Engineering Properties of Shredded Tires in Lightweight Fill Applications

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It is estimated that approximately 240 million automobile and truck tires are discarded annually in the United States. Until recently, these have typically been disposed of in landfills and in tire stockpile sites where they pose potential safety and health problems as well as being unsightly. The latest use of shredded tires as lightweight fill material is encouraging, however, and the number of applications may grow provided that their engineering properties become more understandable and the quantifying parameters are known. Exploratory field and laboratory tests for determining the basic properties of shredded tires are reported in this paper. In the field tests, where large-size shreds were used, the effort necessary for compacting layers of shredded tires with a bulldozer was measured. In the laboratory tests, the compressibility of small-size shreds was investigated by means of a one-dimensional compression test. In addition, for both the large- and small-size shreds, their gradation, bulk density, porosity, and void ratio were determined. For comparison, wood chips were tested. The results show that the bulk density of shredded tires is between that of traditional granular fills and wood chips. However, their compressibility and rebound are much higher than those of the latter material, which could lead to premature fatigue failure of hard surface pavements. The apparent anisotropy of a shredded tire mass may also cause errors in predicting pavement deflections by means of classical, elastic multilayer system analysis, which assumes material isotropy.

Lightweight fill materials are appropriate where dead-load induced settlements of embankments must be reduced or where high stresses on retaining or subsurface structures must be prevented. In the case of embankments, the fill should serve the purpose of reducing the overburden stresses on weak soils such that geometric requirements of the surface can be maintained. At the same time, the fill should be capable of providing enough load-bearing capacity to support any induced stresses transmitted through the pavement structure. The use of lightweight fill behind retaining walls is an effective means of reducing the stresses that the structure must resist. Therefore, a lighter, more economical cross section may be used in the wall.

Traditionally, materials such as wood chips from lumber manufacturing or specially produced aggregates such as expanded shale or clay have been used for lightweight fill construction. Waste wood chips have the advantage of low cost, and as long as they remain submerged in water, they provide a relatively long service life. However, wood is subject to decay when the water table fluctuates, and it is exposed to air periodically. Artificially produced lightweight aggregates have the advantages of strength and durability when compared with wood chips, but they are heavier and many times more expensive because of the energy and equipment required to produce them. An alternative to these sources of lightweight fill materials is shredded waste tires.

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It is estimated that more than 200 million automobile tires and 40 million truck tires are discarded annually in the United States. This is roughly equivalent to 4 million tons of waste (*1*). The safety and health problems created by this refuse have prompted engineers to seek innovative means for reusing the material. Waste tire rubber has been used in asphalt mixtures, as lightweight road fills, as artificial reefs and breakwaters, as erosion control, and as a source of energy (*1–4*). These applications range in the amount of tire-processing required. For instance, tire rubber used in asphalt mixtures must be ground to a relatively fine particle size of less than 2 mm, whereas whole tires can be used in erosion control. The cost of the processed material increases exponentially as the particle size is reduced. Thus, it is attractive to find applications that could benefit from the physical properties of the material while the required amount of size reduction would be minimized.

The use of shredded tires in lightweight fills has the advantage of allowing large quantities of waste tires to be consumed with minimal or moderate processing. Usually, either the tires are reduced to a particle size of about 30 to 50 mm or whole tires sliced only once are used. The use of finer particles is often preferred because it is much more difficult to work and compact the larger particles. The hydraulic systems of equipment such as dump trucks and loaders regularly suffer damage from large tire shreds that catch on the hoses.

The bulk density of the material is lower than that of granular fill and makes it attractive for minimizing settlement of weak, low-stiffness subgrades. The material is not subject to rapid degradation in the presence of air or water. If the load-bearing capacity is sufficient, a durable lightweight fill could be constructed providing long-term performance.

In some respects, largely because of the particle shape, bulk structure, and large voids, shredded tires are difficult to describe with normal geotechnical or pavement engineering parameters. The tire shreds are flat with the aspect ratio (length to width) being defined by the amount of processing used to reduce the particle size. A tire cut once or twice will have a much greater aspect ratio than one that has been passed through a shredder several times. The flatness of the tire particles as well as their possible elongated shape often lead to an anisotropic structure when the mass is compacted.

The elasticity of rubber is intuitive; however, the shredded tire mass is neither linearly elastic nor isotropic, and its stiffness is low even for moderate loads. An individual rubber particle may have a modulus of elasticity of approximately 7 MPa, a value that decreases considerably when voids are present in a mass of rubber particles. Typical modulus values for silty soils range from 35 to 150 MPa, so the rubber particle has a modulus of elasticity 5 to 20 times less than that of a typical subgrade soil (*5*). Although rubber lacks the stiffness of the soil, it has a greater capacity for rebound.

The implications of this elasticity for pavement structural behavior are not well understood, primarily because of lack of data on the mechanical behavior of the shredded tire mass. Projects involving shredded tire fill seldom report on deformability and strength. Local settlement or deflection measurements provide some information, but it is difficult if not impossible to backcalculate the primary parameters such as Young's modulus or internal friction angle. Except for some early work conducted by the California Department of Transportation (CalTrans) (*1*,*2*), no systematic studies on shredded tire properties have been reported in the literature.

The intent of this study was to identify and measure the basic engineering properties of shredded tires relevant in the design and performance of lightweight fill sections in roadways. In order to accomplish this, field observations and laboratory tests on shredded tires were performed. The nature of the tests was exploratory; nonetheless, the results may serve as reference for further studies aimed at developing engineering guidelines.

DESCRIPTION OF STUDY

Field Investigations

The main objective of the field tests was to determine the effort necessary for compacting layers of shredded tires with a bulldozer. The tests were conducted at a site located in Mora, Minnesota. An all-weather access road was being constructed with a layer of compacted shredded tires placed on a moderately stiff silty clay. The tires used in this project had been passed only once through a shredding machine, which resulted in rather large pieces of tire rubber. In addition to monitoring compaction, measurements were taken to determine the particle size, bulk density, and porosity. A detailed description of the site conditions and construction project may be found elsewhere (*6*).

Laboratory Tests

One-dimensional laboratory compression tests were used to determine the compressibility and rebound characteristics of waste tires shredded to small-size particles (approximately 50 mm mean size); for comparison, wood chips were also tested. The material parameters evaluated in the laboratory also included particle size, bulk density, and porosity.

SIZE, DENSITY, AND POROSITY CHARACTERISTICS OF MATERIALS

Particle Size

The methods used for determining particle size and aspect ratio differed between the field and the laboratory. Since the field project involved large pieces, a random sample of 144 particles was taken from the stockpiles and measured with a tape rule. In the laboratory, the shredded tire and wood chip particles were passed through sieves.

As stated earlier, the particle size of shredded tires is a function of the number of passes through the shredding device. Minimal processing (one pass) results in large, elongated pieces that, for the tested sample, are characterized by a dominant aspect ratio of about 2 to 4. Because the particle thickness is much less than the width or length, the size of the pieces is best represented by the largest surface area calculated as the product of width and length. The distribution curve of this area is shown in Figure 1; the mean area is about 0.093 m^2.

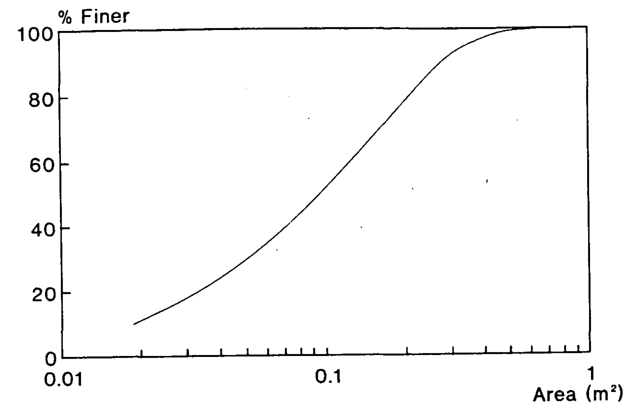

FIGURE 1 Particle area distribution curve of large-size shredded tires.

Two to four passes through a shredder result in much smaller pieces, whose size can be characterized by the opening size of a sieve. The gradation of the shredded tires used in the laboratory compressibility tests is shown in Figure 2, with a mean size of about 30 mm. A similar size was reported by CalTrans (*2*) and compares well with wood chip material used in the tests, whose gradation is shown in Figure 2, with a mean size of about 25 mm.

Bulk Density

The bulk density of the materials in this study was measured by filling a container of known volume and then weighing it. For the large-size tire particles used in the field, the bed of a dump truck was used. The uncompacted bulk density (ρ_o) was determined

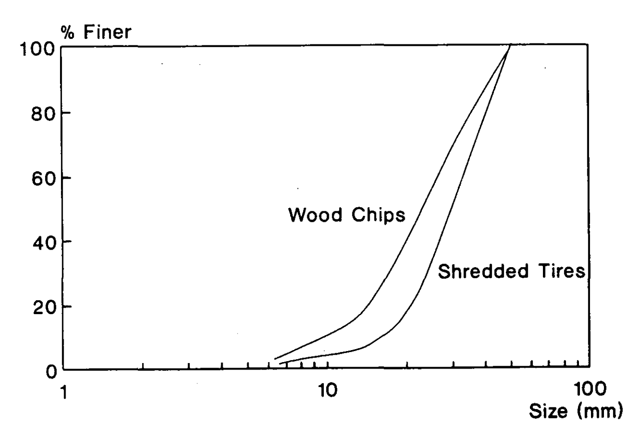

FIGURE 2 Particle size distribution curves of small-size shredded tires and wood chips.

from

$$\rho_o = \frac{m_{st}}{V} \quad (1)$$

where m_{st} is the mass of shredded tires filling a dump truck bed, and V is its volume; m_{st} was determined at a local truck weigh station. The compacted bulk density (ρ_c) was calculated from

$$\rho_c = \rho_o \frac{H_o}{H_o - \Delta H} \quad (2)$$

where H_o is the initial thickness of the shredded tire layer and ΔH is the vertical settlement induced by compaction. For the small-size particles used in the laboratory, a small container was filled and weighed using a laboratory scale.

The bulk density of the shredded tires is a function of the particle size. In general, large-size particles yield a lower bulk density (ρ_o = 230 kg/m^3, ρ_c = 350 kg/m^3) than smaller particles (ρ_o = 500 kg/m^3). Table 1 gives the bulk densities determined in the field and laboratory, including the results obtained by CalTrans (*2*); for comparison, average values of the bulk density of wood chips and granular fills are given also. The following approximate ratio of the average densities of soils (ρ_s), shredded tires (ρ_{st}), and wood-chips (ρ_{wc}) can be established:

$$\rho_s{:}\rho_{st}{:}\rho_{wc} = 12{:}2.5{:}1 \quad (3)$$

This ratio also applies to the bulk unit weight.

Porosity and Void Ratio

The porosity (n) of the large-sized shredded tires was determined indirectly by means of

$$n = \frac{G_s\rho_w - \rho_{st}}{G_s\rho_w} \quad (4)$$

where G_s is the specific gravity of the shredded tire particles, and ρ_w is the density of water; the specific gravity G_s = 1.08 was determined in the laboratory.

For the small-size shredded tires particles and wood chips, the porosity of the uncompacted mass was determined from

$$n = \frac{V_v}{V} \quad (5)$$

where V_v is the volume of voids, and V is the total volume. The volume of voids was measured directly in a mass filling a 0.138-m^3 container by measuring upon drainage the weight of water filling the voids.

Once the porosity was determined, the void ratio (e) was calculated from

$$e = \frac{n}{1 - n} \quad (6)$$

The results shown in Table 1 indicate that the porosity, and thus void ratio, depends on the particle size. Large shredded tire pieces yield a porosity of about 80 percent, whereas smaller particles have a value of about 60 percent; for wood chips the porosity is about 70 percent. In comparison with soils, the porosity of shred-

TABLE 1 Fill Material Properties

Material	Mean Area (m^2)	Mean Size (mm)	Density (kg/m^3)	Porosity (%)	Void Ratio (-)	Compress. Index (-)	Swell Index (-)	Young's Modulus (MPa)	Poisson's Ratio (-)
Shredded Tires	0.093	_	230-350	79	3.76	n.a.	n.a.	n.a.	n.a.
Shredded Tires	_	30	500	57	1.32	0.50	0.27	0.78	0.45
Shredded Tires (4)	_	20-46	500-565	55-60	1.22-1.50	n.a.	n.a.	n.a.	n.a.
Wood Chips	_	25	160	67	2.03	0.35	0.034	70	0.26
Granular Fill	_	~2	1850-2250	12-46	0.14-0.85	0-0.19	_	75-300	~0.40

ded tires and wood chips is not much different. What is significantly different, however, is the size of voids; the latter materials have much greater voids, and this can be evaluated indirectly by measuring the permeability coefficient. As reported by CalTrans (*2*), the permeability coefficient of a small-size shredded tire mass (50 mm size) is about 2.1 m/min, which is 20 to 30 times higher than the permeability coefficient of a typical granular base. The high permeability of shredded tires is one of the main advantages in using them as fill, because water can drain out of the pavement easily.

FIELD COMPACTION OF LARGE-SIZE TIRE SHREDS

The shredded tires were placed in the excavated road bed in two 1- to 2-m lifts. The elevation of the excavation was measured at three transverse points in nine evenly spaced lines throughout a section 45 m long. These points provided the reference datum for subsequent elevation measurements at the same points after the placement and compaction of the shredded tires. Dump trucks were used to deposit the tires, and the compaction was achieved using a 27-ton Caterpillar D7F bulldozer. The compaction effort was quantified as the number of bulldozer passes over the whole width of the road; 22 total passes were performed for the first lift and 12 passes for the second lift.

Figure 3 shows the initial and final lift thicknesses of the shredded tire layer. It can be seen that the initial thickness of the first lift was about 1 m, and the final thickness was about 0.6 m. The initial thickness of the second lift varied from 1.3 to 2 m, and its final thickness was 0.9 to 1.2 m after compaction. The average relationship between the settlement of the shredded tires and the number of bulldozer passes for the first and second lifts is shown in Figure 4. It can be seen that there was little additional compaction of the material beyond 15 passes of the bulldozer for the first lift. A similar number of passes can be anticipated for the second lift.

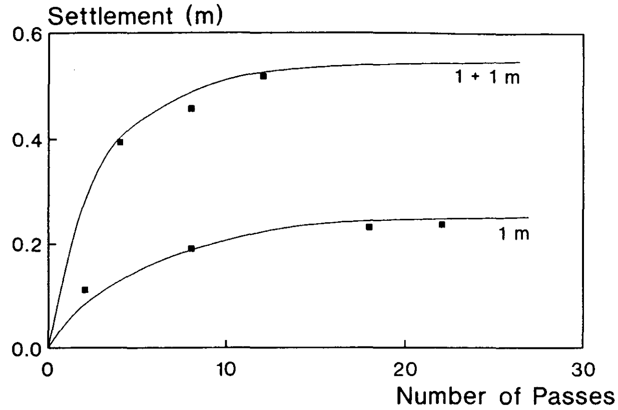

FIGURE 4 Settlement of shredded tires as function of number of bulldozer passes.

ONE-DIMENSIONAL COMPRESSION TEST

Test Procedure

A schematic of the test device used in the laboratory is shown in Figure 5. A cylindrical steel container 97 cm high by 74 cm in diameter was filled with the material to be tested (shredded tires or wood chips) and subjected to a vertical load applied by a closed-loop testing system through steel plates. The load was applied to the samples using a constant rate of displacement of 5 mm/min, and the vertical load was measured by load cells with a capacity of 111.2 kN (shredded tires) or 2668.8 kN (wood chips); loading and unloading cycles were performed to determine the magnitude of rebound. In order to reduce the side friction between the cylinder and the sample, the inner wall was coated with silicon grease.

The vertical stresses (σ_v) were calculated as

$$\sigma_v = \frac{P}{A} \quad (7)$$

where P is the vertical force, and A is the cross-sectional area of the container. The vertical strains (ϵ_v) were computed as

$$\epsilon_v = \frac{\Delta H}{H_o} \quad (8)$$

where H_o is the initial height of the material in the container, and ΔH is the change in height.

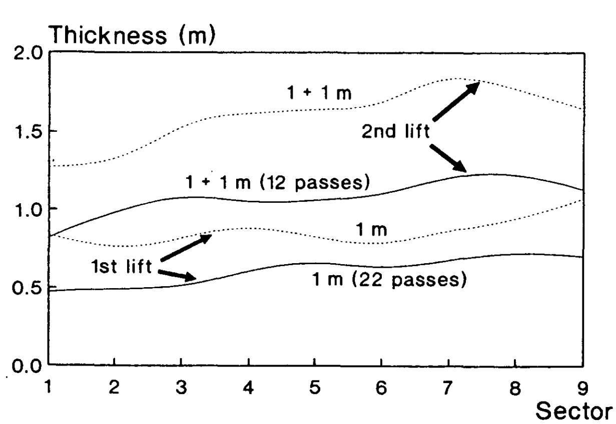

FIGURE 3 Thickness of shredded tire layer.

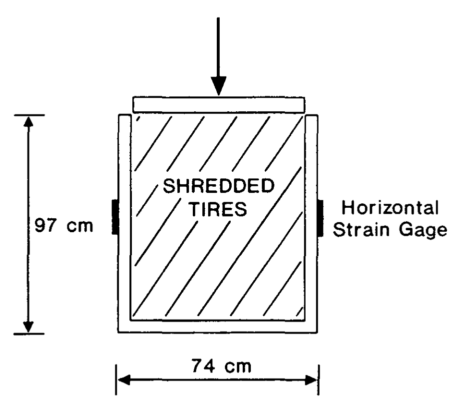

FIGURE 5 Schematic of one-dimensional compression test.

To determine the magnitude of the horizontal (radial) stress (σ_h), the container was instrumented around its circumference with four strain gauges at 90 degrees to one another 30 cm above the base of the container. These measurements allowed for the computation of σ_h using the following relationship:

$$\sigma_h = \epsilon_\theta E \frac{t}{r} \qquad (9)$$

where

ϵ_θ = average circumferential strain,
E = modulus of elasticity of container,
t = thickness of container, and
r = radius of container.

Test Results

Figure 6 shows the typical relationship between vertical stress and vertical strain of shredded tires during multiple loading cycles. The material easily deforms at very low levels of vertical stress and becomes significantly stiffer at about 5 kPa, which corresponds to about 25 percent strain. The maximum stress applied, limited by the ram travel, was about 0.4 MPa with corresponding strains of about 40 percent. Upon unloading and reloading, the stress-strain relationship follows a path parallel to the steeper portion of the initial loading path. This latter behavior would seem to more accurately reflect the characteristics of shredded tires in the field after compaction and placement of overburden. Still, the strain ranges about 10 percent over a range of 0.05 to 0.38 MPa vertical stress.

The typical result for wood chips shown in Figure 7 shows a similarity to the result for shredded tires; the end of the soft response is again at about 20 percent vertical strain although the corresponding stress of about 1 MPa is much higher. At larger strains the material rapidly stiffens, with stresses of about 4 MPa at a strain of 27 percent. The unloading path is very steep and is no longer parallel to the loading path.

The relationship between the horizontal and vertical stress for shredded tires and wood chips is shown in Figures 8 and 9, respectively. Clearly, this relationship is bilinear for shredded tires and linear for wood chips; also, for the same vertical stress, the horizontal stress is higher in shredded tires.

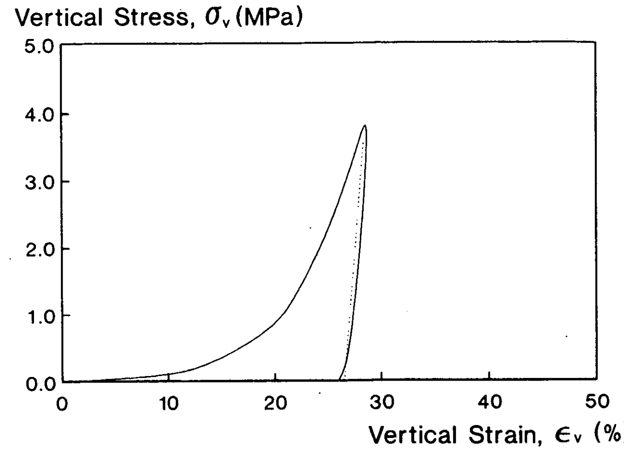

FIGURE 7 Vertical stress versus vertical strain for wood chips.

Analysis of Results

The analysis of compressibility test results was performed within the framework of (*a*) the settlement analysis used in geotechnical engineering and (*b*) deflection analysis applicable to pavement systems.

In the first approach, the compressibility and rebound of a material are characterized by the compressibility index (C_c) and the swell index (C_s) (*5*). These indexes are defined as slopes of a void ratio (e) versus the decimal logarithm of vertical stress (log σ_v) plot obtained directly from the one-dimensional compression test. This implies that the nonlinearity of the stress-strain response and the difference in loading and unloading behavior are accounted for. Because only a one-dimensional response is considered, no assumption as to material isotropy or anisotropy is made.

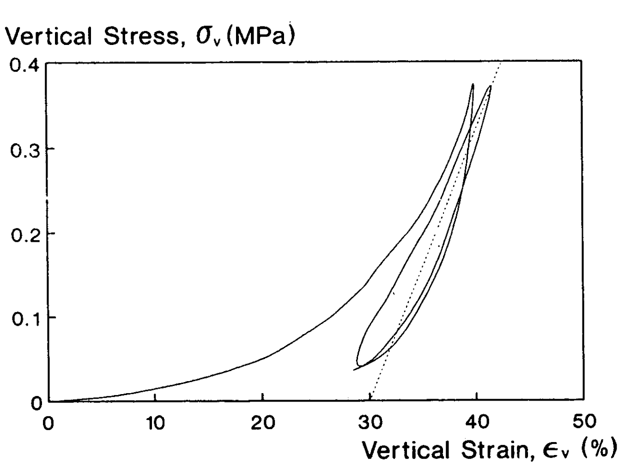

FIGURE 6 Vertical stress versus vertical strain for shredded tires.

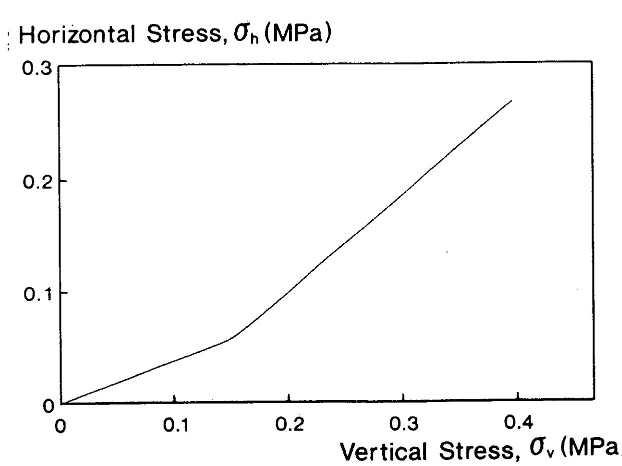

FIGURE 8 Horizontal stress versus vertical stress for shredded tires.

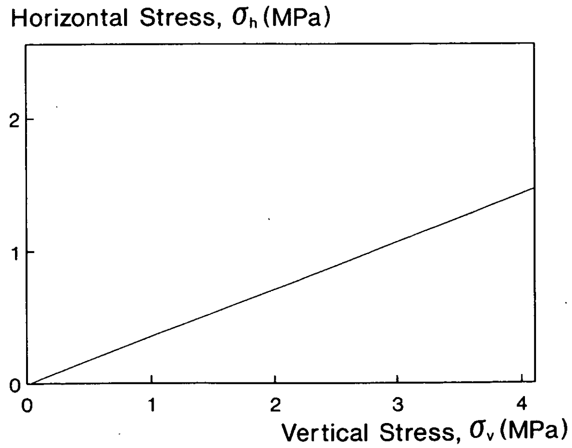

FIGURE 9 Horizontal stress versus vertical stress for wood chips.

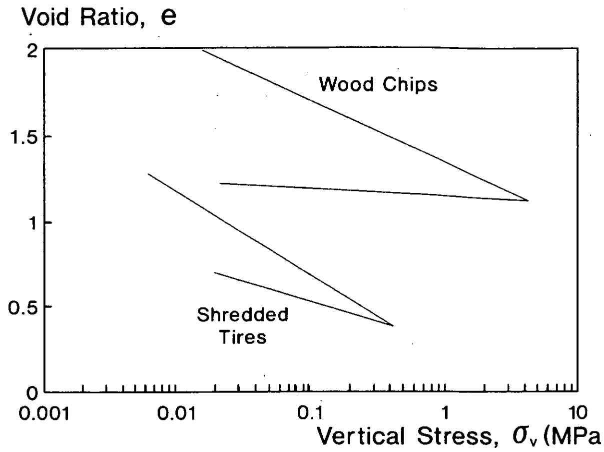

FIGURE 10 Void ratio versus vertical stress for shredded tires and wood chips.

Figure 10 shows the corresponding plots for shredded tires and wood chips. The resulting indexes for shredded tires are $C_c = 0.50$ and $C_s = 0.27$; for wood chips, $C_c = 0.35$ and $C_s = 0.034$ (see Table 1). These results indicate that the compression index for wood chips is comparable to a moderate value for soils, whereas for shredded tires it would be considered high for a typical geotechnical material (*5*). Upon unloading, the swell index for shredded tires is almost eight times that of wood chips.

In the layered system approach, each layer is regarded as linearly elastic and isotropic, with two material parameters: the Young's modulus (E) and Poisson's ratio (ν). As Figures 6 and 7 indicate, the first assumption does not hold true for the shredded tires and wood chips when they are loaded and unloaded from the initial, uncompacted state; the relationship between σ_v and ϵ_v is nonlinear. However, when loading and unloading cycles are applied, which can be regarded as simulation of field compaction, the response is much closer to linear elastic. With this approximation, which is shown in Figures 6 and 7 as dashed lines, parameters E and ν can be determined from the one-dimensional compression test in which the horizontal stress is measured.

In view of symmetry about the vertical axis, and $\epsilon_h = 0$, the three generalized Hooke's law equations for normal strains reduce to two (*7*):

$$\epsilon_v = \frac{1}{E}(\sigma_v - 2\nu\sigma_h) \tag{10}$$

$$0 = \frac{1}{E}[\sigma_h(1 - \nu) - \nu\sigma_v] \tag{11}$$

The proportionality between the vertical stress and strain, and between the horizontal and vertical stress, can be written as

$$\sigma_v = m\epsilon_v \tag{12}$$

$$\sigma_h = K\sigma_v \tag{13}$$

which, when substituted into Equations 10 and 11, gives

$$E = \left(1 - 2\frac{K^2}{1 + K}\right)m \tag{14}$$

$$\nu = \frac{K}{1 + K} \tag{15}$$

It was found that the values of m and K for shredded tires are about $m = 3$ MPa, and $K = 0.82$. For wood chips these are about $m = 150$ MPa, and $K = 0.36$. When these values are substituted in Equations 14 and 15, the Young's modulus and Poisson's ratio for shredded tires are $E = 0.78$ MPa, $\nu = 0.45$, and for wood chips $E = 70$ MPa, $\nu = 0.26$ (see Table 1). It is seen that Young's modulus for shredded tires is about 1/100 that for wood chips, and the Poisson's ratio is about two times higher.

The above calculation of Young's modulus and Poisson's ratio is based on the assumption that the material is isotropic. Because the shredded tires particles are flat, they tend to arrange themselves mutually parallel when compacted or loaded. This creates a structure that is no longer isotropic; a honeycomb-type structure with horizontally elongated cells would be a good approximation. Accordingly, the stiffness in the vertical direction may be higher than in the horizontal plane, and the material can be termed anisotropic-transversely isotropic. This type of elastic material is described by five material constants rather than two (*7*): two Young's moduli, two Poisson's ratios, and one shear modulus (in an isotropic material the shear modulus can be expressed as a function of E and ν). A direct evaluation of these constants requires tests other than one-dimensional compression, and these can be difficult to perform. In particular, evaluating the shear modulus would require a very complex torsion-type experiment. An alternative would be to evaluate some constants from an inverse analysis, in which actual layered-system deflections are measured and the constants are backcalculated. This methodology has found application in evaluating Young's modulus for isotropic materials (*8*); an adequate methodology would have to be developed for anisotropic materials.

CONCLUSIONS

An attempt has been made to address the characterization of shredded tires in terms of standard geotechnical engineering properties. Ranges of values have been identified for properties such as size, bulk density, porosity, and permeability. However, questions remain regarding the mechanical behavior of shredded tire deposits and their effect on the performance of pavements and other geotechnical structures such as retaining walls and foundations. More field and laboratory tests are required to assess the deformability parameters over a wider range of stress levels. From the work presented here, the following conclusions may be drawn:

1. The lightweight nature, durability, and high permeability of shredded tires makes this an attractive material for use in embankments over weak soils. However, such use must be tempered by considerations of its mechanical behavior as discussed below.
2. The bulk density of shredded tires is approximately 2.5 times greater than that of wood chips; yet it is still almost 4 times lower than that of conventional geotechnical materials.
3. Large-size shredded tires (those sliced only once) are difficult to work with during construction. Field observations revealed excessive damage to placement and compaction equipment. Adequate compaction of this material was normally achieved after 15 passes of a 27-ton bulldozer on a 1-m lift.
4. The results of compressibility tests clearly illustrate that shredded tires are far more compressible than wood chips, the Young's modulus of small-size particles is about 100 times lower, and this material possesses much more capability for rebound. The implication for a roadway pavement is that the pavement system would be subject to much higher deflections under loads and that the materials would experience a higher degree of strain reversal. This, if not accounted for, may lead to premature fatigue failure of hard surface pavement materials such as asphalt or portland cement concrete.
5. Classical multilayer elastic analysis for pavement systems may be inadequate for representing the stresses and strains in systems containing shredded tire fill because the structure of the shredded tire mass is anisotropic, with a stiffer response in the vertical direction. It seems imperative to undertake studies on the influence of material anisotropy on layered system response. The difficulty in performing such studies lies not in theoretical solutions but in experimental determination of the material parameters. The simplest transversely isotropic elastic material is characterized by five constants, whose direct determination may be very difficult if not impossible. An inverse analysis (backcalculation) of measured deflections may offer a way for determining some constants.

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