Shear Strength and Compressibility of Tire Chips for Use as Retaining Wall Backfill

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Scrap tires that have been cut into chips are coarse grained, free draining, and have a low compacted density, thus offering significant advantages for use as lightweight fill and retaining wall backfill. The engineering properties needed to put tire chips into use are presented. The properties determined for tire chips, from three suppliers, are gradation, specific gravity, compacted density, shear strength, compressibility, and coefficient of lateral earth pressure at rest. The 76-mm (3-in.) maximum size and high compressibility of the tire chips necessitated design and fabrication of custom-made testing equipment. The tests showed that the tire chips are composed of uniformly graded, gravel-sized particles that absorb only a small amount of water. Their compacted density is 0.618 to 0.642 Mg/m^3 (38.6 to 40.1 pcf), which is about one-third that of compacted soils. The shear strength was measured in a large-scale direct shear apparatus. The friction angle and cohesion intercept ranged from 19 to 25 degrees and 8 to 11 kPa (160 to 240 psf), respectively. The compressibility tests showed that tire chips are highly compressible on initial loading, but that the compressibility on subsequent unloading and reloading cycles is less. The horizontal stress was measured during these tests and showed that the coefficient of lateral earth pressure at rest varied from 0.26 for tire chips with a large amount of steel belt exposed at the cut edges to 0.47 for tire chips composed entirely of glass-belted tires.

Disposal of the estimated 2 billion scrap tires that have been discarded in huge open piles across the United States is a monumental problem. Furthermore, an additional 189 million are added to these piles each year (*1*). These piles are a serious fire hazard, prolific breeding ground for mosquitoes, and ugly scar on our landscape. Society is increasingly looking to the transportation industry to help solve the scrap tire disposal problem, as evidenced by the requirement of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) that, by 1997, one-fifth of all road projects must include 10 kg of recycled rubber per megagram (20 lb/ton) of hot mix and 150 kg of recycled rubber per megagram (300 lb/ton) of sprayed binder.

Another use for scrap tires is fill. In this application the tires are cut into durable, coarse grained, and free draining chips that have a low compacted density. Because each cubic meter of tire chip fill contains about 100 waste tires (75 tires per cubic yard), there is potential for using a large number of tires especially when compared with the 1.5 tires that ISTEA requires be used per megagram (1.4 tires per ton) of hot mix. Furthermore, it is much easier to cut tires into large chips than to produce the crumb rubber or liquefied rubber needed for use in hot mix.

Waste tire chips are already used as lightweight fill for highway embankments (*2–4*) and an insulating layer beneath an unpaved road in a northern climate (*5*). Another use is as backfill behind retaining walls and bridge abutments. The low compacted density would potentially result in low horizontal pressures on the wall. Thus, a lighter wall could be used to retain them. Furthermore, their low compacted density will reduce the settlement of underlying compressible soils and increase the global stability of the wall. In some cases, this will allow the wall to be placed on a spread footing rather than on a pile foundation, which would significantly reduce construction costs. Because tire chips are free draining, there is no need for clean granular backfill.

A necessary first step is to determine the engineering properties of tire chips. The gradation, specific gravity, compacted density, and compressibility of tire chips from a supplier in Hampden, Maine, were determined (*6,7*). In the present study these properties and the shear strength were determined for tire chips from three additional suppliers. This will provide the basis for future field trials using tire chips as retaining wall backfill.

The three tire chip suppliers are F&B Enterprises, New Bedford, Massachusetts; Palmer Shredding, North Ferrisburg, Vermont; and Pine State Recycling, Nobleboro, Maine. The F&B chips were composed entirely of glass-belted tires and were less than 38 mm (1½ in.) in size. The Palmer and Pine State chips were composed of a mixture of glass- and steel-belted tires. The Palmer chips had a large amount of steel belt exposed at the cut edges of the tire chips. The Palmer chips were 76-mm (3-in.) maximum size and the Pine State chips 51-mm (2-in.) maximum size. The Palmer and Pine State chips tended to be long in relation to their thickness, and the F&B chips tended to be more equidimensional.

The large size and high compressibility of the tire chips necessitated modification of conventional test procedures and design and fabrication of custom-made testing apparatus. The test procedures, apparatus, and results for each property will be discussed. Further details are given in a work by Humphrey et al. (*8*).

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GRADATION, SPECIFIC GRAVITY, AND COMPACTED DENSITY

The gradation of the tire chips from the three suppliers was determined using AASHTO T27-87 (*9*). The tire chips are uniformly graded and composed of gravel sized particles (Figure 1). The Palmer chips were the coarsest and the F&B chips the finest.

The specific gravity of the tire chips was determined using AASHTO T85-85 (*9*), except that the samples were air dried rather than oven dried at the start of the tests. The apparent specific gravities based on the average of two tests were 1.14 for F&B chips, 1.27 for Palmer chips, and 1.24 for Pine State chips. These specific gravities are less than half of those typical of soils. The specific gravity of the F&B chips is lower than the other two because the F&B chips are entirely glass belted.

The test procedure used to determine the compacted density of air dried tire chips was adapted from AASHTO T180-86 (*9*). A mold 254 mm (10 in.) in diameter and 254 mm (10 in.) high with a volume of 0.012 m^3 (0.44 ft^3) was used. The tire chips were compacted in three layers with a 4.536-kg (10-lb) hammer falling 0.457 m (18 in.). Previous research showed that decreasing the compaction energy from modified Proctor to 60 percent of standard Proctor reduced the density by only 0.03 Mg/m^3 (2 pcf) and that compaction of wet versus air dried tire chips made only a 0.016 Mg/m^3 (1 pcf) difference in the density (*6,7*). Because the compaction energy and wet versus air dried tire chips had only a small effect, 60 percent of standard Proctor energy and air dried tire chips were used for this study. The compacted density of air dried tire chips from the three suppliers fell within a fairly narrow range. The compacted density based on the average of three tests was 0.618 Mg/m^3 (38.6 pcf) for F&B chips, 0.619 Mg/m^3 (38.7 pcf) for Palmer chips, and 0.642 Mg/m^3 (40.1 pcf) for Pine State chips. These values are about one-third of those typical for compacted soils showing the potential for tire chips to be used as lightweight fill.

SHEAR STRENGTH

Testing Apparatus

The shear strength of tire chips was determined using a direct shear apparatus custom designed to accommodate the large size and high compressibility of the tire chips. In addition, special provisions were made to eliminate friction between the two halves of the shear box.

A 305-mm (12-in.) square shear box (nominal dimension) made from steel 9.5 mm (⅜ in.) thick was chosen for the initial design. This was adequate because the largest-size tire chips to be tested were minus 76 mm (3 in.). Thus, the shear box would be four times larger than the largest tire chip. The lower half of the shear box was 76 mm (3 in.) high and bolted to a supporting bench. The top half of the shear box was 152 mm (6 in.) high. This height was needed to accommodate the large compressibility of the tire chips. To determine whether the area of the shear box influenced the test results, a 406-mm (16-in.) square shear box (nominal dimension) was also fabricated.

It was essential to maintain a gap between the two halves of the box to prevent introduction of additional horizontal stresses due to friction. During sample preparation a 6-mm (¼ in.) gap was opened by placing spacers at each corner between the halves of the box. Then to maintain the gap during testing, two steel wheels 51 mm (2 in.) in diameter

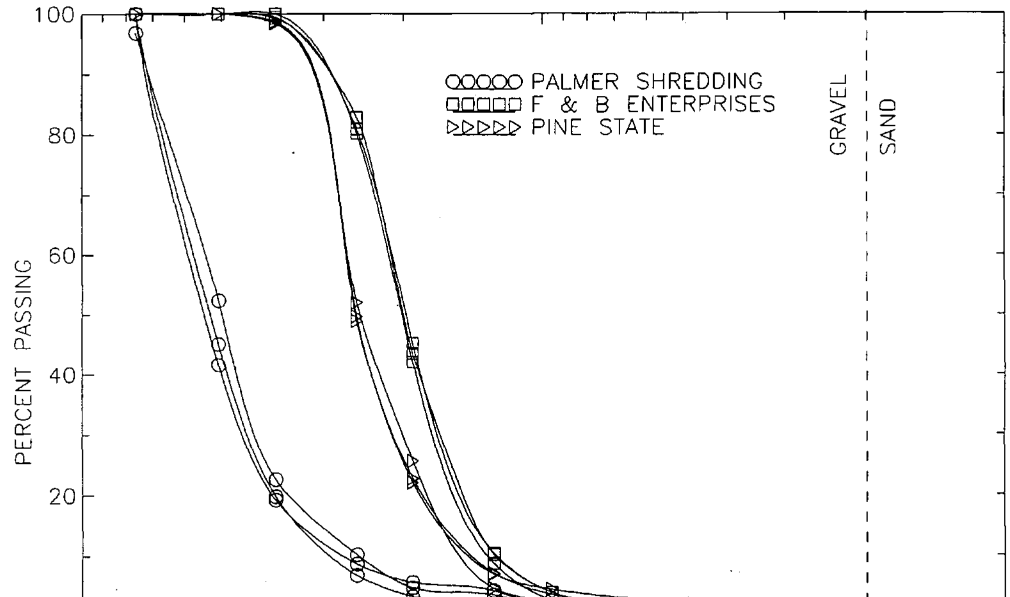

FIGURE 1 Gradation of tire chips from three suppliers.

with low-friction ball bearing hubs (similar to old fashioned roller skate wheels) mounted in a steel frame were clamped to each end of the box. The spacers were then removed. During testing the wheels rode along the top of the supporting bench, carrying the top of the box to maintain the gap between the box halves.

The normal stress was applied using dead weights hung from a hanger suspended under the sample. A maximum dead load of 5570 kN (1,250 lb) could be applied to the sample. This resulted in a maximum normal stress of 68 kPa (9.9 psi) for the 305-mm box, which is equivalent to approximately 3 m (10 ft) of soil fill.

The horizontal shearing force was provided by a ⅛-hp electric motor acting through a gear box, which allowed the rate of horizontal deformation to be adjusted. A rate of approximately 7.6 mm/min (0.3 in./min) was used. The horizontal shearing force was measured with a 4450-kN (1,000-lb) capacity load cell. Two linear variable differential transformers (LVDTs) were used to measure horizontal and vertical displacements.

Sample Preparation

The inside of the upper half of the shear box was greased to minimize the portion of the applied vertical load transmitted to the sides of the box by friction. Then, the samples were compared with 60 percent of standard Proctor energy. The box was filled in three 64- to 76-mm (2.5- to 3-in.) layers to approximately 25 mm (1 in.) from the top. To ensure that there was no effect on the shearing plane from a smooth surface between the first two layers, care was taken that the top of the first layer did not coincide with the gap between the halves of the box.

Results

Direct shear tests were run using the 305-mm box at three normal stresses. Three tests were done for each normal stress for each of the three suppliers. A total of 27 tests was done with the 305-mm box. In addition, tests were done using the 406-mm box with Pine State tire chips with three normal stresses.

In direct shear tests, failure is considered to be the peak shear stress or, if no peak is reached, failure is generally taken as the shear stress at a horizontal displacement equal to 10 percent of the length of box (*9*). The latter criterion controlled for tire chips. Thus, for the 305-mm box, which had an inside dimension of 286 mm (11.25 in.), failure was taken as the shear stress at a deformation of 28.6 mm (1.1 in.). For the 406-mm box, which had an inside dimension of 387 mm (15.25 in.), failure would be at a deformation of 38.7 mm (1.5 in.). However, the travel of the LVDT used to measure horizontal displacement was limited to 35.6 mm (1.4 in.), so failure for tests with this box were taken to be the stress at this displacement.

The shear stress versus horizontal deformation for Pine State tire chips with the 305-mm box is given in Figure 2. This shows that the shear stress continues to increase past a horizontal deformation equivalent to 10 percent of the length of the box. The curves for the F&B and Palmer chips in the 305-mm box and the Pine State chips in the 406-mm box were similar (*8*).

The average shear stress versus average normal stress at each of the three loading increments for each of the samples is given in Figure 3. Each point is the average of two or three trials at a given normal stress. All these lines plot slightly concave down. For the Pine State tire chips, the 305- and 406-mm boxes give nearly identical results (Figure 3). Thus, the 305-mm box is large enough for the size tire chips investigated.

Comparison of the failure envelopes shows that the F&B chips are stronger than the others (Figure 3). This may be because these tire chips were smaller and more equidimensional. During shearing the tire chips would tend to lock together more instead of sliding past one another on the shearing plane as did the larger, flatter pieces. This is particularly true because the large flat pieces tended to be oriented parallel to the horizontal shear plane.

The friction angles ϕ and cohesion intercepts *c* were determined using best fit straight lines through the data and are

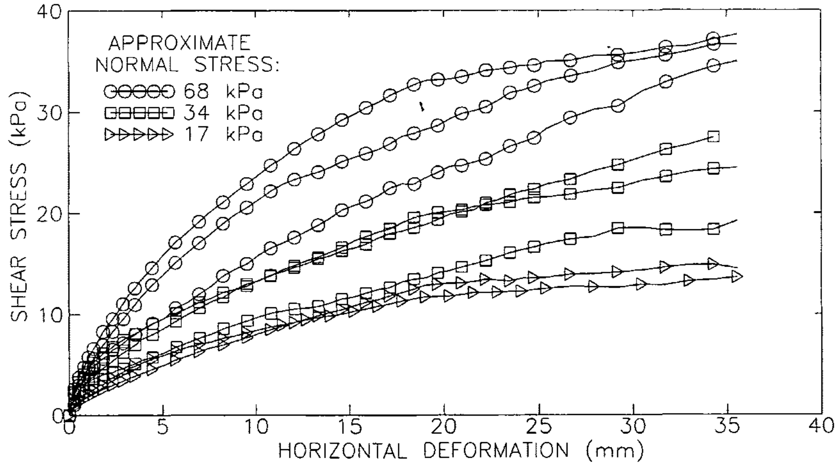

FIGURE 2 Shear stress versus horizontal displacement for Pine State tire chips.

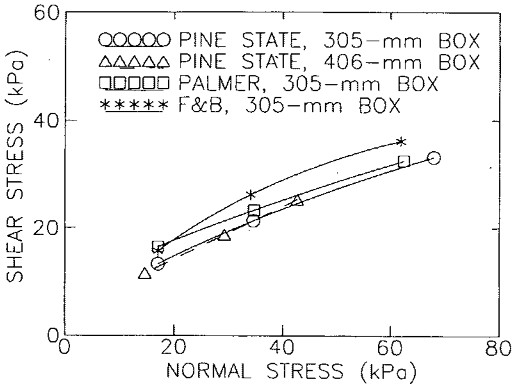

FIGURE 3 Failure envelopes for tire chips from three suppliers.

given in Table 1. This shows that the Palmer chips had the highest cohesion although their friction angle was low. This may be because they have a large amount of exposed steel belts, which interlock and do not rely on normal stress to develop their strength.

The choice of failure as the shear stress at a horizontal deformation equal to 10 percent of the length of the box (28.6 mm for the 305-mm box) is rather arbitrary. To investigate what effect this could have, the ϕ and c were determined for shear stresses at 15.2 mm (0.6 in.) and 35.6 mm (1.4 in.) of horizontal deformation. In general, they showed that the cohesion intercept decreased as the horizontal deformation chosen as failure decreased but that there was only a small effect on the friction angle. This suggests that a low or zero cohesion intercept should be used for design because it appears that significant deformation is needed to develop the cohesion.

Vertical deformation was also measured during the tests. All tests exhibited a decrease in height. The samples with the highest vertical stress tended to have the largest decrease in height.

COMPRESSIBILITY

Testing Apparatus

Sample Container

The container used for the compression tests consisted of a piece of schedule 40 PVC pipe 305 mm (12 in.) in diameter (nominal) and 318 mm (12.5 in.) long with a wall thickness of 8.1 mm (0.32 in.). Four strain gauges were placed with a horizontal orientation 89 mm (3.5 in.) above the base. They were calibrated to give the horizontal stress exerted on the inside of the container by the tire chips. Two additional strain gauges were placed vertically. They were calibrated to measure the portion of the applied load transferred from the tire chips to the container by friction (*6,7*).

TABLE 1 Shear Strength of Tire Chips from Three Suppliers

Supplier	ϕ	c (kPa)
Pine State (305-mm box)	21°	7.7
Pine State (406-mm box)	26°	4.3
Palmer Shredding	19°	11.5
F&B Enterprises	25°	8.6

1 kPa = 20.89 psf

Loading and Data Acquisition System

An Instron 4204 universal testing machine controlled by an IBM-compatible 80286 computer was used to apply the vertical load. The computer controlled the rate of deformation and obtained measurements of the vertical load and vertical displacement. A wheatstone bridge took readings from the strain gauges. The output voltages from the bridge were read by an analog to digital converter with an accuracy of 16 bits. The readings were taken at 10-sec intervals. To help offset electronic noise and imbalance at the time of a reading, the computer would take 10 readings from each strain gauge, which were averaged for the final reading (*6,7*).

Testing Methodology

Sample Preparation

Compacted samples were prepared by clamping the container to the steel base plate. Grease was brushed on the inside of the container to reduce the friction between the tire chips and the wall of the container. The tire chips were compacted in five layers with 60 percent of standard Proctor energy (*6,7*). The sample was then placed in the Instron and the clamps were removed.

Data Acquisition and Stress Computations

The load was applied to the sample at a constant rate of deformation of 13 mm/min (0.5 in./min). Readings from the strain gauges, vertical load, and vertical deformation were taken every 10 sec. From these readings the average vertical stress in the sample (σ_{avg}), the vertical strain (ε_v), vertical stress in the sample at the strain gauge height (σ_{gauge}), and the horizontal stress at the gauge height (σ_h) were calculated. The relationship between σ_{avg} and the known stresses at the top of the sample (σ_{top}) and σ_{gauge} is given in Figure 4. The vertical stress at gauge height (σ_{gauge}) is found by subtracting the load transmitted by friction to the container as measured at the gauge height (P_{frict}) from the load applied at the top of the sample ($P_{applied}$) and then dividing by the area of the sample. The average vertical stress (σ_{avg}) is the vertical stress at mid-height of the sample. It was computed by assuming that the load transmitted by friction to the container varies linearly from zero at the top of the sample to a maximum at the bottom. Because the strain gauges are 89 mm from the bottom, the load carried at mid-height (P_{avg}) is given by

$$P_{avg} = P_{applied} - [(H/2) * P_{frict}/(H - 89)]$$

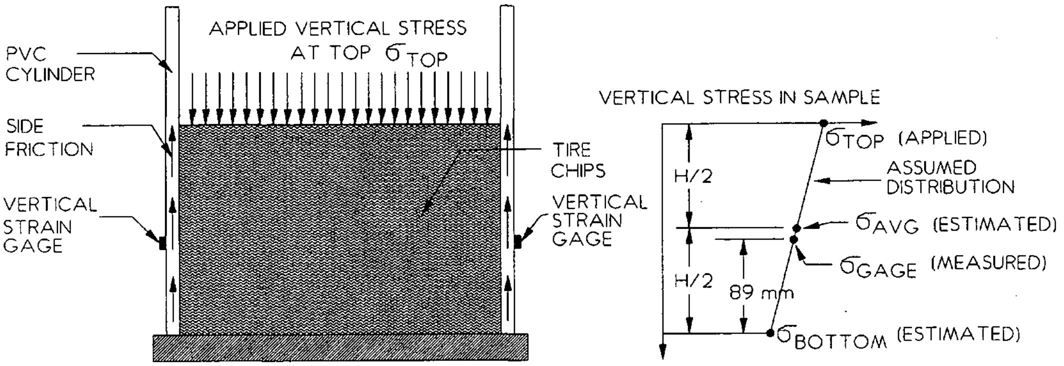

FIGURE 4 Effect of friction on vertical stress (*6,7*).

where *H* is the current height of the sample in mm. The average vertical stress (σ_{avg}) is found by dividing P_{avg} by the area of the sample.

Loading and Unloading Cycles

Most samples were subjected to three cycles of loading and unloading. The loading and unloading cycles are of particular importance for highway applications because they indicate the deformation behavior that would occur under repetitive vehicle loading. To apply the first loading cycle, the vertical load ($P_{applied}$) was increased until it reached 4.1 Mg (9,000 lb). This was chosen as the upper limit of loading because it is near the maximum capacity of the Instron. The clamps that held the container to the base were put in place, and the sample was then unloaded until the average vertical load in the middle of the sample (P_{avg}) was reduced to 2980 kN (670 lb) or about 41 kPa (6 psi). This process continued until three cycles of loading and unloading had been performed. The clamps were left in place for the second and third loading and unloading cycles.

Results

For each supplier, three tests were performed on samples compacted with 60 percent of standard Proctor energy. Most of these tests consisted of three loading and unloading cycles. Vertical compressibility and horizontal stresses are discussed in separate sections. Selected results are presented to illustrate the general compressibility behavior. Summaries are made to permit a comparison of the compressibility of tire chips from the three suppliers. Then elastic parameters computed from the combined measurements of vertical compressibility and horizontal stresses are presented. Complete compressibility results are given in a work by Humphrey et al. (*8*).

Vertical Compressibility

Results from one test on Palmer chips are given in Figure 5 to illustrate a typical graph of vertical strain (ε_v) versus average vertical stress (σ_{avg}). The initial portion of the first loading curve is very steep, indicating high compressibility. The first loading curve then flattens out at higher stresses. The slopes of subsequent unloading and reloading curves are similar to the flatter part of the first loading curve. The reloading curves lie slightly above the unloading curves. Tests on tire chips from the other suppliers showed similar behavior (*8*).

To permit a comparison of the initial compressibility, the vertical strain for the first loading cycle at average vertical stresses of 69 and 276 kPa (10 and 40 psi) is given in Table 2. Ordering the results from least to most compressible (F&B, Pine State, Palmer) shows that there is a general trend of increasing compressibility with increasing amounts of exposed steel belts. However, from a practical viewpoint, the difference in compressibility between tire chips from the three suppliers is small.

Horizontal Stress

The horizontal strain gauges were used to measure the increase in horizontal stress as the sample was loaded. A typical graph for stresses at gauge height of horizontal stress (σ_h) versus vertical stress (σ_{gauge}) for compacted Pine State tire chips is given in Figure 6. For the initial loading the graphs

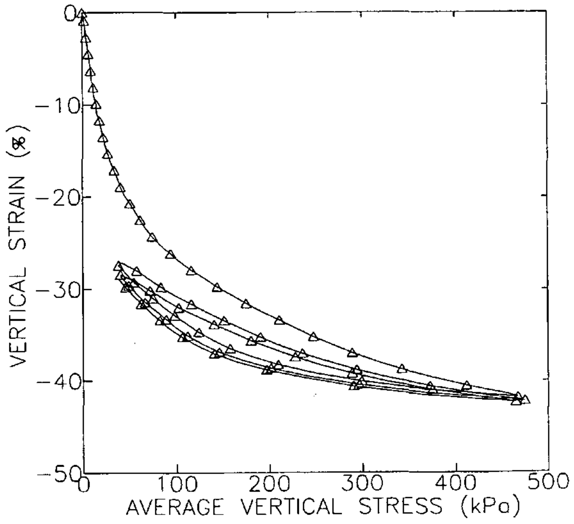

FIGURE 5 Deformation behavior of Pine State tire chips.

TABLE 2 Vertical Strains at Average Vertical Stresses 69 kPa and 276 kPa

		Vertical Strain At Average Vertical Stress =	
Supplier	Test No.	69 kPa	276 kPa
Pine State Recycling	1	23.6	36.4
	2	28.7	39.4
	3	29.5	39.4
	Average	27.3	38.4
Palmer Shredding	1	26.0	40.9
	2	30.6	42.9
	3	30.3	43.8
	Average	29.0	42.5
F&B Enterprises	1	24.8	38.4
	2	21.6	38.4
	3	22.9	35.9
	Average	23.1	37.6

1 kPa = 0.1450 psi

show a flatter slope up to a horizontal stress of approximately 69 kPa (10 psi). After this point the line is steeper. This change in slope coincides with the point at which the calibration curve for the horizontal strain gauges changes from a straight line for stresses less than 69 kPa to a second-order polynomial for higher stresses. This causes the distinct transition at 69 kPa. Nonetheless, the initial portion of the curve has a flatter slope. It has been theorized that the flatter initial slope is due to the compression of the voids and the steeper upper portion is due mainly to deformation of the rubber particles (*6,7*). Tests on tire chips from the other suppliers showed a similar behavior (*8*).

Elastic Parameters

Elastic parameters were calculated using the measurements of vertical compressibility and horizontal stress. These parameters were then used to make another comparison of the compressibility of the tire chips from the three suppliers and will be used for a future numerical analysis of retaining wall behavior when tire chips are used as backfill.

The coefficient of earth pressure at rest K_o was determined from the slope of the vertical stress at gauge height versus horizontal stress at gauge height curves

$$K_o = \Delta\sigma_h/\Delta\sigma_{\text{gauge}}$$

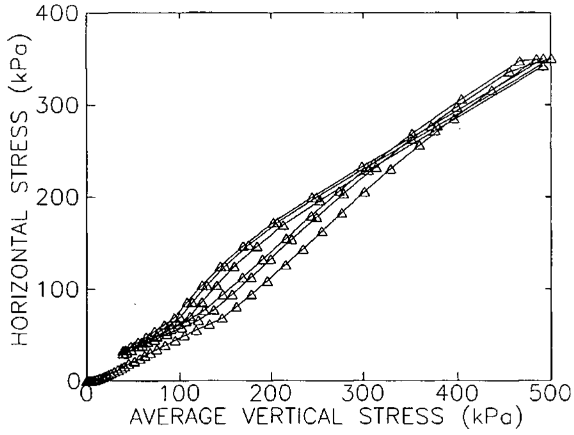

FIGURE 6 Horizontal stress versus vertical stress for Pine State tire chips.

The values of K_o were determined at a horizontal stress less than 69 kPa because this corresponds to vertical stresses most likely to be encountered in highway applications. Using K_o, Poisson's ratio μ can be determined using the following relationship (*10*)

$$\mu = K_o/(1 + K_o)$$

The constrained modulus, D, is found from the slope of the average vertical stress versus vertical strain graphs

$$D = \Delta\sigma_{\text{avg}}/\Delta\varepsilon_v$$

D was determined using the slope of the unloading and reloading portions of the curve between the transition from the unloading to the loading phase and an average vertical stress of 110 kPa (16 psi). This stress was used because it is the smallest vertical stress from all the tests that was observed at a horizontal stress of 69 kPa. Stresses in this range are typical of those encountered in highway applications. The unloading and reloading portion of the curve was used because this is closest to the deformation behavior that will be encountered under repetitive vehicle loading.

Young's modulus, E, can be determined with the following relationship from a work by Lambe and Whitman (*11*) using the constrained modulus and Poisson's ratio

$$E = (1 + \mu)(1 - 2\mu)D/(1 - \mu)$$

The elastic parameters are given in Table 3. By examining K_o and μ and recalling the amount of exposed steel belt in the tire chips from the different suppliers, it is seen that these parameters decrease with increasing exposed steel belt. The implication is that tire chips with a significant amount of exposed steel belt would produce lower horizontal stresses on retaining walls.

It is instructive to compare the K_o and μ for tire chips with values typical for granular soils. The average K_o values for tire chips were from 0.26 to 0.47 as compared with typical K_o of normally consolidated granular soils of 0.35 to 0.50 (*12*). Thus, only the K_o for the Palmer sample falls below the typical range for granular soils. Typical μ for granular soils were from 0.15 to 0.45 (*13*). The average values for tire chips (0.20 to 0.32) fall in the lower half of this range. For comparison the μ of solid tire rubber is 0.5 (*14*).

The constrained modulus of the tire chips was from 1270 kPa (184 psi) for the F&B tire chips to 1680 kPa (244 psi) for the Palmer tire chips. Young's modulus was from 770 kPa (112 psi) for the F&B chips to 1130 kPa (165 psi) for the Pine State chips. This suggests that small glass-belted tire chips have lower unloading and reloading modulus than mixtures of larger glass- and steel-belted tire chips. For comparison, the Young's modulus of the tire rubber itself is from 1240 to 5170 (180 to 750 psi) (*14*) and for granular soils typically from 10,000 to 170,000 kPa (1,500 to 25,000 psi) (*13*). Thus, the Young's modulus of tire chips is two to three orders of magnitude less than the modulus of granular soils typically used

TABLE 3 Elastic Parameters of Tire Chips

Supplier	Test No.	K_0	μ	D (kPa)	E (kPa)
Pine State Recycling	1	0.55	0.35	1340	830
	2	0.33	0.25	1690	1390
	3	0.34	0.25	1390	1160
	Average	0.41	0.28	1470	1130
Palmer Shredding	1	0.29	0.22	790	700
	2	-----	-----	2510	-----
	3	0.22	0.18	1740	1530
	Average	0.26	0.20	1680	1120
F&B Enterprises	1	0.40	0.29	1040	480
	2	0.55	0.36	1240	740
	3	0.45	0.31	1520	1100
	Average	0.47	0.32	1270	770

1 kPa = 0.1450 psi

as a base beneath paved roads. The implication of this is that 0.6 to 1.8 m (2 to 6 ft) of conventional soil fill is needed on top of the tire chip layer to prevent excessive deflections of the overlying pavement. Additional discussion of this statement is in works by Manion and Humphrey (*6*) and Humphrey and Manion (*7*).

CONCLUSIONS

Several conclusions can be drawn from this research.

1. Gradations of the tire chips from the three suppliers show that the chips were uniformly graded from 13 to 76 mm (0.5 to 3 in.) in size.
2. The specific gravity of the tire chips was slightly greater than that of water and ranged from 1.14 to 1.27. Tire chips composed entirely of glass-belted tires have a lower specific gravity than those composed of a mixture of glass- and steel-belted tires.
3. The compacted dry densities of the tire chips were in a narrow range of 0.618 to 0.642 Mg/m^3 (38.6 to 40.1 pcf), which clearly shows the potential of tire chip use as lightweight fill.
4. Compression tests indicate that the tire chips are highly compressible during the initial portion of the first loading cycle but that the compressibility is significantly less during subsequent unloading and reloading cycles.
5. The friction angle of the tire chips was between 19 and 25 degrees and the cohesion between 8 and 11 kPa (160 and 240 psf).
6. The amount of exposed steel belt appears to have a systematic effect on some of the engineering properties of tire chips. Large amounts of exposed steel belts tend to cause higher compressibility during the first loading cycle, higher Young's modulus during unloading and reloading cycles, lower coefficient of earth pressure at rest K_o, and lower shear strength.
7. These laboratory results suggest that there may be some advantage to using tire chips with large amounts of exposed steel belt as retaining wall backfill because they have a lower K_o.

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