct shear tests were performed using a computer-controlled electric motor to control the shear displacement rate while the induced shear stress was measured electronically with a load cell. For the tests involving shredded tires, each normal stress was applied twice to ensure that the variability in the measured shear stress caused by the arrangement and size of the TSs was repeatable and that the strength parameters were not an anomaly.

For the nonwoven geotextile/shredded tire interface, the shredded tires were placed in the bottom or lower container of the direct shear device [see Fig. 4(a)] and the geotextile was anchored to the upper confining ring of the device. Because of the large size of the shredded tires obtained from the Carlinville site, it was anticipated that the arrangement of the TSs in the direct shear device would influence the measured shear strength. The shredded tire specimen in the lower container has dimensions of 30.5 cm × 35.6 cm × 7.6 cm deep, and the dimensions of the TSs ranged from 1.0 to 15.2 cm across. The standard test method for interface testing (ASTM 1998b) does not present any specification for placement of shredded tires in the direct shear device. As a result, it was determined that the TSs would be placed by hand in a pseudorandom fashion [see Fig. 4(b)]. The TSs were placed in the lower container from the bottom to the top in a manner to avoid creating a layered system. Fig. 4 depicts the shredded tire/soil interface test, and the TSs are in the upper confining ring.

Because a significant portion of the measured interface shear strength was likely to be generated by the jagged edges of the TSs and the steel reinforcing strands protruding from many of the TSs, care was taken to create a level surface at the top of the lower container. A level surface was desired so the TSs would settle uniformly under the applied normal stress and to create an even distribution of tire faces and tire edges in contact with the geotextile [see Fig. 4(b)]. TSs larger than approximately 7.6 cm across were too large to fit in the apparatus and were not included in the test specimen.

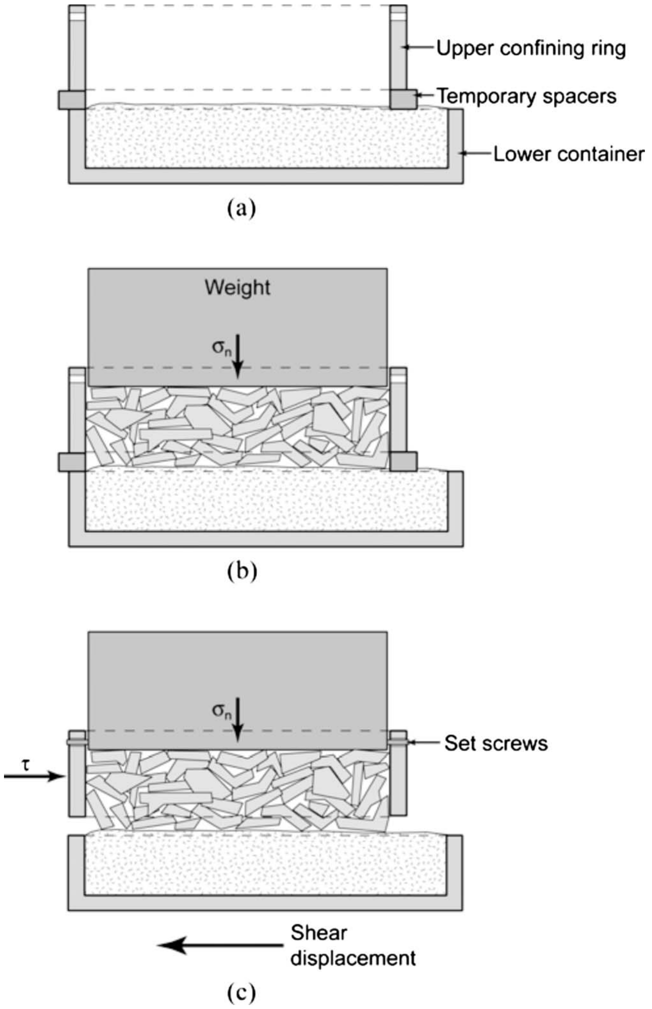


Fig. 4. Schematic of direct shear device showing setup (a) before placement of tires; (b) after placement of tires and application of normal stress; and (c) final testing configuration after removal of temporary spacers

The nonwoven geotextile was secured to the 30.5 cm ×30.5 cm upper portion of the direct shear device using glue and clamps. Aerosol glue was used to fasten the geotextile to a rigid acrylic plate that fits in the upper confining ring and was allowed to dry for 12 h at a normal stress of 4.8 kPa. Care was taken to leave approximately 1.3 to 2.5 cm of geotextile hanging over the sides and back of the acrylic plate to prevent fibers from tearing out of the edge of the geotextile during shearing. The acrylic plate was then clamped into the upper confining ring using set screws [see Fig. 4(c)]. Several inches of material were left overhanging at the leading edge of the geotextile specimen and clamped tightly in place to the outside of the confining ring to prevent the leading edge of the geotextile from peeling or tearing away from the acrylic backing during the test. The calendared surface of the geotextile was placed against the tires in the lower container because the same configuration was used at the Carlinville Landfill; therefore this arrangement simulates the field condition.

For the shredded tires/soil interface, the soil was placed in the lower portion of the device. Because soil placement at abandoned landfills often does not adhere to a set of compaction specifications, the soil was tested under similar field conditions. In other words, no additional moisture was added to the soil. To simulate the field condition, a few large clumps or clods of soil were included in the lower container. Any gaps between the clumps were filled with finer soil obtained from the bottom of the sample buckets. The soil was not densified after it was placed in the lower container. The soil was placed in the lower container by pouring it in and grading it by hand to create a level surface for shearing. The soil was placed approximately 0.64 cm higher than the upper rim of the lower container to keep the tires or geotextile from potentially settling into the lower container and being forced against the walls during shearing [see Fig. 4(c)]. Because there may have been some voids between the tires and soil and no densification of the soil occurred, the measured interface strengths probably represent a lower bound interface strength.

The TSs were placed in the upper portion of the direct shear box for the shredded tire/soil interface test [see Fig. 4(b)]. To ensure that all of the weight from the normal stress was carried through the tires into the soil instead of through the contact between the upper confining ring and the lower container of the direct shear box, steps were taken to support the upper confining ring while the tires were placed in the box and the normal load was applied. To accomplish this, spacers were placed between the upper confining ring and the lower container to hold them approximately 1.9 cm apart while the tires were placed. The tires were then placed in the upper confining ring in the manner previously described. This placement involved ensuring that the normal stress would be uniform and that there was a good distribution of tire faces and edges in contact with the underlying soil. The normal load was then applied and the upper confining ring fastened to the load with set screws [see Fig. 4(b)]. After the application of normal stress, the spacers between the upper portion and the lower container were removed. After removal of the spacers between the upper confining ring and the lower container of the direct shear box, the entire normal load was carried by the shredded tires [see Fig. 4(c)]. In addition, it was verified that the upper and lower containers of the direct shear apparatus were not in contact, which would produce friction and an exaggerated estimate of the interface strength.

For the nonwoven geotextile/soil tests, both materials were prepared as described previously. The soil was placed in the bottom container of the direct shear box and the nonwoven geotextile glued to an acrylic plate in the top part of the direct shear box. Soil was placed slightly higher than the upper rim of the lower container to ensure that the acrylic plate and the geotextile did not enter the lower container during shearing.

Field Demonstration

Following the laboratory research, a field demonstration project was undertaken to evaluate the performance of TSs as a drainage material in landfill cover systems under actual field conditions. An abandoned municipal solid waste landfill located in Carlinville, Ill., was selected for the field demonstration. This landfill was improperly closed by the operator and owner with a nonengineered cover over the waste. The constructed cover was not properly maintained, which lead to abandonment of the landfill. The interim cover was subjected to weathering, which lead to massive erosion and ponding and resulted in the waste being exposed in some locations. Due to the ineffective cover, a significant percolation of rainwater into the landfill was expected, increasing the potential for significant leachate production. The emission of landfill gases at various locations was also observed. In order to protect public health and the environment, the Illinois Environmental Protection Agency (IEPA) undertook remedial action at the site. They performed site investigations and improvements that included the entire landfill area with the site's clayey soil and installation of gas collection vents.

With the collaboration of the IEPA and the Illinois Department of Commerce and Community Affairs, the possible use of TSs as drainage material in a landfill cover system was investigated at this landfill site. Although the total area of the Carlinville landfill is about 10 ha, only 0.8 ha were selected for the demonstration project. The chosen area was divided into two sections. In the first 0.6-ha section, TSs were used as the drainage material, and in the other 0.2-ha section sand was used as the drainage material.

Two different cover designs were developed for the two sections of the demonstration area. In the first section, TSs were used as the drainage material. The cover design in this section included a 61-cm thick barrier layer of compacted clay in immediate contact with the waste, followed by a drainage layer of 30.5 cm of TSs covered with a geotextile, and a 61-cm thick vegetative cover layer over the drainage layer. The cover design in the second section was similar to that of the first cover system except that sand was used as the drainage material. A geotextile filter was used between the drainage layer and the cover soil layer to limit clogging and enhance transmissivity of the drainage layer. The sections were constructed to allow side-by-side comparison of drainage performance of cover systems using TSs as the drainage material with conventional drainage material. The intention in designing the 61-cm thick vegetative cover layer or the protection layer was to meet requirements that are essential for the stability of the landfill cover system incorporating TSs as the drainage material. These requirements include (1) compensating for the compressibility of the TSs, which may create cracks in the surface layer and (2) limiting organic matter from entering the TSs.

In the larger section, TSs were used as a drainage material. The waste tires used for this investigation were obtained from an illegal stockpile in the southern part of Illinois near the landfill. The shredding of the waste tires was done at a penitentiary near the same location. The TSs were then hauled to the landfill site. These TSs were the same as those designated as TS-1. In the smaller test section, sand was used as the drainage material. Laboratory testing was conducted to determine the grain size, distribution, unit weight, specific gravity, hydraulic conductivity, and shear strength. These results show that the sand is poorly graded with 5% fines. The soil used to construct the vegetative cover soil layer over the drainage layer was the same for both TS and sand sections. A sample of soil from the Carlinville landfill was collected and tested in the laboratory. This is the same silty clay soil used in clogging and transmissivity tests. The same nonwoven geotextile used in clogging and transmissivity experiments was used at the interface of the drainage layer and the cover soil layer for both the TS and the sand section.

The construction of the final cover consisted of the following phases: (1) repair and/or construction of the barrier soil layer; (2) construction of the drainage layer; (3) placement of the geotextile; and (4) construction of the vegetative cover soil layer. A nonengineered soil layer existed over the waste prior to the experiment. However, the soil had eroded in many areas due to weather and improper maintenance. It some areas, soil erosion was so deep that waste beneath the final cover was exposed. In places where the soil thickness was not adequate, the on-site soil was conditioned and compacted. This formed the barrier soil layer. In the TS section, TSs were placed randomly over the barrier layer. They were placed and spread to create a 0.3-m thick drainage layer. Sand was placed in the alternate area. During the placement of the drainage material in both sections, slotted pipes were placed at the toe of the test sections and were then connected to outflow pipes. The TS section and sand section were hydraulically separated by constructing a clay berm between them. The drainage layer was then leveled. Standard construction equipment and procedures were found to be adequate to construct both the sand drainage layer as well as the TS drainage layer. The selected nonwoven geotextile was placed over the drainage layer. Finally, a 60.5-cm thick vegetative cover soil layer was constructed over the drainage layer. The on-site soil was conditioned as needed and compacted.

The constructed cover was monitored periodically. During each site visit, the growth of vegetation was observed. Any signs of settlements and/or subsidence in the vegetative cover layer were also observed. Four flow meters were installed at the drainage pipe outlets to measure outflow. Of the four outlets, three outlets were located in the test section where TSs were used as the drainage layer. One flow meter was installed in the sand section. The flow meter readings were noted during each field visit. The flow meters were protected from rodents and any debris by placing steel mesh and geotextile at the outlet. Plastic buckets were connected to the PVC pipes outlets to measure low outflow and to collect representative outflow samples for quality analyses. The samples of outflow collected in the buckets were transferred into glass jars and transported to the laboratory for analyses.

Results and Discussions

Shredded Tire Properties

Table 3 presents a statistical summary of unit weight, hydraulic conductivity, compressibility, shear strength, and interface shear strength of shredded tires based on a comprehensive literature review. The shredded scrap tires possess a wide range in properties with unit weight 1.73 ± 0.4 kPa, hydraulic conductivity 6.8 ± 12.8 cm/s, compressibility $37.3 \pm 11.1\%$, cohesion 12.21 ± 13.60 kPa, and internal friction angle $33.7° \pm 15°$. The interface friction angle value of TSs with soil was reported to be $35.8° \pm 2.9°$, with a smooth geomembrane it was $18° \pm 3°$, with a textured geomembrane it was $33° \pm 2.6°$, and with a geotextile it was $32° \pm 2.8°$. Adhesion values for the interfaces were generally low and ranged widely. They are conservatively assumed to be 0 in most designs. The wide range for each property may be attributed to the differences in the testing procedures adopted and to the different sizes of TSs used.

In spite of a wide variation in engineering properties, shredded scrap tire properties meet or exceed the minimum requirements to serve as a drainage material in landfill covers. The effect of the TS size on the properties of shredded tires is not clear; however, a shred size ranging from 1.3 to 14 cm possesses satisfactory properties to serve as the drainage material in landfill covers. Site-specific testing using actual TSs is recommended to accurately determine the engineering properties of the shreds and to design an effective and inexpensive TS drainage layer for a landfill cover system.

Clogging Potential

Table 1 summarizes the three series of experiments conducted to assess the effects of clogging in the TSs due to soil infiltration from the overlying cover soil layer on the hydraulic efficiency of the final cover system. The measured outflow rate with time, soil infiltration, and hydraulic conductivity data for all experiments

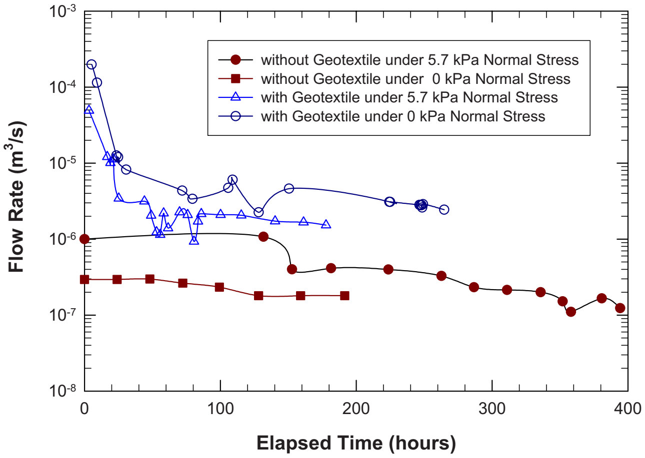


Fig. 5. Clogging Test Series I with TS1 TSs and 7.6-cm cover soil layer

for the Test Series I with TS1 are presented in Fig. 5 and Table 1. Similar results were obtained for Test Series II and III (Reddy and Saichek 2008). The flow rate in the critical test condition, i.e., Experiment 1 in all three series, was similar. The difference in the hydraulic head applied in Series I (16.5 cm) and II (7.6 cm) did not significantly affect the flow rate. The flow rate of the critical experiment in each series remained in the range of 2.83×10^{-6} to 2.83×10^{-8} m^3/s. The amount of soil infiltration, expressed by percentage of weight, was also almost the same (Table 1). Soil infiltration causes clogging of pores in TSs, which results in the reduction of hydraulic conductivity of the TSs. A reduction in hydraulic conductivity affects the drainage potential of the TSs to be used as a drainage layer for a landfill cover system. These results show that to maintain high hydraulic conductivity of TSs, a nonwoven geotextile should be installed above the shredded tire layer to reduce the migration of the soil into the TSs. A geotextile was not used in the critical test condition, i.e., Experiment 1 in all three test series, which resulted in higher soil migration into the TSs. The Series I and III experimental results were similar and thus TS size does not have a large impact on the drainage potential of the TSs. Both the Series I and III flow rate and percent soil infiltration results are comparable with the Series II results even though Series II had a thicker soil cover layer (15.2 cm versus 7.6 cm). The presence of a 15.2-cm soil layer provided less hydraulic head but more opportunity for permeation of soil into the TS layer.

The high hydraulic conductivity of the TSs even without a nonwoven geotextile is sufficient to accommodate the flow rate that is most likely to be encountered in a landfill final cover system (Table 1). However, soil migration from the cover soil to the TSs can cause clogging in the drainage layer. The test results show that inclusion of a nonwoven geotextile at the cover soil/TS interface will reduce the soil migration into the TSs.

Evaluation of Transmissivity

The transmissivity testing allowed an opportunity to examine the changes in lateral flow rate in the TSs with elapsed time due to soil infiltration and erosion. The soil infiltration of the TSs occurred from the upper soil layer, whereas the soil erosion occurred from both upper (cover) and lower (barrier) soil layers due to lateral flow in the drainage layer.

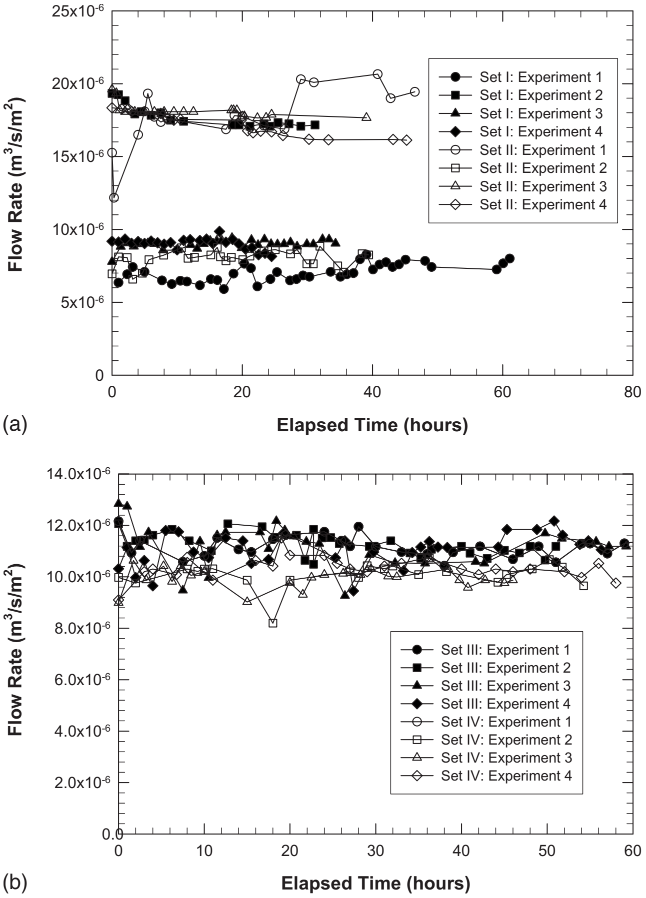


Fig. 6. (a) Transmissivity Test Series I and II with TS1 TSs; (b) transmissivity Test Series III and IV with TS2 TSs

Four series of experiments were conducted to measure the flow rate per unit area with elapsed time in the lateral direction of the tire drainage layer (Table 2). Adopting different conditions, four different experiments were performed in each test series. The experiments in Series I and II were conducted following the same testing procedure except a total normal stress of 5.7 kPa was applied to the cover soil in Series II. The application of a normal stress of 5.7 kPa simulated a 30.5-cm thick cover soil layer on the TSs as is common in a landfill cover system. A comparison of flow rates for Series I and II is shown in Fig. 6(a). The flow rate per unit area of cross section in Series I was greater than the flow rate per unit area of cross section in Series II. This difference is probably a result of no normal stress being applied in Series I, and the higher porosity of TSs results in a higher flow rate. Under a normal stress of 5.7 kPa, the TSs compress, reducing the porosity of the TSs and decreasing the flow rate.

The experiments in Series III and IV used similar procedures as adopted in Series I and II. However, the TS-2 TSs (7.6-cm average size versus 16.5-cm average size of TS-1) were used in these series. In Series IV a normal stress of 5.7 kPa was applied and no normal stress was applied in Series III. The flow rates of each experiment in Series III and IV are compared in Fig. 6(b), and these results show that there is little difference between the flow rates under the no normal stress condition and the 5.7-kPa normal stress condition. These results are different from those obtained using the larger TSs (TS-1) shown in Fig. 6(a). The similar flow rates obtained in Series III and IV may be attributed to the smaller size of TSs. Due to the smaller TS size, the compression of the TSs under the application of 5.7 kPa was not sufficient to cause a measurable difference in the flow rates.

Table 2 compares the soil infiltration in each experiment of each series. These results show that when a nonwoven geotextile was not used, extensive soil infiltration occurred. Providing a geotextile at the interface between the cover soil layer and the drainage layer reduced the soil erosion. When the geotextile was not provided at the interface of bottom soil layer and the TS drainage layer, the soil erosion did not appear to be significant. Despite the significant soil erosion and infiltration from the soil cover layer, the TSs performed as an effective drainage medium and allowed significant flow to occur. This behavior is attributed to the high initial porosity of the TSs and the soil clogging only partially reducing the TS porosity, which does not significantly reduce the flow. The experimental results show that the smaller size TSs (TS-2), in spite of their clogging potential, possess sufficient transmissivity to serve as an effective drainage material even without the use of a geotextile at the soil interfaces.

The transmissivity tests conducted during this study show that both TS sizes (TS-1 and TS-2) are appropriate for use as a drainage material in a landfill cover system. The transmissivity of the TSs under the expected normal stress conditions in cover systems will be high and approximately the same for either TS size. However, to reduce the potential for soil migration and erosion, and thus clogging of the drainage layer, it is recommended that a nonwoven geotextile filter be used at the top and bottom interfaces of the TS drainage layer. If only one geotextile is used, it is imperative that the geotextile filter be used at the interface between the cover soil and TS layers to reduce soil erosion and migration of the cover soil and to ensure adequate long-term transmissivity of the TSs.

Overall, the results from these experiments indicated that when the cover system was placed under an additional normal stress application, the larger size TSs compressed, reducing their porosity and the transmissivity. The compressive effects of normal stress, however, were reduced when the smaller size TSs were employed. It was evident from the results of all the experimental series that providing a geotextile at the interface between the cover soil layer and the drainage layer reduces soil infiltration and/or erosion. Furthermore, providing a geotextile at the interface between the drainage layer and the barrier cover soil was observed to be beneficial for protecting the barrier soil layer and reducing the intrusion of TSs. Overall, in spite of the significant soil erosion and some clogging, both sizes of the TSs performed as an effective drainage medium and allowed high transmissivity as a result of their high porosity. The soil only partially clogged and reduced TS porosity, and this reduction was not significant enough to reduce the flow. In summary, based on the experimental results and visual observations from all the transmissivity test series, it can be concluded that the use of shredded scrap tire as a drainage material in a landfill cover system would be efficient. The use of a geotextile at the top interface and the bottom interface of the shredded tire drainage layer irrespective of the thicknesses of different layers in the final cover system would be beneficial for drainage layer performance.

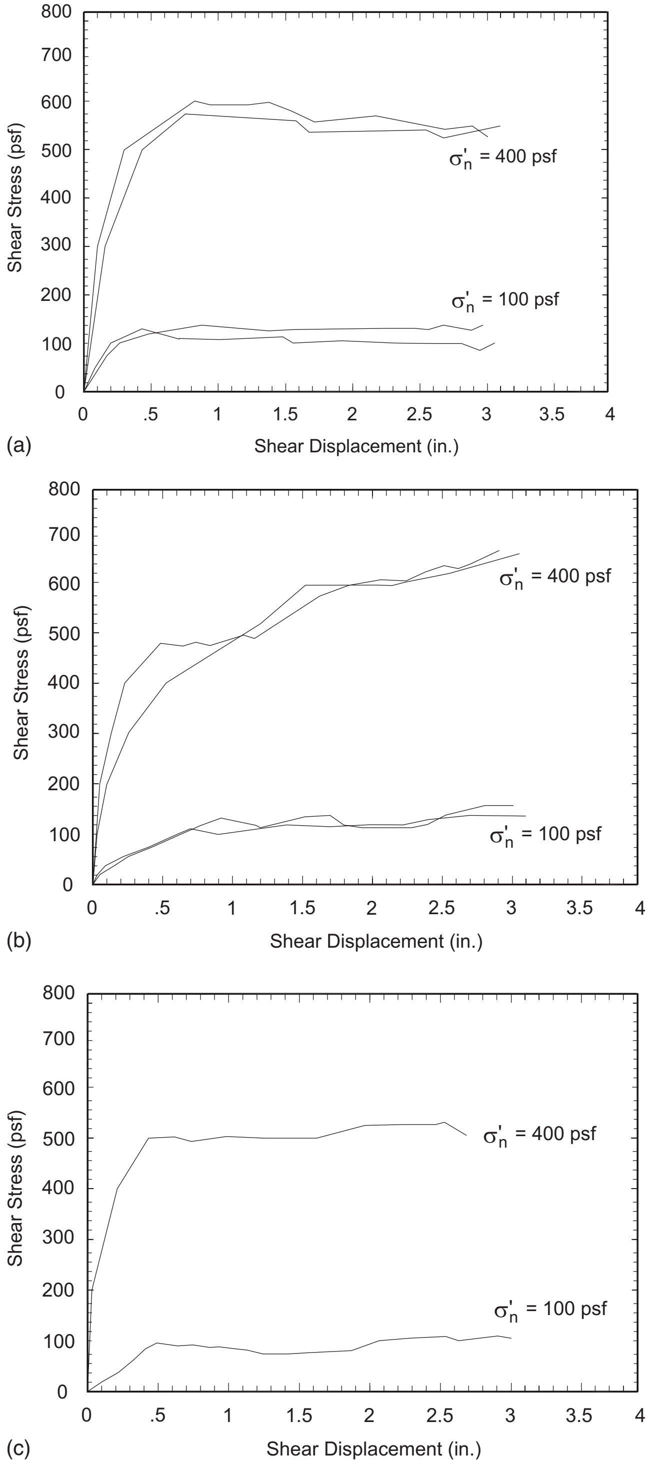


Fig. 7. (a) Shear stress versus displacement relationship for nonwoven geotextile/shredded tires interface; (b) shear stress versus displacement for shredded tires/soil interface; and (c) shear stress versus displacement relationships for soil/nonwoven geotextile interface

Interface Shear Test Results

The shear stress-displacement relationships for the nonwoven geotextile/shredded tire interface are shown in Fig. 7(a). The shear behavior at each normal stress is repeatable [see duplicate test results in Fig. 7(a)] and thus representative of the applicable interface strength. This interface exhibited the most repeatable results. The repeatability is attributed to the TSs being placed in the lower container as opposed to the upper container, which resulted in the tire interface being visible during placement of the TSs and a more consistent relative distribution of tire faces and edges. In the TSs/soil interface tests, the tire interface was placed face down against the soil and could not be inspected as thoroughly before shearing as with the TS/nonwoven geotextile inter-

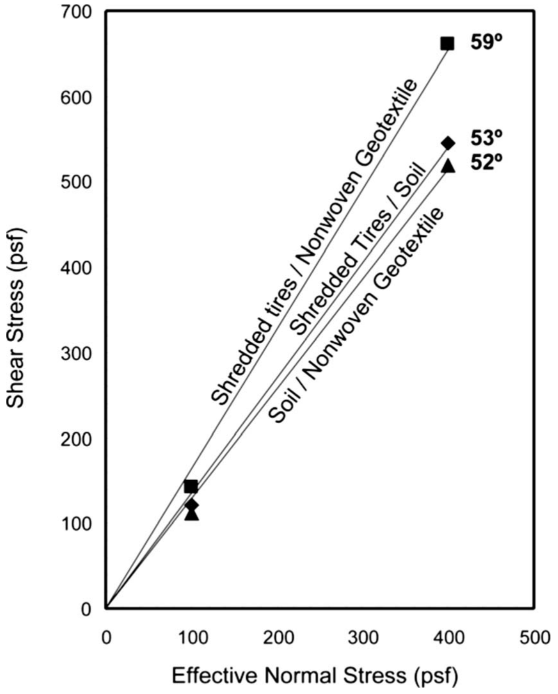


Fig. 8. Peak failure envelopes for the shredded tire drainage layer interfaces

face. The shear stress-displacement relationships for the shredded tires/soil interface are shown in Fig. 7(b). The figure shows that the measured shear stress is still increasing at a displacement of 7.6 cm for both tests using an effective normal stress of 19 kPa. This indicates that more shear strength may be mobilized if larger shear displacements are achieved in the field. The difference in the stress-displacement relationships in the 2.5 cm of shear displacement for the two tests at a normal stress of 19 kPa can be attributed to the differences in the initial arrangement of the TSs. The different arrangements had a lesser effect on the shear strength after the 2.5 cm of shear displacement.

Only one test was performed for each normal stress for the nonwoven geotextile/soil interface because neither material is as variable as the TSs and the results appeared to be representative [Fig. 7(c)]. The arrangement of the materials in the direct shear box forced the shear surface to develop at the nonwoven geotextile/soil interface. After shearing and dismantling the shear box, it was observed that little disturbance of the soil occurred during shearing and thus the geotextile was shearing across the top of the soil. If the internal shear strength of the soil is less than the shear strength of this interface, then it will control the stability in the field. This situation should not occur if some level of compaction is required for the soil.

It should be noted that the maximum shear displacement (7.6 to 10.2 cm) in the direct shear tests is the same order as the dimensions of the TSs. The shear strength measured in these tests does not take into account any strength gain or loss due to rearrangement of the TSs that may occur after larger shear displacements. Little or no settlement was observed in either the TS or the soil interface tests during shearing.

The effective stress failure envelope for each interface is plotted in Fig. 8. The shredded tire/nonwoven geotextile interface yielded the highest failure envelope and an effective stress friction angle of 59º. The shredded tire/soil and soil/nonwoven geotextile interface strengths were both slightly lower with friction angles of 53º and 52º, respectively. The friction angles were measured with a best-fit line through the origin and the data. These interface friction angles are significantly higher than those usually measured for geosynthetic interfaces typically found in geosynthetic landfill final cover systems (Hillman and Stark 2001).

The failure envelopes in Fig. 8 are applicable to a landfill final cover system and not a liner system. The applied normal stresses are much greater for a liner system, and the behavior of the TSs will be different because of the deformability and shape of the tires. The rubber tires are very flexible and the majority of the shreds are not flat. Even a TS with its face placed directly against the soil or geotextile surface, or against another TS, will have a relatively small area in contact with the interface due to its curvature. Increasing the normal stress flattens out many of the TSs, which puts more rubber in contact with the surface and increases the shearing resistance. The same is true, but to a lesser extent, with the soil/geotextile interface. The compacted soil included some larger lumps that were stiffer than the fine-grained matrix surrounding them. A higher normal stress would force these lumps down into the fine-grained matrix by a small amount, putting more geotextile in contact with the soil and increasing the shearing resistance. In summary, the failure in Fig. 8 should only be used for the design of a final cover system using shredded tires.

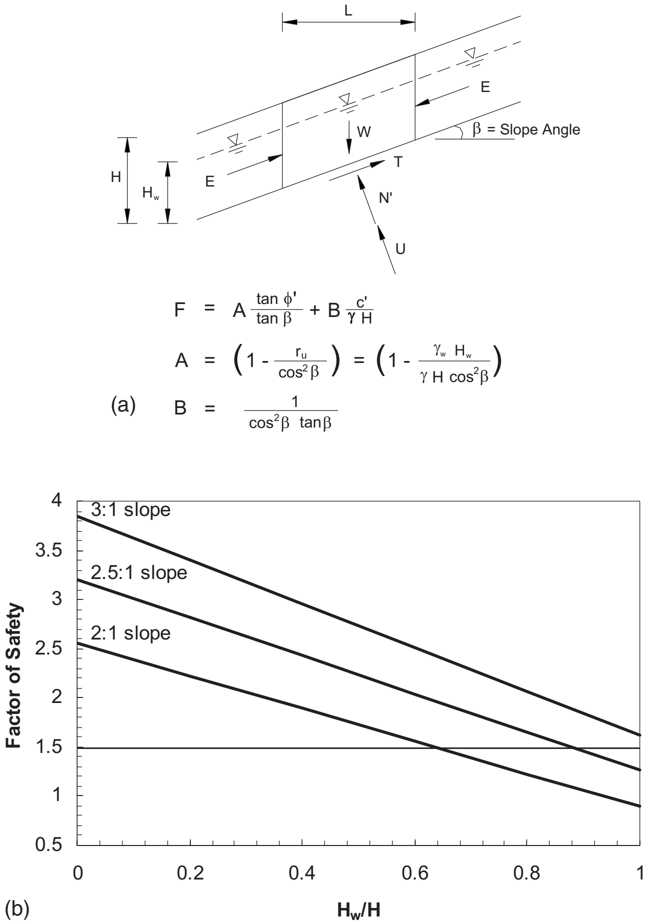
The results of the direct shear tests on these three interfaces are used in slope stability analyses to determine the conditions under which a shredded tire final cover system will be stable and to recommend construction procedures to ensure slope stability during and after final cover construction. The direct shear test results indicate that all of the interfaces are stronger than traditional landfill geosynthetic interfaces and thus the slope stability analyses show that a shredded final cover system will be stable on a $2H:1V$ slope even if the drainage layer were to become clogged. Typical landfill final cover systems are limited to a slope of $3H:1V$ to ensure slope stability because of the weak geosynthetic interfaces that are present in a geosynthetic final cover system.

Slope Stability Analyses

An infinite slope stability analysis is used to evaluate the stability of a landfill final cover system. This analysis assumes that the slide mass is thin and very long, the cross section stays constant, the slip surface is planar, and the effects of the passive and active forces at the ends of the slide mass are negligible in terms of slope stability. These assumptions are usually satisfied for landfill final cover systems.

Final cover systems are composed of multiple layers of materials with internal shear strengths and shear strengths at their interfaces. A typical final cover system for an abandoned landfill using shredded tires may have, from bottom to top, the waste, a soil barrier layer, a shredded tire drainage layer, a nonwoven filter geotextile to protect the shredded tires from the overlying soil, and a vegetative soil cover layer. The weakest component or interface of this layered system will control the stability of the final slope. Because the lowest interface strength measured in the series of direct shear tests conducted herein is 52º, i.e., the nonwoven geotextile/soil interface, this friction angle was used in the slope stability analyses. However, the internal strength of the compacted soil may be less than 52º and thus may be more critical depending on the compaction requirements.

Another important factor in the stability of a landfill cover system is the presence of water. Having water present in the



$$F = A\frac{\tan\phi'}{\tan\beta} + B\frac{c'}{\gamma H}$$

$$A = \left(1 - \frac{r_u}{\cos^2\beta}\right) = \left(1 - \frac{\gamma_w H_w}{\gamma H \cos^2\beta}\right)$$

$$B = \frac{1}{\cos^2\beta \ \tan\beta}$$

Fig. 9. (a) Infinite slope analysis for a landfill cover system; (b) results of infinite slope stability analyses for a landfill final cover system using shredded tires as the drainage layer

drainage layer decreases the effective stress at an interface, which decreases the forces resisting sliding while at the same time not decreasing the forces that cause sliding. Because abandoned landfill cover systems usually include a low-permeability compacted soil layer under the drainage layer, water infiltrating from the ground surface can pond on top of the compacted soil and accumulate. A drainage layer is used to carry this water quickly down and out of the slope to maintain the effective stresses in the final cover system. If the drainage layer clogs, the water level in the drainage layer can increase and, as a result, decrease the stability of the cover system. One of the main advantages of using TSs for the drainage layer is the large amount of flow volume present in a layer of shredded tires. As a result, it is difficult to clog a shredded tire layer and cause a decrease in slope stability.

Fig. 9(a) presents the infinite slope analysis used for landfill final cover systems, and the impact of water accumulating in the drainage layer can be seen. As H_w increases, A and the factor of safety decrease. Fig. 9(b) shows the calculated factor of safety for varying water levels in the final cover system and for three typical slopes ($2H:1V$, $2.5H:1V$, and $3H:1V$). For $H_w/H=0$, the drainage layer is functioning perfectly and there is no build up of piezometric head on the critical interface. All three slope inclinations exhibit a factor of safety greater than 2.5 for this case. The worst water level or pore-pressure scenario for slope stability is the piezometric level at and parallel to the ground surface ($H_w/H=1$). A ratio of $H_w/H=1$ corresponds to the drainage layer being clogged, the entire cover system being saturated, and water seeping down the slope. For this case, the two steepest slopes exhibit a factor of safety less than a regulatory value of 1.5, but the $3H:1V$ slope meets the regulatory value. However, the factor of safety of the 2.5:1 slope is still greater than 1.2, which is sufficient because rainfall is a temporary loading condition. In addition, the permeability test results presented herein for TSs indicate that it is unlikely that the entire flow volume of TSs will become clogged, especially with a steep slope, i.e., $2.5H:1V$ or $2H:1V$, because of the large amount of surface runoff.

Overall, the direct shear test results indicate that all of the shredded tire interfaces tested will be stable on a $2.5H:1V$ slope even if the drainage layer were to become clogged. Typical landfill final cover systems are limited to a slope of $3H:1V$ to ensure slope stability because of the weak geosynthetic interfaces that are present in a geosynthetic final cover system. This is significant because in many instances it is expensive to regrade, or space limitations prevent regrading an abandoned landfill to reduce the slopes to 3H:1V. Thus, the use of TSs may facilitate the final covering of steep abandoned landfills because of the high interface strength generated by shredded tires.

Field Demonstration Results

An experimental cover system using TSs was constructed at the Carlinville landfill. For comparison purposes, an experimental cover system with sand as drainage layer was also constructed. Standard construction equipment and procedures were used to handle the TSs and construct the cover systems incorporating TSs as a drainage layer. The experimental cover systems were monitored for over four years and the performance of the TS drainage layer has been found to be similar to that of a conventional sand drainage layer.

Monitoring of erosion and vegetation growth at the Carlinville landfill was performed during periodic field visits. There was no visible erosion in the TS or sand sections. The vegetation growth was excellent.

The minimum required angle of internal friction value for the TSs to provide a minimum factor of safety was found to be 22º by using the infinite slope analysis for the steepest slope possible at the Carlinville landfill. However, based on direct shear testing, the TSs possessed an angle of internal friction greater than 50º. Observations made from the field monitoring show that the cover slopes were stable.

The outflow from the TS and sand drainage layers was too low to measure with the flow meters used. The plastic buckets placed at the outlets indicated a low outflow. Samples of outflow were collected in 2001 and 2003 for both the TS and sand drainage layers. The samples were analyzed for metals, volatile organic compounds (VOCs), and semi-VOCs (SVOCs) using the U.S. Environmental Protection Agency standard test methods (U.S. Environmental Protection Agency 1986). The results for the two sets of samples collected are summarized in Table 4. None of the organic compounds were detected in any samples for 2001 and 2003 sampling events. Outflow samples collected in 2001 showed the presence of calcium, iron, lead, magnesium, potassium, sodium, and zinc in the sand section. The same metals (excluding zinc and iron) and manganese were detected in outflow samples collected from the TS drainage layer. The concentrations of magnesium, potassium, and sodium were slightly higher in samples from the TS section as compared to that of the sand section. The metal analysis of outflow samples collected in 2003 showed low concentrations of aluminum, barium, calcium, copper, iron, lead, magnesium, manganese, potassium, and sodium for the sand section. For the same sampling event, low concentrations of aluminum, arsenic, barium, calcium, cobalt, copper, iron, lead, magnesium, manganese, potassium, sodium, and zinc were detected in outflow samples from the TS section. Except for iron, all these metal concentrations were very low. The concentrations of metals increased slightly in the 2003 samples when compared with the 2001 samples. A long-term monitoring will be required to systematically assess the temporal variation of the quality of outflow samples from both the sand and TS sections.

Scrap tires have been known to undergo a self-heating reaction. This reaction is still being investigated, but it is believed to be caused by microbes that oxidize the exposed steel belts and rubber (ASTM 1998a,b). The reaction is more likely when there is free access to air and water, retention of heat, and the presence of organic nutrients (ASTM 1998a,b). Scrap tires have a high insulating value, and when they are placed in thick layers or stockpiled, heat is retained, which creates a favorable environment for a self-heating reaction. ASTM standard D 6270—Use of Scrap Tires in Civil Engineering Applications (ASTM 1998a) provides guidelines for preventing this heat reaction. It is suggested that placement of TSs be less than 3-m thickness because no heating occurred in any placement under 4-m thick. It is also suggested that organic matter should not come in contact with the TSs and a geotextile be placed over the TSs. These precautions were taken in the design of the cover system at the Carlinville landfill.

Based on the results obtained and good performance of the final cover constructed using TSs, it can be concluded that TSs can be used as drainage material in any landfill cover system without compromising the minimum requirements and regulations necessary to safeguard the environment. Discarded tires are waste by themselves, and using them as drainage material is a viable, economical, and efficient option that leads to the conservation of natural resources.

Summary and Conclusions

Despite having wide variation in the values of engineering properties, shredded scrap tires meet or exceed the minimum requirements for a drainage material in the landfill covers. There was no distinct correlation between the size of the TS and any of the properties. The hydraulic conductivity value, the prime factor that controls the drainage performance of the TSs, varied with TS size depending upon the stress conditions under which the property was investigated. The hydraulic conductivity values determined using the large-scale permeameter under different stress conditions indicate that TSs possess a very high hydraulic conductivity value, meeting the minimum hydraulic conductivity requirement of 10^{-2} cm/s.

When used as drainage material in landfill cover systems, TSs may be clogged by the soil infiltration from the overlying cover soil layer. To assess the clogging potential, laboratory simulation experiments were conducted using two different size shreds and different imposed hydraulic gradients. The effects of normal stress and the presence of the geotextile at the interface of the TS layer and the cover soil layer on the clogging of TSs was also studied. These test results showed that irrespective of the TS size and hydraulic head over the soil layer, the flow rates in all the cases where the geotextile was used remained almost the same. In other tests, due to the compression of the TS layer under the applied normal stress, the flow rates were less when compared to the conditions where no stress was applied. In tests where there was no geotextile at the interface of the TS layer and the soil layer, there was a large amount of soil infiltration in the form of migration of soil particles into the voids of the TSs. It can be concluded that the presence of the geotextile eliminates the soil migration into the TSs, which otherwise may compromise the hydraulic efficiency of the shredded tire drainage layer.

The lateral flow capacity (transmissivity) of the scrap tires may be affected by the soil infiltration/erosion migration of soil particles from the overlying cover soil layer and underlying barrier soil layer into the voids of the shredded scrap tires. To assess such effects, four series of transmissivity tests were performed with two different size TSs. The effects of applying normal stress and the use of geotextile at the interfaces were assessed. The results of all the tests indicated that the transmissivity flow rate was almost the same in tests when the geotextile was used at both the interfaces. However, when there was no geotextile at the top interface, the amount of soil migration into the voids of the TSs from the cover soil layer was very high and a reduction of flow rate was observed. The absence of the geotextile at the bottom interface had minimal affect on the transmissivity. Based on the results, it can be concluded that the presence of a geotextile at the interfaces between the TSs and the top and bottom soil layers would maintain efficient hydraulic performance of the TS drainage layer, irrespective of the TS size and normal stress conditions.

The results of the interface direct shear tests on the three interfaces that would be encountered in an abandoned landfill final cover system, i.e., (1) nonwoven filter geotextile/shredded tires; (2) shredded tires/soil; and (3) nonwoven filter geotextile/soil, show that these interfaces exhibit high interface shear strengths. The interface strengths are much greater than the interface strengths exhibited by geosynthetics that are typically used in traditional landfill final cover systems. The direct shear test results indicate that all of the shredded tire interfaces tested will be stable on a $2.5H:1V$ slope even if the drainage layer becomes clogged. Typical landfill final cover systems are limited to a slope of $3H:1V$ to ensure slope stability because of the weak geosynthetic interfaces that are present in a geosynthetic final cover system. This is significant because in many instances it is expensive to regrade, or space limitations may prevent regrading an abandoned landfill to reduce the slopes to $3H:1V$. Thus, the use of TSs may facilitate the final covering of steep abandoned landfills because of the high interface strength generated by shredded tires.

The performance of the TS drainage layer in landfill cover systems was demonstrated by constructing and monitoring a final cover with a TS drainage layer at Carlinville Landfill in Carlinville, Ill. This landfill was abandoned and needed immediate remediation by construction of final cover to protect the public and the environment. An area of 0.8 ha was selected and it was divided into two sections. One section was constructed with a cover system using shredded tires as the drainage material and the other section employed sand as the cover system drainage material. Standard construction equipment and procedures were used for construction. Regular field monitoring was performed to evaluate the performance of the cover systems constructed. It was observed that there were no problems regarding slope stability, settlement, and subsidence. Environmental quality analysis for the water samples collected from the flow meters connected to each drainage layer of the two cover systems gave no indication of presenting a hazard to public health or the environment. Due to less outflow volume from the drainage sections, which might be due to less infiltration, the drainage performance of the two cover systems could not be compared. But the performance of the cover system with a shredded scrap tire drainage layer was found to be the same as that of the cover system with a sand drainage layer.

Overall, this study demonstrated that TSs possess the required characteristics of a drainage material in landfill cover systems. The use of TSs as a drainage material in a landfill cover system is economical, efficient, and safe, providing a practical solution to the important environmental problem of scrap tire disposal.

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