Zornberg, J.G., Christopher, B.R., and LaRocque, C.J. (2004). "Applications of Tire Bales in Transportation Projects." *Recycled Materials in Geotechnics*, ASCE Geotechnical Special Publication No. 127, Aydilek, A.H., and Wartman, J. (Editors), Baltimore, Maryland, October, pp. 42-60.

APPLICATIONS OF TIRE BALES IN TRANSPORTATION PROJECTS

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ABSTRACT: There are growing interests in the utilization of recycled tire bales for civil engineering applications, triggered partly by the significant volumes of tires that could be disposed of in transportation projects. However, evaluation of bale properties and performance is, at least, limited. This paper summarizes the benefits and shortcomings of using tire bales in civil engineering projects, as well as information collected to date on their mechanical properties. In addition, a summary of the current U.S. scrap tire market is presented, which is supported with case studies and an economic analysis comparing the cost of tire bales to conventional fills. Finally, recommendations for further research on the behavior of tire bales as a lightweight fill are presented.

INTRODUCTION

According to the Rubber Manufacturers Association (RMA 2002), scrap tires are being generated in the United States at an approximate annual rate of 1.04 per capita, totaling 281 million scrap tires every year. This is in addition to the estimated two billion waste passenger car and truck tires that are currently stockpiled across the nation (Senadheera 2002). Tires are manufactured using vulcanized rubber. Since tire rubber is a thermosetting polymer (i.e. cannot be heated to mold again), tires cannot be "recycled." Instead, they should be reused or discarded.

The specific focus of this paper is to provide a review of the practical use of whole tires compressed into bales, which is a relatively new approach. This method provides an alternative to tire sheds in civil engineering applications, while

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minimizing the potential for exothermic reactions. Tire bales also appear to provide some economic advantage over the use of tire shreds in terms of production cost and construction placement as reviewed later in this paper. However, to date, comparatively little testing and/or research have been completed regarding the engineering properties and performance of tire bales used in civil engineering applications. Ongoing studies conducted by the Texas DOT and Colorado DOT are expected to provide much needed quantitative information on the mechanical behavior of tire bales. After presenting a brief overview of the US waste tire market, this paper will discuss available information on tire bale properties and applications. Case histories, cost estimates, and research needs are finally presented.

THE U.S. WASTE TIRE MARKET

Although various methods of disposing waste tires are currently employed, some of the disposal techniques can create additional environmental problems. Table 1 summarizes the estimated US waste tire market in 2001 (RMA 2002). An estimated 77.58% of the tires generated in 2001 were used for various applications (RMA 2002). The remaining unused tires (22.42%) were stockpiled or illegally dumped in loose random piles of whole tires. Scrap tires have been banned from landfills because they have been reported to trap gases and "float" to the top, punching holes in daily and final landfill covers (Senadheera 2002). In addition, stockpiling whole and processed waste tires can lead to exothermic reactions and insect breeding. Due to 75% void space in discarded tire stockpiles, fires are difficult to extinguish and, in some cases, can burn for several months. Burning tires pose serious environmental problems to air, water and soil. Spraying water on tire fires has been reported to increase the production of pyrolytic oil, which causes contaminants to migrate off-site (Liu et al. 1998). Mosquito breeding becomes a health concern for nearby communities. A recent study showed that 80% of the children suffering from mosquito vectored diseases lived within 100 yards of a tire dump (Liu et al. 1998).

TABLE 1. Estimated total U.S. waste tire market in 2001

Type	Quantity (millions of tires)	%Generation
Tire Derived Fuel (TDF)	115	40.93
Scrap Tire Products	41	14.59
Civil Engineering	40	14.23
Exported	15	5.34
Miscellaneous	7	2.49
TOTAL USE	218	77.58
TOTAL GENERATION	281	100.00

As shown in Table 1, the second leading means of waste tires disposal involves scrap tire products (punched, chipped, or shredded tires for playgrounds, tracks, and other non-civil applications). The third means of tire disposal (40 million waste tires) involves use of tires solely for civil engineering applications in the form of bales or shreds. As will be discussed in this paper, this growing source for disposal as scrap tire products has significant advantages over several conventional lightweight fill

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materials. Scrap tire materials (tire shreds and bales) are lightweight, provide low lateral pressure, low thermal conductivity, are free draining, and are comparatively inexpensive. In addition, tire bales (the focus of this review) involve relatively inexpensive manufacturing and are easy to install, as they are already compacted prior to delivery. Due to tipping fees required by many state laws for tire disposal, tire bales are very economical and can substantially reduce construction costs for large highway projects. The engineering properties of waste tire products make them desirable for use in many applications, including in the construction of nonstructural sound barrier fills, lightweight embankment fills crossing soft or unstable ground, pavement frost barriers, retaining wall backfills, and edge drains (Bosscher et al. 1997). Additional applications are rock fall barriers, field drains, and blasting mats. The vibratory damping property of waste tire products makes them a feasible candidate in seismic stability applications.

If implemented on a large scale, the utilization of tire shreds in civil engineering projects could represent a significant means of disposal for scrap tires. Depending on the size of the projects, anywhere from 100,000 to upwards of 1 million waste tires have been used on a single project (Humphrey 1996). The mixing of tire shreds with soil has been reported to increase the shear strength of soil (Zornberg et al. 2004). Studies have suggested that waste tire products used as tire shred-soil mixtures do not alter the concentrations of any substances affecting the primary drinking water standards set forth by EPA (Bosscher et al. 1993, Humphrey 1996). However, oxidation of exposed steel in shredded tire fill has been reported to increase levels of manganese (Mn) and iron (Fe), often exceeding secondary (aesthetic based) standards (Humphrey et al. 2001).

The most common forms of processed waste tires has involved the use of tire shreds as monofill zones or as a tire shred/soil mixture. Through 1995, more than 70 civil engineering projects had been successfully completed in which tire shreds were used in various forms (Humphrey 1996). Current design guidelines (Humphrey 1998, ASTM D6270-98) include design/construction procedures for reducing the risks associated with exothermic reactions in whole tire stockpiles and in tire shred stockpiles and fills. These procedures include using tire shreds with larger dimensions to minimize exposure of the contained steel, which is thought to be a likely source of internal heating. Only limited research into the sources of internal heating of tires and tire shreds has been conducted so far. Additional understanding of the causes of exothermic reactions in tire shred fills is expected to be gained from ongoing field monitoring studies conducted at the University of Texas at Austin.

CHARACTERISTICS AND ENGINEERING PROPERTIES OF TIRE BALES

General Information on Waste Tires Relevant to Tire Bales

Findings from previous studies have generally focused on the thermal and the mechanical properties of waste tire products. Table 2 provides the typical composition of tires manufactured for passenger cars and trucks (RMA 2002).

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The average weight of a waste tire is 89 N (20 lb) for automobiles and 445 N (100 lb) for truck tires. Table 3 shows the approximate number of tires per cubic yard when waste tires are stored in piles (EPA 2004).

TABLE 2. Typical composition of tires

Material	% by Weight
Natural Rubber	14
Synthetic Rubber	27
Carbon Black	28
Steel	14-15
Fabric, fillers, etc	16-17

TABLE 3. Unit weight of waste tires

Condition	Auto Tires (Tires/yd)	Truck Tires (Tires/yd)
Loose	8.5	3
Medium	10	3.5
Dense	12	4

Laboratory tests that have quantified the thermal conductivity of tire shreds have generally indicated to be 12% smaller than that of typical soils (Humphrey 1996). Additional studies have been conducted to determine the engineering properties of tire shreds and soil/tire mixtures. The friction angle of tire shreds based on triaxial tests has been reported to range from 45 to 60 degrees (Wu et al. 1997, Bosscher et al., Zornberg et al. 2004). The compaction characteristics, compression behavior, shear strength, and hydraulic conductivity of tire chips and soil/tire chip mixtures were studied by Edil and Bosscher (1993), Foose et al. (1996), and Zornberg et al. (2004). These studies illustrated the ability of tire shreds to increase the shear strength of soil. For a given tire shred content, increasing tire shred aspect ratio has been reported to increase overall shear strength. While no similar studies were performed to determine interface shear strength for tire bales, the previously mentioned results for tire shreds can be cautiously used as a reference. The interface shear strength between tire bales is expected to be relatively high, as evidenced by the successful performance of tire bales in stabilization projects (see Case Studies section of this paper).

Characteristics and Engineering Properties of Tire Bales

Tire bales are manufactured using a tire-baling machine, which compresses approximately 100 waste auto tires into a 1.5 m^3, 0.9 metric ton (2 cubic yard, 1-ton) bale. Each bale is fastened with galvanized or stainless steel baling wire (Encore Systems 2000). Tire baling results in an approximate 5:1 volume reduction. Figure 1 shows typical tire bales and the ease in which they can be stacked. Truck tires are 5-passenger tire equivalent, or "5 pte."

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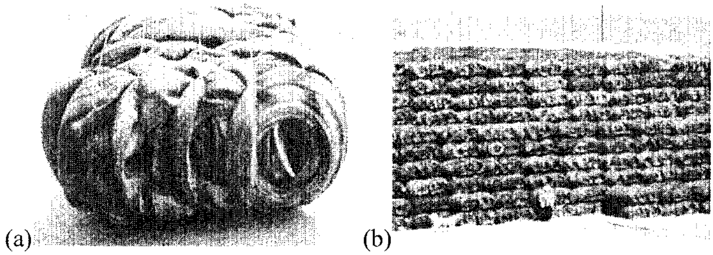

Figure 1 - Tire Bales: (a) single bale, (b) stacked bales

A tire-baling machine can process about 25 bales per day for a 12 month, 20 day per month operation. Some processors have reported 4 to 6 tire bales per hour. Tire-baling machines have also been used to fabricate ½ and ¾ size bales. A tire bale can be manufactured with steel pipes positioned in two directions through the middle of the bale (Encore Systems 2000). After placing the tire bale in its final location, an aircraft cable can be routed through the pipe and bolted at the end row of bales. This approach allows connecting several tire bales together. Various stacking arrangements, the use of concrete, flowable fill, stone, and geosynthetic or metallic reinforcements can also help to maximize bale performance. Typical physical characteristics, including dimensions and weights for compacted tire bales, are shown in Tables 4 and 5.

TABLE 4. Typical physical characteristics of tire bales.

Physical Properties	Typical Values	Range
# of Automobile Tires # of Truck Tires	100 20 (100pte)	90 to 120, 20 to 25
Approx. Dimensions	0.75m x 1.4m x 1.5m (2.5ft x 4.5ft x 5ft)	½ bale, ¾ bale and full bale
Approx. Volume	1.5m^3 (2yd^3)	0.75 to 1.5m^3 (1 to 2.1yd^3)
Weight	8.9kN (2000lb)	4.5 to 13.3kN (1000 to 3000lb)
Unit Weight	5.5kN/m^3 (35pcf)	5.5 to 8.9kN/m^3 (35 to 53pcf)

As noted in Table 4, the unit weight of a typical tire bale is approximately 5.5 kN/m^3 (35 lb/ft^3). This is similar to the unit weight of compacted tire shreds of 5.3 kN/m^3 (40 lb/ft^3) (Humphrey et al. 2000). As the typical dry unit weight of tire bales is

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approximately 30 % of the unit weight of typical soils, the use of tire bales is promising in projects where a lightweight fill is required. However, other engineering properties including compressibility, strength, and time-dependent response of the tire bales are required in order to allow the use of tire bales in major highway projects. Although some projects have involved tire bales, long-term performance is still under evaluation.

The in-situ tire bale unit weight will likely be heavier than the measured unit weight in the laboratory due to water intrusion and long-term moisture absorption. Likewise, the compressibility, strength, and time-dependent response of tire bales have not been quantified to the extent necessary for engineering design. Manufacturers have generally reported adequate bearing capacity of tire bales. For example, Central States Tire Recycling of Nebraska conducted a study showing that loads equivalent to fully loaded semi-trailers caused minimal distortion to the "Enviro Block," without compromising the structural integrity of the bale.

An active "Standard Practice for Use of Scrap Tires in Civil Engineering Applications" (ASTM D6270-98) has been developed, which provides guidance on the use of scrap tires in the form of tire shreds. This guidance includes aspects of relevance for the use of tire bales used in place of, or along with, stone, gravel, soil, sand or other types of fill.

Table 5 lists physical and mechanical properties collected from survey to users, tire bale manufacturers, and technical literature, conducted as part of this study. The table includes reported values and anticipated qualitative values based on the authors' engineering judgment and experience.

Tire Bale Construction

Pertinent sections and requirements relevant to the fabrication and use of whole tires in tire bales is provided by ASTM D6270, developed for tire shreds. Some measurement of rectangular geometry has often been included in the dimensional requirements to control the stacking capability of the bales. These controls are also necessary to define the anticipated in-place unit weight, an important design element. Development of specifications for tire bale fabrication is imperative to maintain consistency with performance. The Texas Department of Transportation (TxDOT) has prepared a draft set of specifications for use of tire bales and associated materials in embankment applications (Williammee 2004). The specifications cover many of the issues required to control tire bale manufacturing and installation. While these specifications are still in draft format, the ASTM D6270 guidelines for tire shreds and the "Guidelines for use of Geofoam" (Stark et al. 2002) can also be used for tire bale specification requirements for projects requiring lightweight fill.

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TABLE 5. Physical and mechanical properties of tire bales.

Property	Value	Source
Unit Weight –kN/m^3(pcf) --Unconfined, dry	 5.6 (35.5)	Tire bale producers: "Similar to Tire Shreds"
--Insitu w/ soil	7.8 to 9.4 (50 to 60)	Authors' estimate: For 8 in. of soil & 30 in. of tire bale every 36 in. high lift, without soil inside
--Encased w/ concrete	11 (70)	Tire bale producers: For ¾ size tire bale, 1.2 m^3 (1.56 yd^3) and a total weight of 15 kN (3.4 kips)
Specific Gravity	1.01 to 1.2	Reported in ASTM D 6270 for bulk, saturated surface dry, and "apparent conditions" for tire shreds having steel or glass belts.
Hydraulic Conductivity --Unconfined --In situ w/ soil matrix	Relatively high, depends on porosity and head Relatively low, depends on soil matrix and amount of soil in void space	 Anticipated by authors Anticipated by authors
Compressive creep	Strain after 1 hr w/ 391 kN (88,000 lb) load: 3.7 % (from 1 hr to 72 hr)	Final Strain: 26.6 % Note that Unload and reload data are not available (Encore Systems 2000)
Unconfined compressive strength		
--In situ --In situ w/ soil matrix	"Fully loaded semi-trailer caused minimal distortion to EnviroBlock." Anticipated compressive strength and modulus should be larger than values from unconfined vertical compression and creep test data.	Central States Tire Recycling statement Authors' interpretation
Interface Shear Strength (kPa) Confined	 22.8	Lower bound value reported for shear strength of tire shreds in Zornberg et al. 2004 is upper bound of interface tire bales.
Thermal Properties --Diffusivity --Exothermic Reaction (Flammability)	 High thermal resistance and diffusivity Low, when compared to pure tire shred fills	 Shock et al., 2001 Function of tire materials, cleanliness, exposed steel, moisture, air, thickness of tire materials
Chemical Durability	High	Rubber tires are affected by ozone and aging mechanism (oxidation, accelerated by heat). In air, embrittlement of tires starts in 5 yrs w/ notable degradation in 10 yrs (e.g., sidewall cracks in tires). In soil, common chemicals do not affect rubber tires and the influence of ozone & oxygen is minimized. Excavated tires from 50 yr old landfills were reported to be in good condition.

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TIRE BALES IN TRANSPORTATION APPLICATIONS

General

The most common form of waste tire products currently in use in civil engineering applications is tire shreds. Tire shreds have been utilized in numerous embankment and wall applications due to their beneficial properties of lightweight, shear and tensile strength, drainage, and thermal insulation value (Zornberg et al. 2004). In applications other than transportation infrastructure, tire shreds have been used as leachate collection layers and cleanup applications. The thermal conductivity of waste tire shreds ranges from 0.16 to 0.18 W/m−°C (0.9-0.10 Btu/hr-ft-°F) (Humphrey 1996). Recently, a number of projects have studied the use of tire shred-soil mixtures as embankment fill material (Hoppe 1998, Zornberg et al. 2004). The use of tire shred-soil mixtures, rather than tire shreds only, has been implemented to minimize concerns associated with exothermic reactions within the fill material, and to increase the shear strength of the soil being used. Tire bales provide a likely alternative to tire shreds in many applications, minimizing the potential fire hazards associated with tire shreds. This is primarily because steel belts remain largely unexposed in the final product. In addition, tire bales are installed as delivered, with no need for compaction.

Tire bales have often been used in transportation applications in association with other materials. Some applications have used shotcrete to protect the tire bale zone. Compacted soil layers have been constructed under, around, within, and above layers of tire bales to fill voids within or around the bales. While no biological or chemical degradation has been reported in these projects, the anticipated longevity of tires has not been fully documented.

Reuse of waste tires has the potential of becoming the most reusable secondary material in the world, possibly reaching 75% of all tires generated in the near future (Enviro-Block 2004). While research is needed to provide guidelines on appropriate design methods and construction practices for using tire bales, significant lessons can be learned from the projects already constructed using them.

The potential usage of tire bales is substantial, as shown in the applications summary contained in Table 6. The feasibility of bale use expressed in Table 6 is based on the literature review performed for this paper and the authors' opinion. However, further research is deemed necessary to demonstrate the suitability of tire bales in transportation systems, as well as to provide design and construction guidelines for use in future projects.

Regarding transportation applications, tire bales have been used for stabilization purposes. Since the bales weigh less than conventional fill materials, they minimize settlement of subsurface soils and induce reduced lateral pressure against structures such as walls or abutments. Their relatively high hydraulic conductivity allows good drainage. Bales are easily handled with a forklift, making construction very simple. The cost of using tire bales in civil engineering applications is less than that of conventional fill materials, as will be presented later in the paper.

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TABLE 6 . Summary of reported and possible uses of tire shreds, whole tires, & tire bales.

Reported & Possible Uses	Tire Shreds + Soil	Whole Tires	Tire Bales
WALL SYSTEMS (note that GRS refers to "geosynthetic-reinforced soil")			
Residential	Feasible as fill for GRS Retaining Walls	Feasible w/ soil filler, connections, & facing	Feasible, w/ facing (e.g., shotcrete)
Commercial	Feasible as fill for GRS Retaining Walls	Feasible w/ soil filler, connections, & facing	Feasible, w/ facing
Sound Barriers	Feasible as fill for GRS Sound Barriers	Feasible w/ connections & facing	Feasible, w/ or w/o facing
Small Site Retaining Walls	Feasible as fill for GRS Retaining Walls	Feasible w/ connections, separation geotextile, & facing	Feasible, w/ or w/o facing
Rock Fall Barriers	Feasible as fill for GRS Retaining Walls	Feasible w/ connections & facing	Feasible, w/ or w/o facing
Culvert Headwalls	No	Feasible	Feasible, w/ or w/o facing
Large Blocks: Tire Material w/ Formed Concrete Encasement	Feasible as concrete aggregate replacement	Possible, but feasible?	Feasible
SLOPE SYSTEMS			
With Layered Geosynthetic Reinforcement	Feasible	Feasible w/ connections	Feasible, w/ connections
Repair Slope Failures	Feasible	Feasible w/ connections	Feasible
Lightweight fill	Feasible	Feasible	Feasible
Embankment Construction			
Lightweight Fill	Feasible	Feasible w/ in filling	Feasible
SUBGRADE STABILIZATION			
Mat for Roads Over Very Soft Foundation Soils	Feasible	Feasible w/ in filling	Feasible
Insulation to Reduce Frost Action	Feasible	Feasible w/ in filling	Feasible
Edge drains	Feasible	No	Feasible
OTHER SYSTEMS			
Drainage Zones in Landfills	Feasible, w/ separation geotextile	Feasible, w/ separation geotextile & in filling	Feasible, w/ separation geotextile
Mix with Soil to Improve Shear Strength & Reduce Unit Weight	Feasible	Feasible	Feasible
Erosion Protection for Water Edges w/ shotcrete	No	Feasible, w/ cables	Feasible w/ shotcrete or concrete facing
Erosion Protection for Swales w/ shotcrete	No	Feasible	Feasible
Blasting Mats	Feasible	Feasible	Feasible
Low cost Culvert Structures	NA	Feasible, tied to form a cylinder	No
POTENTIAL USES			
Crash Barriers	Possible	Feasible w/ ties	Feasible
Temporary Dikes, Dams	NA	Feasible, w/ geomembrane wrap	Feasible, w/ geomembrane wrap
Storm Water Detention Systems	Feasible, but small storage capacity	Feasible	Feasible

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using tire bales in civil engineering applications is less than that of conventional fill materials, as will be presented later in this paper.

Transportation-related applications include, but are not limited to: roadway sub-grade fill, repair of failed slopes and slow stability improvement, embankments for roadway structures, backfill material for retaining walls, frost heave mitigation, sound barrier walls, and rock-fall barriers. Based on the review and assessment conducted in this study, a prioritized list of highway applications involving the use of tire bales is: (1) Embankment material within low embankment systems, (2) Embankment structural elements in slope repair projects, (3) Structural elements in rock fall barriers, (4) Structural elements in sound walls, (5) Embankment on soft ground sub grades and enhanced lateral drainage, (6) Shoulder protection of small retaining walls and abutments, (7) Backfill material in low retaining structure projects, and (8) Structural elements in low retaining walls. Some of these applications are discussed next.

Use of Bales as Lightweight Fill

There are a number of lightweight fill alternatives available for embankment and slope construction. Table 7 lists a number of these materials along with their respective unit weight and relative cost.

General Embankment Construction

The total thickness of tire bales in embankment construction has been less than 6 m (20 ft), with 1 to 8 layers of tire bales placed on a graded subgrade. The subgrade layer typically includes a compacted free draining granular base zone, compacted tire shreds, or compacted native soils. Tire bales are typically placed in "brick fashion" to overlap preceding layers. This helps to maximize the interlocking between the bales. Soil has often been placed and compacted between successive layers and against the sides of in-place tire bales.

General Slope Repair & Stability Improvement System

The tire bales can be placed in an excavated area after removal of soil and/or rockslide debris, as shown in Figure 2, to benefit from the lightweight characteristics of the bales. Depending on the site conditions, the excavation may be supported by temporary earth support systems and require the use of groundwater control measures to facilitate construction of slope repairs.

Crushed stone and/or geosynthetic drainage systems will likely be required along the base and along some portion of the back slope of the tire bale embankment. Geotextile separation layers may prevent movement of adjacent soils into the voids of the tire bale zone. For this application, the design focuses on: 1) the lightweight of the tire bale fill, which leads to a decreased driving force, and 2) the potentially high internal and interface shear strength of the tire bales to develop an integrated reinforced tire bale embankment zone.

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TABLE 7. Summary of various lightweight fill materials

Lightweight Fill Type	Range in Unit Weight, kN/m^3 (lbf/ft^3)	Range in Specific Gravity	Approximate Cost \$/m^3 (\$/yd^3)	Source of Costs
EPS (expanded polystyrene) block geofoam	0.12 to 0.31 (0.75 to 2.0)	0.01 to 0.03	35.00 – 65.00 (26.76 – 49.70)	Supplier
Foamed Portland- cement concrete geofoam	3.3 to 7.6 (21 to 48)	0.3 to 0.8	65.00 – 95.00 (49.70 – 72.63)	Supplier (1)
Wood Fiber	5.4 to 9.4 (34 to 60)	0.6 to 1.0	12.00 – 20.00 (9.17 15.29) (2)	(1)
Shredded tires	5.9 to 8.8 (38 to 56)	0.6 to 0.9	20.00 – 30.00 (15.29 – 22.94) (2)	(1)
Expanded shales and clays	5.9 to 10.2 (38 to 65)	0.6 to 1.0	40.00 – 55.00 (30.28 42.05) (3)	Supplier (1)
Boiler slag	9.8 to 17.2 (62 to 109)	1.0 to 1.8	3.00 – 4.00 (2.29 – 3.06) (3)	Supplier (1)
Air cooled blast furnace slag	10.8 to 14.7 (69 to 94)	1.1 to 1.5	7.50 – 9.00 (5.73 – 6.88) (3)	Supplier (1)
Expanded blast furnace slag	Not Provided	Not Provided	15.00 -20.00 (11.47 – 15.29) (3)	Supplier (1)
Fly ash	11 to 14.1 (70 to 90)	1.1 to 1.4	15 – 21.00 (11.47 – 16.06) (3)	Supplier (1)
Tire bales	5.9 to 8.8 (38 to 56) (4)	0.6 to 0.9 (4)	4 – 29 (3 – 23) (5)	This report (5)

Cost Notes: (1) Cost sources collected from Stark et al. (2002). These prices correspond to projects completed in 1993 to 1994. (2) Price includes transportation cost. (3) FOB at the manufacturing site. Transportation costs should be added to this price. (4) Information based on that for tire shreds. (5) See Cost Estimates for Tire Bales Applications section of this paper for additional information

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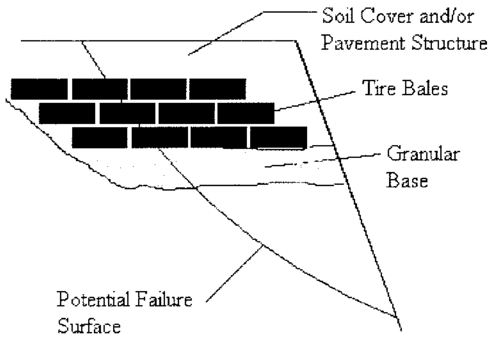

FIG. 2. Tire Bales used to Improve Slope Stability

General Rock Fall Barrier Walls

Generic tire bale rock fall barrier have been placed between a roadway and a steep rock face either as a free-standing wall unit or as the impact face of a geosynthetic-reinforced soil (GRS) wall to prevent falling rock materials from impacting roadway traffic. For either the stand-alone wall, or a GRS wall system, the width, depth, and possible use of shear keys below a foundation pad, will also depend on the design for the velocity of a critical rock block and the modulus of the tire bale system. The inside (back) face does not have a facing in order to maximize impact absorption. For the GRS system, tire bales would generally be laid parallel to the roadway, stacked to cover the underlying joints, and would include tire bales placed perpendicular to the roadway to enhance interlocking behavior. The roadside face of the wall may also require short secondary reinforcements for improved face stability. The subgrade layer for either system may consist of a compacted free-draining granular base zone, compacted tire shreds, or compacted native soils. Site conditions may require installation of drainage systems to control groundwater movement.

Design Guidelines

Design guidelines for use of tire bales in embankments have not yet been developed for embankment applications. As previously indicated, ASTM guidelines have been developed for use of tire shreds (ASTM D6270), and addresses issues relevant to design using scrap tires. FHWA has also prepared guidelines (FHWA 1998), which includes a section of scrap tires as embankment fill. In addition, FHWA has design guidelines for embankments over soft subgrades (FHWA HI-95-038), reinforced soil slopes and reinforced soil walls (FHWA HI-95-038 and FHWA NHI-00-043), which would apply to the use of tire bales as fill. The NCHRP Guidelines for Geofoam Applications in Embankment Projects, (Stark et al. 2002), provides design guidelines for EPS block materials and focuses on the use of this lightweight fill material in embankment applications. This guideline report has considerable value because it documents approximately 30 years of the development of design/construction

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guidelines for use of geofoam materials as a lightweight fill. This guideline, along with the existing FHWA guidelines, provides resources that can be used to assess some of the issues relating to use of tire bales as a reliable engineered material in highway embankments and wall structures.

Construction and Monitoring

Construction activities should initially involve the verification that the tire bales selected/fabricated for the project conform to the project specifications. Conformance tests should be conducted at this stage by the design engineer/and the third-party testing agency, prior to shipping tire bales to the construction site.

The construction sequence for tire bale embankment applications should not be significantly different from those presently used for other embankment projects. Construction activities will include: material handling (e.g., unloading, storage, hauling, placing, etc.), preparation of foundation and subgrade, placement of base drainage (if required), placement of a geosynthetic separation layer, if required (e.g., no in filling), placement of tire bales with matrix fill, connections, and reinforcements (as required), placement of a geosynthetic cover layer, if required, placement of materials required for a buffer zone below pavements, vegetated surface covers, and face protection, monitoring of performance. Thus far, time-dependent movements (creep) do not appear to have been monitored, measured, or reported as detrimental.

Quality control guidelines are needed to ensure short-term and long-term success of the project. The first layer of bales has been generally placed below ground level, serving as a "keyed" layer, which "locks" the entire bale mass. Also, depending on the type of project, the bales can be linked together by pre-installing a pipe through the bale and running aircraft cable through the pipe to connect multiple bales. The bales should be placed as "tightly" together as possible. Control of fill between bales is also important to avoid subsidence after placement. The minimum buffer zone also requires further evaluation and will be application dependent. For example, in embankment fill over EPS, a minimum of 0.5 m (20 in.) is required between the roadway and the EPS blocks (Stark et al. 2002).

Following construction, periodic site visits and measurements should be made to monitor the geometry, appearance, and performance of the tire bale embankment systems. One of the concerns that have been raised regarding the use of tire bales and waste tires involves the potential impact in groundwater quality. Although no specific study has been identified regarding the use of tire bales and its impact on water quality, some studies have been conducted regarding the impact of tire shreds on water quality. An ongoing study sponsored by the FHWA involved testing the impact of tire shreds on water quality (organic and inorganic constituents). This study confirmed that leachate from the tire shreds does not affect water quality. A summary of the data from the 1990s is included in Humphrey (1998) and ASTM D 6270.

Tire bales have been reported to sink to the bottom of a body of water when placed in a lake, river, or pool (Miner 2003), alleviating concerns in areas subject to flooding. An additional aspect that deserves further investigation is the long-term strength of the baling wire as well as the structural integrity of the bale. A study

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reported having cut the wires of tire bales after a set amount of time (usually one year or more), allowing for the tires to be unrestrained. Due to plastic deformation of the bales, it appears that the tires have not elastically rebounded or returned to their original shape.

CASE STUDIES

Case Study 1: Slope Repair Texas

A recent project involving the use of recycled tire bales for a slope failure repair along Interstate 30 east of Fort Worth, TX has shown very good performance. The initial slope failure was due to above average rainfall. This project, carried out in 2002, required the use of 360 recycled tire bales, totaling about 36,000 scrap tires.

Remediation of this slope failure began with the placement of the delivered tire bales at the toe of the slope. Once the bales were secured, the slope was completely covered with soil, followed by reshaping of the slope. Compost and seed were spread to stimulate vegetation growth and minimize future surface slope erosion (TxDOT 2003). Within 8 months of the placement of the first bales, the Fort Worth area had received nearly 50 inches of rainfall. A site visit and a preliminary slope stability analysis revealed that the use of tire bales in place of the original soil slope had improved the factor of safety by 2-3 times (TxDOT 2003).

Case Study 2: Condin Road, Chautauqua County, New York

A road construction project using recycled tire bales in Chautauqua County was recently approved by the State of New York. Due to the cold climate in the New York area, there are often problems with ground freezing, making it necessary to spread deicing chemicals and salt. By employing tire bales as a subgrade lightweight fill for road construction, the low thermal conductivity of the rubber was deemed to help in preventing ground freeze while saving costs on fill material. Estimated savings for this project are $3,030 per 1000 feet of roadbed. For all combined roadbed projects in the Chautauqua County, the total taxpayer savings was over $11,000.00 (Chautauqua County 2001). An estimated 250,000 tires were used during this project. In addition, constructability using tire bales was reported to be much easier and faster, saving labor costs and reduced the time for completion. No compaction was necessary, as the bales simply needed to be placed and secured. Conventional fill would have required compaction requirements and placement in several lifts.

After the first winter following completion of construction, the monitoring results indicated that the test section performed much better than the rest of the road. Significant damage was observed at several locations along the rest of the road, while no damage was observed along the tire bale test section. According to the Chautauqua County Public Works Director, the section of road that utilized the tire bales performed better through the rain, snow, and heavy traffic than ever before. Although the test embankment was not instrumented, the success of the project has been attributed to three main factors (Encore Systems 2000). First, while the bearing

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capacity of the tire bale layers was not quantified, its magnitude is certainly well above that of the subgrade soils. Second, the good drainage characteristics of the tire bales facilitate flow of liquids infiltrating through the bales. Finally, the thermal insulation of the tire bales protected the sub-base from frost damage.

Case Study 3: Front Range Tire Recycle, Inc., Sedalia, Colorado

A tire recycling facility located in Sedalia, Colorado (Front Range Tire Recycle, Inc.) stocked large quantities of tires as the main method of storage. However, this approach was later deemed unsafe because of the significant height of the stockpiles. Accordingly, the facility initiated tire bale operations in order to maximize storage capacity. In addition, tire bales were used for road construction within the facility. Specifically, a portion of the property was essentially unusable due to the steep slope grade. Consequently, a road in 2000 was constructed on top of the slope using tire bales. Construction of the road involved an initial excavation into the slope (i.e. a "cut" excavation), which was conducted to define a relatively flat surface. Next, the tire bales were stacked in a "brick-like" fashion using a forklift. In addition to soil, tire shreds were spread over the surface of the tire bale layers in order to level the roadway. Finally, soil was placed and compacted in uniform layers above the final layer of tire bales.

Visual inspection of the road indicates that the structure has performed very well, with little need for maintenance. Only a few sinkholes have developed due to uncompacted voids between the bales. It should be noted that the road is subjected to heavy truck traffic (e.g. semi with trailers) and occasionally large construction equipment (e.g. front-end loaders and scrapers). Because of the successful performance of the first tire bale road, additional roads with tire bales are currently being constructed at this facility.

Tire Bale Applications for General Civil Engineering Projects

Although the use of tire bales in civil engineering applications is still considered experimental, they have been used in general civil applications. For example, tire bales have been used as wind breaks for livestock on farms by stacking tire bales to the desired height (1.2m to 1.8m), without any particular facing or reinforcing material.

The use of tire bales for erosion control has also yielded good results. However, little published information has been reported on design criteria adopted for such an application. A large project restoration project along Lake Carlsbad in New Mexico used tire bales for erosion control. Specifically, a 1,220 m (4000 ft) long section of the shoreline was protected against erosion by the use of tire bales. The bales were laid in a wet concrete leveling pad, and then covered in shotcrete. Backfill material was then placed behind and on top of the treated bales, upon which a pedestrian sidewalk was ultimately constructed. Based on visual inspections of the project, the tire bales have performed extremely well.

Another civil engineering application involving use of tire bales is for the construction of earth dams. For example, tire bales were used as lightweight fill on

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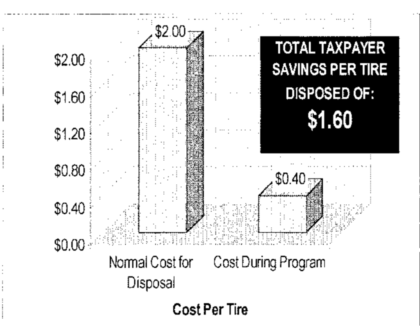
both the upper and lower sides of the clay-core dam in Mountain Home, Arkansas. Tire bales were placed in lifts of one bale deep, with each lift being covered with compacted clay and granular soil. After reaching the desired height, the tire bales were ultimately capped with a compacted soil layer. Initial reports based on visual inspections of the dam indicate very good performance of the system.

COST ESTIMATES FOR TIRE BALE APPLICATIONS

While varying from project to project, the cost of tire bales as embankment material has been reported to be less than the conventional soil alternative. The low cost has been partly due to state legislation and tipping fee subsidies.

An example of the cost associated with the use of waste tires was provided in the Chautauqua County project previously described in Case Study 2. In that project, the total taxpayer savings was estimated as $1.60 per tire, or approximately $160 for a "standard tire bale" (Chautauqua County 2001). This corresponds to the difference between the normal disposal cost of tires and the cost associated with the use of tire bales (Figure 3a). The cost savings associated with tire bales instead of conventional earthwork material was reported as $3,050 per 300 m (1000 ft) of roadbed (Figure 3b).

1993 to 1994 cost estimates for use of other lightweight fill materials are listed in Table 7 (excluding handling and engineering). More generically, the use of tire bales to construct a typical embankment is expected to involve the items listed in Table 8. As indicated in the table, the use of tire bales as fill is estimated to cost from $4 to $29 per m^3 ($3 to $23 per yd^3) with a typical estimated cost to be on the order of $13 per m^3 ($10 per yd^3). By comparison, recent pricing of EPS blocks in special embankment systems installed in the Mid-Atlantic region of the US during the 2000 to 2002 time period ranges from $78 to 90 per m^3 ($60 to $70 per yd^3). Stark et al. (2002) reported a range of bid prices by means of a questionnaire from six United States DOTs, including three for the 1996 to 1999 period. The six prices range from $39 to $98 per m^3 ($30 to $75 per yd^3), averaging $70 per m^3 ($55 per yd^3). One price included the cost of a fascia wall as $7 per m^3 ($10 per yd^3).



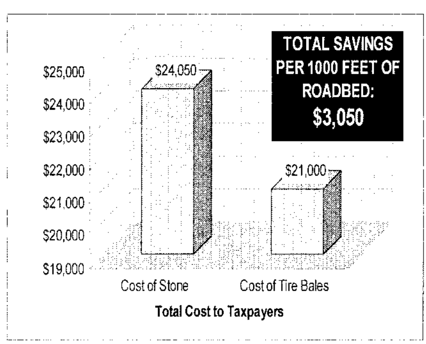


FIG. 3. (a) Total Taxpayer Disposal Costs For Each Tire; (b) Total Savings per 1000 Feet of Roadbed

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TABLE 8. Estimated cost of tire bales as lightweight fill

Activity	Estimated Costs $\$/m^3$($/cy)		Sources
	Range	Estimated	(Assume approx. 100 tpe and 1.5 m^3 / tire bale (2 cy /bale))
1. Purchase & Storage	0	0	A tipping fee pays for current disposal of waste tires.
2. Steam Clean (finished bale)	0 to 10 (0 to 8)	1.30 (1.00)	Usually not required (R. Welle, 2003)
3. Fabricate, Handle, Store	13 to 15.50 (10 to 12)	14.30 (11.00)	Assumed
4. Transport to Site	3.25 to 6.50 (2.50 to 5.00)	4.50 (3.50)	25 miles @ $5.50/ton =$2.50/cy 100 miles @ $10/ton= $5.00/cy
5. Site: Store, Protect, & Handle	1 to 2 (0.8 to 1.5)	1.30 (1.00)	Assumed
6. Earth Matrix	0 to 4 (0 to 3.00)	4.00 (3.00)	Depends on site use
7. Connection devices	0 to 2.50 (0 to 2)	0.00	Assumed
8. Face Protection	0 to 1.30 (0 to 1)	0.00	Not for general embankment
9. Total #2 to #9	17.25 to 41.80 (13.3 to 32.5)	26.50 (20.50)	Estimate Fabricate, Deliver to site, and Install
10. State Rebate	-13.00 (-10.00)	-13.00 (-10.00)	$20/ton rebate to end users or processors of scrap tires if funds are available (State of Colorado)
11. Estimated Net Cost	4.25 to 28.8 (3.30 to 22.5)	13.50 (10.50)	** Adding other unknowns, say $26/m3 ($20/cy)

NOTES: Typical tire disposal cost = $0.00/tire, due to tipping fee paid for disposal, Upper end based on steam cleaning each tire, which may be required on environmentally sensitive projects, Assume 4 to 5 bales per hour (8 to 10 cy/hour), and crew + equipment cost = $100/hr, results in $10 to $12/cy, Assume 0.6 ft of soil per 3 ft lift of TB + soil = 0.2 cy of total vol @ $15/cy =$3/total cy., Engineering for special design details and construction monitoring to incorporate lightweight fill in design is not included. A rough estimate would be 10% of the cost of the bales excluding the state rebate. The actual cost will depend on site conditions, time to develop design details, and specifications. Reported cost comparisons are based purely on materials and construction. However, there are additional value-added applications such as lightweight fills on soft ground where savings also result from benefits such as avoiding precompression and use of deep foundations.

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SUMMARY AND RECOMMENDATIONS

A summary of the various applications using tire bales is presented in this paper. Based on the current understanding of the properties of waste tires, as well as on the good performance of a limited number of projects constructed so far using tire bales, it may be concluded that the use of this approach is feasible and offers significant potential in transportation systems. In addition to the obvious environmental benefit of using recycled waste materials, the lightweight and good mechanical properties expected for tire bales offer advantages over normal fill in terms of reduced stress to the subgrade and improved internal strength of the structure. In the case of rock fall barriers, they also offer excellent impact resistance. Based on rebates for recycling tires, tire bales are essentially free except for hauling and handling costs. However, current understanding of tire bales is based on: (1) the quantification of material properties involving the use of waste tires processed as tire shreds, and (2) visual inspection of transportation applications that did use tire bales but did not incorporate a comprehensive monitoring programs to quantify long-term performance.

ACKNOWLEDGEMENTS

The authors are in debt to Richard Williammee, Texas Department of Transportation, and Naser Abu-Hejleh, Colorado Department of Transportation, for their support provided for this study.

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