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USE OF SCRAP TIRES IN CIVIL AND ENVIRONMENTAL CONSTRUCTION

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Engineering Properties of Tire Chips and Soil Mixtures

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ABSTRACT: The primary objective of the research described herein is to assess the pertinent engineering properties for reusing shredded scrap tires as a construction material for light-weight fill material in highway construction, for drainage material in highway and landfill construction, and for other similar applications. Reuse of scrap tires would not only provide a means of disposing of them but would also help solve difficult economical and technical problems. This paper presents the characteristics of shredded scrap tires and their engineering properties and behavior alone or when mixed with soils. The properties considered include compaction, compressibility, strength and deformability, and hydraulic conductivity. Described are new test procedures or modification of existing methods developed to characterize this unusual material.

KEYWORDS: tire chips, size distribution, compaction, compression, shear strength, friction angle, resilient modulus, Poisson's ratio, hydraulic conductivity

Since the banning of the disposal of automobile and other vehicle tires in sanitary landfills, scrap tire stockpiles have begun to grow in the United States. It is estimated that, on the average, scrap tires are generated one per capita annually, resulting in a significant disposal problem. Currently, it is estimated that 2 billion scrap tires are stockpiled across the United States and that these stockpiles will continue to grow at a rate of 200 to 250 million tires per year. This situation has produced an acute need for finding new beneficial ways to recycle and reuse scrap tires, in particular for large-volume use. Some new ways of using scrap tires are emerging. Notable among these are the burning of ground-up tires in power plants as fuel and the mixing of some in asphalt in pavement construction (Ahmed and Lovell 1992).

The manufacturing process for tires combines raw materials into a special form that yields unique properties such as flexibility, strength, resiliency, and high-frictional resistance. If tires are reused as a construction material, the unique properties of tires can once again be exploited in a beneficial manner (Ahmed 1993). The benefits of using scrap tires are particularly enhanced if they can be used to replace virgin construction materials made from nonrenewable resources. Additionally, scrap tires are shown to have significant sorption capacity for organic liquids and vapors (Park, Kim, and Edil 1993). Recent research indicated that shredded tires do not show any likelihood of being a hazardous waste material or of having adverse effects on groundwater quality (Edil and Bosscher 1992).

The research described herein is an investigation into the engineering properties necessary for use of scrap tires in construction replacing, supplementing, and improving common earthen materials of construction. Using large volumes of scrap tires in construction is desirable for:

- elimination of the need for disposal of scrap tires in landfills
- mitigation of the problems of fill settlement and instability due to the lighter weight of tire chips
- reduction of the use of valuable natural aggregates

In this context, the use of shredded tires in highway applications was considered a potentially significant avenue for putting scrap tires into beneficial reuse. There are a number of ways in which shredded tires can be used in highway construction, for instance, as an aggregate replacement in the construction of nonstructural sound-barrier fills, light-weight embankment fills crossing soft or unstable ground, regular fills, retaining-wall backfills, and edge drains. Potential uses in waste landfills include replacement of drainage layer and daily cover materials and construction of sorption barriers for liquid and vapor organic chemicals. The light-weight fill and sorption barrier applications are particularly interesting because they would provide not only a means of disposing scrap tires but would also help solve difficult economical and technical problems. The primary objective of the research described herein is to evaluate the reuse of discarded shredded tires as a fill and drainage material in construction.

One important component of such an investigation is the characterization of the mechanical and hydraulic properties of this new construction material. Because of its rather different physical properties, the engineering properties of tire chips and its mixtures with soil cannot be determined simply by performing standard test procedures developed for soils and aggregates. The existing test procedures require scrutiny and, in most cases, further modification/development for use in determining the mechanical properties of tire chip products in an unambiguous and general manner. In the following sections, developments in test procedures for tire chip products and the measured mechanical properties and behavioral traits are presented. Many of these findings have already been applied to the design, construction, and analysis of a test embankment that was constructed in 1989 at the Rodefeld Landfill in Madison, Wisconsin (Bosscher et al. 1992).

Characterization and Classification of Materials

To characterize and classify the range in size and shape of shredded tires, an inventory of the scrap tire stockpiles and shred-

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ders in Wisconsin was developed by visiting most of the tire-shredding operation sites (Edil et al. 1990). Most processors use fairly small mobile shredding equipment with engines ranging from 20 to 75 kW. These shredders use a shearing process in contrast to the tearing process in the older versions of shredders. The shearing process produces more uniform products, makes cleaner cuts, and minimizes the partial pulling of the reinforcing wires out of the tire chips. The production rate ranged from 100 to 400 tires per hour depending on the machinery type and desired chip size. The cost of shredding ranged from $30 to $65 per ton, a ton equaling approximately 100 tires.

The size of the tire chips is dictated primarily by the design of a particular machine and the setting of its cutting mechanism. Small-size chips are produced by processing the material through more than one shredder, each adjusted to produce finer cuts than its predecessor. Classifiers can also be used to separate the finer sizes from coarser ones. Usually the chips are irregular shaped, with the smaller dimension being the size specified by the manufacturer and the larger dimension two to four times as large. Samples collected from sites visited range from 25 by 50 mm to 100 by 450 mm with the most common size chip being 50 by 75 mm. Classifiers are not typically used on these sites. Figure 1 provides information regarding the tire chip sizes (minimum dimension) of samples collected from four shredding sites. The names of the tire chips were assigned based on the location of the shredding process.

The average specific gravity of the tire chips was measured to be 1.22. However, specific gravity values ranged from 1.13 to 1.36 depending on the metal content. Tire chips without metal have a narrow range of specific gravity around 1.15.

Five different soils were used in mixtures with tire chips. Four of these soils were granular materials including a well-graded glacial outwash gravelly sand and three uniformly graded clean sands (referred to as casting sand, Portage sand, and lake sand) (Edil and Bosscher 1992). Compaction tests on the outwash sand were run using both the standard and modified compaction efforts. Maximum dry unit weights of 19.7 and 21.2 kN/m^3 and optimum moisture contents of 9 and 7% were measured, respectively, from the standard and modified Proctor tests [ASTM Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort (12 400 ft-lbf/ft^3) (600 kN-m/m^3) (D 698) and Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort (56 000 ft-lbf/ft^3) (2700 kN-m/m^3) (D 1557), respectively]. A low plasticity (CL) clay was also mixed with tire chips. This clay is known as Valley Trail clay and has an optimum moisture content of 18.5% and a maximum standard Proctor dry unit weight of 16.8 kN/m^3. It has a P200 of 99%, an LL of 42, and a PI of 22.

Compaction Characteristics

Since the particular use considered herein for tire chips involves construction of fills with tire chips, their placement characteristics in fills and the improvement of the mechanical properties by specifying the optimum compaction during placement become important. Tire chips are more flexible and compressible than soil particles and as such have a greater capacity to dampen the energy imparted. Secondly, the practical range of tire chip sizes are on the order of 25 or more mm, making the existing compaction test standards for soils inapplicable directly for tire chip products. Because of the granular nature of the tire chips, the first approach involved treating the compaction characteristics in terms of relative density similar to clean sands and gravels. For this purpose, the procedure outlined in ASTM Test Method for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table (D 4253) was used to determine the maximum unit weight using a vibratory table. Because of the wires of the tire chips that tangle with each other and the absorbent nature of rubber to vibrations, this procedure proved inappropriate for studying packing and compaction characteristics of tire chips. Later, field experience also confirmed that vibration provides no significant compaction (Edil and Bosscher 1992).

This situation led to impact methods of compaction such as described in ASTM D 698 and ASTM D 1557, standard and modified Proctor compaction tests, respectively. These procedures require use of 4-in. (101.6-mm) or 6-in. (152.4-mm)-diameter molds, with the larger diameter mold for soils containing a sizable amount of grains larger than 3/4 in. (19 mm) in diameter. If more than 30% by weight of a material is retained on a 3/4-in. (19-mm) sieve, these methods are not recommended for use. Since most

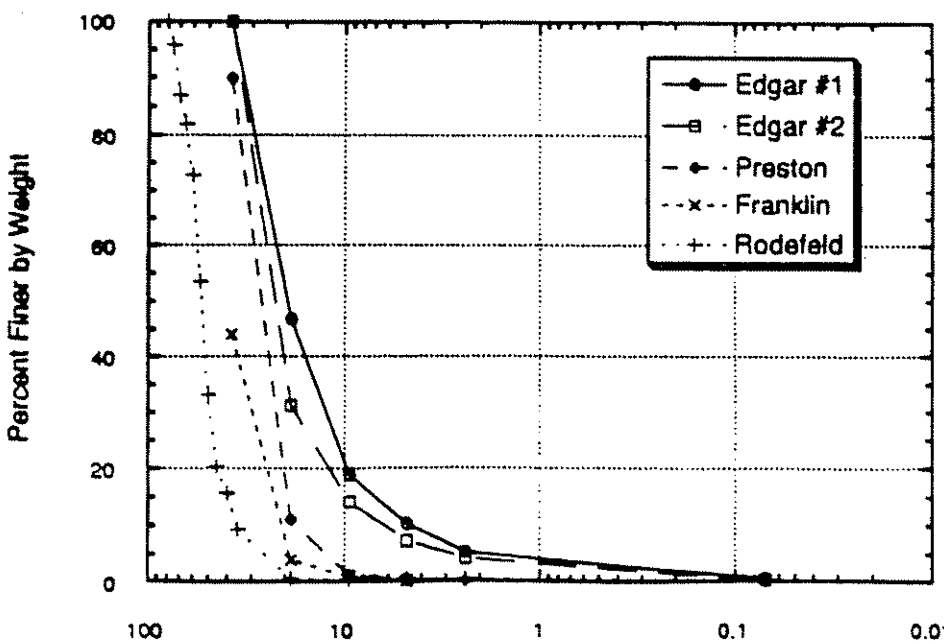

FIG. 1—*Size distribution data of tire chips.*

tire chips contain a significant amount of material larger than 3/4 in. (19 mm), it became necessary to study the possible effect of mold size on the measured compaction characteristics.

Three successive series of compaction tests were performed. In a statistical design of the experimental program, a number of variables and fixed parameters were considered to study the compaction characteristics as summarized in Table 1.

Two compaction mold sizes were considered in this experimental program. The 6-in. (152.4-mm) mold is a standard mold typically used for materials containing coarse grains. A new 12-in. (305-mm) compaction mold was constructed, and the automated compaction hammer was modified such that the same compactive energy per unit volume is delivered irrespective of the size of the compaction mold. The compaction shoe also had to be enlarged to compact in the 12-in. (305-mm) mold. This large mold size is not part of an ASTM standard. Table 2 gives the compaction parameters used in the case of each mold size for the two levels of compaction energy: the standard and the modified Proctor energies. Tire chip–soil mixtures were hand mixed and then placed in the compaction molds in layers as required for compaction. If the sand:tire chips ratio was low, i.e., typically less than 30% by volume, segregation occurred and sand tended to settle at the bottom of the mold; however, higher sand contents stayed unsegregated. Segregation was also observed in the field in a mixture with a sand content of 50% by volume when vibratory compaction was applied (Bosscher et al. 1992).

Two types of sand with different gradations were used in mixtures with Rodefeld tire chips in the first and second test series. The moisture contents of the sand–tire chips mixtures were adjusted on the basis of dry weight of sand used in the mixture to either wet-of-optimum or dry-of-optimum moisture content of the respective compaction effort. The nominal moisture contents used in the first series of tests were 10 and 7% for the standard Proctor and 8 and 5% for the modified Proctor tests, respectively, for "wet" and "dry" of optimum conditions. The second series of tests was performed on dry mixtures (at hygroscopic moisture).

The order of running the tests was randomized. The statistical design generated a block size of two with the block generator confounded with four-factor interactions in the first series of tests according to the statistical code (JASS 1986). The analysis of the results indicated that the most significant factor that controls unit weight is the soil:chips ratio (Edil et al. 1990). It was apparent that soil type and mold size also affect compaction unit weight. These variables explained over 99% of the measured unit weights. Compaction effort and moisture content were insignificant.

The second series of tests was designed and performed involving only three factors (see Table 1). Five levels were used for the sand:chips ratio to define the influence of this variable more clearly. The test results were analyzed by a statistical program called SAS (1989), which follows the general linear models procedure. The analysis indicated that unit weight increases with increasing sand:tire chips ratio as should be expected. Furthermore, sand type and its interaction with the sand:tire chips ratio also appeared to be significant. This test series indicated that mold size and its interactions with the other two variables are insignificant. These results apply to all tests conducted, including those for pure sand.

In order to assess the effect of mixing tire chips with cohesive soils, a third series of experiments was initiated (see Table 1). The test results were analyzed by a statistical program called MINITAB (1989). The analysis indicated that unit weight increases with increasing clay:tire chips ratio as should be expected. This test series indicated that moisture content, mold size, and its interactions with the other variables are insignificant.

The efficiency of packing, i.e. porosity, appears to be controlled by factors other than just soil:chips ratios such as chip size (Edil and Bosscher 1992). Porosity, rather than dry unit weight, may prove to be a more discriminating parameter characterizing the mechanical behavior of mixtures of materials with highly differing unit weights such as soil and tire chips. Table 1 gives the ranges of unit weights and porosities measured.

Compression Behavior

Tire chips are highly compressible because of their high porosity and high rubber content. A mass of tire chips would compress, when a load is applied, primarily due to two mechanisms:

1. Bending and reorientation of chips into a more compact packing arrangement.
2. Compression of individual chips under stress.

Compressibility of tire chips is quite high compared to soils and probably will be the governing design factor in many highway fill applications. To develop an early appreciation of the compression characteristics, a series of quasistatic repetitive constrained compression tests were performed on pure tire chips as well as on mixtures with soils in a mold. The compression tests were performed by placing the material in a 6-in. (1.52-mm) Proctor mold (at a dry unit weight of tire chips of about 4 kN/m^3) and then applying a vertical load using a compression machine.

Figure 2 provides the vertical displacement (compression) versus load response of pure Rodefeld tire chips. The initial porosity of

TABLE 1—*Compaction and constrained compression tests and ranges of measured values.*

Variable or Fixed Parameters	1st Series of Tests	2nd Series of Tests	3rd Series of Tests
Mold size	6 in./12 in. (152.4 mm/305 mm)	6 in./12 in. (152.4 mm/305 mm)	6 in./12 in. (152.4 mm/305 mm)
Soil:chips ratio (weight)	70:30/50:50	0:100/30:70/50:50/70:30/100:0	30:70/70:30
Type of soil	Outwash sand/casting sand	Outwash sand/casting sand	Valley trail clay
Compactive effort	Standard/modified Proctor	Standard Proctor	Standard Proctor
Moisture content	Wet/dry of optimum	Dry (hygroscopic)	Wet/dry of optimum
Number of tests	32	20	8
Unit weight, kN/m^3	11.9–16.6	5.5–14.3[a]	8.5–16.8
Porosity at seating load, %	13.5–27.2	25.9[a]–54.1	12.9–40.5
Static strain	0.012–0.133	0.042[a]–0.296	0.048–0.159
Cyclic strain	0.004–0.105	0.013[a]–0.121	0.007–0.065
Constrained modulus, kPa	2200–82 000	1000–9700[a]	1500–10 000

[a]Excluding 100% sand.

TABLE 2—*Compaction parameters.*

Compactive Effort	Mold Size, mm	Number of Layers	Weight of Hammer, N	Hammer Drop, m	Number of Blows per Layer	Compactive Energy, kJ/m³
Standard	152.4	3	45	0.30	31	593
Standard	305	5	272	0.45	14	593
Modified	152.4	3	45	0.30	140	2693
Modified	305	5	272	0.45	64	2693

tire chips is about 0.67, which decreases to a porosity of 0.5 as a result of about 37% compression at a vertical pressure of about 690 kPa. Hall (1991) reported about 30% compression under a pressure of 69 kPa for his tire chips (19 to 38 mm in size). Figure 2 indicates that major compression takes place in the first cycle. A portion of this compression is irrecoverable in this laterally confined test, but there is significant rebound upon unloading. The subsequent cycles tend to have similar load-displacement curves, however with less rebound than the first cycle. An interesting observation is that the slope of the recompression/rebound curve becomes markedly lower beyond a certain vertical load of about 300 kPa. The other chips, namely Edgar and Franklin (see Fig. 1), displayed a similar response. The only exception is that the final compression was the same at the end of each cycle for Rodefeld and Franklin, whereas for the smaller-size Edgar chips there was a greater final compression at the end of the second cycle, which thereafter stayed constant. A similar compression test performed on pure sand for comparison indicated that the displacement was only about 5% compression at a vertical stress of 690 kPa. This corresponds to about 14% of the compression of pure tire chips at the same load. Figure 3 gives the percent compression of tire chips–sand mixtures at a pressure of 690 kPa as a function of volumetric sand content. Beyond a sand content of about 40%, the compressibility is significantly reduced from about 30 to 40% to less than 20%. Sand filling the open voids of the tire chips skeleton reduces volumetric compression. These tests indicated a significant plastic (unrecoverable) strain under the first cycle of load application followed by reduced plastic and elastic strains under subsequent load cycles. This important finding serves as the key to design of tire-chip fills with tolerable settlements (Edil and Bosscher 1992).

The compacted specimens of the three series of tests, listed in Table 1, were subjected to quasistatic compression in their molds to investigate the effects of the chosen factors. This type of laterally constrained compression tests is used to determine deformation modulus of deep fill materials where lateral constraint is approximated in the field. The compression tests were preceded by the application of a small initial seating load to obtain a reference initial specimen height for strain computations since the surfaces of the specimens are quite uneven. The seating load was about 24 kPa in the first series, 6 kPa in the second, and 9.6 kPa in the third series of tests. Subsequent to the application of the seating load, the vertical load was increased quasistatically to a maximum value in about 6 min and then was lowered back to the seating load followed by three cycles of loading/unloading between the seating load and the maximum load. The maximum loads were 196 and 672 kPa in the first series of tests in the 12 and 6-in. (304 and 152-mm) molds, respectively. In the second and third series of tests, the maximum load was about 120 kPa for both molds.

The quasistatic constrained repetitive loading test results were examined in terms of the maximum strain obtained at the end of first cycle of loading as well as the maximum strain generated in the subsequent cycles of loading as shown previously in Fig. 2 on a typical displacement-load plot. The strains are called, respectively, "static" and "cyclic" strains. The ranges of these strains are reported in Table 1 along with the *constrained modulus*, which is the slope of the cyclic loading portion of the strain-stress plot (Edil and Bosscher 1992).

The static strain decreased as the percentage of soil (sand or clay) increased. The only variable which dramatically affected the amount of static strain was the soil:chips ratio. The cyclic strain also decreased with increasing soil percentage. Similar to the compaction results, the key predictor is the soil:chips ratio. No other factors tested in either the sand or clay test series affected the cyclic strain. However, the type of sand and the size of the mold do

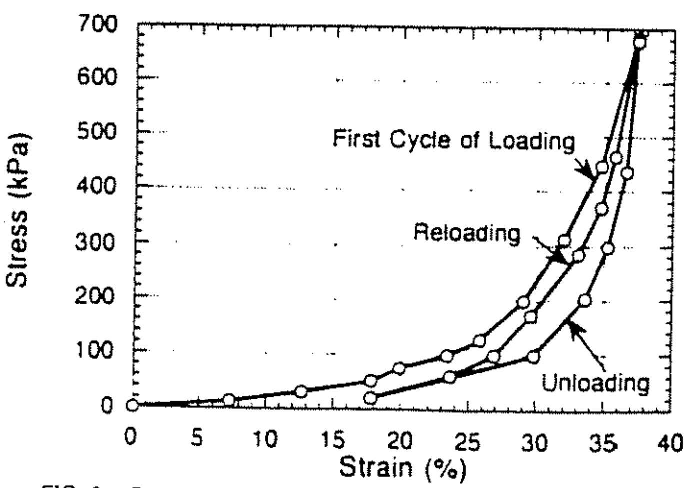

FIG. 2—*Constrained strain-stress response of Rodefeld tire chips.*

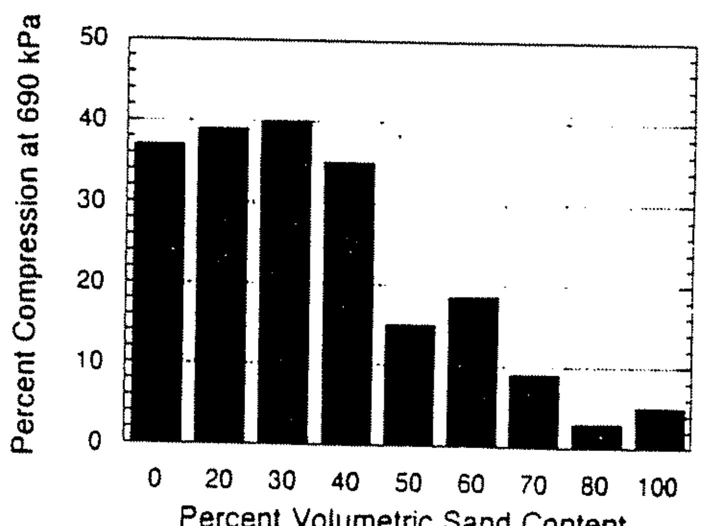

FIG. 3—*Compression versus sand content of tire chips–sand mixtures.*

affect the magnitude of the static stain. A comparison of repetitive constrained moduli indicated that clay mixtures generally have somewhat lower moduli at the same soil:tire chips ratios.

Resilient Modulus

The resilient modulus of pavement materials defines their recoverable deformation response under repetitive loading. It is a primary material property used in the analysis and design of flexible pavement systems. Under repetitive loading, materials undergo certain unrecoverable (or plastic) deformations in addition to the recoverable (or elastic) deformations. The plastic strains can be determined by monitoring the accumulating unrecovered strains during the cycles of repetitive loading. These permanent strains are indicative of the rut potential in a flexible pavement system. Therefore a series of resilient modulus tests were performed on tire chip and soil-tire mixtures. The resilient modulus testing of tire chips presented unique problems not addressed in present standards. A procedure for tire chips was developed by following the new SHRP protocol P46 as closely as possible. The major issue causing a deviation from the P46 protocol was membrane failure due to the wire ends extending from the tire chips. A PVC membrane (0.1 mm thickness) was utilized in place of the latex membrane; however, there was concern about the membrane thickness affecting the results. In order to assess the effect of membrane thickness, two tests were run on the outwash sand, one with a typical latex membrane and one with the PVC membrane. The data are plotted in Fig. 4*a*. The results indicate that the PVC membrane produces a noticeable but small increase in the measured resilient modulus, perhaps due to added confinement.

Four resilient modulus tests were run on mixtures of sand and chips prepared by compaction in the laboratory. Compaction was achieved by tamping in a split mold. Due to excessive sample displacement and distortion, pure tire chips could not be tested. The results of the laboratory-prepared specimen tests are shown in Fig. 4*b*. The results indicate that the modulus is strongly correlated with the sand:chips ratio. The largest jump in resilient modulus occurs as the chip percentage increases from 0 to 30%.

Poisson's Ratio

For the structural analysis and design of highways as a multilayer elastic system, two fundamental mechanical parameters are needed: elastic modulus and Poisson's ratio. During the first cycle of load application, large plastic (unrecoverable) strain is observed, whereas essentially nonlinear elastic behavior is observed for all subsequent load cycles. Therefore, the analysis of highway systems including tire chips or tire chips–soil mixtures can be performed using the elastic theory under traffic loads. For such analysis, Poisson's ratio is required in addition to the resilient modulus, M_r. One approach to assess Poisson's ratio, ν, is to compute it from the coefficient of earth pressure at rest, K_0, in accordance with the following equation

$$\nu = \frac{K_0}{1 + K_0} \tag{1}$$

To measure K_0, first a cylindrical tube (about 305 mm in diameter and 254 mm long) was instrumented with strain gages in accordance with the scheme described by Edil and Dhowian (1981). Sand and tire chip samples were placed in this K_0 tube and subjected to vertical pressure by a loading plate during which the lateral strains in the tube caused by the tire chips were monitored. The thickness of the tube was carefully selected so that the strains were sufficiently low to approximate the at-rest condition on one hand and sufficiently high to be measured accurately. This method was not successful in measuring the Poisson's ratio of either sand or tire chips even though a similar system was used by Humphrey and Manion (1992) for tire chips. Consequently, it was decided to measure Poisson's ratio directly in a uniaxial (unconfined) compression test.

In the uniaxial test, the tire chips were compacted in a 305-mm mold to a height of 254 mm and subjected to an axial pressure of 5.8 kPa. At 5.8 kPa, the mold was removed and four segments of a PVC membrane were placed on the sides of the standing specimen. These segments were attached together using latex rubber as shown in Fig. 5 to allow lateral expansion with negligible lateral confinement. Thereafter, the axial pressure was increased in increments of about 3.1 kPa up to a peak pressure of 18 kPa while the lateral

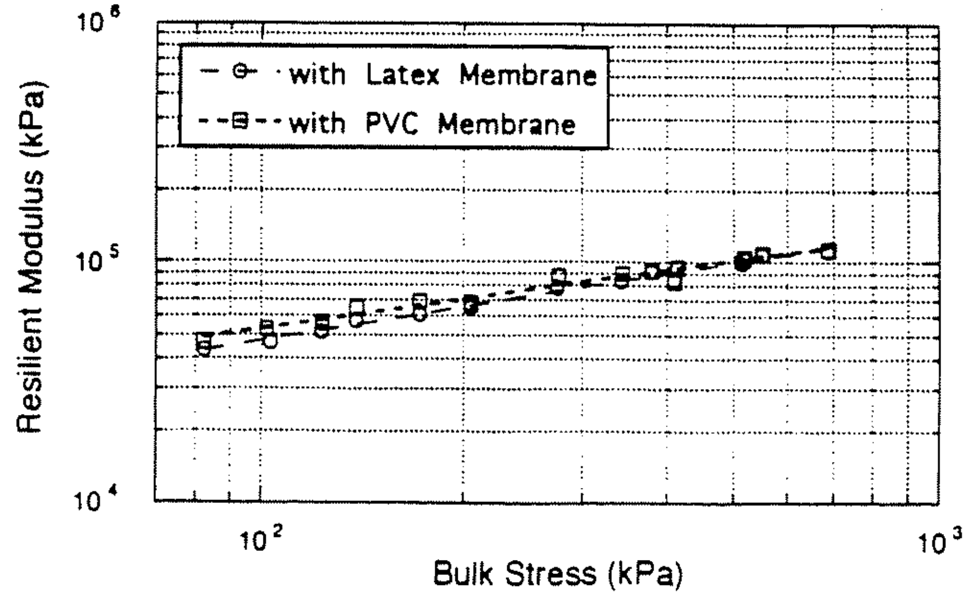

FIG. 4*a*—*Comparison of membrane type on resilient modulus of sand.*

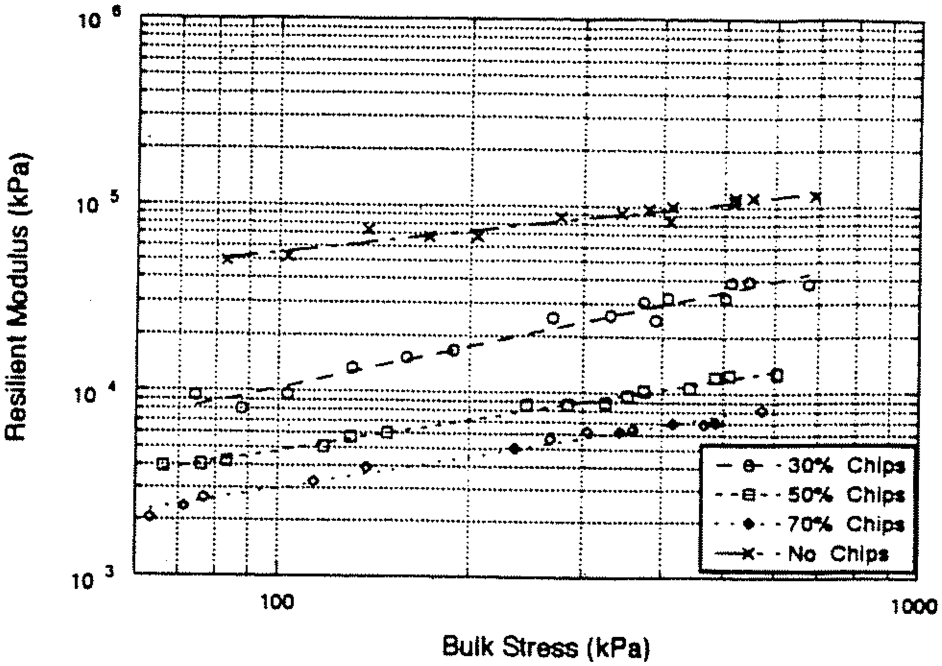

FIG. 4b—*Resilient modulus of till-chip mixtures.*

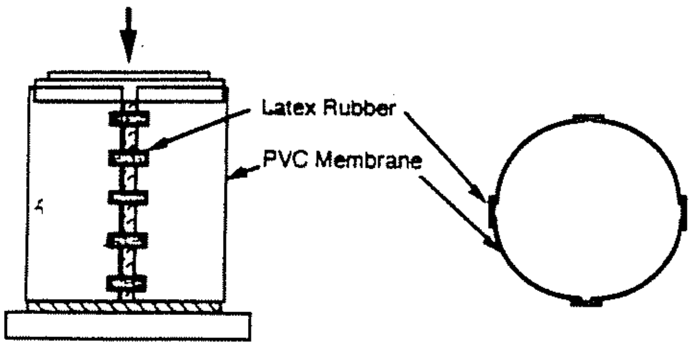

FIG. 5—*Membrane cell (305-mm diameter, 254-mm height).*

expansion of the specimen was measured at midheight by a tape and the vertical displacement was measured by an LVDT. Three loading cycles were applied to see how stable the results were. The stress-strain curves of the third cycle of loading are shown in Fig. 6. Poisson's ratio varied between 0.2 and 0.3 during the

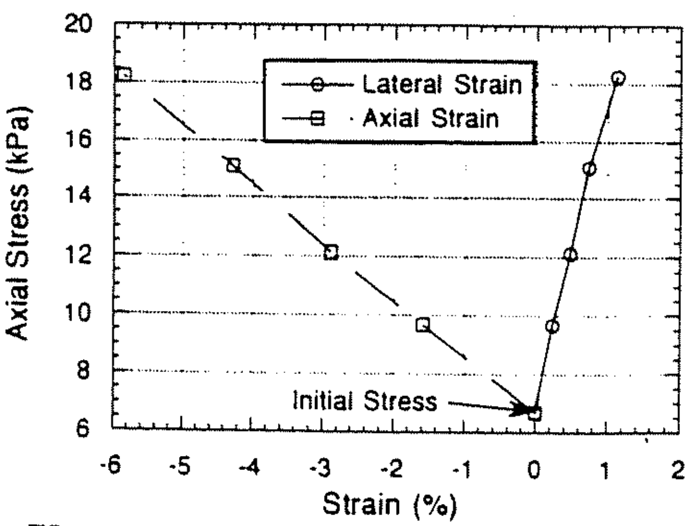

FIG. 6—*Stress versus axial and lateral strain on pure tire chips (average Poisson's ratio = 0.17).*

three cycles of loading. These values of Poisson's ratio correspond to K_0 values of 0.3 to 0.4. These K_0 values are similar in magnitude to those reported for a variety of tire chips with or without exposed belt material, i.e., K_0 of 0.25 to 0.50 (Humphrey and Manion 1992; Humphrey et al. 1993).

Shear Strength

Shear strength is a fundamental mechanical property that governs fill stability design. Tire chips appear to have high friction angles based on observed angles of repose of tire chip piles. The angle of repose of loose tire chips gave values of 37 to 43°. The angle of repose of compacted tire chips was as high as 85°. These values imply that tire chips exhibit higher friction characteristics compared to normal soils; however, the integrity of individual chips under shearing action and potential shear degradation are issues that need to be investigated for a proper characterization of the material. Reported test results indicate a range of friction angles for pure tire chips. Humphrey and Manion (1992) reported friction angles for tire chips ranging from 19 to 25° with cohesion intercepts between 8 and 11 kPa. Foose (1993) measured a friction angle of 30° without any cohesion intercept for tire chips ranging in size from 50 to 150 mm. Since there is no well-defined failure point, the failure load was taken at 25-mm horizontal displacement in a 305-mm direct shear apparatus. The effect of tire chip inclusions in the sand matrix on the shear strength of sand, i.e., the reinforcement effect, is also an interesting issue that should be explored.

Based on these premises, a large-size direct shear apparatus was constructed as shown in Fig. 7. The test apparatus consists of two 305-mm-diameter shear rings. The lower ring can slide relative to the upper ring by means of roller bearings for minimal frictional resistance. The normal stress (vertical load) is applied on the specimen by means of an air Bellofram®, and the shear stress is applied by means of an MTS® actuator with a 25-kN capacity. The actuator has a built-in load cell and displacement gage. The output of these sensors is recorded by a data acquisition system.

In order to test the new large direct shear apparatus, initial tests with Portage sand were performed at two unit weights correspond-

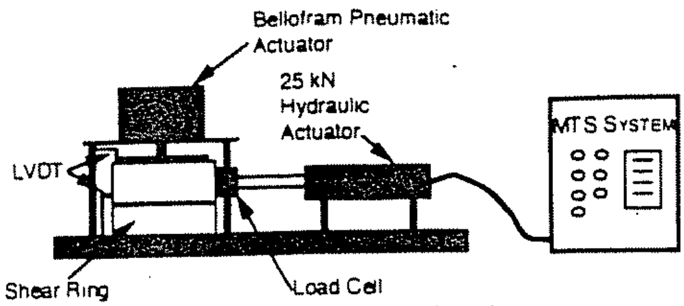

FIG. 7—*Large-scale direct shear device.*

ing to loose and dense conditions, and the results were compared with the tests performed on the same sand using the conventional direct shear apparatus with a 63.5-mm-square box. This comparison indicated that the large direct shear box performs satisfactorily. There was small but measurable friction in the case of dense sand tests attributed to sand grains possibly forced between the rings during relatively intense compaction of the sand to generate a dense condition.

Large direct shear tests were performed on Rodefeld tire chips in four mixtures with Portage sand. The specimens were prepared by compacting the premixed materials in four lifts into the direct shear ring. Each lift received 15 blows of a 22.5-N wooden ram dropped from a height of 300 mm. The mixture ratios and the resulting unit weights are given in Table 3.

The results of a test on a mixture of Rodefeld tire chips and outwash sand at a weight ratio of 25:75 under a range of vertical stresses is presented in Fig. 8. Figure 9 gives the failure envelope for the mixture with the largest amount of tire chips. These data are directly reduced from Fig. 8. Also indicated in Fig. 9 are the results obtained from the tests on pure Portage sand in the loose and dense packings. Addition of more than 10% tire chips results in shear strength greater than that of the dense sand at low or moderate normal stresses. However, at the highest normal stress level employed (76 kPa), the effect of tire chips on shear strength was not as dramatic irrespective of the tire chips content. It is clear that randomly mixed tire chips can reinforce sand to a strength greater than the strength of pure sand at its densest state while resulting in a somewhat lighter material. The unit weight of the sand portion in the mixtures was computed to be about 17.3 to 17.5 kN/m³, looser than the densest state.

The reinforcement effect of tire chips seems due to those chips that lay across the shear plane. In random mixtures, it is likely that more chips are encountered across the shear plane. In an effort to delineate the reinforcement orientation effect of tire chips, a series of tests were performed in which the same size tire chips were vertically inserted across the shear plane as shown in Fig. 10. The corresponding shear strength diagram is given in Fig. 11.

The reinforcing effect of tire chips is dependent on the amount of tire chips across the shear plane as well as the intensity of

TABLE 3—*Specimen parameters for direct shear tests.*

Mixture Ratio by Weight, $W_{chips}:W_{sand}$	Mixture Ratio by Volume, $V_{chips}:V_{sand}$	Unit Weight, kN/m³
0:100	0:100	17.0
4:96	6:94	17.1
8.8:91.2	13:87	16.8
15:85	21:79	16.6
25:75	35:65	16.0

normal stress. In the case of ten chips, the strength envelope shows bilinearity with a friction angle of 55° up to 40 kPa normal stress and thereafter 41°. The shear strength of the reinforced sand is always greater than the dense sand. This is remarkable in view of the fact that the weight ratio of ten chips is only 3%. When the number of chips is reduced to only 5 across the shear plane, the reinforcement effect is evident but not as significant. The resulting shear strength is comparable to that of dense sand even though the unit weight is somewhat lower (17.3 versus 17.6 kN/m³).

Hydraulic Conductivity

This section summarizes an investigation of the hydraulic conductivity of scrap tire chips and mixtures with sand under varying hydraulic gradients and vertical overburden pressures. Shredded scrap tires mixed with sand were investigated for use as a drainage material in road edge drains, leachate collection systems, or other drainage applications.

This phase of the research focused on the physical attributes of tire chips for use as a drainage material, that is, the hydraulic conductivity under anticipated overburden pressures. In order to measure the hydraulic conductivity under varying pressures, a special constant-head, rigid-wall permeameter was constructed (Edil et al. 1992). The test variables in the hydraulic conductivity tests included: (1) vertical pressure (0 to 172 kPa), (2) hydraulic gradient (0.5 to 1.2), and (3) mixtures with sand (0 to 100% by volume). In this phase of the research project, Rodefeld tire chips were investigated. The dry unit weight of tire chips when placed in a container (without vertical pressure) averaged about 4 kN/m³, which corresponds to a porosity of 67%.

The sand used in hydraulic conductivity tests in mixtures with tire chips was a clean, uniformly graded (poorly sorted) lake sand having a specific gravity of 2.65. The hydraulic conductivity of this sand is about 0.07 cm/s at a porosity of 40%. This sand would meet typical specifications for drainage materials.

The permeameter, shown in Fig. 12, consisted of a rigid steel ring with an inside diameter of 284 mm. Due to the high permeability of tire chips, the principal design consideration was to minimize the resistance of the permeameter itself to flow. This was accomplished by machining the base plate with a network of concentric circular grooves, channels, and numerous vertical holes leading to four effluent tubes with inside diameters of about 8 mm. A top loading plate was constructed with vertical holes allowing water to enter and be distributed laterally by a similar network of circular grooves and channels. On the inside of the top and bottom plates, stainless steel screens were used to support a No. 200 nylon mesh (0.075-mm openings) intended to prevent sand grains from entering the grooves and impeding flow. The impact of the filters was small in the permeameter (Edil et al. 1992). A vertical load could be applied on the specimens through the top plate by means of a Bellofram® air cylinder.

A constant $q\sqrt{h}$ at varying heads implies that the flow is essentially turbulent. The flow rate in the tests with pure tire chips varied with the applied driving head; however, $q\sqrt{h}$ was constant. On the other hand, the flow rate was nearly constant at varying heads when sand or sand–tire chips mixtures were tested. These observations indicate that flow through large, open pores of tire chips is turbulent and that smaller pores formed by sand result in laminar flow (Edil et al. 1992).

Hydraulic conductivity of pure tire chips is very high and therefore difficult to measure. A test using a 254-mm-thick mass of tire chips under a driving head of 127 mm gave a flow rate of

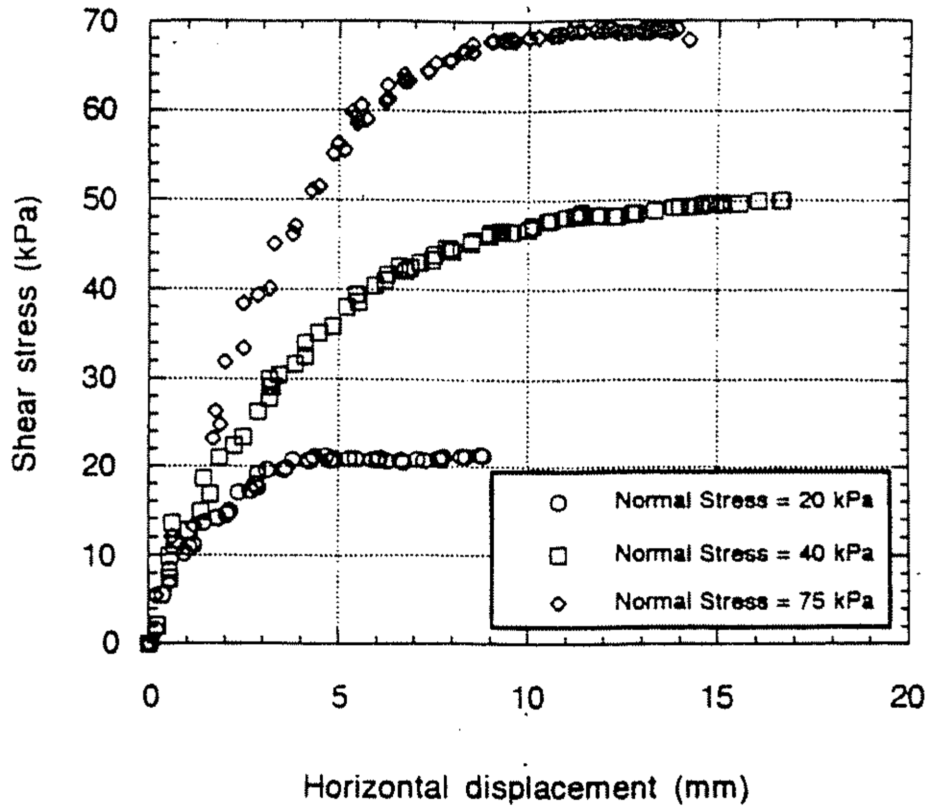

FIG. 8—*Direct shear test results on 25:75 mixture of tire chips and sand at several normal stresses.*

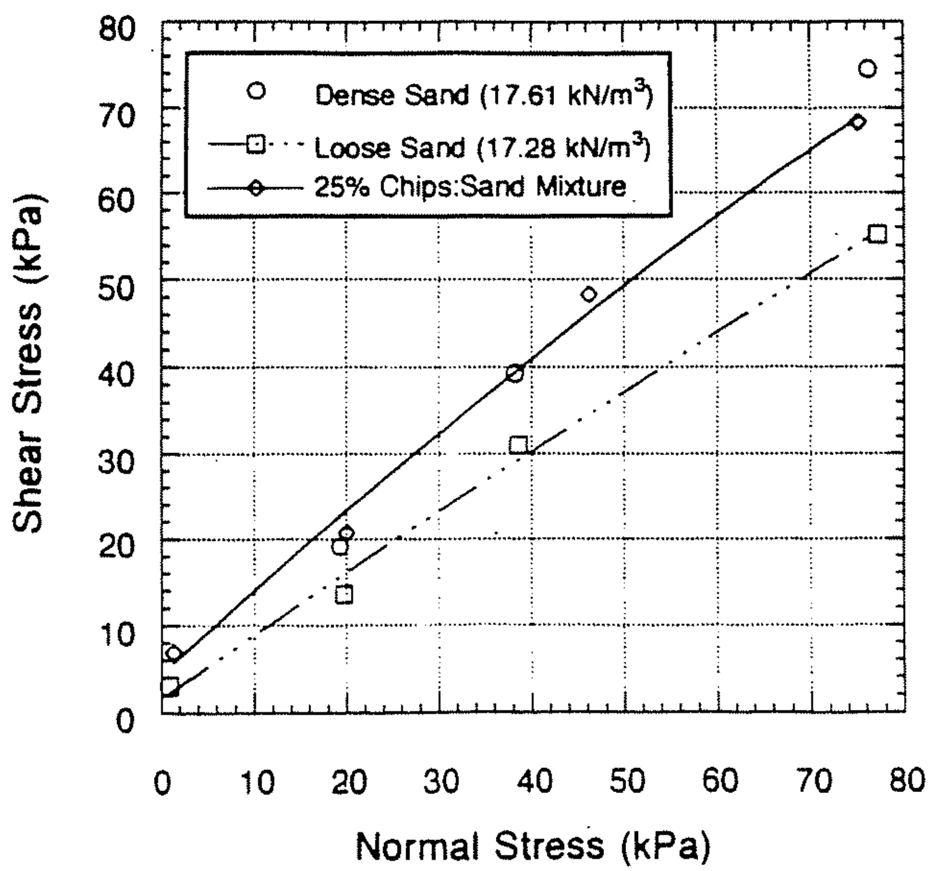

FIG. 9—*Shear strength diagram of pure Portage sand and 25:75 tire chips:Portage sand mixture.*

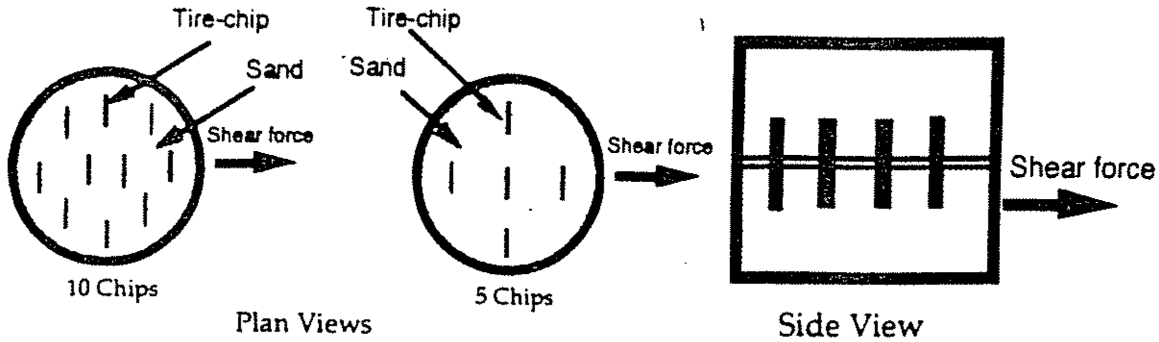

FIG. 10—*Schematic of tire chip orientation along failure surface.*

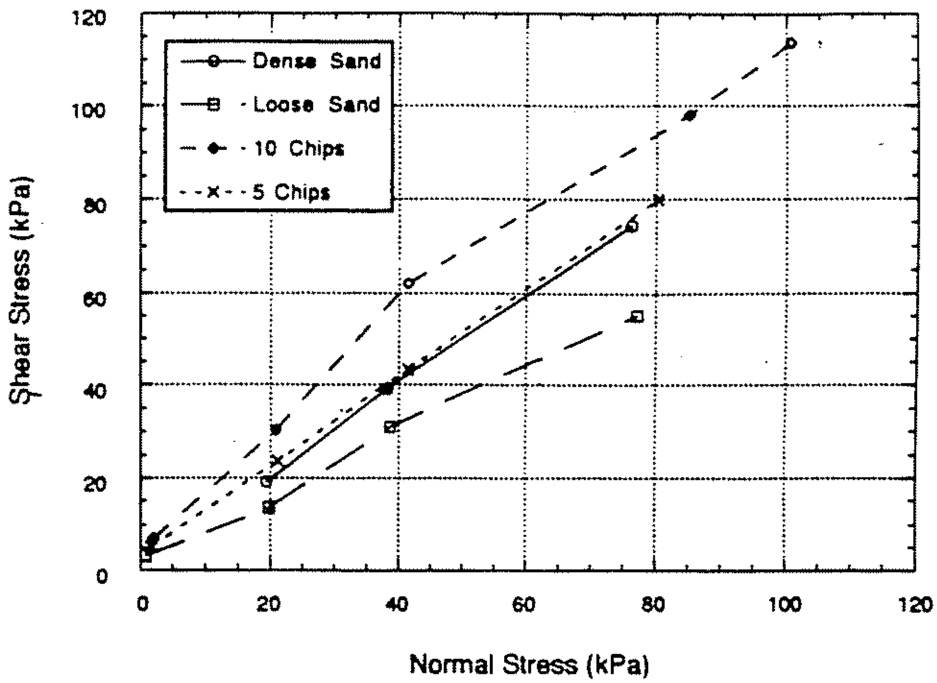

FIG. 11—*Shear strength diagram of vertically oriented chips.*

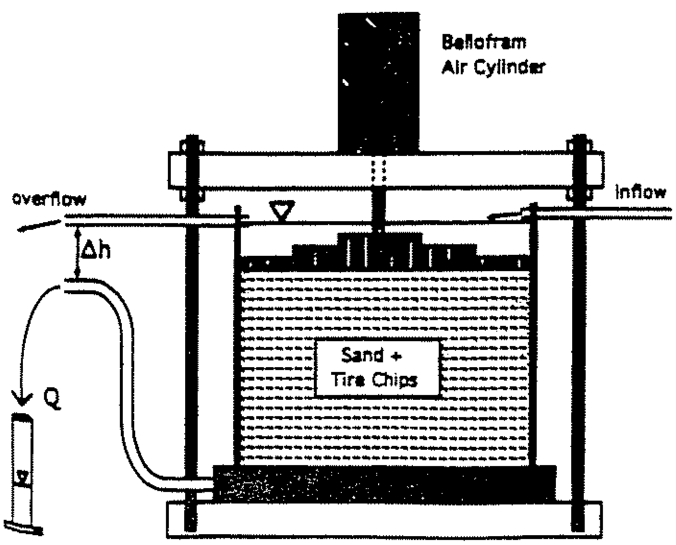

FIG. 12—*Schematic diagram of the permeameter.*

16 140 cm^3/min, which is only slightly lower than the rate of flow through the permeameter without a specimen (16 990 cm^3/min). It is possible to make a correction for the equipment resistance to flow and compute a hydraulic conductivity for tire chips. However, because of the small difference in the rate of flow, the error in computed hydraulic conductivity would be quite high. The rate of flow when sand or sand–tire chips mixtures are tested is nearly ten times lower. In these cases, the effect of the permeameter resistance on the computed hydraulic conductivities is negligible. Hydraulic conductivity values were calculated based on the measured flow rate without any correction for equipment resistance. The reported values would be indicative of the trends discussed; however, in the case of pure tire chips, they would be lower than the actual hydraulic conductivities, perhaps as much as by an order of magnitude. Of course, the values for sand–tire chips mixtures correspond to correct hydraulic conductivities.

The hydraulic conductivity is given as a function of hydraulic gradient in Fig. 13. Hydraulic conductivity of pure tire chips without overburden indicates a dependency on gradient. The implication is that the flow through the pores of tire chips is turbulent and the hydraulic conductivity will depend on the driving head. When an overburden pressure of about 100 kPa is applied, this

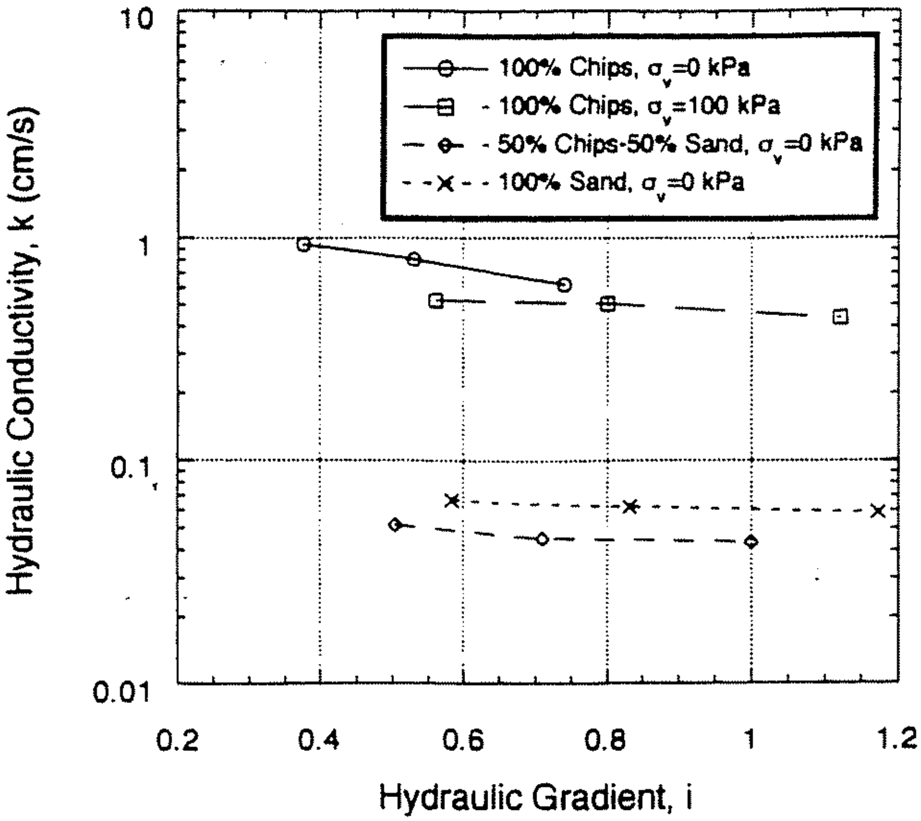

FIG. 13—*Hydraulic conductivity versus hydraulic gradient.*

dependency is reduced. Applied pressure reduces the porosity (i.e., the pore sizes) and tends to make the flow less turbulent. Figure 13 also shows the hydraulic conductivity versus gradient relationship for pure sand and a 50:50 volumetric mixture of sand and tire chips. Since the flow is governed by the smaller pores of the sand in these cases, hydraulic conductivity exhibits essentially no dependency on the gradient and the flow is laminar. The corresponding plots at 100 kPa of pressure also showed no dependency.

The influence of overburden pressure on hydraulic conductivity of pure tire chips and sand is demonstrated in Fig. 14 at a constant hydraulic head. The most significant drop in permeability takes place at the first increment of overburden pressure applied; thereafter, it continues to drop at a lower rate.

It is clear that while overburden pressure causes some reduction in hydraulic conductivity of tire chips, a significantly high hydraulic conductivity is retained at pressures as high as 100 kPa. Hydraulic conductivity under no confining pressure is close to 1 cm/s; however, this value reflects the limitation of the permeameter, and the actual value of hydraulic conductivity is probably several times more. For instance, Hall (1991) reported an average hydraulic conductivity of about 2 cm/s under no confining pressure based on his tests. Nevertheless, hydraulic conductivity of tire chips can be expected to remain high, at least on the order of 10^{-1} cm/s or more under typical overburden, a value comparable to the hydraulic conductivity of gravel. Hall (1991) reported only a 12% reduction in hydraulic conductivity under a pressure of about 69 kPa.

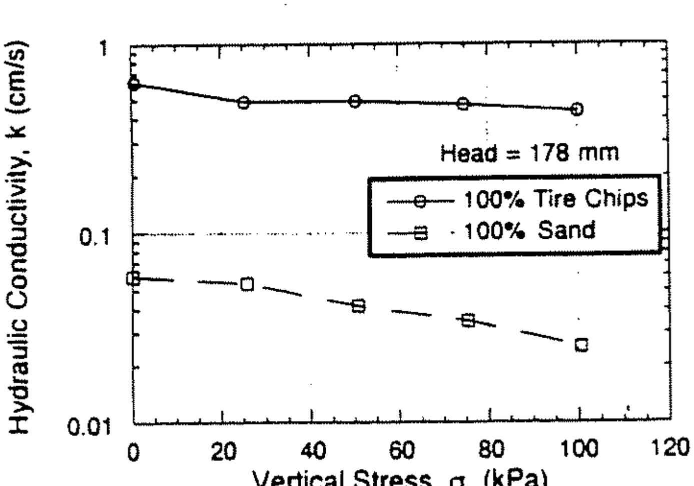

FIG. 14—*Hydraulic conductivity versus vertical pressure.*

The dependency of hydraulic conductivity on percent sand mixed into tire chips at various vertical pressures is shown in Fig. 15. At less than 30% volumetric sand content, sand does not completely fill the voids of the tire chips and tends to flow down to the bottom of the container and collect there, blocking the lower voids in the tire chip skeleton. However, in mixtures with more than 30% sand content, sand is retained in the voids throughout the tire chip skeleton and essentially controls the hydraulic conductivity of the mixture (in the range of 0.02 to 0.06 cm/s). The practical implication of this observation is that if the hydraulic conductivity of tire chips needs to be reduced, mixing 30% or more sand by volume would accomplish this objective.

Conclusions

Based on the test results, the following observations and conclusions are made regarding the engineering properties and behavior of tire chips and tire chips–soil mixtures:

1. Densification of tire chips is best achieved by application of pressure rather than vibrations. The unit weight of soil–tire chip

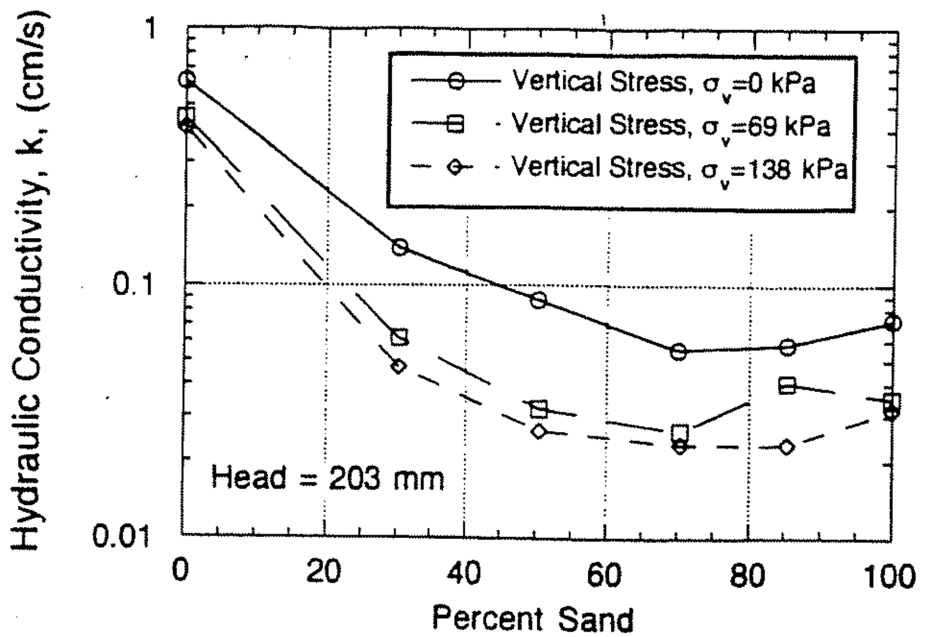

FIG. 15—*Hydraulic conductivity versus sand content of tire chip–sand mixtures.*

mixtures is controlled most significantly by the percentage of soil in the mixture and somewhat by soil type. Other factors (water content, compactive effort) are found to be insignificant. There seems to be a readily achievable level of densification which cannot be improved by controlling the moisture content and/or increasing the compactive effort. Furthermore, standard Proctor tests using a 6-in. (152.4-mm) mold can be used to determine compaction characteristics of tire chip products of equal or less than 75-mm chip size.

2. 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. Therefore, a constant overburden (like a soil cap) may be placed over tire chips to limit the compressibility under a road. 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 by weight in the tire chip matrix restores the modulus to a level comparable to pure sand. Clay mixtures exhibit lower moduli than sand mixtures at the same mixing ratios. Both the laterally constrained and resilient modulus tests can be used to determine the deformation properties of tire chip products.

3. The porosity of tire chips affects the material's stiffness. The material's porosity is affected by the size of the tire chips and by the presence of soil within the tire chip voids.

4. Tire chips display frictional behavior and appear to improve the frictional response of sand in mixtures.

5. Tire chips have high hydraulic conductivity when unconfined (more than 1 cm/s). The flow through tire chips is turbulent, and the hydraulic conductivity depends on hydraulic gradient. Overburden pressure reduces hydraulic conductivity; however, a relatively high hydraulic conductivity on the order of 0.1 cm/s or more can still be expected under typical drainage applications. There may be some concern about leachate quality since scrap tires are considered a waste material. Laboratory and field evidence available do not show any likelihood of scrap tire shreds being a hazardous waste or having a potential for significant adverse effects on water quality (Edil and Bosscher 1992).

6. Hydraulic conductivity and compressibility can be reduced significantly by mixing sand at least 30 to 50% by volume with tire chips. At such concentrations, sand begins to control the overall behavior of the mixture.

The preceding conclusions support the use of tire chips as a lightweight fill if properly confined. Tire chips also offer great potential as a drainage material in construction.

Recommendations for Testing and Specifying Tire Chips

The following recommendations are offered by the authors to aid first-time users of tire chips in testing and development of construction specifications based on the results presented here and elsewhere:

1. Specify tire chip quantities on the basis of weight, not volume.
2. Tire chip size should not be a critical specification item. Construction activities may be eased by specifying tire chips less than 75 mm (maximum dimension). Compression performance of large and small tire chips is comparable (Edil and Bosscher 1992; Edil et al. 1990).
3. Compaction specifications should not be based on a final unit weight, but the optimum number of passes should be determined based on a test section in the field. Vibratory compaction should not be specified.
4. The unit weight of pure tire chip fills typically ranges from 3 to 6 kN/m^3. This number is a function of chip size and compaction. The specific gravity of tire chips ranges from 1.13 to 1.36 (average value of 1.22) depending on the metal content. These values along with the specific gravity of other soils can be used to determine the unit weight of soil–tire [illegible] mixtures.
5. [illegible]ssibility is the governing parameter in designing [illegible]al fills using tire chips. To achieve minimum compressibility, a minimum soil cover thickness of 1 m (over the tire chips) could be specified (Edil and Bosscher 1992; Edil et al. 1990). Use of a geotextile to separate the cover soil from the porous tire chip fill is recommended to prevent

migration of the soil into the tire chip matrix, which could cause localized depressions.

6. Specifications for repetitive constrained modulus tests on tire chip products (with a maximum dimension of chips ~75 mm) should include:

   a. Minimum of 6-in. (152.4-mm)-diameter mold.
   b. Standard Proctor compactive effort during sample compaction.
   c. A seating stress of 15 kPa.
   d. Repetitive vertical stress of 125 kPa.
   e. Cyclic loading frequency of ~0.5 Hz.
   f. Repeat cyclic load until load-deformation curves converge.
   g. Computation of cyclic strain (based on specimen length at seating stress) determined from last cycle of load.
   h. Computation of repetitive constrained modulus as the ratio of cyclic stress (125 kPa) to cyclic strain.

7. Sand or clay soils can be used in tire chip mixes, although the mixing of clay and tire chips in the field may prove difficult. In addition, sand mixtures exhibit higher moduli than clay mixtures at the same soil:tire chips ratio.

Acknowledgments

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References

Ahmed, I., 1993, "Laboratory Study on Properties of Rubber-Soils," Ph.D. thesis, School of Civil Engineering, Purdue University, W. Lafayette, IN.

Ahmed, I. and Lovell, C. W., 1992, "Use of Waste Materials in Highway Construction: State of the Practice and Evaluation of the Selected Waste Products," Transportation Research Record No. 1345, Transportation Research Board, Washington, DC, pp. 1–9.

Bosscher, P. J., Edil, T. B., and Eldin, N. N., 1992, "Construction and Performance of a Shredded Waste-Tire Test Embankment," Transportation Research Record No. 1345, Transportation Research Board, Washington, DC, pp. 44–52.

Edil, T. B., Bosscher, P. J., and Eldin, N. N., June 1990, "Development of Engineering Criteria for Shredded or Whole Tires in Highway Applications," Interim Report to Wisconsin Department of Transportation, Madison, WI.

Edil, T. B. and Dhowian, A. W., February 1981, "At-Rest Lateral Pressure of Peat Soils," *Journal of the Geotechnical Engineering Division, ASCE*, Vol. 107, No. GT2, pp. 201–217.

Edil, T. B. and Bosscher, P. J., 1992, "Development of Engineering Criteria for Shredded Waste Tires in Highway Applications," Final Report to Wisconsin Departments of Transportation and Natural Resources, Research Report GT-92-9, Madison, WI.

Edil, T. B., Fox, P. J., and Ahl, S. W., 1992, "Hydraulic Conductivity and Compressibility of Waste Tire Chips," *Proceedings*, 15th Annual Madison Waste Conference, Department of Engineering Professional Development, University of Wisconsin—Madison, pp. 49–61.

Foose, G. J., 1993, "Reinforcement of Sand by Tire Chips," M.S. thesis, Department of Civil and Environmental Engineering, University of Wisconsin, Madison, WI.

Hall, T. J., 1991, "Reuse of Shredded Tire Material for Leachate Collection Systems," *Proceedings*, 14th Annual Madison Waste Conference, Department of Engineering Professional Development, University of Wisconsin—Madison.

Humphrey, D. N. and Manion, W. P., 1992, "Properties of Tire Chips for Lightweight Fill," *Grouting, Soil Improvement and Geosynthetics*, American Society of Civil Engineers, New York, Geotechnical Special Publication No. 30, Vol. 2, pp. 1344–1355.

Humphrey, D. N., Sandford, T. C., Cribbs, M. M., and Manion, W. P., 1993, "Shear Strength and Compressibility of Tire Chips for Use as Retaining Wall Backfill," Paper No. 930925, *Proceedings*, 72nd Annual Meeting of the Transportation Research Board.

JASS, 1986, Joiner Associates, Inc., Quality Improvement Software, Madison, WI.

MINITAB, Inc., 1989, Sowers Printing Company, Lebanon, PA.

Park, J. K., Kim, J. Y., and Edil, T. B., 1993, "Sorption Capacity of Shredded Waste Tires," *Green '93*, Symposium on Geotechnics Related to the European Environment, R. W. Sarsby, Ed., Bolton, U.K.

SAS Institute, Inc., 1989, Cary, NC.

SAND REINFORCED WITH SHREDDED WASTE TIRES

By Gary J. Foose,[1] Craig H. Benson,[2] and Peter J. Bosscher,[3] Members, ASCE

ABSTRACT: The objective of this study was to investigate the feasibility of using shredded waste tires to reinforce sand. Direct shear tests were conducted on mixtures of dry sand and shredded waste tires. The following factors were studied to evaluate their influence on shear strength: normal stress, sand matrix unit weight, shred content, shred length, and shred orientation. From results of the tests, three significant factors affecting shear strength were identified: normal stress, shred content, and sand matrix unit weight. A model for estimating the strength of reinforced soils was also evaluated to determine its applicability to mixtures of sand and tire shreds. When the model is calibrated using results from one shred content, it may be useful for estimating the friction angle for other shred contents. In all cases, adding shredded tires increased the shear strength of sand, with an apparent friction angle (ϕ') as large as 67° being obtained. Shred content and sand matrix unit weight were the most significant characteristics of the mixes influencing shear strength. Increasing either of these variables resulted in an increase in ϕ'. Tests were also conducted on specimens consisting of only shredded tires (no sand), and the friction angle obtained was 30°.

INTRODUCTION

Approximately 240,000,000 tires are disposed in the United States each year and currently 5 billion tires are stockpiled ("Markets" 1991; Tarricone 1993). If growing stockpiles of discarded tires are to be avoided, additional recycling and reuse of tires are essential. Such increases are contingent on the development of secondary markets (Edwards 1992), that is, markets that consume tires after collection. These markets must possess three primary attributes: (1) a need for large quantities of tires: (2) minimal requirements for processing; and (3) robustness to difficulties encountered from commingling and contamination ("State" 1994). Furthermore, the applications using reclaimed tires should be permanent. That is, the products in which used tires are employed should have a long life cycle such that the recycled tires will not be sent to the landfill in another form a few years after the product is produced.

The objective of the study described herein was to investigate the feasibility of using shredded waste tires as a means to enhance the shear strength of soil. A series of direct shear tests were conducted on mixtures of sand and tire shreds to determine which factors influence their strength. The factors that were evaluated included normal stress, sand matrix unit weight, shred content, shred length, and shred orientation. Results of the tests have also been fit to a soil reinforcement model to determine its applicability for predicting the shear strength of sand-tire shred mixtures.

BACKGROUND

Shredded Waste Tires as Construction Material

The drawbacks associated with stockpiling waste tires have prompted interest in developing new ways to reuse or recycle waste tires. Shredded waste tires are now being used as subgrade reinforcement for constructing roads over soft soils, as aggregate in leach beds for septic systems, as an additive to asphalt, as a substitute for leachate collection stone in landfills, and as sound barriers [e.g., Hall (1991); Ahmed and Lovell (1993); Park et al. (1993)]. Crumbed or shredded waste tires are being used as a fuel-supplement in coal-fired boilers, an admixture in bituminous concrete, and in low-grade rubber products, such as truck bed liners, doormats, and cushioning foams (Bader 1992; Ahmed and Lovell 1993).

Large earthwork projects using recycled tires such as those encountered in highway construction are an ideal application for shredded tires because there is potential to use vast quantities of tires while improving or maintaining performance of the earthen structure. For example, the Oregon Department of Transportation used 400,000 tires as a lightweight fill above a landslide in conjunction with a counterweight of soil to increase the factor of safety for slope stability. Slightly larger deflections than commonly encountered with fills constructed of soil only have been observed on this project, but the fill has performed satisfactorily (Upton and Machan 1993).

Large earthwork projects over soft soils have also been constructed in Minnesota (52,000 tires used), Pennsylvania, and Vermont (2,700 m^3 of tires used). Satisfactory performance has been documented in each of these projects (Read et al. 1991; Blumenthal and Zelibor 1993; Turgeon 1989; "Recycled" 1989; "Tire Fill" 1990). Plans are also being made in North Carolina for a test embankment using 65,000 tires (Ahmed and Lovell 1993).

Bosscher et al. (1993) conducted a detailed field study and reported that an embankment constructed with outwash sand and tire shreds has performed satisfactorily even after being subjected to extensive heavy truck traffic. The embankment was constructed in seven sections having different types of tire shreds and had different arrangements of soil (mixtures versus individual layers of shreds and soil). Bosscher et al. (1993) found that after a two-year period, sections constructed with pure tire shreds settled slightly more than sections constructed with soil. However, sections composed of tire shreds that were overlain with a thick (1 m) soil cap performed equally as well as the sections constructed with soil only.

However, there have been reports of problems with embankments constructed of shredded waste tires igniting ("How to" 1996). A roadway embankment containing shredded waste tires near Pomeroy, Washington had to be closed because it caught fire.

One factor limiting more widespread use of shredded tires is lack of information regarding their bulk mechanical properties. However, some laboratory studies investigating the engineering properties of tire shreds and soil-tire shred mixtures have been conducted. Edil and Bosscher (1994) and Humphrey and Manion (1992) have shown that tire shreds and soil-

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tire shred mixtures are highly compressible at low normal pressures. However, most of the compression that occurs is plastic; that is, the compressibility decreases substantially once the tire shreds have experienced one load application. Thus, preloading can be used to eliminate plastic compression once the fill has been constructed. Confinement has also been shown to reduce compressibility. Bosscher et al. (1993) and Humphrey and Manion (1992) have indicated that a vertical stress imposed by a soil cap 1 m thick will significantly reduce compressibility and deflections of overlying pavements. This finding, which is derived from both laboratory studies and finite element modeling, is consistent with field observations made by Bosscher et al. (1993).

Bosscher et al. (1993), Ahmed and Lovell (1993), and Humphrey and Manion (1992) report that tire shreds and soil–tire shred mixtures can be compacted using common compaction procedures. They have found that unit weight is primarily controlled by the amount of soil in the mixture, whereas compactive effort and molding water content appear to have little influence. Bosscher et al. (1993) and Ahmed and Lovell (1993) also report that vibratory compaction is ineffective for compacting soil–tire shred mixtures.

Edil and Bosscher (1992) and Humphrey et al. (1993) report on the shear strength of tire shreds and soil–tire shred mixtures. Edil and Bosscher (1993) conducted direct shear tests on mixtures of outwash sand and tire shreds in a large-scale shear box. They found that for dense outwash sand, adding 10% tire shreds by volume in a random arrangement resulted in greater strength than the sand alone. They also report that placing tire shreds vertically (as opposed to randomly) resulted in higher shear strength on a plane perpendicular to the shreds. However, only a few tests were conducted and definitive conclusions regarding the effects of shred content and orientation could not be made. Direct shear tests on pure shredded tires were also conducted by Humphrey et al. (1993). They reported an effective friction angle ranging from 19 to 25° and an effective cohesion ranging from 4.3 to 11.5 kPa.

MATERIALS AND METHODS

Soil and Shredded Tires

Dry Portage sand was selected for use in this study because its unit weight can be readily controlled and nearly identical specimens could be easily constructed. The particle size distribution for Portage sand is shown in Fig. 1. Portage sand has a coefficient of uniformity of 1.0, a coefficient of curvature of 1.0, and a specific gravity of 2.68. The minimum unit weight of the sand is 15.5 kN/m^3 and the maximum unit weight is 17.7 kN/m^3. Portage sand has a peak friction angle of 25° when its unit weight is 15.5 kN/m^3 and 34° when its unit weight is 17.7 kN/m^3 (Foose 1993; Benson and Khire 1994).

The shredded waste tires used in this study were selected from shredded tires remaining from a previous study conducted at the University of Wisconsin–Madison (Edil and Bosscher 1992). The stockpile included a mixture of different types of tires (steel and fiber reinforced) that were shredded at different sites in Wisconsin with various types of machinery.

The tire shreds were segregated into three groups based on length: <5 cm; 5–10 cm; and 10–15 cm. Herein, the groups are referred to as the 5-cm shreds, 10-cm shreds, and 15-cm shreds. The longest dimension of the shred was recorded as it length. A maximum length of 15 cm was selected because it was believed that mixtures containing shreds larger than this size could be severely affected by boundary effects when sheared in the direct shear machine used for testing. A minimum shred length of 0.6 cm was selected because shreds shorter than this are difficult to separate from the sand after testing. Histograms illustrating the range of shred lengths in each group are shown in Fig. 2.

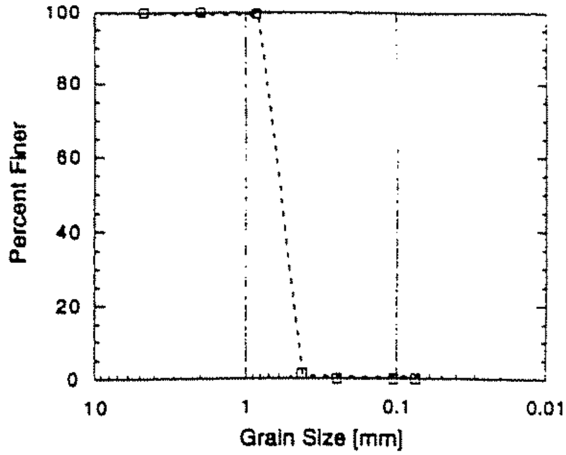

FIG. 1. Particle Size Distribution of Portage Sand

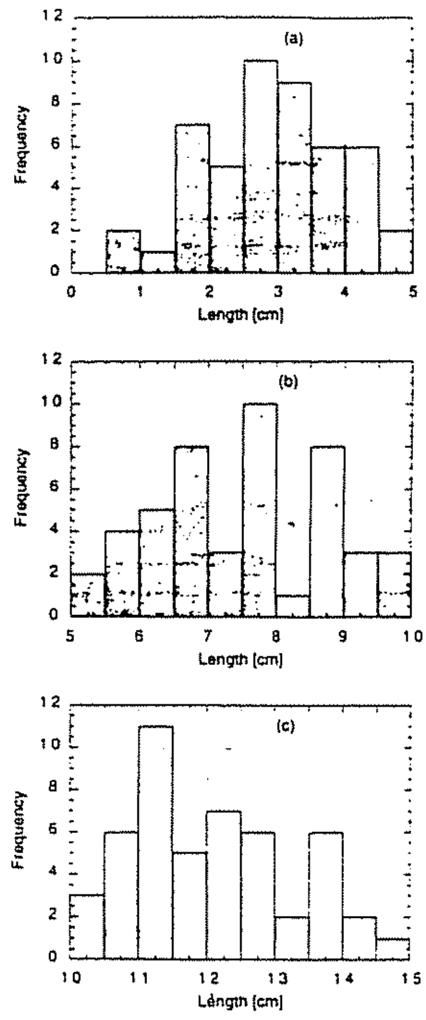

FIG. 2. Histograms of Three Groups of Shreds: (a) 5-cm Shreds; (b) 10-cm Shreds; (c) 15-cm Shreds

A photograph of grab samples collected from the three groups of shreds is shown in Fig. 3. Care was taken to maintain a wide range of surface textures in each group (e.g., treaded and sidewall). Within each group, the shreds had several notable characteristics. For the 5-cm shreds it was difficult to distinguish whether the shreds were derived from tread, sidewall, or other parts of a tire. In contrast, the 10-cm and 15-cm shreds were readily recognized as portions of tires. Three basic types of tire reinforcement were identified: large metal wires roughly 1 mm in diameter, fine metal wires with

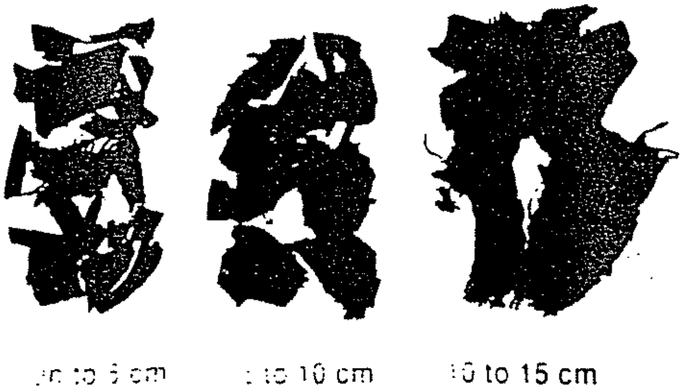

FIG. 3. Grab Samples of Tire Shreds

diameter less than 0.5 mm, and reinforcing fabric. Many of the shreds had sharp, tangled, and twisted metallic reinforcement protruding from the rubber mass (Fig. 3).

Mixtures of sand and shredded tires were prepared at specified shred contents defined on a volumetric basic (i.e., volume of tire shreds/total volume of specimen). A volumetric basis was used (instead of gravimetric) because the writers believe that a volumetric specification would be more easily implemented in the field, e.g., by courting the relative number of truck loads of soil and tire shreds. However, preparing specimens in the laboratory was more easily performed using measurements of weight instead of volume. Thus, to calculate volume from a known weight, an average specific gravity (G_{shred}) was determined for each size group of shreds using a procedure similar to ASTM D 854 (Foose 1993). The average specific gravity for each group of shreds was 1.21 for 5-cm shreds, 1.25 for 10-cm shreds, and 1.27 for 15-cm shreds. The slight increase in specific gravity with increasing shred size reflects a greater quantity of metallic reinforcement.

An approximate peak interface friction angle for the treaded portion of shredded waste tires and Portage sand was measured in a direct shear machine. Specimens were cut from shredded tires and placed in a direct shear ring (diameter = 6.35 cm). The treaded surface of the tire was set flush with the shear plane by mounting it on a disk of plywood. Shearing was then conducted at normal stresses between 7 and 70 kPa. The peak interface friction angle was 34° when the unit weight of the soil was 15.5 kN/m^3 and 39° when the unit weight was 16.8 kN/m^3. These friction angles are slightly larger than those for sand alone at the same unit weights. This may be due to the difficulty of precisely mounting the shredded tire in the shear box so that it was just flush with the interface between the two shear rings.

Direct-Shear Machine

Ideally, the shear strength of soil–tire shred mixtures should be evaluated using triaxial shear tests. However, testing mixtures of soil and tire shreds in triaxial shear is difficult, because of the size of the shreds and the sharp metallic reinforcement emanating from the shreds. Because tire shreds are relatively large, a triaxial apparatus used for testing must also be fairly large. The membrane used must be tough enough to resist puncture by metallic reinforcement yet adequately compliant such that the stiffness of the membrane would not influence the measured strength. To avoid these problems, the writers chose to evaluate shear strength using a large-scale direct shear machine. The writers believe that errors in shear strength incurred by using direct shear rather than triaxial shear were acceptable for this feasibility study.

The direct shear machine is described in detail by Foose (1993). Stainless steel rings having an inside diameter of 27.9 cm were used to construct the shear ring. The top and bottom halves of the shear ring were both 15.7 cm tall. Normal stress was applied with a pneumatic piston acting on a top plate. The shearing force was applied with an oil-driven diaphragm system and measured with a load cell. The rate of displacement was 0.13 cm/min. Horizontal and vertical displacements were measured with linearly variable differential transformers (LVDTs). A computerized data acquisition system was used to record the data.

The 15-cm shreds had an average length of 12.3 cm. This length is slightly less than one-half the diameter of the shear ring. The writers acknowledge that this could result in significant boundary effects influencing the results of tests on the 15-cm shreds and that the effect of shred length is difficult to assess from the tests conducted in this machine.

Direct-shear tests were conducted on unreinforced Portage sand in both the large-scale machine and in a Wykeham-Farrance machine having a 6.4-cm-wide square box (Model 25301) to ensure that the large-scale machine was operating properly. Nearly identical Mohr-Coulomb failure envelopes corresponding to peak strength were obtained with both machines (Foose 1993).

Preparation of Specimens

The specimens were prepared directly in the shear ring. Approximately one-fourth of the tire shreds needed to attain the desired tire shred content were initially hand placed in the bottom of the ring. Sand was rained into the shear ring on top of the shreds using a circular motion similar to the motion used to prepare a specimen for a relative density test (ASTM D 4254). The specimens were then vibrated on a vibrating table until the desired sand matrix unit weight γ_m (defined as the weight of sand divided by volume of the sand matrix) was achieved. This process was repeated until the height of the specimen was 27.5 cm. A more detailed description of the preparation procedure is contained in Foose (1993).

Definition of Failure

The direct-shear machine had a maximum lateral displacement of 2.54 cm. Some specimens tested at low normal stress (~0 kPa) exhibited a distinct peak shear stress at displacements less than 2.5 cm [Fig. 4(a)]. In these cases, shear strength was reported as the peak shear stress. However, for the majority of the tests, a peak shear stress was not reached after 2.5 cm of displacement. Instead, the shear stress continued to increase throughout the test [Fig. 4(b)]. For these tests, the increase in shear stress was greatest for displacements up to 2.0 cm. After 2.0 cm of displacement, the shear stress increased only slightly. Additional tests conducted using a modified shear box permitting 9 cm displacement had no clearly defined peak strength. Increases in strength mobilized by the additional displacement were less than 5% of the strength measured at 2.5 cm displacement (Tatlisoz 1996).

Specimens for which no peak shear stress was observed, shear stress at a displacement of 2.5 cm (relative displacement of 9%) was reported as the shear strength. A description of the failure criterion applied to each test is contained in Foose (1993).

PRELIMINARY INVESTIGATION

Significant Factors

A preliminary investigation consisting of a two-level half-fractional factorial design (Box et al. 1978) was used to identify the major factors influencing shear strength of mixtures of

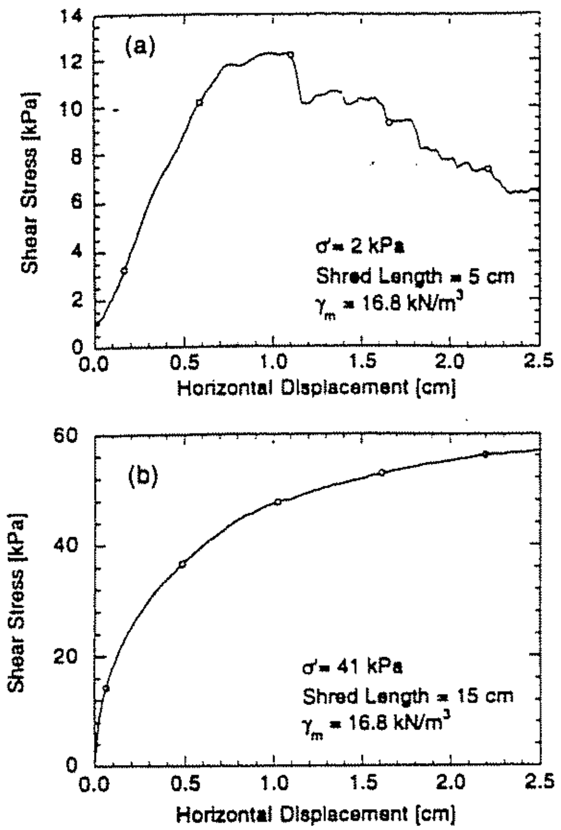

FIG. 4. Typical Relationships between Shear Stress and Displacement: (a) Case Where Definitive Peak Stress Occurs; (b) Case Where No Peak Occurs

TABLE 1. Design of Preliminary Experiment

Run (1)	Block (2)	Shred content (by volume) (3)	Shred length (cm) (4)	Orientation (5)	Matrix unit weight (kN/m³) (6)	Normal stress (kPa) (7)	Response—shear strength [kPa] (8)
1	1	10%	15	Random	16.8	25.5	37.9
2	1	10%	15	Vertical	16.8	6.2	18.6
3	1	10%	15	Random	14.7	6.2	8.3
4	1	30%	5	Vertical	14.7	25.5	37.2
5	1	30%	5	Random	14.7	6.2	11.0
6	1	30%	5	Vertical	16.8	6.2	20.7
7	1	30%	5	Random	16.8	25.5	55.2
8	1	30%	5	Vertical	14.7	25.5	32.4
9	2	10%	15	Vertical	14.7	6.2	32.4
10	2	10%	5	Random	16.8	6.2	32.4
11	2	10%	5	Vertical	14.7	6.2	13.8
12	2	30%	15	Vertical	16.8	25.5	78.6
13	2	30%	15	Random	16.8	6.2	22.8
14	2	10%	5	Vertical	16.8	25.5	29.0
15	2	30%	15	Random	14.7	25.5	42.1
16	2	10%	5	Random	14.7	25.5	19.3

sand and tire shred. The five factors studied in this first phase of experimentation were normal stress, sand matrix unit weight γ_m, shred content, shred length, and shred orientation. The measured response was shear strength (peak shear stress or shear stress at displacement of 2.5 cm). The two levels for each factor were low versus high normal stress (6.2 versus 25.5 kPa), low versus high sand matrix unit weight (14.7 versus 16.8 kN/m³), 10% versus 30% shred content, 5 versus 15-cm shreds (shred length), and random versus vertical shred orientation. A summary of the experimental design and the measured responses is listed in Table 1.

Achieving a sand matrix unit weight γ_m of 14.7 kN/m³, which is less that the minimum dry unit weight of Portage sand (γ_{min} = 15.5 kN/m³), was possible because the addition of bulky shredded tires resulted in void spaces between the

TABLE 2. Results of Preliminary Experiment

Factor (1)	Effect (2)	Standard error of effect (3)	t-statistic (4)	Significant (α = 0.05) (5)
Average	4.250	0.323	13.165	—
Block	−0.475	0.646	−0.736	No
Normal stress	3.525	0.646	5.460	Yes
Unit weight of soil matrix	−1.525	0.646	−2.362	Yes bor-der2line
Shred content	−2.375	0.646	−3.678	Yes
Shred length	1.400	0.646	2.168	No border-line
Orientation	0.875	0.646	1.355	No

Note: Critical t-statistic = 2.262 at significance level of 0.05.

TABLE 3. Results of Repeatability Analysis on Specimens Having 30% Reinforcement Content and 5 cm Shreds

Normal stress (kPa) (1)	Shear strength (kN/m²) (2)
9	18
9	16
9	16.5
9	18
9	17.3
50.3	63
50.3	62
50.3	60
50.3	58
50.3	64

shreds that could not always be filled with sand. The presence of air-filled pockets and their effect on unit weight is the primary reason why the writers chose the term sand matrix unit weight instead of "unit weight of the sand." The sand matrix unit weight is the weight of all sand and occluded air per unit volume of matrix.

A summary of the results of the two-level half-fractional factorial experiment is shown in Table 2. Yate's algorithm (Box et al. 1978) was used to calculate the effects; the variance of an effect was estimated assuming that higher order interactions were negligible. Three factors were found to be significant at the 95% confidence level (t-statistic > 2.362): normal stress, shred content, and sand matrix unit weight. Shred length and orientation were not significant for the ranges of parameters explored, although shred length was borderline. Also, the testing block [i.e., Block 1 versus Block 2 (see Table 2)] was not a significant factor, meaning there was no serial or temporal correlation between measurements.

Repeatability

Another objective of the preliminary investigation was to assess repeatability of the testing procedure. Five replicate tests were conducted at two normal stresses on the mixture having a shred content = 30%; 5-cm shreds; and γ_m = 16.8 kN/m³. Results of these tests are listed in Table 3. For replicate specimens tested at 9 kPa, the average shear strength was 17.2 kPa and the reported shear strengths ranged from 16.5 to 18 kPa. For the replicates tested at 50.3 kPa, the average shear strength was 61.4 kPa and the reported shear strengths ranged from 58 to 64 kPa. Results of the replicate tests are indicative that the procedures used to construct and shear specimens are repeatable.

PARAMETRIC STUDY

Following the preliminary investigation, a more detailed testing program was designed to examine how strength envelopes for sand-tire shred mixtures are affected by shred content, normal stress, sand matrix unit weight, and shred length. The first three factors were found to have a significant effect on the shear strength of sand–tire shred mixtures at the 5% level (Table 2) in the preliminary investigation. Shred length was also studied because it was found to be borderline significant in the preliminary investigation. However, inferences from the investigation of the effect of shred length were possibly influenced by boundary effects in the direct shear machine. Hence, results pertaining to the effect of length are not discussed in this paper. A discussion of shred length can be found in Foose (1993).

Nonlinearity of Strength Envelope

Shear-strength envelopes for sand-tire shred mixtures were developed for various mix designs. Mixtures having high sand matrix unit weight (γ_m = 16.8 kN/m^3) had strength envelopes that were nonlinear (Fig. 5). Similar strength envelopes for sand reinforced with randomly oriented discontinuous inclusions have been reported by Gray and Ohashi (1983), Gray and Al-Refeai (1986), Maher and Gray (1990), and Benson and Khire (1994). Nonlinear strength envelopes were obtained for mixtures with high γ_m at all three lengths of shreds and reinforcement contents. Therefore, it is unlikely that this behavior is strictly the result of boundary effects in the direct-shear apparatus.

The principal goal of this study was to demonstrate that shredded waste tires can be used to increase the strength of sand. Hence, it was not clearly established whether or not the strength envelopes for mixtures having high sand matrix unit weight (γ_m = 16.8 kN/m^3) were curvilinear or bilinear. The slope of the initial portion of the envelope was defined as the initial friction angle ϕ'_1 (Fig. 5), whereas the slope of the latter portion of the envelope was defined as ϕ'_2. In general, ϕ'_2 was similar to ϕ' for unreinforced sand at the same unit weight.

Maher and Gray (1990) and others refer to the normal stress at which the transition between ϕ'_1 and ϕ'_2 occurs as the critical normal stress. For the writers' experiments on sand reinforced with shredded waste tires, the normal stress corresponding to the transition between ϕ'_1 and ϕ'_2 was not clearly defined. Therefore, the critical normal stress was interpreted as a range of normal stresses rather than a precise stress at which the transition from ϕ'_1 and ϕ'_2 occurred.

Envelopes for lower γ_m (γ_m = 14.7 kN/m^3 or 15.7 kN/m^3) were approximately linear in the range of normal stresses that were tested (3–120 kPa). The only exception was a single mix having γ_m = 15.7 kN/m^3. Nevertheless, to retain consistency, the terms ϕ'_1 and ϕ'_2 were used to describe all of the strength envelopes. That is, when the envelope was linear, ϕ'_1 was the slope of the envelope and no transition from ϕ'_1 to ϕ'_2 existed.

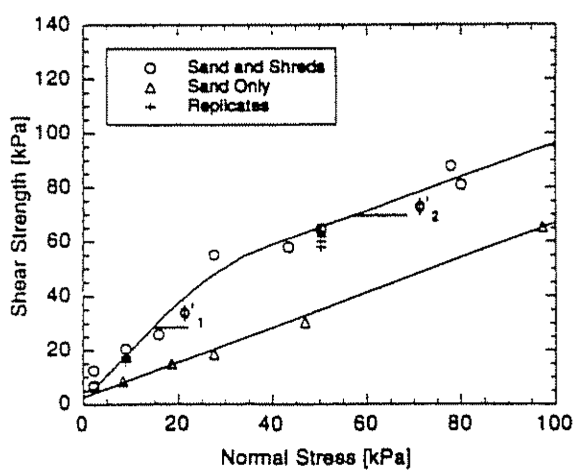

FIG. 5. Nonlinear Strength Envelope for Specimens Having 30% Reinforcement Content and 5 cm Shreds

Effect of Shred Content and Sand Matrix Unit Weight on ϕ'_1

Strength envelopes for specimens prepared with a dense sand matrix (γ_m = 16.8 kN/m^3) reinforced with 10-cm shreds and varying shred content are shown in Fig. 6. Increasing the shred content results in significant increases in shear strength, which is manifested in part as an increase in ϕ'_1.

A graph of ϕ'_1 versus shred content for all tests is shown in Fig. 7. All specimens reinforced with shredded waste tires had ϕ'_1 that was higher than the friction angle for unreinforced sand having similar unit weight. Furthermore, ϕ'_1 increased with increasing reinforcement content.

Greater ϕ'_1 was also obtained when the sand matrix unit weight was increased. The two bands shown in Fig. 7 contain data for specimens having γ_m = 16.8 kN/m^3 (upper band) or γ_m = 15.7 and 14.7 kN/m^3 (lower band). That is, the specimens with low or medium γ_m had lower ϕ'_1 (and lower shear strength) than specimens with high γ_m. On average, ϕ'_1 is approximately 15° higher for specimens having high γ_m = 16.8 kN/m^3 as compared to those having medium and low γ_m. The increase in ϕ'_1 for unreinforced Portage sand due to the same change in unit weight is only 9°.

Volume Change

Specimens having low or medium γ_m (γ_m = 14.7 or 15.7 kN/m^3) compressed during shear. For these specimens, there

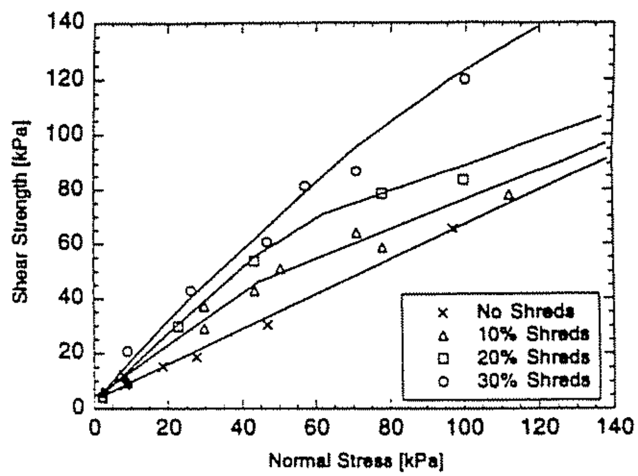

FIG. 6. Strength Envelopes for Dense Sand Reinforced with Varying Shred Content

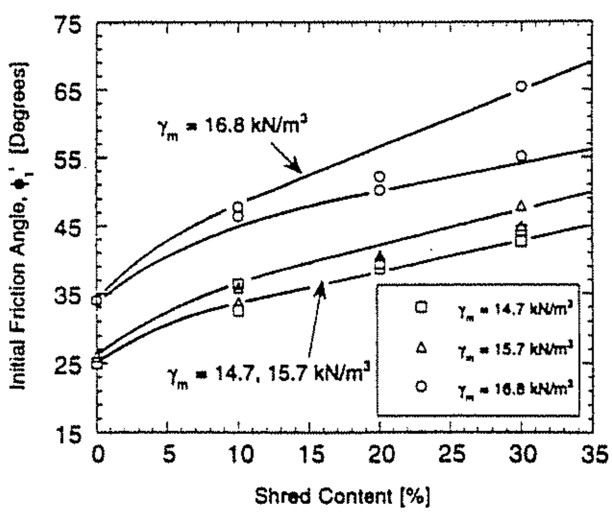

FIG. 7. Initial Friction Angle ϕ'_1 versus Shred Content

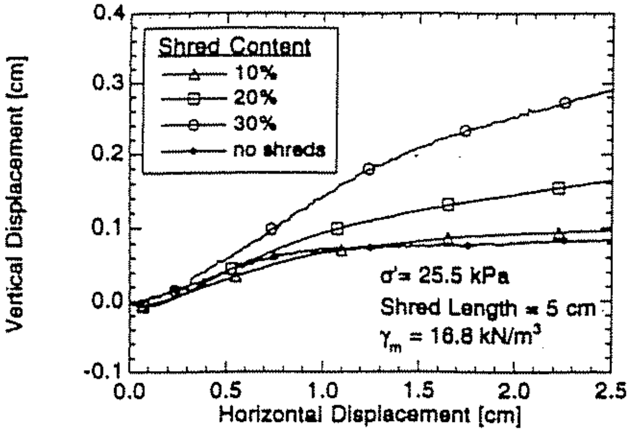

FIG. 8. Vertical Displacement for Specimens Having Varying Shred Content and 5 cm Shreds

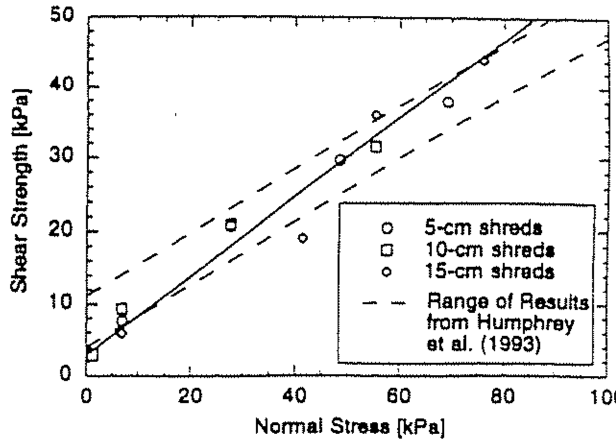

FIG. 9. Strength Envelope for Specimens Containing Only Tire Shreds

was no clear relationship between shred content or shred length and volume change.

In contrast, specimens with high γ_m dilated during shear, and greater dilation occurred in specimens having higher shred content (Fig. 8). The increased dilation that occurred at higher shred contents was probably caused by an expansion of the zone active in shear. Similar behavior has been observed by others in shear tests conducted on dense, reinforced sands [e.g., Shewbridge and Sitar (1989); Benson and Khire (1994)].

TESTS ON SPECIMENS CONTAINING ONLY TIRE SHREDS

Strength envelopes were also developed for specimens consisting solely of shredded tires. The specimens were prepared using a random arrangement of tire shreds without compaction.

Results of the tests are shown in Fig. 9. The same envelope was obtained regardless of length of the shreds; it was essentially linear having $\phi'_i = 30°$ and an effective cohesion of 3 kPa for the range of normal stresses considered (<80 kPa). This ϕ'_i is larger than the ϕ'_i reported by Humphrey et al. (1993), who found ϕ'_i for shredded tires to be between 19° and 25°. However, Humphrey et al. (1993) reported cohesion intercepts between 4.3 and 11.5 kPa, which compares favorably to the writers' data (Fig. 9).

None of the specimens exhibited a peak shear stress for displacements up to 2.54 cm. Thus, the reported ϕ'_i may be less than the friction angle that would exist in the field or under conditions in which greater displacements may occur. In fact, the writers have observed stable stockpiles of shredded tires having slopes steeper than 1:1. This is possibly indicative that the friction angle existing in the field may be much larger than that measured in this study or by Humphrey et al. (1993). It may also be that shredded tires have significantly higher cohesion in the field or that the Mohr-Coulomb failure criteria may not be an appropriate description of shear strength of shredded waste tires. Similar observations have been reported by Edil and Bosscher (1992). They observed stable stockpiles of shredded tires having a slope of 85°.

ESTIMATING STRENGTH ENVELOPES

Conducting a parametric study of the strength of soil–tire shred mixtures, such as the study described in this paper, may not be practical during design. Thus, a mechanistic model proposed by Maher and Gray (1990) for estimating the shear strength of sand reinforced with randomly distributed fibers was evaluated in this study to determine its applicability for estimating the shear strength of sand–tire mixtures. The model is formulated based on force equilibrium principles for randomly distributed fibers in soil. It was selected for two reasons: (1) It has been shown to be reasonably accurate for estimating the shear strength of reinforced soil (Maher and Gray 1990); and (2) it is relatively simple and thus can be readily applied by the design engineer. The writers acknowledge, however, that the model does not include many factors necessary for a comprehensive constitutive model.

Details describing formulation of the model can be found in Maher and Gray (1990). The key assumptions used in this formulation are that (1) The length L and diameter d of the reinforcing fibers are constant; (2) the fibers provide no resistance to bending; (3) the smaller portion of each fiber that lies on either side of a failure plane is uniformly distributed between zero and half the length of the fiber; (4) orientation of the reinforcing fibers relative to a fixed axis (e.g., the shear plane in a direct shear test) follows a uniform distribution; (5) the number of fibers in the soil mass and the number of fibers intersecting the failure plane are randomly distributed following a Poisson process; (6) sand-fiber composites have a bilinear failure envelope; and (7) at normal stresses less than the critical normal stress the fibers slip, whereas at greater normal stress they yield. In this analysis, tire shreds are assumed to behave as the fibers used in Maher and Gray's (1990) model.

Two equations are used to predict the strength envelope. Eq. (1) is used to calculate the increase in shear strength ΔS for normal stresses less than σ'_c

$$\Delta S = N_s \left(\pi \frac{d^2}{4}\right) (2\sigma' \tan \delta)(\sin \theta + \cos \theta \tan \phi')(\zeta) \quad (1)$$

where N_s is defined in (2); d = diameter of reinforcement; σ' = effective normal stress; δ = friction angle between the soil and fiber; θ = angle of shear distortion (Fig. 10); ϕ' = friction angle for the sand; and ζ = an empirical coefficient that accounts for sand granulometry and fiber properties. The parameter N_s is

$$N_s = \frac{2\beta_f}{\pi d^2} \quad (2)$$

where β_f = volumetric reinforcement content (tire shred content). The angle of shear distortion is

$$\theta = \arctan\left(\frac{x}{z}\right) \quad (3)$$

where x = shear distortion; and z = thickness of the shear zone (Fig. 10). For normal stresses greater than the critical normal stress (σ'_c), the increase in shear strength predicted by the model is (Maher and Gray 1990)

$$\Delta S_R = N_s \left(\pi \frac{d^2}{4}\right) (2\sigma'_c \tan \delta)(\sin \theta + \cos \theta \tan \phi')(\zeta) \quad (4)$$

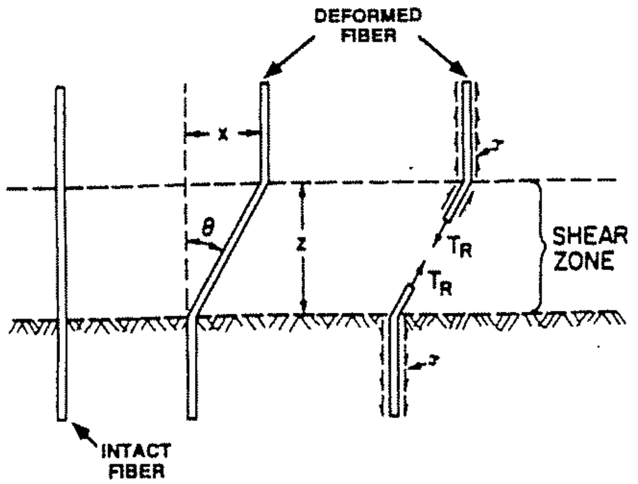

FIG. 10. Fibers Reinforcing Soil [from Gray and Al-Refeai (1986)]

TABLE 4. Measured and Predicted ϕ_i'

Shred length (cm) (1)	Matrix unit weight (kN/m³) (2)	ζ from 20% shred content (3)	Shred content (%) (4)	Measured ϕ_i' (deg) (5)	Predicted ϕ_i' (deg) (6)	Difference in ϕ_i' (deg) (7)
5	14.7	2.5	30	43	44	+1
5	14.7	2.5	10	36	33	−3
5	15.7	2.6	30	48	45	−3
5	15.7	2.6	10	34	34	0
5	16.8	3.3	30	65	55	−10
5	16.8	3.3	10	48	43	−5
10	14.7	3.4	30	44	44	0
10	14.7	3.4	10	33	33	0
10	15.7	2.3	30	45	40	−5
10	15.7	2.3	10	36	31	−5
10	16.8	4.7	30	55	58	+3
10	16.8	4.7	10	46	44	−2
15	14.7	3.9	30	49	44	−5
15	14.7	3.9	10	37	33	−4
15	15.7	5.2	30	59	50	−9
15	15.7	5.2	10	35	36	+1
15	16.8	10.4	30	67	68	+1
15	16.8	10.4	10	47	52	+5

Note: Parameter ζ calculated from tests conducted with shred content = 20%. Difference is predicted − measured ϕ_i'.

where the parameters in (4) have the same meaning as those in (1).

Fitting the experimental results to the model proposed by Maher and Gray (1990) required several simplifying assumptions. First, it was assumed that the average shred length for each group of shredded tires could be used to represent the length of reinforcement in the model. Second, the diameter of the reinforcement was assumed to equal the "diameter" of the shredded tires in each group. Because the shredded tires had irregular shapes, an effective diameter was used that corresponds to a circular cross section with equal area. Third, because the thickness of the shear zone was unknown, its width was assumed to range from the average shred length to one-half the average shred length. The friction angle between the soil and fiber δ was assumed to equal 34°. Finally, because the normal stress on the fibers was unknown, it was assumed to equal the vertical normal stress applied during shear. Errors resulting from this assumption are compensated for by the fitting parameter ζ. Finally, the shear distortion x was assumed to be 2.54 cm (the maximum displacement in the direct shear tests). Based on these assumptions, all variables in (1)–(4) were known or could be estimated, except ζ.

Maher and Gray (1990) report that ζ is an empirical coefficient that accounts for sand granulometry, fiber properties, fiber aspect ratio, and other factors not accounted for in the analyses. However, from a practical perspective, ζ is a fitting parameter.

To obtain ζ, it was back-calculated [using (1)–(4)] from strength envelopes obtained for specimens having 20% shred content. Table 4 contains a summary of the calculated ζ for mixtures having a shred content of 20%. Values of ζ vary from 2.5 to 10.4, with larger values corresponding to shreds of greater length. For sand reinforced with shredded tires the parameter ζ is the most significant factor in (1). Thus, it appears that some important phenomena of reinforcing sand with shredded waste tires may not be accounted for by the model. It is also noted that the effect of the dimensions of the reinforcement are accounted for entirely by the parameter ζ, because the effect of diameter in (1) is canceled out in (2).

A sensitivity analysis was conducted to determine the significance of the assumed shear-zone thickness. The width of the shear zone was varied from the average shred length to one-half the average shred length. For the assumed range of shear-zone thickness, the parameter ζ did not change significantly. This is to be expected considering that in (3) changes in the width of the shear zone alter the parameter θ, which is multiplied by $\tan \phi'$ in (1). Because $\tan \phi'$ is typically less than 1 and θ is generally small, changing the shear-zone thickness results in only small changes in the predicted increase in shear strength.

Predictions of ϕ_i' for shred contents of 10% and 30% were made using (1) and the ζ obtained for tests conducted at a shred content of 20%. Measured and predicted ϕ_i' for shred contents of 10% and 30% are summarized in Table 4. On average, ϕ_i' predicted using the model was 2° lower than the measured ϕ_i'. However, this close agreement can be misleading; the predicted ϕ_i' was as much as 10° lower than and as much as 5° higher than the measured ϕ_i'.

Nevertheless, Maher and Gray's (1990) model does appear useful for estimating strength envelopes for mixes with different shred contents based on results of direct shear tests performed at a single reinforcement content. However, once a mix is selected for use, prudence would dictate that additional tests be conducted to verify that the strength predicted with the model is in fact representative of the actual strength of mixture, and that similar strength envelopes will be obtained in the field.

SUMMARY AND CONCLUSIONS

The shear strength of sand-tire shred mixtures was investigated in this study. Three factors were found to significantly affect their shear strength: normal stress, shred content, and sand matrix unit weight. Furthermore, in all cases, sand containing shredded tires had higher shear strength than sand alone. Several conclusions are made based on the test results.

Strength envelopes for mixtures containing dense sand are nonlinear. Envelopes for loose or medium density sand are approximately linear in the range of normal stresses applied.

Addition of shredded waste tires to Portage sand increased its shear strength. Initial friction angles as large as 67° were obtained when the sand matrix was dense. The friction angle for unreinforced Portage sand at the same unit weight is 34°.

The initial friction angle ϕ_i' increased as the shred content was increased.

Sand matrix unit weight is an important parameter affecting the initial friction angle. Mixtures with a sand matrix unit weight of 16.8 kN/m³ have an initial friction angle that is 15° higher (on average) than the friction angle for reinforced specimens having a sand matrix unit weight = 14.7 or 15.7 kN/m³. The friction angle for Portage sand alone increases only 9° for a similar change in unit weight.

A nearly linear strength envelope having $\phi_i' = 30°$ was obtained from direct shear tests performed on specimens consisting solely of shredded tires. Similar ϕ_i' was obtained regardless of the shred length that was used.

A model proposed by Maher and Gray (1990) was used to predict the initial friction angle for sand–tire shred mixtures. On average, the measured and predicted ϕ_i' differ by 2°. However, in some cases the difference in ϕ_i' is as much as 10°. The fitting parameter ζ is the most significant factor in the model, which suggests that crucial phenomena of reinforcing sand with shredded tires are not accounted for in the model. Nevertheless, such a model may be useful during design for evaluating the benefits of different mixtures.

Shredded waste tires and mixtures of sand and shredded waste tires may be useful as soil reinforcement in highway fills, leachate collection systems on steep slopes, and other applications where strong and lightweight fill is needed. However, further study is needed to assess other important factors such as the importance of shred length, the economic aspects of using shredded waste tires as soil reinforcement, the effectiveness of shredded waste tires as reinforcement in cohesive fine-grained soils, and to see if results obtained in the laboratory are representative of field applications.

ACKNOWLEDGMENTS

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APPENDIX. REFERENCES

Ahmed, I., and Lovell, C. (1993). "Use of rubber tires in highway construction." *Utilization of Waste Mat. in Civ. Engrg. Constr.*, ASCE, New York, N.Y., 166–181.

Bader, C. (1992). "Where will all the tires go?" *Municipal Solid Waste Mgmt.*, 2(7), 26–34.

Benson, C., and Khire, M. (1994). "Soil reinforcement with strips of reclaimed HDPE." *J. Geotech. Engrg.*, ASCE, 120(5), 838–855.

Blumenthal, M., and Zelibor, J. (1993). "Scrap tires used in rubber-modified asphalt pavement and civil engineering applications." *Utilization of Waste Mat. in Civ. Engrg. Constr.*, ASCE, New York, N.Y., 182–201.

Bosscher, P. J., Edil, T. B., and Eldin, N. (1993). "Construction and performance of shredded waste tire test embankment." *Transp. Res. Rec., No. 1345*, Transp. Res. Board, Washington, D.C., 44–52.

Box, G., Hunter, W., and Hunter, J. (1978). *Statistics for experimenters*. Wiley-Interscience, New York, N.Y.

Edil, T., and Bosscher, P. (1992). "Development of engineering criteria for shredded waste tires in highway applications, final report." *Res. Rep. GT-92-9*, Wis. Dept. of Transp., Madison, Wis.

Edil, T., and Bosscher, P. (1994). "Engineering properties of waste tire chips and soil mixtures." *Geotech. Testing J.*, 17(4), 453–464.

Edwards, J. (1992). "Markets first." *Municipal Solid Waste Mgmt.*, 2(6), 6.

Foose, G. (1993). "Shear strength of sand reinforced with shredded waste tires," MSc thesis, Dept. of Civ. and Envir. Engrg., Univ. of Wisconsin-Madison, Wis.

Gray, D., and Al-Refeai, T. (1986). "Behavior of fabric-versus fiber-reinforced sand." *J. Geotech. Engrg.*, ASCE, 112(8), 804–820.

Gray, D., and Ohashi, H. (1983). "Mechanics of fiber reinforcement in sand." *J. Geotech. Engrg.*, ASCE, 109(3), 335–353.

Hall, T. (1991). "Reuse of shredded tire material for leachate collection systems." *Proc., 14th Annu. Madison Waste Conf.*, Dept. of Engrg. Prof. Devel., Univ. of Wisconsin, Madison, Wis., 367–376.

"How to 'burn rubber' on a gravel road." (1996). *East Washingtonian*, (114:31; Jan. 31).

Humphrey, D., and Manion, W. (1992). "Properties of tire chips for lightweight fill." *Grouting, Soil Improvement, and Geosynthetics, Vol. 2*, ASCE, New York, N.Y., 1344–1355.

Humphrey, D., Sandford, T., Cribbs, M., and Manion, W. (1993). "Shear strength and compressibility of tire chips for use as retaining wall backfill." *Transp. Res. Rec., No. 1422*, Transp. Res. Board, Washington, D.C., 29–35.

Maher, M., and Gray, D. (1990). "Static response of sands reinforced with randomly distributed fibers." *J. Geotech. Engrg.*, ASCE, 116(11), 1661–1677.

"Markets for scrap tires." (1991). *EPA/530-SW-90-074A*, U.S. Envir. Protection Agency, Office of Solid Waste, Washington, D.C.

Park, J., Kim, J., and Edil, T. (1993). "Sorption capacity of shredded waste tires." *Green 93, An Int. Symp. on Geotech. Related to the Envir.*, A. A. Balkema, Rotterdam, The Netherlands, 341–348.

Read, J., Dodson, T., and Thomas, J. (1991). "Use of shredded tires for lightweight fill." *Rep. No. DTFH-71-90-501-OR-11*, Oregon Dept. of Transp., Hwy. Div., Rd. Sec., Salem, Oreg.

"Recycled rubber roads." (1989). *Biocycle*, 30(2).

Shewbridge, S., and Sitar, N. (1989). "Deformation characteristics of reinforced sand in direct shear." *J. Geotech. Engrg.*, ASCE, 115(8), 1134–1147.

"State on recycling edge—despite new laws, plenty of trash still goes to waste." (1994). *Wisconsin State J.*, Jan. 9, 9A.

Tarricone, P. (1993). "Recycled roads." *Civ. Engrg.*, ASCE, 63(4), 46–49.

Tatlisoz, N. (1996). "Using tire chips in earthen structures," MSc thesis, Dept. of Civ. and Envir. Engrg., Univ. of Wisconsin, Madison, Wis.

"Tire fill stabilizes roadway embankment." (1990). *Public Works*, 120(11), 68.

Turgeon, C. (1989). "The use of asphalt-rubber products in Minnesota." *Rep. No. 89-06*, Minnesota Dept. of Transp., Minneapolis, Minn.

Upton, R., and Machan, G. (1993). "Use of shredded tires for lightweight fill." *Transp. Res. Rec., No. 1422*, Transp. Res. Board, Washington, D.C., 36–45.

Construction and Performance of a Shredded Waste Tire Test Embankment

PETER J. BOSSCHER, TUNCER B. EDIL, AND NEIL N. ELDIN

The construction and performance of a test embankment designed to evaluate the use of shredded waste tires as soil replacement in highway construction are described. The shredded tires offer the advantage of low unit weight and durability. The test embankment was designed and built to test key variables including chip size, confining overburden pressure, and use of chip-soil mixtures or chip-soil layering. The embankment consisted of sections, each 20 ft long, containing differing chip-soil compositions. The embankment was constructed parallel to the access road of a sanitary landfill and exposed to the heavy incoming truck traffic. Field data were collected to assess the stability and deformation of the road surface, compaction of tire chips, and quality of tire chips leachate. Observations were made to assess the potential difficulty of depositing and compacting layers of tire chips. Normal construction machinery can be used successfully with tire chips, though rubber tires can be punctured by the exposed wires at the edge of the chips. Vibratory or static compaction does not significantly induce compaction in tire chips. After an initial adjustment period, the overall road performance was similar to most gravel roads. Tire chips used as a replacement for fill under a road perform better when covered by 3-ft-thick soil caps compared with chips covered by only 1 ft of soil. Furthermore, the void ratio of the pure tire chips affects its stiffness. The leachate quality data indicate that shredded automobile tires show no likelihood of having adverse effects on groundwater quality. The findings support the use of properly confined tire chips as a lightweight fill in highway applications.

With the banning of whole tires in sanitary landfills, stockpiles of waste tires are growing in the country. For example, it is estimated that there are 20 million waste tires in Wisconsin, with an additional 4 million generated each year. Whole tires are not easily disposed of for several reasons, including their poor compressibility and their potential combustibility and associated toxic fumes. Recycling is also difficult due to the composite structure of tires: integrally combined rubber, synthetic fibers, and steel wire. Shredding is one common means of modifying waste tires to ease disposal. Finding large-volume uses of shredded tires is desirable to increase the lifetime of sanitary landfills.

The findings from an experimental test embankment designed and constructed to provide information regarding the behavior of waste tire chips as a fill material are summarized. The research specifically examined the difficulty of constructing a fill made of tire chips, the stability and deformability of tire chips used below a road surface, and the environmental acceptability of the leachate that passed through the tire chip fill (*1*).

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CHARACTERIZATION AND CLASSIFICATION OF TIRE CHIPS

To characterize and classify the range in size and shape of shredded tires, an inventory of the waste tire stockpiles and shredders in Wisconsin was developed by visiting most of the tire-shredding operation sites. The shredding process was videotaped at the sites visited, representative bag samples were taken, and the owners/operators were interviewed. Data were collected regarding shredding operations, type of machinery used, product cost, and product types and characteristics. Most processors use fairly small mobile shredding equipment of 30 to 100 HP. These shredders use a shearing process in contrast to the tearing process in the older versions. The shearing process produces more uniform products, makes cleaner cuts, and eliminates the partial pulling of the reinforcing wires out of the tire chips. The production rate ranged from 100 to 400 tires per hour depending on the machinery type and desired chip size. The cost of shredding ranged from $30 to $65 per ton, 1 ton equaling approximately 100 tires.

The size of the tire chips is dictated primarily by the design of a particular machine and the setting of its cutting mechanism. Small chips are produced by processing the material through more than one shredder, each set to produce finer cuts than its predecessor. Classifiers can also be used to separate the finer sizes from coarser ones. Usually the chips are shaped irregularly, with the smaller dimension being the size specified by the manufacturer and the larger dimension two to four times as much. Samples collected from sites visited range from 1 × 2 in. to 4 × 18 in., with the most common size chip being 2 × 3 in. Classifiers are not typically used on these sites. Figure 1 shows information concerning the minimum tire chip sizes of samples collected from four shredding sites. The names of the tire chips were assigned on the basis of the location of the shredding process.

After reviewing the tire chip samples collected, three distinct size groups were recognized. The Edgar chips were the smallest and were produced by a tearing action resulting in significant amounts of loose metal fibers. At the other extreme, the Verona chips (not plotted in Figure 1 because of size extremes) had passed through only one cycle of shredding and consisted of large striplike pieces up to a length of 12 in. Between these two extremes were the Franklin and the Rodefeld tire chips. These chips had an intermediate size, the Rodefeld chips being somewhat coarser than the Franklin chips. Because of the availability of the Rodefeld chips at the construction site, it was decided to use the Edgar, Verona, and Rodefeld tire chips with the Rodefeld the main tire chips to be investigated. The large chips, referred to as the Verona

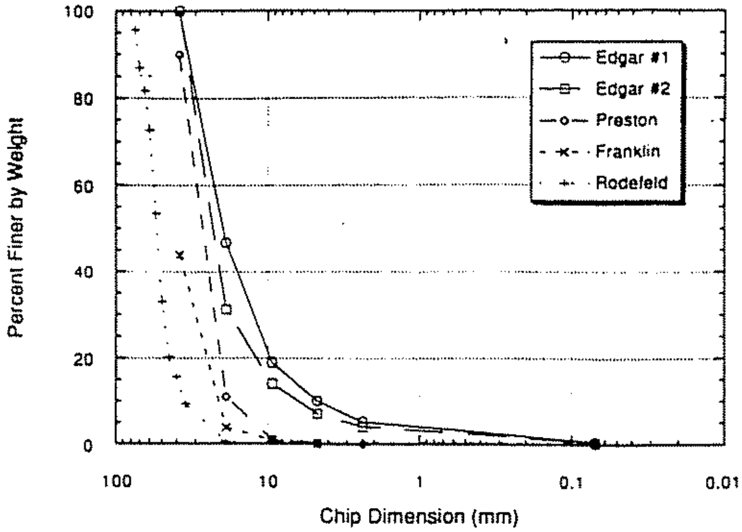


FIGURE 1 Size distribution data of tire chips.

chips, were originally sampled at the Dane County Verona Landfill. However, the first cycle of shredding at the Rodefeld site produced a product similar to the Verona chips. Therefore, in the construction of the test embankment, the coarse Rodefeld material was used. However, the name "Verona" was retained for ease of identification.

TEST EMBANKMENT DESIGN AND CONSTRUCTION

The test embankment was constructed in Dane County Landfill No. 2 (Rodefeld Landfill) near Madison, Wisconsin. This site offered a sufficient supply of the main chip size to be tested and an abundant soil source. The test embankment was constructed parallel to the access road near the landfill entrance, allowing the diversion of a known quantity of heavy traffic (incoming refuse trucks) onto the test embankment as desired. The trucks were individually weighed as they brought their refuse to the landfill, providing a record of the traffic. Regular weather monitoring and ground and surface water monitoring at the landfill site provided environmental data.

Test Embankment Design

In designing the test embankment, the following factors were considered:

1. Tire chip size and type.
2. Soil type and chip-to-soil ratio for chip-soil mixture, and
3. Placement conditions (pure chips, mixed with soil, or layered).

An available soil at the landfill site (a glacial outwash gravelly sand) was chosen to be mixed with the chips. The grain size curve of this sand is given in Figure 2. It is a well-graded, predominantly coarse-grained material with some fines in it. It is classified as an A-1-b(0) granular material in the AASHTO system and an SW well-graded sand with gravel in the USCS.

Three soil-chip compositions were adopted for study: pure tire chips, tire chips mixed with soil, and tire chips layered with soil. For the chip-soil mixture, a ratio of 50 percent tire chips and 50 percent sand by volume was chosen. The mixing was achieved in the field by a relatively simple operation using a backhoe. The layered tire chip and soil section was built by placing alternating 1-ft lifts of tire chips and sand. In this section, an overall ratio of tire chips to sand was targeted to be the same as used in the mixture.

In two of the sections a thicker soil cap was designed to assess its effect in reducing the deformation of the chips under traffic loading. In addition to testing tire chips, it was decided to include a fiber-reinforced soil in the construction of the test embankment. Reinforcement fibers obtained from Synthetics Industries were mixed into the sand at two different ratios and placed in two separate sections in the test embankment. This paper will focus only on the behavior of the tire chip sections of the embankment. However, reference is made to these fiber-reinforced sections for the purpose of comparison.

On the basis of site geometry and number of variables, the test embankment has eight sections, each 20 ft long as shown in Figure 3. The six tire chip–soil cross sections are shown in Figures 4a and 4b. Along with the approaches built of sand, the test embankment included a total of 10 sections to be monitored and compared. The test embankment has a nominal height of 6 ft with side slopes of 1V:2H. The crest width is 16 ft wide to permit safe passage of large trucks.

Field Compaction

After scraping off the surface organic soils, an elevation survey was made of the foundation base. A geotextile was then placed to separate the foundation soils from the embankment materials. A geotextile was also placed between the tire chips and the soil cap in Section 4 as well as over the whole embankment before placing the gravel wear coarse and the organic soils on the slopes. The embankment was constructed in six lifts of approximately 1 ft each. During the compaction

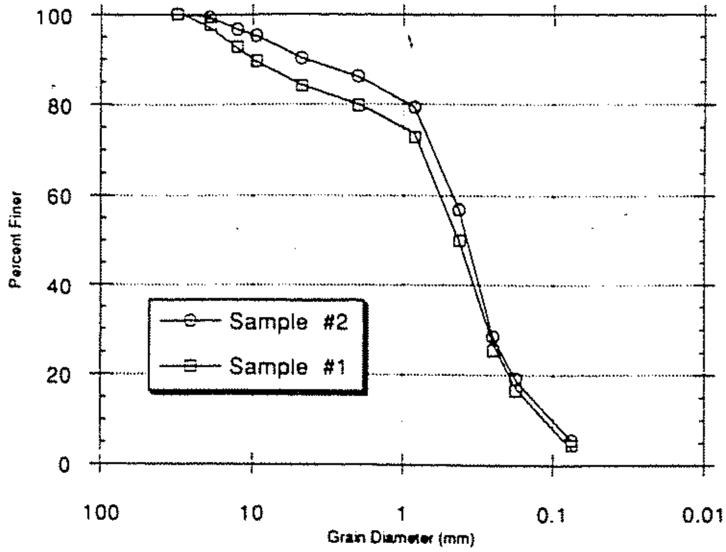


FIGURE 2 Grain size distribution of outwash sand.

of the first lift, surface elevation measurements were made after each pass of the compactor. Since the surface was irregular due to the large tire chips, these measurements were made from a 2 × 2 ft steel plate placed at the center of each section. The compactor used was a Case 1102 PD 12-ton sheepsfoot roller with vibratory capability (26 ft-tons). The north half of the first lift was compacted with vibration on, whereas the south half was subjected to no vibratory action. The corresponding lift thicknesses were computed from the surface elevations.

Examination of the data indicated that vibratory action improved compaction of the tire chips somewhat (25 measurements out of 40 showed more compaction for the vibrated side), but not enough to support use of vibratory rollers. A comparison of the first pass with the fifth pass indicated no additional compaction in the tire chip sections. In general, tire chips showed little plastic deformation due to compaction, unlike the soil sections.

The density achieved during construction was monitored by computing unit weights from a record of the weights of the soils and chips used and the embankment dimensions. Figure 5 shows the calculated unit weights of each material as they were encountered in each section (e.g., S1 = Section 1). Densities of the Rodefeld and Edgar tire chips (medium and finest size) were comparable at 25 to 35 lb/ft³ range, but the density of the Verona chips (coarser chips) was decidedly lower at 19.3 lb/ft³ even though the Verona chips were confined with an additional foot of sand because of their large initial compression during the placement of the soil cap (*1*). Sand used in interlayering with the Rodefeld chips in Section 1 was not compacted as well as the top cap sand layer in Sections 3 and 4 (60 lb/ft³ versus 105 to 111 lb/ft³). In Section 1 this may be due to the lack of inertial mass of soil to compact against, whereas in Sections 3 and 4 the soil mass is two or three times thicker. The Rodefeld/Sand mixture used in Section 6 had an average unit weight of 75 lb/ft³.

Embankment Instrumentation

The instrumentation of the embankment was designed to evaluate the compressibility of the embankment. Slope stability was not deemed to be a problem because of the high friction angle of tire chips; the angle of repose of the piles of tire chips was more than 50 degrees. The compressibility behavior of the test embankment was monitored by regular surveys of surface markers and settlement plates located in the embankment. For surface surveys, target markers were placed at seven locations in the center of each section, as shown in Figure 6. The marker consists of a 2-in. square, ¼-in.-thick plate with a 10-in.-long #4 rebar anchor welded in its center. There are 70 markers on the embankment and the two approaches. Periodic surveys of these markers provide the x, y, and z coordinates of these points and the changes thereof.

In addition, 10 settlement plates were placed in the embankment. The settlement plates are standard Wisconsin DOT plates, consisting of a 2-ft-square plate with a rod and a friction pipe. They were placed roughly in the midheight of the embankment (on the third compacted lift from the base) in each test section. An additional plate was placed on the foundation base in Section 4 to measure foundation settlement (see Figure 4b).

Two leachate collection lysimeters used for obtaining leachate samples were constructed by cutting a 1-ft-deep, 10-ft by 12-ft hole in the sand base (see Figure 3). The collection lysimeters were placed in the base of Sections 2 and 5 because these sections contained pure tire chips and were thought to be the sections in which the leachate would be the most affected by the tire chips. The lysimeters consisted of a 10- × 12-ft square, 30-mil-thick PVC liner with 1-ft-high sidewalls. It was filled with gravel and fitted with a 4-in. pipe boot. A nonwoven geotextile covered the collection system. The base of the hole was sloped to the center and in the direction of the 4-in. pipe. The pipe conducts the collected leachate to

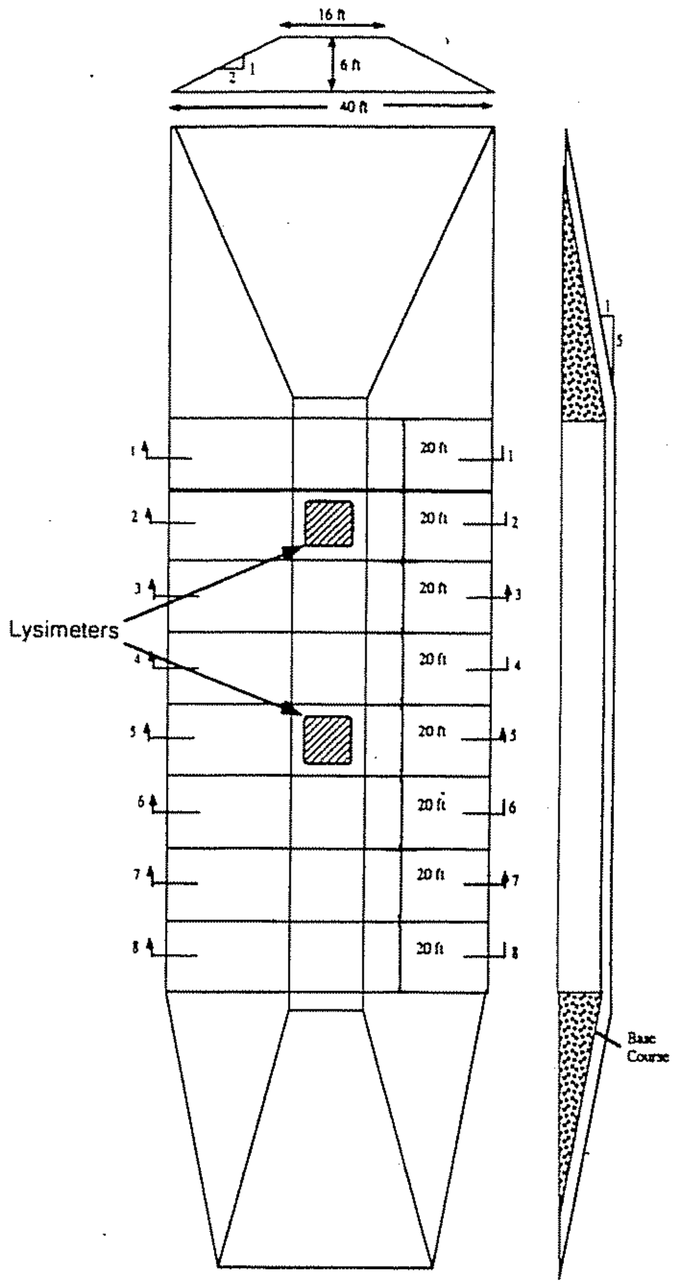


FIGURE 3 Plan view of test embankment design.

the south side of the slope into a 66-in.-deep cylindrical container of inside diameter 6 in. The container is fitted with a cap and allows retrieval of leachate samples. The pipes and the container were all built using PVC.

Construction Observations

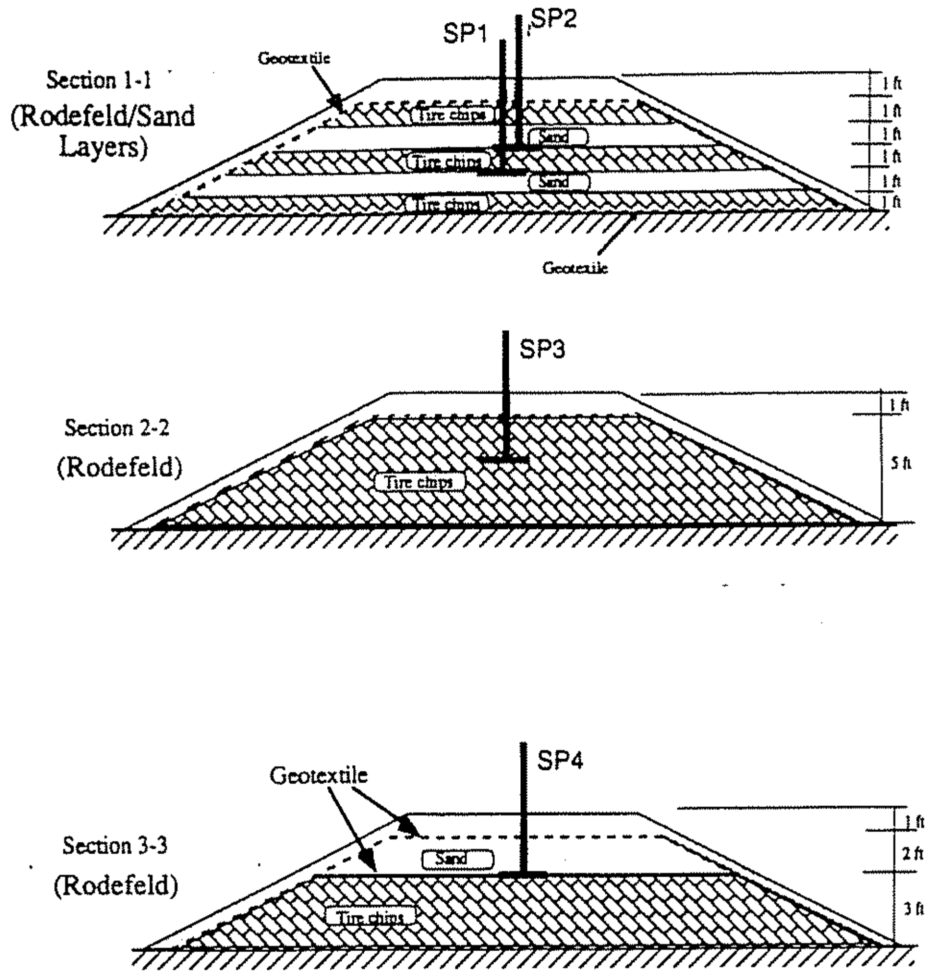
The following observations were made during the construction process:

1. The handling and placement of the tire chips were not problems. The backhoe seemed more capable of spreading the material evenly for each section than the front-end loader or grader.

2. Tracked equipment had no trouble maneuvering over the shredded tire fill, but trucks occasionally became stuck and had to be pulled out when the lifts of pure tire chips were more than 2 ft thick. Flat tires on dump trucks also occurred from driving over tire chips.

3. Vibratory compaction did not have an advantage over nonvibratory compaction because of the low inertial mass of the tire chips and their tendency to rebound.

4. Although the chips compressed with each pass of the roller, rebound of the chips was visible behind the compactor. Only the first pass appears to induce a small amount of per-



(a)

FIGURE 4 Elevation view of test embankment sections as designed: (*a*), Sections 1, 2, and 3; (*b*), Sections 4, 5, and 6. (*continued on next page*)

manent compaction, with the other passes being totally ineffective.

TEST EMBANKMENT PERFORMANCE

Traffic and Maintenance

The embankment was constructed parallel to the access road of a sanitary landfill and exposed to the heavy incoming truck traffic, which is weighed before entering the landfill. Approximately 60 to 100 trucks per day weighing an average of 21.6 tons per vehicle pass over this embankment. The standard deviation of truck weight is approximately 10 tons; the weight of some trucks is more than 45 tons. On June 4, 1990, the test embankment was opened to traffic. On June 8, 1990, the embankment required regrading because of immediate rutting under the traffic load. This was accomplished by adding 32 tons of crushed rock (base course) over the whole test embankment. From June through August the embankment went through several cycles of regrading, opening to traffic, rutting and pothole formation, closing to traffic, and back to regrading. The west approach of the embankment was particularly affected even though it was built using soil without any tire chips. Furthermore, dust due to traffic was threatening the air quality near the landfill. On October 3, 1990, the west approach was regraded using 31 tons of base course. In addition, minor work was performed on the east approach. Later a calcium chloride treatment for dust control was applied, and the embankment was reopened to traffic on October 26, 1990. On December 3, 1990, the test embankment was closed to traffic for the winter after a record snowfall (17 in.). On April 10, 1991, potholes that developed in the east approach, especially at the contact with the asphalt pavement, were repaired, and the embankment was again opened to traffic. Traffic has been routed over the embankment throughout spring, summer, and fall 1991 with virtually no closures. At the present time, an asphalt concrete pavement is being placed on the embankment to permit traffic throughout the coming winter months and to investigate the performance of asphalt concrete pavement founded on a tire chip fill.

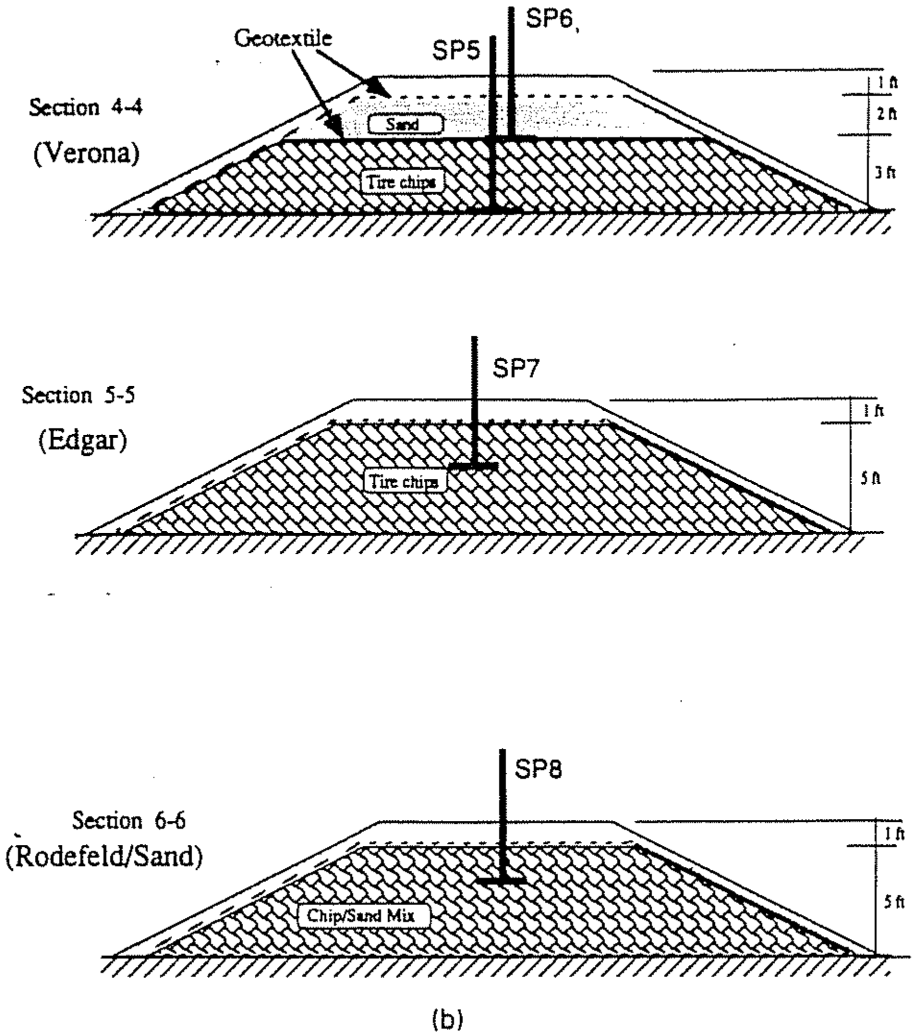


FIGURE 4 (*continued*)

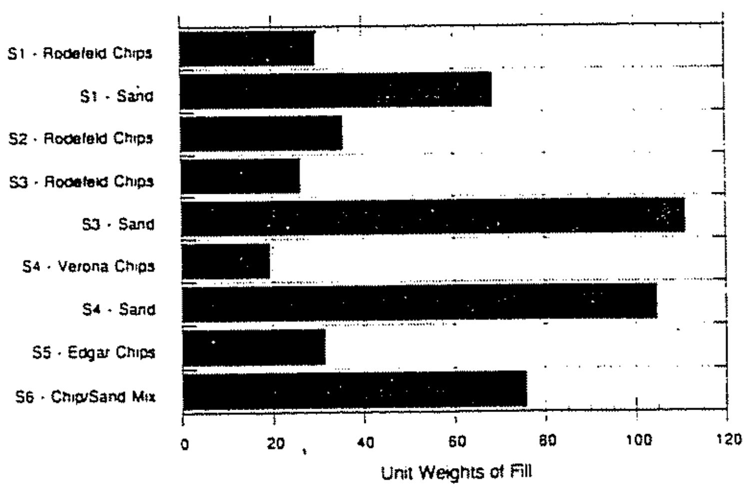


FIGURE 5 Calculated unit weights of fill components.

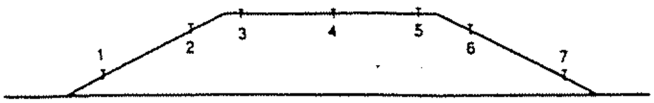


FIGURE 6 Settlement marker locations.

Roadway Rating

Gravel roads provide service to agricultural, forestry, and recreational areas with fairly high traffic volumes. Surface evaluation and rating of such roads are needed for planning their maintenance and overall management. A system for evaluating and rating gravel roads was developed by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) in 1987 (*2*). A simplified visual method for gravel road evaluation based on the work at CRREL was prepared as a PASER manual by the Transportation Information Center of the University of Wisconsin-Madison (UW) in 1989 (*3*). The evaluation is based on major factors such as the road cross section, drainage, and adequacy of the gravel layer. Five road conditions are used to evaluate and rate gravel roads: crown, drainage, gravel layer, surface deformation, and surface defects.

Using the PASER system, the test embankment surface conditions were inspected and evaluated after the first year of service on April 5, 1991, by the Wisconsin DOT District 1 maintenance supervisor and UW personnel. The overall condition of the road surface was excellent (a score of 10) for drainage, good to excellent (a score of 8 to 10) for crown, and somewhat variable (a score of 6 to 10) for potholes. This over condition after the initial period of adjustment and repairs puts the test embankment among the better gravel roads. However, there were notable variations in the ratings of each section. For instance, the crown rating was 10 for all sections constructed using earth and for three of the six sections constructed using various tire chip products (Sections 3, 5, and 6). Pothole ratings showed more variation between the various sections constructed of earth or tire chips. Just about every section and the two approaches (built entirely of earth) developed potholes under the heavy garbage truck traffic.

The embankment surface was regraded one final time on April 10, 1991, rendering the rating of all sections excellent (a score of 10). After 7 months of continuous traffic, the embankment surface conditions were again assessed. The ratings were similar to those found on April 5, 1991.

Surface Settlement

To date, five surveys have been run on (*a*) the ground surface elevation; (*b*) the surface markers placed just after the construction was completed, which became buried after additional gravel was applied; and (*c*) the settlement plates buried in the test embankment.

Three of these surveys were carried out with total stations permitting the collection of three-dimensional data, whereas the other two surveys obtained only the elevation of the surveyed points. The results from these surveys permit a quantitative evaluation of the performance of the embankment.

A review of the lateral movement of the individual markers indicated that there was no apparent bulging of the slopes of any sections or any noticeable longitudinal stretching. The measured lateral movements of the markers placed on the embankment crest (Markers 3, 4, and 5) also indicated relatively small movements (less than 1 to 2 in.) between the initial and final surveys. Consequently, the measured elevations of the embankment crest markers can be used in studying the overall settlement of the embankment section free of local surficial disturbances. The markers were not removed throughout the observation period, and actually the base coarse overlay was excavated to reach the markers during the surveys.

Figure 7 shows the settlement data collected from several surface markers (shown in Figure 6). The data in Figure 7 are the average settlement of Markers 3 and 5, the two surface markers located near the track made by the truck tires as a function of number of days of traffic. The data indicate that the settlement increased rapidly during the first 20 days after truck traffic was first allowed on the embankment, corresponding to the time of major pothole and rut formation. After the surface was regraded and a crushed gravel layer added, the settlement rate tapers off (20 to 60 days). After 60 days, the settlement remains relatively constant. This is further supported by Figure 8, which gives the settlement rates for each of the sections in these time intervals of traffic load.

Using the maximum values of settlement (at 152 days of traffic on Figure 7) as the measure of performance, comparisons of the sections support grouping of the sections as follows:

1. Best performance—Sections EA (east approach), 7, and 8 (Sections 7 and 8 are not shown—they are the fiber-reinforced soils);
2. Higher performance—Sections 3, 4, and 6;
3. Lower performance—Sections WA [west approach (also not shown)], 2, and 5; and
4. Poorest performance—Section 1.

Examination of these groups indicates that the best performance is found in sections composed entirely of soil or fiber-reinforced soil. The exception to this is in the west approach; however, this approach was built initially with frozen soil, which is thought to have contributed to its lower performance. On October 3, 1991, this soil was removed and the west approach was reconstructed. Since then, its performance has been similar to other earthen sections. The next-best-performing group is composed of sections having thick soil caps (Sections 3 and 4) and a section made with a mixture of chips and soil (Section 6). The presence of a thick soil cap is important to reduce the amount of plastic deformation of the chips. The mixture of soil and chips provides performance similar to the pure chip sections with a thicker soil cap; however, the amount of chips recycled in either Sections 3 or 4 is larger than that recycled in Section 6. In addition, the extra operation of soil mixing could be avoided by constructing roads similarly to Sections 3 or 4. The sections made of pure chips that did not have the thicker soil cap did not perform as well, most likely because of the lack of confinement of the surface tire chips. The worst-performing section was the layered section. The performance can be traced back to the lack

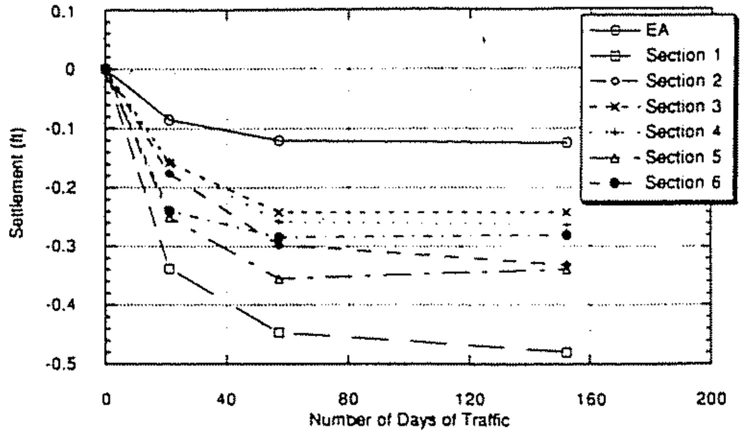


FIGURE 7 Tire track settlement versus days of traffic.

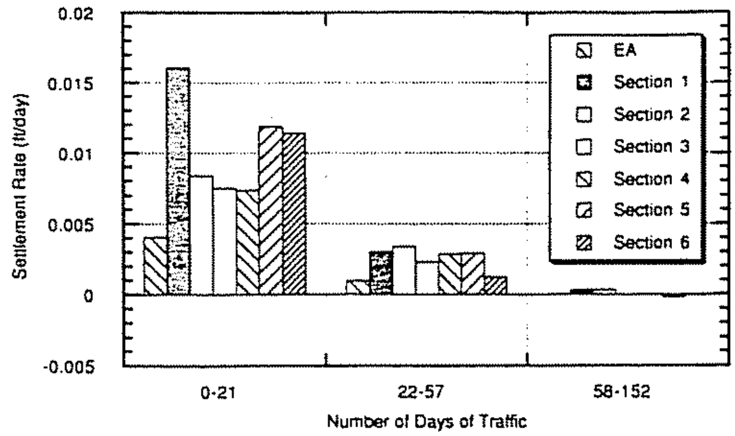


FIGURE 8 Tire track settlement rate versus days of traffic.

of compaction imparted to the soils (see Figure 5) in that section as well as the near-surface tire chips without adequate confinement.

Compressibility of Deep Materials

The settlement of the surface markers depicts the plastic deformation associated primarily with the surface materials (crushed stone, gravel, and some tire chips), where the stress increase due to the traffic loading is the largest. The movement of the deep settlement plates describes the response of the deeper materials (chips, chip-soil mixture, or layered chips-soils) to smaller stress increases from traffic loads. A comparison of the observed surface marker settlement with the movement of the deep settlement plates indicates a much-reduced response of the deep settlement plates, though the trends are similar: higher initial movement compared with the period after 60 days. Table 1 summarizes an analysis of the stiffness of the deeper materials as measured by the movement of the deep settlement plates. The stiffness index is defined as the ratio of the overburden stress to the plastic strain. A comparison of the stiffness differences between the sections supports the previous performance grouping based on surface settlement. The settlement plate data is useful for further differentiation within each of these performance groups. In addition to the influence of thick soil caps, the data indicate effects of the tire chip void ratio. In Table 1, the bulk unit weight gives a measure of the void ratio of tire chips except for Section 6, where the bulk unit weight is that of the chip-soil mixture. A comparison of SP4 and SP6 indicates that the Verona chips do not perform as well as the Rodefeld chips even though they were subject to a higher cap overburden stress.

Test Embankment Environmental Testing

Waste tires are essentially a solid waste, and the recycling of tires in highway applications will probably require a permit from state or federal environmental regulatory agencies. To obtain an early evaluation of potential environmental problems before construction, duplicate EP toxicity and AFS leaching tests were performed on tire chip samples by the State Laboratory of Hygiene (*1*). The test results indicate that the shredded automobile tire samples show no likelihood of

TABLE 1 DEEP LAYER COMPRESSION DATA FROM SETTLEMENT PLATES FOR 58 TO 152 DAYS OF TRAFFIC

Section-Settlement Plate	Description	Bulk Unit Weight	Settlement	Layer Thickness	Overburden Stress	Plastic Strain	Stiffness Index
		pcf	feet	feet	psf	%	psf
1-SP1	Layered	29.6	0.156	0.98	294	15.9	1846
1-SP2	Layered	29.6	0.205	1.45	278	14.1	1965
2-SP3	Rodefeld	35.7	0.069	1.92	273	3.6	7594
5-SP7	Edgar	31.4	0.075	1.85	328	4.1	8093
6-SP8	Rodefeld/Sand Mixture	75.7	0.080	2.27	373	3.5	10588
4-SP6	Verona + Cap	19.3	0.098	1.86	565	5.3	10724
3-SP4	Rodefeld + Cap	26.2	0.032	2.02	481	1.6	30375

TABLE 2 WATER QUALITY ANALYSIS OF LEACHATE—EAST LYSIMETER

SAMPLE	Units	5/9/90	3/28/91
pH	su	7.7	7.7
Alkalinity	mg/L	533	705
Barium	µg/L	210	350
BOD	mg/L	14	70
Calcium	mg/L	170	340
Chloride	mg/L	460	1400
COD	mg/L	170	560
Conductivity	µmhos/cm		5150
Iron	mg/L	0.05	0.7
Lead	µg/L	<3	22
Magnesium	mg/L	150	390
Manganese	µg/L	270	3200
Sodium	mg/L	220	200
Sulfate	mg/L	140	450
Total solids	mg/L	2000	4630
Zinc	µg/L	46	560
Hardness	mg/L	1100	2500

being a hazardous waste. Table 2 provides the results of the water quality analyses performed on two samples taken from the east lysimeter established under the tire chip test embankment. Samples were retrieved initially on a monthly basis, quarterly since April 1990, and are retrieved semiannually now. The data given in Table 2 are typical of the changes observed in the water quality samples obtained.

A review of the data to date support our expectations based on earlier leach tests. The pH is stable around 7.5. Consistent with that pH, most of the parameters stay within acceptable limits. As indicated by the leach tests, there is an elevated manganese concentration in the field samples too, especially in the last samples.

To clarify the possible source of higher manganese concentration in the samples, ground and surface water data from the vicinity of the test embankment were obtained from the Dane County Public Works Department. It is believed that the geological formations here cause the higher-than-usual manganese concentration. The test embankment is located at the foot of the landfill. The volume of water pumped out of the two lysimeters and the elevations of the lysimeters indicate that surface and groundwaters are entering the lysimeters laterally through the slope cover soil. The general characteristics of the water quality at the site are reflected to a certain extent in the measured quality of the lysimeter leachate samples (*1*).

CONCLUSIONS

On the basis of the results of the research program, the following can be concluded:

1. Normal construction machinery can be used successfully with tire chips, though rubber tires can be punctured by the exposed wires at the edge of the chips. Vibratory or static compaction does not significantly induce compaction in tire chips.
2. After an initial period of adjustment, the overall performance of a gravel road founded on tire chips appears similar to that of most gravel roads.
3. Tire chips used as a replacement for fill under a road perform better when covered by 3-ft-thick soil caps compared with chips covered by only 1 ft of soil.
4. The void ratio of the pure tire chips affects its stiffness. The void ratio is affected by the size of the tire chip and by the presence of soil within the tire chip voids.
5. Shredded automobile tires do not show any likelihood of being a hazardous waste. Compared with other wastes for which leach test and environmental monitoring data are available, the tire leach data indicate little or no likelihood of shredded tires having adverse effects on groundwater quality.
6. The preceding conclusions support the use of tire chips as a lightweight fill in highway applications if properly confined.

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REFERENCES

1. T. B. Edil, P. J. Bosscher, and N. N. Eldin. *Development of Engineering Criteria for Shredded or Whole Tires in Highway Applications*. June 1990 (updated May 1991).
2. R. A. Eaton, S. Gerard, and D. W. Cate. *Rating Unsurfaced Roads—A Field Manual for Measuring Maintenance Problems*. Special report 87-15. Army Corps of Engineers Cold Regions Research and Engineering Laboratory, 1987.
3. *Gravel-PASER Manual, Pavement Surface Evaluation and Rating*. Transportation Information Center, University of Wisconsin-Madison, Madison, 1989.

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DESIGN OF HIGHWAY EMBANKMENTS USING TIRE CHIPS

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ABSTRACT:

This paper describes research undertaken to develop design procedures for using shredded scrap tires as a light-weight fill material in highway construction. The benefits of using scrap tires are particularly enhanced if they can be used to replace virgin construction materials made from non-renewable resources. This paper addresses the use of tire chips as a highway embankment material. Design parameters for embankments constructed using discarded shredded tires are presented based on laboratory model studies, numerical analyses and field performance of test fills. The conclusions of this report support the use of tire chips as an environmentally acceptable light-weight fill in highway applications if properly confined. Recommendations for design procedures and construction specifications for the use of tire chips in highway fills are provided.

Keywords: Scrap tires, tire chips, pavement design, light-weight fills, resilient modulus, modulus of subgrade reaction, Poisson's ratio, modeling, constrained modulus, laboratory testing

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INTRODUCTION

Since the banning of the disposal of automobile and other vehicle tires in sanitary landfills, scrap tire stockpiles have begun to grow in the U.S.A. It is estimated that on the average, scrap tires are generated one per capita annually resulting in a significant disposal problem. Currently, it is estimated that 2 billion scrap tires are stockpiled across the United States and that these stockpiles will continue to grow at a rate of 200 to 250 million tires per year. This situation has produced an acute need for finding new beneficial ways to recycle and reuse large volumes of scrap tires.

The manufacturing process for tires combines raw materials into a special form that yields unique properties such as flexibility, strength, resiliency, and high frictional resistance. If tires are reused as a construction material instead of being burned (burning is currently the leading method of reuse accounting for 17% of scrap tires), the unique properties of tires can once again be exploited in a beneficial manner. The benefits of using scrap tires are particularly enhanced if they can be used to replace virgin construction materials made from non-renewable resources. Recent research indicates that shredded tires do not show any likelihood of being a hazardous waste material or of having adverse effects on groundwater quality (Edil and Bosscher, 1992).

In this context, the use of shredded tires in highway applications was considered a potentially significant avenue for putting scrap tires into beneficial reuse. There are a number of ways in which shredded tires can be used in highway construction as an aggregate replacement, for instance in the construction of nonstructural sound-barrier fills, light-weight embankment fills crossing soft or unstable ground, pavement frost barriers, regular fills, retaining-wall backfills, and edge drains. The light-weight fill application is particularly interesting because it would not only provide a means of disposing scrap tires but also help solve difficult economical and technical problems associated with settlement and instability of highway construction over soft ground. The primary objective of this paper is to present design parameters for embankments constructed using discarded shredded tires based on laboratory model studies and field performance of test fills.

DESIGN OF PAVEMENT STRUCTURES OVER TIRE CHIPS FILLS

Based upon the American Association of State Highway and Transportation Officials (AASHTO) guidance, the design of pavement structures is partly based on the mechanical properties of the subgrade (AASHTO, 1993). For flexible pavement design, the critical subgrade property has been identified as the elastic or resilient modulus. This property should be determined from laboratory tests on representative samples in stress and moisture conditions simulating those of the primary moisture season. Alternatively, they may be determined by correlations with other subgrade properties. An effective roadbed resilient modulus is then established which is equivalent to all the seasonal modulus values. Like the effective subgrade resilient modulus for flexible pavement design, an effective modulus of subgrade reaction (K-value) should be used for rigid pavement design (AASHTO, 1993). Since the K-value is directly proportional to roadbed resilient modulus, seasonal moduli developed similar to the flexible pavement design can be used in the estimation of an effective design K-value. These design properties, for tire chips and tire chips-soil mixtures are determined in the following sections.

Flexible Pavement Design

The flexible pavement design method recommended by AASHTO (1993) is based on an application of elastic layer theory in which the asphalt pavement is characterized as a multi-layered elastic system. The Asphalt Institute (MS-1, 1991) provides a comprehensive multi-layer elastic pavement design procedure based on established theory, experience, and test data. In this method the subgrade, the lowest layer, is assumed infinite in the vertically downward and horizontal directions. The other layers, of finite thickness, are assumed infinite in extent in the horizontal directions. Traffic is expressed in terms of repetitions of an equivalent 80 kN (18 kip) single-axle load applied to the pavement on two sets of dual tires. The design is based on identifying a flexible pavement structural number (SN) to withstand the projected level of axle load traffic. The determination of the required structural number is based on specific conditions prevailing including the effective resilient modulus of roadbed material.

Rigid Pavement Design

The performance of rigid pavements is less sensitive to changes in soil conditions than is the performance of flexible pavements. The AASHTO design procedure is based on the AASHTO Road Test pavement performance algorithm. Before determining design slab thickness, it is necessary to estimate the possible levels of slab support that can be provided. This is accomplished by developing an effective modulus of subgrade reaction, K. The effective K-value is dependent upon several factors beside the roadbed material resilient modulus such as the type and thickness of subbase, loss of support due to erosion, and depth to rigid foundation, i.e. bedrock. If the pavement slab is placed directly on the subgrade (i.e., no subbase), the composite K-value can be obtained from a plate load bearing test or from the theoretical relationship between K-values from a plate bearing test and the elastic modulus of the roadbed material. The following equation can be used to calculate the modulus of subgrade reaction (Poulos and Davis, 1974) from the resilient modulus:

$$K = \frac{p}{\delta} = \frac{M_R}{0.82B} \tag{1}$$

where B = foundation width

p = load or force

δ = deflection or displacement

M_R = resilient modulus

Equation 1 is derived from elastic theory for average displacement of a uniformly loaded rectangular area. K-values are given in the units of $MN/m^2/m$ or MN/m^3. Often plate bearing tests are not run but use of published correlations of K to various soil gradations is made. K-values range from 80 MN/m^3 for the best subgrade soils to about 20 MN/m^3 for the poorest subgrade soils. Therefore, in order to classify the performance of tire chips as a subgrade material, a K-value must be assigned to this material. In summary, both the flexible and rigid pavement design methods are based on the mechanical behavior of the subgrade as measured in the resilient modulus, M_R.

CHARACTERISTICS OF TIRE CHIPS

Size

The size of the tire chips is dictated primarily by the design of a particular shredding machine and the setting of its cutting mechanism. Small size chips are produced by processing the material through more than one shredder, each adjusted to produce finer cuts than its predecessor. Classifiers can also be used to separate the finer sizes from coarser ones. Usually the chips are irregular shaped with the smaller dimension being the size specified by the manufacturer and the larger dimension 2 to 4 times as much. Samples collected from sites visited range from 25 x 50 mm to 100 x 450 mm with the most common size chip being 50 x 75 mm.

Deformability

One important component of the design of an embankment is the deformability of the construction material. Quasi-static constrained repetitive loading tests were performed to characterize the compressibility of tire chips and mixtures with sand and clay (Edil and Bosscher, 1994). The compression tests were performed by placing the mixture in a 152-mm diameter mold and then applying a vertical load using a compression machine. Figure

1 provides the vertical displacement (compression) versus load response of pure tire chips 50 to 75 mm in size. The initial porosity of tire chips is about 0.67 (at a dry unit weight of tire chips of about 4 kN/m^3) and it decreases to a porosity of 0.5 as a result of about 36% compression at a vertical pressure of about 690 kPa. Figure 1 indicates that major compression takes place in the first cycle. A portion of this compression is irrecoverable in this laterally confined test but there is significant rebound upon unloading. The subsequent cycles tended to have similar load-displacement curves however with less rebound than the first cycle. An interesting observation is that the slope of the recompression/rebound curve is nearly constant and markedly lower beyond a vertical load of about 350 kPa. Chips of both smaller and larger sizes displayed a similar response. In contrast, a similar compression test performed on pure sand resulted in a displacement of only 5% compression at a vertical pressure of 690 kPa. This corresponds to about 1/7 of the compression of pure tire chips at the same load. These quasi-static constrained repetitive loading tests were characterized in terms of the maximum strain obtained at the end of first cycle of loading as well as the maximum strain generated in the subsequent cycles of loading as shown in Figure 1. The strains are called respectively *static* and *cyclic* strains. *Constrained modulus* is defined as the slope of the cyclic loading portion of the strain-stress plot. These tests indicated a significant plastic (unrecoverable) strain under the first cycle of load application followed by reduced plastic and elastic strains under subsequent load cycles (Edil and Bosscher, 1994). The key predictor of these parameters was the soil:chips ratio. Beyond a sand content of about 40%, the compressibility is significantly reduced from 30 to 40% strain to less than 20%. Sand filling the open voids of the tire chip skeleton reduces volumetric compression. No other factors tested (compactive effort, moisture content, and mold size) in either the sand or clay tests affected the cyclic strain. However, the type of sand and the size of the mold do affect the magnitude of the static strain. A comparison of repetitive constrained moduli indicated that clay mixtures generally

have somewhat lower moduli than sand mixtures at the same soil:tire chips ratios (Edil and Bosscher, 1994).

Resilient Modulus

For the structural analysis and design of highways as a multi-layer system, two fundamental mechanical parameters are needed: an elastic modulus and Poisson's ratio. Because only minor unrecoverable strains are observed after several load cycles, tire chip products exhibit essentially non-linear elastic behavior after the first few cycles of load application. Therefore, the analysis of highway systems including tire chips or tire chips-soil mixtures can be performed using the elastic theory under traffic loads. For such analysis, Poisson's ratio is required in addition to the resilient modulus, M_R. Direct measurements of Poisson's ratio in uniaxial compression tests on pure tire chips indicated a Poisson's ratio between 0.2 and 0.3 (Edil and Bosscher, 1994).

The resilient modulus of pavement materials defines their recoverable deformation response under repetitive loading corresponding to a given state of stress. Therefore a series of resilient modulus tests were performed on tire chip and soil-tire mixtures. The resilient modulus testing of tire chips presented unique problems not addressed in present standards. A procedure for tire chips was developed by following the new Strategic Highway Research Program (SHRP, 1989) Protocol P46 as closely as possible. The major issue causing a deviation from the P46 protocol was membrane failure due to the wire ends extending from the tire chips. A PVC membrane (0.1 mm thickness) was utilized in place of the latex membrane . The tests indicate that the PVC membrane produced a noticeable but small increase in the measured resilient modulus (Edil and Bosscher, 1994). Due to excessive sample displacement and distortion, pure tire chips could not be tested. However, the resilient modulus of pure tire chips can be computed from the measured constrained modulus using the following relationship (Poulos and Davis, 1974):

$$M_R = \frac{(1-2\nu)(1+\nu)M_C}{1-\nu} \qquad (2)$$

where M_C = constrained modulus

ν = Poisson's ratio

M_R = resilient modulus

The results of the resilient modulus tests on laboratory prepared specimens of soil-tire chips mixtures are shown in Figure 2 along with the resilient moduli for pure tire chips computed using Equation 2. The results indicate that the modulus is strongly correlated with the sand:chips ratio and tends to increase 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 chip percentage increases from 0% to 30%.

VERIFICATION OF M_R

The measurement of M_R in the laboratory does not guarantee that the values found can be successfully applied in the design methods described earlier. In order to verify the applicability of the measured M_R values for the tire chips or tire chips-soil mixtures and the use of the AASHTO pavement design methods, two testing programs were performed: 1) large-scale model testing of rigid plates over tire chips, and 2) actual field testing of flexible pavements over tire chips.

Model tests

Description

Large-scale models of tire chip embankments were constructed in the University of Wisconsin Structures and Materials Testing Laboratory and tested under repetitive loads. The model embankments were similar in thickness to the field test embankment. The objectives of the model testing were: (1) to generate deformation response data of various tire chips-embankment construction configurations under highway loading conditions and (2) to provide a means of back-computing tire chip modulus for comparison with known moduli for soils in order to derive practical design indices.

To confine the embankment material in the laboratory, a wooden box about 3.6 m in length, 2.8 m in width, and 1.2 m in height was constructed. The model test set up is shown schematically in Figure 3. The height of the embankment itself was 1.5 m. The repetitive loading was generated by means of an MTS 244.7 kN structural load actuator. To mimic typical traffic loads on the road, a sine function type of loading with an amplitude between the maximum load and nearly zero was applied (see the inset in Fig. 4). A steel beam was connected to the actuator to transmit the load to two wooden plates (0.3 m square) acting as the contact medium between the steel beam and the road material and separated from each other by 1.6 m center to center. The separation and size of the wooden plates were chosen to simulate the actual car/truck wheel loadings. Linear variable differential transformer (LVDT) transducers were attached to each wooden plate to measure vertical displacements relative to a separate reference frame. The tests results were recorded using a data acquisition computer to rapidly record load and displacement data. Custom software built using a data acquisition authoring language (ASYST) was used for this purpose.

The experimental program included four model embankments:

Model 1: 0.9 m of tire chips under 0.6 m of outwash sand

Model 2: 1.2 m of tire chips under 0.3 m of outwash sand

Model 3: 1.5 m of tire chips without any cover soil

Model 4: A layered system consisting of (from the bottom): 0.3 m of tire chips, 0.3 m of outwash sand, 0.3 m of tire chips, and 0.6 m of outwash sand.

In each model, the cover outwash sand was separated from the underlying tire chips using a geotextile. In Model 4, additional sheets of polyethylene were placed between each layer.

Model 1 was the first test conducted in the series. The initial load amplitude was increased gradually. After a few hundred cycles, excessive plastic deformation developed under the wooden plates due to compaction of the tire chips and outwash sand. These deformations had the appearance of typical local shear failure in compressible soils. At that moment, loading was interrupted and the surface leveled by adding sand (or tire chips, in Model 3) over the load application areas. Loading was then resumed with a higher amplitude. At the end of approximately 1000 cycles of load application with occasional leveling of the surface, the model embankment would be deemed compacted and ready for traffic loading. To simulate traffic loading, a cyclic load was applied 10,000 times at a frequency of 0.5 Hz with readings taken every 2000 cycles. The applied pressure by the wooden plates simulating wheel loads, cycled approximately between 7 and 200 kPa except in Model 3 (1.5-m Tire Chips) which was only loaded to 50% of the load of the other model tests due to the high cyclic displacement which exceeded the limits of the displacement transducers.

A typical load-displacement hyteresis curve is shown in Figure 4. The shape of this curve is quite representative of all other data recorded from the model tests. A subgrade modulus of the resilient response, K, was computed as the change in load over a cycle of loading divided by plate area and displacement. Figure 5 shows this subgrade modulus as a function of number of load repetitions for all model tests.

The stiffness of the subgrade increases as the volume of the sand increases in each model. This increase is attributed to two main factors:

1) an increase in bulk stress due to the increased unit weight of the sand/chip mixture and the surcharge weight of sand on the tire chips (resulting in an increase in stiffness of the tire chips)

2) substantially higher sand bulk modulus than that of tire chips.

For instance, Model 4 (layered sand-tire chips) exhibited nearly a two-fold increase in stiffness compared to Model 1 (0.6-m sand cover - 0.9-m tire chips). Both of these models were covered with 0.6 m of sand; however, in the case of Model 4 the volume of tire chips was 2/3 that of Model 1. Other effects from plastic sheeting between layers and additional wall friction may have contributed to the additional stiffness measured in Model 4.

The plastic displacements that accrued during the 10,000 cycles of loading are shown in Figure 6 for the three models loaded to approximately 200 kPa (Models 1,2 and 4). The plastic displacements are all less than 12.5 mm except for Model 2 (0.3-m Sand - 1.2-m Tire Chips) case. It is not clear why Model 2 accumulated larger plastic displacements. Model 3 was loaded to 50% of the load of the other model tests and it had plastic displacements less than 10 mm.

Numerical analysis of model tests

The model test sections were analyzed for elastic deformation using the finite element method (FEM) code known as ANSYS (ANSYS, 1996). As observed both in the model tests and in the field (Bosscher et al., 1992), embankments constructed of tire chips initially go through a period of excessive unrecoverable (plastic) deformation which is followed by resilient elastic behavior. It is anticipated that in actual road construction using tire chips, an early regrading may be required until the system stabilizes and then the roadway can be paved. Thereafter, the integrity of the pavement would depend primarily on the resilient (elastic) properties of the supporting layers of the system including the tire chips. In order to properly design a suitable pavement thickness, the designer requires mechanical property values of tire chips and soil-tire mixtures. There exists a body of knowledge about the mechanical properties of soils as measured on soil specimens and verified by large-size model testing or field analyses. To obtain corresponding values for tire chip products, the mechanical properties measured on laboratory specimens of tire chips must also be verified to be the operating moduli in the field by large-size model testing or field analyses incorporating mass behavior. Then, such values can be used with confidence. A comparison of verified mechanical properties of tire chips products with those of soils will then permit recommendation of design values for tire chips. These design values can be expressed in the form typically used by the designers. For instance, it could be a resilient modulus to be used in multi-layer structural analysis or it could be a group index or subgrade modulus (Edil and Bosscher, 1992).

The objectives of the finite element analyses were therefore: (1) to assess the applicability of the assumed material deformational properties of tire chips based on laboratory tests to actual mass behavior and (2) to provide a comparative basis to assign values to practical design parameters used by highway designers.

Assumptions and Limitations

1. Linear elastic idealization of the material properties

Figure 7 shows the idealization of the tire chips and soil mixtures as linear elastic materials (defined by two constants: Young's modulus, E, i.e., resilient modulus and Poisson's ratio, ν) after a number of initial load cycles. It was initially assumed that the material constants are independent of the level of stress. The constrained modulus tests of the tire chips however show that the material becomes stiffer as the load increases (Edil and Bosscher, 1994) implying that the tire chips in the embankment exhibit non-linear stiffness which is a function of the state of stress. The relationship given in Equation 2 was used with a Poisson's ratio of 0.2 in calculating the elastic or resilient modulus to be used in the finite element method analyses. In order to take into account the effect of stress level in the model tests, specific repetitive constrained modulus tests were performed using a mold 305-mm in diameter at stress levels of 45 to 120 kPa. Similarly, repetitive constrained modulus tests were performed on outwash sand in a mold 152-mm in diameter. Based on these tests, the material properties given in Table 1 were adopted for use in the model tests.

2. Method of Analysis

The boundary conditions of the model embankment are neither axisymmetric nor two-dimensional, in fact it is basically three dimensional. Both two and three dimensional analyses were performed on the model geometries. The two dimensional analyses (both plane strain and plane stress) indicate that the difference between the three dimensional analysis and the two dimensional analysis was small relative to the variation of results due to the scatter in the material properties. Hence, a two dimensional (plane strain) analysis was used.

3. Wooden Box Boundaries

The wooden wall boundaries of the box were assumed to have no friction in Models 2 and 3 (the 0.3-m soil cover and the pure tire chip cases) because of low normal stresses obtained along the boundaries in the initial analyses due to the light weight of tire chips. However, Coulomb interface elements were used at the lateral boundaries for Model 1 because of the significant normal stresses generated by the 0.6-m sand layer. The friction angle between wood and the other two materials making up the model (tire chips and outwash sand) were estimated based on a simple laboratory experiment. In this experiment a 305-mm diameter PVC mold (300-mm height) was filled with either tire chips or outwash sand and placed on a horizontal wooden board which was gradually tilted until slippage occurred between material and wood. These tests gave friction angles of 25° between wood and tire chips and 30° between wood and outwash sand. The results with or without an additional overburden load were similar. In Model 4 (the layered system), initially frictionless boundaries were assumed however this assumption subsequently had to be modified to frictional boundaries for more realistic modeling.

Results of Numerical Analysis

The model tests described above were analyzed by the FEM method. The modeling of the cases is schematically shown in Figure 8. A summary of the results of the FEM analysis is presented in Table 2. This table shows that the FEM typically over-predicts the amount of displacement measured at the surface of the model test. It is important to note the differences between the various analyses that were conducted. "Model Number" refers to the same number as used in the model tests. "Geometry" briefly describes the model represented in each FEM run. The measured deflection is the amount the laboratory model deflected under the maximum applied load; the predicted deflection is the amount of deflection predicted by the FEM analysis. "Property Choice" refers to the choice of single or multiple values to be used to describe the stiffness of the tire chips. A single property as given in Table 1 was used most of the time, however multiple values as given in Table 3 were used in Model 3 where a single thick layer of tire chips was analyzed. The values in Table 3 reflect the dependency of the modulus on the stress level and were obtained from repetitive constrained modulus tests at the stress levels indicated. The boundary characteristics refers to the modeling method used to describe the interaction with the wall.

A comparison between the measured and actual values indicates that an elastic finite element model provides a reasonably accurate response of the material to loading. Therefore, the assumed moduli based on the tests on specimens can be used in the analysis of mass behavior of road sections built of tire chips.

Test Embankment

Description

A test embankment was constructed parallel to the access road to a landfill near Madison, Wisconsin. This arrangement allowed the diversion of a known quantity of heavy traffic (incoming refuse trucks) onto the test embankment as desired. Regular weather and ground and surface water monitoring at the landfill site provided environmental data.

Based on site geometry and number of variables, the test embankment had 8 different sections, each 6 m long (Bosscher et al., 1992). Along with the approaches built of sand, the test embankment included a total of 10 sections to be monitored and compared. Six sections had tire chips of various sizes and placement conditions such as pure chips, mixed with soil, or layered:

Section 1: A layered section (three 0.3-m thick tire chips and two 0.3-m thick soil cap)

Section 2: 1.5-m of tire chips under 0.3 m of soil cap

Section 3: 0.9-m of tire chips under 0.9-m thick soil cap

Section 4: 0.9-m of coarse tire chips under 0.9-m thick soil cap

Section 5: 1.5-m of fine tire chips under 0.3-m thick soil cap

Section 6: 1.5-m of 50:50 by volume tire chips-soil mixture under 0.3-m thick soil cap

In Sections 1, 2, 3, and 6, tire chips of 50 to 75 mm in size were used. Sections 4 and 5 had coarser (up to 300 mm in size) and finer (about 25 mm in size) tire chips, respectively. A well-graded glacial outwash gravelly sand (same as in the laboratory and model tests) was the soil used in the construction. The top 0.3 m of the soil cap was constructed using crushed rock (base course). The two soil sections (Sections 7 and 8 constructed to test fiber reinforcement for another project) and the two approaches were constructed using only the outwash sand.

The test embankment had a nominal height of 2 m with side slopes of 1V:2H. The crest width was 4.8-m wide to permit safe passage of large trucks. Two of the cross-sections are shown in Figure 9. The construction of the test embankment and the instrumentation used to monitor the performance of various sections are described by Bosscher, Edil and Eldin (1992).

The heavy incoming truck traffic which is weighed prior to entering the landfill could be diverted onto the test embankment. Approximately 180 trucks per day pass over this embankment with an average truck factor of 2.035 (Edil and Bosscher, 1992). The number of equivalent 80 kN single-axle load applications contributed by one passage of a single vehicle is called the truck factor. The gross weight of some trucks is over 45 tons. On June 4, 1990, the test embankment was opened to traffic and subjected to 152 days of traffic. The embankment required several cycles of grading early on but eventually stabilized. On November 20, 1991 the embankment was overlain with an asphalt concrete pavement to permit traffic throughout the winter months and to investigate the performance of asphalt concrete pavement founded on a tire chip fill. Traffic has been routed over the embankment throughout 1991 and up to 1995 with no closures. The test embankment was removed in 1995 for landfill expansion.

Using a manual for gravel road evaluation (Gravel-PASER Manual, 1989), the test embankment surface conditions were inspected and evaluated after the first year of service and prior to application of asphalt pavement. The performance of the asphalt concrete pavement was similarly evaluated and rated using an Asphalt-PASER Manual (1989).

Verification of Design Method and M_R values

The Asphalt Institute MS-1 method was used to predict the amount of damage that would be accumulated in each section of the test embankment from incoming traffic after the embankment was paved with asphalt concrete. A computerized procedure (DAMA, 1982) based on the Chevron N-Layer program, developed by Chevron Research Corporation and published by the Asphalt Institute, was used to predict this damage and service life of the pavement on the test embankment. The DAMA program calculates selected deflection and critical strain values at points along each interface within the embankment however only the maximum strain at a given depth is used for damage computations. Pavement life based on both fatigue cracking of each asphalt stabilized layer and subgrade deformation distress is determined using monthly cumulative damage concepts.

Choice of Input Parameters

The input parameters needed for this model are 1) layer geometry, 2) traffic loads, 3) asphalt cement and hot mix asphalt (HMA) characteristics, 4) subbase and base elastic parameters, and 5) damage parameters. The input values for each of the layers are listed in Table 4. These values represent performance of tire chips after the initial 7000 to 22,000 equivalent single axle loads (ESAL) of traffic.

Results of Runs

The DAMA program predicts the number of load repetitions to failure for each distress mode (fatigue and deformation) and critical layer from distress strain criteria and the maximum strain responses. Damage, computed on a monthly basis for a given monthly traffic repetition input value, is accumulated until failure for both distress modes. The design life and number of load repetitions to failure are summarized for cracking and deformation. The governing layer for the design situation is also noted.

The results from use of this program are shown on Figure 10. This figure shows the design life predicted for each section of the test embankment. Section 1 is missing due to a limitation of the DAMA program in the number of layers it can analyze.

Comparison to Actual Conditions

The test embankment was paved on November 20, 1991 using a 2.5 inch surface course asphalt (Grade 3, WisDOT Specification Section 401, [WisDOT, 1989]). On Dec. 28, 1991, nearly a month after the embankment was paved and again opened to traffic, the pavement was inspected and photographed. Subsequently on June 1, 1992, August 24, 1992, and August 12, 1993, the pavement was evaluated using this Asphalt-PASER system. Photographs were also taken at these times. In June 1992, the overall condition of the road surface was found to be excellent (a score of 9-10) except for a few notable exceptions. The sections that showed significant distress of the asphalt surface were 1,2, and 5 (score of 2-4). Section 6 was rated as good (score of 7-8). The distress in Sections 2 and 5 was already apparent a month after paving. Between the period of June 1 and August 24, 1992, there was no notable change in the pavement ratings. The survey conducted on August 12, 1993 confirmed the original rankings of the embankment sections however the distress observed in the earlier surveys had grown more.

The nature of pavement distress in Section 5 involved both transverse and alligator cracks and rutting (in both tracks). It represents classical subgrade failure. It is noted that common to all sections that showed some clear asphalt distress was a single foot of soil cover overlying the tire chips. All other sections which performed excellently over nearly a year had more than one foot of soil cover over the tire chips.

Immediately after paving, survey nails were driven into the pavement at three points (one in each track and one at the centerline of the roadway) in each section. A survey of these points was conducted immediately as well as on May 6, 1992 and August 25, 1992. The results from these surveys indicated rutting in the damaged sections up to 40 mm.

The performance of the pavement as revealed by the PASER rating system confirm the trends predicted by the Asphalt Institute (MS-1) method as shown in Figure 10. In fact the same method predicted inferior performance in test embankment Sections 2 and 5 (Section 1 could not be analyzed) which coincides with the PASER ratings. Additionally, superior performance of Sections 3, 4, 7 and 8 as well as the embankment approaches were predicted. Section 6 was rated intermediate in performance between these extremes in Figure 10 which mimics the field performance.

MODULUS OF SUBGRADE REACTION FOR RIGID PAVEMENTS

From constrained modulus testing and tire chips fill model test results described earlier, modulus of subgrade reaction (K) for use in rigid pavement design has been determined for tire chips. The K-value for tire chips varies based on the amount of confining overburden pressure placed on the chips. Figure 11 illustrates this. The values in Figure 11 were determined from back-calculations from the constrained modulus using Equation 1 with a Poisson's ratio of 0.2 as determined from the uniaxial compression tests. Figure 12 presents the K-values for chips with varying amounts of soil placed over the chips. These values were computed from the finite element runs of the models tested in the laboratory. The values are verified by the K-values (see Figure 5) obtained from the model tests. Both Figures 11 and 12 indicate that K is a function of stress (due to the weight and stiffness of the soil cover layer as well as vehicle loads). For a 1-m soil cover (recommended based on field and laboratory observations), a modulus of subgrade reaction of 16 MN/m^3 is recommended. Additional support for these values maybe gained by running plate load tests on the test embankment however such tests could not be performed within the scope of this project.

CONCLUSIONS

Based on this investigation, the following observations and conclusions are made regarding the design of highway embankments using tire chips and tire chips-soil mixtures as highway fill material:

1. 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. 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 by weight in the tire chip matrix increases the modulus to a level comparable of pure sand. Clay mixtures exhibit lower moduli than sand mixtures at the same mixing ratios. Laterally constrained modulus tests can be used to determine the deformation properties of tire chip products.
2. Tire chips used as a replacement for fill under a road perform better when covered by thick soil caps (~ 1 m) compared to tire chips covered with a thin layer of soil (~ 0.3 m). After an initial period of adjustment, the overall performance of a gravel road founded on tire chips is similar to most gravel roads.
3. The porosity of tire chips affects the material's stiffness. The material's porosity is affected by the size of the chips (smaller chips tend to have lower porosity), applied pressure and the presence of soil within the tire chip voids.

5. Existing design methods for flexible and rigid pavements can be used with the appropriate modulus for tire chips and tire chips-soil mixture.

The preceding conclusions support the use of tire chips as a light-weight fill in highway applications if properly confined.

RECOMMENDATIONS FOR DESIGN

The following recommendations are offered for design of highway fills using tire chips based on the results presented herein as well as other publications:

1. Tire chip size should not be a critical specification item. Construction activities may be eased by specifying tire chips less than 75-mm (maximum dimension). Compression performance of large and small tire chips is comparable at the same density.
2. The unit weight of pure tire chip fills typically ranges from 3 to 5.5 kN/m^3. This number is a function of chip size and compaction. The specific gravity of tire chips ranges from 1.13 to 1.36 (average value of 1.22) depending on the metal content. These values along with the specific gravity of other soils can be used to determine the unit weight of soil-tire chips mixtures.
3. Compressibility is the governing parameter in designing structural fills using tire chips. To achieve minimum compressibility, a minimum soil cover thickness of 1 m (over the tire chips) should be designed. Use of a geotextile to separate the cover soil from the porous tire chip fill is recommended to prevent migration of the soil into the tire chip matrix which could cause localized depressions..
4. An initial period of differential settlement in the fill should be expected. Final surfacing should be constructed after this period.
5. A satisfactory flexible pavement structural design can be achieved by use of multi-layer elastic theory using appropriate resilient moduli for tire chip products as obtained in the laboratory. The resilient modulus test cannot be run on pure tire chips. The elastic

modulus can be estimated from the repetitive constrained modulus test and Poisson's ratio.

6. The modulus of subgrade reaction (K) used in the AASHTO rigid pavement design method depends on pressure level and soil cover thickness. For a 1-m soil cover, a modulus of subgrade reaction of 16 MN/m^3 is recommended for pure tire chips.
7. Spontaneous combustion of shredded waste tire embankments have been reported (EW, 1996) in the State of Washington. Many other embankments have been built and in operation in other locations around the U.S. without any reports of this phenomenon.

REFERENCES

AASHTO Guide for Design of Pavement Structures (1993), American Association of State Highway and Transportation Officials, Washington, D.C., 800 p.

ANSYS (1996), ANSYS Engineering Analysis System, Swanson Analysis Systems, Inc., Houston, PA.

Asphalt–PASER Manual (1989), Pavement Surface Evaluation and Rating, Transportation Information Center, University of Wisconsin-Madison.

Bosscher, P.J., Edil, T.B., and Eldin, N.N. (1992), "Construction and Performance of a Shredded Waste-Tire Test Embankment," Transportation Research Record, No.1345, Transportation Research Board, Washington, D.C., pp.44-52.

DAMA (1982), Computer program developed for the Asphalt Institute by M.W. Witczak and D.K. Hwang, Asphalt Institute, Lexington, KY.

Edil, T.B. and Bosscher, P.J. (1992), "Development of Engineering Criteria for Shredded or Whole Tires in Highway Applications", Final Report to Wisconsin Department of Transportation, GT-92-9, 89p.

Edil, T.B., and Bosscher, P.J. (1994), "Engineering Properties of Tire Chips and Soil Mixtures", Geotechnical Testing Journal, ASTM, Vol. 17, No. 4, pp. 453-464.

EW, "How to 'burn rubber' on a Gravel Road," East Washingtonian, January 31, 1996.

Gravel–PASER Manual (1989), Pavement Surface Evaluation and Rating, Transportation Information Center, University of Wisconsin-Madison.

MS-1(1991), "Thickness Design, Asphalt Pavements for Highways and Streets," Manual Series No. 1, Asphalt Institute, 97 p.

Poulos, H.G. and Davis, E.H. (1974), Elastic Solutions for Soil and Rock Mechanics, Wiley and Sons, Inc., 411p.

SHRP (1989), "SHRP Protocol P-46-Resilient Modulus of Unbound Granular Base, Subbase Materials and Subgrade Soils," SHRP-LTPP Laboratory Material Testing Guide, Version 1.0, P46-1-34.

WisDOT Standard Specifications for Road and Bridge Construction (1989), State of Wisconsin Department of Transportation, Madison, WI, 642p.

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Table 1 List of Material Properties Used in Finite Element Analyses

Material	Modulus (kPa)	Poisson's Ratio	Unit Weight (kN/m^3)
Tire Chips	1,770	0.2	5.5
Outwash Sand	57,480	0.3	16.4
Wood	10,059,000	0.3	3.1

Table 2 Results from FEM Runs

Model Number	Geometry	Measured Deflection (mm)	Predicted Deflection (mm)	Property Choice	Boundary Characteristics
1	0.6-m Sand-0.9-m Tire Chips	9.65	11.94	Single	With Wall Friction
2	0.3-m Sand-1.2-m Tire Chips	21.84	22.86	Single	No Wall Friction
3	1.5-m Tire Chips	26.67	25.91	Multi	No Wall Friction
4	Layered	4.83	9.65	Single	Fixed

Table 3 Multiple Elastic Parameters used in Model 3

Max and Min Pressure in the Test (kPa)	Corresponding Depth in the Model (m)	Modulus (kPa)	Poisson's ratio
120 - 45	0 - 0.3	1,770	0.2
50 - 20	0.3 - 0.6	1,295	0.2
35 - 16	0.6 - 1.5	1,055	0.2

Table 4 Input Parameters for DAMA Flexible Pavement Analysis

Layer Name	Material Type	Modulus Value	Poisson's Ratio
Asphalt	2	calculated*	0.25
Base Course	3	K1=1,357 MN/m^3	0.25
Outwash Sand	4	M_r=69,000 kPa	0.25
Tire Chips-Sand Mixture	4	M_r=4,140 kPa	0.25
Tire Chips	4	M_r=480 kPa	0.20
Base	4	M_r=69,000 kPa	0.25

*The program calculates asphalt modulus based on mean monthly air temperature.

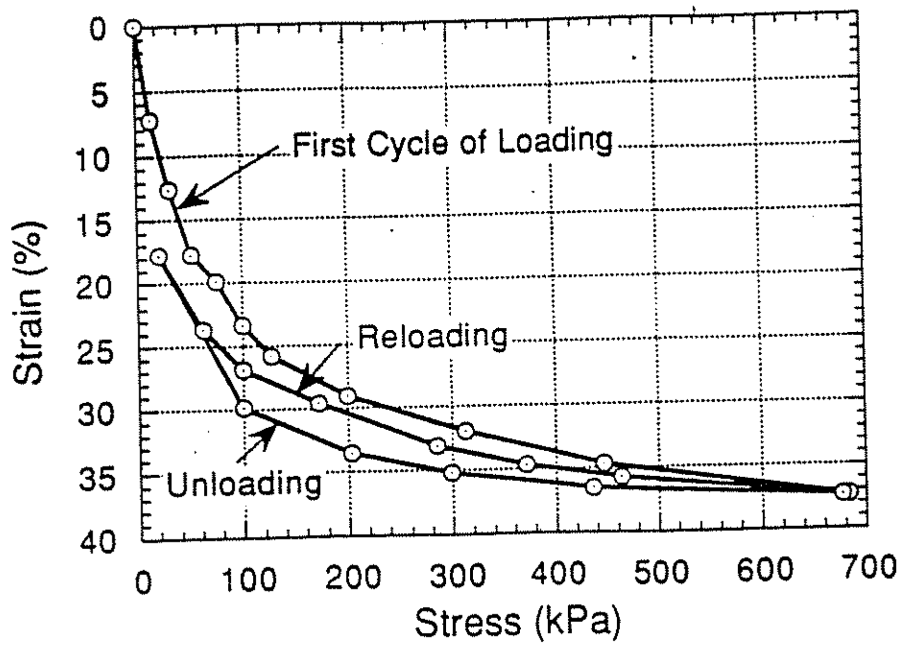

Figure 1. Constrained Stress-Strain Response of Medium Size Tire Chips.

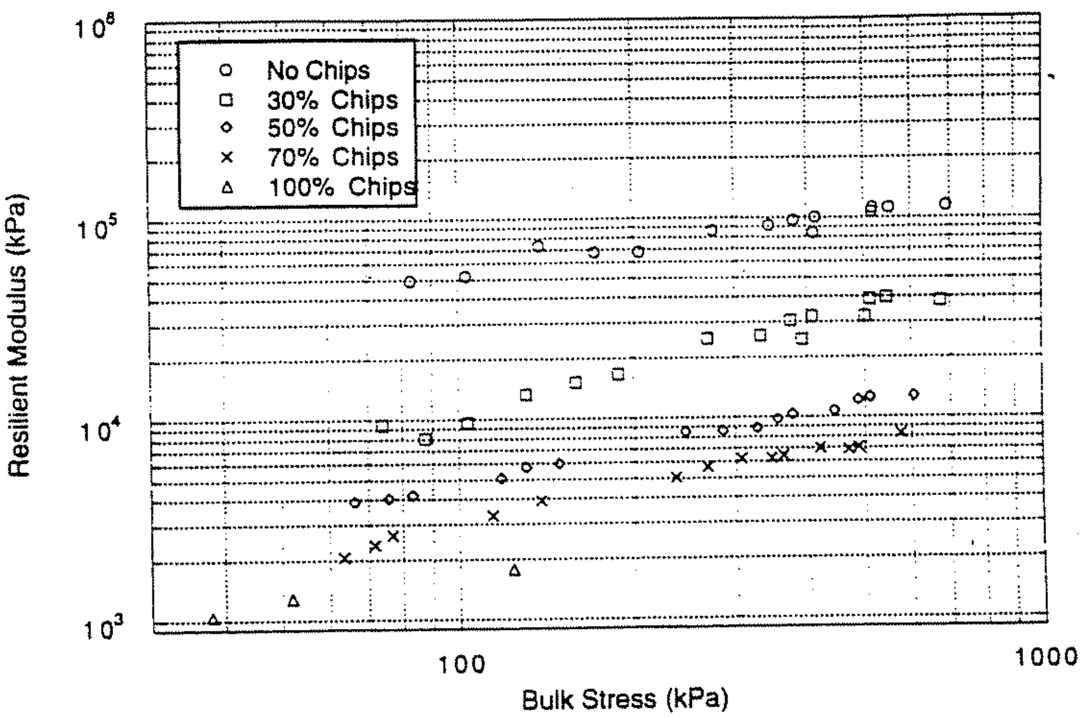

Figure 2. Resilient Modulus of Till-Chip Mixtures

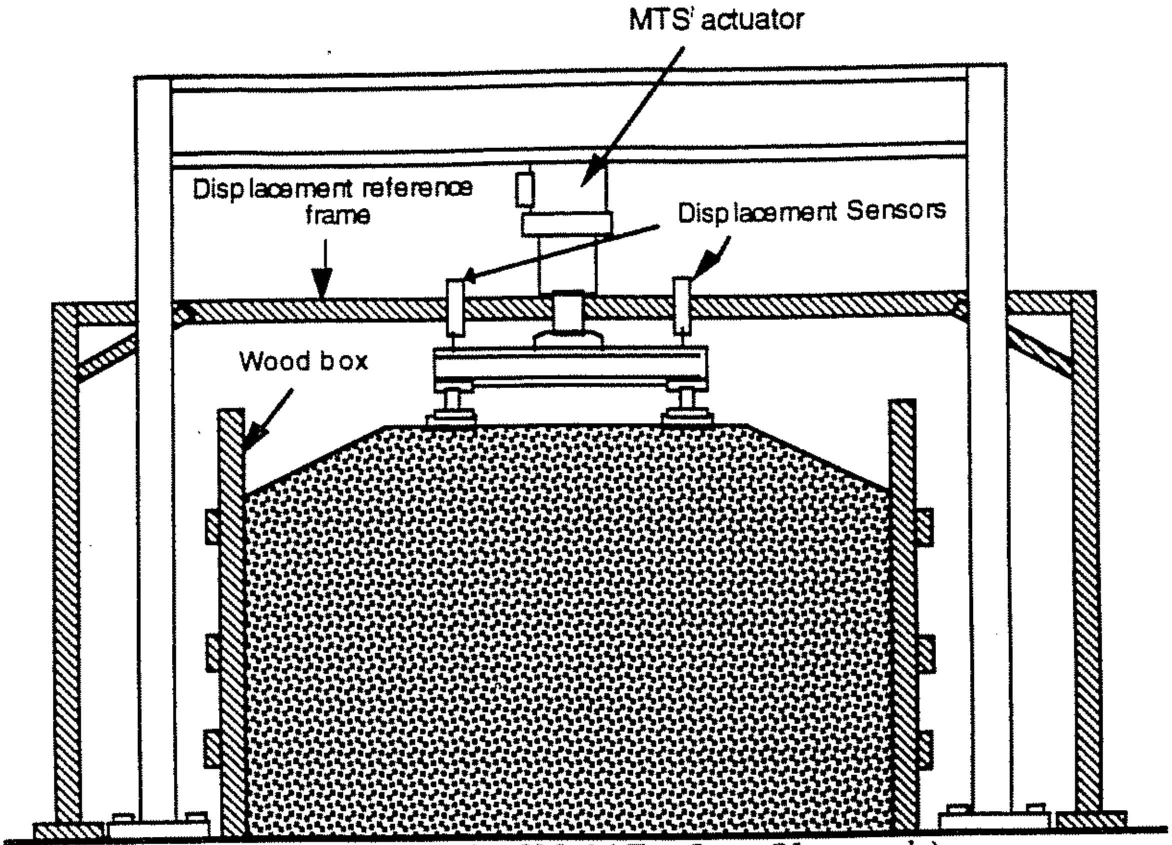

Figure 3. Schematic of Model Test Setup (Not to scale)

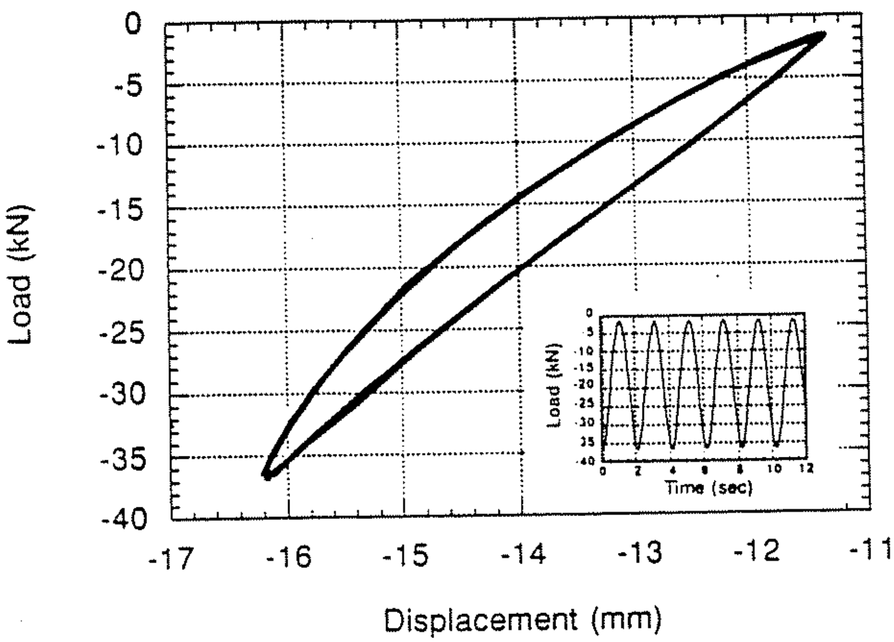

Figure 4. Typical Load-Displacement of Model Tire Test

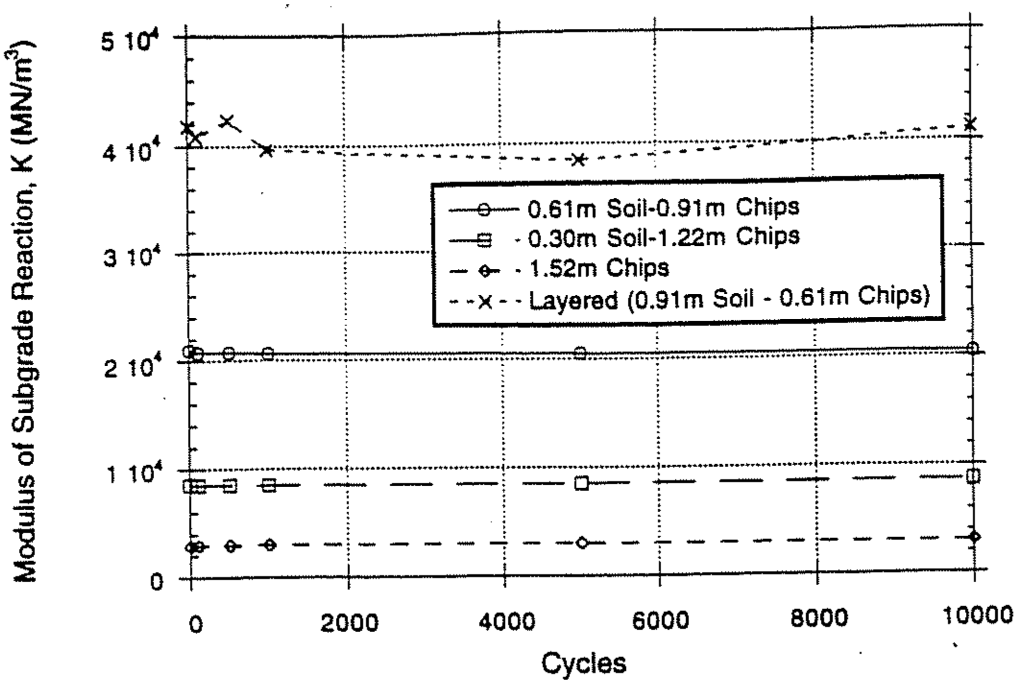

Figure 5. Resilient Modulus of Subgrade Reaction vs. Number of Cycles

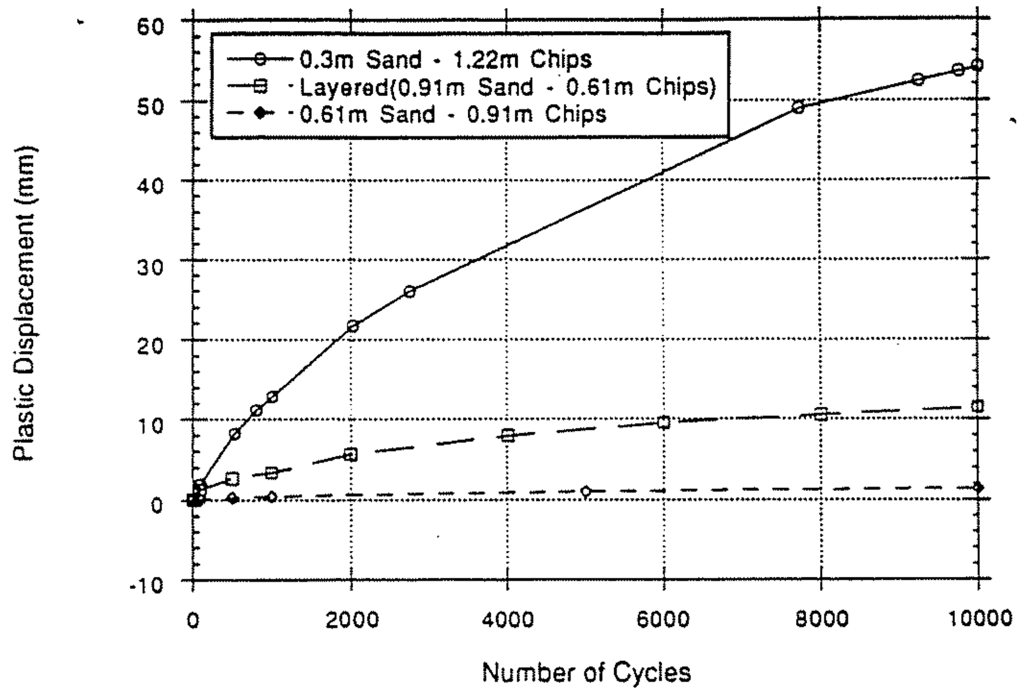

Figure 6. Plastic Displacement vs. Number of Cycles

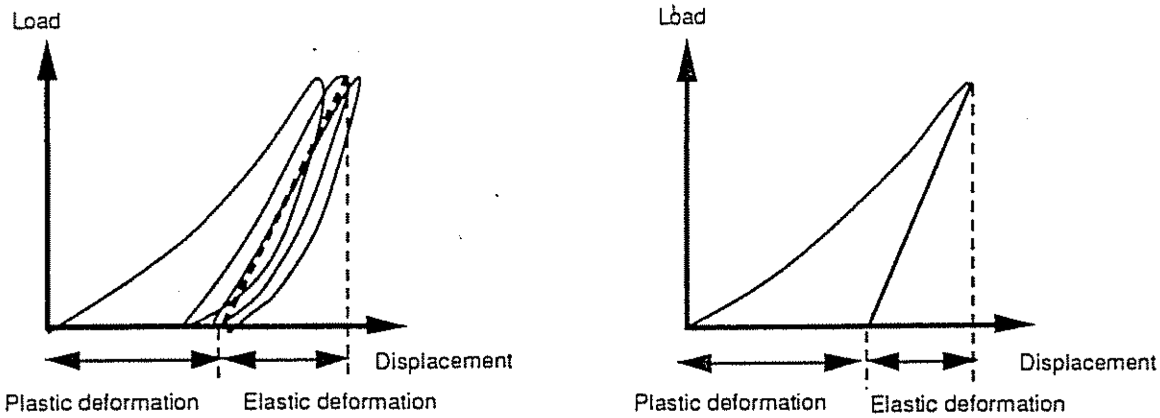

Figure 7. Load-Displacement Curves (Actual and Idealized) from Constrained Modulus Test.

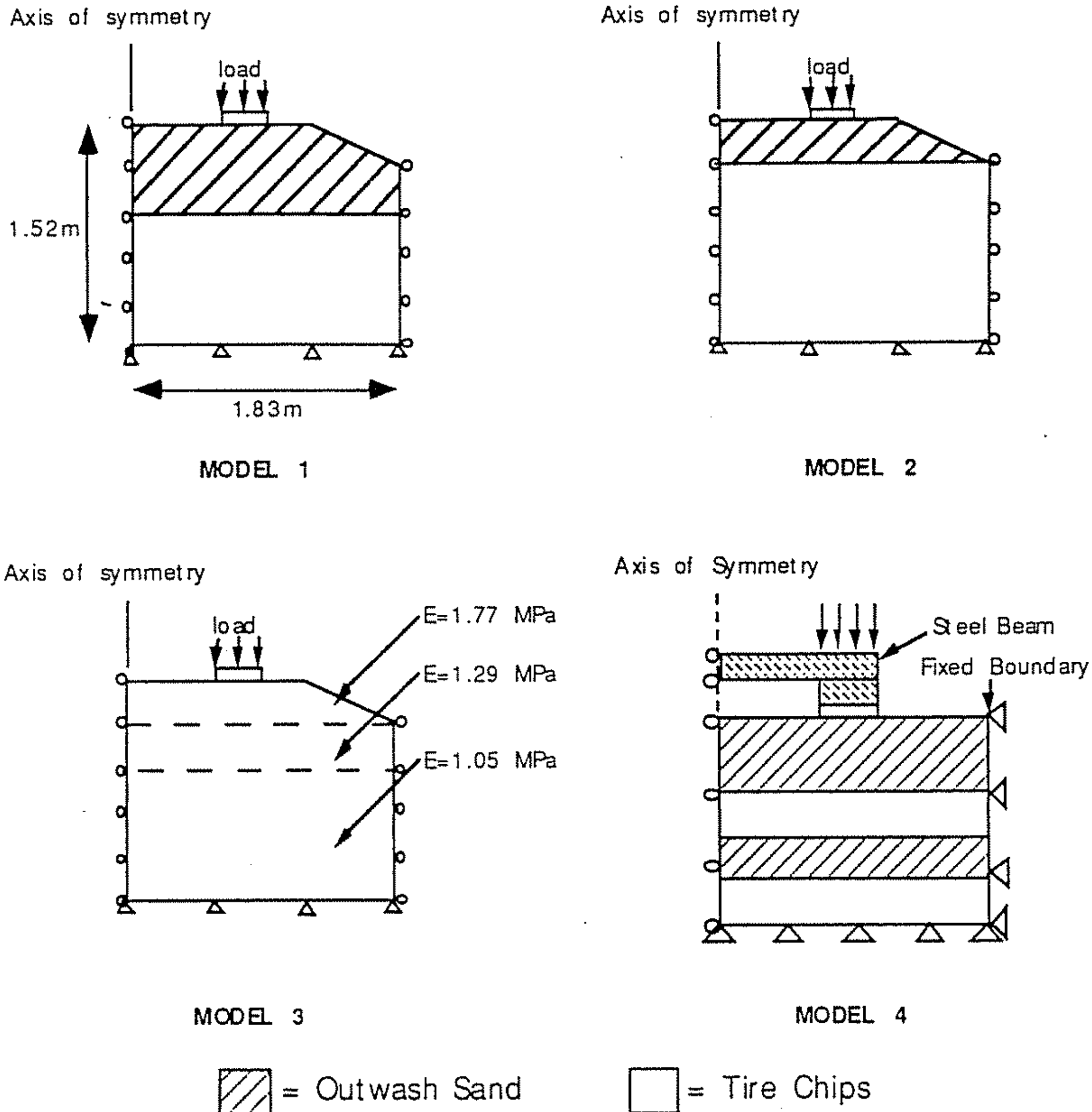

Figure 8. Schematics of Finite Element Method Analyses

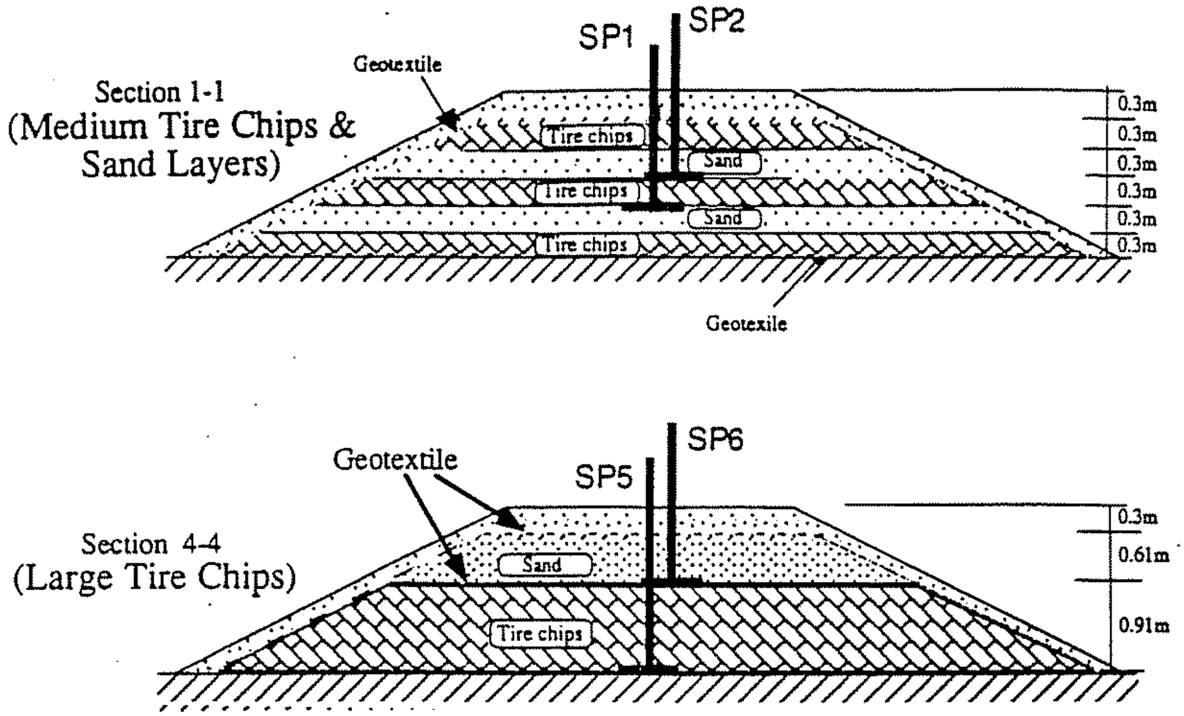

Figure 9. Elevation View of Two Test Embankment Sections as Designed

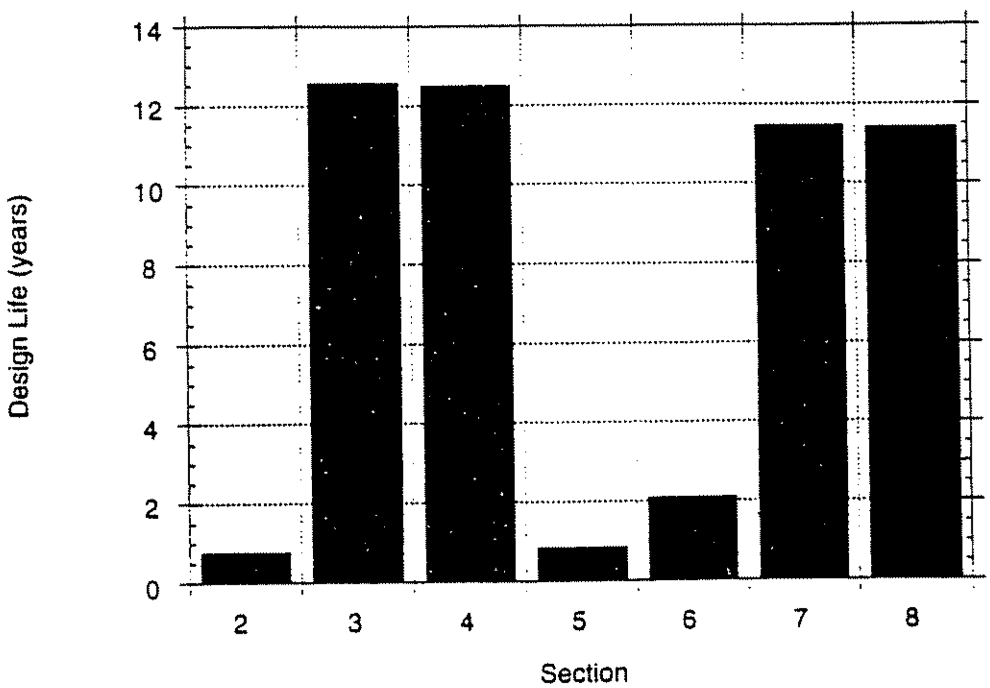

Figure 10. Prediction of Design Life of Asphalt Concrete Paved Sections

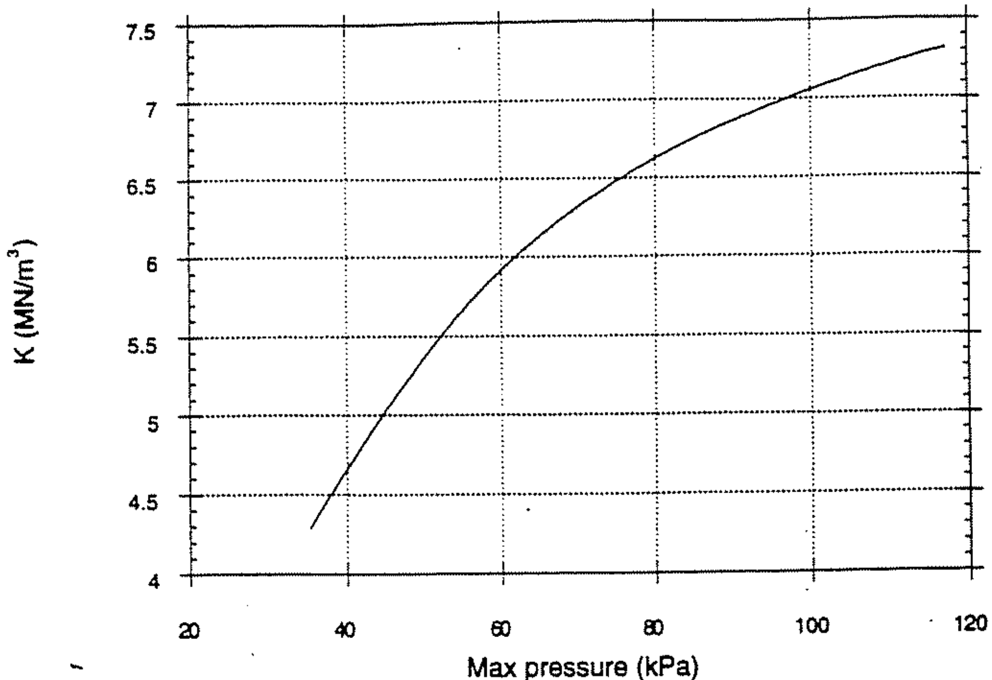

Figure 11. Calculated K values from Constrained Modulus Tests on Pure Tire Chips

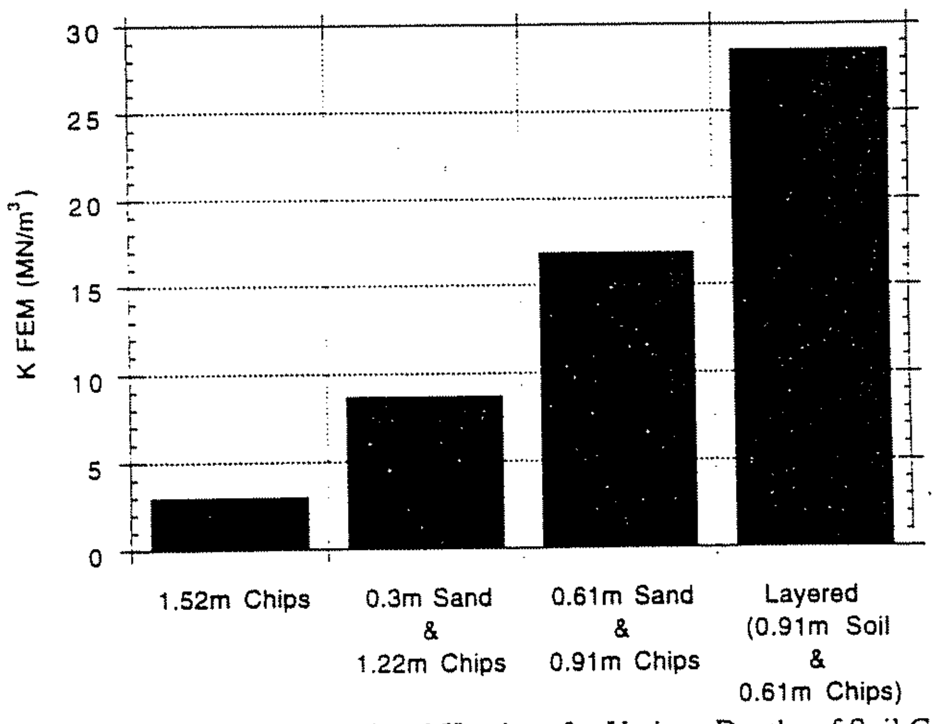

Figure 12. Calculated K values for Various Depths of Soil Cover

REVIEW OF ENVIRONMENTAL SUITABILITY OF SCRAP TIRES

by

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REVIEW OF ENVIRONMENTAL SUITABILITY OF SCRAP TIRES

1. INTRODUCTION

Since rain water will percolate through earth structures constructed with shredded tires, concern exists regarding the potential for leaching of organic and inorganic constituents. Tires contain numerous ingredients such as carbon black, vulcanizing agents, metallic reinforcements, antioxidants, pigments, accelerators (Miller and Chadik 1993) and may also contain petroleum residues obtained through use. Thus, leaching studies have focused on both organic and inorganic compounds. Table 1. summarizes the studies conducted on tire leachate characteristics.

2. POTENTIAL CONTAMINANTS REPORTED IN THE LITERATURE

2.1 Organic Compounds

A study prepared for the Minnesota Pollution Control Agency (MPCA) (1990) indicates that under alkaline conditions, the concentration of polynuclear aromatic hydrocarbons (PAHs) leached from tire chips exceeds drinking water standards. PAHs may leach from carbon black, recipe extenders (Miller and Chadik 1993), or petroleum residues.

The second class of potential contaminants includes nitrogen and sulfur containing organic compounds which form the basis of vulcanizing agents, anti-oxidants, and/or accelerators. Volatile organic compounds (VOCs) are used in tire

Table 1. Studies on Leaching from New and Scrap Tires.

Research	Reference	Type of Tire	Type of Study	Variables	Leachate Analysis	Results
Tire Chip Evaluation Permeability and Leachability Assessments	Waste Management of Pennsylvania (1989)	Tire Chips	Column testing with leachate	Temp 23°C, 50° C Analysis at 0, 30, 60, 90 days	pH, sulfides, cyanides, EPA tox-metals	No appreciable change in concentration in 90 days
TCLP (Toxicity Characterization Leaching Procedure) Assessment Project	Rubber Manufacturers Association (RMA 1990)	Shredded tires (new)	Batch Tests	Leaching Sol. pH 4.9, pH 2.9 cured, uncured ground, unground	Volatiles, semi-volatiles, metal ions	None of the samples exceeded TCLP levels
Environmental Study of the Use of Shredded Waste Tires for Roadway Subgrade Support	Minnesota Pollution Control Agency (1990)	Shredded Tires (new, old)	Laboratory and field test	pH 3.5, 5, 7, 8	14 metal ions, hydrocarbons	Drinking water standards were exceeded under worst case conditions, but EP-toxicity limits were not exceeded. Field tests were not reliable.
Evaluation of the Potential Toxicity of Automobile Tires in the Aquatic Environment	Environment Canada National Water Institute (1992)	Whole tires (breakwater, old, new)	Effect of tire leachate on fish and *Daphnia*	time, 5, 10, 20, 40 days	Toxicity analysis on living organism	Substances contributing to toxicity are water soluble and persistent.
Development of Engineering Criteria for Shredded Waste Tires in Highway Applications	Edil and Bosscher (1992)	Shredded tires (old)	Lab (AFS leach & EP-toxicity) test, field samples (lysimeter under embankment fill)	Samples taken 10 times in 2 years in the field	Metal ions, water quality index tests (pH, alkalinity, BOD,COD etc.)	Slight alkaline conditions but no specific health concern. Field samples were affected from other sources. Laboratory samples leached Ba, Fe, Mn, and Zn but leachate showed no likelihood of hazardous levels
A Study of Waste Tire Leachability in Potential Disposal and Usage Environments	Miller and Chadik (1993)	Shredded tires (old)	Lab (batch) test, field samples (septic tank drain fill field)	Shred size, pH 5.4, 7.0, 8.6, time	Semi-volatiles, volatiles, metal ions	Metal ions, VOCs (benzene, toluene) and semi-volatiles leached. Biological activity may have affected results.
Water Quality Testing For Dingley Road Tire Chip Test Project	Humphrey and Katz (1995)	Shredded tires (old)	Field samples, (monitoring wells near tire chip embankment)	15 cm and 30 cm thick tire chip layer above groundwater table	Metal ions, water quality index tests (pH, alkalinity, BOD,COD etc.)	All substances (except Mn) had concentrations below drinking water standards.
Analysis of Leachate from Column Tests of Soil-Tire Chip and Soil	Kim (1995)	Shredded tires (old)	Column tests	Soil-Tire Chips (830 days) Soil (790 days)	Metal Ions Zn, Pb, Ba, As, Se	No sample exceeded drinking water limits in terms of metal concentration.

manufacturing for mixing the rubber, promoting elasticity, and producing stickiness. Although most VOCs are driven off during the curing process, approximately 8% of total VOCs used in rubber manufacturing remain in the tire (Miller and Chadik 1993).

Miller and Chadik (1993) present results of a laboratory analysis of organic compounds. They conclude that aromatic components of gasoline (e.g., ketones), carboxylic acids, and aniline can be leached from tire shreds. Several other volatile compounds such as benzene and toluene were also present in their leachate. In a field study conducted by Miller and Chadik (1993), however, benzene was not found in the leachate. Toluene was found in the field leachate at low concentrations, and trimethylbenzene and 3-ethyltoluene were present in significant concentrations.

A study for the Rubber Manufacturers Association (RMA) (1990) indicates that volatile organics such as toluene, carbon disulfide, and methyl ethyl ketone may leach from tire chips. However, benzene was not detected in any samples. Only phenol was detected as a semi-volatile compound. The concentrations of organic compounds are below TCLP (Toxicity Characterization Leachability Procedure) limits.

Edil and Bosscher (1992) report biological (BOD) and chemical oxygen demand (COD) as indicators of organic compounds in leachate collected in their laboratory and field studies in Wisconsin. They report that laboratory tests show decreasing BOD and COD with time (Grefe 1989). In the field, however, they could not determine whether organic compounds in the leachate were generated by percolation through the tires or from surrounding soil.

2.1 Inorganic Compounds

Steel belts which become exposed during shredding are also a potential source of contamination. The Minnesota Pollution Control Agency (1990) tested for the presence of 14 metals in tire chip leachate. The laboratory test program concentrated on "worst case" conditions (in this case low or high pH conditions); USEPA's method SW-846 was used for sampling and handling procedures. The study reports that silver and mercury were not detected in any tests, whereas selenium, arsenic, calcium, iron, zinc, and chromium were detected. Depending on the test condition (e.g., pH), the concentration of some metals (barium, cadmium, chromium, lead, selenium, and zinc) exceeded Minnesota's Recommended Allowable Limits (RALs) for drinking water.

Grefe (1989) reports that zinc, barium, iron, and manganese were detected in their laboratory leachate tests (AFS-American Foundry Society test and EP-toxicity test). Concentrations of iron and manganese were above or at drinking water standards, whereas concentrations of zinc and barium were below drinking water standards.

Edil and Bosscher's (1992) field test showed no significant leaching of barium or lead, but possible leaching of zinc and manganese. They indicate that leaching of zinc, manganese, and iron may also have occurred from the surrounding soil. Their field data showed high concentrations of cationic index parameters, such as conductivity, hardness, and calcium and magnesium concentrations, which may be due to leaching through the soil from activity at the site, such as roadway dust treatment.

Field study performed by Humphrey and Katz (1995) reported concentrations of barium, cadmium, chromium, copper, lead, and selenium that were lower than drinking water standards. Their field samples were taken 3 times in 28 months from groundwater monitoring wells installed in the vicinity of a tire chip roadway embankment. Only manganese was found at concentrations above drinking water standards in three of the wells adjacent to tire chip sections and the control well. Humphrey and Katz (1995) also explained the higher cationic index parameters as the result of the dust treatment in the summer and deicing treatment in the winter.

Miller and Chadik (1993) report that zinc and arsenic were found in their laboratory leaching tests at concentrations below drinking water standards. Low concentrations of chromium were also detected. They also pointed out that biological activity, co-precipitation, or the common ion in the leachate may make evaluating leaching of metals from tire chips complex.

The RMA (1990) study indicates that no silver, cadmium, and selenium exist in tire chip leachate. However, barium, chromium, and lead may leach at low concentrations that do not exceed TCLP limits.

Kim (1995) reports on an analysis of tire chip leachates that were obtained from column tests. Leachate samples were collected 830 days and 790 days after initial exposure from columns containing tire chips and soil or soil only. Filtered and unfiltered leachate samples were analyzed. Tap water was also tested for control purposes. Analyses were conducted for metals such as zinc, barium, arsenic, lead, and chromium. None of the samples had concentrations exceeding drinking water standards. However, unfiltered leachate from the column tests conducted with tire chips had higher concentrations of zinc and barium than the unfiltered leachate from the column containing soil only. Also, arsenic was found in higher concentrations in the unfiltered and filtered leachate from the soil-only tests. Lead was found in the highest concentration in the unfiltered leachate from the soil-tire chip tests. Filtered samples usually resulted in low metal concentrations. Differences in the metal concentrations in samples from different specimens may also be due to the different sampling period (i.e. 830 days for the soil-tire chip test and 790 days for soil only tests).

3. TEST METHODS

Batch tests are usually used to determine the leaching characteristics of tires. The mass of tires, extraction liquid, and volume of the container vary from study to study, even when standardized procedures like TCLP (Toxicity Characterization Leachability Procedure EPA, 1986) are used. With a few exceptions (Waste Management Pennsylvania 1989, Kim 1995), the experimental focus has been on leaching under stagnant conditions, which is not realistic. For example, a tire chip embankment partially submerged in groundwater is not in a stagnant condition. In a more realistic condition, liquid in the pores of a tire chip mass is diluted by the flowing groundwater.

Although the analytical equipment is usually the same for each study (e.g., gas chromatrography for organics or spectrometry for inorganics), procedures for sample handling and the detection limits vary. Handling and detecting organic compounds requires more attention than is required for inorganics. In addition, the precision of measurements at the parts per billion (ppb) level is questionable in most of the cases.

3.1 TCLP and EP-Toxicity Tests

The TCLP is normally used to determine if a waste material is hazardous. In the TCLP, the type and size of container and the extraction liquid are defined. The container has zero head space and a volume of 500-600 mL. Two types of extraction liquid are recommended, having a pH of 4.93 and pH of 2.88. The minimum amount of solid placed in the extractor is 100 grams for a non-volatile compound analysis or 25 grams for a volatile compound analysis. The study by the RMA (1990) used 600 g of tires in the TCLP. The time period for leaching is 16 hours in the TCLP.

The EP-Toxicity test (Extraction Procedure Toxicity Test), which was developed before TCLP, is also used for classifying a waste material as hazardous. EP-toxicity differs from TCLP because it specifies a 24-hour leaching period, no standard size extractor, and a pH of 5.0. The RMA (1990) compared leaching results from TCLP and EP-toxicity tests and found that there was no significant difference between the EP-toxicity and TCLP results. In the RMA (1990) study, 300 grams of tire chips were used in the EP-toxicity test.

3.2 Batch Tests

The MPCA (1990) used batch tests. In their study, the container volumes and weight of the tire chips varied. However, in the report, concentrations were normalized with respect to the weight of tire chips in the containers, providing a basis for comparing different concentrations of leachate.

Miller and Chadik (1993) used 20 L polyethylene carboys with approximately 15 kg of tire chips, even though plastic containers can sorb or leach chemicals. The American Foundry Society batch test was used by Grefe (1989). In Grefe's study, tire chips were leached using distilled water at a liquid to solid mass ratio of 5:1.

3.3 Column Tests

Waste Management of Pennsylvania (1989) investigated tire chip leaching in column tests (20.3 cm diameter and 121.9 cm long) with leachate flowing at a percolation rate of 5.8 cm/day. Kim (1995) used steel containers (61 cm diameter and 91.4 cm long) for column testing of soil and tire chips. In Kim's study, the influent reservoir containing the tire chips (5 to 10 kg) had a volume of 170 L.

4. FACTORS AFFECTING LEACHATE CHARACTERISTICS

Factors that can affect the characteristics of leachate from tire chips include the aquatic environment in which the tire is exposed, the age of the tire chips, the size of the tire chips, and the time period that the tire chips are exposed to water.

4.1 Aquatic Environment/pH

The aquatic environment is described by the chemical characteristics of the solution, such as pH. MPCA (1990) investigated how acidic and alkaline environments affect tire chip leachate. Four different leaching tests designed to simulate a range of pH conditions (pH 3.5, 5.0, 7.0, 8.0) were performed. It was concluded that the highest concentration of metal ions (such as calcium, iron, and magnesium) occurred at a pH of 3.5. At this pH, cadmium, chromium, selenium, and zinc from old tire chips exceeded Minnesota RALs for drinking water. Leachate from new tire chips contained zinc, arsenic, and cadmium at concentrations exceeding the RALs when the solutions had a pH of 3.5 or pH of 5.0. However, none of the leachate samples exceeded the EP-toxicity criteria, which are used for classifying wastes as hazardous. It was also reported that slightly alkaline conditions (pH=8.0) resulted in the highest concentration of hydrocarbons.

Miller and Chadik (1993) prepared slightly acidic (pH=5.4), neutral (pH=7.0), slightly alkaline (pH=8.6) solutions to investigate how pH affects leachate characteristics. They also reported pH changes during the test, which were attributed to microbial enzymatic activity. They did not have a strong correlation between pH and the concentration of metal ions in the leachate. They proposed a possible reaction mechanism resulting in adsorption of metal ions by tire chips.

Edil and Bosscher (1992) report that tire chip leachates are slightly alkaline (pH =7.13 to 7.43), based on their field test results. They also recommend not using tire chips in highly acidic or alkaline environments to avoid generating stronger leachates.

4.2 New vs. Scrap Tires

Leachate from new tires may also contain inorganic and/or organic compounds. The leachate study on new tires prepared for the RMA (1990) found that leachate from new tires contains inorganic and organic compounds, but none of the concentrations exceed TCLP levels. MPCA (1990) indicates that newer tires contain slightly higher concentrations of leachable PAHs (new tires=1.2 ppb, old tires=0.6 ppb).

The Canada National Water Research Institute (1992) reports that new tires are also toxic to rainbow trout as scrap tires, which suggests that toxicity is associated with materials present in or on the rubber as a result of manufacturing process as opposed to being picked up later, when the tires are used or after they have been discarded. Toxicity concentrations of scrap tires, however, were found higher than those of new tires.

4.3 Tire Chip Size

Due to their larger surface area, it is expected that tire chips generate stronger leachates than whole tires. Miller and Chadik (1993) report that leachates from medium and large chips had higher concentrations of benzene (215 ppb and 253 ppb) than leachates from small chips (62 ppb). They also report that ethylbenzene, xylenes, and 2-ethyltoluene were found in approximately the same concentration regardless of chip size. They conclude that the effect of chip size is specific to each compound detected. However, they also report that higher or lower concentrations of a particular compound from smaller chip sizes can be due to variability in test samples. The study prepared for RMA (1990) indicates that leachates from ground and unground tires are comparable.

4.4 Immersion Time

The Canada National Water Research Institute (1992) investigated the toxicity of leachate generated by 5, 10, 20, or 40 days of exposure to tires on rainbow trout. Contaminants leached from tires reached lethal toxic concentrations for rainbow trout within 5 days. Afterwards, no appreciable change in concentration occurred in 40 days. Waste Management of Pennsylvania (1989) indicates that no significant change in leachate concentrations throughout a 90 day exposure period. Miller and Chadik (1993) report that benzene concentrations in laboratory leaching tests are highest at the beginning of a test and decrease rapidly and exponentially with time. In contrast, they found that toluene concentrations were initially low and then increased slowly with time. Miller and Chadik (1993) also report that the zinc concentration continually increased for 63 days and thereafter decreased.

Edil and Bosscher (1992) also report time-dependent composition of leachate collected in lysimeters underneath their shredded tire embankment. They attributed the changes to construction activities, such as roadway dust treatment with calcium chloride and asphalt paving. Humphrey and Katz (1995) indicate that the time since construction (28 months) may be too short for substances to migrate from the tire chips to their monitoring wells. However, there was no significant increase in the concentrations of metal ions at three sampling dates and even some of the metals had lower concentrations at the last sampling date (e.g., Zn concentration decreased from <0.01 mg/L to less <0.003 mg/L for unfiltered samples taken from the vicinity of tire chip embankment). In addition, leachate from tire chips can be diluted when it mixes with groundwater.

4.5 Microbial Activity

Miller and Chadik (1993) report that gas was produced in several of their laboratory containers after 180 days of immersion. They also observed that attempts to maintain a constant pH using a buffer solution failed, which is indicative of a biological decomposition process (Miller and Chadik 1993). However, because Miller and Chadik (1993) performed no microbial analyses, there are no data to confirm their hypothesis.

The MPCA (1990) indicates that it is not necessary to investigate biological activity in scrap tires because the vegetation survey they performed in the field showed no difference between vegetation in waste tires and in background areas. The lack of a difference in vegetation indicates that off-gases generated by biological activity in scrap tires are not significant.

Kim (1995) observed gas formation in columns containing soil-tire chips and soil only, indicating possible biological activity. Gases formed a few months after starting the tests. Methylene chloride dissappeared in a few months in the tanks.

5. EFFECT OF LEACHATE ON GROUNDWATER

Several studies have been conducted to asses how metal ions, VOCs, and semi-volatile organic compounds leached from tire chips under worst case scenarios (such as acidic and alkaline conditions) affect groundwater quality. When tire chips are used as fill in earthwork construction, however, such extreme conditions are not likely to exist. Most often, tire chips are exposed to groundwater or percolating rain water. Thus, leachate from aqueous solutions that simulate groundwater or rainwater (or actual groundwater or rainwater) should be considered when investigating groundwater impacts.

The Minnesota Pollution Control Agency (1990) used a field test to determine how groundwater characteristics changed when exposed to tires. Concentrations of inorganic and organic compounds in groundwater samples collected under tire chip stockpiles were compared to concentrations in groundwater samples. Groundwater samples collected from Floodwood, Minnesota showed that zinc concentrations increased from less than 0.1 mg/L (background) to 0.87 mg/L (tire chips), iron concentrations increased from 5.8 mg/L to 298 mg/L, and magnesium concentrations increased from 6.2 mg/L to 383 mg/L. In contrast, the concentration of petroleum hydrocarbons decreased from 11.8 mg/L (background) to less than 0.5 mg/L (tire chips). This may indicate that hydrocarbons can be removed by tires if a concentration gradient exists between the tire and the surrounding environment. The study also indicates that samples collected beneath stockpiles at the Floodwood site exceeded Minnesota RALs for barium, cadmium, chromium, and lead while background samples did not exceed RALs. Soil samples taken from the area have concentrations of arsenic, barium, calcium, and selenium higher than in background samples. In contrast, aluminum, iron, magnesium, and zinc were found in lower concentrations.

Two of the nine laboratory test solutions that Miller and Chadik (1993) evaluated can be considered similar to groundwater in terms of pH (slightly alkaline) and total dissolved solids (< 1321 mg/L). In these solutions, the benzene concentration was as high as 0.0115 mg/L. Toluene had the highest concentration among other organic compounds (0.112 mg/L). Although the most predominant metal ions were zinc and arsenic, their concentrations were 4.25 mg/L and 0.008 mg/L, respectively, which are lower than drinking water standards.

Humphrey and Katz (1995) installed six groundwater monitoring wells in the vicinity of a tire chip embankment to investigate the change in groundwater quality due to tire leaching. They found no relationship between concentrations of metal ions in samples from the control well and the other wells. Sometimes, the concentrations from the control well were higher than the other wells (e.g., the zinc concentration was 0.01 mg/L in the control well and 0.004 mg/L in a well close to the tire chip embankment).

Figure 9.6 Photograph of Sections 5 (foreground)
and 3 & 4 (background) on June 1, 1992

10. Environmental Suitability

Waste tires are essentially a solid waste and recycling of tires will likely need an analysis and exemption from the Wisconsin Department of Natural Resources. An analysis is needed to support the department's ultimate decision. Furthermore, the information generated through waste characterization testing should also be of use in evaluating disposal and recycling proposals for abandoned tire piles.

In order to obtain an early evaluation of potential environmental problems, duplicate EP toxicity and AFS leaching tests were performed on tire chip samples by the State Laboratory of Hygiene (Edil, Bosscher, and Eldin, 1990). The duplicate results showed excellent correlation for all substances (see Appendix C). These test results indicate that the shredded automobile tire samples show no likelihood of being a hazardous waste. The shredded tires appear to release no base-neutral regulated organics. The tire samples showed detectable but very low release patterns for all substances tested and a declining concentration with continued leaching for most substances. Four metallic elements (Ba, Fe, Mn, and Zn) exhibited increasing concentrations with continued leaching. The highest concentrations for Fe and Mn were at or above their applicable drinking water standards, while those for Ba and Zn were well below their standards. Styrene-butadiene rubber is the most important synthetic rubber used by the tire industry. This material is known to absorb large amounts of hazardous organic chemicals from the surrounding environment (Park, Kim, and Edil, 1992). This can actually impart certain beneficial environmental attributes to shredded tires. In summary, shredded tires leach very small amounts of substances compared to other wastes. By comparison to other wastes for which leach test and environmental monitoring data are available, the tire leach data indicate little or no likelihood of shredded tires to have effects on ground water.

In a study conducted for the Minnesota Pollution Control Agency (1990), it was reported that metals are leached from tire materials in the highest concentrations under acid conditions. This study indicated that Ba, Cd, Cr, Pb, Se, and Zn concentrations in adjusted acid conditions (pH of 3.5 to 5) exceed the recommended allowable limits set by the Minnesota Department of Health for drinking water. However, the field ground water and soil samples near tire construction areas had a pH of 6.1 to 6.9 and did not exceed the recommended allowable limits. This study also found that polynuclear aromatic hydrocarbons and total petroleum hydrocarbons are leached from tire materials in the highest concentration under basic conditions (pH of 8.0). This study indicates potential problems under either acidic or basic conditions, i.e., if waste tires are utilized in locations where exposure to pH extremes is expected.

It is apparent that there is need for additional field studies. As part of this project, leachate samples were collected 10 times from the two lysimeters constructed under the test embankment since April 11, 1990. Both the quantity of the leachate generated and its quality are monitored. The chemical analysis of the leachate samples was performed by the State Hygiene Laboratory. The parameters tested include COD, BOD, Cl, SO_4, pH, alkalinity, hardness, TDS, Ba, Fe, Mn, Zn, Pb, Na.

The two lysimeters were sampled originally on a monthly basis and later at decreasing frequency for a period of more than two years. Prior to retrieving each sample the lysimeter collector was pumped out and the samples were taken from the next fresh inflow. The cumulative volume of water pumped out of the lysimeters is given in Figure 10.1. There is a drastic growth of water inflow into the West lysimeter after the initial 50 days period. This is a result of lateral surface water penetration into this portion of the test embankment where the West lysimeter is located. The base elevation of the embankment drops towards west and a swale cut on the north side of the embankment collects the surface water draining from the side slope of the landfill and conducts westward to a drain pipe under the west approach. This water invades the West lysimeter giving rise to collection of significant quantities of water in the collector. The east lysimeter being located at a higher elevation is not affected as much as the West lysimeter and is likely to collect more of the water percolating vertically down the tire chips embankment. However, this too would terminate after November 20, 1991 when the embankment was paved with asphalt.

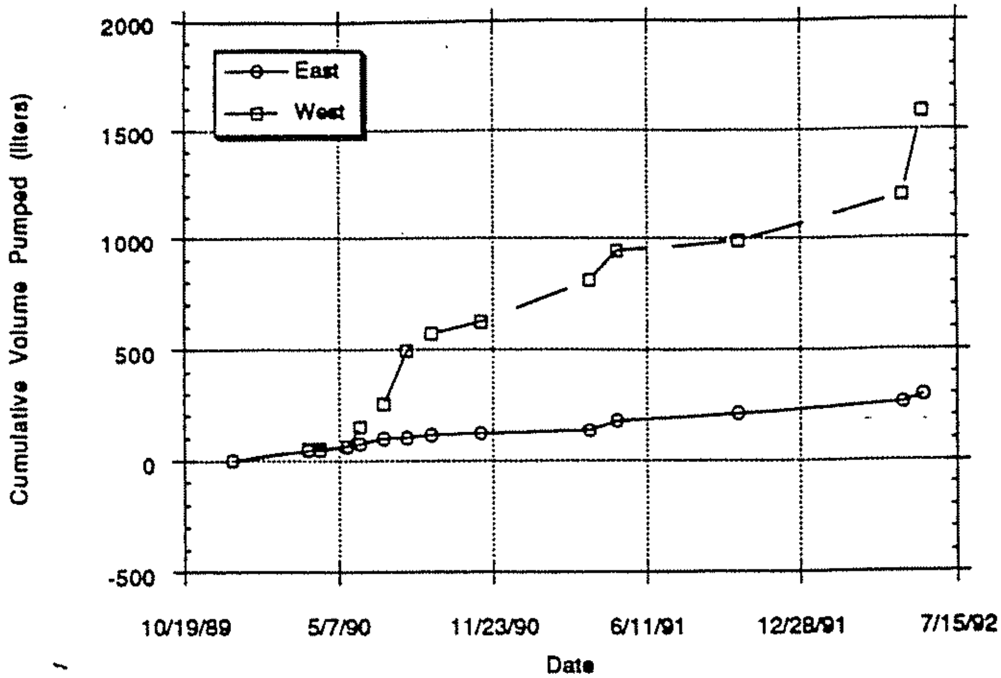

Figure 10.1 Cumulative Volume of Water Pumped from Lysimeters

The results of water quality analyses performed at the State Hygiene Laboratory are summarized in Tables 10.1 and 10.2 along with the limits given for the parameters considered in the primary and secondary drinking water standards.

Based on a review of the data, the following summary observations are made:

1. The lysimeter data show little or no likelihood of significant leaching of tire chips for substances that are specific public health concern, such as lead and barium. The leachate pH indicates slightly alkaline conditions (7.3 to 7.9).

2. Tire chips may have some leaching potential for two other metallic elements, manganese and zinc. Leaching of these elements also occurs from soil. Iron concentrations in the leachate were quite low, comparable to concentrations detected in undisturbed soils by monitoring wells.

3. The lysimeter samples contained high concentrations of cationic compound parameters, such as conductivity, hardness, calcium, and magnesium. It is very difficult to separate the source of these as soils or tire chips based upon the lysimeter data. These parameters also show increases after the fall of 1990 which may have been due to the roadway dust treatment on the embankment by application of calcium chloride in early October, 1990 (see Figure 10.2). The leach test data indicate that tire chips are very unlikely to release these constituents in the concentrations observed in the lysimeters.

Table 10.1 Water Quality Data from West Lysimeter

SAMPLE	Unit	Limits for Primary and Secondary Drinking Water Standards	4/11/90	5/9/90	6/6/90	7/5/90	8/3/90	9/4/90	12/14/90	3/28/91	10/10/91	6/1/92
pH	su		7.6	7.5	7.6	7.9	7.3	7.5	7.8	7.2	7.1	7.8
Alkalinity	mg/L		381	557	656	722	710	726	760	729	766	910
Barium	µg/L	1000 (P)	240	240	230	210	360	470	690	430	430	160
B O D	mg/L		41	15	<6	5.2	17	40	LA	4.1	<3	—
Calcium	mg/L		190	180	160	140	120	110	160	240	200	300
Chloride	mg/L	250 (S)	770	570	300	230	120	150	480	760	580	810
C O D	mg/L		200	110	84	120	140	230	290	140	71	240
Conductivity	µmhos/cm		3880						2660	3100	2960	3840
Iron	mg/L	0.3 (S)	0.05	<0.05	0.24	0.57	0.26	4	0.25	0.96	0.13	0.56
Lead	µg/L	50 (P)	<3	<3	<3	<3	<3	<3	<3	5	<3	<3
Magnesium	mg/L		190	160	150	130	120	130	180	220	240	320
Manganese	µg/L	50 (S)	170	200	220	350	2500	2100	1900	1200	45	2600
Sodium	mg/L		330	290	220	130	86	89	140	87	58	230
Sulfate	mg/L	250 (S)	130	97	130	150	140	110	117.5	140	95	42
Total solids	mg/L	500 (S)	3010	2150	1400	1330	1180	1290	1850	2610	1770	2240
Zinc	µg/L	5000 (S)	19	12	17	ND	16	44	19	30	13	750
Hardness	mg/L		1300	1100	1000	900	780	830	1100	1500	1500	2100

Table 10.2 Water Quality Data from East Lysimeter

SAMPLE	Unit	Limits for Primary and Secondary Drinking Water Standards	4/11/90	5/9/90	6/6/90	7/5/90	8/3/90	9/4/90	12/14/90	3/28/91	10/10/91	6/1/92
pH	su			7.7	7.4	7.8	7.5	7.3		7.7	7.3	7.4
Alkalinity	mg/L			533	567	625	671	705		792	616	657
Barium	µg/L	1000 (P)	220	210	240	190	270	310		350	190	570
B O D	mg/L			14	10	39	75	57		70	5.7	—
Calcium	mg/L		200	170	180	110	130	140		340	290	180
Chloride	mg/L	250 (S)		460	340	130	170	200		1400	900	1200
C O D	mg/L		280	170	220	320	290	390		560	200	78
Conductivity	µmhos/cm									5150	3880	4820
Iron	mg/L	0.3 (S)	1.3	<0.05	0.12	0.54	5.3	0.36		0.7	0.15	1.6
Lead	µg/L	50 (P)	9	<3	5	4	15	6		22	<3	<3
Magnesium	mg/L		200	150	150	96	110	120		390	240	270
Manganese	µg/L	50 (S)	230	270	300	1200	1700	2300		3200	3200	1300
Sodium	mg/L		280	220	260	98	120	140		200	210	210
Sulfate	mg/L	250 (S)		140	140	92	150	180		450	290	260
Total solids	mg/L	500 (S)		2000	1480	1110	1290	1510		4630	2460	3080
Zinc	µg/L	5000 (S)	84	46	44	540	560	120		560	84	33
Hardness	mg/L		1300	1100	1100	660	780	860		2500	1700	1500

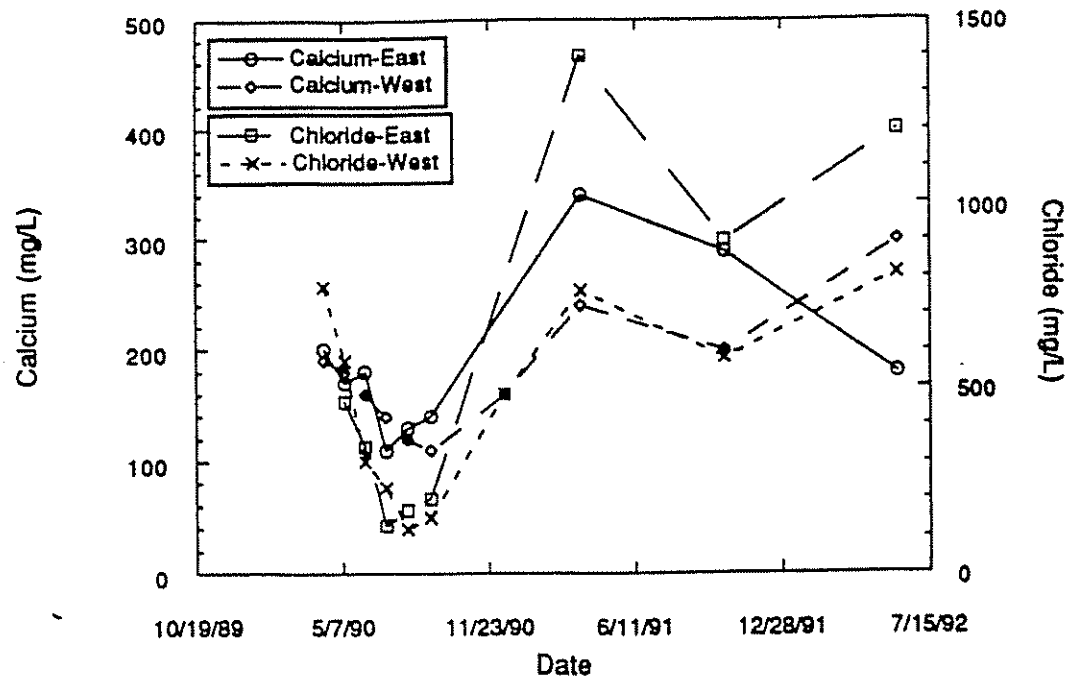

Figure 10.2 Calcium and Chloride Concentrations vs. Time

4. The lysimeter samples contained very high concentrations of anionic compounds, alkalinity, chloride, and sulfate. Chloride concentrations increased dramatically in the samples retrieved subsequent to October 1990 dust treatment on the embankment (see Figure 10.2). The leach test data for tire chips were extremely low in these parameters indicating that tire chips are very unlikely to release these constituents in any significant concentration. The high concentrations seen in the lysimeter samples for these substances are most likely due to another source.

5. The lysimeter samples contained elevated and relatively constant concentrations of organic compounds represented by COD and BOD, with no particular pattern over time. The leach tests indicated that the tire chips release these parameters but the concentrations decline rapidly. Tire chips may have contributed organic substances to the lysimeter fluids but are not likely to be responsible for the continuous presence of these compounds over the monitoring period.

Lysimeter samples showed concentrations of most parameters that were much higher than those seen in most groundwater monitoring wells near the embankment. The data indicate that effects of leaching of tire chips can be heavily masked or overwhelmed by leaching of soil materials used in the embankment. The data appear to be strongly influenced by other sources and factors as well. Some of the sources and factors that may have affected the measured concentrations include the following:

1. There was a salt (calcium chloride) treatment of the embankment surface course in October 1990 to control dust and air quality.

2. Asphalt pavement of the surface in November 1991 would inhibit downward percolation of water along the longest path through the tire chips after this date (only would impact the tenth sample).

3. While it was intended to drain the lysimeter collectors prior to sampling and then to collect a sample from the subsequent fresh inflow, there is doubt that this was followed strictly after the first few samples. So some samples may reflect the cumulative effects of collection over a period of time.

4. The type of flooding of the West lysimeter in particular, as described above, would allow intrusion of large quantities of surface water laterally traversing only a small amount of tire chips into the lysimeters. The quality of this water would overshadow the contribution of the tire chips to the measured parameters.

5. There is a possibility that the base course material used may have some salt to keep it from freezing.

6. The slopes of the adjacent landfill upstream from the lysimeters and the slopes of the embankment itself were treated with fertilizers to support vegetation.

These considerations help understand some of the concentrations above normal groundwater concentrations measured in the lysimeter samples. It is not a pristine water but not much of the observed concentrations are attributable to tire chips. Highway construction results in disturbance of soils and allows stripping of certain elements. The gravel used in constructing the base course may contain dolomite or limestone; if so, this would be a major source of constituents such as hardness, alkalinity, calcium, magnesium and sulfate. The leaching effects of tire chips could be more easily evaluated if the tire chips had some unique tracer constituent. The leach tests did not reveal one and what is known of tire composition does not suggest one.

APPENDIX B

CHEMICAL ANALYSIS OF TIRE LEACHATE FROM TANK TESTS

by

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A series of tank tests have been conducted at the University of Wisconsin-Madison. The primary objective of the tank tests was to investigate the movement of organic contaminants through compacted clay liner materials. The scrap tires are shown to have good organic compound sorption capacity and therefore tire chips were placed above the compacted clay in the test tanks to help mitigate the organic compounds. The tank tests simulated the long term behavior of tire chips in contact with landfill leachate.

A 30-cm thick compacted clay was placed at the bottom of each tank which resulted in a 60-cm deep influent reservoir on the top of the clay. Tire chips were placed on the compacted clay in the influent reservoir. The volume of the influent reservoir was approximately 170 L. The tests started in May, 1992. After permeating with tap water (approximately one month), a synthetic leachate was introduced. The synthetic leachate consisted of tap water and contained 16 mg/L of each of methylene chloride, trichloroethylene, and toluene. As a tracer, bromide was injected at a concentration of 20 mg/L in the form of lithium bromide. Also, some disinfectants, mercury chloride and sodium azide, were introduced together to prevent any biological degradation of the injected organic compounds. The tests were terminated in mid 1995.

At the end of the tests, the liquid samples taken from the mid-depth of the influent reservoirs were sent to the Soil & Plant Analysis Laboratory (Madison, WI) to analyze the potential leaching of inorganic substances, especially metals, from tire chips during the test periods. Table 1 describes the tank tests.

Table 1. Description of Tank Tests.

Sample	Elapsed time (days)	Tire Chip Quantity
Tank 4	830	10 kg/170 L
Tank 5	790	0 kg/ 170 L

Raw and filtered samples using 0.45 μm glass fiber filter were prepared. For the quality control, a sample of tap water was also sent together for analysis. Samples were analyzed using an Inductively Coupled Plasma Mass Spectrometry (ICP-MS) equipment at the Soil & Plant Analysis Laboratory. Ten inorganic ions were selected for analysis and their measured concentrations in the influent reservoir liquid found at the end of approximately 800 days of exposure and in tap water are listed in Table 2.

Table 2. Concentrations of selected parameters in the samples from the tank tests (unit = ppb).

Analysis Parameters		Filtered Samples		Raw Samples	
	Tap Water	Tank 4 (Tire Chips)	Tank 5 (No Tire Chips)	Tank 4 (Tire Chips)	Tank 5 (No Tire Chips)
Li	2.2	1187.8	1057.0	1316.2	1145.4
S	13000.0	655.0	5807.0	756.0	5871.0
Cr	4.9	7.7	6.4	8.7	7.5
Zn	96.5	1.0	25.2	92.4	27.3
As	N.D. [1]	1.4	7.9	5.7	12.1
Se	N.D. [1]	4.4	7.5	3.1	6.2
Cd	N.D. [1]	N.D. [1]	N.D. [1]	N.D. [1]	N.D. [1]
Ba	24.2	72.3	94.9	121.5	101.8
Hg	2.4	13.8	38.5	205.5	475.7
Pb	1.8	N.D. [1]	0.4	8.4	1.0
pH				6.9	6.7
DO [2]				< 1.0 ppm	< 1.0 ppm

1: Not detected.

2: Dissolved oxygen.

The concentrations of Li and Hg in the tank samples were high because significant amounts of them was injected as a tracer and disinfectant during the test periods. As previous investigations also showed, Hg was uptaken by the tire rubber. Consequently, the concentrations of Hg in Tank 4 is lower than those in Tank 5. Some metals seems to have leached from the clay.

If the concentration of a metal in Tank 4 is higher than that in Tank 5, the metal can be considered to be leached from tire chips. In the cases of Zn, Ba, and Pb, a higher concentration is observed. Five of the metals, Zn, As, Se, Ba, and Pb, were re-analyzed using replicates of the same samples. Since As and Se have been considered to be leached from tires, these two metals were also included in further analysis even though the concentrations of them in Tank 4 were not significantly higher than those in Tank 5. The range of concentrations from all analyses are listed in Table 3.

Table 3. Range of five metal concentrations from replicate samples of tank tests (unit = ppb).

Metals	Filtered Samples		Raw Samples	
	Tank 4 (Tire Chips)	Tank 5 (No Tire Chips)	Tank 4 (Tire Chips)	Tank 5 (No Tire Chips)
Zn	1.0 - 3.8	21.2 - 26.1	62.1 - 96.3	25.4 - 27.3
As	1.3 - 4.4	6.3 - 7.9	3.9 - 5.7	9.1 - 12.1
Se	4.4 - 7.3	5.0 - 7.5	3.1 - 5.1	6.2
Ba	72.3 - 110.8	93.6 - 96.2	121.5 - 123.2	95.9 - 102.3
Pb	N.D.	0.3 - 0.6	8.4 - 8.5	1.0 - 1.1

6. SYNTHESIS AND CONCLUSION

No leaching study in the literature yielded concentrations of inorganic and organic compounds that exceed TCLP and/or EP-toxicity limits. However, some of the inorganic compounds (e.g., Zn, Fe, Ba, Mn etc.) were found in concentrations higher than drinking water standards. Variability in the type of test setups, amount of tire chips and extraction liquid make the comparison among literature findings difficult, even though some tests were performed following standard procedures (e.g., TCLP). Converting leachate concentrations and the concentrations of different standards [TCLP, USEPA's Recommended Maximum Contamination Level (RMCLs), and Wisconsin's Groundwater Preventive Action Limits (PALs)] from the mass of compound per volume of liquid to the mass of compound per mass of tire chips, helps to compare the findings. Such a comparison is presented for laboratory studies in Table 2.

Two studies (RMA 1990, Miller and Chadik 1993) identified organic compounds that may exist in the tire leachate. The concentrations of toluene and phenol exceed Wisconsin PALs, but not RMCLs or TCLP limits. Although Miller and Chadik (1990) report high benzene concentrations (nearly twice the TCLP limit for benzene), the RMA (1990) study indicates no existence of benzene in the tire leachate.

Analysis of inorganic compounds is easier than organics and thus is performed in almost every study in the literature. Zinc, iron, barium, manganese, selenium, lead, chromium, and cadmium were found at concentrations higher than the RMCLs and Wisconsin PALs in most studies. Zinc and iron (two compounds

Table 2. Compounds in Tire Chip Leachates.

Compound	Concentration Limits based on Tire Chip Mass			Reported Concentrations based on Tire Chip Mass				
	TCLP[1] (mg/kg)	USEPA's RMCLs[2] (mg/kg)	WI PALs[2] (mg/kg)	Grefe[3] (1989) (mg/kg)	RMA[3] (1990) (mg/kg)	MPCA (1990) (mg/kg)	Miller and Chadik[4] (1993) (mg/kg)	Kim[5] (1995) (mg/kg)
As	25.9	0.06	6.15×10^{-3}		-		0.02	
Ba	518.0	2.27	0.25	0.55	0.1	1.08		0.37
Cd	5.18	6.15×10^{-3}	1.23×10^{-3}		-	0.27		
Cr	25.9	0.15	6.15×10^{-3}		0.008	0.51		0.019
Pb	25.9	0.025	6.15×10^{-3}	0.075	0.003	0.92		0.14
Fe		0.37	0.18	1.15		1081		
Mn		0.06	0.03	1.5				
-Zn		6.15	3.1	3.15		50.3	5.02	1.13
Se	5.18	0.055	1.23×10^{-3}			0.44		0.05
Hg	1.03	3.7×10^{-3}	2.5×10^{-3}		7.2×10^{-5}			
NO_2-NO_3		1.23	2.46	1.85				
Toluene	333.79	2.46	84.3×10^{-3}		0.034		0.28	
Carbon Disulfide	332.64				0.012			
Phenol	332.64		1.23×10^{-3}		0.01			
Benzene	0.36	6.15×10^{-3}	0.08×10^{-3}		-		0.63	

[1]TCLP are converted to mass of compound per kg of tire chips assuming that 100 g of tire chips with a specific gravity of 1.22 is used. (Volume of extractor= 600 mL, Mass of Solid= 100 grams for inorganics and 25 grams for volatile organics)

[2]RMCLs and WI PALs of 1.22. (1 mg/L=1.23 mg/kg of tire chips)

[3]The liquid concentrations are converted to mass of compound per kg of tire chips based on the given quantities of tire chips and liquid used in the study.

[4]Concentrations for compounds are taken from approximately 16 hour readings which are usually the highest concentrations achieved during the test. The liquid concentrations are converted to mass of compound per kg of tire chips based on the given quantities of tire chips and liquid used in the study.

[5]Concentrations for compounds are the final concentrations reached in 800 days. The liquid concentrations are converted to mass of compound per kg of tire chips based on the given quantities of tire chips and liquid used in the study.

with the highest concentrations) are not classified as hazardous metals in TCLP limits. Concentration of arsenic exceeded Wisconsin PALs, but not RMCLs, in the study by Miller and Chadik (1993). In contrast, arsenic was not detected in the RMA (1990) study. The concentrations of barium reported by Grefe (1989), MCPA (1990), and Kim (1995) were below RCMLs but above Wisconsin PALs. Iron concentration reported in the MCPA (1990) study is the highest concentration obtained at the "worst case" condition (i.e., pH=3.5).

Although inorganic and organic compounds are found in tire chip leachates, they are generally below TCLP limits and are not significantly greater than USEPA's RMCLs and Wisconsin PALs, regardless of differences in the test conditions. It is also important to consider that in many studies the extraction liquid or test setup is designed for "worst case" conditions that do not necessarily exist in the environment that tire chips are used. For example, laboratory tests performed under stagnant conditions or tire chips exposed to aggressive extractions do not simulate conditions likely to exist in a tire chip embankment. Thus, in the field, lower concentrations are likely to exist. In fact, in results of two field studies, (MPCA 1990, Humphrey and Katz 1995), tire chips were found to have no significant effect on groundwater quality.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

Edil, T.B. and Bosscher, P.J. (1992), "Development of Engineering Criteria For Shredded Waste Tires in Highway Applications," *Final Report Research Proj. No.-WI 14-92.*

Environment Canada National Water Research Institute (1992), "Evaluation of the Potential Toxicity of Automobile Tires in the Aquatic Environment," *B.A.R. Environmental Inc.*

Federal Register (1985), "Toxicity Characteristic Leaching Procedure (TCLP)," *Appendix I to Part 268.*

Grefe, R. (1989), "Review of Waste Characterization of Shredded Tires," *Interdepartmental Memorandum, Wisconsin Department of Natural Resources, Madison, Wisconsin (published in Edil and Bosscher 1992).*

Humphrey, D.N. and Katz, L.E. (1995), "Water Quality Testing for Dingley Road Tire Chip Test Project," *Report to Town Manager.*

Kim, J. Y. (1995), "Soil and Tire Chip Column Testing," *Internal Report UW-Madison.*

Miller, W.L. and Chadik, P.A. (1993), "A Study of Waste Tire Leachability in Potential Disposal and Usage Environments," *Amended Final Report to Florida Department of Environmental Regulation No. SW67.*

Minnesota Pollution Control Agency (1990), "Environmental Study of the Use of Shredded Waste Tires for Roadway Sub-grade Support," *Twin City Testing Corporation..*

Rubber Manufacturers Association (1990), "RMA Leachate Study," *Radian Corporation.*

Waste Management of Pennsylvania (1989), "Use of Tire Chips in Liner Protective Cover," *Waste Management of North America, Inc. Job No. 89R414-01.*

APPENDIX A

An Excerpt on Environmental Suitability from the Report:

DEVELOPMENT OF ENGINEERING CRITERIA FOR SHREDDED WASTE TIRES IN HIGHWAY APPLICATIONS

Final Report

by

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CONCLUSIONS

According to the Soil & Plant Analysis Laboratory, the tank test samples were not easy to analyze. For example, the determination of Se was less reliable than the other ions because it was interfered with bromide. Each sample contains considerable amount of bromide introduced as a tracer. Some metals showed great difference between the raw and filtered samples because the filtering process can remove precipitates of metal ions.

The analysis of raw samples can be considered to represent the total release of metal ions form tire chips. Based on the analysis of the raw samples, it can be said that tire chips release at least Zn, Ba, and Pb among the ten tested metals in the aqueous environment. In terms of the effect of metal release from tire chips on the surrounding groundwater system, the filtered sample results may be more appropriate to assess the potential effect. According to Table 3, the concentrations of the three released metals in Tank 4 ,i.e., Zn, Ba, and Pb, were in the same levels or less than those in Tank 5. Thus, the released metals from tire chips may not readily spread out and affect significantly the surrounding aqueous environment. However, under different conditions of the surrounding groundwater system, e.g., level of dissolved oxygen, pH, groundwater flow, etc., different impacts may happen in the field.

APPENDIX C - Review of the Waste Characterization of Shredded Tires

State of Wisconsin

CORRESPONDENCE/MEMORANDUM

FILE REF: 4410-1

DATE: October 19, 1989

To: Paul Koziar - SW/3

FROM: Robert Grefe - SW/3 R. Grefe

SUBJECT: Review of the Waste Characterization of Shredded Tires

This memo is in followup to my memo dated January 31, 1989 and the waste characterization information provided by the State Laboratory of Hygiene (LOH) to the Department under contract. The information consists of various leaching test data transmitted to you in July of this year. I provided a verbal analysis to you on the data in early August. This memo formally documents my review of the leaching test data.

The LOH suggested some changes to the proposed leach test protocol in a meeting in June. They explained that they could not do an oil & grease analysis under the circumstances of the leaching tests. They did not report total dissolved solids or conductivity. Given the low level of organics and other dissolved substances in the data, these variances are not serious. In all other respects, they appear to have followed the recommendations in my memo, including the use of the AFS test leach test method with three elutions.

The leaching tests were performed in duplicate, with the duplicate results showing excellent correlation for all substances. The duplicates appear to have been performed for all leach tests, although the supplementary test results provided on August 1, 1989 did not include the initial leach test results for Cd.

To summarize, the leach tests indicate that the shredded automobile tire samples show no likelihood of being a hazardous waste. The shredded tires appear to release no base-neutral regulated organics, including the PAH compounds that I suggested would be the most likely substances to be extracted from tires. The tire samples showed detectable but very low release patterns for all substances tested and a declining concentration with continued leaching for most substances. I suspect that several of the substances were released from surface coatings rather than leached from the tire material. Four metallic elements (Ba, Fe, Mn, and Zn) exhibited increasing concentrations with continued leaching. The highest concentrations for Fe and Mn were at or above their applicable drinking water standards, while those for Ba and Zn were well below their standards.

My summary judgement is that the test results indicate that shredded automobile tires leach very small amounts of substances compared to other wastes. The leaching behavior does not indicate that use of tires in earthen embankments or other earthwork structures would constitute a threat to groundwater or surface water. The minor amount of leaching of indicators and some metals suggests that tires are best used in buried locations above the water table, rather than in surface applications or in contact with open water bodies. Use of shredded tires need not be restricted in ways different from those placed on whole tires.

This opinion does not mean that use of tires should be deregulated. Waste tires are still a public health and nuisance threat. They present problems with both aesthetics and combustion effects. Their use in earthwork structures should continue to be reviewed on a case-by-case basis. There is flexibility within the low-hazard waste exemption (s. 144.44(7)(g), Stats.) to review and approve use of waste tires either in an individual project or in a category of projects controlled by a single sponsor.

Blanks

Blank water samples were run for all of the EP Toxicity, Base-Neutral, and AFS test results. The three sequential blank samples for each test all showed suitably low detectable or nondetectable concentrations for the substances tested for in each test. There was no significant variation between samples.

EP Toxicity Test Results

The EP toxicity test was run for the elements Ba, Cd, Cr, Pb, and Hg, but not for As, Se, or Ag. Relatively high detection levels were used for Cr and Pb. Neither duplicate had concentrations above the detection levels used in the test. The AFS test results also indicate that there is little likelihood that this test protocol will produce high concentrations of any regulated metal. The test results indicate that waste automobile tires are extremely unlikely to be classified as a hazardous waste.

Base-Neutral Organics Test Results

Both duplicates exhibited identical results. No compounds were detected at detection limits of 2 to 40 micrograms per liter for the listed 45 compounds. The analytical equipment used was GC-MS. There were no changes in the particular detection limits for each compound between either duplicate, the sequential elutions, or between blanks and samples. This information, plus the low organic content indicated in the AFS test results, indicates that there were no interference effects present which might distort sample results.

AFS Test Results

The LOH followed the AFS test procedure for evaluating the leaching behavior of metals, anions, and organic and inorganic indicator parameters. The shredded tire samples were leached in three sequential elutions with distilled water at a liquid to solid mass ratio of 5:1. Detection limits for metals were in the single micrograms per liter (ug/l) range, while the indicators and anions had detection limits in the milligram per liter (mg/l) range. In contrast to the results of the tests discussed above, several substances were detected in one or more of the elutions. The results allow discussion of the trends in leaching behavior of groups of substances.

pH The samples indicate that the shredded tires cause the leaching medium to be slightly alkaline (7.13 to 7.43), with no apparent trend over the three elutions.

Alkalinity and Hardness

In both samples, alkalinity showed a constant concentration (17-19 mg/l) over the 3 elutions, while hardness showed a slight decrease (19 to 13 mg/l). The hardness appears to consist entirely of Ca, as elemental analyses revealed no Mg over a detection limit of 1 mg/l.

Anions and Organic Indicators

Cl decreased from 3.9 to less than 0.3 mg/l.

SO_4 decreased from 6.5 to 1 mg/l.

BOD decreased from 22 to 6.5 mg/l. In both duplicates, no results were obtained from the second elution, apparently due to some toxicity effects on the organisms. COD decreased from 68-72 to 24-27 mg/l. The BOD/COD ratio declined from .33 to .25 over the three elutions.

NO_2-NO_3 concentrations were an order of magnitude below those for TKN and decreased from .37 to .02 mg/l. TKN decreased from 3 to 1.2 mg/l.

Most of these parameters exhibited the greatest decline in concentrations between the first and second elutions. Concentrations are low compared to leachate or other contaminated liquids. The organic fraction appears to be moderately biodegradable. The rapid decrease between the first and second elutions indicates that the majority of the mass for these substances may come from surface coatings rather than the structure of the tire compounds.

Metallic Elements

Below Detection limits

The following elements were not detected at the indicated detection limits in any elution:

As	10 ug/l
Cd	0.2 ug/l
Cr	3 ug/l
Cu	20 ug/l
Se	5 ug/l
Ti	ND=3 ug/l

Decreasing Concentrations

Pb decreased from 15 to less than 3 ug/l.

Na decreased from 4 to 1 mg/l.

The greatest decreases occurred between the first and second elutions. The concentrations involved are very low compared to other waste leaching results and many natural groundwater results. As with the substances in the previous section, it may be that the majority of the leached mass originates in surface coatings on the tires. Pb is a common road surface contaminant due to the use of lead compounds in gasoline.

Increasing Concentrations

Ba exhibited a constant or slightly increasing concentration of approximately 110 ug/l.

Fe concentrations increased at the third elution from below the detection limit of 50 ug/l to 150-230 ug/l.

Mn concentrations increased between the second and third elutions, from 80-85 to 250-300 ug/l.

Zn concentrations also increased between the second and third elutions, from 38-40 to 360-630 ug/l.

The patterns in the increasing trends indicate that these substances are being extracted from the mass of the shredded tires rather than from a surface coating. The delay in release until the third elution may be due to oxidation of the wire bead or tire compounds. If so, leaching under anaerobic conditions may be less than the leach tests indicate.

The Mn concentration at the third elution exceeded the drinking water standard (50 ug/l), and that for Fe was close to its standard (300 ug/l). The concentrations for Ba and Zn were an order of magnitude below their respective standards.

Neither groundwater standards nor leach test results can be used to predict the actual effects of shredded tires on groundwater in a disposal or reuse project. However, by comparison to other projects where leach test and environmental monitoring data are available, the tire data indicate little or no likelihood of shredded tires to have effects on groundwater even in restricted groundwater flow regimes. Confirmation of this can be obtained from the monitoring of pilot or full scale projects. I recommend the use of collection basin lysimeters rather than groundwater monitoring wells for this purpose.

rpg

cc. Gene Mitchell - SW/3
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Mitigation of organic compound movement in landfills by shredded tires

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Mitigation of organic compound movement in landfills by shredded tires

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ABSTRACT: This paper evaluates the feasibility of using shredded tires for removal of organic compounds from landfill leachate. From the batch sorption isotherm experiments, tire chips were found to have 1.4% to 5.6% of the sorption capacity of granular activated carbon on a volume basis. The sorption equilibrium occurred within 2 days for 0.6-, 1.3-, and 2.5-cm size tire chips. The capacity of tire chips to adsorb organic compounds in a multisolute system was almost equal to that in single-solute systems. Only 3.4% to 7.9% of the organic compounds sorbed in tire chips were desorbed. A design method was proposed to estimate the thickness of a tire layer required for a target organic compound removal from the landfill leachate based on a structure-activity relationship obtained from laboratory tests. *Water Environ. Res.*, **68**, 4 (1996).

KEYWORDS: diffusion, landill, leachate, organic compounds, shredded tires, sorption.

The management of scrap tires has become a growing problem in recent years. Annually over 240 million scrap tires are generated in the U.S. (Scrap Tire Management Council, 1990; U.S. EPA, 1991). Additionally, approximately 2 billion waste tires have accumulated in stockpiles or uncontrolled tire dumps across the country (U.S. EPA, 1991). It is estimated that less than 7% of the 240 million tires discarded in 1990 were recycled into new products and about 11% were converted into energy. Over 77%, or about 188 million tires per year, were landfilled, stockpiled, or illegally dumped, and the remaining 5% were exported. Whole tires are difficult to landfill because they tend to float to the surface and also take up a large volume of valuable landfill space. Stockpiles of scrap tires are located in many communities, resulting in public health, environmental, and aesthetic problems. The piled tires provide breeding sites for mosquitoes, which can spread serious diseases and bear potential fire hazards. The simple disposal methods thus bring in public health, aesthetic, and environmental problems. Desirable disposal methods should at least include three facets: minimum environmental impact, maximum reutilization of potential resources, and economic feasibility.

Tires are principally composed of vulcanized rubber, rubberized fabric containing reinforcing textile cords, steel or fabric belts, and steel wire-reinforced rubber beads. Although natural rubber is still used in tires, synthetic rubbers have become an integral part of modern tire manufacturing. Styrene-butadiene rubber (SBR) is the most important synthetic rubber used by the tire industry. This is a result of its good mechanical and physical properties coupled with its favorable cost. The SBR is made by copolymerizing 75% butadiene and 25% styrene. Other elastomers such as natural rubber (*cis*-polyisoprene), synthetic *cis*-polyisoprene, and *cis*-polybutadiene are also used in tires in varying amounts. Carbon black is used to strengthen the rubber and aid abrasion resistance. Extender oil, a mixture of aromatic hydrocarbons, serves to soften the rubber and improve workability. Sulfur, the vulcanizing agent, is used to cross-link the polymer chains within the rubber and to harden and prevent excessive deformation at elevated temperatures. The accelerator is typically an organosulfur compound that acts as a catalyst for the vulcanization process. Zinc oxide and stearic acid also act to control the vulcanization process and to enhance the physical properties of the rubber (Dodds *et al.*, 1983). A typical composition of tire rubber is shown in Table 1.

Park *et al.* (1991a) investigated the permeation of organic compounds through SBR gaskets used for potable water distribution systems and found a high organic compound sorption capacity for SBR. Many hazardous organic compounds have recently been detected in leachate from industrial hazardous-waste and municipal solid waste landfills (Gibbons *et al.*, 1992). However, both the earthen liners and geomembranes (flexible membrane liners) were found to have limited abilities for containing organic compounds (Park *et al.*, 1991b; Edil *et al.*, 1992a; Sakti *et al.*, 1992; Park and Nibras, 1993; Park *et al.*, 1994).

Park *et al.* (1991b) evaluated the effect of organic carbon content in clay using the Ogata and Banks' solution with the parameters commonly encountered in hazardous-waste landfill sites (Figure 1). The left-hand abscissa denotes the pore volume. The right-hand abscissa denotes the time when the breakthrough curve reaches 10% of the initial concentration (0.1 C_0). In the case of methylene chloride, the breakthrough time was not significantly affected by an organic carbon content of up to 1%. However, toluene and trichloroethylene (TCE) breakthrough times were greatly affected by organic carbon content. It was postulated that the breakthrough time could be significantly retarded by installing a layer(s) of shredded tire chips in proper locations in landfills.

There may be some concern over a potential detrimental and environmental impact caused by scrap tires. EPA's toxicity characteristics leaching procedure (TCLP) was used for various types of tires under different scrap tire processing scenarios (House of Representatives, 1990). Carbon disulfide was detected ranging from no detection to 0.067 mg/L. Toluene was detected at the range from 0.007 to 0.19 mg/L. Phenol was detected at the range of no detection to 0.046 mg/L. Trace levels of barium, chromium, lead, and mercury were also detected. All results reported were below EPA's regulatory levels (House of Representatives, 1990). Another series of leaching tests using the American Foundry Society (AFS) procedure was conducted by the Wisconsin Department of Natural Resources (Grefe, 1989). Zinc and lead were detected at concentrations of 0.38 to 0.63 mg/L and no detection to 0.015 mg/L, respectively, at three sequential elusions. Iron and manganese concentrations ranged from no detection to 0.23 mg/L and 0.082 to 0.3 mg/L, respectively. No base or neutral priority pollutants were detected. EP

Table 1—Rubber compounding composition (adopted from Dodds *et al.*, 1983).

Component	% Weight
SBR	62.1
Carbon black	31.0
Extender oil	1.9
Zinc oxide	1.9
Stearic acid	1.2
Sulfur	1.1
Accelerator	0.7

toxicity test results for barium, cadmium, chromium, lead, and mercury were all below the detection limits. Additionally, leachate generated by percolating water through tire chips used in construction of a roadway was monitored in the field for a period of 2 years for a range of parameters (Edil and Bosscher, 1992). On the basis all of these studies, it can be said that the potential leaching of toxic pollutants from scrap tires is minimal.

The objectives of this research were: (1) to determine the capacity of shredded tires to adsorb and desorb hazardous organic compounds, (2) to estimate the partition and diffusion coefficients of organic compounds in tire chips, and (3) to develop design guidelines for use of shredded tires in landfill.

Materials and Methods

Shredded tires were obtained from a local tire processor. No attempt was made to separate tires based on different manufacturers or sizes. The density of shredded tires with metal material was measured to be 1.22 g/cm^3. Before tests, the tires were washed with deionized water, dried in a 40°C oven for a day, and stored in a desiccator. The tire chip sizes tested ranged from 0.6 to 2.5 cm.

Methylene chloride (MC), TCE, toluene, and *m*-xylene were selected for testing. These organic compounds are the most frequently detected compounds at waste disposal sites (Plumb and Pitchford, 1985; Gibbons *et al.*, 1992). The organic compounds selected cover wide ranges of the aqueous solubility (S) and the molecular weight (MW).

Gas chromatographic analysis was performed on a Varian 3600 gas chromatograph with 60-m-long, 0.25-mm ID Supelcowax-10 megabore column and a flame ionization detector (FID). An aliquot of 2-μL sample was directly injected into the column using a gas-tight microsyringe. Helium was used as a carrier gas. The column temperature was programmed to initially hold at 60°C for 5 minutes, then climb to 230°C at a rate of 15°C/min and then to hold for 1 minute. A Varian® 1093 Septum Equipped Programmable Injector was programmed to start at 50°C, to immediately climb to 230°C at a rate of 150°C/min, and then hold for 1 minute to clean any potential contamination of the injector by residual organic compounds. The FID detection limits were approximately 0.5 mg/L for MC and TCE and 0.3 mg/L for toluene and *m*-xylene, respectively.

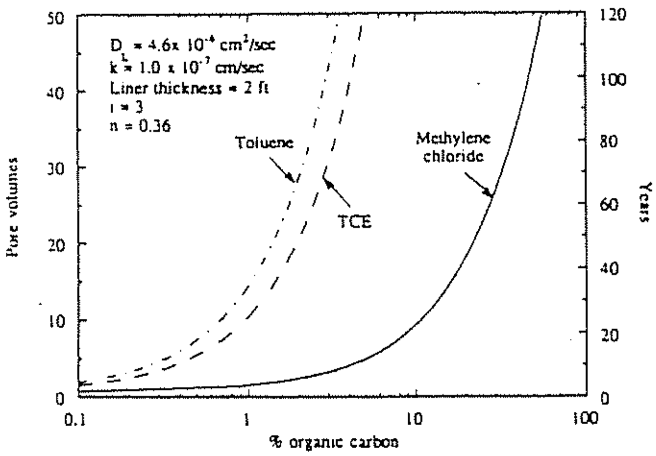

Figure 1—Effect of clay organic carbon content on the breakthrough pore volume.

A series of batch sorption-desorption tests were conducted using tire chips. The batch sorption test consisted of submerging tire chips in a 350-mL glass reactor, mixing the tire chips with the solution containing target organic compounds for up to 2 weeks, and measuring the concentration periodically. Each reactor is 15-cm long and 5-cm in diameter with a sampling port and Teflon® plugs. Four glass reactors were used and rotated by a rotary agitator. All experiments were conducted in a 20°C constant temperature room. There was no significant loss of target organic compounds through reactor joints for a week (<5%). After equilibrium was achieved, the solution containing the target organic compounds was replaced with deionized water and a desorption test was performed for 7 days.

The partition coefficient, *K*, expresses the ability of the tire chip to sorb organic compounds from the solution. *K* is the ratio between the organic compound concentration in the medium and the organic compound concentration in sorbate at equilibrium as follows:

$$C_s = K \cdot C_l \qquad (1)$$

Where

C_s = the organic compound concentration in tire chips, mg/L; and
C_l = the organic compound concentration in the liquid, mg/L.

K can be determined from the experimental data using the following relationship:

$$K = \frac{M_{eq} \times \rho_t}{M_t \times C_{eq}} \times 10^6 \qquad (2)$$

Where

M_{eq} = the weight of organic compound sorbed at equilibrium, g;
M_t = the initial weight of tire, g;
ρ_t = the density of tire, g/cm^3; and
C_{eq} = the concentration in the medium at equilibrium, mg/L.

The rate of diffusion is expressed in terms of the diffusion coefficient. The mass balance for pure Fickian diffusion is expressed as follows:

$$F = -D\frac{dc}{dx} \qquad (3)$$

Where

F = the mass flux, mg/cm^2/s;
D = the diffusion coefficient, cm^2/s;

c = the concentration of organic compound in tires, mg/cm^3; and

x = the distance along the direction of diffusion, cm.

The concentration of an organic compound in the material diffused at any point varies with time according to Fick's second law. The experimental system is represented by the condition that a plain sheet of tire chip is suspended in a well-stirred solution of limited volume. The mass transport of organic compounds in a tire chip and the boundary conditions at the interface between the tire chip and the solution can be expressed as follows:

$$\frac{\partial c}{\partial t} = -\frac{\partial F}{\partial x} = -\frac{\partial}{\partial x}\left(-D\frac{\partial c}{\partial x}\right) = D\frac{\partial^2 c}{\partial x^2} \qquad (4)$$

$$-A\frac{\partial C}{\partial t} = -\frac{A}{K}\frac{\partial c}{\partial t} = \pm D\frac{\partial c}{\partial x} \quad \text{at } x = \pm l \text{ and } t > 0 \qquad (5)$$

Where

2A = the length of the solution in contact with both sides of the tires, cm;

C = the concentration of the organic compound in the solution, mg/L;

t = the time, s; and

$2l$ = the thickness of the tire chip, cm.

The length of the solution in contact with both sides of the tire chip, 2A, is the ratio of solution volume to the surface area of the tire chip. The boundary and initial conditions are:

$$C = C_0, \quad c(x, 0) = 0 \quad \text{at } -l < x < +l \qquad (6)$$

The analytical solution of Equation 4 subject to Equations 5 and 6 is approximated as follows (Crank, 1975):

$$\frac{C_t}{C_0} = \exp\left(\frac{T}{\alpha^2}\right) \times \text{erfc}\left(\frac{T}{\alpha^2}\right)^{0.5} \qquad (7)$$

where $T = D \times t/l^2$ and $\alpha = A/K \times l$.

The sorption half-time, $t_{1/2}$, is defined as the time when C_t/C_0 is 0.5. Equation 7 can be converted to the following equation by using the sorption half-time, $t_{1/2}$ (Reynolds *et al.*, 1990):

$$t_{1/2} = 0.585 \times \frac{A^2}{K^2 \times D} \qquad (8)$$

If K and $t_{1/2}$ are determined from the batch isotherm test, then D can be estimated using Equation 8.

A thermodynamic model derived by Park and Bontoux (1991) was used to evaluate M_{eq}/M_s at any concentration. The mathematical expression of the thermodynamic model is as follows:

$$\frac{1}{M_{eq}/M_s} = a + b \times \frac{l}{C_{eq}/S} \qquad (9)$$

Where

M_{eq} = the mass of organic compound sorbed, mg;

M_s = the mass of tire chips, g;

a and b = regression constants; and

S = the aqueous solubility, mg/L.

The recorded weight gain data can be evaluated based on percent weight gain of the organic compound by the tire chip, where percent weight gain was calculated by the following expression (Berens, 1985; Park *et al.*, 1991a):

$$\%\text{ weight gain} = \frac{100 \times V_1 \times \rho_{oc}}{(1 - V_1) \times \rho_t} \qquad (10)$$

Where

V_1 = the volumetric fraction of organic compound sorbed per unit volume of tire chip; and

ρ_{oc} = the density of organic compound, g/cm^3.

V_1 is a function of the organic compound sorbed, i.e., weight gain, and is given as:

$$V_1 = \frac{M_w/\rho_{oc}}{M_i/\rho_t + M_w/\rho_{oc}} \qquad (11)$$

Where

M_w = the weight gain calculated from the concentration changes in the liquid phase during the experiment, g; and

M_i = the initial weight of the tire chip, g.

Results and Discussion

A series of batch sorption tests were conducted using only a single compound to assess the sorption capacity of tire chips. The K and D values were estimated using Equations 2 and 8, respectively. The concentration changes over time were predicted using Equation 7 with these estimated K and D values and compared with the measured concentrations to assess the accuracy of this data analysis method. Figure 2 gives a comparison of the predicted curve and the measured data, typical of the case for other organic compounds tested. It can be seen that the predicted curve using the estimated K and D values is in good agreement with the observed data. Thus, this method was used to determine K and D values throughout the study.

Table 2 summarizes the single-solute sorption test results for tire chips along with M_{eq}/M_s values for granular activated carbon (GAC), which are calculated on the basis of the parameters reported by Dobbs and Cohen (1980). Because of its higher octanol-water partition coefficient and lower solubility, *m*-xylene had 2 to 3.5 times greater partition coefficients than toluene and TCE. As expected, MC has the lowest partition coefficient because of high solubility and a low octanol-water partition coefficient, but

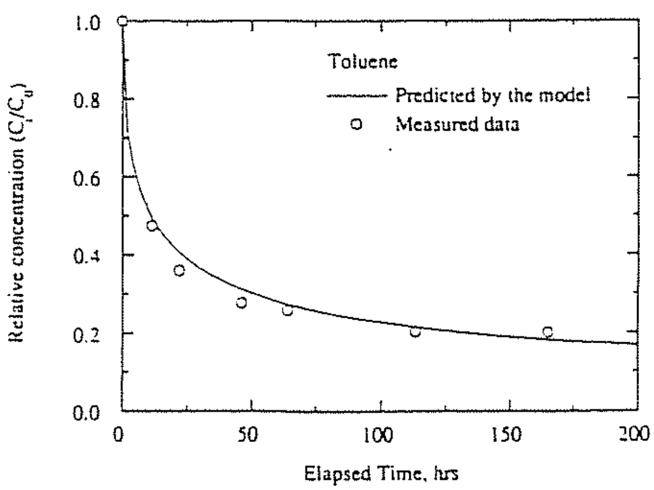

Figure 2—Comparison between the calculated curve and measured data.

Table 2—Summary of experimental conditions and results for single-solute experiments.

Organic compounds	Tire-liquid ratio, % by volume	C_{eq}/C_o	$t_{1/2}$, hr	Tire M_{eq}/M_s, g/kg	GAC M_{eq}/M_s, g/kg	K	D, cm²/s
MC	1.22	0.476	120	0.9	23	89.0	1.23×10^{-7}
	2.83	0.431	100	0.4	21	45.4	1.37×10^{-7}
	4.65	0.421	95	0.3	20	28.2	1.59×10^{-7}
	5.96	0.418	80	0.2	20	22.0	1.71×10^{-7}
TCE	0.72	0.373	30	3.0	154	230.4	0.74×10^{-7}
	2.09	0.167	8	1.3	103	234.4	0.65×10^{-7}
	3.89	0.106	2.7	0.8	77	208.5	1.01×10^{-7}
	5.26	0.080	1.7	0.6	65	206.3	0.92×10^{-7}
Toluene	1.23	0.202	11	2.6	72	316.1	1.06×10^{-7}
	2.66	0.096	3	1.3	49	345.0	0.79×10^{-7}
	3.77	0.083	1.7	0.9	46	280.0	0.92×10^{-7}
	4.21	0.074	1.9	0.8	44	285.9	0.79×10^{-7}
m-Xylene	0.74	0.135	6.8	5.1	122	856.1	0.24×10^{-7}
	2.45	0.062	2.1	1.7	105	601.8	0.37×10^{-7}
	3.52	0.046	1.1	1.2	100	569.1	0.35×10^{-7}
	4.34	0.038	1.2	1.0	96	555.4	0.33×10^{-7}

the highest diffusion coefficient because of its smaller molecular diameter. It can be seen that tire chips had 1% to 4% of the GAC sorption capacities. Because tire chips have approximately 1.4 times greater apparent density than GAC, the sorption capacity of tire chips per unit volume would be approximately 1.4% to 5.6% that of GAC.

The thermodynamic relationship of M_{eq}/M, and C_{eq}/S for the results of single-solute experiments expressed in Equation 9 is plotted in Figure 3. The thermodynamic model appeared to predict the sorption of organic compounds to tire chips accurately.

Another series of batch sorption tests was conducted to investigate the effect of organic compound mixtures on sorption capacity. The MC, TCE, and toluene were added simultaneously to a reactor. The experimental conditions and results for the batch sorption test are summarized in Table 3. Tire chip size varied from 0.6 to 2.5 cm and tire-liquid ratios from 0.75% to 1.12% by volume. There seemed to be no significant difference between the sorption capacities for the multi- and single-solute systems.

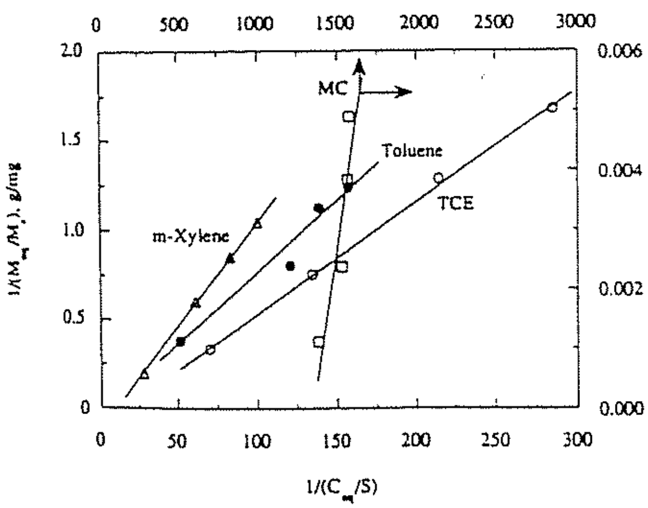

Figure 3—Thermodynamic relationships of four organic compounds in single-solute experiments.

The changes in the liquid phase TCE concentration over time for three different tire chip sizes from a multisolute test are shown in Figure 4. The half sorption times for TCE and toluene were approximately 3 times less for 1.3-cm-size tire chips than with 2.5-cm chips. However, the half sorption times for 0.6-cm-size tire chips were practically the same as the 1.3-cm-size tire chips. The equilibrium concentrations for different tire chip sizes were almost the same. The equilibrium was reached within 2 days for TCE and toluene; thus, the reaction rate may not be a limiting factor if tire chips are used in landfills as a sorbent. This indicates that the size of the tire chips does not need to be smaller than 1.3 cm. Practical tire chip sizes would range from 1.3 to 2.5 cm or even greater.

Park *et al.* (1991a) found that the partition and diffusion coefficients can be predicted from the relationships with the octanol-water partition coefficient (K_{ow}) and the molecular diameter (D_m), respectively. Figure 5 shows the logarithmic relationship between the measured partition coefficient and K_{ow}. Figure 6 shows the relationship between log D and D_m. The following empirical relationships are obtained from the experimental results in the equilibrium concentration range of 2 to 24 mg/L:

$$\log K = 0.824 + 0.614 \log K_{ow} \qquad (12)$$

$$\log D = -4.426 - 5.001\, D_m \qquad (13)$$

Sorption-desorption tests were also conducted with tire chips (Table 4). During desorption, the mass of compound sorbed previously was not leached out completely. After desorption reached equilibrium, most of the organic compounds sorbed still remained in the solid phase. Of the organic compounds sorbed in tire chips, only 3.5% to 7.9% were desorbed, indicating the desorption is irreversible.

A continuous-flow experiment may be more suitable for evaluating the sorption capacity of tire chips in landfills. However, the sorption of organic compounds onto tires was relatively fast and reached equilibrium within a few days. Considering the detention time of leachate in landfills, the batch results could be

Table 3—Summary of experimental conditions and results for multisolute experiments.

Run no., % tire-liquid ratio, tire chip size	Organic compounds	C_{eq}/C_o	$t_{1/2}$, hr	M_{eq}/M_t, g/kg	Weight gain, %	K	D, cm²/s
Run 1	MC	0.789	NA[a]	1.16	0.12	35.1	NA[a,b]
0.75%	TCE	0.277	8	3.01	0.30	344.5	NA[b]
2.5 × 2.5 cm	Toluene	0.254	8	3.50	0.35	233.1	NA[b]
Run 2	MC	0.807	NA[a]	1.03	0.10	28.6	NA[a,b]
0.82%	TCE	0.267	8	2.54	0.25	332.3	NA[b]
1.3 × 1.3 cm	Toluene	0.237	8	3.19	0.32	389.3	NA[b]
Run 3	MC	0.866	NA[a]	0.56	0.06	13.7	NA[b]
1.12%	TCE	0.296	27	1.99	0.20	209.9	1.37×10^{-7}
0.6 × 0.6 cm	Toluene	0.254	24	2.17	0.33	387.6	1.59×10^{-7}

[a] Not available; because the concentration decrease of methylene chloride was too small to observe the $t_{1/2}$, it was not possible to estimate the diffusion coefficient.

[b] Not available; the same method for the diffusion coefficient could not be used because the shape of the tire chips changed. The diffusion through the sides of chips could not be ignored.

used for field conditions. Equations 12 and 13 allow the prediction of the partition and diffusion coefficients for various organic compounds, which, in turn, allows the estimation of the sorption capacity and rate. The thickness of the tire chip layer needed to remove a given amount of organic compounds, d (cm), may then be determined in a waste management system using the following relationship:

$$d = 2.471 \times 10^{-5} \times \frac{M_a}{(1-n) \cdot \rho_t} \qquad (14)$$

Where

n = the porosity of the tire chip layer and
M_a = the required mass of tire chips per unit area, (kg/ac).

If a certain percentage of these organic compounds needs to be removed from the leachate, then the mass of tire chips required can be estimated as follows:

$$M_a = \frac{f \cdot Q_r \cdot t_d \cdot \rho_t \cdot 10^3}{(1-f) \cdot 10^{0.824+0.614 \log K_{ow}}} \qquad (15)$$

Where

f = the fraction of organic compound to be removed
Q_r = the leachate generation rate (m³/ac/yr); and
t_d = the landfill design life, yr.

Note that the tire chip layer depth is not a function of organic compound concentration but a function of the fraction of organic compound to be removed.

Let's assume that the leachate generation rate in a landfill is 600 m³/ac/yr (typically 20% of the annual precipitation), the concentration of benzene, TCE, *m*-xylene, and pentachlorophenol (PCP) is 1 mg/L each, and a landfill design life time is 20 years. For 90% removal of each organic compound over 20 years of the landfill design life, the thickness of a tire chip layer is estimated to be 39.4, 22.4, 8.7, and 0.7 cm, respectively. If a 30-cm-thick tire layer is used, then the removal efficiencies of benzene, TCE, *m*-xylene, and pentachlorophenol are expected to be 86.4%, 90.3%, 94.6%, and 99.0%. Figure 7 shows the required tire layer thickness for 90% organic compound removal over various design lives. As a rule of thumb, 10 automobile tires are needed to form a 10-cm-thick layer over 1-m² area.

It should be noted that organic compounds that require large

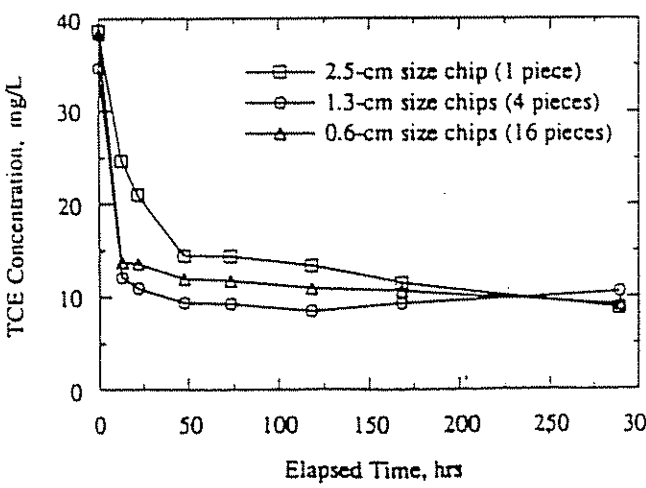

Figure 4—The effect of tire chip size on the TCE sorption rate.

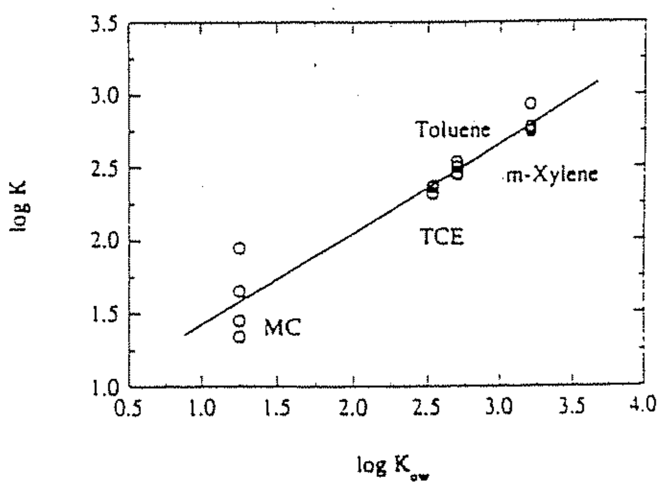

Figure 5—Relationship between K_{ow} and K.

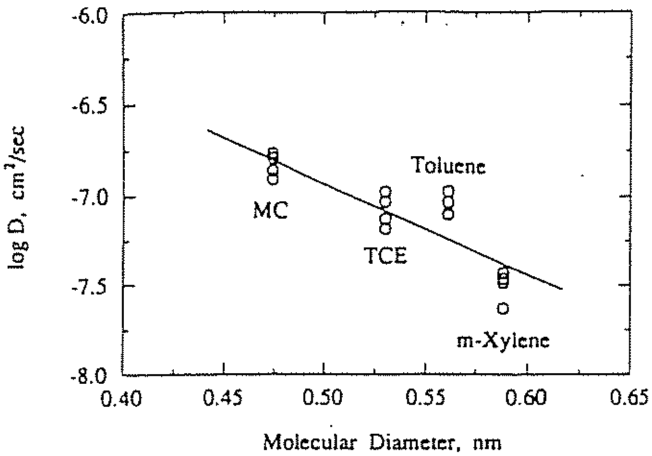

Figure 6—Relationship between molecular diameter and *D*.

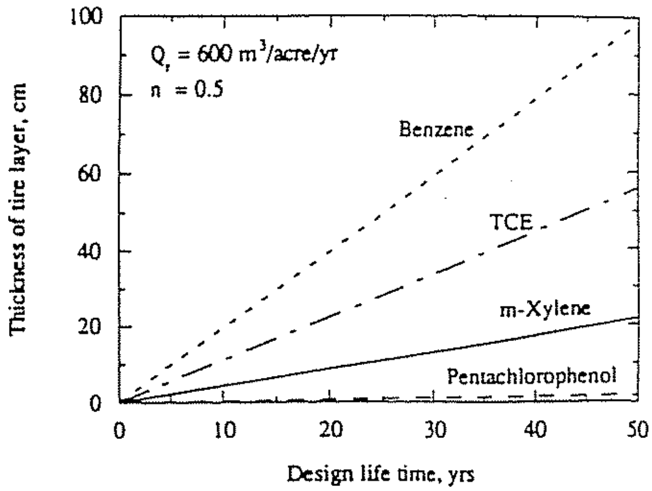

Figure 7—Thickness of a tire layer for 90% organic chemical removal.

quantities of shredded tires tend to be more biodegradable. In general, the compounds with high solubilities (>2 000 mg/L) and less chlorine atoms (<2 chlorines) are relatively easy to biodegrade. Therefore, it may not be necessary to increase the thickness to much greater than 30 cm.

As shown in the aqueous phase batch isotherm tests, tire chips could sorb significant amounts of organic compounds. The installation of a 15- to 30-cm-thick tire chip layer over the landfill liner could result in three major advantages: (1) retardation of potentially hazardous organic compound movement from landfills by sorption, (2) an effective avenue of disposal for scrap vehicle tires, and (3) substitution of sand and gravel typically used in the drainage layer of the leachate collection system by tire chips (tire chips behave as an excellent drainage material as shown by Edil *et al.*, 1992b). One study indicated that in the protective cover and primary leachate collection system, which consists of a minimum 45-cm-thick layer of select granular material overlain by a minimum 15-cm-thick additional layer of an alternative select-free draining material, the replacement of the overlaying 15-cm-thick select-free draining material by tire chips could result in 40% cost saving (Waste Management of North America, Inc., 1990). The following additional advantages are also likely to be achieved: (1) decreasing persistent organic compound concentration in liquid phase, (2) furnishing a longer detention time for acclimation and biodegradation, (3) providing ideal sites for microbial consortia to grow, and (4) maintaining constant liquid phase concentration by sorption or desorption.

Conclusions

From the batch isotherm experiments using shredded tire chips, the following conclusions can be drawn. Tire chips are

Table 4—Sorption-desorption tests of tire chips. The numbers in brackets denote % of the total mass in each phase.

	Mass distribution, mg						
	Initial			Final			
	Liquid	Solid	Total	Liquid	Solid	Total	*K*
Sorption							
Methylene chloride	17.48 (100)	0.00 (0.0)	17.48 (100)	7.04 (40.3)	10.44 (59.7)	17.48 (100)	122
TCE	18.91 (100)	0.00 (0.0)	18.91 (100)	3.17 (16.8)	15.75 (83.2)	18.91 (100)	408
Toluene	19.32 (100)	0.00 (0.0)	19.32 (100)	3.17 (16.4)	16.15 (83.6)	19.32 (100)	419
m-Xylene	18.35 (100)	0.00 (0.0)	18.35 (100)	1.63 (8.9)	16.72 (91.1)	18.35 (100)	841
Desorption							% desorbed
Methylene chloride	0.08 (0.8)	10.44 (99.2)	10.53 (100)	0.45 (4.3)	10.08 (95.7)	10.53 (100)	3.5
TCE	0.24 (1.5)	15.75 (98.5)	15.99 (100)	1.46 (9.1)	14.53 (90.9)	15.99 (100)	7.7
Toluene	0.19 (1.2)	16.15 (98.8)	16.34 (100)	1.47 (9.0)	14.87 (91.0)	16.34 (100)	7.9
m-Xylene	0.16 (0.9)	16.72 (99.1)	16.87 (100)	0.94 (5.6)	15.93 (94.4)	16.87 (100)	4.7

found to have relatively high organic compound sorption capacities. Tire chips have 1.4% to 5.6% of the sorption capacity of granular activated carbon on a volume basis. The sorption equilibrium occurs within 2 days for 0.6-, 1.3- and 2.5-cm-size tire chips, although the sorption rates for 0.6- and 1.3-cm-size tire chips are slightly faster than 2.5-cm-size tire chips. Recommended tire chip size would be 2.5 cm. The capacity of tire chips to adsorb organic compounds in a multisolute system was not much different from that in single-solute systems.

The partition coefficient increases logarithmically with the octanol-water partition coefficient, and the diffusion coefficient decreases with increasing molecular diameter. Of the organic compounds sorbed in tire chips, only 3.5% to 7.9% were desorbed. The partition coefficient after desorption tests were 2 to 15 times greater than those obtained from sorption tests. A 30-cm-thick tire chip layer as a primary leachate collection system is expected to sorb significant levels of organic compounds, thereby reducing the liquid phase concentration. This will result in the mitigation of organic compound movement from landfills.

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References

Berens, A. R. (1985) Prediction of Organic Chemical Permeation Through PVC Pipe. *J. Am. Water Works Assoc.*, 77, (11), 57–64.

Crank, J. (1975) *The Mathematics of Diffusion.* 2nd ed. Clarendon Press, Oxford, U.K.

Dobbs, R. A., and Cohen, J. M. (1980) *Carbon Adsorption Isotherms for Toxic Organics.* EPA-600/8-80-023, U.S. EPA, Cincinnati, Ohio.

Dodds, J., Domenico, W. F., Evans, D. R., Fish, L. W., Lassahn, P. L., and Toth, W. J. (1983) Scrap Tires: A Resource and Technology Evaluation of Tire Pyrolysis and Other Selected Alternative Technologies. Rep. EGG-2241, U.S. Dep. of Energy, Washington, D.C.

Edil, T. B., and Bosscher, P. J. (1992) Development of Engineering Criteria for Shredded Waste Tires in Highway Applications. Final Rep. to Wisconsin Dep. Transportation and Natural Resources, Research Rep. GT-92-9, Madison, Wis.

Edil, T. B., Fox, P. J., Ahl, S. W. (1992b) Hydraulic Conductivity and Compressibility of Waste Tire Chips. *Proc. 15th Annual Madison Waste Conf.*, Madison, Wisconsin, 49–61.

Edil, T. B., Park, J. K., Berthouex, P. M. (1992a) Attenuation and Transport of Volatile Organic Compounds in Clay Liners. *Proc. Mediterranean Conf. Environmental Geotechnology.* Usmen, M. and Acar, Y. B. (Eds.), Cesme, Turkey, 77–86.

Gibbons, R. D., Dolan, D., Keough, H., O'Leary, K., O'Hara, R. (1992) A comparison of chemical constituents in leachate from industrial hazardous waste and municipal solid waste landfills. *Proc. 15th Annual Madison Waste Conf., Municipal and Industrial Waste.* Dep. Engineering Professional Development, Univ. Wisconsin-Madison, 251–276.

Grefe, R. T. (1989) Review of the Waste Characterization of Shredded Tires. Correspondence/Memorandum, File Ref. 4410-1, Wisconsin Department of Natural Resources.

House of Representatives (1990) *Scrap Tire Management and Recycling Opportunities.* Committee on Small Business, U.S. House of Representatives, Washington, D.C.

Park, J. K., and Bontoux, L. (1991) Effects of Temperature, Repeated Exposure, and Aging on Polybutylene by Organic Chemicals. *J. Appl. Polymer Sci.*, 42, (11), 2989–2995.

Park, J. K., Bontoux, L., Holsen, T. M., Jenkins, D., Selleck, R. E. (1991a) Permeation of Polybutylene Pipe and Gasket Material by Organic Chemicals. *J. Am. Water Works Assoc.*, 83, (10), 71–78.

Park, J. K., Edil, T. B., Berthouex, P. M. (1991b) *Transport of Volatile Organic Compounds (VOCs) through a Clay Liner. Proc. Special Conf. Sponsored by the Environ. Eng. Div. of the American Society of Civil Engineers.* P. A. Krenkel (Ed.), Reno, Nev., 6–11.

Park, J. K., and Nibras, M. (1993) Mass Flux of Organic Chemicals through High Density Polyethylene. *Water Environ. Res.*, 65, (3), 227–237.

Park, J. K., Sakti, J. P., and Hoopes, J. A. (1994) *Determination of Volatile Organic Compound Permeation through Synthetic Geomembranes.* Int. Symp. Volatile Organic Compounds in the Environment, American Society for Testing and Materials, Philadelphia, Pa.

Plumb, R. H., and Pitchford, A. M. (1985) Volatile Organic Scans: Implications for Ground Water Monitoring. *Proc. NWWA/API Conf. Petroleum Hydrocarbons and Organic Chemicals in Ground Water—Prevention, Detection, and Restoration.* Natural Water Well Association, Dublin, Ohio.

Reynolds, G. W., Hoff, J. T., Robert, W. G. (1990) Sampling Bias Caused by Materials Used to Monitor Halocarbons in Groundwater. *Environ. Sci. Technol.*, 24, (1), 135–142.

Sakti, J. P., Park, J. K., Hoopes, J. A. (1992) Transport of Aqueous Organic Chemicals through HDPE Geomembranes, to be presented in *Water Forum '92*, Baltimore, Md.

Scrap Tire Management Council (1990) *Scrap Tire Use/Disposal Study.* 1–4.

U.S. EPA (1991) *Market for scrap tires.* EPA/530-SW-90-074B, U.S. EPA, Washington, D.C.

Waste Management of North America, Inc. (1990) Application for minor permit modification for use of tire chips in liner protective cover, Pottstown Landfill, West Pottsgrove Township, Pennsylvania. Waste Management of North America, Inc., Northeast Region Design Group, Morrisville, Pa.

Water Environment Federation

Management of Odors and VOCs and the
Fate of Contaminants in WWTPs I

Removal of Volatile Organic Compounds Emitted during Wastewater Treatment by Ground Tires

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66th Annual Water Environment Federation Conference
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Oct. 3-7, 1993

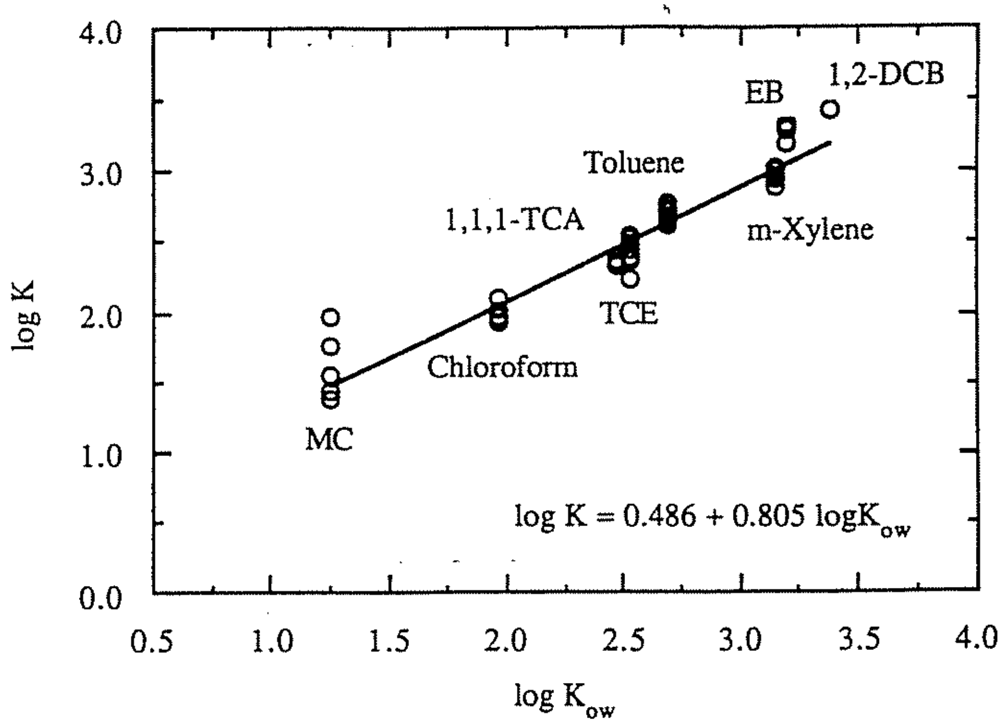

Figure 2. Relationship between the partition and octanol-water partition coefficient.

From a series of column tests, the VOC removal efficiencies were measured with a 20-cm thick ground tire layer. Figure 3 shows the VOC removal efficiencies at different Q_a/Q_W ratios along with error bars. The VOC removal efficiency improved significantly with the decrease in the Q_a/Q_W ratio.

Nonpolar compounds such as TCE, toluene, and *m*-xylene were removed more than 90% at the Q_a/Q_W ratio of 40, while polar (and semi-polar) compounds such as MC and chloroform were removed less (50 - 70%) due to their lower octanol-water partition coefficients. At the typical full-scale aeration basin Q_a/Q_W ratios of 5 to 10 (Namkung and Rittmann, 1987), MC and chloroform were removed more than 80% and TCE, toluene, and *m*-xylene were removed more than 95% . When the Q_a/Q_w ratio increased to above 20, the removal efficiency dropped significantly for polar compounds. This indicates that the diffusion within ground tires is a sorption limiting factor at the Q_a/Q_W ratio above 20 while the surface sorption or the mass flux through a liquid film on the surface of ground tires is a limiting factor at the Q_a/Q_w ratio below 20.

The humidity in the off-gas is known to be one of the most important factors in removal of VOCs in the off-gas. It has been known that the humidity in the off-gas of > 45% significantly reduces the sorption capacity of GAC (Cagwin and Lager, 1990). The off-gas stripped from the column was passed through a layer of dried or wetted ground tires at the Q_a/Q_W ratios of 5, 10, and 20 so as to investigate the effect of humidity on the sorption. Also ground tires were submerged in an activated sludge aeration basin for four weeks to grow microorganisms on their surface. Then, the experiments were conducted under the same condition to assess the effect of biomass growth on the ground tire surface on the sorption capacity. The microorganisms were not acclimated with target compounds.

Table III summarizes the percent removal efficiencies with dried, wetted and biomass grown ground tires. A layer installed with dried ground tires had slightly higher removals of MC, TCE, and toluene than that with wetted or biomass grown ground tires. In general, the removal efficiency was reduced by approximately 5% when ground tires were wetted or covered with biomass. The moisture content of dried ground tires after off-gas sampling was still very low (~ 0.4%), indicating that the results represent the sorption capacity of ground tires for a dried off-gas.

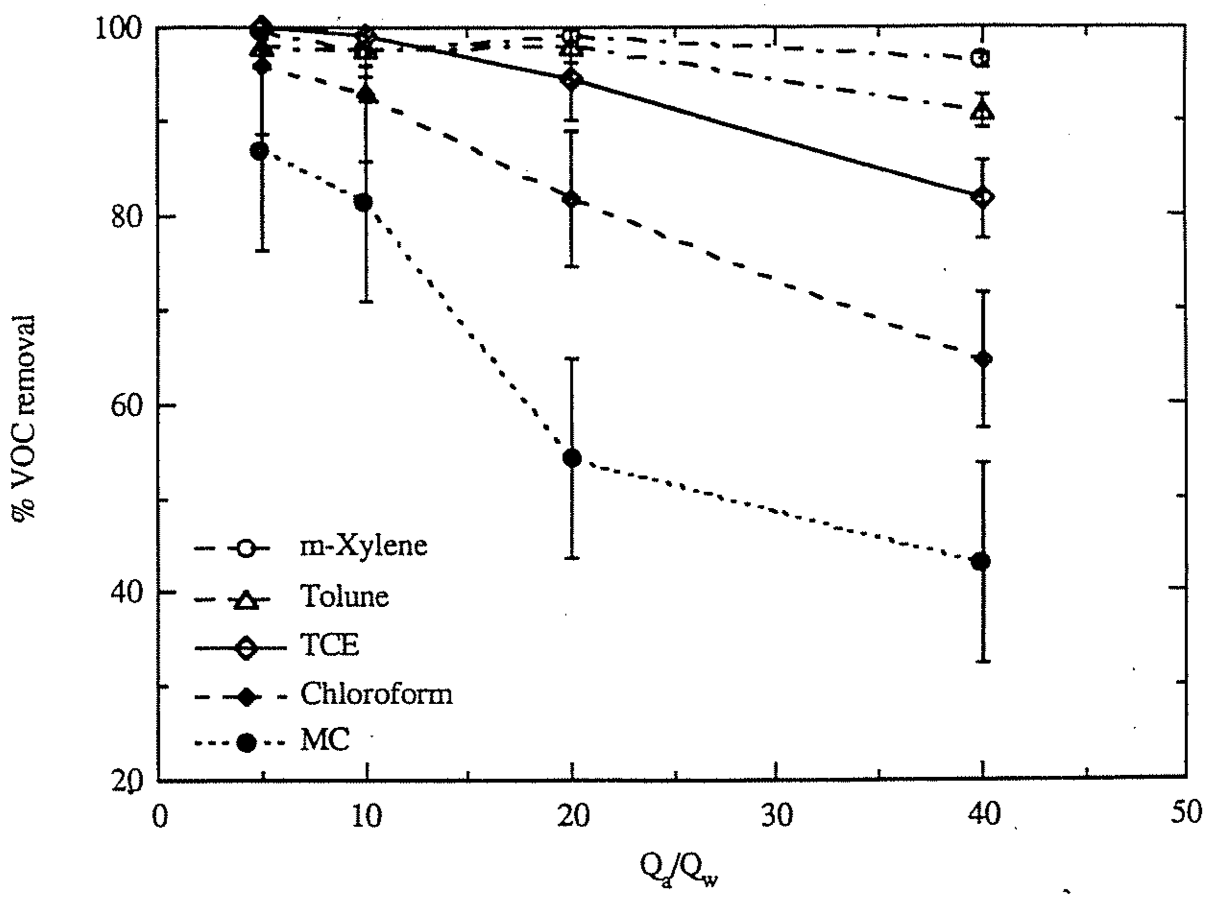

Figure 3. VOC removal efficiencies at various air/water flow ratios.

Table III. Percent VOC removal efficiencies depending on ground tire conditions.

Q_a/Q_w ratio	MC			TCE			Toluene		
	Dried	Wetted	Biomass	Dried	Wetted	Biomass	Dried	Wetted	Biomass
5	89.6	84.5	85.0	96.2	92.2	90.0	98.5	97.8	94.0
10	70.8	68.0	72.0	95.5	92.6	87.0	95.6	93.4	92.0
20	33.5	41.0	30.0	90.4	86.4	72.0	87.5	85.0	81.0

The biomass grown ground tire layer removed approximately 7 to 20% less VOCs than the dried ground tire layer. This may indicate that the diffusion of VOCs through the biomass or the sorption rate on the biomass is slower than the diffusion through ground tires or the flux through a liquid film covering ground tires. It appears that a critical residence time is required to remove VOCs by a ground tire layer. When the Q_a/Q_w ratio is 20, the removal efficiencies by biomass grown ground tires dropped more noticeably than dried or wetted ground tires. Again, the removal efficiencies were more markedly reduced for MC with three differently treated ground tires than for TCE and toluene.

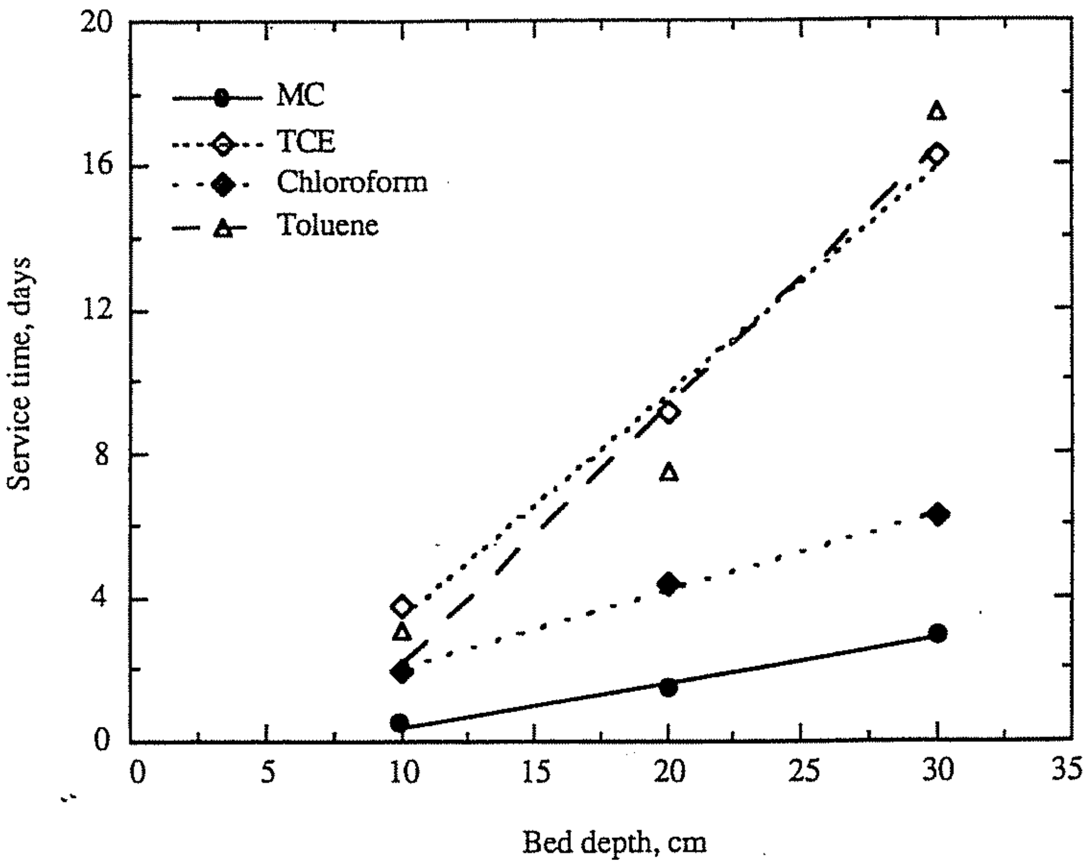

Figure 4. Service time versus bed depth.

Further study is underway to evaluate the effect of biodegradation on the removal efficiency and service time. Similar to GAC, the removal efficiencies of polar compounds were not good with ground tires. We are currently testing with Styrofoam® since this has a good sorption capacity for polar compounds.

A potential application of this technique is to install the ground tire layer above aeration basins or channels with a simple supporting structure. This will eliminate the need to cover the entire aeration basins or the wastewater treatment plants. Another potential application is to install a bed consisting of ground tires, soils and compost. This requires a off-gas collection system.

CONCLUSIONS

The removal of VOCs in the off-gas appears to be feasible with a layer of ground tires installed above an activated sludge aeration basin or a grit chamber. The removal efficiency was greatly affected by the air/water flow ratio. When the ratio is greater than 10, ground tires are thought to be too inefficient to use as a sorbent. However, at the ratio below 5, ground tires showed a great potential as a cheap and readily available sorbent. It is believed that this concept has a great potential for field application in POTWs and industrial wastewater treatment plants.

From the batch sorption isotherm tests and laboratory-scale column experiments, the following conclusions can be drawn:

(1) Ground tires had slightly higher sorption capacities than tire chips since ground tires do not have fabrics or steel wires. The sorption capacity increased logarithmically with the increase in the octanol-water partition coefficient.

(2) The VOC removal efficiencies by a ground tire layer were > 95% for nonpolar compounds and > 80% for polar compounds at the Q_a/Q_w ratio between 5 and 10.

(3) The Q_a/Q_w ratio affected the off-gas VOC removal efficiencies by 25 to 40% for polar compounds but slightly for nonpolar compounds.

(4) The humidity in the off-gas affected the sorption capacity of ground tires slightly (< 5% decrease in the removal efficiency).

(5) A biomass grown ground tire layer removed approximately 7 to 20% less VOCs in the off-gas than a dried ground tire layer.

(6) The service times for a 30-cm thick ground tire layer with the Q_a/Q_w ratio of 10 were all less than three weeks for the organic compounds tested and thus, the sorbent utilization rate was low at this ratio. However, when the ratio was decreased to 5, the service times almost doubled.

(7) In general, polar compounds were less sorbed by ground tires than nonpolar compounds.

REFERENCES

Cagwin, D.J. and Lager, J.A. (1990) Volatile organic carbon emission - control systems, *Water Envionment Technol.*, 2(6), 56-61.

Hand, D.W., Crittenden, J.C., and Thacker, W.E. (1984) Simplified models for design of fixed-bed adsorption system, *Jour. of Environ. Eng. Div., Am. Soc. Civil Eng.*, 110, 440.

Hutchins, R.A. (1973) New method simplifies design of activated-carbon system, *Chemical Engineering*, **80**, 19, 133.

Dostal, K.A. (1990) *WERL treatability data base*, Risk Reduction Engineering Laboratory, US EPA, Cincinnati, OH 45628.

Kim, J.Y., Park, J.K., Emmons, B., and Armstrong, D. (1993) Fate of volatile organic compounds in municipal solid waste at a co-composting facility, The 66th Annual Conference of the Water Environment Federation, Anaheim, CA, Oct. 3-7, 1993.

Namkung, E. and Rittmann, B.R. (1987) Estimating volatile organic compound emissions from publicly owned treatment works, *Jour. Water Poll. Control Federation*, **59**(7), 670-678.

Nirmalakhandan, N.N. and Speece, R.E. (1988) QSAR model for predicting Henry's constant, *Environ. Sci. Technol.*, **22**(11), 1349-1357.

Park, J.K. Kim, J.Y., and Edil, T.B. (1993) Mitigation of organic compound movement in landfills by a layer of shredded tires, The 66th Annual Conference of the Water Environment Federation, Anaheim, CA, Oct. 3-7, 1993.

Snoyink, V.L. (1990) Adsorption of organic compounds, In "Water quality and treatment", Edited by F. W. Pontius, American Water Works Association, Fourth Ed., McGraw-Hill, Inc., New York.

Witherspoon, J.R., Bishop, W.J., and Wallis, M.J. (1992) Emission control options for POTWs, *Environ. Protection*, **4**(5), 59-66.

Figure 4 shows the breakthrough curves of the target VOCs with respect to treated air volume with a 30-cm thick ground tire layer. It can be seen that MC and chloroform are not well removed by ground tires due to the high polarity of these compounds compared with nonpolar compounds (TCE, toluene, and *m*-xylene). The service times for 30% removal of MC, chloroform, toluene, and TCE were approximately 3, 6, 18, and 17, respectively. *m*-Xylene did not reach 30% of the influent concentration after 25 days of operation.

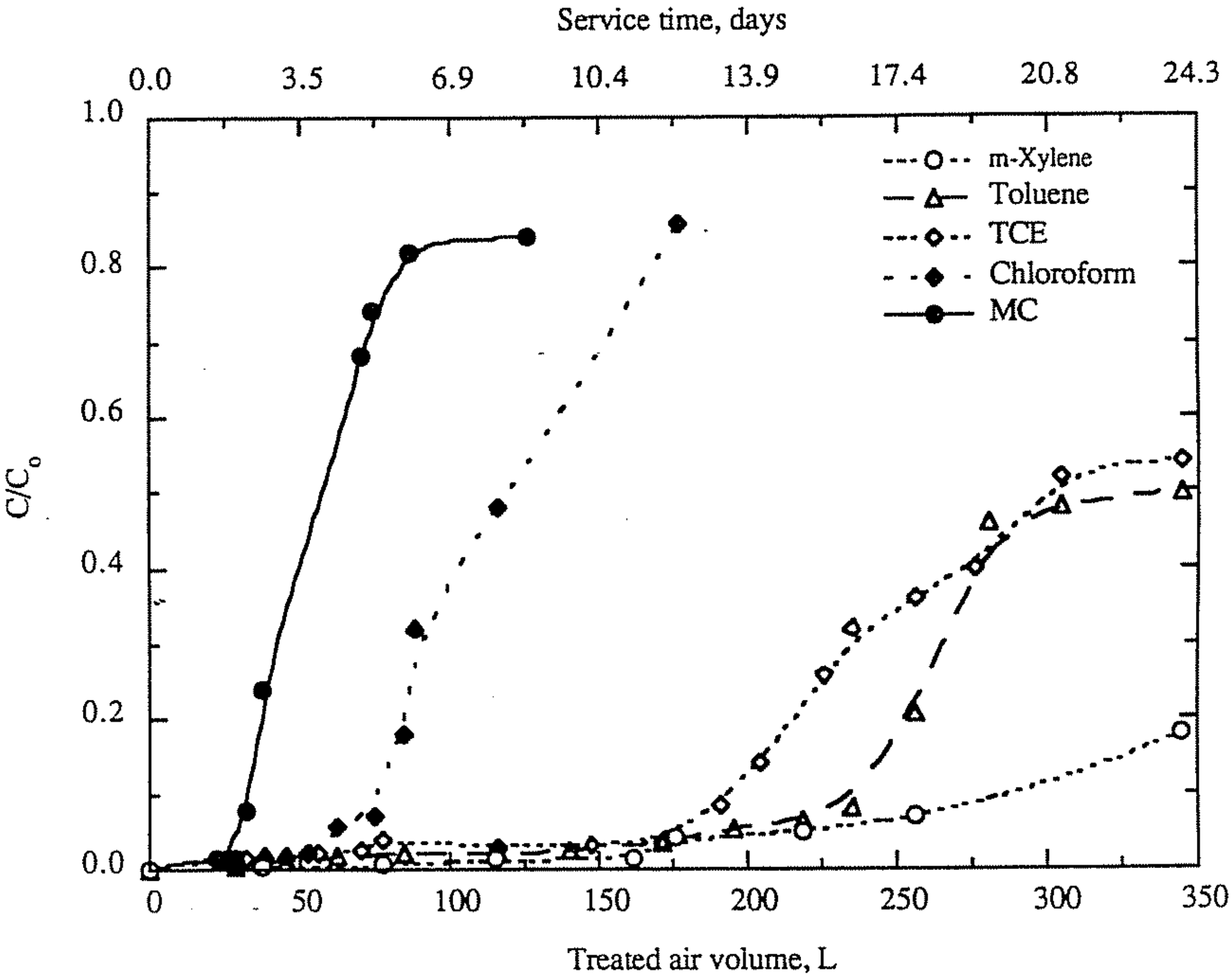

Figure 4. VOC breakthrough curves in a multi-solute system.

An attempt was made to fit the breakthrough curves using the homogenous surface diffusion model (HSDM) constant pattern solutions developed by Hand *et al.* (1984) along with the parameters measured. Unfortunately, however, the curve fitting was not successful for the five organic compounds tested. Further investigation is underway to develop a mathematical model suitable for the ground tire sorption mechanism.

The ground tire utilization rate, R (g/L), the rate at which ground tires are spent, can be expressed as follows (Snoeyink, 1990):

$$R = \frac{\rho_t}{\text{Bed volumes to breakthrough}} = \frac{\rho_t}{\text{Volume treated}/Q_a} \qquad (1)$$

The ground tire utilization rates at the Q_a/Q_w ratio of 10 were estimated to be 72, 11.5, 4.7 and 5.2 g of ground tires/L of air treated for MC, chloroform, toluene, and TCE, respectively. These rates appeared to be significantly higher than activated carbon, indicating inferior sorption performance. Therefore, the air flow rate should be reduced at least by half to use ground tires more efficiently as a sorbent.

Park *et al.* (1993) found that only 3.5 to 6.8% of the organic compounds sorbed in tire chips in the liquid phase were desorbed. After 25 days of operation of the column for the determination of breakthrough times (Figure 4), a desorption test was conducted. MC and chloroform were almost saturated, and the breakthrough toluene and TCE concentrations were approximately 60% of the influent concentrations. The feed was replaced with deionized water while other operational conditions remained unchanged. Then, sampling was conducted immediately for 6, 16, 24, and 36 hours consecutively. None of the samples showed a sign of peaks in a GC output. This indicates that the desorption in the gas phase is irreversible and the desorption rate is very small as found in the liquid phase by Park *et al.* (1993).

From the breakthrough curves, the mass of organic compounds sorbed per unit mass of ground tires (X/M) were estimated to be 2.2, 5.1, 6.7 and 6.5 mg/g for MC, chloroform, toluene and TCE, respectively. Since the mass of ground tires were 150 g, the total mass of organic compounds sorbed onto ground tires are 336, 774, 1005, and 975 mg. If the desorption occurred at the detection limits of 0.5 mg/L for MC, chloroform, and TCE, and 0.3 mg/L for toluene as a conservative estimate, the masses lost during 6 hours of the off-gas sampling are calculated to be 6 mg for MC, chloroform, and TCE, and 3.6 mg for toluene. Therefore, the percent desorbed during 6 hours of the desorption test are at the most 1.8%. This indicated that the sorption mechanism is a chemical bonding.

The column tests were conducted using 10-, 20-, and 30-cm thick ground tire layers to determine the service time using the adsorption column design technique developed by Bohart-Adams (Hutchins, 1973). The equation is expressed as follows:

$$t = a\,x + b \tag{2}$$

where $a = \text{slope} = \dfrac{N_o}{C_o \cdot V}$;

$b = \text{intercept} = \dfrac{1}{K \cdot C_o} \ln\left(\dfrac{C_o}{C_B} - 1\right)$;

C_o = initial concentration of solute (mg/L);

C_B = desired concentration of solute at breakthrough (mg/L);

K = rate constant (L liquid/mg ground tires/hr);

N_o = adsorption capacity of ground tires (mg/L);

x = depth of the ground tire layer (m);

V = linear flow velocity (m/hr); and

t = service time of the layer (hr).

Figure 5 shows the service times for 30% removal versus bed depth for chloroform, MC, toluene, and TCE. The slope a and intercept b for the four compounds were estimated to be 5.1, 2.9, 17.25, and 15.0, and -1, -18.7, -120, and -66.7, respectively. This allows the calculation of the service time at various depths of ground tire layers and linear flow velocity. From this relationship, the service time at another linear flow velocity can be determined by multiplying the original slope a by the ratio of the original and new flow rates.

If the Q_a/Q_w ratio decreases to 5, then the service times for chloroform, MC, toluene, and TCE are calculated to be 13, 6, 34, and 31 days. If the ratio decreases further to 1, the service time would be 52, 30, 170, and 155 days. Therefore, if the Q_a/Q_w ratio is less than 5, the installation of a ground tire layer above the aeration basin will be feasible and economical. Since aerated grit chambers typically have the Q_a/Q_w ratio of less than 1, this technique is very attractive. Furthermore, the ground tire layer above channels will also be effective for VOC removals.

Batch isotherm tests were conducted using 300 mL glass bottles to determine the organic chemical sorption capacity of ground tires. The sorption test in the liquid phase was thought to simulate the saturated condition which would occur in the off-gas above the aeration basin. The bottles were not rotated. Instead, the bottles were manually shaken in a regular interval. This method gave almost no loss in the target organic compounds.

A 190-cm long and 2.5-cm in diameter laboratory-scale column shown in Figure 1 was aerated under various air to water flow rate (Q_a/Q_w) ratios ranging from 5 to 40. The column received a constant flow containing the mixture of chloroform, MC, toluene, TCE, and *m*-xylene from a 10-L Teflon bag. The target initial concentration of each organic chemical ranged from 5 to 50 mg/L. A Teflon diaphragm pump was used to feed the influent. By a coarse bubble aeration, the target VOCs were stripped from the column and subsequently passed through a 10-, 20-, or 30-cm thick layer of ground tires located 10 cm above the water level. Before reaching the reactor, the air supply passed through a series of anhydrous $CaSO_4$ and charcoal bed designed to remove organics and grease present in the air stream. The air supply was monitored using an air flowmeter. The Q_a/Q_w was controlled by varying the air flow rate with the fixed hydraulic residence time (HRT) of 30 minutes.

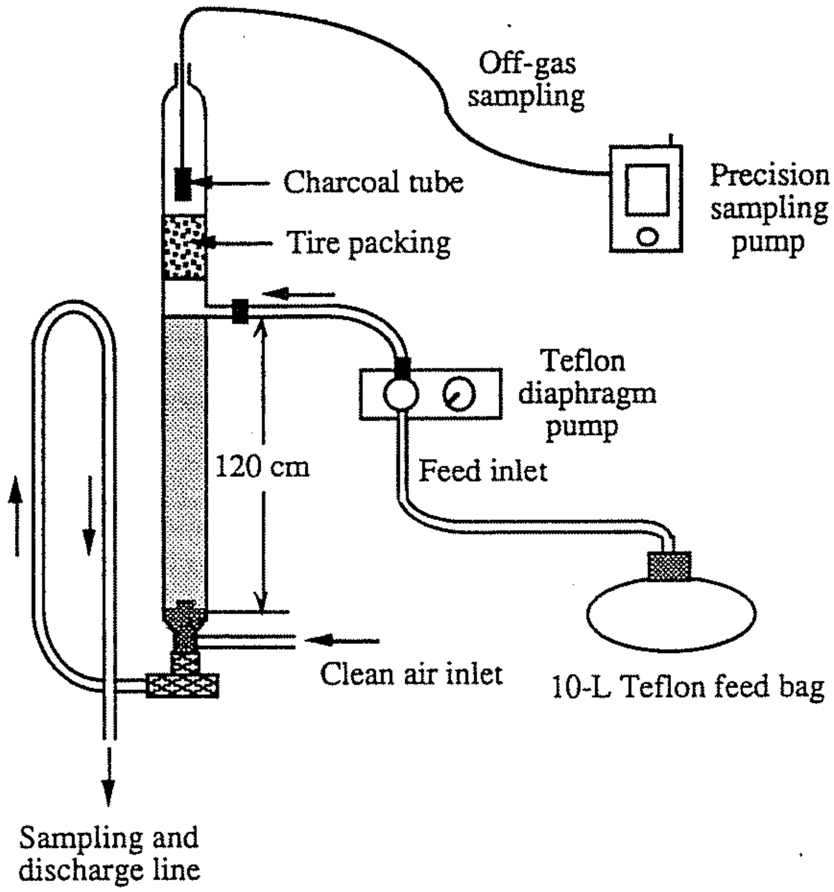

Figure 1. Schematic of column test apparatus.

The experimental conditions and specific objectives are summarized in Table II. For easy handling, ground tires were packed in a plastic net (1 × 1 mm screen size) and installed in the column after a steady state condition was achieved, i.e., when the off-gas VOC concentrations were steady. Samples were collected for analysis 30 minutes after tire packing. Each sampling lasted for 10 minutes. Most experiments were repeated two to five times under the same condition. The empty bed contact times (EBCTs) in the ground tire layer ranged from 0.25 to 2 minutes. The total porosity of ground tire layers ranged from 0.55 to 0.58. The pressure drops were all below around 0.01 cm H_2O/cm of ground tire packing. All experiments were operated at 20°C.

The off-gas above the water level or the ground tire layer was collected by pumping the air through the Supelco® Orbo-32 activated charcoal tube at a known flow rate. The charcoal tube was divided into two sections. The backup section was designed to check the breakthrough at the primary section. After sampling the off-gas for 10 minutes, the activated carbon was immediately removed from both the primary and backup sections of the sampling tubes and placed in 2 mL glass vials. Then, VOCs were extracted from the charcoal by adding 1 mL of carbon disulfide (CS_2) to the vials and shaking for several minutes. The extracts were analyzed for target compounds using direct injection gas chromatography. Used was a Varian 3600 gas chromatograph (GC) equipped with a flame ionization detector and a 60 m long, 0.25 mm I.D. Supelcowax® - 10 megabore column. Helium was used as a carrier gas. The FID detection limits were approximately 0.5 mg/L for chloroform, MC, and TCE, and 0.3 mg/L for toluene and *m*-xylene, respectively. The recovery efficiencies of the CS_2 extraction for chloroform, MC, TCE, and toluene ranged from 99 to 104% (Kim *et al.*, 1993). CS_2 blanks were analyzed approximately every sixth sample and exhibited no significant peaks. Analyses of samples from the activated charcoal tube backup section also showed no identifiable peaks. The standards used for calibration were analyzed before and after the unknown samples.

Table II. Experimental conditions and objectives.

HRT (min)	Water flow (L/hr)	Air flow (L/hr)	Q_a/Q_w ratio	EBCT (min)	Packing depth (cm)	Tire condition	Experimental objectives
30	0.6	3	5	1.0 2.0	10 20	Dry, wetted[1], biomass growth[2]	VOC removal; effects of packing depth, humidity, and biomass growth
30	0.6	6	10	0.5 1.0 1.5	10 20 30	Dry, wetted[1], biomass growth[2]	VOC removal; effects of packing depth, humidity, and biomass growth; breakthrough.
30	0.6	12	20	0.25 0.5	10 20	Dry, wetted[1], biomass growth[2]	VOC removal; effects of packing depth, humidity, and biomass growth
30	0.6	24	40	0.25	20	Dry	VOC removal

[1] Wetted with deionized water

[2] Covered with biomass

RESULTS AND DISCUSSION

The single-solute batch isotherm tests were conducted with ground tires. It was found that the partition coefficient had a logarithmic relationship with the octanol-water partition coefficient as shown in Figure 2. The trend of the sorption capacity and the relationship between partition coefficient versus octanol-water partition coefficient of ground tires agreed well with those of tire chips reported by Park *et al.* (1993). Ground tires seemed to have slightly greater sorption capacity than tire chips except MC. On volume basis, ground tires were a more efficient sorbent than tire chips. It can be explained by the fact that ground tires are composed of relatively pure rubber materials whereas tire chips contain fabrics and steel. In general, the partition coefficient increased with the increase in the octanol-water partition coefficient. The partition coefficient for MC is naturally small; thus, the accuracy of the test was relatively low as can be seen in Figure 2.

REMOVAL OF VOLATILE ORGANIC COMPOUNDS EMITTED DURING WASTEWATER TREATMENT BY GROUND TIRES

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ABSTRACT

Batch sorption tests and laboratory-scale column tests were conducted to evaluate the sorption capacity of ground tires and the factors affecting the removal efficiencies of volatile organic compounds (VOCs) in the off-gas by ground tires. The removal efficiencies decreased significantly with the increase in the air/water flow rate ratio from 5 to 40. The effect of the increased ratio was more pronounced with polar compounds than nonpolar compounds. When the air/water flow rate ratio is less than 5, the service time with a 30-cm thick ground tire layer was over a month for 30% removal of input nonpolar compounds. The biomass grown ground tire layer removed 7 to 20% less VOCs in the off-gas than a dried ground tire layer. A few field-scale application methods were proposed to use ground tires for removal of VOCs from the off-gas in wastewater treatment plants.

KEY WORDS

Granular Activated Carbon, Ground tires, Off-Gas, Removal, Volatile Organic Compounds, Volatilization, Wastewater Treatment

INTRODUCTION

Many publicly owned treatment works (POTWs) will be required by local and state regulatory agencies to reduce emissions to meet air quality or health risk standards. Emission include odors and other pollutants which are toxic, reactive, and volatile. Volatile organic compounds (VOCs) contained in wastewater from commercial, industrial, and agricultural activities comprise 31 of the 129 priority pollutants designated by U. S. Environmental Protection Agency (EPA). In most cases, VOC concentrations are low and vary greatly with time. Removal mechanisms of VOCs in wastewater treatment plants include volatilization (stripping), biodegradation, chemical oxidation, and sorption onto sludge. Volatilization, however, has been considered to be one of the dominant mechanisms for removal of VOCs from wastewater. VOCs entering wastewater treatment plants can be released to the atmosphere from aerated grit chambers, weirs, pump station wet wells, tank surfaces, aeration tanks, aerated channels, tunnel shafts, etc.

POTWs have both stack and large fugitive air emission sources. Stack emission sources are combustion exhaust vents and/or covered and ducted wastewater treatment processes such as headwork scrubbers, aeration basins, and sludge handling building blower vents. Fugitive emission sources include settling basins, clarifiers, compost files, and channels. Air emissions for POTWs are characterized by high off-gas flow rates, high moisture content, trace air emission concentration, corrosiveness, and the existance of aerosols (Witherspoon *et al.*, 1993).

The Clean Air Act Amendments of 1990 requires new technology-based regulations to meet stringent ambient air quality and risk standards. There are a number of technologies available for controlling VOCs: adsorption (50-95% removal), absorption (> 90% removal), condensation (50-90% removal), flares (> 98% removal), thermal incineration (> 98% removal), and catalytic incineration (> 95%). The use of granular activated carbon (GAC) as a sorbent appears to be one of the most effective treatment technologies for removing many VOCs from the off-gas. However, it is a relatively expensive process. An economical and effective alternative needs to be developed. Biofilters supported by GAC or other supporting media has been evaluated as an alternative. It was found that scrap vehicle tires have 1.4 to 5.6% of the sorption capacity of GAC on volume basis (Park *et al.*, 1993). Therefore, it was postulated that ground tires may be a good sorbent and supporting medium in a biofilter for removal of VOCs in the off-gas.

The objectives of this research were to determine the organic compound sorption capacity of ground tires, to assess the effects of humidity and biomass growth on the surface of ground tires on the VOC removal efficiency, to evaluate the desorption rate, to estimate the service time at various operational conditions, and to propose potential application methods for removal of VOCs emitted from a POTW.

EXPERIMENTAL METHODS

Ground tires were obtained from a local tire processor. Fabrics and steel wires were separated from ground tires during tire processing. No attempt was made to separate tires based on different manufacturers or sizes. The diameter of ground tires ranged from 0.18 to 1.67 cm and the average diameter was 0.34 cm. The surface area of ground tires was measured by a BET instrument. The surface areas ranged from 0.16 to 0.56 m^2/g. These values were 1,600 to 7,000 times smaller than the surface area of granular activated carbon (GAC). Due to small pore sizes, the pore diameter was measured by a porosity meter. The pore diameter ranged from 0.003 to 3.0 μm and the average pore diameter was 0.0385 μm. The apparent particle density and the bulk bed density were 1.204 and 0.902 g/cm^3, respectively.

Before tests, tires were washed with deionized water, dried at a 40°C oven for a day, and stored in a desiccator. The pollutants of concern in POTWs are chloroform(CF), formaldehyde, benzene, carbon tetrachloride, methylene chloride (MC), toluene, tetrachloroethylene (PCA), trichloroethylene (TCE), and *m*-xylene (Witherspoon *et al.*, 1993). Several target VOCs were selected based on the physical properties. Table I summarizes the physical properties of target organic compounds.

Table I. Properties of organic compounds tested.

Organic compounds	Molecular weight (g/mol)	Specific gravity	Solubility[1] (mg/L)	log K_{ow}[2]	Henry's constant[3] (dimensionless)	Vapor pressure[1] (torr)
Chloroform	119.38	1.489	8,000	1.97	0.18	160
1,2-Dichlorobenzene	147.01	1.305	100	3.38	0.10	1.0
Ethylbenzene	106.17	0.867	152	3.15	0.35	7.5
Methylene chloride	84.93	1.327	16,700	1.25	0.09	429
Toluene	92.14	0.867	515	2.69	0.28	28
1,1,1-Trichloroethane	133.41	1.350	4,400	2.47	0.66	100
Trichloroethylene	131.39	1.467	1,100	2.53	0.48	77
m-Xylene	106.17	0.866	200	3.20	0.26	6

[1] Dostal (1990).
[2] K_{ow} : octanol-water partition coefficient.
[3] Nirmalakhandan and Speece (1988).

Retardation of Volatile Organic Compound Movement by a Bentonite Slurry Cut-Off Wall Amended with Ground Tires

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INTRODUCTION

Bentonite slurry cut-off walls have been used under site-specific conditions as an alternative to substantially reduce the spreading of groundwater contamination. Typically, these groundwater contaminants consists of a class of compounds called volatile organic compounds (VOCs) and are associated with hazardous waste facilities undergoing remediation. Recent studies have raised considerable evidence that VOCs have higher mobility through engineered containment systems than previously thought. A series of studies conducted at the University of Wisconsin showed that shredded tires could be used as a supplement to the engineered landfill clay liner system in order to retard VOC transport to a greater degree than that which occurs in the traditionally constructed engineered containment system.

The objectives of this study were to investigate the effect of ground tire addition to slurry cut-off walls on the hydraulic conductivity, to evaluate the retardation of VOC movement through a sand-bentonite mixture by the addition of ground tire pieces, and to determine the parameters which may be used in the design of slurry walls (containing an additive of ground tire pieces) as they pertain to VOCs (i.e., partition coefficient, dispersion coefficient, hydraulic conductivity, and effective porosity).

for *m*-xylene. Ground tire amended slurry wall permeameters (#2, #3, and #4) did not breakthrough for more than a year for TCE and over 450 days for toluene and *m*-xylene.

Table 2. Breakthrough time to reach 10% of the influent concentration.

	#1-A	#1-B	#2	#3	#4
MC	< 10 days.	N.A.[1]	35 days	40 days	50 days
TCE	< 10 days	30 days	360 days	430 days	> 450 days
Toluene	< 10 days	150 days	450 days	> 450 days	> 450 days
m-Xylene	< 10 days	180 days	> 450 days	> 450 days	> 450 days

[1] Not available due to biological degradation during the test.

In the case of the permeameter #1-A, all the organic compounds completely broke through the slurry wall within 20 days, simultaneously. It means that the slurry wall failed to retard the transporting substances by crack. Even if sodium azide was introduced as a disinfectant, it seems that methylene chloride was biodegraded in Permeameter #1-A.

Figure 2 shows the breakthrough curve of TCE predicted from the parameters determined from the bromide tests and batch sorption tests. As shown in Figure 2, the addition of ground tire into slurry wall can effectively retard the movement of the organic compounds. For example, when 15% (by wt.) of ground tire is added into a 10.2-cm thick slurry wall, the time for TCE to breakthrough the slurry wall at 10% of the influent concentration will be approximately 25 times delayed.

CONCLUSIONS

From the laboratory-scale slurry wall permeameter tests, the following conclusions can be drawn:

(1) The hydraulic conductivity was not affected by addition of ground tires nor spike of organic compounds at 10 ~ 15 mg/L.

EXPERIMENTAL METHODS

A series of laboratory tests were conducted to evaluate VOC transport through the slurry wall and the suitability of the method to meet the objectives of this study according to conditions expected in the field. The column test consisted of 10.2 cm diameter, 10.2 cm thick slurry wall specimens in a 12.7 cm high fixed-wall permeameter. The volume of the effluent reservoir was approximately 0.2 L. Permeameter #1 contained silty-sand and a 6% (by weight) solution of a bentonite-water slurry (prepared by mixing 22.3 g of powdered bentonite per 350 mL of tap water) mixed to an 5 inch slump, Permeameter #2 & 3 contained silty-sand, a 6% bentonite-water slurry, and 7.5% ground tires (8 ~ 10 mesh) by volume and served as a duplicate, and Permeameter #4 contained 15% ground tires by volume. Permeameter #1-A had one order of magnitude greater hydraulic conductivity than other permeameters so the run was repeated with a new specimen (Permeameter #1-B). To minimize the potential short-circuiting along the wall of the permeameters, a bentonite paste was applied by hand on the interior of the permeameter.

The influent and the effluent were supplied and collected by means of Teflon® bags. The hydraulic conductivity was estimated by weighing the change in both the influent and effluent bags. The hydraulic gradient applied was 4. The total porosity was estimated by using water content and particle density. The dry densities of soil and ground tire were assumed to be 2.70 g/cm^3 and measured to be 1.15 g/cm^3.

Initially, all four permeameters received tap water containing sodium azide as a disinfectant. Once hydraulic conductivity readings were stable, each column was permeated with tap water containing methylene chloride (MC), trichloroethylene (TCE), toluene (TOL), and *m*-xylene (XYL) at the concentration ranges of 10 to 15 mg/L. Despite the addition of sodium azide and mercuric chloride, methylene chloride disappeared in both the influent and effluent reservoirs. Lithium bromide was used as a conservative tracer to determine the effective porosity.

RESULTS AND DISCUSSION

The average hydraulic conductivities of Permeameters #1-A, #1-B, #2, #3, and #4 are 2.9×10^{-6}, 5.6×10^{-7}, 7.2×10^{-7}, 5.6×10^{-7} and 5.0×10^{-7} cm/sec. It appears that the hydraulic conductivity was not affected by the presence of ground tires in slurry wall mixtures. The hydraulic conductivity of a clay layer has been considered to be affected by the organic permeant. In this study, no significant change of the hydraulic conductivity has been observed because most of the soil specimen consisted of silty-sand and the concentration of organic compounds was relatively low.

The retardation factor for the contaminant transport through porous media can be expressed by using the partition coefficient, particle density, and total porosity. The partition coefficient and particle density of the composite material, i.e. the mixture of soil and ground tire, can be calculated as follows:

$$R_f = 1 + K_p \cdot \rho_p \cdot \frac{(1 - n_t)}{n_t}$$

$$K_p = \Sigma K_{p,i} \cdot \theta_i$$

$$\rho_p = \Sigma \rho_{p,i} \cdot \theta_i$$

where R_f = retardation factor; n_t = total porosity; K_p = partition coefficient (L/kg); ρ_p = particle density (g/cm^3); and θ = weight fraction.

The retardation factors of the tested organic compounds estimated are listed in Table 1. As the weight fraction of ground tire increased, the partition coefficient of the composite material dramatically increased.

It is necessary to determine the effective porosity and hydrodynamic dispersion coefficient in order to predict the breakthrough of the transporting substance. In this study, the hydrodynamic dispersion coefficient was estimated by Myrand's approach that the tortuosity factor has the similar value with the total porosity of the porous medium (Myrand,

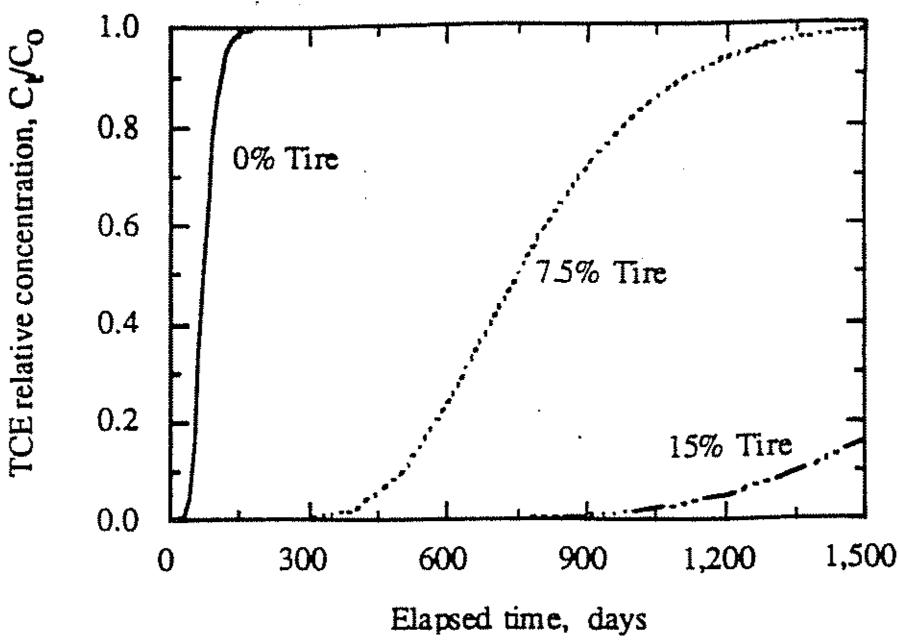

Figure 2. Prediction of TCE breakthrough curve.

(2) A typical slurry cut-off wall does not appear to be a good barrier for the containment of organic compounds.

(3) The organic compound breakthrough times were significantly prolonged by addition of ground tires. For example, *m*-xylene did not breakthrough in ground tire amended permeameters over 450 days but brokethrough in the silty-sand and bentonite mixed permeameter.

(4) Ground tires had a great deal of organic compound sorption capacity without deteriorating the performance of slurry cut-off walls. It appears that addition of ground tire to slurry cut-off walls significantly improve the efficiency of organic compound containment with little additional costs.

REFERENCES

Myrand, D., and Gillham, R. W., Sudicky, E. A., O'Hannesin, S. F. and Johnson, R. L. (1992), "Diffusion of Volatile Organic Compounds in Natural Clay Deposits: Laboratory tests," *J. of Contaminant Hydrology*, Vol. 10, pp. 159-177.