Proceedings of the International Workshop on Lightweight Geo-Materials (IW-LGM2002)
March 26-27, 2002, Tokyo, Japan, pp. 17-32.

MECHANICAL PROPERTIES AND MASS BEHAVIOR OF SHREDDED TIRE-SOIL MIXTURES

Tuncer B. Edil[1]

ABSTRACT : Scrap automobile tires are not fully recycled. When shredded, tires can be used as a lightweight construction material alone or in mixture with soils. When mixed with soils, shredded tires generate a low unit weight geomaterial often with improved engineering properties compared to those of the soil alone, especially in terms of strength. There has been significant amount of research in the last decade to characterize the engineering properties of tire chips and tire chips-soil mixtures in the laboratory and also some investigation of mass behavior in the field. This paper summarizes the behavior of shredded tire-soil mixtures as a lightweight geomaterial based on the research carried out at the author's institution and as found in the literature.

KEYWORDS: Ligt weight geomaterials, scrap tires, strength, compressibility, constrained modulus, resilient modulus, geosynthetic interaction, mass behavior

1. INTRODUCTION

Construction of highway embankments using strong but lightweight geomaterials over soft ground alleviates both problems of instability and long-term settlement. Backfills of retaining structures also can be constructed using lightweight materials resulting in less earth pressures and improved economics. There are a variety of lightweight geomaterials available. However, large volumes needed in embankment and backfill construction often places limits on the use of costlier manufactured lightweight materials. In recent years, there has been a growing emphasis on using industrial by-products and scrap materials in construction. Banning disposal of scrap automobile tires, which are generated at a rate of approximately 250 million per year in the United States, resulted in large stockpiles of scrap tires (in excess of 1 billion tires in 1990). A dramatic increase in recycling and re-use of tires has taken place in the last decade. In 2000, there was only a stockpile of 300 million tires and the number of tires used in civil engineering applications had risen to 30 million tires per year and overall 70% of scrap tires were marketed in the United States according to the Scrap Tire Management Council. Shredded scrap tires exhibit excellent frictional properties alone or in mixtures with soil by enhancing the strength properties of soils by internal reinforcement. In addition, because of their lower specific gravity (typically 1.15 to 1.21) relative to that of soil solids (2.55 to 2.75), tire chips, alone or in mixtures with soils, offer an excellent lightweight and strong fill material for use in fills, earthen structures, etc. Unit weight varies from about 5 kN/m^3 for 100% tire chips to 13 kN/m^3 for 50-50 by volume mixture of tire chips and soil. Results of the tests on soil-tire chip mixtures indicate that the unit weight decreases as the tire chip content increases, at a rate of approximately 1.5 kN/m^3 per 10% tire chips [1, 2, 3].

Although there are many advantages to using recycled tires in civil and environmental applications, concerns have been raised about their self-combustion potential and environmental suitability. Three fills constructed with shredded tires self-heated and caught fire in 1995 [4]. These sites contained

[1] University of Wisconsin-Madison, U.S.A., Professor of Civil and Environmental Engineering

thick sections of tire chips, i.e., 7.9 to 15 m thick. It has been determined that decreasing the thickness of tire layer alleviates this problem as it was found that temperatures were decreasing after a slight increase in thinner layers [4]. It is recommended that the thickness of a tire shred layer be limited to 3 meters and that relatively large shreds with a minimum of rubber fines be used along with limiting the flow of air and water into the interior of tire-shred fills (ASTM D6270-98). Thus, it is possible to use tire chips alone as a lightweight geomaterial by following certain precautions and directly in mixtures with soils without the fear of self-combustion.

The impact the tires may have on the quality of surface or groundwater that may come into contact with them has also been evaluated in a number of investigations indicating that tire chips do not cause significant contamination [5, 6]. Moreover, Park et al. [7] found that the tire chips have relatively high volatile organic chemicals sorption capacity based on batch sorption tests on scrap tire chips. This suggests yet another innovative application in which shredded tire chips are used to eliminate chemicals from contaminated water. Therefore, in a contaminated environment tire chips may even have a beneficial function as a sorptive medium [8].

The emphasis in this paper is on soil-tire chip mixtures because these geomaterials often optimize the many advantages both mechanical and environmental while being significantly lighter than common earthen materials though heavier than pure tire chips.

2. SHEAR STRENGTH

Tire chips are irregularly shaped, plate-like particles with a larger dimension typically two to four times larger than the smaller dimension. The common tire chip used in construction is 50 to 100 mm long [1] though larger shreds and even large sections of tires can be used. One of the desirable properties of tire chips is their lightweight. The specific gravity of tire chips is slightly greater than water, and ranges between 1.08 and 1.36 depending on the metal content [9, 10]. Tire chips devoid of metal have an average specific gravity of about 1.15. In most cases, however, the specific gravity of tire chips is about 1.20 [1].

Pure tire chips have friction angles of 20 to 35^{o} and cohesion of 3 to 11.5 kPa based on large-size direct shear tests [9, 10, 11]. Triaxial compression tests conducted on small tire chips (< 40 mm long) indicate that the friction angle can be in excess of 40^{o} and that the cohesion intercept is negligible [12]. Field observations also support high friction angles for pure tire chips and sand-tire chip mixtures.

Adding tire chips reinforces sand, e.g., friction angles as large as 65^{o} are obtained for mixtures of dense sand containing 30% tire chips by volume (21% by weight). Foose et al. [10] shows, however, that the strength decreases when the tire chip content increases beyond 30% because the sand-tire chip mixture behaves less like reinforced soil and more like a tire chip mass with sand inclusions. They also found that reinforcement content, unit weight of the soil matrix, and confining stress are significant factors affecting the shear strength of soil-tire chip mixtures. It has been reported that sand-tire chip mixtures prepared with dense sand have non-linear failure envelopes [1, 10]. In contrast, mixtures made with looser sands have linear failure envelopes [10].

In a later study, Tatlisoz et al. [3] investigated the shear strength, deformability, and compressibility of waste tire chips and their mixtures with fine- and coarse-grained soils. Large-scale laboratory testing equipment was used to conduct the study. Mixtures, made with typical backfill soils such as clean sand, sandy silt, and clay, were tested. Results of the tests show that tire chips and soil-tire chip mixtures behave like soils, but are more compressible and also require more deformation to mobilize their ultimate shear strength. Incorporation of tire chips in the backfill results in a reduction in unit weight and, for mixtures containing sand or sandy silt, an increase in shear strength. In contrast, clay-tire chip mixtures have the same or lower shear strength as clay alone. Strength envelopes for sand-tire chip mixtures can be non-linear, and have virtually no cohesion intercept. Mixtures containing sandy silt behave similar to mixtures made with sand, except the shear strength envelope for the sandy silt-tire chip mixture is linear and has a cohesion intercept.

The relationship between shear stress and horizontal displacement is different as shown in Figure 1 for sandy silt and sandy silt-tire chip mixtures. For the sandy silt alone, the shear stress initially increases and then levels off at a horizontal displacement of 0.5 to 1.0 cm. In contrast, the shear stress for the sandy silt-tire chip mixtures continues to increase with horizontal displacement; i.e., no distinct peak occurs. Thus, shear strengths reported for the sandy silt-tire chip mixtures are the shear stresses achieved at a certain displacement, e.g., 6 cm. Thus, greater displacements are required to reach the ultimate strength of sandy silt-tire chip mixtures than for sandy silt alone. Similar findings are reported for sand-tire chip mixtures [10].

Results of the direct shear tests on the sandy silt-tire chip mixtures are shown in Figure 2. The sandy silt-tire chip mixtures have greater strength than sandy silt alone, which is due to higher friction angle and greater cohesion. Moreover, the mixtures containing 20% tire chips by volume have higher strength than the mixtures containing 10% tire chips. There appears to be a point of diminishing returns, however, because the strength envelopes for the mixtures containing 20% and 30% tire chips are essentially the same.

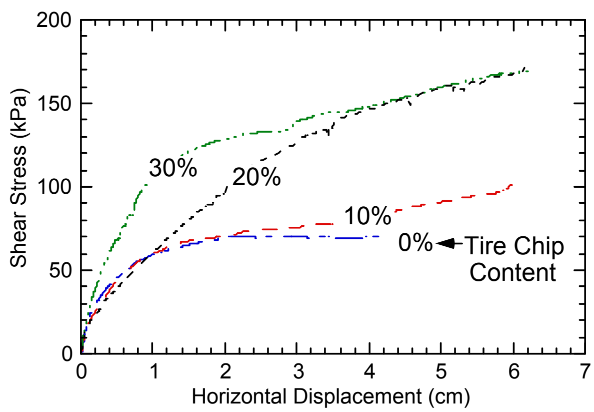

Figure 1. Shear stress vs. horizontal displacement for sandy silt-tire chip mixtures [3]

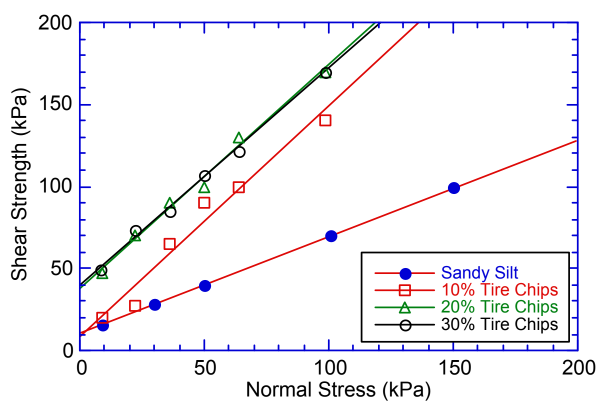

Figure 2. Shear strength envelopes for sandy silt-tire chip mixtures [3]

Foose et al. [10] report similar increases in shear strength for their tests on sand-tire chip mixtures, but the strength increases were primarily caused by an increase in "initial" friction angle (Table 1). Increasing the tire chip content increased the initial friction angle, with values as high as 65^{o} being obtained for dense sands and tire chip contents of 30%. The results for the sandy silt (Figure 2, Table

1) indicate that the friction angle of sandy silt-tire chip mixtures is essentially independent of tire chip content (~54°). That is, increases in strength of sandy silt-tire chip mixtures obtained by increasing the tire chip content beyond 10% are due primarily to increases in cohesion, not friction angle.

Increases in strength were not observed in the clay-tire chip mixtures. In fact, adding tire chips results in a decrease in shear strength at low normal stresses. Increases in strength were probably not obtained because of poor bonding between the clay and tire chips.

Table 1. Shear strength parameters of tire chips, sand, sandy silt, and mixtures [1, 3]

Material	Tire Chip Content (%)[c]	Unit Weight (kN/m^3)	c (kPa)	ϕ (degrees)
Tire Chips	100	5.9	~0	30
Sand	0	16.8	2	34
Sand-Tire Chips	10	15.6[b]	2	46
Sand-Tire Chips	20	14.5[b]	2	50
Sand-Tire Chips	30	13.3[b]	2	52
Sandy Silt	0	18.3	11	30
Sandy Silt-Tire Chips	10	17.6	8	55
Sandy Silt-Tire Chips	20	17.0	38	54
Sandy Silt-Tire Chips	30	16.3	39	53

Note: [a]shear strenght parameters for soil-tire chip mixtures correspond to a shear displacement of 100 mm, [b]unit weight of sand fraction = 16.8 kN/m^3, and [c]tire chips content is by volume.

The increase in shear strength achieved by adding tire chips can be described in terms of the shear efficiency, E_t, which is defined as [3]:

$$E_{\tau} = \frac{\tau_{st}}{\tau_s} \quad (1)$$

where τ_{st} is the shear strength of the soil-tire chip mixture and τ_s is the shear strength of the soil. Shear efficiency vs. normal stress for the mixtures of sand and sandy silt with tire chips is shown in Figure 3.

The shear efficiency for the sand-tire chip mixtures ranges between 1.1 and 2.2 (Figure 3a). For a given tire chip content, the shear efficiency is constant until the "critical confining stress" is reached, which corresponds to the change in slope of the shear strength envelope. As the normal stress is increased further, the efficiency decreases and asymptotically approaches 1.0 for all tire chip contents. The efficiency asymptotically approaches 1.0 because the strength envelopes for the sand and sand-tire chip mixtures are essentially parallel at higher confining stresses. Thus, reinforcing sand with tire chips is most beneficial in applications where the confining stress is lower.

The shear efficiency for the sandy silt-tire chip mixtures ranges between 1.3 and 3.2 (Figure 3b). For the mixture containing 10% tire chips, the shear efficiency gradually increases with increasing confining stress and asymptotically approaches 2.3. In contrast, for the 20% and 30% mixtures, the efficiency decreases asymptotically to 2.4. The asymptotic efficiencies are nearly identical, because the sandy silt-tire chip mixtures have essentially the same friction angle (Table 1). That is, the efficiencies at lower stresses differ only because the mixtures have different cohesions. As with the sand-tire chip mixtures, these results suggest that the reinforcing effect of tire chips is most beneficial at lower confining stresses. Unlike the sand-tire chip mixtures, however, sandy silt-tire chip mixtures are always significantly stronger (> 2 times) than sandy silt at all confining stresses.

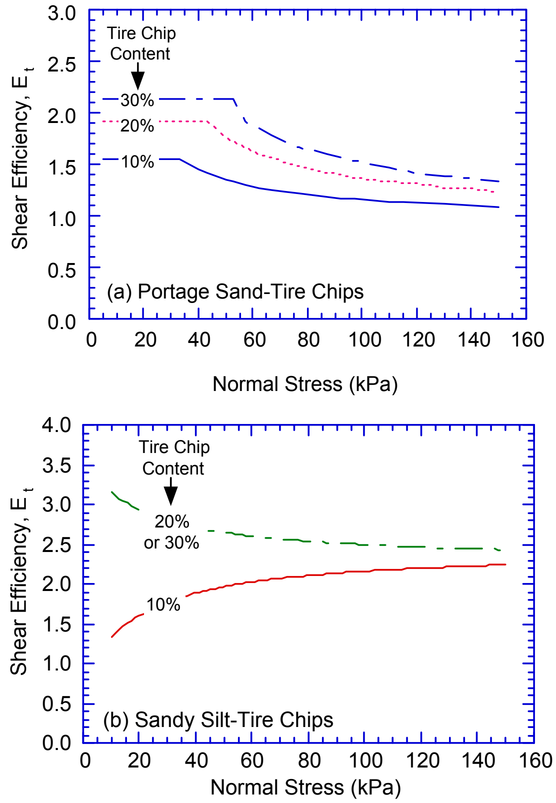

Figure 3. Shear efficiency for sand-tire chip (a) and sandy silt-tire chip (b) mixtures (tire chip content is by volume) [3].

3. INTERACTION WITH GEOSYNTHETICS

To use tire chips or tire chip-sand mixtures as backfill behind geosynthetics-reinforced walls and embankments, interaction properties between the backfill and geosynthetics are needed. Pull-out testing (e.g., Geosynthetic Research Institute (GRI) Test Method GT6) is a method in which interaction properties of geosynthetics with a backfill are determined. A common method of interpreting pull-out test results is in terms of the interaction coefficient, C_i, which compares the effective strength of the soil-geosynthetic interface to the shear strength of the soil. The interaction coefficient C_i, is defined for cohesionless backfill as (GRI Test Method GT6):

$$C_i = \frac{P}{2\,WL(\sigma_n \tan\phi)} \tag{4}$$

and for cohesive backfill as [13]:

$$C_i = \frac{P}{2\,WL(\sigma_n \tan\phi + c)} \tag{5}$$

where P is the measured pullout force, L is the embedded length of reinforcement in soil, W is the width of the geosynthetic specimen, σ_n is the applied normal stress, and ϕ and c are the total stress shear strength parameters for the backfill. The interaction coefficient represents the ratio of the average interface friction strength to the internal shear strength of the backfill. The average interface friction strength is a combination of resistance provided by strike-through and the non-uniform shear resistance that develops on the surface.

Bernal et al. [11] performed pull-out tests on geogrids using tire chips as backfill and obtained interaction coefficients (C_i) lower than common interaction coefficients for geogrids with soils. Tatlisoz et al. [14] performed pullout tests on a variety of geotextiles and geogrids with tire chips and soil-tire chips mixtures. Interaction coefficients are reported from each test at the pull-out capacity. The interaction coefficients are summarized in Table 2.

Table 2. Summary of pull-out test results [14].

Backfill	**Geosynthetic**	Normal Stress (kPa)	Shear Strength (kPa)	Pull-Out Force (kN/m)	Interaction Coefficient (C_i)
Tire Chips	Geotextile	8	4.6	14	1.51
		29	16.7	45	1.67
		50	28.9	66	1.27
	Miragrid 5T	8	4.6	17	1.95
		29	16.7	31	0.99
		50	28.8	40	0.72[a]
	Miragrid 12XT	29	16.7	35	1.05
Sand	Geotextile	10	6.7	10	0.65
		30	20.2	47	0.93
		51	34.4	52	0.78
	Miragrid 5T	10	6.7	8	0.73
		30	20.2	28	0.63
		51	34.4	31	0.47[a]
	Miragrid 12XT	30	20.2	25	0.61
Sand-30% Tire Chips	Geotextile	10	12.8	18	0.73
		30	38.4	42	0.54
		51	65.3	66	0.52
	Miragrid 5T	10	12.8	16	0.65
		30	38.4	36	0.47[a]
		51	65.3	40	0.30[a]
	Miragrid 12XT	30	38.4	44	0.57
Sandy Silt	Geotextile	10	16.8	22	0.79
		30	28.3	44	0.86[b]
		51	40.4	86	1.15
	Miragrid 5T	10	16.8	18	0.57
		51	40.4	44	0.57[a]
	Miragrid 12XT	30	28.3	40	0.71
Sandy Silt-30% Tire Chips	Geotextile	10	52.3	20	0.20
		30	78.8	48	0.31
		51	106.7	78	0.38
	Miragrid 5T	10	52.3	24	0.24
		51	106.7	45	0.22[a]
	Miragrid 12XT	30	78.8	49	0.31

Note: [a]Geogrid broke, [b]Clamp failure

Interaction coefficients for both geosynthetics in the tire chip backfill are greater than or near unity within the normal stresses that were used. For the other backfills (soils and soil-tire chip mixtures), the interaction coefficients are less than unity, indicating that the effective interface friction was lower than the shear strength of the backfill. Most of these interaction coefficients are between 0.5 and 1.0. The only low interaction coefficients (< 0.5) occurred when the geogrid broke. The interaction coefficients for the soil-only backfills (sand and sandy silt) are similar to interaction coefficients reported by the manufacturer of the Miragrid geogrids, i.e., 0.7 to 0.9 for sand and sandy silt backfills.

The lowest C_i values were obtained with the sandy silt-tire chip backfills. However, the sandy silt and sandy silt-tire chip backfills yielded the largest pull-out capacity. In fact, all backfills containing tire chips yielded similar or higher pull-out capacity than the backfills consisting of soil only. The increase in pull-out capacity is probably the result of increased friction caused by the movement of rough edges of tire chips moving against the geotextile or by tire-chip strike-through in the geogrid.

Low C_i values were obtained for the sand-tire chip and sandy silt-tire chip backfills because these backfills are reinforced internally via tensile forces and bending resistance, not friction enhancement. Consequently, the shear strength of the soil-tire chip mixture is not transferred to the geosynthetic layer. Instead, the force transmitted from the backfill to the geosynthetic is due to friction transferred from the soil and tire chips as they abrade against the geosynthetic, and strike-through of tire chips. The pull-out capacity for the geotextile was similar in the sandy silt and sandy silt-tire chip backfills, even though these backfills had very different shear strength at the normal stresses considered. The slightly higher pull-out capacities for the geogrid in the sand-tire chip and sandy silt-tire chip backfills (relative to sand or sandy silt backfills) are probably due to increased resistance caused by strike-through of tire chips. Examination of the geogrid after testing showed that strike-through occurred in about 5% of the geogrid apertures.

The C_i values for the geogrids either decrease (sand, tire chip or their mixture) or remain constant (sandy silt and sandy silt-tire chip mixture) as the normal stress increases (Table 2). Similar results are reported by Bernal et al. [11]. In contrast, the interaction coefficients for the geotextile show no consistent trend with normal stress. This observation is consistent with the displacements measured along the geotextile during pull-out; i.e., similar displacements occurred along the geotextile in the tests, regardless of normal stress. Consequently, the degree of progressive failure was probably similar at each confining stress.

The Miragrid 5T, a low-strength geogrid, broke in all tests conducted at high normal stress (50 kPa), regardless of the backfill material and once even at 30 kPa (Table 2). The higher strength Miragrid 12XT never broke, although it was only tested at a normal stress of 30 kPa. The 12XT generally had equal or higher interaction coefficients than the 5T at a normal stress of 30 kPa.

4. COMPRESSIBILITY

One-dimensional immediate compression of soil-tire chip mixtures are determined under laterally constrained conditions. In an investigation of compressibility, specimens were compressed in compaction molds using a 225-kN Universal Testing Machine [1, 3]. A stiff plate was used to distribute the vertical force uniformly across the surface of the specimen. Vertical deformation was recorded at normal stress intervals of 4 kPa. Prior to compression, a seating stress of 6 kPa was applied to obtain a reference height for strain computations. The maximum normal stress applied to the specimens was 120 kPa, which corresponds to an overburden stress exerted by a soil-tire chip fill approximately 7 m high. The normal stress was increased continuously at 5 kPa/min. until the maximum stress was achieved. The stress was then released at the same rate until the seating stress was obtained. Three loading and unloading cycles were performed following this procedure.

Stress-Strain Curves

Vertical strains for sand-tire chip and sandy silt-tire chip mixtures containing 30% tire chips by volume are shown in Figure 4. The general shape of the compression curves is similar regardless of the type of soil or the tire chip content, suggesting that compression was primarily controlled by the tire chips. However, slightly greater strains occur in mixtures containing clay. For all soil-tire chip mixtures, the largest strain occurs in the first loading cycle (~5%). Strains in subsequent cycles are smaller (2 to 3%).

The strain obtained at the end of first cycle of loading is called the "static strain," whereas the maximum strain generated in subsequent cycles of loading is called the "cyclic strain" [1]. Mixtures having higher tire chip content undergo greater static strain. The static strain increases proportionally with tire chip content, which also suggests that compressibility is governed primarily by the tire chips, and not soil type [3]. However, the clay-tire chip mixtures do compress slightly more than sandy silt-tire chip and sand-tire chip mixtures. The specimen containing only tire chips (unit weight = 5.1 kN/m^3) compressed the most, having a static strain of 26% compared to 5% static strain for sand or sandy silt having 30% tire chips content. Thus, soil-tire chip backfills are likely to be substantially less compressible than backfills consisting only of tire chips.

Although a significant portion of the static strain is not recoverable, some rebound does occur during unloading (Figure 4). In addition, subsequent loading cycles do not result in much additional permanent strain (< 0.5% strain/cycle). The recoverable strain component of the cyclic strain (the "elastic strain") ranges between 0.2% and 10% for soil-tire chip mixtures, and is higher for greater tire chip contents. In contrast, the elastic strain is 13% for specimens consisting of only tire chips [3].

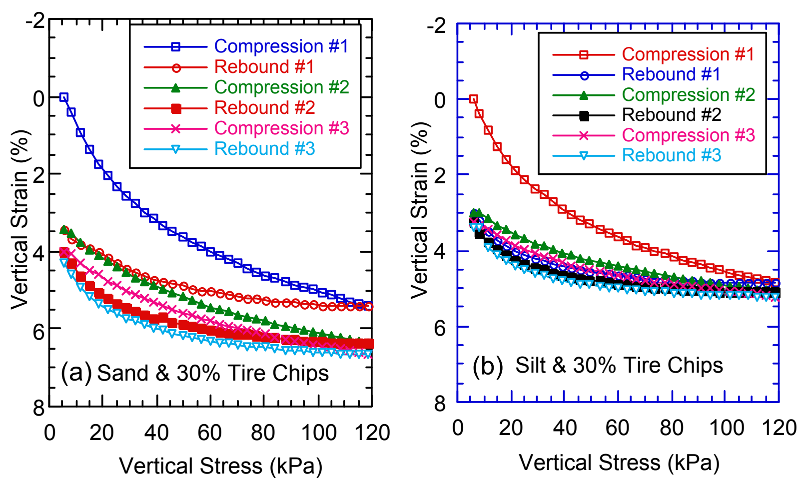

Figure 4. Stress-strain curves from laterally constrained compression tests: (a) sand and (b) sandy silt in mixture with 30% tire chips by volume [3]

Constrained Modulus

The constrained modulus, M_i, can be used to describe the compressibility of soil-tire chip mixtures and to calculate settlement of soil-tire chip fills. The constrained modulus is obtained from the slope of the initial compression curve, or from the cyclic loading curves. Constrained moduli are computed by:

$$M_i = \frac{\Delta\sigma_{n_{i,j}}}{\Delta\varepsilon_{i,j}} \quad (2)$$

where $\Delta\sigma_{n\,i,j}$ is the stress increment between loads i and j and $\Delta\varepsilon_{i,j}$ is the change in strain between loads i and j. Since the compression curves are non-linear, the constrained modulus is a function of stress, with higher stresses yielding higher constrained moduli. A model can be fitted to the moduli obtained from the initial loading curve of soil-tire chip mixtures to calculate the constrained modulus at any vertical stress as follows [3]:

$$\log M = K + n\,\log(\sigma_n - \sigma_o) \qquad (3)$$

where K and n are constants, σ_n is the vertical normal stress (kPa), and σ_o equals 10 kPa. The constants K and n for different soil-tire chip mixtures are shown in Figure 5. Both K and n decrease with increasing tire chip content, which indicates that the modulus decreases with higher tire chip content. In addition, decreasing n with increasing tire chip content indicates that the rate of increase in modulus due to increasing stress is smaller for higher tire chip contents. Parameters for soil only were as follows: sand-K = 10,000 kPa, n = 0; sandy silt-K = 4000 kPa; n = 128; clay-K = 2000 kPa; n = 100.

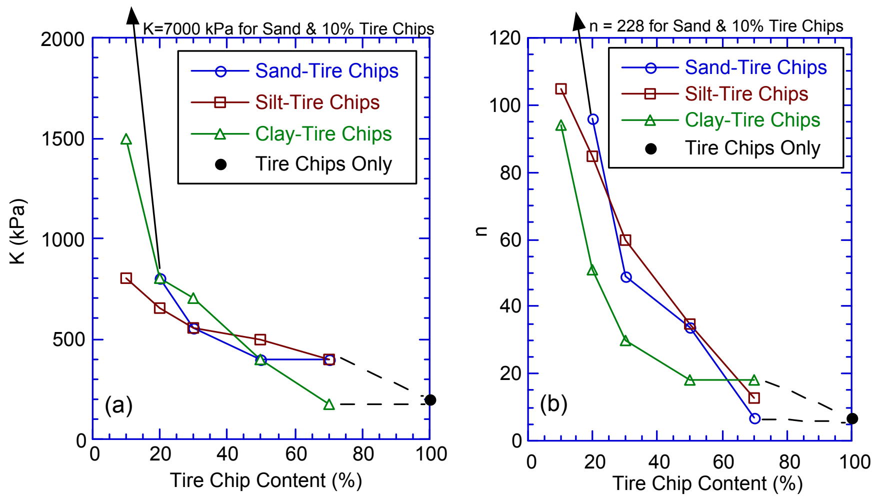

Figure 6. Parameters K (a) and n (b) describing constrained modulus (tire chip content by volume) [3]

Constrained moduli of sand-tire chip, sandy silt-tire chip, and clay-tire chip mixtures generally decrease with increasing tire chips content with the greatest decrease occurring as the tire chip content is increased to 30%. For higher tire chip contents, the constrained modulus does not change significantly. Sandy silt-tire chip mixtures have almost the same constrained moduli as sand-tire chip mixtures, provided the tire chip content is at least 30%. In contrast, the constrained modulus for the clay-tire chip mixtures is generally lower than for mixtures made with sand or sandy silt, regardless of tire chip content [3].

Long-Term Compression

Large-scale consolidometers 306-mm in diameter and 37-mm deep were used for evaluating the time-dependent vertical deformation of tire chips and soil-tire chip mixtures under a constant vertical stress of 20 kPa [3]. The consolidometer rings were made from self-lubricating fiberglass bearings to minimize side friction. Stepped acrylic loading caps were used to evenly distribute the load. The vertical load on each consolidometer was applied with a 136 kg iron weight. Two dial gages with a 75 mm stroke were used to measure vertical deformation.

Three long-term compression tests were conducted, one on a specimen containing only tire chips and the other two on soil-tire chip mixtures (sand or sandy silt) containing 30% tire chips by volume. The specimen containing only tire chips had a unit weight of 4.7 kN/m^3. The sand-tire chip and sandy silt-tire chip specimens were compacted to unit weights of 16.8 kN/m^3 and 16.3 kN/m^3, respectively. The long-term compression tests were conducted for approximately four months, after which water was added to the tire chip and sand-tire chip consolidometers to determine if the specimens would undergo sudden or more rapid deformation under soaked conditions. Results of the tests are shown in Figure 6.

The tire chip specimen deformed more than the sand-tire chip and sandy silt-tire chip specimens. The tire chip specimen compressed approximately 8% immediately after applying the load and continued to compress to a total strain of 13%. In contrast, the sand-tire chip specimen had small immediate compression (1.5%), and less subsequent strain (only 2% cumulative strain under constant loading for 150 days). The sandy silt-tire chip specimen compressed more than the sand-tire chip specimen, with an immediate compression of 3.6%. Soaking of the specimens did result in a small increase in the rate of compression. Furthermore, the tire chip specimen deformed more than the sand-tire chip specimen after soaking. Nevertheless, from a practical perspective, the additional compression induced by soaking was very small, if not negligible.

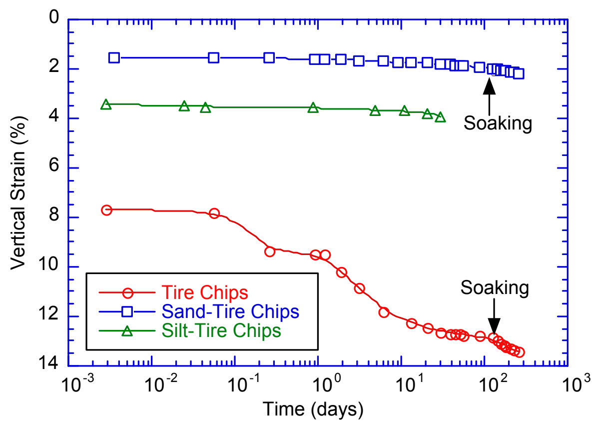

Figure 6. Long-term compression of tire chips and soil-tire chip mixtures [3]

Resilient Modulus

Resilient modulus defines the recoverable deformation response of roadway materials under repetitive traffic loading. It is defined as the ratio of deviator stress to recoverable axial strain in a repetitive loading test. The results of the resilient modulus tests performed in general compliance with the SHRP 1989 Protocol P46 on laboratory prepared specimens of gravelly sand-tire chips mixtures along with the resilient moduli for pure tire chips derived from their constrained modulus [1] indicated that the modulus is strongly correlated with the sand to tire chips ratio and tends to increase moderately with bulk stress. Bulk stress is defined as the sum of the applied deviator stress and three times the confining pressure. A large decrease in resilient modulus occurs as the tire chip percentage increases from 0 to 30% by volume (i.e., from about 50, 000 to 10,000 kPa at a bulk stress of 100 kPa). Similarly, pure tire chips have a markedly lower resilient modulus compared to sand-tire chips mixtures with 30% tire chips by volume (i.e., 1,500 kPa at a bulk stress of 100 kPa).

5. MASS BEHAVIOR

Mechanical properties of soil-tire chips mixtures determined in the laboratory indicate significantly higher shear strength than that of the soil used in the mixture. Interaction coefficients for soil-tire chip backfills are typically about 0.5, even though the pull-out capacity of soil-tire chip backfills is often equal or greater than the pull-out capacity in a soil backfill. Soil-tire chip mixtures made with soils containing fines (silt or clay) are slightly more compressible than sand-tire chip mixtures, but are still less compressible than tire chips alone. In geotechnical practice, it is prudent to verify the expected behavior based on laboratory specimen testing on the basis of mass behavior observed in either large-scale experiments or field tests. There are not many large-scale or field-scale tests available; however, some field tests exist to observe mass behavior of soil-tire chips mixtures. Two of them will be summarized.

Roadway Test Embankment

A roadway test embankment consisting of 8 sections each about 7-m long was constructed to evaluate the use of shredded scrap tires in highway construction [15]. These sections were constructed using different size tire chips and placement configurations and also included two control sections constructed of soil only. Only one of the sections had a mixture of tire chips with a locally available glacial outwash gravelly sand (Figure 7). The test embankment had a nominal height of 2 m with side slopes of 1V:2H. The crest width was 5.3 m to permit safe passage of large trucks. The field unit weight of the sand-tire chips section was 11.8 kN/m^3 whereas the control sections built with sand only had field unit weight of 16.5 to 17.5 kN/m^3. Because of the limited height of the embankment, the mass shear strength behavior could not be assessed; however, deformation behavior could be observed by means of settlement platforms installed 1.7 m above the embankment base in different sections and surface markers placed after construction on the crest and side slopes. Approximately 60 to 100 garbage trucks per day weighing an average of 21.6 tons per vehicle passed over the embankment for a period of nearly 2 years. The lateral movement of surface markers indicated that there was no apparent bulging of the slopes of any sections including the sections built with shredded tires. The surface markers located in the track made by the truck tires indicated the surface settlement increased rapidly the first 20 days of truck traffic and remained relatively constant after 60 days of traffic. The sections built with tire chips only performed well when covered by a 1-m thick soil cap. The tire chips-sand section, though it had only a 0.3-m soil cap performed similar to these sections. The settlement of the surface markers depicts the plastic deformation associated with the surface materials (crushed stone) where the stress increase due to the traffic loading is the largest. The movement of deep settlement plates describes the response of the deeper materials comprised of main embankment fill materials to smaller stress increases from traffic loads. The settlement plates indicated a similar trend to the one shown by the surface markers with respect to time, i.e., higher initial movements slowed after 60 days and remained stable by 152 days of traffic (the last reading). A plastic stiffness index, defined as the ratio of the overburden stress above the settlement plate to the accumulated plastic strain after the initial 60 days of plastic strain, was calculated. The section built with sand-tire chips mixture had a stiffness index of 507 kPa whereas the sections built with tire chips only had 364 - 388 kPa. Introducing a 1-m thick soil cap over pure tire chips improved the plastic stiffness to 514 - 1,455 kPa during this period from 60 to 152 days.

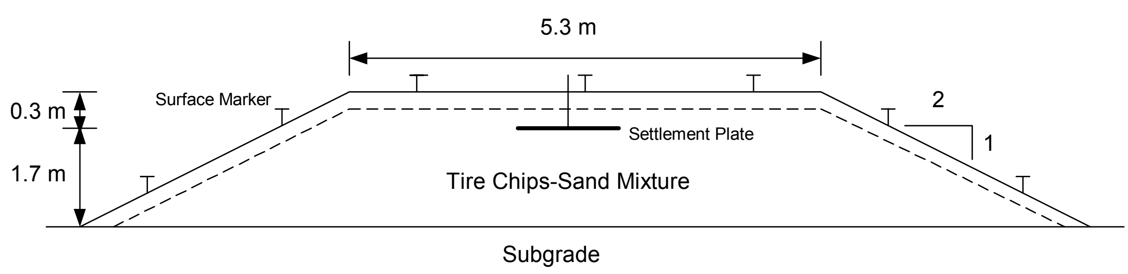

Figure 7. Embankment cross section

Plastic stiffness defines overall vertical deformation of the embankment under self-weight; however, response under traffic loads is characterized by an elastic response. Because only minor unrecoverable strains are observed after several load cycles, tire chip products exhibit essentially nonlinear elastic behavior after the first few cycles of load application. Therefore, the analysis of highway systems including tire chips and soil-tire chip mixtures can be performed using elastic theory under traffic loads. The amount of damage that would be accumulated in a flexible (asphalt) pavement from traffic (or the service life) can be evaluated using a multi-layer mechanistic analysis. Input parameters for such an analysis include the layer geometry of roadway, traffic loads, and resilient modulus and Poisson's ratio of various layer materials, i.e., surface, base, subbase, and embankment fill. Such an analysis was performed for the various test sections in the roadway embankment [2]. Based on laboratory tests, a modulus of 480 kPa and 4,140 kPa and Poisson's ratio of 0.2 and 0.25 were assumed for pure tire chips and sand-tire chip mixtures, respectively. The analysis indicated a design life of 2 years for the asphalt pavement over the sand-tire chips section and less than 1 year for the pure tire chips sections. Presence of a 1-m thick soil cap on pure tire chips fills improved the design life to 12 years, a number comparable to those of pure soil sections of the test embankment.

While this test embankment did not provide direct verification of mass shear strength behavior because the sections were not built to fail in shear, it did provided significant insights relative to compression behavior. Lack of lateral bulging in any of the tire chips sections, though there was significant initial vertical compression (up to 15% in some sections but mostly 3-5% in those sections with a 1-m soil cap or in the sand-tire chips mix section), implies that high friction angle and low lateral stress transfer. Settlement data due to overburden and traffic load confirmed the laboratory observations that initially high plastic compression takes place but thereafter the system stabilizes. To take out this initial high plastic compression and to limit the subsequent plastic strains, a soil cap of about 1-m thick is recommended for fills built with pure tire chips. Tire chips mixed with sand performed as well as the pure tire chips under a 1-m soil cap without requiring this cap. Long-term plastic stiffness could be related to void ratio; for instance, larger shreds can be expected to have more compression compared to small shreds. Similarly, tire chips mixed with soil would have a smaller void ratio due to the presence of soil within the tire chips voids and therefore less compression.

Modular Block Wall with Geosynthetics-Reinforced Sand-Tire Chips Backfill

A 4-m high modular block retaining wall was constructed using a sand and tire chips mixture as backfill [16] (Figure 8). The sand contained 1.8% fines, had a d_{60} = 0.30 mm and a d_{10} = 0.16 mm. The tire chips were obtained by mechanically shredding steel-belted automobile tires and had lengths ranging from 50 mm to 550 mm. The sand and tire chips were mixed at a ratio of 1 part tire chips to 3 parts sand by volume, and therefore the mixture contained 25% tire chips by volume.

Two geosynthetics were used in this study: a woven geotextile (Nicolon HS 1150) and a geogrid (Stratagrid 150). Nicolon HS 1150 is a polyester woven geotextile that has a wide-width tensile strength of 201 kN/m (machine direction) and 1213 kN/m (cross direction). Stratagrid 150 is a high tenacity polyester yarn geogrid coated with black PVC. The wide-width tensile strength of Stratagrid 150 is 23 kN/m in the machine and cross-machine directions. After construction, the backfill was loaded with a surcharge of 200 kPa placed in 4 steps on top of the wall. Lateral displacements under surcharge, vertical and lateral stresses behind the wall, and strains in geosynthetics were monitored (see Figure 8 for instrumentation locations).

The wall was analyzed using the finite element method (FEM) in the PLAXIS code employing a hyperbolic elasto-plastic model, which is called the hardening-soil model by PLAXIS. This model is certainly appropriate for sands and expected to reflect the behavior of tire chips-sand mixtures. Model parameters for the backfill were assumed based on the laboratory behavior of sand-tire chips mixtures and are summarized in Table 3. Geosynthetic reinforcement was represented as axial (no bending) beam elements, which are called geotextiles elements by PLAXIS, with the specified tensile strength, elastic modulus, and interaction coefficients. The wall facing elements were represented as elastic materials. The foundation layer (gravel) and native soil behind the backfill (sand) were represented with the typical hardening-soil model material properties given for such materials by PLAXIS. The FEM model was first subjected to a self-weight loading and subsequently a surcharge was applied in steps on top of the backfill simulating the field experiment. In the field experiment, lateral displacement was measured at a depth of 0.1 m and 2.8 m from the top of the wall in reference to the completed wall during surcharge application (designated "top" and "bottom", respectively).

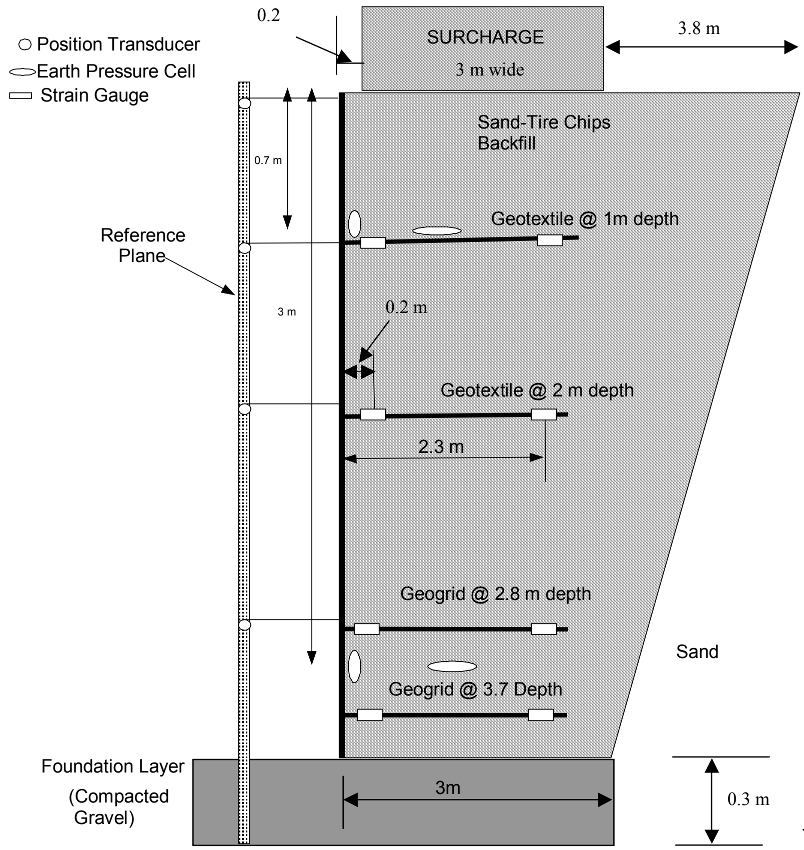

Figure 8. Wall Cross Section

Figure 9 shows the lateral wall displacement at these points as obtained from the FEM simulation and as recorded in the field. The wall deflected laterally 25 mm at the top in response to the highest surcharge of 200 kPa and the FEM model simulates this rather well. This is a remarkably low lateral deflection. The FEM gave higher vertical and lateral stresses in general compared to the ones measured in the field. The trends in the model predictions and the experimental data were similar but the measured values were roughly 1/3 to 1/2 of the FEM model estimates for both the vertical and the horizontal stresses at the top earth cell location where the largest stresses due to the surcharge are indicated. This systematic discrepancy is attributed to the earth cell performance since the model vertical stresses during self-weight loading checks with the expected vertical stress at the location of the cells. Similar discrepancies were reported by Lee et al. [17] in their analysis of full-scale tests walls.

Table 3. Material Properties of Backfill and Interfaces

Material	Unit Weight γ_d [kN/m^3]	Elastic Modulus E [kPa]	Constrained Modulus E_{oed} [kPa]	Unload/Reload Modulus E_{ur} [kPa]	Cohesion C [kPa]	Friction Angle Φ [°]
Backfill	13.3	80,000	68545	20,0000	5	60
Angle of Dilatancy φ [°]	Unload/Reload Poisson Ratio υ_{ur}	Ref. Press. for Hyper. Model P_{ref} [kPa]	Modulus Stress Dependency Coeff. m	Earth Press. Coeff. At-Rest K_0	Failure Ratio Hyper. Model R_f	Geosyn. Interact. Coeff. C_i
35	0.2	100	0,5	0.4	0.9	0.75

The lateral earth pressure coefficient (ratio of lateral to vertical stresses) was 0.4 to 0.6 under self-weight loading based on the measured values. They were 0.15 to 0.25 under increasing surcharge on the top of the wall. The FEM model gave lower values i.e., approximately 1/2 of these values.

Use of tire chips mixed with sand in a geosynthetics-reinforced modular block wall resulted in a robust wall with relatively low lateral displacement under heavy surcharge load. Mass behavior observed in the field demonstration and provided by the finite element method analysis supports the use of laboratory-measured properties for tire chip-soil mixtures in design using such backfill materials.

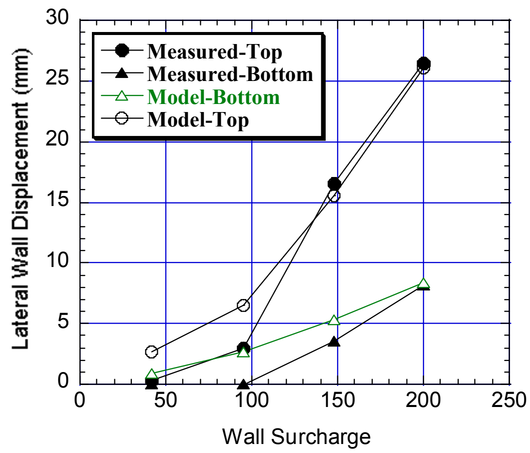

Figure 9. Horizontal Displacement of Wall Face from FEM Model and as Measured

6. SUMMARY

Based on laboratory investigations of mechanical properties and limited field observations of mass behavior of soil-tire chip mixtures as a lightweight geomaterial, the following conclusions and recommendations are made:

1. Soil-tire chip mixtures have unique mechanical properties that are primarily governed by the tire chip content, not by soil type. Furthermore, silty soils are as suitable as sands for use in soil-tire chip backfill mixtures, provided that free drainage is not necessary.

2. Both sandy silt-tire chip and sand-tire chip mixtures have higher strength than the soil alone, and the increase in strength is a function of tire chip content. In contrast, strength increases are not realized for clay-tire chip mixtures. Soil-tire chip mixtures do not exhibit a peak shear strength, but rather the shear strength continues to increase with increasing displacement. For the sandy silt mixtures, increases in strength are obtained until the chip content reaches 20% by volume, beyond which the strength remains constant. In contrast, the strength of sand mixtures increases up to 30% tire chip content.

3. The strength envelopes of soil-tire chip mixtures differ depending on soil type. The sandy silt-tire chip mixtures have linear failure envelopes, and have the same slope (i.e., friction angle) regardless of tire chip content. In contrast, mixtures made with dense sand have non-linear strength envelopes that become approximately parallel to the strength envelope for sand alone at higher confining stresses. For mixtures containing looser sands, the shear strength envelope is linear.

4. Interaction coefficients for soil-tire chip backfills are typically about 0.5, even though the pull-out capacity of soil-tire chip backfills is often equal or greater than the pull-out capacity in a

soil backfill. Interaction coefficients for geosynthetic pull-out in pure tire chip backfills are typically greater than 1 when the displacement is 100 mm.

5. Tire chip-soil mixtures exhibit a significant initial plastic compression under load. This could be as high as 40% of the initial placement thickness for pure tire chips. Once the material is subjected to this level of compression with the associated reduction in porosity, it behaves like an elastic material. Thus, most of the deformation should occur during construction. Soil-tire chip mixtures made with soils containing fines (silt or clay) are slightly more compressible than sand-tire chip mixtures, but are less compressible than tire chips alone. The constrained deformation modulus in the elastic range of pure tire chips is about 100 times smaller than pure sand however inclusion of as low as 30% sand in the tire chip matrix restores the modulus to a level comparable of pure sand. The constrained moduli for initial loading vary between 500 and 30,000 kPa, depending on the stress level, soil type, and tire chip content. The constrained moduli can be predicted using a simple piece-wise linear model. The constrained modulus of all soil-tire chip mixtures increases with increasing confining stress.

6. Soil-tire chip mixtures do not undergo significant long-term deformation, even if soaked. Long-term deformations are slightly greater for sandy silt mixtures than sand mixtures; however, they are much smaller for soil-tire chip mixtures than tire chips alone.

Example calculations suggest that fewer geosynthetic layers are needed to reinforce walls constructed with soil-tire chip backfills than with soil backfill, primarily because the backfill has higher strength and lower unit weight [14]. Calculations also suggest that embankments can be constructed with steeper slopes and a smaller volume of material when soil-tire chip fill is used. Soil-tire chip fill also should provide greater resistance against lateral sliding of embankments on geosynthetic layers because of their lower active earth pressure and higher interface resistance. Greater resistance to bearing capacity failure is also achieved with soil-tire chip backfills, because of their lighter weight. Smaller settlements should also occur when lighter weight fill is used. After an initial period of adjustment, the overall performance of a gravel road founded on tire chips is similar to most gravel roads.

7. REFERENCES

[1] Edil, T.B. and Bosscher, P.J., "Engineering properties of tire chips and soil mixtures," Geotechnical Testing Journal, ASTM, Vol. 17, No. 4, pp. 453-464, 1994.

[2] Bosscher, P.J., Edil, T.B., and Kuraoka, S., "Design of highway embankments using tire chips," J. of Geotech. and Geoenviron. Eng., ASCE, Vol. 123, No. 4, 295-304, 1997.

[3] Tatlisoz, N., Benson, C.H., and Edil, T.B., "Effect of fines on mechanical properties of soil-tire chip mixtures," Testing Soil Mixed with Waste or Recycled Materials, American Society for Testing ands Materials, STP 1275, pp. 93-108, 1997.

[4] Humphrey, D.N., "Investigation of Exothermic Reaction in Tire Shred Fill Located on SR 100 in Ilwaco, Washington," Federal Highway Administration, 1996.

[5] Edil, T.B., Benson, C.H., and Tatlisoz, N., "Leaching of Groundwater Contaminants from Tire Chip Fills," Environmental Geotechnics Report 98-5, Dept. of Civil and Environmental Engineering, University of Wisconsin-Madison, 1998.

[6] Humphrey, D. N. and Katz, L. E., "Five-year field study of the effect of tire shreds placed above the water table on groundwater quality," TRB Annual Meeting, Washington, D.C., 2000.

[7] Park, J. K., Kim, J. Y, Edil, T. B., "Mitigation of organic compound movement in landfills by shredded tires." Water Environment Research, Vol. 68, No. 1, pp. 4-10, 1996.

[8] Edil, T.B., Park, J.K., and Kim, J.Y., "Effectiveness of scrap tire chips as sorptive drainage material, J. of Environmental. Eng., ASCE, submitted for publication, 2001.

[9] Humphrey, D.N. and Sandford, T., "Tire chips as lightweight subgrade fill and retaining wall backfill," Proc. Symp. on Recovery and Effective Reuse of Discarded Materials and By-

Products for Construction of Highway Facilities, Federal Highway Administration, pp. 5.55-5.68, 1993.
[10] Foose, G., Benson, C.H., and Bosscher, P.J., "Sand reinforced with shredded waste tires," J. of Geotechnical Engineering, ASCE, Vol. 122, No. 9, pp. 760-767, 1996.
[11] Bernal, A., Salgado, R., Swan, R., and Lovell, C., "Interaction between tire shreds, rubber-sand, and geosynthetics," Geosynthetics International, 4(6), 623-643, 1997.\
[12] Wu, W., Benda, C., and Cauley, R., Triaxial determination of shear strength of tire chips, J. of Geotech. and Geoenviron. Eng., ASCE, 123 (5), 479-482, 1997.
[13] Bergado, T. and Chai, J., "Pull-out force/displacement relationship of extensible grid reinforcements, Geotextiles and Geomembranes, No. 13, pp. 295-316, 1994.
[14] Tatlisoz, N., Edil, T.B. and Benson, C.H., "Interaction between reinforcing geosynthetics and soil-tire chip mixtures," J. of Geotech. and Geoenviron. Eng., ASCE, Vol. 124, No. 11, pp. 1109-1119, 1998.
[15] Bosscher, P.J., Edil, T.B. and Eldin, N., "Construction and performance of shredded waste tire embankment, Transportation Research Record, No. 1345, Washington, D.C., pp. 44-52, 1993.
[16] Abichou, T., Edil, T.B., Benson, C.H., "Mass behavior of geosynthetics-reinforced shredded tire-soil backfill" Environmental Geotechnics Report 02-1, Dept. of Civil and Environmental Engineering, University of Wisconsin-Madison, 2002.
[17] Lee J.H., Salgado R, Bernal A, Lovell C.W., "Shredded tires and rubber-sand as lightweight backfill," J. of Geotech. and Geoenviron. Eng., ASCE, Vol. 125, No. 2, pp. 132-141, 1999.