Rubber Soils as Lightweight Geomaterials

IMTIAZ AHMED AND C. W. LOVELL

The literature review and laboratory testing results from an ongoing research study, which investigates the feasibility of using rubber soils as lightweight geomaterial in highway construction, are presented. An overview of conventional lightweight materials; generation and disposal options for scrap tires; a summary of the various field and laboratory studies on the use of shredded tires as lightweight fill; results from compaction, compressibility, and permeability testing of compacted rubber soils samples; and the salient conclusions of this study are also presented. The use of shredded tires in highway construction offers technical, economic, and environmental benefits under certain conditions. The benefits are reduced weight of fill and backfill pressures. Shredded tires serve as a good drainage medium and have longer life. Tire chips are practically indestructible and available in abundance at practically no cost. Recycling large quantities of discarded tires has a positive impact on the environment. Potential problems are leachate of metals and hydrocarbons, fire risk, and large compressibility of tire chips. Information about stress-strain-strength behavior of tire chips for design and performance prediction of tire embankments and long-term environmental impacts of shredded tires is lacking.

Both the stability and settlement of embankments on soft foundations can be improved by using lightweight embankment fill (*1,2*). Lightweight materials that have been used successfully in highway embankments are bark, sawdust, dried peat, fly ash, slags, cinders, cellular concrete, expanded clay or shale, expanded polystyrene, and oyster and clam shells (*3*). Engineers and researchers are constantly trying to develop civil engineering materials that are more durable, more economical, and lighter to replace conventional materials to enhance the stability of slopes and foundations and reduce settlements in problem areas. Field and laboratory studies (*4*) have indicated that these apparently contradictory requirements can be potentially reconciled by the use of rubber soil.

Millions of scrap tires are discarded annually in the United States and other developed countries of the world. Most of them are currently landfilled or stockpiled. This uses valuable landfill space, creates a fire hazard, and provides a breeding ground for mosquitos. Efforts to sharply reduce the environmentally and economically costly practice of landfilling have stimulated the pursuit of nonlandfill disposal or reuse of scrap tires. Tires have useful engineering properties and have been used in a variety of engineering applications. Various highway agencies in the United States (Colorado, Minnesota, Oregon, Vermont, and Wisconsin) and abroad have experimented with and evaluated the use of shredded tires as a lightweight fill material. The experiences of these agencies show that the use of shredded tires in embankments is feasible and quite beneficial (*4–6*).

This paper is based on an ongoing laboratory study that investigates the feasibility of using shredded tires in highway construction.

CONVENTIONAL LIGHTWEIGHT MATERIALS

Various types of lightweight materials and their salient properties are given in Table 1. All have been used in the past, although some materials are more popular than others and some have only been used experimentally or for structures other than highway embankments. The performance and cost differences between the various materials are significant. However, all have compacted densities significantly less than the unit weights of soils commonly used in embankment construction. Their use can therefore substantially reduce the effective weight of embankment. A questionnaire survey by Holtz (*2*) showed that lightweight fill has been used to some extent by 40 percent of the U.S. highway agencies that responded to the questionnaire.

Lightweight materials are usually expensive, especially if they are manufactured (e.g., expanded shales and clays, foamed plastics, lightweight concrete, etc.). Typically, costs range from \$50 to \$100/yd^3 and includes the cost of transportation (*2*). Some waste materials (i.e., sawdust, bark, shells, cinders, slags, and ashes) are almost free at the source and need only to be transported to the site. Their cost will depend on the distance between the source of waste material and the site.

GENERATION AND DISPOSAL OPTIONS FOR SCRAP TIRES

The waste tire problem in the United States is great and has far reaching environmental and economic implications. Current estimates by the Environmental Protection Agency (*7*) indicate that more than 242 million scrap tires are generated each year in the United States. The current waste tire disposal practice is that of the 242 million tires discarded annually in the United States, 5 percent are exported, 6 percent recycled, 11 percent incinerated, and 78 percent are landfilled, stockpiled, or illegally dumped. In addition, about 2 billion waste tires have accumulated in stockpiles or uncontrolled tire dumps across the country. The various tire disposal options are given in Figure 1.

Of the available options, no single one can significantly minimize the tire disposal problem, economically and environmentally. Many options must be simultaneously tried and developed to solve the problem (*8*). Three nonhighway applications that can potentially use large quantities of waste tires are breakwaters, artificial reefs, and reclaiming of rubber

---

School of Civil Engineering, Purdue University, West Lafayette, Ind. 47907.

TABLE 1 Lightweight Embankment Fill Materials (*2,22–25*)

Material	Unit Weight (pcf)	Comments
Bark (Pine & Fir)	35-64	Waste material used relatively rarely as it is difficult to compact and requires pre-treatment to prevent groundwater pollution. Long-term settlement of bark fill may amount to 10% of compacted thickness.
Sawdust (Pine & Fir)	50-64	Usually used below permanent groundwater level. May be used in embankments, if properly encapsuled.
Peat	19-64	Long term large settlement is a major concern.
Fuel ash, slag, cinders, etc.	64-100	Such materials may: possess cementing properties; absorb water with time, which may increase density; and leach substance which may adversely effect adjacent structures and groundwater quality.
Scrap cellular concrete	64	Significant volume decrease results when the material is compacted. Excessive compaction reduces the material to a powder.
Expanded Clay or shale	20-64	Possesses good engineering properties for use as lightweight fill; is relatively expensive; and should be encased in minimum of 20 in. soil cover.
Shell (oyster, clam, etc.	70	Commercially mined or dredged shells available mainly off Gulf and Atlantic coasts. Sizes 0.5 to 13 in. (12 to 75 mm). When loosely dumped, shells have a low density and high bearing capacity because of interlock.
Expanded polystyrene	1.3-6	A super light material. The material is very expensive, but the very low density may make it economical in certain circumstances.
Low-density cellular concrete, Elastizell: Class I Class II Class III Class IV Class V Class VI	 24 30 36 42 50 80	This is a lightweight fill material manufactured from portland cement, water, and a foaming agent with the trade name "Elastizell EF" and is produced by Elastizell Corporation of America, Ann Arbor, Michigan. Six different categories of engineered fill are produced. The material is cast in situ and has been used as lightweight fills in a variety of geotechnical applications, such as highway embankments, bridge approaches, foundations, etc.

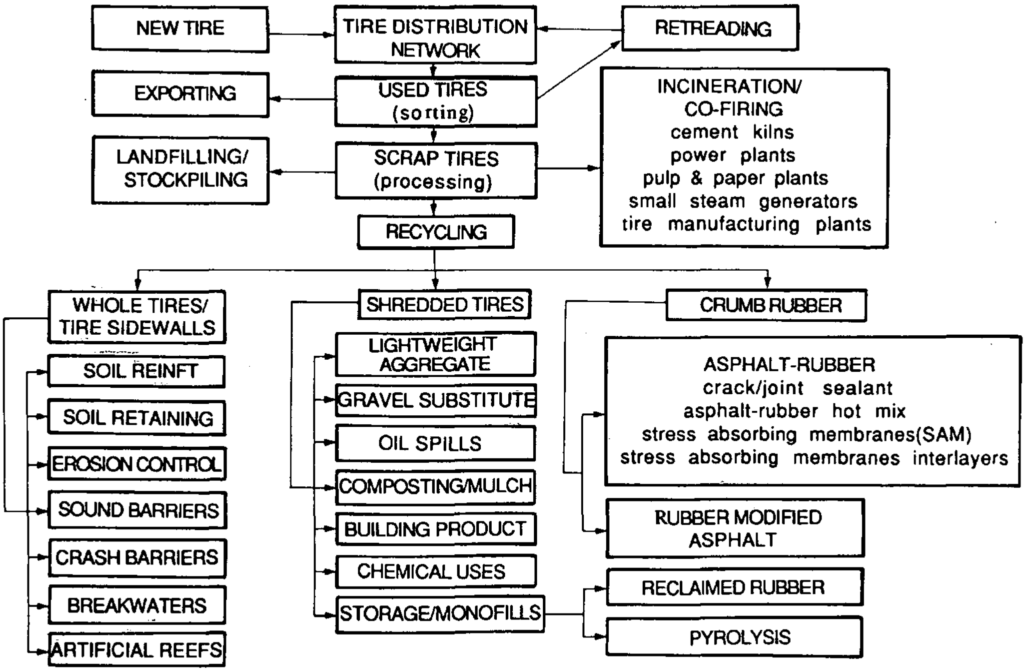

FIGURE 1 Summary of recycling and disposal options for scrap tires.

and other ingredients. A review of available technologies and markets suggests that these applications are not commercially beneficial now. Three possible uses of tires, which hold significant potential for future projection in highway construction, are use of crumb rubber additive in asphalt pavements, use of tires and their products for soil reinforcement, and use of shredded tires as a lightweight material. This paper addresses the use of shredded tires as lightweight fill material in highway construction.

FIELD EXPERIENCE

Various agencies, in the United States and abroad, have evaluated the use of shredded tires as a lightweight material in embankment construction and also for enhancing the stability of slopes in slide areas. The experience of some of the state highway agencies is described in detail.

Minnesota Projects

The Minnesota Pollution Control Agency (MPCA) documented over 23 sites in February 1992 that have used more than 80,000 yd^3 of shredded tires (about 2.2 million tires). More than half of these projects are on privately owned driveways and roads, four on city and township roads, three on county roads, and two on DNR forest roads. A few of the projects used shredded tires for purposes other than in road fills. One project in Minneapolis used the lightweight tire shreds as a fill material to support a park and landscaping above an underground parking garage. At another site, tire chips were used as lightweight fill over an existing water main (*9*).

Its experience indicates that the use of shredded tires as lightweight fill material is technically feasible and cost effective. In Minnesota the tire shreds cost from $1.25 to $3.25/yd^3 ($5 to $12/ton) delivered to the job site. This cost is further reduced when subsidized by the state to clean up tire dump sites. Economic analysis indicates that tire chips are cost-effective compared with other conventional lightweight materials, such as foamed or cellular concrete and polystyrene. However, there is concern about lack of information on long-term environmental impacts and mechanical behavior of chips (*9*).

Oregon Slide Correction Project

The Oregon Department of Transportation (DOT) used shredded tires in a slide area on U.S. Highway 42 (Oregon State Route 35, Coos Bay–Roseburg), approximately 25 mi west of Roseburg, Oregon (*10*). The construction involved replacement of 12,800 yd^3 of existing soil with 5,800 tons of shredded tires (an estimated 580,000 tires). The tire chips were spread and compacted by a D-8 bulldozer. At least three compaction passes were specified for each 3-ft lift of tires. A 10 percent compression was anticipated on the basis of in situ performance of a tire chips embankment constructed in Minnesota (*11*). It was observed that the thickest portion of the shredded-tire fill (approximately 12.5 ft) compressed 13.4 percent during construction in the following manner (*10*).

- Sixteen in. during placement of 3 ft of soil cap,
- Two in. during placement of 23 in. of aggregate base, and
- Two in. during 3 months of traffic and placement of 6 in. of asphalt concrete.

Read et al. (*10*) concluded that embankment construction using waste shredded tires is a viable technology and can use large quantities of discarded tires with significant engineering benefits. The cost of the tire chips delivererd to the site, by vendors of the shredded tire materials from a distance of 150 to 250 mi, has been reported as $30/ton. The cost of placing and compacting the tires was $8.33/ton. The total cost of the fill at final in-place density of 52 pcf, after $20/ton reimbursement from Oregon Department of Environmental Quality, was $18.33/ton.

Wisconsin Test Embankment Containing Shredded Tires

The University of Wisconsin–Madison, in cooperation with the Wisconsin DOT, conducted a field experiment to determine the feasibility of incorporating shredded tires in highway embankments (*12,13*). A 16-ft-wide and 6-ft-high test embankment consisting of 10 different sections, each 20 ft long, was constructed. Locally available soil and shredded tires were used in a number of different ways—pure tire chips, tire chips mixed with soil, and tire chips layered with soil. The embankment configuration for different sections of embankment was varied to determine the optimum side slope. A geotextile fabric was placed on all sides of tire chips to serve as a separator between materials of the embankment and the surrounding materials. The embankment was constructed parallel to the access road of a solid waste landfill and exposed to the heavy incoming truck traffic.

Edil et al. (*12*), on the basis of construction and early post-construction evaluations, reported that construction of embankment with tire chips does not present unusual problems. Leachate characteristics indicated little or no likelihood that shredded tires would affect groundwater. The main problem is reportedly related to control of compressibility. Monitoring and evaluating the test embankment for 2 years support the use of properly confined tire chips as a lightweight fill in highway applications (*13*).

Tire Chips Use on New Interstate in Colorado

The Colorado DOT recently experimented with the use of shredded tires as a lightweight fill material (*13*). Shredded tires have been used on a 200-ft portion of Colorado's new Interstate 76. More than 400,000 tires chips of about 4 in. have been used in a 5-ft fill. The tire embankment was instrumented for monitoring the long-term performance of the fill. The shredded tires for this project were donated by the local vendors. The cost of transportation for a 20-mi distance, placement, and compaction was initially estimated to be $8.00

to \$8.50/yd^3. The actual cost of the project has not yet been published.

LABORATORY STUDIES

Wisconsin Study

A limited experimental program was carried out at the University of Wisconsin–Madison to develop quantitative information about the compaction and compression behavior of tire chips and analysis of leachates from a test embankment made of rubber soil (*12*). The experiment involved placement of rubber chips of different sizes, alone and mixed with sand in a 6-in. Proctor mold, followed by load application using a disk placed on the tire chips. The load-deformation response of rubber chips indicated that the major compression occurs in the first cycle of loading. A portion of this compression is irrecoverable, but there is significant rebound on unloading. The subsequent cycles tend to be similar with less rebound; however, the rebound is nearly the same from one cycle to another. It is observed that the slope of the recompression-rebound curve is markedly lower beyond a certain vertical pressure of about 35 psi.

Edil et al. (*12*) also conducted compression tests on rubber-sand mixes, varying sand and chip ratios. Their tests on rubber-sand mixes yielded compression curves similar to rubber chips alone. However, the maximum compression increased as more and more cycles of loading took place, and the magnitude of the maximum compression was less than 0.1 in. as compared with about 2 in. for the tire chips alone. The test results, on specimens of sand and chip ratios varying from 100 percent sand to 100 percent chips, indicated that the compression increases significantly when tire chips content was increased more than 30 percent by weight of sand. Edil et al. performed experiments in a compaction mold that was probably too small in diameter for the size of chips tested (chip sizes of 1.5 in. and even larger were tested in a 6-in. Proctor mold).

Edil et al. (*12*) have also reported duplicate EP toxicity and AFS leaching tests performed on tire chip samples by the Wisconsin State Laboratory of Hygiene. The EP toxicity test was run for barium, cadmium, chromium, lead, and mercury but not for arsenic, selenium, or silver. The AFS test procedures were followed for evaluating the leaching behavior of metals, anions, and organic and inorganic indicator parameters. The 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 organic materials. The tire samples showed detectable, but very low release patterns for all substances and declining concentrations with continued leaching for most substances. Bosscher et al. (*13*) reported that an overall review of the available leach data and results of the recent leach tests on samples collected from two lysimeters, installed during construction of the test embankment in December 1989, confirm that shredded automobile tires show no likelihood of having adverse effects on groundwater quality.

Minnesota Study on Tire Leachates

The MPCA sponsored a study on the feasibility of using waste tires in subgrade road beds (*14*). Twin City Testing Corporation (TCTC) of St. Paul, Minnesota, performed the laboratory study to evaluate the compounds produced by the exposure of tires to different leachate environments. As a result of elaborate testing and analysis, TCTC reached the following conclusions (*14*):

- Metals are leached from tire materials in the highest concentrations under acid conditions; constituents of concern are barium, cadmium, chromium, lead, selenium, and zinc.
- Polynuclear aromatic hydrocarbons and total petroleum hydrocarbons are leached from tire materials in the highest concentrations under basic conditions.
- Asphalt may leach higher concentrations of contaminants of concern than tire materials under same conditions.
- Drinking water recommended allowable limits (RALs) may be exceeded under worst-case conditions for certain parameters.
- Codisposal limits, EP toxicity limits, and TCLP criteria are generally not exceeded for the parameters of concern.
- Potential environmental impacts from the use of waste tires can be minimized by placing tire materials only in the unsaturated zone of the subgrade.

Permeability of Tire Chips

A laboratory study was conducted by Bressette (*15*) to determine the feasibility of using tire chips as an alternative to conventional aggregate in drainage layers or channels. Bressette performed constant head permeability tests on compacted and uncompacted specimens of chopped scrap tire material (approximately 2-in. squares), shredded tires (100 percent passing 2-in. sieve), and coarse aggregate (open-graded, percent passing sieves 2-, 1½-, 1-, ¾-, and ½-in. was 100, 99, 43, 39, and 1 percent, respectively). The permeability values for the three materials were within the same order of magnitude—10^4 ft/day (3.53 cm/sec), with only 3 exceptions in 42 tests. All values were in the upper range of permeability values required for subdrainage material.

Blumenthal and Zelibor (*16*) reported the study, performed by Shive-Hattery Engineers & Architects, Inc. (1990) for the Iowa Department of Natural Resources, that investigated the hydraulic properties of shredded scrap tires as a drainage soil substitute. They found that the average coefficients of permeability of 1.5-in. and 0.75-in. scrap tire chips were 2.07 and 1.93 cm/sec, respectively.

LABORATORY TESTING OF RUBBER SOILS

Testing Materials

The first phase of this study consisted of determining the compaction and compression behavior of rubber soils. The testing program was formulated to develop quantitative information about the compaction and compression characteristics of the tire chips alone and when mixed with different soils. The tire chips used for this study were supplied by ASK Shredders Corporation, East Chicago, Indiana; Baker Rubber, South Bend, Indiana; Rubber Materials Handling, East Chicago, Indiana; and Carthage Machine Company, New York. The samples of tire chips vary in size from sieve No. 4 to 2 in. plus. The tire chips have generally clean cuts, and only a small percentage of steel wires is exposed at the edges. A mechanical analysis was performed on tire chip samples collected from the various shredding agencies, the results of which are given in Figure 2. The grading curves of various chip samples generally indicate a uniform gradation of tire chip samples.

Two types of soils, fine and coarse grained, were used for this study. Crosby till, which is a natural fine-grained soil, has been routinely used in many research studies at Purdue University (*17*). The test soil was thoroughly mixed in the laboratory to eliminate the possibility of spatial variabilitiy in the properties of this natural soil and to correctly understand the effects of adding rubber chips on the compaction and compression behavior of soil. The soil has been classified as CL-ML (sandy silty clay) according to the Unified Soil Classification System (USCS) and A-4(0) according to the AASHTO classification system. The coarse-grained soil used in this study is white medium to fine Ottawa sand. The desired gradation was achieved by mixing three different types of Ottawa sand in equal proportions—Flintshot (AFS Range 26-30), #17 Silica (AFS Range 46-50), and F-125 (AFS Range 115-130). The sand is classified as SP (poorly graded sand) according to USCS and A-3(0) according to AASHTO classification system. The grain size distribution curves of the test soils are given in Figure 2.

Compaction Testing

The compaction tests conducted for this research were performed using manual compaction, a mechanical compactor, and an electromagnetic, vertically vibrating table. The compaction tests on Crosby till were performed following procedures described in ASTM D698 (AASHTO T99-61) and ASTM D1557 (AASHTO T180-61). A mechanical rammer and 6-in. diameter mold were used to perform the compaction tests on rubber soil with tire chips of sizes up to 1 in. A steel mold 12 in. in diameter and 12.5 in. high was used for testing chip sizes up to 2 in. The compaction tests on Ottawa sand were performed using procedures described in ASTM D4253. An electromagnet, vertically vibrating table was used for providing the desired level of vibration. The variables considered included compactive effort, size of chips, and the ratio of soil and chips. Three different compactive efforts were used—modified Proctor, standard Proctor, and 50 percent of standard Proctor. Tire chips of seven different sizes ranging from sieve No. 4 to 2 in. plus are investigated in this study. The soil and chip ratios were varied from pure soil to pure chips—quantity of chips in mix varied from 0 to 100 percent of dry weight of soil.

The following conclusions are drawn, on the basis of a critical analysis of the results obtained from the compaction testing of rubber soils and rubber chips alone (*4*).

- It is found that vibratory methods of compaction are suitable for rubber sands. Nonvibratory methods (e.g., Proctor-type compaction) are more appropriate for compacting chips alone and mixes of chips and fine-grained soils.
- The effect of compactive effort on the resulting unit weight of rubber soils decreases with increasing chip/soil ratios. Only a small effect is observed for the amount of chips greater than 20 percent of dry weight of soil (see Figure 3). Figure 4 also shows that the unit weight of chips alone is not much affected by the compactive effort. Only a modest compactive effort is required to achieve the maximum unit weight of chips. This unit weight is about one-third that of the conventional soil fills.
- The chip unit weight is not very sensitive to the size of chips. However, a trend of increasing unit weight with increasing chip size is found, except in the case of vibratory compaction. In this case the maximum unit weight decreases with increasing chip sizes (Figure 4).

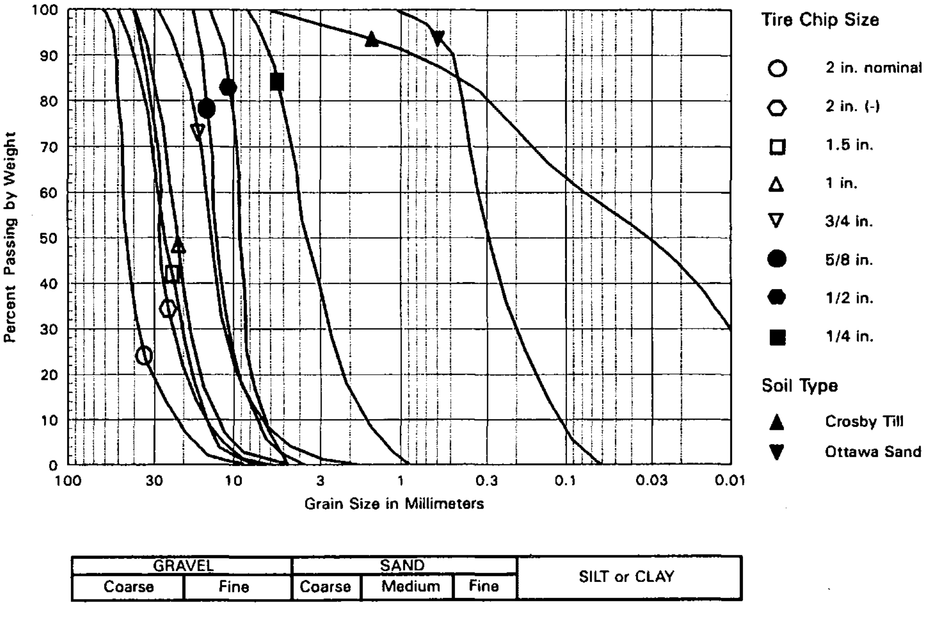

FIGURE 2 Gradations of rubber chips and test soils.

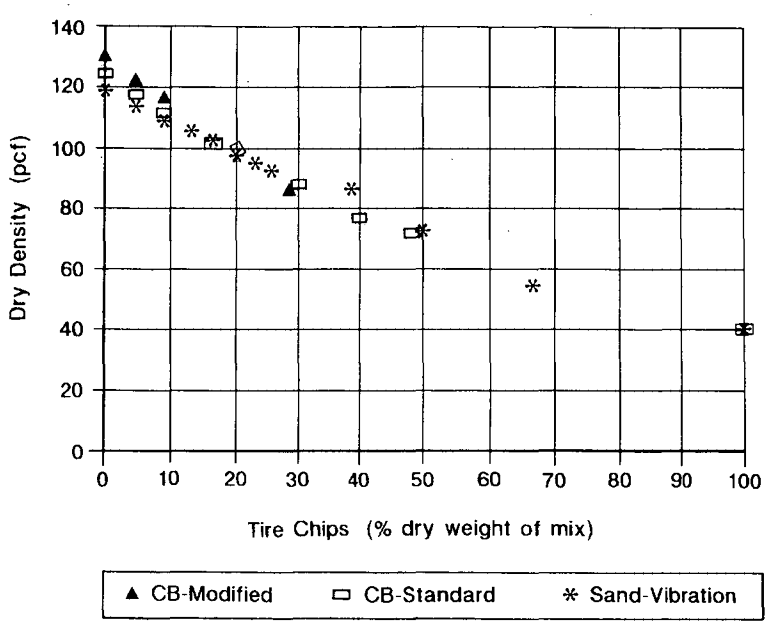

FIGURE 3 **Comparison of compacted densities of rubber sand and rubber soil samples.**

Compressibility Testing

A stainless steel compression mold 12 in. in diameter, 12.5 in. high, and having a wall 0.4 in. thick was used to perform compression tests on tire chips of sizes varying from 0.5 in. to less than 2 in. (See Figure 2 for the gradation curves of various chip sizes.) The samples were compacted in eight layers using a 10-lb hammer with 18-in. drop. Three different compactive efforts were used—modified Proctor, standard Proctor, and 50 percent of standard Proctor. Tests were also performed on uncompacted tire chip samples. All the samples were subjected to four cycles of loading and unloading using an MTS soil testing system. The samples were loaded and unloaded incrementally using a loan increment ratio of one. For the first two cycles, the samples were loaded to a maximum stress of about 25 psi, which is equivalent to approximately 25 ft of soil fill, and then unloaded to a seating load of 0.12 psi. For the third cycle, the samples were loaded to about 15 psi and then unloaded to 1 psi. Finally, in the fourth cycle, the samples were reloaded to the maximum stress and

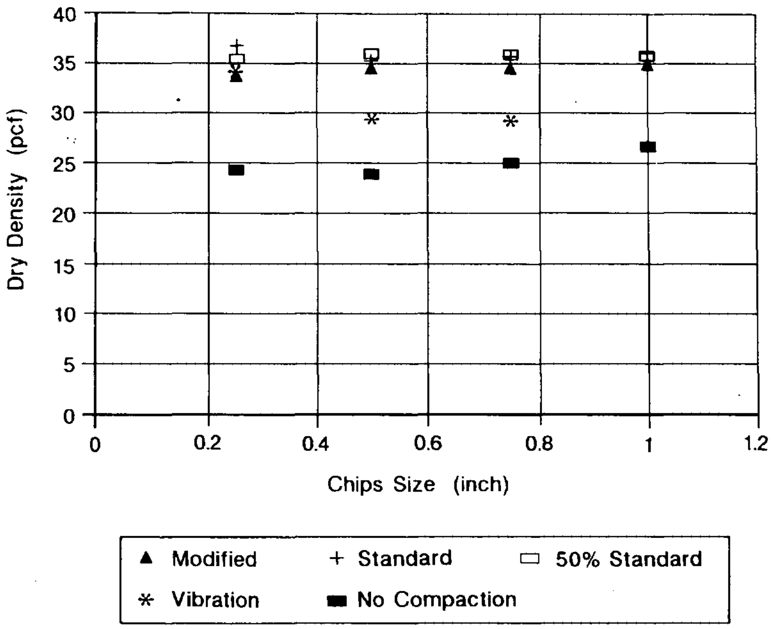

FIGURE 4 **Unit weight versus chip size for different methods of compaction and compaction effort levels.**

then completely unloaded. Similarly, a blend of rubber-sand mix with tire chips varying from 0 to 100 percent were also tested.

The data obtained were plotted as vertical strain versus log stress. On the basis of a critical analysis of the test results, the following observations are made. The load-deformation response of tire chips (see Figure 5 for typical compression curves) indicates that the three mechanisms mainly responsible for total compression of tire chip samples are (a) compression due to rearrangement/sliding of chips—a small compression occurs, mainly during first loading cycle, and is mostly irrecoverable, (b) compression due to bending/flattening of chips—responsible for the major portion of total compression and mostly recoverable on unloading, and (c) compression due to elastic deformation of tire chips—a small compression occurs because of this mechanism and all of it is recoverable. This indicates that compression of rubber chips can be reduced by increasing confining and overburden pressures or filling air voids with material less compressible than tire chips.

The vertical strain decreased with increasing chip size in the case of samples compacting using 50 percent of standard effort. A maximum difference of about 4 percent was observed for chip sizes varying from 0.5 in. to 2 in. However, variation in chip sizes had little effect on load-deformation response for higher compactive efforts. The higher compression of large-size chips observed in the case of lower compactive effort is mainly due to rearrangement/sliding of particles, because the large-size chips could not be tightly packed by a very small compactive effort.

The increase in compactive effort from standard to modified had no effect on the compression curves for various chip sizes. However, samples compacted using 50 percent of standard effort yielded vertical strains 2 to 4 percent higher during the first loading cycle than those compacted with standard or modified effort. The uncompacted samples also produced higher strains during the first loading cycle. However, compactive effort had little effect on the load-deformation response of chips for subsequent loading and unloading cycles.

Figure 6 shows a plot of vertical strain versus log vertical stress for various ratios of rubber-sand mixes. The curves show that the total compression of samples increases with increasing percent of tire chips, the highest value of compression being for 100 percent tire chips. This demonstrates that a blend of rubber soil provides a mix with lower void ratio, which compresses less than one of pure chips, and will also cause lesser settlement of foundation soil due to reduced weight of fill. About 40 percent chips by weight of soil is an optimum value for the quantity of chips in a rubber-soil mix, where large settlements are a matter of concern. This chip/soil ratio will yield a compacted dry unit weight of rubber-soil mix that is about two-thirds that of soil alone (see Figure 7).

Permeability Testing

A stainless steel mold, 8 in. in diameter, is used to determine the hydraulic properties of compacted samples of tire chips under constant head conditions. The samples are 9 in. high and compacted using three different compactive efforts—modified Proctor, standard Proctor, and 50 percent of standard Proctor. The results indicate that the coefficient of permeability for 1-in. size tire chips varies from 0.54 to 0.65 cm/sec with compactive effort decreasing from modified Proctor to 50 percent of standard Proctor.

DISCUSSION OF RESULTS

A review of commonly used lightweight materials (see Table 1) indicates significant diversity in their engineering charac-

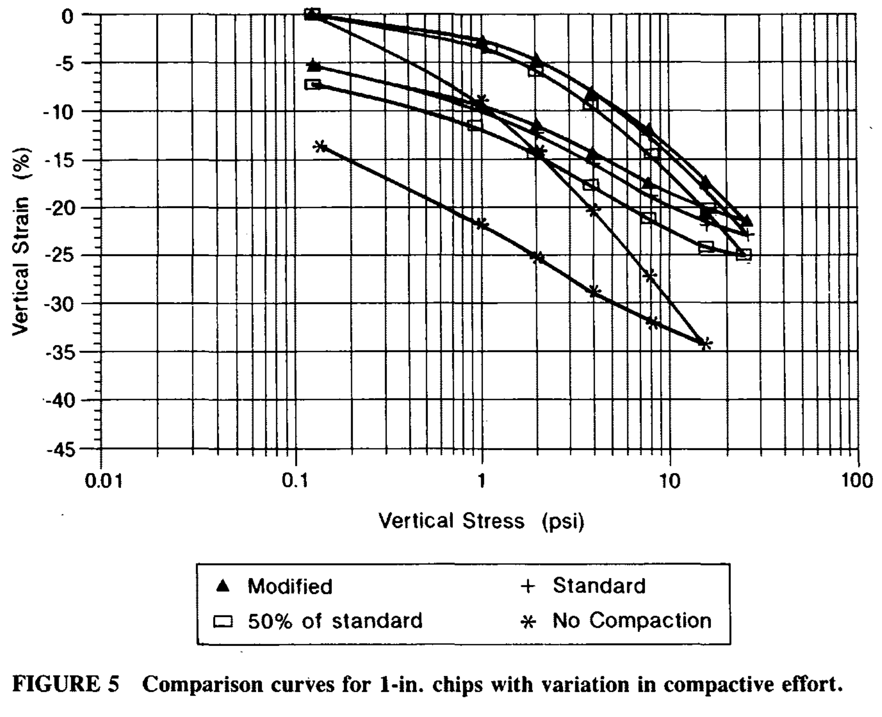

FIGURE 5 Comparison curves for 1-in. chips with variation in compactive effort.

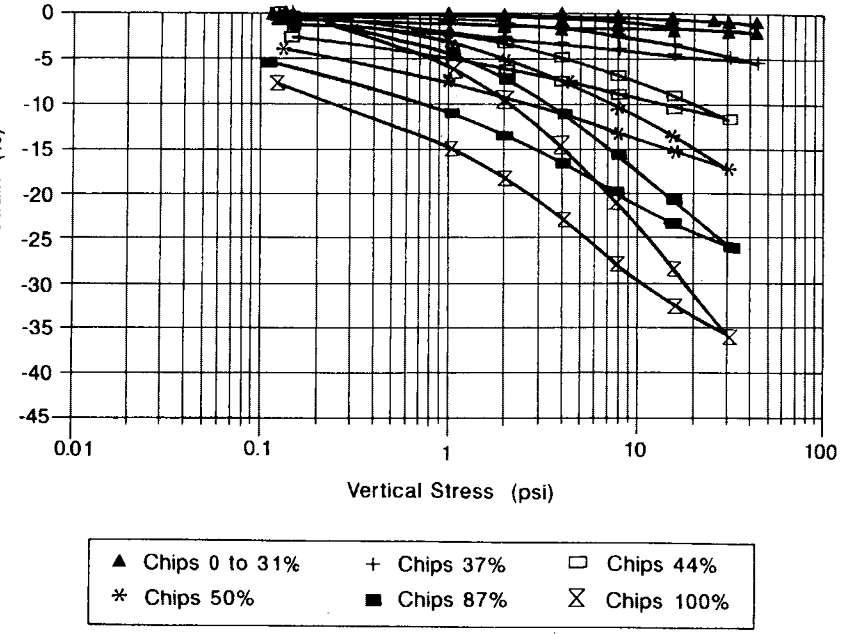

FIGURE 6 Compression behavior of rubber sand with variation in chip/soil ratios—first cycle.

teristics. They also differ widely in their relative cost and impact on the environment. Hence, dry unit weight or any other single characteristics cannot be used as the sole basis for material selection. Some materials, especially manufactured ones, have very attractive engineering properties, but they also cost more. In certain cases some manufactured materials are not available in the large quantities required for highway construction purposes.

Lightweight waste materials, such as sawdust, bark, slags, cinders, and ashes, are generally available in abundance and mostly for no cost at the source. These materials have traditionally been used as lightweight fills by highway agencies in the United States and may be rationally compared with another discard, such as tire chips. Sawdust and bark have unit weights ranging from 35 to 64 pcf (see Table 1), are biodegradable, difficult to compact, require treatment to prevent groundwater pollution, need to be encapsuled by a soil cover, and undergo significant long-term settlement. Salient properties of slags, cinders, and ashes are dry unit weights ranging from 64 to 100 pcf. They may absorb water, resulting

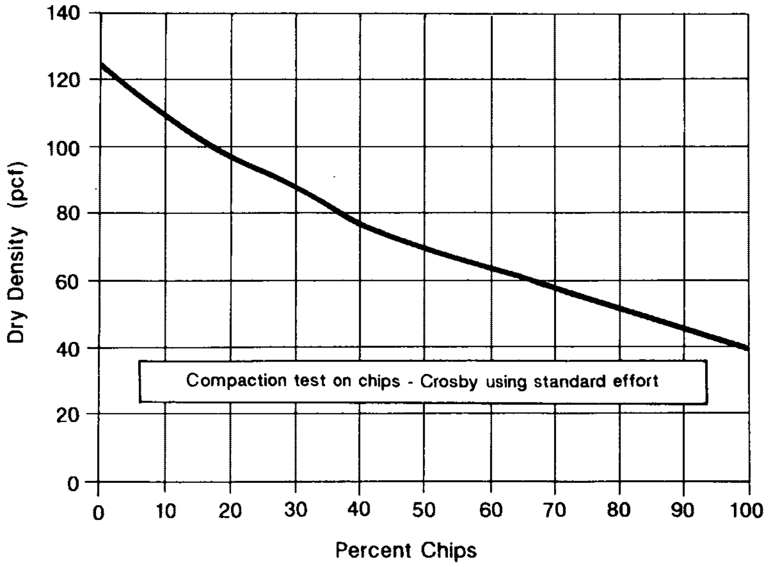

FIGURE 7 Variation in compacted density of rubber chip/Crosby soil mixes with change in percentage chips—standard Proctor effort.

in an increase in unit weight, and have high variability. Leachates may adversely affect groundwater quality or the structures in the vicinity of waste material (see Table 1; *5,18*).

Millions of rubber tires are discarded annually in the United States and tire chips are available in abundance (*7*). Tire rubber has high tensile strength, is chemically stable, and practically indestructible (*19*). Field density of shredded tires varies from 20 to 52 pcf, depending on the size of chips, method of compaction, and thickness of compacted layers (*4*). No unusual problems have been encountered during field compaction of tire chips. A backhoe is suitable for spreading the chips and a D-8 crawler tractor is appropriate for compaction (*10,12*). The environmental impact studies indicate that shredded tires are not a hazardous material, because the parameters of concern do not generally exceed the EP toxicity and TCLP criteria (*12–14*).

To minimize the potential adverse effects of leachates from tire chips, MPCA (*14*) recommended the use of tire chips in unsaturated zones only. The various leaching parameters of concern depend on the environmental conditions prevalent in embankment fill—pH of permeant and soil. Hence, the conditions upon which the conclusions have been based (low pH values) may not exist in a shredded tire embankment.

A major concern in using tire chips in embankments is the large settlements (about 10 to 15 percent) observed in various field and laboratory studies (Figures 5 and 6 and *4,9–12*). Holtz (*2*) emphasizes that little information is available on tolerable settlements of highway embankments. It has been reported (*20*) that postconstruction settlements during the economic life of a roadway of as much as 1 to 2 ft are generally considered tolerable provided they are reasonably uniform, do not occur next to a pile-supported structure, and occur slowly over a long period of time. Postconstruction settlements of shredded tire embankment can be reduced by placing a thick soil cap over tire fills—increasing confining pressure and using a rubber-soil mix instead of tire chips alone. The detrimental effects of settlements can also be reduced by using flexible pavement over such fills and perhaps using stage construction.

Another concern in using tires in embankment may be the potentially combustible nature of tires. To reduce the possibility of fire, a protective earth cover may be placed on top and side slopes of tire embankments. A similar soil cover is recommended for some other lightweight materials, such as wood chips, sawdust, slags, ashes, expanded clay, or shale, for protection against fire or to prevent leaching of undesirable materials into groundwater. During construction, normal caution is required to avoid any fire in tires stockpiled on the site or tires placed in the embankment and not yet capped with soil.

Compacted tire chips (2.0 to 0.75 nominal size) have permeability values equivalent to typical values for coarse gravel (*5,16,21*). This property of chips renders them suitable for use in subdrainage as an alternative aggregate, if feasible environmentally. Pore pressure developments are minimized in tire fills and backfills, because they are a highly permeable material. Use of tire chips in alternating layers with fine grained soils, such as clays and silty clays, will provide a shorter drainage path and thus help to accelerate consolidation of the soil layers.

The use of shredded tires in embankments offers the potential benefit of disposing of large volumes of tires in short sections of highway. For example, the use of an asphalt-rubber pavement overlay uses only about 3,600 tires/mi of a two-lane road. On the other hand 1 mi of two-lane embankment 20-ft high would use about 5 million tires (one tire equals approximately 1 ft^3 loose bulk unit weight before compaction (*15*).

The cost of using shredded tires in embankments depends on a number of factors that vary with the local conditions—cost of chips (primary shreds are generally available now free at the source in most of the states, distance of shredding facilities from the site and the cost of transportation, cost of placement and compaction, subsidies or rebates offered by the state, and the cost of conventional mineral/lightweight aggregates. In Indiana, the major vendors of shredded tire materials are in East Chicago. Currently, they are willing to offer the primary tire shreds without cost. The transportation costs in Indiana vary from $5 to $10/ton for a distance of 100 mi.

CONCLUSIONS

A solution to enhance the stability and reduce the settlement of highway structures on slopes and highly compressible soils is to replace the existing material with a material of lower unit weight or use lighter weight fills. On the basis of an analysis of limited data on rubber soils from this study and those reported in the literature, it is concluded that the use of shredded tires in highway construction offers technocal, environmental, and economic benefits under certain conditions. The salient benefits of using tire chips are reduced weight of fill, which helps increase stability, reduce settlements, and correct or prevent slides on slopes, and reduced backfill pressure on retaining structures. Tire chips serve as a good drainage medium, preventing development of pore pressures during loading of fills. They can be substituted for conventional premeable materials for subdrainage, provide separation to prevent the underlying weak or problem soils from mixing with subgrade and base material, allow conservation of energy and natural resources, and use large quantities of local scrap tires—a positive impact on the environment.

Potential problems associated with the use of shredded tires in highway embankments are leachate of metals and hydrocarbons, fire risk, and large compressibility of tire chips. RALs for Minnesota are found to be exceeded under worst-case conditions (*14*). However, a recent field study reports that shredded automobile tires show no likelihood of having adverse effects on groundwater quality (*13*). However, concerns for long-term effects still persist. Proper soil cover is required on the top and side slopes of shredded tire embankments for safety against fire. During construction, precautions are required to prevent fire in stockpiles or in tires placed in the embankment but not yet capped with soil.

A major concern in using tire chips in embankments is the large settlements (about 10 to 15 percent) observed in various field and laboratory studies. However, potentially large settlements can be reduced by providing a thicker soil cap and using a rubber-soil mix instead of chips alone. It is found that about 40 percent chips by weight of soil is an optimum value for the quantity of chips in a rubber-soil mix, where large settlements are a concern. This chip/soil ratio will yield a compacted dry unit weight of rubber-soil mix that is about two-thirds that of soil alone. Detrimental effects of postconstruction settlements can be reduced by using tires under flexible pavements only and allowing the chips to compress gradually under traffic for some time.

Information on the use of shredded tires in highway structures is severely lacking. Areas of concern are lack of requisite data on stress-strain and strength behavior of chips and chip-soil mix for design and prediction of performance of highway structures, and long-term impact on the environment.

ACKNOWLEDGMENTS

The authors thank the Indiana DOT and FHWA for support of this work.

REFERENCES

1. Moore, L. H. Summary of Treatments for Highway Embankments on Soft Foundations. In *Highway Research Record 133,* HRB, National Research Council, Washington, D.C., 1966, pp. 45–57.
2. Holtz, R. D. *NCHRP Synthesis of Highway Practice 147: Treatment of Problem Foundations for Highway Embankments.* TRB, National Research Council, Washington, D.C. 1989.
3. Holtz, R. D., C. W. Lovell, and M. L. Steinberg. Special Soil Deposits and Embankment Materials. In *State of the Art Report 8: Guide to Earthwork Construction,* TRB, National Research Council, Washington, D.C., 1990, pp. 94–102.
4. Ahmed, I. *Laboratory Study on Properties of Rubber Soils—Interim Report.* Report FHWA/IN/JHRP-92/11. School of Civil Engineering, Purdue University, West Lafayette, Ind., 1992.
5. Ahmed, I. *Use of Waste Materials in Highway Construction.* Report FHWA/IN/JHRP-91/3. School of Civil Engineering, Purdue University, West Lafayette, Ind. 1991.
6. Ahmed, I., and C. W. Lovell. Use of Waste Products in Highway Construction. *Environmental Geotechnology* (M. A. Usmen and Y. B. Acar, eds.), A. A. Balkema, Brookfield, Vt., 1992, pp. 409–418.
7. *Markets for Scrap Tires.* Report EPA/530-SW-90-074A. Environmental Protection Agency, 1991.
8. Ahmed, I., and C. W. Lovell. *Use of Rubber Tires in Highway Construction. Utilization of Waste Materials in Civil Engineering Construction* (H. I. Inyang and K. L. Bergeson, eds.), ASCE, New York, 1992, pp. 166–181.
9. Lamb, R. *Using Shredded Tires as Lightweight Fill Material for Road Subgrades.* Draft report. Materials and Research Laboratory, Minnesota Department of Transportation, Maplewood, 1992.
10. Read, J., T. Dodson, and J. Thomas. *Use of Shredded Tires for Lightweight Fill.* Report DTFH-71-90-501-OR-11. Oregon Department of Transportation, Salem, 1991.
11. Geisler, E., W. K. Cody, and M. K. Niemi. Tires for Subgrade Support. Presented at Annual Conference on Forest Engineering, Coeur d'Alene, Idaho, Aug. 1989.
12. Edil, T. B., P. J. Bosscher, and N. N. Eldin. *Development of Engineering Criteria for Shredded or Whole Tires in Highway Applications.* Department of Civil and Environmental Engineering, University of Wisconsin–Madison, 1990.
13. Bosscher, P. J., T. B. Edil, N. N. Eldin. *Construction and Performance of a Shredded Waste-Tire Embankment.* Department of Civil and Environmental Engineering, University of Wisconsin–Madison, 1992.
14. *Waste Tires in Subgrade Road Beds.* Minnesota Pollution Control Agency, St. Paul, 1990.
15. Bressette, T. *Used Tire Material as an Alternative Permeable Aggregate.* Report FHWA/CA/TL-84/07. California Department of Transportation, Sacramento, 1984.
16. Blumenthal, M., and J. L. Zelibor. Scrap Tires Used in Rubber-Modified Asphalt Pavement and Civil Engineering Applications. *Utilization of Waste Materials in Civil Engineering Construction* (H. I. Inyang and K. L. Bergeson, eds.), ASCE, New York, 1992, pp. 182–192.
17. Holtz, R. D., and W. D. Kovacs. *An Introduction to Geotechnical Engineering.* Prentice-Hall, Englewood Cliffs, N.J., 1981.
18. Huang, W. H. *The Use of Bottom Ash in Highway Embankment and Pavement Construction.* PhD thesis. Department of Civil Engineering, Purdue University, West Lafayette, Ind., 1990.
19. Cadle, S. H., and R. L. Williams. Environmental Degradation of Tire-Wear Particles. *Rubber Chemistry and Technology*, Vol. 53, No. 4, 1980, pp. 903–914.
20. *NCHRP Synthesis of Highway Practice 8: Construction of Embankments.* TRB, National Research Council, Washington, D.C., 1971.
21. Freeze, R. A., and J. A. Cherry. *Groundwater.* Prentice-Hall, Englewood Cliffs, N.J., 1979.
22. Hartlen, J. Pressure Berms, Soil Replacement, and Lightweight Fills. Soil Improvement Methods. *Proc., 3rd International Geotechnical Seminar*, Nanyang Technological Institute, Singapore, 1985, pp. 101–111.
23. *Construction of Roads in Compressible Soils.* Organization for Economic Cooperation and Development, Paris, France, 1979.
24. *Engineering and Research Reports on Elastizell Engineered Fill.* Sales literature, Elastizell Corporation of America, Ann Arbor, Mich., 1992.
25. Mitchell, J. K. In-Place Treatment of Foundation Soils. *Journal of the Soil Mechanics and Foundations Divisions*, Vol. 96, No. SM1, ASCE, 1970, pp. 93–130.