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TIRE BALES IN HIGHWAY APPLICATIONS: FEASIBILITY AND PROPERTIES EVALUATION

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16. 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 tire bale properties and performance of tire bale embankments is, at least, limited. This report summarizes the benefits and shortcomings of using tire bales in civil engineering projects, as well as information collected to date on their mechanical properties. The report includes the results of eight laboratory tests on typical tire bales (most of which had never been performed prior to this study) to provide critical information on tire bale geometry, both air dry and submerged unit weights, permeability, unconfined and confined compressibility characteristics including horizontal deformations, rebound and potential expansion pressures, creep behavior, and external shear strength between two tire bales. An economic analysis comparing the estimated cost of tire bales to conventional fills is presented, supported by information on Colorado DOT costs for earth embankments. Finally, detailed recommendations for utilization and implementation of tire bales as a lightweight fill in embankments are presented.

Implementation:

Following a review of the final report by CDOT and FHWA experts, a special provision for tire bale embankments should be developed as part of CDOT Section 203 "Embankments." The CDOT regional offices should be informed of the new specification and the potential cost savings for using tire bales in generic embankment applications. Prototype sections where tire bale embankments can be used should be identified on noncritical projects (e.g., embankments on secondary, non-lifeline roads). All embankments constructed with tire bales should be monitored, and annual performance reports will be prepared during a recommended five-year observation period. The study has also demonstrated that tire bales: 1) should be considered a viable cost-effective alternative when and where lightweight fills are required on CDOT projects, and 2) have a potential for other applications, including slope repairs, rockfall barriers, insulation of frost-susceptible soils, drainage zones, and erosion protection.

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The Colorado Department of Transportation Study Panel consisted of Dr. Naser Abu-Hejleh (Research), Mr. Rob Beck, Geotechnical Program (Materials), Mr. Rich Griffin (Research), and Mr. C. K. Su (Materials).

The research was conducted from January 2003 to November 2004. The principal investigators for the project were: Dr. Jorge Zornberg, Clyde E. Lee Assistant Professor, Department of Civil Engineering, The University of Texas at Austin; Dr. Barry R. Christopher, Ph. D., P.E., Geotechnical Consultant, Roswell, GA.; and, Mr. Marvin D. Oosterbaan, P.E. Oosterbaan Consulting LLC, Cape May, NJ. Also working on this project were Mr. Christopher J. LaRocque, Graduate Student at The University of Texas at Austin, Department of Civil Engineering, Austin, TX, and Mr. Timothy Fitzgerald, Graduate Student, University of Colorado at Boulder, Colorado.

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Executive Summary

Recent estimates indicate that more than 2 billion scrap tires are currently stockpiled in the United States and approximately 280 million more tires are added annually. State regulations now guide the stockpiling of scrap tires and their reuse for beneficial purposes. Approximately 77 percent of the tires discarded each year are processed and recycled for various uses. Since 1985, scrap tires have been used in a variety of civil engineering applications, including tire shreds to provide economical lightweight embankments for transportation projects. This application can use 100,000 to 1,000,000 tires per project. Another approach that has slowly developed in the past 15 years is mechanically compressing and tying 100 whole tires to form large "bales" which are stacked to form part of an embankment.

This research was performed to evaluate the technical and economic feasibility of using tire bales in embankment construction and determine relevant engineering properties for design. The research work was conducted in two phases. The objective of Phase I was to review, document, and synthesize approximately 14 years of experience, primarily in the USA, UK, and Australia, using tire bales in civil engineering applications. The Phase II objectives were to evaluate the technical and economic feasibility of tire bales as an embankment material; compare tire bales with other lightweight fill materials; perform laboratory tests to determine some of the basic engineering properties of typical tire bales; review design guidelines; and identify construction issues, quality control requirements, estimated costs, and limitations associated with the use of tire bales. Prior to this study the only available laboratory tests of tire bales consisted of two tests of unconfined compression and short-term creep conducted in 2000. Therefore a significant part of the Phase II work included performing a series of laboratory tests to evaluate engineering properties of tire bales relative to embankment applications, which provide essential data for the feasibility evaluation. A series of eight laboratory tests on eight typical tire bales were performed under a Colorado Department of Transportation contract with GeoTesting Express in 2004 - 2005. Most of the eight tests had never been performed or at least reported in the available literature, prior to this study. The results of the 2004 - 2005 tests are presented in Appendix D and included in the tables of typical tire bale properties along with the 1999 laboratory test data, which is reported in Appendix C.

The results of the Phase II work confirmed the initial expectation that tire bales are a feasible structural material for various embankment applications. This report combines the Phase I and Phase II work and is the product of the three principal investigators.

The research study to date confirms that tire bales can be an economical material that provides a lightweight, strong, porous embankment, easily and rapidly constructed in a number of civil engineering applications. This use of scrap tires also provides a significant opportunity to enhance the environment, continue the cleanup of unregulated tire dumps, reduce the possibility of expensive tire fires, and remove potential breeding grounds for mosquitoes. This use of tire bales provides additional opportunities for the scrap tire recycling industry because it utilizes simple machinery that can be operated by relatively unskilled workers to fabricate a product that can be stored in strategically located stockpiles (in a protected facility) until it can be trucked to and utilized at a construction site.

However, additional information should be obtained by monitoring in-service performance of prototype tire bale embankments. Instrumentation must be installed in the prototype tire bale embankment sections to monitor internal temperatures, assess the heat buildup, and further evaluate the potential and possibility of significant exothermic reactions. Compression settlement must also be monitored to compare the results of laboratory tests on tire bales with in-service performance.

The observations will be used to enhance the development of design procedures, construction specifications, and other requirements for Class I and Class II tire bale embankments. The detailed recommendations for the next steps are included in Section 10 of this report.

Cost estimates for a basic tire bale embankment are presented in Tables 7.1 to 7.3. The analysis indicates that the net cost of a tire bale core zone, replacing embankment fill material in a typical highway embankment, is in the order of \$3.70 to \$9.70 /m^3 (\$2.80 to \$7.40 cy) (assuming the current Colorado rebate for using scrap tires is in force). This use of tire bales indicates a potential cost savings when compared to the average annual cost of embankment material backfill of \$12.60/m^3 (\$5.00/cy) for 125 CDOT projects in the 2001 to 2003 time period. The

125 projects constitute 50 percent of the CDOT embankment projects, all having embankment volumes in the range of 3,300 to 38,200 m^3 (2,500 to 50,000 cy), during the 2001 to 2003 time period. This estimate does not include costs for cleaning scrap tires, connection materials, earth matrix infilling, drainage materials, or engineering services that usually vary with any project and the site constraints.

Implementation Statement

Following a review of the final report by CDOT and FHWA experts, a special provision for tire bale embankments should be developed as part of CDOT Section 203 "Embankments." The CDOT regional offices should be informed of the new specification and the potential cost savings for using tire bales in generic embankment applications. Prototype sections where tire bale embankments can be used should be identified on noncritical projects (e.g., embankments on secondary, non-lifeline roads). All embankments constructed with tire bales should be monitored, and annual performance reports will be prepared during a recommended five-year observation period.

In addition to use of tire bale zones in generic embankments, tire bales have a high potential for a number of special applications, including slope repairs, rockfall barriers, insulation of frost-susceptible soils, drainage zones, and erosion protection. The study has also demonstrated that tire bales should be considered a viable cost-effective alternative when and where lightweight fills are required on CDOT projects. Implementing the use of tire bales for these special applications will require use and assimilation of the additional information obtained by monitoring in-service performance of prototype tire bale embankments as described above. In some cases additional instrumentation should be installed in the prototype tire bale embankment sections to obtain particular data. The observations of the test embankments will be used to enhance the development of design procedures, construction specifications, and other requirements for Class I and Class II tire bale embankments and special applications. The detailed recommendations for the next steps are included in Section 10 of this report.

The benefits derived from this research will accrue to the state of Colorado, as well as the national and international community. The primary benefits include lower cost for transportation embankments, development of another use of a significant waste material, by use of “low-tech” fabrication equipment, low-cost labor, conventional transport, a low-end handling system, and conventional support materials.

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1 INTRODUCTION

Recent estimates indicate that more than two billion waste passenger car and truck tires are currently stockpiled across the nation (Senadheera, 2002). In addition to the existing stockpiles, scrap tires are being generated in the United States at an approximate rate of one per capita annually, totaling 280 million scrap tires (RMA, 2002 and Bosscher et al., 1997).

Tires are made of vulcanized rubber, allowing them to retain their elasticity. By definition, thermosetting polymers cannot be returned to their original form. Because of this, waste tires cannot be "recycled" but must be reused or discarded. An estimated 77.6% of the total generated tires in 2001 were used for various applications (RMA, 2002). The remaining unused tires are stockpiled or illegally dumped in loose random piles of whole tires. Large stockpiles of whole and processed waste tires can present environmental problems and dangers, such as the breeding of mosquitoes and rodents, and become serious fire hazards (Humphrey and Manion, 1992). Another significant means of disposing waste tires is incineration for tire-derived fuel (TDF). This accounts for approximately 17% of the waste tires produced (Bosscher et al., 1997). While this means of reuse may be a significant source of energy, it results in increased atmospheric pollution.

Alternative means of disposing waste tires have been introduced in the last decade including the reuse of waste tire products in civil engineering applications. Scrap tire materials are characterized by their lightweight, low lateral pressure, low thermal conductivity and good drainage characteristics. Due to tipping fees required by many state laws for tire disposal, tire bales are very economical. The economics and engineering properties make waste tire products desirable for use in many applications, including 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 and Baker et al., 2003). Additional applications are rockfall barriers, field drains, and blasting mats. The vibratory damping property of waste tire products makes them a possible 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 may be used on a single project (Humphrey, 1996). The use of waste tires, either whole or processed, in civil engineering projects tends to reduce the environmental problems associated with alternative means of disposal, and also reduces the use of other non-renewable mineral aggregates. In some cases, it has been determined that mixing tire shreds with soil increases the shear strength of the soils (Zornberg, et al., 2004a). Various studies suggest that waste tire products used in these applications do not pose a significant threat as a hazardous waste material, and do not alter the concentrations of any substances affecting the primary drinking water standards set forth by EPA (Edil and Bosscher, 1992 and Humphrey et al., 1997) (Edil and Bosscher, 1992 and Humphrey et al., 1997). In some cases, oxidation of exposed steel in shredded tire fill caused increased levels of manganese (Mn) and iron (Fe), often exceeding their secondary (aesthetic based) standard (Humphrey, et al., 2001).

The most common form of processed waste tires has been the use of tire shreds as monofill zones within a soil matrix, or as a tire shred/soil mixture. Through 1995, more than 70 civil engineering projects had been successfully completed in which tire shreds, the prominent reusable waste tire product applicable to the civil engineering industry, were used in various forms and did not experience an exothermic reaction (Humphrey, 1998). This document includes a table which lists 18 projects in 10 states during the 1989 to 1994 time period where significant construction information is available. Baker et al. (2003) cites 32 projects in 13 states where tire shreds were used in geotechnical applications. Apparently, well over a hundred projects involving the reuse of tire shreds have been constructed in the past 20 years.

Several cases have been documented in which whole tire and tire shred stockpiles and tire shred embankments have experienced internal heating, resulting in severely damaging, costly fires (Humphrey, 1996 and Baker et al., 2003). Humphrey 1998 and ASTM D6270-98 include guidelines to reduce the risks associated with development of an exothermic reaction in stock piles of whole tires and tire shred embankments more than 1 meter (3.3 ft) thick. One recommendation states that tire shreds with larger dimensions will minimize exposure of the exposed steel, the corrosion of which is thought to be the major source of internal heating.

Presence of organic material and exposure to air, water, increase the potential for corrosion and are therefore restricted in the guidelines. Limitations on fill height are also imposed. Although some research into the sources of internal heating of tires and tire shreds has been conducted, a complete understanding of the causes of exothermic reactions in tire shred fills is still lacking.

A Special Report titled “Scrap and Shredded Tire Fires” (United States Fire Administration, 1998), based on a detailed analysis of seven tire fires in the 1995 to 1997 time period, describes 12 key issues associated with reducing the possibility and impacts of tire fires in various settings. The key issues include code enforcement, agency coordination, equipment needs, extinguishing tactics and agents, disposal of burned tires, and costs. A detailed discussion of the 12 key issues is beyond the scope of this study, however, they must be considered in the in-service use of waste tire products for civil engineering applications as described in later sections of this report.

The focus of this study and the report is the practical use of whole tires compressed into bales and placed as part of an earth embankment. This is a relatively new approach, which appears to provide a viable alternative to the use of tire sheds in civil engineering applications and reduces the potential for exothermic reactions. Tire bales also appear to provide some economic advantage over the use of tire shreds in terms of production, storage, and construction costs as reviewed later in this report. However, when this study was initiated, comparatively little testing and/or research have been completed regarding the engineering properties and performance of tire bales used in civil engineering applications.

As the reuse of various waste tire products in civil engineering applications increases, the need for better understanding of the engineering properties of whole and processed waste tires becomes paramount. It has been noted that reuse of waste tires has the potential of becoming the most reusable secondary material in the world, possibly reaching 75% of all scrap tires generated in the near future (Enviro-Block). While research is needed to provide guidelines on appropriate design methods and construction practices for using baled tires in transportation systems, significant lessons can be learned from a review of projects already constructed using baled tires.

The overall objectives of this study are to:

1. Evaluate the feasibility of using baled tires as embankment materials in highway applications.
2. Evaluate the engineering characteristics of tire bales through are view of the literature and the performance of laboratory tests.
3. Provide recommendations for construction of tire bale embankments, in conjunction with appropriate soil, rock, connecting systems, and geosynthetic materials based on the lessons learned from limited experience with using tire bales as embankment materials, and the comparison of tire bale properties with similar applications using other lightweight materials, e.g. tire shred fills, expanded polystyrene (EPS), and the authors' opinions and judgment.
4. Provide preliminary recommendations for the use of tire bale embankments in slope repairs and rockfall barriers.
5. Provide a summary of the issues that need further research to demonstrate the suitability of tire bales in transportation systems, including the engineering properties of tire bales related to design, construction, and long-term performance.
6. Provide a research plan with detailed tasks and an estimated budget for the construction, instrumentation, and monitoring of a prototype tire bale embankment constructed to address the issues described in Objective 4 above.

This report summarizes:

- Reported and possible uses of scrap tires in Section 2.
- The current design guidelines for tire shred fills (ASTM D6270-98) in Section 2.
- Typical characteristics of whole tires, tire sheds, and tire bales in Section 3.
- Measured physical and mechanical properties of tire bales in Section 4.
- Typical properties of tire bales, tire shreds, EPS blocks, and conventional earth fills in Section 4.
- The status of knowledge and understanding, as well a relative assessment of the design issues relating to use of tire bales in embankments, slope repairs, and rockfall barrier applications in Section 5.
- Tire bale specifications in Section 6.
- Construction issues in Section 6.

- Estimated costs for tire bale embankments in Section 7.
- Special considerations, limitations and performance issues in Section 8.
- Available information on performance of tire bale embankments.
- An outline of future laboratory and field research activities in Section 9, including appropriate field instrumentation.

Several Appendices are included which contain selected case studies of reported tire bale applications (Appendix A and B), results of available laboratory tire bale tests (Appendix C and Appendix D), typical specifications (Appendix E), references to governmental legislation relating to use of scrap tires (Appendix F), reference to fire protection issues and guidelines for scrap tires (Appendix G) and recent Colorado DOT costs for embankment materials and related items (Appendix H).

2 CURRENT REUSE OF WASTE TIRE PRODUCTS

While waste tire products are currently being used in various civil engineering applications, the search continues for products and applications that maximize the performance capabilities, pose limited risks, and are comparatively economical. The typical forms of waste tires include: powdered, ground and granulated rubber, tire shreds, split tires, whole tires, and tire bales.

2.1 Whole tires

Whole tires have been used in applications ranging from residential construction to reinforced soil slopes. In residential construction, whole tires have been used as the primary material for constructing both exterior and interior walls before the tires are covered with a surface finish layer of cement material. The use of tire bales in these projects is beneficial both in terms of the use of waste tires, as well as the energy efficiency of the completed walls. Whole tires are generally laid on concrete footers and subsequently filled with compacted soil. Walls are built by using several layers of whole tires filled with soil and stacked on one another. These "tire walls" are typically 'finished' by applying a layer of shotcrete, stucco, or some other finish material. The result is a house built with relatively inexpensive materials and the exterior walls have extremely high thermal resistance values. (Touch the Earth Construction, 2004).

Whole tires have also been used to form the face of reinforced soil structures, using a similar technique to the residential wall construction with geosynthetic reinforcement placed between the tire layers. This technique has been used to construct rockfall barriers as shown in Figure 2.1, with the tire facing providing significant energy dissipation.

Whole tires have also been used as a means of reinforcement in soil slopes and retaining structures in the United States, France, and other countries since approximately 1976 (O'Shaugnessy and Garga, 2000). In these applications, layers of whole tires are tied together by polyethylene ropes or cables, and function as a reinforcement layer (similar to geotextiles and geogrids) to provide adequate tensile and shear strength that stabilizes the soil mass. In the particular project completed by O'Shaugnessy and Garga (2000), 'tire mats' were placed with a

Figure 2.1 Geosynthetic reinforced soil (GRS) rockfall barrier with tire facing in New Mexico (Christopher, 2002)

vertical spacing of 0.5 m (1.6 ft). In a manner similar to the design of soil slopes reinforced with geosynthetics, limit-equilibrium methods were used to analyze the reinforcing effect of the waste tires. The same failure mechanisms that apply to soil slopes reinforced with geosynthetics were analyzed, including pullout and breakage of the tire mats.

2.2 Tire pieces and tire shreds

Currently, waste tire pieces and tire shreds are predominantly more common in civil engineering applications than their whole tire counterparts. One example of the applications for tire pieces, although somewhat limited, is the construction of blasting mats using tire pieces tied with bailing wire. These heavy mats are often used in blasting projects to reduce flying debris and subsequent damage to nearby structures. The tire mats are placed on the soil surface around the blast area providing a surcharge that prevents projectile debris otherwise generated from the blast energy.

The most common form of waste tire products currently in use in civil engineering and transportation applications is the use of tire shreds as an engineered fill material. Tire shreds have been utilized in numerous embankment and wall applications due to the beneficial properties of lightweight, shear and tensile strength, drainage, and thermal insulation value. In landfill applications tire shreds have been used to insulate landfill liners (Benson et al., 1996) and as subgrade insulation material (Eaton et al., 1994). Tire shreds have also been used to provide drainage layers, daily cover, and support for final cover and leach fields in landfills.

The potential use of tire shreds as lightweight fill material represents one of the most significant means of use of waste tire products in civil engineering applications. (Bosscher et al., 1993). The use of tire sheds had a temporary setback in the mid 1990s due to concerns relating to potential exothermic reactions. However, the current design and construction guidelines (ASTM D6270) for use of tire shred fills address the issues that can promote an exothermic reaction, primarily by reducing the thickness of tire shred fill zones, controlling the size and cleanliness of the tire shreds, limiting the amount of exposed steel wires, and limiting the access of air and water to the tire shreds. The guidelines focus on limiting the amount of exposed steel and the environmental conditions which support corrosion and rusting of exposed steel.

As noted in ASTM D6270, the current design guidelines for tire shred fills include:

- Use tire shreds free of contaminants.
- Eliminate tire shreds which have been subjected to a fire.
- Specify and test the gradation and size of the tire shreds and limit the amount of granulated rubber.
- Specify and test the amount of exposed steel and metal particles.
- Minimize infiltration of soil and organic matter into the tire shreds by use of mineral soil covers and geosynthetic separation materials.
- Provide geotextiles as separation fabrics between mineral soil and a tire shred zone.
- Limit tire shred thickness to 1 m (3.3 ft) in Class I tire shred fills and 3 m (9.8 ft) in Class II tire shred fills.
- Mineral soil layers between tire shred zones should be at least 0.6 m (2 ft) thick and consist of soils having at least 30 % fines and no organic materials.

- Soil cover layers on the side slopes of tire shred fills should be at least 0.5 m (1.6 ft.) thick.
- Drainage outlets at the base of tire shred zones, or weep holes in retaining wall, must be designed and constructed to reduce air movement into the voids in the tire shreds fill zone.

ASTM D6270 indicates that tire shreds can and should be manufactured in sizes ranging from 4.75 mm-(0.18 in.) to 300-mm (12 in.) sieve sizes. The shreds are then graded and placed to minimize conditions favorable for exothermic reactions. *Class I* fills are defined as tire shred fills less than 1 m thick and *Class II* fills are defined as tire shred fills which range from 1 to 3 m thick. The gradation requirements for *Class I fills* are:

- a maximum of 50 % by weight passing the 38-mm (1.5 in.) sieve and
- a maximum of 5 % by weight passing the 4.75 mm sieve (0.18 in.).

and, the gradation requirements for *Class II fills are:*

- a maximum of 25 % by weight passing the 38-mm (1.5 in.) sieve and
- a maximum of 1 % by weight passing the 4.75-mm (0.18 in.) sieve.

ASTM D6270 indicates that no special design features are required for Class I fills. However for Class II tire shred fills, the material requirements include:

- tire shreds shall be free of fragments of wood, wood chips, and other fibrous organic matter.
- tire shreds shall have less than 1 % by weight of metal fragments which are not at least partially enclosed in rubber, and
- metal fragments that are encased in rubber shall protrude no more than 25 mm (1 in.) from the cut edge of the tire on 75 % of the pieces and no more that 50 mm (2 in.) on 100 % of the pieces.

2.3 Soil and tire shred mixtures

Recently, a small number of projects have studied the use of soil/tire shred mixtures as embankment fill material (Hoppe, 1998), including research involving the use of tire shred-soil mixtures (Zornberg et al., 2003). Tire shred-soil mixtures minimize concerns associated with exothermic reactions within the tire sheds only fill material as well as increase the shear strength of the soil being used.

2.4 Tire bales

The beneficial reuse of waste tires in the form of tire bales in civil engineering applications has recently gained interest. Tire bales appear to a likely alternative in many of the applications where whole tires and tire shreds have been used. The use of tire bales appears to facilitate construction operations and tire bales are believed to reduce the potential fire hazards associated with tire shreds. Tire bales are fabricated and installed as large blocks and generally do not require the spreading and compaction efforts required for tire shred and geotechnical materials. The potential for an exothermic heating causing a fire hazard in tire bales is reduced because steel belts and reinforcement of whole tires have very limited exposure to oxidation in the final product and the smaller sizes of tire shreds are not present in the tire bale. The absence of large quantities of exposed steel also implies that tire bales can be stored with less concern for moisture content and weather exposure, which causes corrosion of the exposed steel in a tire shred product.

Because the practice of embankment construction with tire bales is not well established, the current design approach and details are still somewhat “experimental”. The “experimental uses” of tire bales to date constitute significant achievements and show promising potential for increase their use as described later in this report. The potential use of tire bales is substantial as shown in the applications summary contained in Table 2.1. The technical feasibility of tire bale use expressed in Table 2.1 is based on the literature review performed for this study and the authors’ opinions. However, further research is recommended in Section 9 and 10 of this report to demonstrate the suitability of tire bale embankments in transportation systems, as well as to provide design and construction guidelines for use in future projects.

Table 2.1 Reported and possible uses of tire shreds, whole tires, and tire bales.

REPORTED AND POSSIBLE USES	Tire Shreds	Whole Tires	Tire Bales
WALL SYSTEMS			
Residential	Feasible as fill for Geosynthetic Reinforced Soil (GRS) Retaining Walls	Feasible with soil filler, connections, & facing	Feasible, with facing (e.g., shotcrete)
Commercial	Feasible as fill for GRS Retaining Walls	Feasible with soil filler, connections, & facing	Feasible, with facing
Sound Barriers	Feasible as fill for GRS Sound Barriers	Feasible with connections & facing	Feasible, with or without facing
Small Site Retaining Walls	Feasible as fill for GRS Retaining Walls	Feasible with connections, separation geotextile, & facing (CalTrans in 1988)	Feasible, with or without facing
Rockfall Barriers	Feasible as fill for GRS Retaining Walls	Feasible with connections & facing	Feasible, with or without facing
Culvert Headwalls	No	Feasible	Feasible, with or without facing
Large Building Blocks: Tire Bales Encased in Concrete	Feasible	Possible, but feasible	Feasible
SLOPE SYSTEMS			
With Layered Geo-synthetic Reinforcement	Feasible	Feasible with connections	Feasible
Repair Slope Failures	Feasible	Feasible with connections	Feasible
Lightweight fill	Feasible	Feasible	Feasible
EMBANKMENT CONSTRUCTION			
Lightweight Fill	Feasible	Feasible with in filling	Feasible
SUBGRADE STABILIZATION			
Mat for Roads Over Very Soft Foundation Soils	Feasible	Feasible with in filling	Feasible
Insulation to Reduce Frost Action	Feasible	Feasible with in filling	Feasible
Edge drains	Feasible	Not feasible	Feasible

Table 2.1 **Reported and possible uses of tire shreds, whole tires, and tire bales (continued)**

OTHER SYSTEMS			
Drainage Zones in Landfills	Feasible, with separation geotextile	Feasible, with separation geotextile	Feasible, with separation geotextile
Mix with Soil to Improve Shear Strength and Reduce Unit Weight	Feasible	Feasible	Feasible as inclusions or zones in an embankment
Erosion Protection for Water Edges w/ Shotcrete	Not Applicable	Feasible, with cables	Feasible with and without shotcrete or concrete facing
Erosion Protection for Swales and Channels w/ shotcrete	Not Applicable	Feasible	Feasible
Blasting Mats	Feasible	Feasible	Feasible
Low-cost Culvert Structures	Not Applicable	Feasible, tied to form a cylinder	May be Feasible
POTENTIAL USES			
Crash Barriers	Possible	Feasible with ties	Feasible
Temporary Dikes, Dams	May be feasible	Feasible, w/geomembrane wrap	Feasible, w/geomembrane wrap
Storm Water Detention Systems	Feasible, but small storage capacity	Feasible	Feasible

2.4.1 Selected case histories

The case histories in Appendix B illustrate and describe three different types of embankment projects in transportation applications. A brief description of each case history follows.

Case Study 1 describes the use of tire bales as strong lightweight fill in the repair of a side slope failure on a compacted fill embankment in Texas. The initial slope failure for this project was initiated by above average rainfall. Reconstruction, carried out in 2002, required the use of 360 tire bales, totaling about 36,000 scrap tires. Remediation of the slope failure began with 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 the eight months following placement of the first bales, the Fort Worth area experienced nearly 50 inches of rainfall. A site visit and a preliminary slope stability analysis revealed that the use of tire bales instead of reconstructed a soil embankment had improved the factor of safety by 2 to 3 times.

Case Study 2 describes the reconstruction of a roadway using tire bales as lightweight embankment fills and insulation of frost-susceptible subgrades on segments of county roads in Chautauqua County, south of Buffalo, New York. The initial project in 1999 involved the excavation of 1000 feet of the existing road sub grade, and replacing it with tire bales. After excavation, a nonwoven geotextile was placed over the in-situ soil. Tire bales were then placed on top of this geotextile in a "brick-like fashion" to form the core of the roadbed structure. Voids between and within the tire bales were filled with coarse sand, which was compacted using traditional methods (a vibratory roller was used). Finally, three 6-inch thick gravel layers were placed and compacted, using vibratory rollers, on top of the tire bales to provide the unpaved roadway section.

After the first winter following completion of construction of the test section of the road, the 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. This application of tire bales has continued since 1999 and by the end of 2004 the County expects to complete a total of five road bed stabilization projects, using a total of approximately 6,240 tire bales. The current rate of tire baling and use of tire bales to rehabilitate selected problematic low traffic volume roads matches the annual whole tire scrap rate in the county. The tire baling effort utilizes prison labor to fabricate the tire bales and reduce costs. (Chautauqua County, Ken Smith, Personal communication, 2004). The New York State Department of Environmental Conservation has given the County a Beneficial Use Designation which allows the County to only submit drawings and plans for tire bales in roadway embankment for project approval. (Chautauqua County, Kate Hill email to Dr. Naser Abu-Hejleh, dated 02 Jul 2003).

Case Study 3 describes embankment construction to provide grade separation for an access road and improved land usage at the Front Range Tire Recycling Facility in Sedalia, Colorado. Construction of the road involved an initial excavation into the slope (i.e. a "cut" excavation), to provide a relatively flat surface to support the tire bales. Next, the tire bales were stacked in a "brick-like" fashion using a forklift. Once the stacked bales reached the desired height for the roadway, the bales were compacted using a front-end loader. In addition to soil, tire shreds were spread over the surface of the tire bale layers in an effort to level the roadway. Finally, soil was placed in uniform layers above the final layer of tire bales and compacted.

Visual inspection of the access road indicates that the structure has performed very well so far, with little need for maintenance. The only reported maintenance needed involved the repair of small sinkholes that developed near the edges of the roadway. The mechanism for sinkhole generation is attributed to incomplete filling the voids of the tire bales with soil. As a result of the good performance of the first tire bale road, additional tire bale roads are being constructed.

2.4.2 Other transportation applications

Other transportation related applications which are expected to show a high benefit to cost ratio include situations where tire bales are used to provide improved subgrade support, embankments for roadway structures, backfill materials for bridge abutments, retaining walls, sound barrier walls, and rockfall barriers. For example, tire bales were used as the core of a retaining wall along 1,220 m (4,000 ft) of the Pecos River in Carlsbad, New Mexico.

2.4.3 Need for additional research

Even though there have been a number of "experimental" tire bale civil engineering applications similar to the case studies described above, there is a need for additional research. Nearly all of the civil engineering projects that have utilized tire bales to date have been completed on a "trial" basis. This method has apparently proven to be very successful in most cases.

Several concerns have been raised about the use of tire bales in embankment applications, based on the experience of tire shred fills. The concerns include:

- potential for significant exothermic reactions.
- appropriate fire protection requirements.
- potential impacts on groundwater quality.
- permeability and drainage characteristics.
- potential buoyancy problems for flooded embankments.
- long-term compression and creep rates.
- the need for long-term integrity of tie systems or methods.
- internal and external shear strengths.
- requirements for soil buffer, or soil cap layers.
- requirements for exterior protection and facing materials.
- requirements for ancillary materials such as geotextiles (for filter and separation requirements), geomembranes (for separation and barrier requirements), and geogrids for reinforcement requirements.

These issues and their relative importance for selected tire bale applications are discussed and in most cases addressed in Sections 3 to 10. Items requiring additional study are included in the field study and implementation plan proposed in Sections 9 and 10. The proposed field research is important to extend the knowledge of tire bale properties and capabilities, efficiently design all tire bale projects with adequate factors of safety, and ultimately make tire bales available as an accepted material on a large scale for civil engineering applications.

3 CHARACTERISTICS OF WASTE TIRES, TIRE SHREDS AND TIRE BALES

Previous studies have evaluated the engineering properties of the various waste tire products used in civil engineering applications. This has involved both laboratory and field programs. Findings from these studies, which have generally focused on the thermal and the mechanical properties of waste tire products, are summarized herein.

3.1 General characteristics of rubber tires

Rubber tires manufactured for passenger cars and trucks have the following typical composition: (See Appendix C and www.rma.org/scraptires/scraptiremarkets/scraptirecharacteristics/)

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

A typical weight is approximately 110 N (25 lb) for new automobile and light truck tires and 556 N (125 lb) for new truck tires. The average weight of scrap automobile tires is 89 N (20 lb) and 445 N (100 lb) for truck tires. When scrap tires are stored in piles, the approximate number of tires per cubic yard has been reported (Appendix C and email communications on EPA website regarding tire conversion rates: www.epa.gov/jtr/jtrnet/tireconv.htm):

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

Rubber is characterized by its comparatively low thermal conductivity. Some research has already been conducted on the thermal characteristics of waste tire products. The ability of tire shreds to serve as subgrade insulation, due to their low thermal conductivity, was illustrated by a field study in New Hampshire (Eaton et al., 1994). The thermal characteristics of tire shreds were also evaluated as part of a field study regarding insulated landfill liners (Benson et al., 1996). Laboratory tests that have quantitatively characterized the thermal conductivity of tire shreds have generally indicated it to be below 12% of that for typical soils (Humphrey et al., 1997). Thermal diffusivity of whole tires has also been studied by the Colorado School of Mines (Shock et al., 2001). A field monitoring program is underway at the University of Texas at Austin to evaluate the thermal properties of waste tires and tire/soil mixtures.

3.2 Characteristics of tire shreds

A number of laboratory and field studies have been conducted that illustrate the engineering properties of waste tire products, particularly tire shreds. Tire shreds were first used as lightweight fill material to replace a conventional fill and to reduce settlement of a soft organic foundation soil (Geisler et al., 1989). Since then, numerous projects have utilized tire shreds as a homogeneous monofill zone to replace mineral soil and aggregate in road embankments (Bosscher et al., 1993; Bosscher et al., 1997; Hoppe, 1998; Dickson et al., 2001, and Baker et al., 2003). These studies indicate that the structural performance of embankments, which are properly designed and constructed with tire shreds, can be as good as or at least comparable to that of soil-only embankments.

Laboratory studies have been conducted to determine to the basic engineering properties of tire chips and soil/tire mixtures. Humphrey and Manion (1992) completed an early study in which characteristics of tire shreds such as the specific gravity, compacted unit weight, compressibility, and coefficient of lateral earth pressure at rest were determined. The shear strength of tire shreds was studied by conducting triaxial tests and direct shear tests. Humphrey (1998) presents failure envelopes of direct shear tests of tire shreds at low stress levels. The envelopes for normal stresses less than 100 kPa (2000 psf), are characterized by a 4 kPa (80 psf) “adhesion” intercept and a concave downward curved envelope with friction angles in the range of 25 to 30 degrees. This data was reported in 1992 to 1995 for eight laboratory tests of tire shreds sizes ranging from 9.5 mm to 75 mm (3/8 in to 3 in.) in 305 mm to 405 mm (12 to 16 in. shear boxes.)

The compaction characteristics, compression behavior, shear strength, and hydraulic conductivity of tire chips and soil/tire chip mixtures were studied by Edil and Bosscher (1994). Humphrey (1998) presents a summary of the results of laboratory tests of the vertical strain compressibility of tire shreds and the design procedure to estimate the compressibility of a tire shred fill and to compute the amount of overbuild required to compensate for the short-term settlement of tire shred fills during construction, and up to two months following placement of the tire shred fill. The short-term construction settlement of tire shreds is usually less than the laboratory test values on 75 mm (3 in.) shreds, which indicates a 10 to 25 % strain for vertical stresses ranging from 1 to 5 psi (Humphrey, 1998). This settlement is usually addressed by (1) constructing an "overbuild zone" equal to, or somewhat larger than, the estimated settlement, and (2) applying a temporary surcharge to accelerate tire shred settlement and "over consolidate" the tire shred embankment. The secondary, or long-term creep settlements have generally been less than 1 percent of the height of the tire shred zone (Baker et al., 2003). Tire shred settlement is usually monitored by survey of settlement platforms during and following construction to confirm the embankment performs as expected. Temperatures inside the tire shred zone are often monitored to check the potential for exothermic reactions.

The engineering properties of a soil/tire shred mixture including 50% Ottawa sand and 50% shredded tires by volume were studied by Masad et al. (1996). This study illustrated the ability of tire shreds to significantly increase the shear strength of soil. This finding is supported by the findings of Foose et al. (1996) in a study that determined the friction angle to increase from 34 degrees for unreinforced Portage sand to as much as 67 degrees when reinforced with tire shreds. A recent study was conducted using a large scale triaxial apparatus with the goal of evaluating the optimum dosage and aspect ratio of tire shreds within granular fills (Zornberg et al., 2003). The effects on shear strength of varying confining pressure and sand matrix relative density were also evaluated. The tire shred content and tire shred aspect ratio were found to influence the stress-strain and volumetric strain behavior of the mixture. The axial strain at failure was found to increase with increasing tire shred content. Except for specimens of pure tire shreds and soil with comparatively high tire shred content, the test results showed a dilatant behavior and a well-defined peak shear strength. The optimum tire shred content (i.e., the one leading to the maximum shear strength) was approximately 35%. For a given tire shred content, increasing tire shred aspect ratio led to increasing overall shear strength, at least for the range of tire shred aspect ratios considered in this study. The shear strength improvement induced by tire shred inclusions was found to be sensitive to the applied confining pressure, with larger shear strength gains obtained under comparatively low confinement.

3.3 Characteristics of tire bales

3.3.1 Tire bale fabrication

Tire bales are fabricated by a lightweight tire baling machine, which is readily transportable and easily moved by towing with a truck. It should be noted that some cardboard baling machines have been used for forming tire bales. This practice is questionable because a cardboard baler may not be designed for the loads and stresses associated with "conventional" machines specifically designed for baling scrap tires. (Encore Systems, Inc.). The baling machine typically compresses approximately 100 waste auto tires into a 1.5 m^3, 0.9 metric ton (2 cubic yard, 1-ton) bale. Tires are usually "laced" with half the tires overlapped in each layer prior to compression and tying. Each bale is typically fastened with a series of galvanized or stainless steel baling wire (Encore Systems, Inc.). Tire baling results in a 5:1 volume reduction of loose tires. Figure 3.1 shows a typical tire bale with tires that have been laced.

Figure 3.1 Typical tire bale

When truck tires are included with auto tires, each truck tire is considered to be equivalent to five (5) automobile tires and that bale is described as 100 passenger tire equivalent, or "100 pte" (Gilbert email). Truck tires can be cut to remove the sidewalls from the tread. The sidewalls and treads have been used to fabricate construction barrels (Encore, 2004).

It has been reported that one tire baling machine can process 600,000 tires per year in a 1-shift per day operation (Encore, 2004). This is equivalent to 25 bales per day for a 12 month, 20 day per month operation. Other processors report 4 to 6 tire bales per hour, or approximately 40 bales per day. Tire bales can also be fabricated to produce ½ and ¾ size bales, or to make tire bales larger (and heavier) than a typical 1.5 m^3, 0.9 metric ton (2 cubic yard, 1 ton) tire bale. Some of the smaller bales have been encased with concrete (Northern Tyre, 2004). Typical tire bales can usually be easily moved and placed using a forklift.

In some applications, the tire bales are required to be linked together to avoid shifting after placement in the field and improve shear resistance. In this case, the tire bale can be manufactured with a steel pipe positioned in two directions through the middle of the bale (Encore, 2004.). After placement of the tire bale in the final location, an aircraft cable can be routed through the pipe and bolted at the end of the last bale, or clamps can be used to fasten the pipes of adjacent bales together. This allows the connection of several tire bales together. Stacking arrangements, the use of concrete, flowable fill, and inclusion of geosynthetic or metallic reinforcement can also provide beneficial interlocking characteristics to maximize interface shear resistance of tire bales and reduce post-construction movements.

The typical physical characteristics including the dimensions and weights for compacted tire bales as reported in the literature reviewed for this report are shown in Table 3.1.

Table 3.1 Typical physical characteristics of tire bales.

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

Note 1. Numerical values for dimensions, volume, and unit weight depend on the spacing of measurements made around the non planar outer sides of a tire bale (see Figure 3.1).

3.3.2 Tire bales as engineered lightweight fill

Tire bales are classified as an Engineered Lightweight Fill (E.L.F.) material. As noted in Table 3.1, the unit weight of a typical tire bale is approximately 5.5 kN/m^3 (35 lb/ft^3), and comparable to a reported unit weight of 5.3 kN/m^3 (40 lb/ft^3) reported for compacted tire shreds. As the typical dry unit weight of tire bales is approximately 30 % of the weight of typical soils, tire bales become a candidate for use in a situation where a lightweight fill is required for economic and stability reasons and possibly eliminate the need for foundation improvements on soft ground sites. However, other engineering properties including in situ unit weight, compressibility, strength, and time-dependent response of the tire bales are required to evaluate the anticipated performance of a tire bale embankment before tire bales can be used on major highway projects. The tire bale projects completed to date indicate successful applications, but careful monitoring of several projects is necessary to assess and confirm that the long-term performance of tire bales is satisfactory and in accordance with design assumptions.

3.3.3 Tire bale properties

Tire bale properties have generally been qualitatively characterized by the manufacturer of the tire baler, or by limited tests of individual tire bales in a laboratory setting. Although some basic physical characteristics of tire bales have been evaluated as shown in Table 3.1, little information has been reported on the mechanical properties of tire bales which are of interest for civil engineering applications. The engineering properties of in situ tire bales will depend on:

- Mechanical and hydraulic systems of a particular tire baler.
- The size and type of tire, including partial cutting of tires used in a bale.
- Methods used to stack, and the loads used to compress, tires in the baler chamber during each stage of tire bale fabrication.
- The restraining system including the type of tie—wire, strap, or cable, the number of ties applied to a bale, the tensile load applied to the tie, and the fastener.
- The in-service placement geometry for the tire bales, and any connection systems used to develop a tire bale embankment zone.

- The interaction of the surrounding soil/rock/geosynthetic materials which form the matrix within and around the in place tire bales.
- Internal and external physical, mechanical, and hydraulic characteristics (e.g., density, strength, and permeability, respectfully).
- Long-term durability issues for both the tires and the ties used to fabricate the bales.

Due to the compression load and side restraint used by the baling machine to compress tires in the compaction chamber, and the restraint the tie system places on the compressed tires, free-standing tire bales and tire bales installed in an embankment are expected to show a higher shear strength and modulus than other waste tire products. However, short and long-term compressibility of tire bales is one property that deserves further investigation. The compressibility, strength, and time-dependent response of tire bales have not been extensively quantified to the extent necessary for engineering design. Up to 2004 only a few laboratory and field tests on tire bales have been reported, and those tests provide only very limited results, especially considering the potential variability of tire bales, either as manufactured, or in situ where the bale is filled with, or surrounded by, other materials.

The first available laboratory test report, conducted by the Twin City Testing Laboratory for a Minnesota Department of Transportation project, is dated March, 2000 and included in Appendix C.2. The report describes one unconfined compression test and a short-term (3-day) creep test on one tire bale. The limited nature of this study, and the absence of other test data to define the basic engineering properties of tire bales, led to a comprehensive laboratory testing program that was conducted as part of this study and is described in the next section.

Manufacturers of tire bales have generally reported a good bearing capacity for fabricated tire bales. For example, Central States Tire Recycling of Nebraska conducted a study that evaluated the effect of a static load applied to an “Enviro Block” type tire bale. This study showed that loads equivalent to a “fully loaded semi trailer” (dimensions and weight not reported) caused minimal distortion to the “Enviro Block.” The loads were reported to have not compromised the structural integrity of the bale.

The American Society for Testing and Materials has published a "Standard Practice for Use of Scrap Tires in Civil Engineering Applications" (ASTM D6270-98) that provides guidance on the use of scrap tires in the form of tire shreds. Some of the data and guidance has applicability for tire bales used in place of, or along with, stone, gravel, soil, sand or other types of fill.

Tire bales are used in association with other materials. Compacted soil layers have been constructed beneath, between, and above layers of tire bales with the intent to fill voids within or around the tire bales. Tire bales have been reported to maintain their structural integrity in association with surrounding soil layers. In one case the soil matrix around tire bales has exhibited small "sink holes" where subsequent compaction and construction traffic (and possibly precipitation) may have caused internal movement of the soil matrix into voids within the tire bales/soil embankment zone (see Case Study 3 in Appendix B.3). In another example, some applications have used shotcrete, which was applied after installation of the tire bales to provide a facing layer as well as protect and consolidate the tire bale zone. The use of shotcrete reportedly has not caused long-term negative effects on the tire bale performance.

Tire bales have been used in civil engineering and embankment projects for more than 14 years with no reported biological or chemical degradation. However, the authors are not aware of any reports on tire bales, which have been exhumed and subjected to laboratory testing. In addition, the anticipated longevity of tire bales in the various application environments, aging factors and environmental factors that may be detrimental to their use have not been documented.

3.4 Evaluation of potential exothermic reactions in tire bales

The internal heating observed in tire shred embankments raises a similar concern for tire bales. The potential exothermic reaction of tire bales is evaluated in this section and is based on the design guidelines for tire shred fills that were developed in 1997 to reduce significant internal heating created by exothermic reaction in tire shred fills. The guidelines were developed in response to three spontaneous internal fires in tire shred embankment fills greater than 8 m (26 ft) thick in 1995.

An Ad-Hoc Civil Engineering Committee prepared "Design Guidelines to Minimize Internal Heating of Tire Shred Fills". This committee, composed of members from industry, government, and academia, was jointly sponsored in 1995 by the Scrap Tire Management Council and the International Tire and Rubber Association Tire and Rubber Recycling Committee to produce a set of guidelines so that scrap tire use could continue. The principal author was Dr. Dana Humphrey, currently at the University of Maine. The design guidelines were issued by the FHWA in 1997 as a memorandum which stated the guidelines were conservative. These guidelines were adopted by ASTM as a recommend standard of practice in 1998 (ASTM D 6270). The ASTM requirements for tire shred fills are listed below in Column 1 of Table 3.3. For comparison, the preliminary requirements for tire bales placed in a transportation application are listed in Column 2 and a qualitative relative comparison of the requirements for tire bales versus tire shreds are listed in Column 3.

Table 3.2 Preliminary application of tire shred guidelines to tire bale embankments

Guidelines to Reduce Exothermic Reactions in Tire Shred and Tire Chip Embankment Fills (**ASTM D 6270**)	**Apply Column 1 Guidelines to Tire Bale Embankments (Preliminary)**	**Compare Column 2 to Column 1 (Preliminary)**
G.1 **Cut/shred all tires** to: a) largest piece is less than a quarter circle in shape, b) less than 0.6 m long, and c) one sidewall is severed from the tire tread	Fabricate tire bales with whole tire, or allow maximum % of cut tires. (Note 7)	Not required & no cost for tire bales.
G.2 **All tire shreds shall be free of contaminants** that could create a fire hazard (Note 1)	Monitor visually, remove or clean contaminated tires.	Same requirement
G.3 **Eliminate all tire shreds that contain remains of tires subjected to fire. (**Note2)	Monitor visually, remove or clean contaminated tires.	Same requirement
For CLASS I Fill (< 1 m thick) of Tire Shred or Tire Chip Materials	(Note 8)	
I.1. Maximum of 50% (by wt) pass 38 mm (1.5 in) sieve (Note 3)	Not Applicable	No cost for tire bales
I.2 Maximum of 5% (by wt) pass 4.75 mm (0.18 in) sieve (Note 3)	Not Applicable	No cost for tire bales
For CLASS II Fill (1 – 3 m thick) of **TS-TC Materials** (Note 4)		Note 7
II.1. Maximum of 25% (by wt) pass 38 mm (1.5 in) sieve. (Note 3)	Not Required	No cost for tire bales
II.2. Maximum of 1 % (by wt) pass 4.75 mm (0.18 in) sieve. (Note 3)	Not Required	No cost for tire bales

Table 3.2 Preliminary application of tire shred guidelines to tire bale embankments (continued)

II.3 Tire shreds free of wood fragments, wood chips, and other organic matter. (Note 1)	Monitor visually & clean to remove organics	Same requirement
II.4. Maximum of 1 % (by wt) of metal fragments that are not at least partially encased in rubber. (Note 3)	Not Required	No cost for tire bales
II.5 Metal fragments partially encased in rubber shall protrude no more than 25 mm (1 in.) from the cut edge of a tire shred on 75 % of the pieces and no more than 50 mm (2 in.) on 100 % of the pieces. (Note 3)	Not Applicable (Tire bales are fabricated using whole tires, or a maximum percent of cut tires.) (Note 8)	No cost for tire bales
II.6 Minimize infiltration of water into the tire shred fill. (Note 5)	Not Applicable	No cost for tire bales
II.7 Minimize infiltration of air into the tire shred fill. (Note 5)	Not Applicable	No cost for tire bales
II.8 No direct contact between tire shreds and soil containing organic matter, such as topsoil. (Note 6)	Geotextile is not required to reduce exothermic reactions, but used to provide separation.	Limited cost increase for tire bales Limited contact of exposed steel to organics in a tire bale
II.9 Tire shreds/chips shall be separated from the surrounding soil by a geotextile. (Note 6)	See above note, not needed on subgrade	Limited cost for tire bales
II.10 Avoid drainage features at bottom of the tire shred chip fill that provide air free access to the fill. (Note 5)	Not Applicable	No cost for tire bales

Notes

1. Implies specification to visually monitor and remove unsuitable materials as needed.
2. Implies specification to visually monitor and segregate unsuitable materials as needed.
3. Requires visual monitoring, sampling, and laboratory testing for verification.
4. A 0.6 m (2 ft). thick layer of soil is typically placed between each 3 m (10 ft) or less, thickness of tire shred fill.
5. Requires: (a) sealed geomembrane to encapsulate the tire shred zone and (b) back flow seals on bottom drains.
6. Requires geotextile, geomembrane, or a 6 in. minimum thick layer of soil as separator/filter material.
7. The maximum thickness of Class I and II Tire Bale Embankments has not been determined.
8. The allowable percentage of cut tires has not been determined.

To summarize the evaluation in Table 3.2, the application of the ASTM D 6270 tire shred guidelines to a tire bale fill would indicates that three (3) of the 15 tire shred fill guide lines should be applied to a tire bale fill. The three guidelines generally applicable to a tire bale fill relate to monitoring and removal of contaminants and tire pieces that had been subjected to a previous fire and could cause a fire hazard. In addition the separation requirement for tire shreds in II.8 can be provided by a geotextile between tire bales and adjacent soils instead of a layer of mineral soil.

In reference to Note 8 in Table 3.2, it is the authors' opinion that the maximum thicknesses of a Class I and a Class II tire shred fill in ASTM D 6270 are conservative for tire bales and may ultimately be somewhat larger than the maximum thicknesses of 1 m (3.28 ft) for a Class I tire shred fill, and approximately 3 m (10 ft) for a Class II tire shred fill. The specific requirements for each class will require further evaluation in prototype field applications as recommended later in Sections 9 and 10.

The ASTM D 6270 guidelines primarily cover in-situ application issues. Other ancillary operations also require control including processing whole tires into compacted tire bales, pre-placement handling, storing and stockpiling, hauling, and installing the tire bales. However, the guidelines provide the basis for project specifications, which should be prepared specifically for each tire bale project to address both the design issues and the ancillary issues that are the responsibility of the material supplier and contractor.

Some of the fire protection and safety issues relating to storage of scrap tires and operation of tire recycling facilities have been codified. Plans for scrap tire processing operations are typically reviewed and permitted by local and state fire marshal officials. Examples of fire protection codes and fire protection/safety policies and requirements are discussed below.

3.4.1 Regulatory guidance for storing scrap tires

In addition to the ASTM D 6270 design and construction guidelines to reduce exothermic reactions in tire shred fills, requirements to reduce and control fire hazards associated with storage of new whole tires, scrap tires piles, and tire shreds have been evaluated by a number of agencies. The documents would apply to permanent and temporary tire bale stock piles, both at the fabrication facility and at the construction site, and include:

1. The Colorado Department of Public Health and Environment, State Board of Health/Hazardous Materials and Waste Management Division regulations pertaining to Recycling Facilities in 6 CCR 1007-2, Section 8 and Scrap Tire Facilities in Section 10. Section 10 includes requirements for a fire control plan, tire pile storage dimensions, separation distances, and reporting fire incidents. (See Appendix G).

2. Title 14 California Code of Regulations Division 7 Integrated Waste Management Board (IWMB), Chapter 3, Article 5.5 titled Waste Tire Storage and Disposal Standards (Sections 17350 to 17356) includes a list of outdoor storage requirements and a table of minimum separations distances depending on the size and height of tire stockpiles. (See Appendix G)

3. The National Fire Protection Association, in NFPA 231D 1998, includes Guidelines for Outdoor Storage of Scrap Tires. NFPA 231 D primarily addresses code and fire protection requirements related to inside storage of rubber tires in warehouse and retail structures and the related fire protection systems. However, an appendix is included for information and is not a NFPA requirement. This appendix provides information on fire experience, separation of tire piles based on size and height of tire piles, fire department access to storage sites, site security, pre-incident planning, water supply, pile geometry, separation distances, and fire-fighting tactics and strategy for both whole tires and processed tire fires. Information in the document is similar to information provide in the California Code in Item 2 above.

4. The U. S. Fire Administration (1998) prepared Special Report 093 titled "Scrap and Shredded Tire Fires", which examined seven case histories of typical tire fires. It summarizes key issues associated with the historical background of tire recycling, regulatory impacts, tire storage and processing conditions, and the supply – demand issues related to production of tire shreds and crumb rubber for highway applications. The report also discusses the issues and hazards related to ignition of tire materials, selection of materials and equipment to control and suppress tire fires, problems related to fire operations, and cleanup costs. The three stages of tire product combustion are described in the report and the difficulties of controlling and extinguishing tire fires. Depending on the strategy and approach tire fires can continue for days or months.

   It should be noted that the U.S. Environmental Protection Association (EPA) does not consider scrap tires a hazardous waste. However, once there is a fire, the tire product breaks down in hazardous compounds including gases, heavy metals, and oils. The average auto tire is estimated to produce more than two gallons of oil which is a significant environmental pollutant that can move into groundwater and contaminate well water.

5. The California Integrated Waste Management Board (IWMB) has published an extensive training manual titled “Tire Pile Fires: Prevention, Response, Remediation” dated September 23, 2002. The manual focuses on California’s history of tire regulation, fire prevention, response to tire fires, and post fire assessment and remediation.

3.4.2 Reports of tire bale storage requirements and fires

The number of available reports on tire bale storage requirements and tire bale fires is limited. The only available paper providing a direct comparison of the effects of burning the three different types of scrap tires available to the authors at this time is a paper published in Interflam "96" March 1996, titled "Fire Safety Assessment of the Scrap Tire Storage Methods" (Williamson and Schroeder, 1996). This paper is also cited as a reference in NFPA 231D "Standard for Storage of Rubber Tires", 1998. The report describes three instrumented experimental fires conducted in September 1993 at a scrap tire yard in Tracy, California to compare whole tires, tire shreds, and small tire bundles (16 to 18 tires per 0.75 m (30 in.) long stacked, tied with 2 strands of wire and polymer cord).

The test, sponsored by the California State Fire Marshal’s office, consisted of burning piles of each type with approximately 100 tires in each pile. Fire monitoring included measurement of flame height and change in heat flux with distance. The test data was analyzed with a computer program (Building Radiation Program Version 1 --BRAP1) in order to calculate the thermal radiation from an equivalent building fire. The program was then used to solve the configuration factor equation and relate the observed heat flux and temperature data to separation distances that would be required between scrap tire piles composed of three different tire materials. The calculation of a required minimum separation distances between storage piles was based on the maximum heat flux (10 kW/m^2) which would not ignite an adjacent target tire pile, and the maximum heat flux (5 kW/m^2) which human skin (fire fighters) can tolerate in normal turnout gear. The separation distance computed by these criteria was then compared with the California regulations.

Williamson and Schroeder (1996) include several observations and conclusions relating to open air storage of scrap tires. These are:

- Whole tires should be barrel stacked (because fires in horizontally stacked tires are much easier to control – (Williamson, personal communication 2004).
- Shredded tires reduce tire volume but exhibit rapid spread of surface flames.
- Piles of shredded tires should be placed on level ground, limited in size, and not placed against a wall or sloping hillside (to reduce rapid spread of surface flames).
- The bundled tires expanded in size when the tie wires and cords burned, reaching a size approximating the whole tire pile. (Note: The tire bundles were much smaller in size, and had approximately half of the compressed density of typical tire bales, and apparently used different tie materials than the typical tire bales described in Section 4 of this report.)
- The required minimum separation of tire piles is related to the height and length of tire piles.
- Minimum separation distances should also consider the impacts of a tire fire on air quality, wind conditions, and nearby occupants and use of the surrounding area.

The authors' personal communication with Mr. Rodney Slaughter, California Deputy State Fire Marshall (2004) indicates that tire bale fires in open storage facilities could be difficult to control and extinguish, more so than tire shreds apparently based on the results of the Williamson and Schroeder (1996).

3.4.3 Summary of fire protection evaluation

In summary, the issue of appropriate fire protection and design procedures to reduce the risk of fires involving tire bales is a complex issue that involves many conditions. Developing an appropriate approach to fire protection issues for tire bales requires consideration of the current regulatory guidance for tire storage, experience with fires in uncontrolled outdoor storage of whole scrap tires, and the observed success of tire shred fills designed and constructed in accordance with the ASTM 6270 design guidelines. The general experience with tire fires includes the following issues:

1. **Ignition sources.** Piles of whole tires and tire shreds occasionally burn as the result of unexpected human or natural events such as arson, adjacent small fires, and lightning strikes. Tire fires also start due to the presence of contaminants, organics, air, water, small sized rubber particles and shreds (placed in thin to thick layers) in uncontrolled tire stockpile and/or tire shred fills, which result in the oxidation of exposed steel and develop a significant exothermic reaction that ultimately reaches ignition temperatures which range from 400 to 1000°F. However, implementation of the ASTM D6270 guidelines for tire shreds indicates that controlling the factors that lead to an exothermic reaction can substantially reduce the risk of fires in tire shred fills, and no fires have been reported to date for those projects. In addition, tire bales (as illustrated in Table 3.2) do not inherently "fit" 13 of the 15 design guidelines for tire shreds. The tire shred guidelines for cleanliness, are considered initially appropriate for tire bales, but particle size criteria and limitations on air and water access for tire shreds are not currently considered a substantial requirement for tire bales because tire bales are inherently considered less susceptible to exothermic reactions than tire shreds.

2. **Tire Stockpiles** Current regulated practices for outdoor storage of whole tires and shredded tires is to control size of storage piles, provide and implement appropriate fire prevention practices, provide minimum separation between stockpiles, and restrict and control site access, etc. These practices should also be used for storage and transportation of tire bales until sufficient laboratory test data is available to justify modification of current practices and state guidelines for whole tires and tire shred fills which are already under the jurisdiction of local and state fire marshals as discussed above and codified in state codes and requirements.

3. **In-service Conditions** In-service conditions for tire bale embankments can be considered similar to typical tire shred embankments. However, the response and performance of tire bale materials is expected to be somewhat better than the inherent performance of tire shred embankments. As a starting point, some of the current ASTM 6270 guidelines for tire shred embankments could be appropriate guidance for tire bale fills. Field test sections and in-service temperature measurements are required to evaluate the benefits of soil covers for fire protection purposes and develop a feasible design approach for tire bale embankments that could include the use of soil barriers to form "fire walls" and limit the lateral dimensions of tire bale zones.

4 MEASURED PHYSICAL AND MECHANICAL PROPERTIES OF TIRE BALES FROM LABORATORY TESTS

The literature review and the authors’ discussions with tire baler manufacturers and public works engineers who have used tire bales in embankment applications indicates that a very limited number of laboratory tests have been conducted to determine the engineering properties of fabricated tire bales for design purposes. The absence of test data to define the basic engineering properties of tire bales led to the performance of the 2004 laboratory testing program that is the basis for the tire bale properties including in this report. The following laboratory test program was developed to determine the essential material properties needed for the design and construction of embankments with tire bales. Results of each test are presented followed by a summary of tire bale properties as determined from the test results and literature review. This section concludes with a comparison of tire bale and other lightweight fill material properties.

The 2004 laboratory testing program consisted of performing laboratory tests on eight tire bales, fabricated by Front Range Recycling, Sedalia, Colorado. The tests were performed for CDOT by GeoTesting Express, Roswell, GA in 2004. The 2004 laboratory tests included measurement and evaluation of tire bale to determine typical values for the:

- Range and average geometry of the exterior surfaces of the tire bales.
- Range and average unit weight, both air dry and submerged.
- Vertical permeability
- Compressibility characteristics with both vertical and horizontal deformation measurements on tire bales.
- Confined compressibility of tire bales (with a dry sand infill materials), including static and cyclic modulus evaluation.
- Rebound and potential lateral expansive pressure.
- Time-dependent deformations of single bales under sustained load (i.e. creep) for up to 1,000 hours.
- External shear strength along the surface between two vertically stacked bales.

The detailed test procedures and results of these tests are presented in Appendix D. The following sections provide a summary of the test procedures and results for each of the tests performed.

4.1 Geometry of the exterior surfaces of the tire bales

Unit weight tests were made on all eight tire bale samples. The procedure consisted of volumetric measurements, weight of the sample as received, and noting any presence of moisture in the bale. The volume was measured by taking dimensional measurements of the height, width, and length of each tire bale. The height was measured with the bale lying on its flat base with the tires oriented in a vertical direction (as was shown in Figure 3.1). This position is also assumed to be the “vertical direction” for both laboratory testing and field placement. For dimensional measurements, a significant number of measurements were taken to obtain unit weight measurements within a 1 % accuracy and repeatability. Digital image analysis was used to confirm the measurements with two digital photos (front and side view) taken of each bale along with a visible reference scale mounted on the bale using a level camera located vertically at the mid height of the bale. Representative images are shown in Appendix D of this report. The typical measured dimensions were:

Height	0.7 ± 0.03 m	(2.3 ± 0.1 ft.)
Width (band direction)	1.46 ± 0.02 m	(4.8 ± 0.07 ft)
Width (cross-band direction)	1.55 ± 0.06 m	(5.1 ± 0.2 ft)
Volume =	1.59 ± 0.085 m^3	(56 ± 3 ft^3)

4.2 Dry, wet and submerged unit weight of “as received” tire bales

Two tire bales were stored in a dry environment for a sufficient period of time (i.e., no weight change within a 1 day period of time) in order to obtain an air dry unit weight for these two samples. These two samples were also used to obtain the submerged and wet unit weight of the tire bales. Submerged unit weight measurements were obtained by submerging the entire bale in a tank of water for a sufficient period of time to allow all free air to escape and obtain the weight below water. Prior to placement in the tank, the water in the tank was maintained at room temperature for over 24 hours to reduce the amount of and equilibrate the dissolved oxygen in the water. After obtaining the submerged weight, each sample was extracted from the water, allowed to freely drain, and weighed immediately after drainage to obtain the wet unit weight. The following unit weights were determined for the tire bales tested:

Dry unit weight =	5.74 ± 0.47 kN/m^3 (36.5 ± 3 pcf)
Wet unit weight =	6.21 ± 0.31 kN/m^3 (39.5 ± 2 pcf)
Submerged unit weight =	0.67 ± 0.23 kN/m^3 (4.3 ± 1.5 pcf)

The submerged unit weight result indicates that tire bales do not float, which can be a major advantage in below water or flooding applications over lightweight fills which float (e.g., EPS).

4.3 Vertical permeability of tire bales

Note that the permeability of an in-place tire bale will vary in all three directions, and vary in different parts of the tire bale due to the heterogeneity of the tires and the void sizes and the adjacent infill materials. For embankment applications the vertical permeability, which defines flow vertically through stacked tire bales, is considered to be the most critical value due to drainage of infiltration seepage water and potential buoyancy during flooding. The vertical permeability of two tire bales was evaluated by rapidly extracting the bale, after it was submerged in a water filled tank, and then monitoring the time for water to completely drain from the tire bale under gravity flow. The horizontal sides of the tire bale were wrapped with a membrane before the bale was submerged to prevent lateral water flow from the sides of the bale as it was extracted from the tank. The time to extract the tire bale was sufficiently rapid to provide differential head between the water in the tank and the water level in the tire bale. About 75% of the water flowed out of the bale during extraction from the submerged condition in less than 1 min., indicating a permeability of greater than 0.1 cm/sec. After extraction, approximately 0.068 m^3 (2.4 ft^3) of free water remained in the bale based on the weight of water that drained from the bale. Approximately 90 % of the remaining free water was found to drain from the tire bales in 10 to 15 min. and practically all of the free water drained within 20 to 25 min. The measured flow rates indicate that tire bales have a relatively high intrinsic vertical permeability on the order of 0.05 to over 0.1 cm/sec, which is similar to that of gravel.

4.4 Compressibility tests with both vertical and horizontal deformation measurements

Compression tests on the tire bales were performed generally following the ASTM D2166 Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. Figure 4.1 shows a photo of the test setup. The top and bottom loading platens consisted of large concrete slabs, with dimensions that extended in all directions beyond the edge of the fully loaded sample, and a surface area larger than the surface area of the compressed tire bale. The loading platens were also sufficiently stiff to distribute the load uniformly across the sample in order no to bend or deform during testing.

A minimum of three vertical deformation measurements were made to an accuracy of 2.5 mm (0.1 in.), by gages located within equal distances around the sample (e.g., 3 gages located at the third points around the sample.) Lateral movement was also measured in at least three equally spaced (from top to bottom) vertical locations on all four sides of the sample. A calibrated load cell was used to measure the applied load. Both continuous data monitoring (with data acquisition methods) and manual readings were used to check vertical and horizontal deformation as a minimum at every 45 kN (10 kips) up to 450 kN (100 kips) and at every 112.5 kN (25 kips) up to the full load condition. An unload–reload test was performed on one tire bale.

The stress-strain curves obtained from the tests are shown in Figure 4.2. The test results indicated that the tire bales tested did not have a peak strength at stress levels of less than 815 kPa (17 ksf). The vertical strain of the tire bales was over 60% at the maximum test loads. However, at working stress levels [less than 50 kPa (1 ksf)], strains are much lower and will be further reduced by confinement as discussed in the next section. Circumferential deformation measurements also indicated a relatively low Poison’s ratio on the order of 0.1 to 0.2 at low working stress levels [less than 50 kPa (1 ksf)], increasing to 0.3 to 0.4 at higher stress levels. Lateral movement at low stress levels is likely restricted by the combination of compression during baling, vertical orientation of the tires in the bale and the restraint from the wire ties.

Figure 4.1 Typical tire bale compression test setup

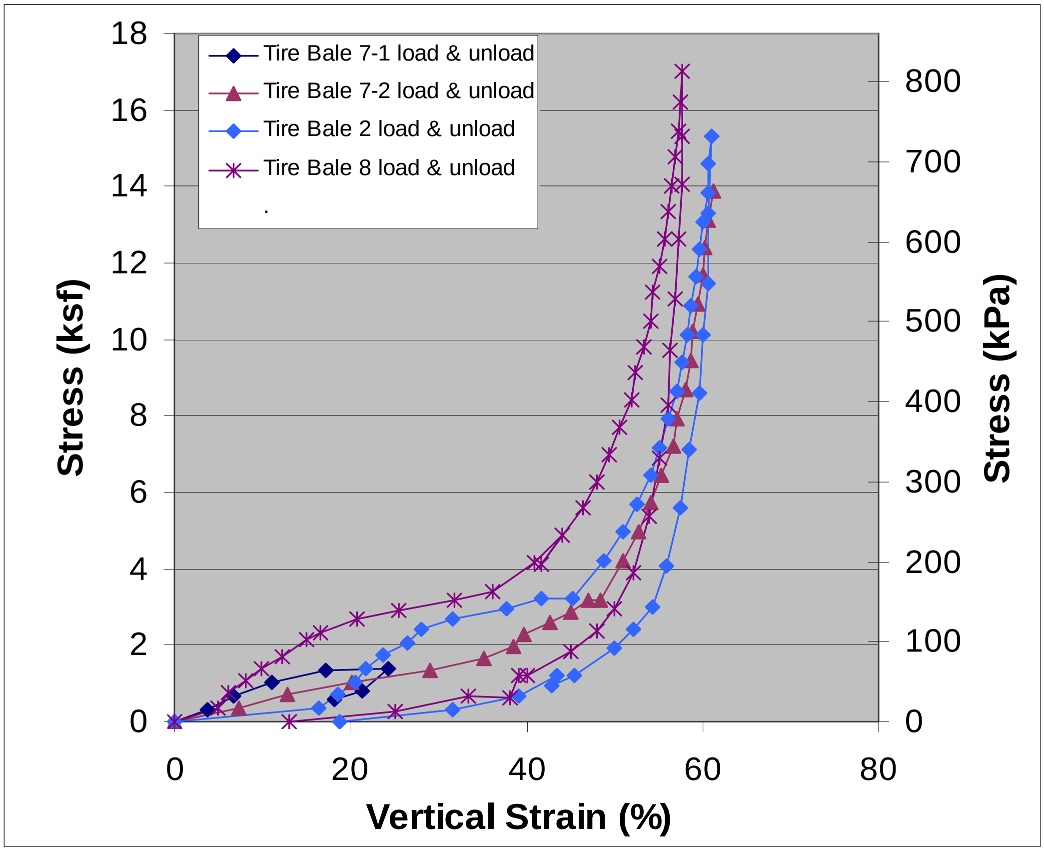

Figure 4.2. Stress-strain results from tire bale compression tests

4.5 Unconfined and confined compressibility tests (i.e., without and with infill materials) at working loads, including static and cyclic modulus evaluation

These tests were performed in a similar manner as the previously described compression tests except that the maximum load was 90 kN (20 kips), e.g. equivalent to a 5.2 m (17 ft) thick tire bale embankment above the sample, and the cyclic load test was performed at 40.5 kN (9 kips) using a 0.3 m (1 ft.) diameter plate to simulate a vehicle load at the surface of the tire bale.

Two tests were performed on two separate tire bale samples, one was performed on the tire bale alone “unconfined” and the other was “confined” by surrounding the bale with a minimum of 0.15 m (6 in.) of dry, fine to medium sand. For the confined test, the sample was placed in a rigid concrete box, the sand was placed in the annulus between the sides of the box and the sample, and the surface of the sand was compacted with a minimum of five passes by a vibratory plate compactor. Surface depressions in the sand that developed during compaction were refilled and compacted to form a level surface prior to applying the test load.

Prior to performing the static compression tests, cyclic load tests were performed. These tests were performed to evaluate deflection under construction traffic and to provide a pseudo evaluation of resilient modulus. The test was developed specifically for this study and is a type of plate bearing test. A rigid circular plate of 1 ft (300 mm) in diameter and a load of 45 kN (9 kip) applied at a 1 ± 0.5 hertz frequency was used to simulate traffic loading (i.e., a standard single wheel load moving at construction speeds). A level bearing surface was provided beneath the circular plate using a non-shrink mortar mix. The test was performed for a minimum of 1000 cycles. Vertical deformation measurements (to an accuracy of 0.0254 mm (0.001 in.) were made using LVDT’s and a data acquisition system.

The cyclic load test results for the unconfined and confined tire bales are shown in Figure 4.3. The minimum deformation represents permanent deformation in the tire bale and appears to be fairly similar for the unconfined and confined conditions. However the peak deformation is significantly reduced for the confined case and correspondingly the peak deformation minus the minimum deformation, representing a resilient value, is correspondingly reduced.

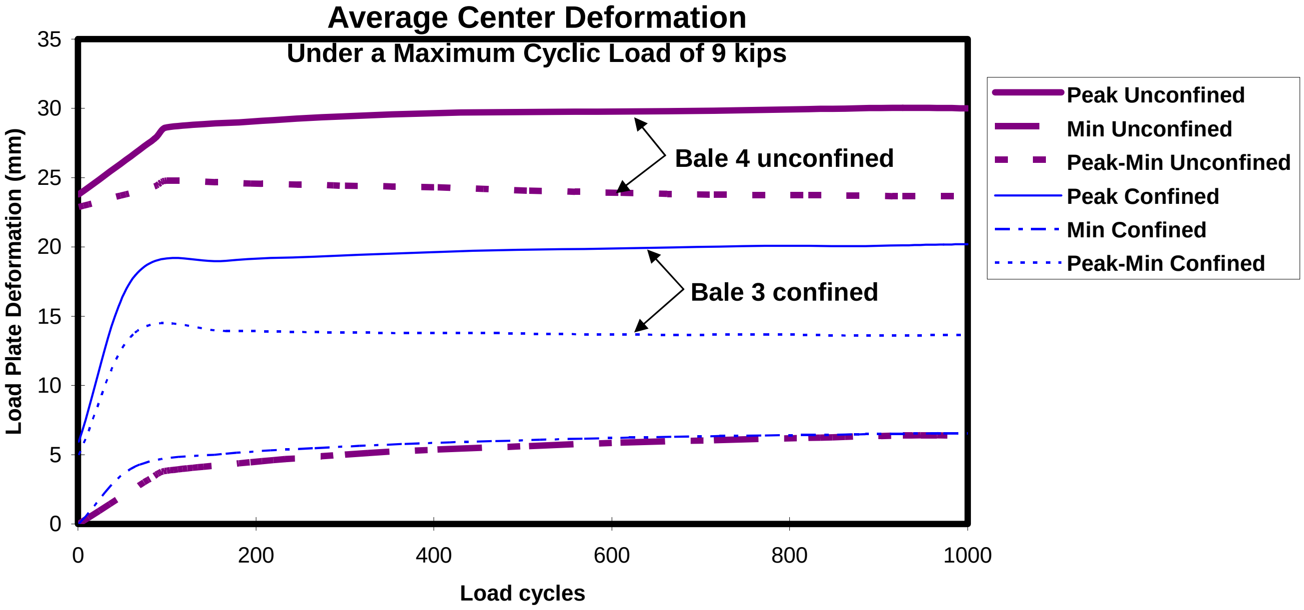

Figure 4.3. Confined and unconfined cyclic load test results

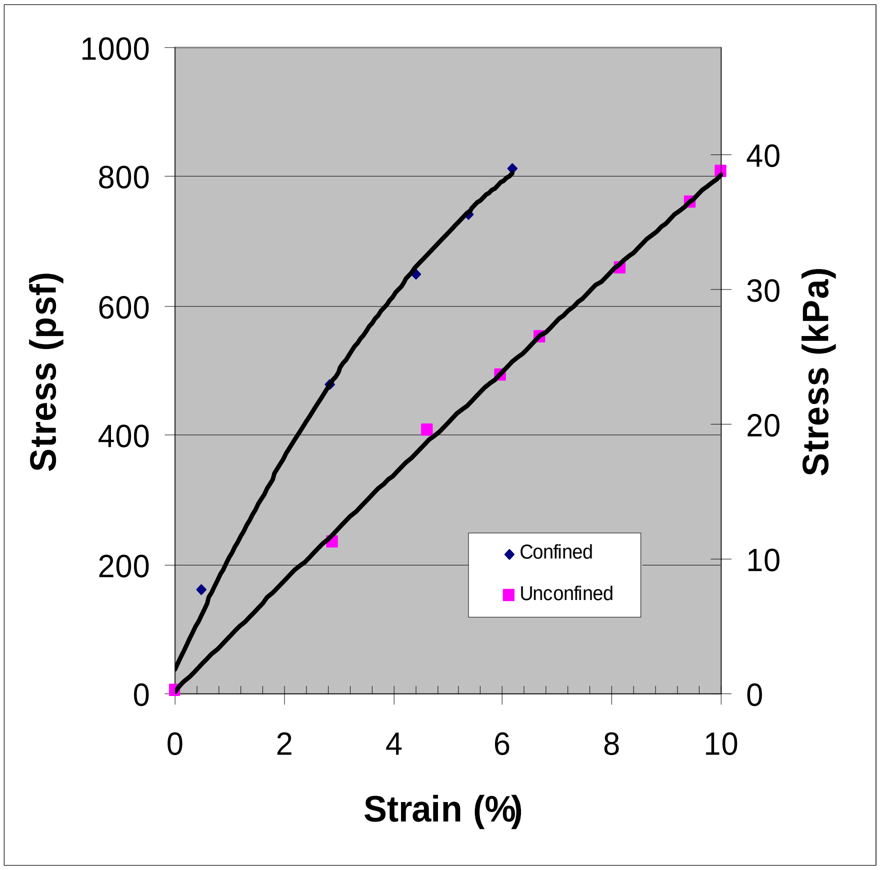

Figure 4.4. Unconfined and confined stress-strain characteristics of tire bales

The resilient value corresponds to a modulus of subgrade reaction of approximately 21 MN/m^3 (77 pci) for the unconfined case and 41 MN/m^3 (150 pci) for the confined case. An equivalent resilient modulus value would be on the order of 21 MPa (3 ksi) unconfined and 52 MPa (7.5 ksi) confined, which even unconfined is over twice that of tire sheds and equal to that of EPS.

Following the cyclic load test, a static load deformation test was performed to 95 kN (20 kips). The stress-strain results obtained from the unconfined and confined tests are shown in Figure 4.4. The curves in Figure 4.4 clearly show that the modulus of the system is improved with confinement of the tire bale, indicating a benefit of infilling. Even when infill is not used, some confinement will be provided by the surrounding bales, indicating that strains under working stress conditions (i.e., settlement of a pavement surface due to tires in embankment) will be low (on the order of 6 to 10 %), most of which should occur during construction. Settlement of the pavement surface could be further controlled by preloading (e.g., overbuild the embankment by approximately 10%), as is currently done for tire shreds (with 20% overbuild typically required).

4.6 Time-Dependent deformation of tire bales under sustained load (i.e. creep)

The tire bale creep tests consisted of placing a constant load on a single, “fresh” (i.e., previously not used) unconfined tire bale and monitoring the deformation response for a period of up to 1,000 hrs (1.39 months) at a constant room temperature. The test setup is shown in Figure 4.5. As shown in the figure, the tire bale was placed on the base of a concrete box, which provided the reaction. A 25 mm (1 in.) thick steel plate with an area greater than the compressed tire bale was placed over the bale as a load platen. Twin air bags were used to sustain the required load. A second steel plate was placed above the air bags, and a load cell was placed between the upper steel plate and a reaction beam to monitor the applied stress. The vertical deformation measurements were made using three gages, with an accuracy of 0.0254 mm (0.001 in.) placed evenly (at the third points) around the sample. Three tests were performed. One tire bale was tested with an applied load of 36 kN (8 kips), equivalent to a vertical stress of 15 kPa (314 psf) based on the cross sectional area of the bale, for a period of 60 hours. This stress simulates a normal cover thickness over the bales [i.e., 0.6 to 1 m (2 to 3 ft) of cover soil]. The other two tests were loaded to 90 kN (20 kips), equivalent to a vertical stress of 39 kPa (815 psf),

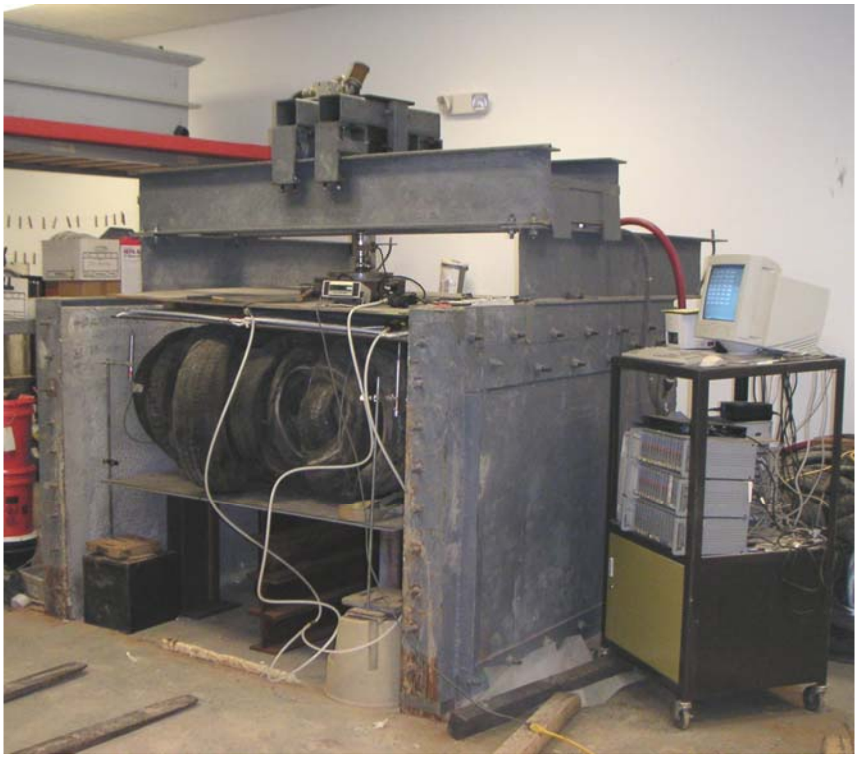

Figure 4.5. Creep test setup.

simulating the stress on the bottom bale of a 5.5 m (18 ft) thick embankment including 1 m (3 ft) of soil cover. The first 90 kN (20 kips) test experienced accelerated movement on one corner after approximately 190 hours and the test had to be terminated. There is a tendency for tires to shift laterally in their unconfined condition. This problem was also noted in the compression testing, but should not occur when tires are confined by other tires (as well as infill, if used). The second test was performed for a period of 1000 hours.

Creep curves for all tests are shown in Figure 4.6 and indicate relatively little creep response at low, working stress levels. Approximately 95 % of the deformation occurred in the first day and the maximum deformation appeared to occur within three days. Progressive deformation in different regions of the bale resulted in variation in both deformation and load, making the determination of creep strain rate difficult. However, the creep deformation did not exceed 1.5 mm (0.06 in.) on average over the last 900 hours of sustained loading resulting in an estimated creep strain rate of 0.005 %/day. This post 3-day movement would roughly be the anticipated post construction movement and, as previously indicated, could be reduced by preloading.

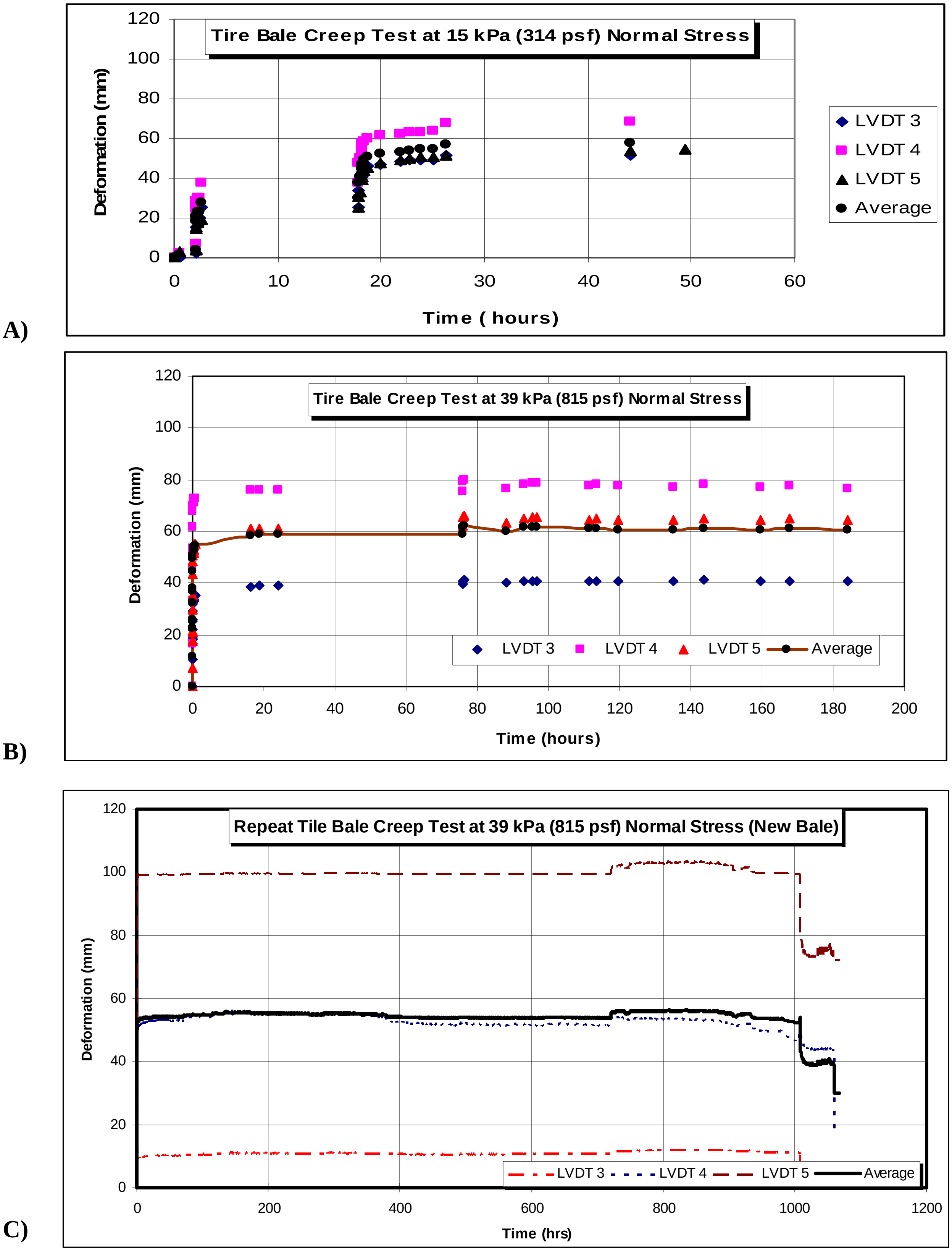

Figure 4.6. Creep test results showing: a) 15 kPa (314 psf) normal stress test, b) 39 kPa (815 psf) normal stress test, and c) repeat 39 kPa (815 psf) normal stress test

4.7 Shear strength of interface between two vertically stacked tire bales

In this test, a direct shear test of the tire bale interface was performed by: 1) vertically stacking two tire bales, with the tire treads in each tire bale oriented in the same direction; 2) restraining the upper bale from moving laterally; and, 3) measuring the force required to pull out the bottom tire bale, which was supported by a steel plate moving on low friction rollers. A hydraulic jack and steel frame placed over a steel load platen was used to apply the normal load. Tests were conducted at normal loads of 9 kN (2 kips) (i.e., the dead weight of the upper bale), 18 kN (4 kips), and 27 kN (6 kips). During application of shear force the bales tended to roll due to interlocking at undulations on the interface surfaces, rather than slide along the interface. This resulted in eccentric loading on the load cell used to monitor the normal stress and the test had to be stopped before a peak shear stress could be reached. Figure 4.7 shows the results of the shear tests and represents a lower bound shear envelope due to the loading problem. The interlock is represented in the results by the adhesion intercept (approximately 2.4 kPa (50 psf)) and a lower bound interface friction angle δ ranging from 25° to 30°.

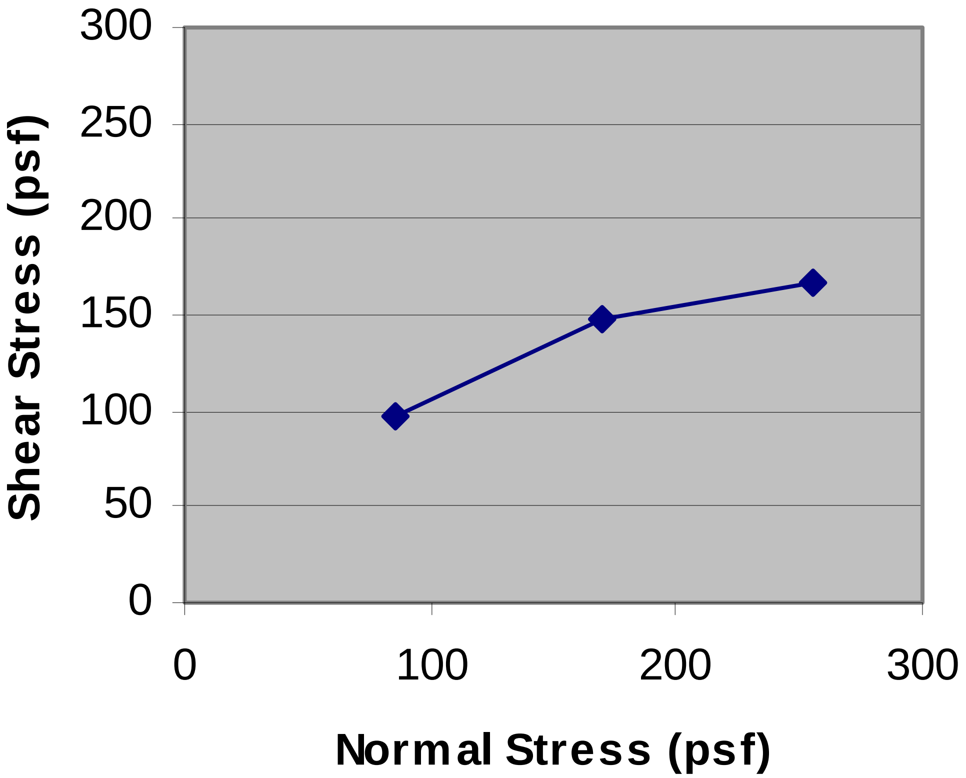

Figure 4.7. Shear at interface between two vertically stacked tire bales (1 psf = 48 Pa)

4.8 Rebound of tire bales and potential expansive pressure of tire bales

Tests were performed to investigate the long-term performance of tire bales (before the end of service life) when there is a possibility that tie wires around the tire bales could break, allowing the tire bales to swell. Wire breakage would primarily be of concern for the upper level bales and bales near the sides where vertical and lateral earth pressures are low. In order to evaluate the uplift potential of tire bales, two tests were performed, one to evaluate free swell and the other to evaluate swell pressure. In the first test, a rigid piston with a load cell was placed on the sample using a wooden pallet as a platen to facilitate cutting of the wires. The five vertical tie wires were then cut and the load required to prevent any upward vertical movement was measured. The load to prevent uplift was relatively small and stabilized within an hour at 1.6 kN (360 lbs), which is equivalent to a normal stress of only 0.70 kPa (14 psf). However, after cutting of the wires, significant lateral movement was observed and continued after the load had stabilized. After no increase in upward pressure was observed, the load was released and the upward vertical movement was monitored until no additional movement occurred. A relatively small average vertical movement of 25 mm (1 in.) was measured. The lateral movement was significant with almost 600 mm (2 ft) of movement observed in the band width direction [300 mm (1 ft) on each side], until the bale was restrained by the sides of the 2 m wide (6.6 ft) container as shown in Figure 4.8.

Due to the significant lateral movement observed during the first test, the second test was performed by restraining the lateral movement with several lifting straps, simulating confinement by adjacent tire bales. All five vertical tie wires on a tire bale were cut and the upward vertical movement monitored. The vertical movement appeared to stabilize within the first few hours at approximately 36 mm (1.4 in). Monitoring continued for a period of 4 days with no additional movement observed. These results indicate that the band width direction, which is the direction of compression loading during fabrication, is the most critical direction in terms of swelling movements and pressures. The bales used in the test were manufactured at different times. However, due to differences in test setup, no observations could be made concerning age of the bales. In future rebound tests, aging should be evaluated and an effort should be made to evaluate the stress required to laterally constrain the bales (i.e., prevent lateral movement).

Figure 4.8. Rebound test on tire bales showing lateral expansion in the first test

4.9 Summary of measured tire bale properties

Table 4.1 lists physical and mechanical properties that will likely be required to develop design and construction practices for tire bale embankment systems. The data is taken from the laboratory tests in Appendices C and F, information cited by tire baler manufacturers, and literature reviewed for this report.

Table 4.1 Physical and mechanical properties of tire bales.

PROPERTY	VALUE	COMMENTS
UNIT WEIGHT		
--Unconfined, dry	5.2 to 6.1 kN/m^3 (33 to 39 pcf)	See Appendix D. Agrees with typical values cited by tire bale producers.
--Unconfined, wet	5.8 to 6.4 kN/m^3 (37 to 41 pcf)	See Appendix D
--Unconfined, submerged	0.5 to 0.9 kN/m^3 (3 to 6 pcf)	See Appendix D
--Insitu with soil	7.8 to 9.4 kN/m^3 (50 to 60 pcf)	Estimated by authors assuming 0.15 m (0.5 ft) of soil in void between tires + 0.76 m (2.5 ft) of tire bale in each 0.91 m (3 ft.) layer & no soil in bales.
--Encased with concrete	11 kN/m^3 (70 pcf)	For ¾ size tire bale, 1.2 m^3 (1.56 yd^3) & a total weight of 15 kN (3.4 kips) (Urro Block by Northern Tyre ,2004)
SPECIFIC GRAVITY	1.01 to 1.2	Range of values for bulk, saturated surface dry, and "apparent conditions" for tire shreds having steel or glass belts (ASTM D 6270).
HYDRAULIC CONDUCTIVITY		
--Unconfined Intrinsic	0.05 to 0.1 cm/sec	Depends on head. See Appendix D
--Unconfined Bale layer	unknown	Anticipated: Relatively high, depends on opening size between tire bales.
--In situ with soil infill	≥ tire bale intrinsic value	Depends on soil type used to fill opening between tire bales.
COMPRESSIVE STRENGTH		
(March 2000 Test) **Load to 1,507 kN (339 kip)**		See March 2000 Test Data - Appendix C Test Bale ~ 30 in. x 50 in. x 60 in.
• **Maximum Applied Stress**	773 kPa (16.28 ksf)	Load Deflection Test (LDT) used 50 in by 60 in. (20.8 ft^2) steel plate.
• **Strain at Maximum Stress**	54 %	Sample preloaded by Creep Test (see below) before performing LDT. Strain based on 11.5 in deflection at maximum load and H (after creep) of 22 in.
Reload Modulus (Initial Tangent)	831 kPa (17.5 ksf)	After Creep Test, initial modulus in LDT computed at 150 kip & 9 in. deflection (i.e., strain = 41 %.)

Table 4.1 Physical and mechanical properties of tire bales (continued)

PROPERTY	VALUE	COMMENTS
COMPRESSIVE STRENGTH (2004 Test Data) background Loads up to 2670 kN (600 kip)		See 2004 Test Data in Appendix D and Figure 4.2.
• **Maximum Applied Stress**	815 kPa (17 ksf)	Stress based on corrected area of loaded tire bale.
• **Strain at Maximum Stress**	57.7 %	Strain based on initial bale height
• **Modulus (Initial Tangent)**	400 kPa (8.3 ksf)	
Confined Modulus (Initial Tangent)	960 kPa (20.0 ksf)	**See Appendix D**
CREEP TEST		
Load to (390 kN (88 kip))		
• **Applied Stress**	202 kPa (4.2 ksf)	See March 2000 Test Data in Appendix C
• **Settlement**		
--Immediate (within 1st hr)	183 mm (7.22 in)	24 % strain, based on Ho = 30 in.
--Short-term (72 hrs.)	204 mm(8.06 in.)	26.7 % strain
Creep Rate (at 72 hrs)	4.6 mm/day (0.18 in./day)	0.6 % strain/day
Working Stress Tests (89 kN (20 kip))		See 2004 Test Data in Appendix D
• **Applied Stress**	39 kPa (0.82 ksf)	Stress based on corrected area of loaded tire bale and strain based on initial bale height
• **Settlement**		
--Immediate (within 1st hr)	51 mm (2 in)	
--Short-term (72 hr)	54.5 mm(2.1 in.)	
--Long-term (at 1000 hr)	56 mm (2.2 in.)	
• **Creep Rates**		
--Short-term (72 hr)	1.0 mm/day (0.04 in./day)	
--Long-term (at 1000 hr)	0.04 mm/day (0.0015 in./day)	
Lateral Earth Pressure Insitu: Ko, Ka, Kp	To be evaluated	Function of applied stress and confinement

Table 4.1 Physical and mechanical properties of tire bales (continued)

PROPERTY	VALUE	COMMENTS
Poisson Ratio • **Working Stress (≅10 to 30 kPa)** • **High Stress levels**	 0.1 to 0.2 0.3 to 0.4	See Appendix D
Interface (Between Bales) Shear Strength	$\delta \geq 25^{o}$ and a = 2.4 kPa (50 psf)	Lower bound value. Function of applied stress and confinement – See Appendix D
Rebound due to breakage of tie wires		Note only 1 or 2 wires failed under max. compressive stress. Long-term tie wire durability is a function of installation damage and environment.
• **Free vertical movement**	36 mm (1.4 in.)	Laterally restrained
• **Uplift pressure**	0.7 kPa (14.5 psf)	Unconfined
Thermal Properties		
• Thermal Conductivity, k_{bale} W/m-°C (Btu/hr-ft-°F)	0.15 to 0.21 (0.085 to 0.120)	Based on theoretical k of whole tires = 0.128 (Shock et al., 2001) and 50 to 10 % air in tire bales.
• Thermal Resistance, R (°F-ft2-hr)/(Btu-in)	0.98	Based on 1/k per inch of material and 50% air in tire bale from lab test (App.F).
• Exothermic Reaction – Flammability	To be evaluated	Function of size of tire materials, cleanliness, exposed steel, moisture, air, thickness of tire materials.
Chemical Durability	High	Tires are affected by ozone. Aging mechanism principally oxidation accelerated by heat. In air and sunlight, embrittlement of tires starts in about 5 years with notably degradation in 10 years (e.g., sidewall cracks in tires). In soil, common chemicals apparently do not affect rubber tires and the influence of ozone and oxygen are minimized. Tires, still in good condition, have been excavated from 50 year old landfills.

4.10 Material properties of tire bales and other lightweight fills

There are a number of lightweight fill alternatives available for embankment and slope construction. Table 4.2 provides a list of lightweight materials along with their respective unit weight and relative cost for comparison with tire bales. The table verifies the relative low-cost of tire bale materials as compared to other lightweight fill alternatives.

Table 4.3 provides a comparison of the typical design properties considered pertinent for use of a hypothetical tire bale embankment, tire shreds in embankments, expanded polystyrene (EPS) blocks, with a conventional earth embankment. This comparison focuses on the use of tire bales and conventional materials that would typically be utilized for general embankment and slope repair applications. The numerical values were obtained from literature reviews and interviews conducted for this report.

The comparison clearly indicates that EPS provides the lightest weight and is thus the preferred material where very lightweight fill is required. However, in many applications, the 60 to 70 % weight reduction over soil provided by tire bales would be more than adequate to provide embankment stability and/or reduce settlement to tolerable levels. In applications where other characteristics such as permeability, compressive strength, resilient modulus and cost are important, tire bales would appear to provide superior characteristics over tire sheds and EPS. As previously indicated, the ability for tire bales to sink also offers an advantage in applications where floating and uplift of EPS blocks would be of concern.

Table 4.2 Summary of various lightweight fill materials (from Stark, et al., 2002)

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) (3)	Supplier (16)
Wood Fiber	5.4 to 9.4 (34 to 60)	0.6 to 1.0	12.00 – 20.00 (9.17 – 15.29) (1)	(17)
Shredded tires	5.9 to 8.8 (38 to 56)	0.6 to 0.9	20.00 – 30.00 (15.29 – 22.94) (1)	(18)
Expanded shale and clay	5.9 to 10.2 (38 to 65)	0.6 to 1.0	40.00 – 55.00 (30.28 – 42.05) (2)	Supplier (16)
Boiler slag	9.8 to 17.2 (62 to 109)	1.0 to 1.8	3.00 – 4.00 (2.29 – 3.06) (2)	Supplier
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) (2)	Supplier
Expanded blast furnace slag	Not Provided	Not Provided	15.00 -20.00 (11.47 – 15.29) (2)	Supplier
Fly ash	11 to 14.1 (70 to 90)	1.1 to 1.4	15 – 21.00 (11.47 – 16.06) (2)	Supplier

Cost Notes: These prices correspond to projects completed in 1993 to 1994.
Current costs may differ due to inflation.
(1) Price includes transportation cost.
(2) FOB at the manufacturing site. Transportation costs should be added to this price.
(3) Mixed at job site using pumps to inject foaming agents into concrete grout mix.

* Baker, et al., (2003) indicates that common borrow for earth embankment in Washington generally ranges from $5.25 to 7.85 /m^3 ($4. to 6 /cy) and lightweight fill materials have the following unit prices:

Tire shreds, in place	$18.30 /m^3 ($14/cy)
Wood Fiber	$5.88 to 26.16 /m^3 ($4.50 to 20 /cy)
EPS-Geofoam	$78.50 /m^3 ($60 /cy)
Foam Concrete	$72 to 104 /m^3 ($55 to 80 /cy)

Reference Notes: (13), (16), (17) and (18) refer to references in Stark, 2002.

Table 4.3 Comparison of typical reported properties of tire bales, tire shreds, EPS blocks, and earth fill materials.

Property – (Units)	Tire Bale (No ASTM Tests)		Tire Shreds (ASTM D6270)		EPS BLOCKS (ASTM D6817)		Earth Fill (ASTM / AASHTO / DOT Tests)	
	Reported Values	Remark	Reported Values	Remarks & ASTM Test Methods	Reported Values	Remarks	Reported Values	Remarks
Dimensional Tolerances	+/- 5%	Based on lab test App. F confirm for different balers	Specification	Measure D 422	+/- 0.5 % of theoretical	Cut to spec *(3)*	NA	
Shape Tolerances	Unknown	Rounded corners very rough faces	Specification	Measure	Manufactured	Cut to specification	NA	
Unit Weight kN/m^3 (pcf) --Dry	5.2 – 6.3 (33 – 40)	Lab test App. F *Compute % soil	3.3 to 6.8 (21 to 43) (dry, no soil)	Lab test, loose to compacted ASTM D1557	0.1 – 0.5 (0.7 to 3)	ASTM C578 *(3)*	15 to 22 (100 to 140)	Lab test
--Wet (Long-term)	5.8 to 6.4 (37 to 41)				1.0 (6.4)			
Specific Gravity	1.02 to 1.2	Not critical	1.02 to 1.27	Lab test, C 127	0.01 to 0.03		2.5 to 2.7	Lab test
Water Adsorption (%)	2 to 9.5	~ Same as Tire Shreds – 8% in lab test App. F	2 to 9.5	Lab test, C 127	2 to 4	ASTM C272	Varies	
Permeability (cm/sec)	0.05 to 0.1	Lab test App. F	0.8 to 59	Without soil matrix	Relatively impermeable		10^{-6} to 10^{+2}	Lab Test
Compressive Behavior -- Ultimate Strength kPa (ksf)	> 815 (17)	Lab test App. F Function of fabrication	480 (10)	Maximum reported from lab test	at 10% strain = 40 to 690 (0.8 to 14.4)	Function of density, stress, strain, time, temperature*(3)*	100 to 1000 (2 to 20)	Lab Test
--Elastic Limit kPa (psi)	NA	Lab test App. F indicate strain hardening	NA		15 to 280 (2.2 to 40.6)	Value at 1% recommended for design *(3)*	Variable	Lab test

Property – (Units)	Tire Bale (No ASTM Tests)		Tire Shreds (ASTM D6270)		EPS BLOCKS (ASTM D6817)		Earth Fill (ASTM / AASHTO / DOT Tests)	
	Reported Values	Remark	Reported Values	Remarks & ASTM Test Methods	Reported Values	Remarks	Reported Values	Remarks
-- Vertical Strain (%) ---- Ultimate ---- At Working Stress	60 2 to 10	Lab test App. F 10 to 40 kPa (210 to 840 psf)	50 10 to 25	Varies with vertical stress & time*(2)* 10 to 40 kPa (210 to 840 psf)	50 1* to 10	*Design value (3)	5 to 20% 1 to 5%	Lab test
--Modulus ----- initial tangent, kPa (ksf) ----- resilient modulus MPa (ksi)	400 (8.3) 960 (20) 21 (3) 52 (7.5)	Lab test App. F Unconfined Confined -sand Unconfined Confined - sand	50 to 250 (1 to 5.2) 2 to 10 (0.3 to 1.5)	Bulk modulus from compression tests mixed with 30 % sand	4k to 10k (80 to 210) 21 (3.0)	based on CBR = 2 *(3)*	5k to 200k (100 -4,000) 55 to 275 (8 to 40)	Lab test
Poisson's Ratio	0.1 to 0.3	At working stress	0.17 to 0.32	*(2)*	0.09 to 0.18	In elastic range *(3)*	0.15 to 0.45	
Earth Pressure - Ko, Ka, Kp	TBD	Test TBD	Ko =0.26 to 0.47 Ka = 0.22 to 0.25	Ko decreases with depth. Part of compression tests, measure in walls *(2)*	Ko = ? Ka = 0.1 Kp = ?	*(3)*	0.3 to 0.8	Lab test
Shear Strength kPa (psf) - Internal: in material	TBD	Test TBD	N= 20° to 39° a = 0 to 2.4 (0 to 50)	Dry shreds, varies with normal stress& deformation	Su = 36 (758)	Rare test *(3)*	N= 25° to 45°	Lab test
- Internal Interface (within embankment) kPa (psf)	$\delta > 25^{o}$ and adhesion a = 2.4 (50)	Bale to bale. Lab test App. F confirm -field test	δ = 20° to 39° a = 0 to 2.4 (0 to 50)	Dry shreds, varies with normal stress & deformation	30°	*Typical (3)*	NA	
- External Interface (embankment & adjacent material)	As req'd by design	Bale on soil, geotextile or geomembrane Test - TBD	As req'd by design	Sheds on Soil, geotextile or geomembrane determine by tests	10° to 55°	Varies with materials (3) determine by tests	NA	Lab test

Property – (Units)	Tire Bale (No ASTM Tests)		Tire Shreds (ASTM D6270)		EPS BLOCKS (ASTM D6817)		Earth Fill (ASTM / AASHTO / DOT Tests)	
	Reported Values	Remark	Reported Values	Remarks & ASTM Test Methods	Reported Values	Remarks	Reported Values	Remarks
Connection Strength	As req'd by design	Field Test TBD	NA		Mechanical by barbed steel plates	26° Pseudo – cohesion (3)	NA	
Thermal Conductivity, k (effective) W/m-°C (Btu/hr-ft-°F)	0.15 to 0.21 (0.085 to 0.120)	Theoretical based on whole tire and 50 to 10 % air in tire bales	0.16 - 0.32 dry (0.09 to 0.18)	Varies with size & density of shreds (back calculated in 1998 at NETC field test section) (3)	~ 0.02	*(3)*	~ 0.17 to 0.7 (0.1 to 0.4)	Lab test, typical soils *(2 & 5)*
-- Thermal Resistance, R (°F-ft^2-hr)/(Btu-in)	~ 1.0	Based on 50% air per lab test App. F	~ 0.8		~ 4.5		0.5	
Exothermic Reaction & Flammability	Control by design guides and storage procedures	Protect exposed tires	Concern in stockpiles and exposed materials	Control by design guidelines, specification, use soil separation layers (2)	Flame retardant by ASTM C578	Blowing agent has ignited. Use flame retardant (3)	NA	
Leachability	TBD	Same as, or less than tire shreds	Ba, Cd, Cr, Hg, Pb, & Se are below regulated amount.	TCLP data D 6270, (Fe, Mn, & Zn also noted in some tests)	NA	*(3)*	NA	Except for contam-inated materials

NOTES: NA = not applicable, TBD =to be determined,

(1) "Normal chemicals used in current environment do not attack whole synthetic rubber tires," personal communication with M. Blumenthal Rubber Manufacturers Association, 7 Oct 2003.

(2) Humphrey, 1998

(3) Stark et al., 2002

(4) Baker, 2003

(5) Oosterbaan, 1963

5. TIRE BALES IN TRANSPORTATION APPLICATIONS

5.1 Introduction

As was shown in Table 2.1, there are a number of potential civil engineering applications for tire bales. Several case histories of general civil applications including use in erosion control features and in the construction of an earth dam are included in Appendix A.

With regard to transportation applications, tire bales are a promising product that can be used for stabilization purposes (e.g. similar to a stabilizing effect provided by thick gravel layers or geosynthetic reinforcements). The lightweight of tire bales allows them to serve as a fill while reducing the driving force and stabilizing a slope that would otherwise experience potential failure. Since the bales weigh less than conventional fill materials, they will induce less settlement of subsurface soils and lower lateral pressure on structures such as walls or abutments. Because of their relatively high hydraulic conductivity, they allow for good drainage. In addition, the bales are easily handled with a wheeled or tracked forklift (or a light hydraulic crane lift). The use of small equipment for placement combined with the elimination of conventional fill requirements for moisture control, ballast, and compaction makes construction with tire bales easy and relatively fast. The environmental benefits of using these waste materials rather than disposing of them is undeniable. Finally, the cost of using tire bales in civil engineering applications is less than that of conventional fill materials. In short, tire bales offer both environmental and economic benefits.

Transportation related applications include, but are not limited to: roadway sub-grade fill, repair of failed slopes, improving slope stability, embankments for roadway structures, backfill material for retaining walls, frost heave mitigation, sound barrier walls, and rockfall barriers. Case histories for a failed slope remediation project and two roadway embankment projects are included in Appendix B.

Based on the review and assessment conducted in this study, a prioritized list of highway applications involving the use of tire bales is presented next. This list provides the Colorado Department of Transportation (CDOT) with an assessment of research needs to enhance the use of tire bales in future projects. The list of highway applications includes use of tire bales as:

- Embankment material within embankment systems.
- Embankment mechanical stabilizing elements in slope repair projects.
- Impact elements and fill material in rockfall barriers.
- Core material for constructing sound walls.
- Embankment on soft ground subgrades and enhanced lateral drainage.
- Shoulder protection of small retaining walls and abutments.
- Backfill material in retaining structure projects.
- Mechanical stabilizing elements in low, less critical retaining walls.

Based on discussions with the CDOT, the first three of these applications were determined to be readily implementable and there are a significant number of projects in Colorado where tire bale structures could be used. We understand that the fourth application, sound barriers, is already being evaluated by others within the CDOT.

The remainder of this section is focused on the use of tire bales in the first three transportation applications, namely: Embankment Construction; Slope Repairs, and Rockfall Barriers. All three applications involve placement of fabricated tire bales, using appropriate connections and anchors, filling void space (if required) and surrounding the assembled tire bales with appropriate matrix materials suited for each application. Each application is discussed separately, using Section 5.2 General Embankment Construction as a "basic construction element" and then discussing the other two applications in Section 5.3 Slope Repairs and Section 5.4 Rockfall Barriers. Each section notes the issues and items which should be considered, or not considered as the case may be, in addition to Section 5.2 General Embankment Construction.

5.2 General embankment construction

General: The total thickness of tire bales in embankment construction has typically been considered as less than 6 m (20 ft), utilizing one to perhaps eight layers of tire bales placed on a graded subgrade. The subgrade below the bottom tire bale layer normally includes compacted native soils. Some site conditions might require localized placement of a compacted free-draining granular base zone or compacted tire shreds. Tire bales are typically placed in "brick fashion" with the

0.75 m (30 in) dimension vertical and each layer is staggered to offset vertical joints on overlapping layers. This arrangement helps to maximize the interface friction between the bales and effectively minimizing any differential movement. Tire bales may be connected, depending on site requirements. In some cases soil has been placed and compacted between successive layers and against the sides of in-place tire bales to isolate individual tire bales. Alternately, the tire bale/soil zone could be encapsulated with a flowable fill, or encapsulated with a high strength geotextile separator, to reduce soil and moisture penetrations into void space in a tire bale. The use of a geotextile separator is considered simpler to construct and more cost effective (as will be discussed in Section 7).

Application: The generic tire bale embankment system typically involves 0.75 m (2.5 ft) thick layers of tire bales in conjunction with other materials, as shown in Figure 5.2, to provide specific benefits that can be tailored to a range of site conditions. The benefits can include:

- An economical embankment.
- Subgrade enhancement, that can insulate, drain, and strengthen.
- Stabilization of soft subgrades to provide a working platform, possibly incorporating a geosynthetic reinforcement/separation at the base, in order to construct an embankment.
- Engineered lightweight fill, to reduce settlement of soft foundation soils, and provide increased shear strength for global and sliding stability reasons.
- Reinforced zones, consisting of tire bales alone, or improved by placing geosynthetic reinforcement between bales, that provide relatively high internal shear strength to facilitate construction of steep slopes and near vertical headwalls.
- Erosion control from surface flow, channelized flow, or wave action at the edges of lagoons, ponds, and lakes.

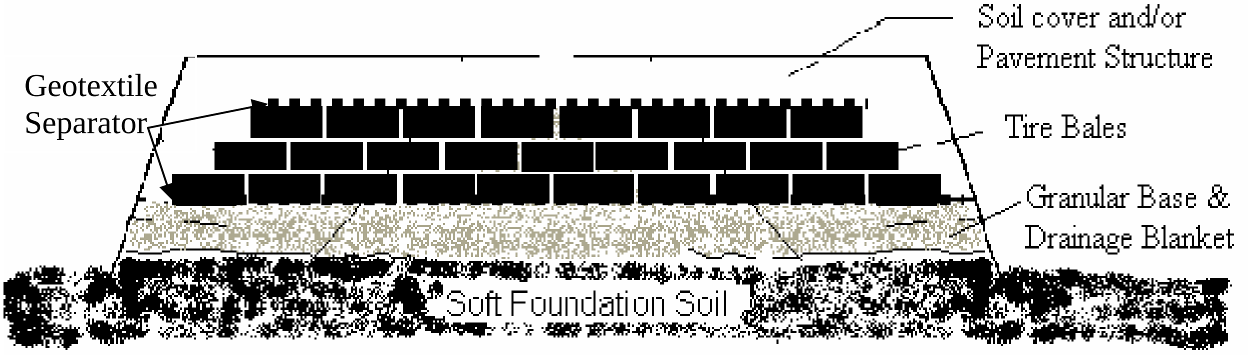

Figure 5.1 Application of tire bales in embankment construction.

5.3 General slope repair and stability improvement system

General: The generic tire bale embankment zone is placed in an excavated area after soil and/or rock slide debris are removed as shown in Figure 5.2. Depending on the site conditions, the excavation may require temporary earth support systems and the use of groundwater control measures to facilitate construction of slope repairs.

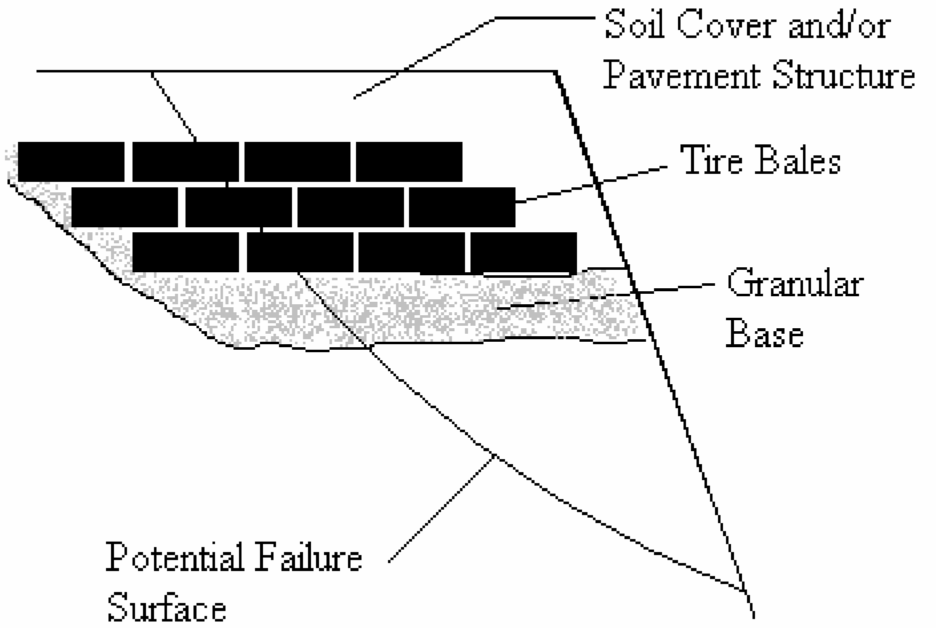

Figure 5.2 Tire Bales Used to Improve Slope Stability

The thickness, face slope, back slope and face angle for the tire bale embankment depends on the site conditions and the use of stability analysis of various cross-sections to provide an adequate Factor of Safety (Fs) for the remedial construction. Crushed stone and/or geosynthetic drainage systems will likely be required along the base and along some portion of the backslope of the tire bale embankment. Geotextile separation layers may be required to prevent movement of adjacent soils into the voids in and between the tire bales.

Development of a stacking and placement pattern to maximize interlocking of the tire bales, including the possible inclusion of soil or crushed stone separation layers and geosynthetic reinforcement materials in conjunction with mechanical connection devices, may be a significant aspect of the design and construction work. For this application the design will focus on the benefits of: (1) the lightweight tire bale fill to decrease the 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 with reliable shear strength properties.

The subgrade layer could consist of a compacted free-draining granular base zone, compacted tire shreds, or compacted native soils. Site conditions may also require installation of drainage systems to control groundwater movement as well as consideration of small to large size drainage pipes exiting through the face or below the toe of the face slope. The available foundation area will directly impact the design face angle and the selection of facing materials.

In some situations a stepped face, covered with soil and a vegetated surface, or an unvegetated rock fill, may be acceptable to the owner. It is also conceivable that in other situations the tire bale face could be “stepped” to provide a steep, very steep, or vertical face covered with shotcrete or metal, concrete, and treated timber panels. The panels could be fabricated, formed, and colored to provide an aesthetically pleasing surface that blends with the natural topography and vegetation that would be environmentally acceptable as natural habitat for animals, birds, etc.

Application: A typical Tire Bale Slope Repair or Stability Improvement System can provide:

- An engineered lightweight fill, with a high strength embankment fill volume.
- Internal drainage.
- Shear strength to satisfy global and sliding stability factor of safety requirements.
- Support for an acceptable face system.
- Connection strength for soil/rock anchors extending behind the excavation.
- Erosion control from surface flow, channelized flow, or at the edges of lagoons, ponds, and lakes.

5.4 General rockfall barrier walls

General: The generic tire bale rockfall barrier wall is usually 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 (as was shown in Figure 2.1), to prevent falling rock materials from impacting roadway traffic. Depending on site conditions, the offset from the highway, the height and thickness of the barrier wall and the appropriate use of other rockfall control devices (such as cables and wire mesh) would be integrated with the tire bales.

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 size and velocity of a critical rock block and the modulus of the tire bale system. Pylons, earth/rock anchors, or tire bale buttress elements may be required to provide stability and/or additional impact resistance for the free standing system.

For the stand alone wall, the use of crushed stone and/or geosynthetic drainage systems is not anticipated as a typical design issue. Development of an interlocking stacking and placement pattern to maximize the benefits of tire bale interlock, inclusion of geosynthetic reinforcement materials to a modular block face wall with the tire bale section, and inclusion of connection devices, may be a significant aspect of the design and construction work. The angle of the outside “design face” is expected to be near vertical. We anticipate that the “impact face“ (back side) would not have a facing material in order to cushion and stop falling rocks. The exterior of the road side face could be a modular dry laid block, shotcreted, or stepped at varying face angles with a soil/vegetation cover, and/or covered with a placed stone/rock cover for aesthetic reasons, as was discussed in the slope repair application section. Fire protection issues for the impact face should be examined.

For the GRS system, tire bales would generally be laid parallel to the roadway, stacked to stagger and cover the underlying joints, and could include tire bales placed perpendicular to the roadway to enhance interlocking behavior. Figure 5.3 shows a stacked tire bale arrangement similar to that of the impact face of the rockfall barrier. Geosynthetic reinforcement would be placed between each layer relying on friction between the modular block face wall and the geosynthetic reinforcement to provide the face connection. The vertical spacing would be at every bale, i.e., 0.75 m (2.5 ft) vertical spacing. The geosynthetic reinforcement would extend to the outside (road side) wall face where either modular block or wrapped face with shotcrete construction could be used. The roadside face of the wall may also require short secondary reinforcements for improved face stability. Design and construction would follow standard CDOT GRS design guidelines.

Figure 5.3. Stacked tire bales, e.g., to form the impact face of a rockfall barrier (Encore Systems, 2004)

For the stand alone wall application, the design may also include the use of soil/rock vertical anchors to resist lateral impact loadings from roadway traffic and/or rockfall materials. The design should also consider the low unit weight of the tire bale fill, and utilize the internal shear strength and interlock strength of the tire bales, with connection/anchor devices to develop an integrated reinforced tire bale rock barrier wall zone with reliable strength properties.

The subgrade layer for either system could consist of a compacted free-draining granular base zone, compacted tire shreds, or compacted native soils. Specific site conditions may require installation of drainage systems to control groundwater movement and consideration of small to large size drainage pipes exiting through the face or below the toe of the face slope.

Application: A typical Tire Bale Rockfall Barrier Wall System can provide:

- An engineered high strength wall system to resist the impact of falling soil/rock debris and control the bounce and roll of the debris.
- Adequate shear and connection strength to satisfy desired Factor of Safety (Fs) for overturning, global, and sliding stability failure modes.
- Support for an acceptable outside face system, and other materials such as cables and wire mesh.
- Connection strength for soil/rock anchors extending below or behind the foundation zone.
- Erosion control from surface flow, channelized flow adjacent to the barrier wall structure.

6 DESIGN GUIDELINES FOR TIRE BALE EMBANKMENTS

6.1 General

Complete design guidelines have not yet been developed for use of tire bales in embankment applications. However, as previously indicated, ASTM has prepared a general guideline specification for use of tire shreds (ASTM D6270), which addresses some issues relevant to proposed design guidelines for tire bales. FHWA has prepared "User Guidelines for Waste and By-Product Materials in Pavement Construction," which includes a section on use of scrap tires as embankment fill. However, the FHWA document does not cover design issues specifically related to tire bales. In addition, FHWA has design guidelines for embankments over soft subgrades (FHWA HI-95-038), which would apply to the use of tire bales as fill and could accordingly be modified to form a basis for design. At this time there is no recognized material specification, laboratory testing procedure, or design practice guideline for tire bale embankments as existing applications have been designed and constructed in piecemeal fashion.

6.2 Lightweight fill systems

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. The report includes state-of-practice design approaches for:

- Support of overlying pavement systems.
- Evaluating internal and global stability of geofoam embankments on very soft soil foundations.
- Manufacturing quality control and quality assurance (MQC/MQA) issues.
- Typical design details.
- Economic analyses.
- Topics for future research and development, and
- AASHTO formats for provisional design guidelines and material standards.

This National Cooperative Highway Research Program (NCHRP) guideline report has considerable value because it documents approximately 30 years of the development of design/construction guidelines for use of geofoam materials as a lightweight fill. We believe this guideline along with the existing FHWA and Colorado DOT guidelines provide excellent resources that can be used to assess some of the issues relating to use of tire bales as a reliable engineered material in reinforced and unreinforced highway embankments and wall structures. As indicated in both Table 3.1 and Table 4.3, the properties of tire bales in embankment applications are not well defined or available in the engineering literature. However, the general design issues and approaches relating to use of conventional earth fill, EPS blocks, and tire bales are very similar.

Table 6.1 provides a preliminary comparison of the design issues, assuming that in the future tire bales can be fabricated with an adequate level of MQC/MQA that will provide consistent verifiable quality of manufactured tire bales for confident use as a reliable engineering material. The comments in the table provide the authors' opinion on the relative importance of each design issue for the selected application with status and knowledge of the design issue for tire bales relatively ranked as: "Not Available", "Very Limited", "Limited", and "Satisfactory". The notations of "1", "2", and "3" are intended to indicate a preliminary relative assessment of the importance of a design issue in the design of tire bale systems (1 is high and 3 is low).

6.3 Tire bale specifications

Development of specifications for tire bale fabrication, testing, and construction is a very important issue at this time. The Texas Department of Transportation (TxDOT) has prepared a preliminary draft specification for use of tire bales and associated materials in the repair of a localized slope stability failure of an embankment. Note that this specification has not been finalized and that it would be substantially modified before it is used in a construction contract (Williammee, 2004). This specification is included in this report solely for the reader's information because it does address some of the issues involved with a tire bale construction project. The specification is included in Appendix E (for information only) and summarized below.

Table 6.1 Authors' summary of design issues for tire bale embankments, slope repairs and rockfall barrier applications.

Issue	Status of Knowledge & Understanding	Embankment Construction*	Slope Repairs*	Rockfall Barriers*
I. Reliable Tire Bale Properties				
Material Standard	Not Available	1	1	1
Physical Properties				
Weight	Satisfactory	2	1	1
Dimensions & Tolerances	Very Limited	2	2	1
Flammability	Not Available	1	1	1
Durability / Environmental	Limited	3	3	3
Impact of Baler Design and Operation	Not Available	2	2	1
Mechanical Properties				
Compressive Strength	Limited	2	1	1
Creep & Relaxation	Limited	1	1	1
Tension	Not Available	3	3	1
Flexure	Not Available	3	3	2
Shear Strength: Internal & External	Very Limited	2	1	1
Interfaces of tire bales	Very Limited	2	1	1
Interface with Separation Materials	Very Limited	2	1	1
Thermal Properties	Very Limited	3	3	3
II Site Constraints	TBD –Depends on ranking site issues for each application			
Key items include requirements for: drainage, base separation, infilling, cover layers, and buffer zones.	Very Limited	2	1	1
III. Design Guidelines				
Manufacturer's experience	Limited	2	1	1
Private Consultant Experience	Very Limited	1	1	1
University Research	Very Limited	1	1	1
State DOT's	Very Limited	1	1	1
Federal Highways	Not Available	1	1	1
IV. Tire Bale Specifications				
Private Consultant Experience	Very Limited	1	1	1
University Research	Very Limited	1	1	1
State DOTs	Very Limited	1	1	1
Federal Highways	Not Available	1	1	1

Note: * Importance of a design issue to application development with 1 = high, 2 = moderate, and 3 = low.

6.3.1 Summary of Texas DOT preliminary draft specification

General Requirements. The Texas specification indicates the following:

- Tire bales restricted to auto or light to medium truck scrap tires generated or stored within the State of Texas.
- Tire balers and baling sites shall be authorized to process scrap tires by the Texas Commission of Environmental Quality.
- Obtain approval of plans by engineer and local fire department for fire prevention and suppression two weeks before start of tire bale production and storage.
- Tire bales are specified as Type A.
- Tire bales required to be uniform in shape and size, or "equivalent as approved by engineer" (but measure not specified) and density > 5.6 kN/m^3 (35 pcf.).
- Bale ties shall be galvanized or stainless wires, with maximum break stress of 345 kPa (50 psi.). (Corrosion protection of ties as required by Item 423.2 should be followed. However, this protection is not required when bales are covered by a geomembrane which makes a tire fill impermeable to air and water and not subject to pH and resistivity requirements.) Requires that tire bales shall not explode when wires are cut/broken.
- Tire bales used as core of embankment.

Laboratory testing. The specified laboratory tests of tire bales include:

- Compression test equipment uses 25 mm (1 in.) inch thick steel plates top and bottom, approved test floor, I-beam to distribute load, max 1,777 kN (400 Kip) load capacity hydraulic ram.
- Creep test for 72 hrs, test at 172 kPa (25 psi = 3.6 ksf).
- Max creep strain < 0.25 or 190 mm (7.5 in.) for a 762 mm (30 in.) high tire bale.
- On same bale do load test to failure, or to maximum of 690 kPa (100 psi =14.4 ksf).
  (Note: failure load, failure stress, and failure strain are not defined)

Design and construction. These requirements for tire bale embankments include:

- Prepare subgrade, operate parallel to final road grades.
- Maximum tire bale height = 6.56 m (20 ft.), and is the core of the structure.
- Place granular base below tire bales, 300 mm (12 in.) thick, extended to allow drainage.

- Construct embankment to minimize air and water infiltration.
- Place bales with straps in longitudinal direction of roadway.
- Place and compact soil between each layer of tire bales, 200 mm (8 in.) thickness, soil PI<35, 300 mm (12 in.) maximum loose thickness, provide moisture control, and proof roll if required by the Engineer.
- Organics not allowed and soil to be checked by color test.
- Geomembrane is placed over final layer.
- Soil placed on side slopes, minimum of 450 mm (18 in.), then 50 mm to 100 mm (2 to 4 in.) thick layer of compost.

6.3.2 Comments on the Texas DOT draft tire bale specification

The specification requires creep tests at loads of approximately 2.5 times the maximum service stress at the bottom of the bales with a maximum stress of 690 kN/m^2 (100 psi). This is equivalent to total load of approximately 1450 kN (325 kips) on a 1.4 m by 1.5 m (4.5 ft by 5 ft) tire bale. The test is intended to fail the material in unconfined compression. For reference, the creep test load, e.g. 2.5 times maximum service stress, for an embankment section composed of 1 m (3.3 ft) of soil and 6.1 m (20 ft) of tire bales would be approximately 150 kN/m^2 (3 ksf)

The authors suggest the following additional laboratory tests:

- Measure and evaluate the rebound movement and the lateral bulge of the tire bale during both loading and rebound.
- Creep tests should be conducted at 0.5, 1.0 and 1.5 times maximum service stress at the bottom of the tire bale embankment in order to evaluate estimated settlement of the upper portions of the tire bale embankment during construction and the amount of over build required (using tire shreds, tire bales, or soil buffer materials) to develop and maintain design grades for the top of the tire bale embankment, and/or develop preload/surcharge requirements to reduce most construction creep settlements. The creep period may extend beyond 72 hours for some design conditions.
- rebound movement (vertical heave) on confined or restrained tire bales along with lateral pressure exerted by tire bales on the restraints should be evaluated when tie wires are cut.

The authors believe the draft Texas DOT specification provides a good starting point for developing a comprehensive tire bale specification and also suggest that some of the items in the draft specification may not be needed for all tire bale embankments. Specifically the use of intermediate soil layers between each tire bale layer and the requirement for a geomembrane cover or wrapping may not be required (or desirable) in many applications. The intermediate soil cover appears to be related to the exothermic issue and is more stringent than required for tire sheds in ASTM D 6270. As indicated in Section 3, the exothermic problem does not appear to be as significant for tire bales as it does for tire sheds; and, for tire shed projects, intermediate cover is only required for embankments greater than 3 m (10 ft or approximately 4 bales) in height. Although not included in the specifications, geotextiles should be required between the cover soils and the tire bales unless infill is used between the bales. The geomembrane requirement is apparently related to the exclusion of water and air to reduce both the exothermic problem and the potential long-term corrosion of tie wires. As noted in the specifications, by reducing air and water, the pH and resistivity requirements for intermediate covers and infill are reduced. If infilling is not used then the pH and resistivity of adjacent fill are less of a concern. As discussed later in this section, tire bales are not expected to produce a leachate that is as severe as tire sheds. However, until further studies have been performed on the leaching potential of tire bales and to prevent contamination from residual materials that may be left in the tires, a geomembrane cover should be used where the embankment will be located near a water supply or when placed at or below groundwater (as would also be recommended for tire sheds).

In comparison to the draft Texas DOT specification, the structure and content of the ASTM D6270 Guidelines for tire shreds and the “Guidelines for Geofoam Applications in Embankment Projects” (Stark et al., 2002) are very detailed and inclusive for the respective materials given the time those processed materials have been used in a variety of civil engineering applications. ASTM D6270 documents the body of knowledge developed over the past 14 years by extensive testing of typical tire shred materials and the design guidelines developed in 1997 address the issues involved with reducing exothermic heating reaction in tire shred fills. ASTM D6270 includes a Material Data Sheet (MSD) for whole scrap tires. The Guidelines for Geofoam Applications…” are very comprehensive and detailed, covering EPS material properties developed over approximately 50 years and the design approaches that have evolved since extruded polystyrene insulation layers were first tested in highway pavements in the United States in 1960s and expanded polystyrene blocks (EPS) were first used as a lightweight highway fill material in the early 1970s in Norway." (Stark et al., 2002).

The proposed Colorado DOT tire bale specification should address the following issues:

- Reference documents, including terminology, and laboratory test procedures.
- The responsibilities of the parties involved with the fabrication, storage, transport, and installation of a tire bale embankment system.
- Permitting requirements for waste tire storage, transport, including pre-processing, cleaning, storing, etc.
- Equipment and procedures for fabricating tire bales, including confinement devices.
- Physical, material, and chemical properties and requirements for MQC testing, possibly including third-party testing and certifications to verify the tire bales have the requisite properties before they are transported to storage or to a construction site.
- Product storage and transportation with fire protection and fire suppression requirements.
- Site preparation, including placement of ancillary foundation materials.
- Handling and placement of tire bales, ancillary materials, and any connection devices.
- Requirements for handling and installing facing materials.
- Field quality control monitoring and testing tire bales and ancillary materials.
- Performance monitoring, both short-term (from placement to the end of construction) and in-service monitoring. Appropriate instrumentation to monitor and measure settlement, lateral movement, temperature, and water head may be required at some sites to verify the tire bale embankment is performing as anticipated during design.

Table 6.1 lists the current understanding of some of the tire bale properties and their relative importance for the selected applications. In order to establish preliminary pre-design test values and increase the amount of available background, an effort should be made on each project to pretest tire bales for relevant properties. It is also important to note that laboratory test values are sometime different from observed in-service behavior (Humphrey, 1998 and Baker et al., 2003) The critical properties include:

- Compressive stress-strain properties for different types of tire bales (function of fabrication stresses, tire type, and resulting density) for unconfined and in situ confined conditions.
- Internal shear strength, lateral sliding resistance for tire bale interfaces, as a function of stacking, geometry, and interlocking arrangement.
- External sliding resistance in conjunction with proposed abutting and interlay materials, including soil, stone, concrete, geotextiles, geogrids, or geocomposite drains.
- Short-term and long-term creep behavior for a range of design loads.
- Lateral and vertical expansion characteristics, assuming tie systems may break after construction.

Developing this information requires the construction, instrumentation, and monitoring a full scale test embankment where the tire bale system can be subjected to typical design loadings and appropriate instrumentation is installed to enable comparison of laboratory test data to in-service performance.

6.4 Tire bale fabrication

Current typical tire bale dimensions have developed from commercially available tire bale equipment to compress approximately 100 auto size tires to produce a 1.5 cubic meter (2 cubic yard) tire bale weighing approximately 8.9 kN (2,000 lb = 1 ton). However, there is no recognized national or international standard for the number of tires, tire bale dimensions, and weight of a tire bale. The number of tires included in the bale can vary with the compaction pressure, the type of tire, and modification of whole scrap tires by pre-splitting. Tire bale dimensions are based on the baler, but there is no baler standard. In addition to the "nominal standard", ½ size and ¾ size bales have been reported by several producers, especially for tire bales encased with concrete. The smaller sizes for concrete encased tire bales may be related to a perceived limitation that an 8.9 kN (2,000 lb) weight per unit is a relative maximum for transportation and site handling activities.

The number of tires in a tire bale and the tire bale dimensions should be consistently controlled to provide uniformity and consistency in tire bale properties and size for structural design and installation requirements. Requirements for “surface planeness”, deviation from the nominal size of the baler chamber, and tire bale “squareness” should be included in the dimensional requirements to provide uniformity and facilitate stacking several layers of tire bales and result in relatively level top surface, and reduces void space between adjacent tire bales. Reducing void spaces between tire bales will also reduce the amount of soil filling required, if that feature is required on certain projects. These requirements are also necessary to define and control the anticipated total bulk inplace unit weight and volume of the tire bale zone and the ancillary soil materials that may be used for infill, buffer, and side slope filling.

Measurement of tire bale properties, including geometry, unit weight, permeability, and cleanliness should be responsibility of the tire bale fabricator. The fabricator should provide a statement or certification that the tire bale product conforms to the project specifications, including conformance with state legislation for reuse of waste tires. (See reference to state laws, and the summary of Colorado regulations included in Appendix F).

6.5 Construction sequence

6.5.1 Pre-construction

The first construction activity should be the verification that the tire bales fabricated and selected for the project conform to the project specifications. This may involve use of a third-party testing agency to certify that the tire bale producer’s MQC/MQA materials and fabrication procedures are satisfactory and conform to the project requirements. Conformance tests should also be conducted at this stage, if required by the design engineer/and the third-party testing agency, preferably prior to shipping tire bales to the construction site.

6.5.2 Field operations

The construction sequence for tire bale embankment applications should not be significantly different than those presently used for any other embankment project and will thus include:

- Material handling (e.g., unloading, storage, hauling, placing, etc.).
- Prepare foundation and subgrade.
- Place base drainage (unless it can be shown that drainage is not required).

- Place a bottom geosynthetic separation layer, if required, on the embankment subgrade.
- Place tire bales, and, if required, matrix fill, connections, and reinforcements.
- Place a geosynthetic separation over the tire bale zone, as required.
- Place soil and stone materials required for a buffer zone between the tire bale zone and the pavement system, and side slope fills to support vegetated surface covers, and face protection as required on the sides of the tire bale zone.
- Monitor performance.

Use of a “standard 100 pte tire bale” is attractive from a constructability standpoint, because that size and weight can conveniently handled by conventional forklift equipment. Field reports have noted that the bales exhibit “good performance” when they are stacked in a “brick-like” fashion. Many applications have simply stacked the bales in a “brick-like” fashion, utilizing no other methods for joining the bales. In some of these cases, the stacked bales were used for roadway subgrade, where the bales are exposed, and they have shown good short- and long-term performance. Specifically, it appears that time-dependent movements (creep) have not been monitored, measured, or reported as detrimental.

Even though the tire bales are simply stacked in a “brick-like” fashion for many of the experimental applications, quality control guidelines are needed to ensure short and long-term success of the project. The first layer of bales has been generally placed below ground level. That is, the first layer has served as a “keyed” layer, which “locks” the entire bale mass into the ground by not allowing lateral movement along the base of the lowest layer of tire bales.

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. When the bales are stacked together, a 50 to 125 mm (2 in. to 5 in.) variation in surface height may be typical on the top, sides, and bottom of a tire bale. Tire bales should be placed as close together as possible.

When a geosynthetic separation layer is not used in the design, control of soil infills or other materials between bales will be very important to avoid subsidence after placement. Typically, the infill material has been a clean coarse to fine sand, and the estimated cost in Colorado to install this material could range from \$19 to \$59 / m^3 (\$15 to \$45 / cy) (See Appendix H) with a average cost of \$28.50 /m^3 (\$22.00 /cy) for moderate size projects. A flowable cementatous fill (i.e. flowable fill) could also be a viable alternative to sand in some situations. Other infill materials should be explored with respect to ease of construction and void filling reliability.

It is the authors' opinion that filling the voids in the horizontal and vertical interfaces between each tire bale is not required for all projects. However, at this time, the need for soil infilling should be addressed by the design engineer, based on the conditions at each site and the availability of geosynthetic separation materials. The recommended alternative to soil in filling is the use of a geotextile separation layer above the tire bale fill zone. This approach is often used for separating rock and boulder fills from fine grained soils. The geotextile will need to be selected based sufficient durability to survive construction, which is anticipated to require, as a minimum, a Class I geotextile as defined by AASHTO M288.

The minimum buffer zone required above a tire bale fill zone also requires further evaluation and will be application dependent. For example, for a soil embankment fill over Expanded Polystyrene (EPS) blocks, a minimum thickness of 0.5 m (20 in.) is required between the roadway subbase layer and the EPS blocks (Stark et al., 2002). Humphrey recommends a thickness of 0.6 to 1.8 m (2 to 6 ft) of adequately compacted soil cap over a tire shred fill (Baker, 2003). Considering the nonuniform surface of tire bales, a minimum of 1 m (3.3 ft) of additional fill should be required between the top of the tire bales and the bottom of the pavement base course where roads are to be constructed over tire bales. If thinner cover is used an FWD test should be performed on the inplace cover material to determine the design requirements for the pavement.

The project contractor should be responsible for transportation, site storage, and installation of the tire bales. The installation phase should include site survey for layout, geometric limits of the tire bales, integration with other materials, and environmental protection until the 0wner accepts the project.

The design engineer, or another responsible qualified agency retained to provide construction testing and monitoring services, should monitor the installation of the tire bales and develop as-built drawings and a summary construction report to document the tire bale installation.

Following construction, periodic site visits and measurements should be made to monitor the geometry, appearance, and performance of the tire bale embankment systems.

6.5.3 Monitoring field activities

The design engineer should be available to provide the following services during construction:

- Review adequacy instrumentation design verification monitoring program (e.g., temperature and settlement during construction and in-service) including types of instruments, calibration and installation procedures.
- Review daily field activity and QC/QA reports prepared by the Owner's representative.
- Periodic site visits to verify the field conditions are consistent with design conditions.
- Develop changes to the design plans and specifications as justified by site conditions, review the as-built drawings and the final construction report prepared by the contractor and the testing agency. The final construction report should include all quality control data, field reports, data obtained by survey and instrument readings, and an interpretation of the data.

7 ESTIMATED COSTS FOR TIRE BALE EMBANKMENTS

7.1 Colorado rebates and reported cost savings

As in any other transportation application, cost is an important aspect in the selection of tire bales as a design alternative. 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. In fact, the cost for materials, shipping, and handling tire bales could be offset by the Colorado Division of Local Government and Counties which provides a \$20 per ton (~\$10/cy) rebate for end users or processors of scrap tires. This is due to state legislation and tipping fee subsidies.

An example of the costs and savings associated with the use of waste tires in Western New York state is provided in Case Study 2 in Appendix B. On that project the total taxpayer savings was estimated as \$1.60 per tire, or approximately \$160 for a “standard tire bale” (~\$80/cy). This corresponds to the difference between the normal disposal cost of tires and the cost associated with the use of tire bales (Figure 7.1). The cost savings associated with tire bales instead of conventional earthwork material in Case Study 2 was reported as \$3,050 per 300 m (1000 ft) of roadbed (Figure 7.2). (Chautauqua County, 2001). A summary of Chautauqua County’s experience on four consecutive projects from 1999 to 2002 is included in Appendix B.

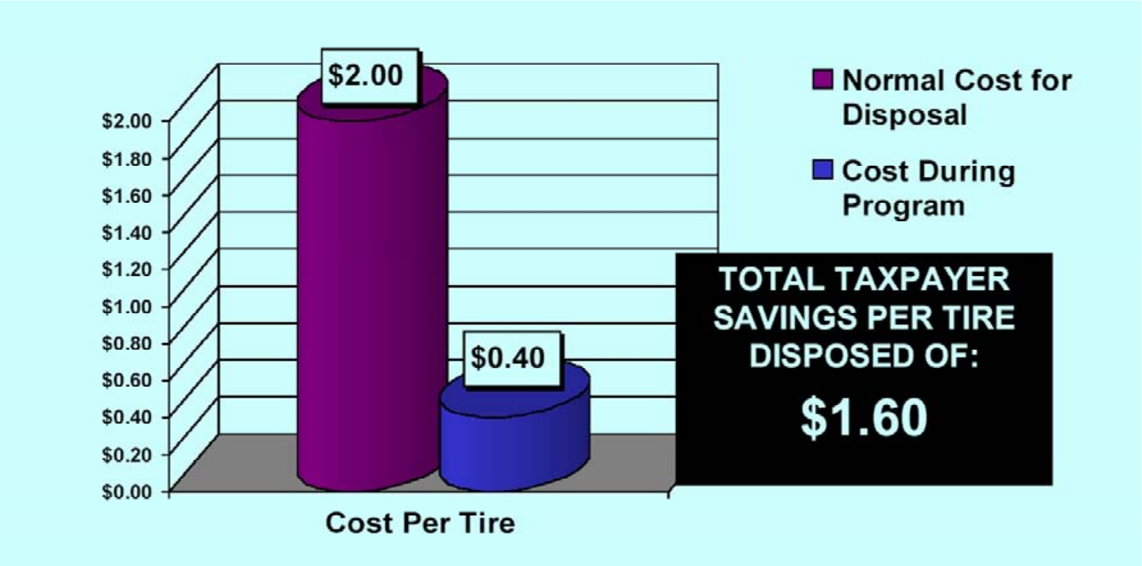

Figure 7.1 Total taxpayer disposal costs for each tire

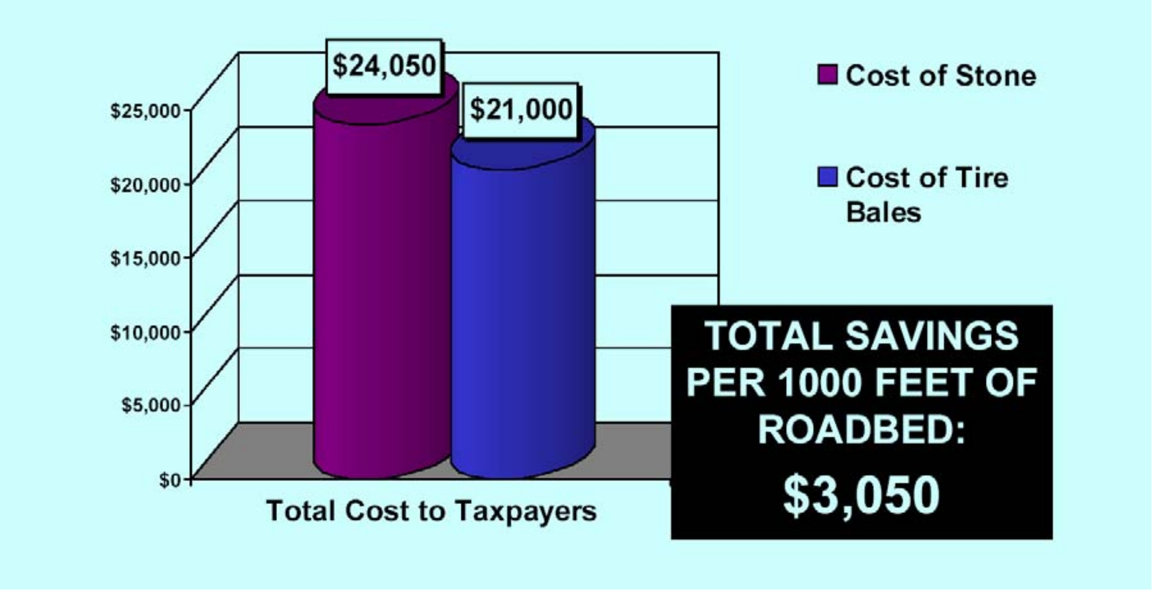

Figure 7.2 Total savings per 1000 feet of roadbed

7.2 Estimated cost of a tire bale embankment in Colorado

Table 7.1 provides a tabulation of the estimated costs to procure, fabricate, transport, and install typical tire bales in a generic transportation embankment. For this example the volume of tire bales required for support of a two-line highway was computed for a tire bale zone with dimensions of 16 m (52 ft.) wide, 0.75 m to 6 m (2.5 to 20 ft.) thick, and 1H:1V side slopes, covered by a separation geotextile and a 1 m (3.2 ft) earth/stone cover below the pavement base course. The cost of the pavement and soil cover on the side slopes is not included in this estimate.

The comment column, notes, and references cited in this table provide background information on the rational for each cost item. The Colorado DOT provided average annual contract costs for earthwork, geotextile, and filter materials for the 2001 to 2003 time period. This data is listed in Table H.1 in Appendix H.

The comparative replacement cost for using tire bales as a substitute for embankment backfill in Colorado is listed below in Table 7.2. It should be noted that with respect to the average annual cost of embankment backfill for the 2001 to 2003 time

Table 7.1 Estimated base cost of tire bale embankments in Colorado

Item or Activity	**Estimated Costs - \$/m^3(\$/cy)**		**Comments (Note 1)**
	Range	Base Estimate	
1. Material Cost of Scrap Tires	0	0	A tipping fee pays for current disposal of waste tires.
2. Fabricate, Handle, Store	13.08 to 15.67 (10 to 12)	14.39 (11.00)	Includes wire ties. (Note 2)
3. Transport to Site	2.49 to 4.71 (1.90 to 3.60)	3.27 (2.50)	Estimate: 25 miles @ \$5.50/ton =\$2.50/cy [varies to 100 miles @ \$10/ton = \$5.00/cy]
4. Store, protect, handle tire bales at site	0.65 to 1.31 (0.50 to 1.00)	0.78 (0.5)	Assume \$0.50 / cy
5. Class A Geotextile above Tire Bales	0.52 to 1.05 (0.40 to 0.80)	0.78 (0.60)	(Note 3)
6. Total 1 to 5	**16.74 to 22.76 (12.80 to 17.40)**	**19.10 (14.60)**	**Estimate Base Cost to Fabricate, Deliver, and Install**
7. Less Colorado Rebate	13.08 (10.00)	13.08 (10.00)	(Note 4)
8. Estimated Net Cost	3.66 to 9.67 (2.80 to 7.40)	6.02 (4.60)	(Note 5)

NOTES

1. Assume approximately 100 tpe and 1.5 m^3 / bale, (2 cy /bale = 1 ton / bale). CDOT unit costs for 2001 to 2003 are listed in Appendix H, Table H-1.
2. Assume: Crew & equipment costs \$100/hr and production rate is 4 to 5 bales per hour, (8 to 10 cy/hour). Then unit cost is \$10 to \$12/cy.
3. Assume: Tire bale zone is 3 m (10 ft) thick, total volume = 30 m^3 (23 cy) / LF of roadway, geotextile covers 8.3 m^2 (10 sy) / LF of roadway, and geotextile costs \$2.40 / m^2(\$ 2.00/sy).
4. \$20/ton rebate to end user or scrap tire processor = \$20/bale = \$10/cy. (R. Welle, personal communication)
5. Does not include engineering services, special design details, construction monitoring, etc. Actual cost depends on site conditions and time required to prepare design plans and specifications and monitor construction.

Table 7.2 Estimated cost of tire bales for embankment construction

Item or Activity	**Estimated Costs - \$/m^3(\$/cy)**		**Comments (Note)** (Note 1)
	Range	Base Cost Estimate	
1. Average Project Cost for Embankment Backfill	8.13 to 18.75 (6.22 to 14.34)	12.61 (9.64)	(Note 2)
2. Estimated Net Cost (Item 8 in Table 7.1)	3.66 to 9.67 (2.80 to 7.40)	6.02 (4.60)	
3. Savings by use of Tire Bales instead of CDOT Embankment Backfill	4.47 to 9.08 (3.42 to 6.94)	6.59 (5.04)	(Note 3)
Notes 1. Assume approximately 100 tpe and 1.5 m^3 / bale , (2 cy /bale = 1 ton / bale). CDOT unit costs for 2001 to 2003 are listed in Appendix H, (\$10.00 /cy = \$13.08 /m^3.) 2. CDOT average of 2001 to 2003 annual costs for 50.6 % of the 125 projects, (only project volumes from 2,500 to 50,000 cy) range from \$6.22 /cy to \$14.34 /cy and **average \$9.64 /cy.** 3. Estimated net savings are in the order of \$185,000 for a 48,000 cy replacement of Embankment Backfill. A 48,000 cy replacement would relate to a 10 ft thick tire bale zone, 60 ft. wide for 2,150 ft.			

period, the annual cost varies with the size of the project. The unit cost in item 1 of Table 7.2 is based on the average value for 50 percent of the projects where project volume ranged from 3,270 to 65,400 m^3 (2,500 to 50,000 cy) in that time period. The reported range of average cost vs. project volume is tabulated in Appendix H.

When significant quantities of tire bales are used in a particular cross-section, the cost of the cover soil in the side slopes areas and the soil buffer between the pavement and the tire bale zone will likely be somewhat larger than the “typical” average value of \$12.61 / m^3 (\$9.64 / cy) used in Table 7.2. In addition, the comparative cost of a conventional cross section using embankment backfill must be compared to the cost of all the materials at unit prices appropriate for the material quantity in the alternate backfill / tire bale cross-section. The thickness of the soil buffer layer, the side slope cover volume, the side slope angles, and the type of earth/rock material (if any) used in the side slope covers will likely be the most significant factors that impact the cost estimate for the alternate cross section. Based on the unit costs for embankment backfill, the unit cost for smaller volumes could be in the range of \$13 to \$20 /m^3 (\$10 to \$15/cy) for earthwork quantities less than 6,550 m^3 (5,000 cy).

In addition to the estimated costs for alternate cross sections of tire bales and embankment backfill described above, some materials and/or site conditions may require additional efforts or materials. Some of the additional site specific issues that may influence the total cost of the alternate cross-sections are listed in Table 7.3.

Table 7.3 Estimated cost for special material and site requirements

Possible Requirements for Tire Bale Embankments	**Estimated Costs - \$/m^3(\$/cy)**		**Based on tire bale volume**
	Range	Base Estimate	
R-1. Steam clean scrap tires or bales	0 to 10 (0 to 8)	~2 (~2)	(Note 1))
R-2. Devices to connect tire bales	0 to 5 (0 to 4)	~3 (~2.50)	(Note 2)
R-3. Earth Matrix & Infill Material		~8.60 (~6.60)	(Note 3). Does not include intrusion of sand into bales.
R-4 Crushed stone drain below tire bale zone	0.10 to 0.20 (0.80 to 0.16)	~0.14 (~0.11)	(Note 4)
R-5. Face protection	10 to 30 per m^2 (1 to 3 per ft^2) of face vertical projection	20 per m^2 (2 per ft^2) face vertical projection	Not required for a generic general embankment. Depends on available materials and site requirements.

Notes

1. Usually not required (R. Welle, personal communication). Perhaps required for contaminated tires or, if tire bales are used on environmentally sensitive projects.
2. Probably not required for a generic tire bale embankment.
3. Assume: Earth infill averages 100 mm to 150 mm (4 to 6 in) thick between tire bales. The average unit cost to install clean sand could range from \$15 /cy to \$40/cy for CDOT projects. (Appendix H). At \$28.50 /m^3 (\$22.00 /cy), the soil matrix costs \$8.50 /m^3 (\$6.60 /cy) of tire bale volume.
4. Assumes: 150 mm (6 in) thickness, 15 m (50 ft) wide of Filter Material Class B crushed aggregate at \$39 / m^3 (\$30/cy). For a drain layer along 10 percent of a roadway and a 3 m (10 ft) thickness of tire bales, the unit cost per cy of tire bale is \$0.15/ m^3 (\$0.11 /cy). bale. Note that actual costs will vary with site conditions.

7.3 Comparison of estimated cost for lightweight fill

The net cost for fabricating, transporting, and installing tire bales for a typical project is estimated to be in the range of \$3.70 to \$9.70 / m^{3} (\$2.80 to \$7.40 /cy), averaging \$6.00 / m^{3} (\$4.60 / cy) depending on fabrication, transportation, storage, and installation costs. These values are at the low end of the 1993 to 1994 range of cost estimates for other lightweight fill materials listed in Table 4.2. The unit costs in that table indicate the following unit cost ranges (excluding handling and engineering):

EPS blocks:	\$35 to \$65/m^{3}	(\$26 to \$50/cy)
Foamed concrete	\$65 to \$95/m^{3}	(\$50 to \$73/cy)
Fly ash and slag	\$ 3 to \$21/m^{3}	(\$2.30 to \$16/cy)
Shredded tires	\$20 to 30/m^{3}	(\$15 to \$23 /cy)

Stark et al., (Appendix A, page 14) by means of a questionnaire obtained a range bid prices from six United States DOTs, including three for the 1996 to 1999 period. The six prices ranged from \$39 to \$98 per m^{3} (\$30 to \$75 per cy), averaging \$70 per m^{3} (\$55 per cy). From the authors experience, recent (2000 to 2002) pricing of EPS blocks in special embankment systems has ranged from \$78 to 90 per m^{3} (\$60 to \$70 per cy) installed in the Mid-Atlantic region of the United States.

7.4 Discussion of other cost issues for tire bale embankments

In addition to the typical ranges of unit prices the Colorado DOT provided for the 2001 to 2003 time period, as tabulated in Appendix H, the comparative cost of a tire bale embankment vs. conventional construction is also affected by other factors involving the project design for specific site conditions, material availability, and contractor bidding practices that should be evaluated on a case by case basis. The significant factors can include:

- Adequate subsidy to offset cost of fabrication.
- Lack of prior experience with design and construction of tire bale embankments.
- Overly conservative design approach, such as soil infill around each tire bale, or implementation of design elements related to tire shred embankments.

- Extensive QA/QC requirements.
- Inclusion of drainage elements.
- Limited supply of tire bales near the project site, and/ or the high cost of tire bale transportation.
- Unbalanced or “opportunity pricing”, instead of Owner supply of tire bales from stock piles at nearby sites, and contractor installation of tire bales on a time and material basis.

A significant consideration for the design and construction of tire bale embankments is the possible requirement to construct a soil zone around each tire bale. This approach has been suggested and implemented on several preliminary tire bale embankments in other states, perhaps based on a conservative perspective that a soil matrix between tire bales, (or other material injected into the interior of a tire bale) is necessary to maximize fire protection and reduce risk of fire propagation, or to decrease deformation of the tire bales during loading. As noted above in Table 7 .3, the use of a clean sand as a soil matrix –only around the tire bale -- can be quite expensive (~\$8.60 /m^3 or ~\$6.60 /cy of tire bale volume). This cost is on the order of 10 times the comparable cost of a single layer of Class A separation geotextile between the tire bales and the overlying soil buffer layer, unless suitable materials are available near the site. It is the authors’ opinion at this time that use of a CDOT Class A, or a AASHTO Class I, geotextile should be sufficiently strong to survive construction and thus prevent infiltration of the soil buffer layer into the underlying tire bales.

8 FEASIBILITY, FEATURES, BENEFITS, AND DESIGN/ PERFORMANCE ISSUES

8.1 Feasibility

The assessment of tire bales presented in this report indicates that the use of tire bales in transportation applications is considered feasible. However, some laboratory and field research is required to obtain design parameters, understand some aspects of the insitu service behavior, develop appropriate engineering design procedures, and prepare appropriate contract specifications for use of tire bales in this application. The perceived features, benefits, potential limitations, and field and laboratory research issues are noted in the following sections of this report.

8.2 Features and benefits

With regard to transportation embankment applications, tire bales are considered a promising product that can be used as a relatively low-cost lightweight fill with relatively good mechanical properties. The perceived benefits when tire bales are used as embankment fills are listed below:

- Waste tires are readily available in Colorado.
- Tire bale fills are relatively low-cost, on the order of \$3.70 to \$9.70 /m^3 (\$2.80 to \$7.40 cy) (assuming the current Colorado rebate for using scrap tires is in force).
- As a lightweight fill embankment on compressible soils, insitu unit weights in the range of 30 to 50 percent of normal soil fills will induce less settlement.
- Relatively high internal and external shear strength properties, above that of very stiff or dense soil.
- High permeability values, in the clean sand and gravel range, allowing gravity drainage.
- Fabrication of tire bales does not require high quality control requirements, sophisticated molding procedures, and skilled labor.
- Tie bales can be fabricated at convenient locations and stored, with some protection, until they are used.
- Lightweight tire bales, approximately 1 ton units, are easy to transport to construction sites.

- Tire bales can be easily moved and placed by conventional lightweight lifting equipment.
- Colorado Department of Health and Environment does not require permits for use of tire bales in transportation applications.
- Use of scrap tires, presently stockpiled in tire dumps and other waste disposal sites, provides a significant benefit to the state's environment by using them in beneficial applications.
- Tire bales are generally compatible with other construction materials such as soils, concrete, and geosynthetic materials.
- Tire bale fills are considered to be less likely than tire shred fills to develop exothermic heat reactions, leach manganese and iron, and release organic compounds when placed below a ground water table because much less exposed steel in baled tires.
- Low service creep strains (Lab test on one tire bale indicates less than 0.1 % strain per month with normal stress of 38 kN/m^2 (800 psf), which is equivalent to a 5.5 m (18 ft) high embankment with an average unit weight of 45 pcf.).
- Tire bales do not expand significantly or "explode" when the wire tires are cut because the fabrication load and "time of restraint" holds the deformed tires together.

8.3 Special considerations, limitations, and research issues

Some of the potential limitations to the use of tire bales in transportation projects are summarized in this section.

- **Fire Protection** A prudent and practical level of fire protection practice should be developed and employed to protect tire bales in storage, in transit, and in an embankment. The required level of protection practices should consider appropriate planning, conformance to fire prevention practices, protection from possible acts of vandalism, localized fire sources, and lightning strikes. The available literature does not provide test reports, or codes, that adequately address the ignitability and flammability of tire bales exposed to a natural (outside) or the soil covered soil environment. Part of the observed practice and practical experience in many states is that a number of large to very large piles, containing more than several million whole scrap tires, have not ignited when exposed to natural (outdoor) conditions for years. However, this experience does not preclude the possibility that a small number of such stockpiles may burn as the result of unexpected fire conditions.

Typical fire codes for whole tires usually address storage and stacking of tires inside buildings. Guidelines for constructing and monitoring stockpiles of tire shreds limit the conditions which can cause exothermic reactions in shredded tire embankments have apparently been successful for projects constructed since 1997. The guidelines require separation of tire shred piles, roads for fire fighting equipment, fencing around the site, and fire marshal approval of storage plans. By extension of the codes and guidelines for the current uses of tire shreds, it appears that storage of tire bales will require similar codes and guidelines.

Compared to tire shreds, the use of tire bales (covered with soil) in embankments should not pose an unusual, or increased fire hazard. Temperature monitoring of the proposed prototype tire bale embankments should provide data that can be compared to temperature buildup in tire shred fills and thus provide additional information on the relative performance of tire bales to tire shred fills with respect to the potential in service fire protection issues.

- **Ground Water Quality**. One concern regarding the use of tire bales and waste tires involves their potential impact on groundwater quality. Although no specific study has been conducted to identify the impact of tire bales on water quality, some studies have been conducted regarding the impact of tire shreds on water quality. For example, an ongoing study sponsored by the Federal Highway Administration involves testing the impact of tire shreds on water quality (organic and inorganic constituents). This study concluded 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.

  Section 7.3 of ASTM D 6270 indicates that field studies of tire shred fills above the water table tend to leach Manganese, and under some circumstances, iron at levels above the secondary drinking water standards. Secondary drinking standards refer to aesthetic factors, such as color, odor, and taste – not health concerns. Release of organics from tire shreds above the water table is not considered a significant concern. However, Section 7.4 of ASTM D 6270 indicates that tire shreds below the water table can leach levels of Manganese and iron that are significantly above secondary drinking standards (aesthetic factors, such as: color, odor, taste – not health concerns). Tire shreds below the water table can leach low levels of a few organic compounds into the groundwater. Section 7.4 indicates “further studies are needed to determine if these levels are high enough to be of concern.” It should be noted that the typical design of tire shred fills usually includes a sealed geomembrane wrap to reduce surface and groundwater infiltrations, as well as base drains to discharge condensation water, in an effort to reduce the free access of air and to keep the tire shred fill in an unsaturated condition and thereby reduce the possibility of exothermic reactions resulting in fires. In addition, a typical design for tire shred fills includes approximately two-ft thick layers of compacted soil to limit the vertical thickness of tire shred fill zones to approximately 8 to 10 feet.

In contrast to tire shred fills, where shred sizes typically range from sand sizes up to approximately 600 mm (24 in.) dimensions, tire bales are usually made with whole tires. Use of whole tires in tire bales is therefore expected to significantly reduce the exposure of steel tire reinforcements and result in a lower level of concern for the possibility of leachate affecting the groundwater environment. (Note, however, that some fabricators do cut truck tires, which exposes part of the steel core, and include them in an “equivalent 100 tire bale”.)

Water flow through permeable tire bale embankments is not expected to produce a leachate with lower quality than that of tire shreds. Considering the leaching potential of tire sheds as reported in ASTM D6270 (as discussed above) and the potential for residual (oils, etc.) materials to remain on tires, it would be prudent to take special precautions at sites located near water supplies or where bales will be place at or below ground water level. For these applications, CDOT should require that:

a) tires are cleaned prior to fabrications, and
b) a geomembrane be incorporated in the design to restrict vertical percolation of water into the tire bale embankment.

Leachate from the tire bale embankments could also be collected and stored in holding basins for periodic analysis of leachate quality prior to site discharge (i.e., if the leachate quality is within Colorado guidelines).

Requirements for conducting leachate testes on typical tire bales, cleaning tires, and/or implementation of geomembrane or other leachate control measures to comply with Colorado water quality requirements, should be part of the design engineer's scope of work.

- **Drainage and Buoyancy**. Concerns have also been raised over the use of tire bales in areas of significant ground water fluctuation and flooding conditions. However, tire bales were reported and confirmed by the laboratory testing performed in conjunction with this study to behave as a "free-draining" unit. That is, water can easily flow through the tire bale. Tire bales were also found to have a submerged unit weight of 0.5 to 0.9 kN/m^3 (3 to 6 pcf) and thus should not float due to buoyancy force, which would alleviate concerns in areas subject to flooding. In supporting the laboratory test results, 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, personal communication). In addition, the in-service condition for a tire bale embankment zone would likely usually include 0.6 m to 2 m (2 ft to 6 ft.) of earth, rock, and pavement materials which would reduce the risk of a buoyant condition.

- **Integrity of Tie Wires and Straps** An additional aspect that deserves further investigation is how the insitu physical and structural integrity of the tire bale, and the tire bale zone, is affected if tie wires or straps deteriorate and rupture during the design service life of the embankment. Observations and experience with handling tire bales with a fork lift, or other mechanical handling devices, indicates that as a minimum, ties are needed to confine the tires after fabrication and during shipment and installation. The need for longer term physical confinement of each bale, involves selection of corrosion protection for metal ties and specification of a long-term strength for all types of ties while the tire bale is in service. Tie design requirements appear to be a controversial issue.

  A study reported cutting the wires of tire bales after a set amount of time (e.g. usually one year or more), and observing an unrestrained tire bale. Due to plastic deformation of the bales, the individual tires were reported to not change or expand significantly from the placed geometry. That is, it appears that after a period of time, the tires will not elastically rebound or return their original shape. In fact, it has been observed that less distortion takes place when the baling wires are cut after long periods of time (Miner, 2003, personal communication). This is an important issue considering that tire bale ties maybe cut during construction or degrade with time. .

Laboratory rebound tests performed as part of this study (see section 4.3.1) confirmed that vertical movement (heave) was minor when tire bales were in either laterally confined or unconfined. Only a small amount of soil cover (less than ½ ft) would be required to prevent any vertical heave should tie wires break. However significant lateral movement did occur in the unconfined test and a significant force was required to restrain the tires in the confined test to prevent such movement. Tire bales could be placed in the embankment with tie wires oriented parallel to the edge of the embankment to avoid failure along the side walls of the embankment. However there could be locations where this is an issue. Nevertheless the lateral stress exerted by tire bales should tie wires break requires further evaluation for designing lateral restrain features (e.g., buttressing berms) where they are required.

Another aspect of this issue is the situation when an excavation must be made into the tire bale fill zone in the future. As excavations are sometimes made in highway embankments for subsurface explorations, install utility poles, utility lines, or to repair or replace existing utility lines. If such an excavation is required, it appears that conventional subsurface explorations drills would not be very effective in penetrating a tire bale fill, but a large backhoe would be able to make a large excavation.

It is the authors' opinion that removal of discrete tire bales, or removal of individual tires from bales after the ties are cut or broken would also be a difficult situation. In order to effectively deal with this situation, accurate as-built drawings will be a very important resource when future excavations or subsurface explorations are conducted. It is also the authors' opinion that replacing the excavated tire bales would not be feasible in small excavations but could be feasible in large excavations. Selection of bedding, backfill, separation materials, and development of construction procedures should be addressed in future tire bale studies.

8.4 Design / performance issues

Table 8.1 provides a list of primary design and performance issues that in the author's opinion should be considered and evaluated in order to implement the three tire bale applications which are the focus of this report.

Table 8.1 Issues related to use of tire bales as embankment fill.

Tire Bale Issues	Short-term	Long-term	Comments
Comprehensive specifications for fabrication of tire bales with consistent properties	Very Important	Very Important	Requires cooperation among the tire balers, bailer manufacturers, and a competitive market for fabricated tire bales
Compression and creep rates, as affected by fabrication variables (compression loads, number of auto tire equivalents, unit weight, and confining bands)	If required, address by preload, surcharge, and monitoring the time to settle and the overbuild thickness required to compensate for short-term compression	Must be confirmed as relatively small for pavement performance reasons; roadway type and traffic loadings should also be considered	Requires laboratory tests and monitoring field test sections
Relaxation or expansion if confining bands break or relax	Possibly repair prior to installation. In place requires monitoring prior to completion of construction.	Important to evaluate, however, may not be an issue based on comments from field projects.	Requires monitoring laboratory tests of tire bales with movable side walls
Interaction with existing and future utilities.	Important for installation of utilities during construction.	Important to evaluate, however, tire bale embankments should be designated as "No Dig Zones"	Requires coordination with utility owners and utility locator systems.
Internal and external shear strength values are function of tire bale interlock, surface asperities, separation materials, and unit weight.	Very Important	Very Important	Requires laboratory tests and monitoring field test sections

Table 8.1 Issues related to use of tire bales as embankment fill (continued)

Fire protection measures	Important during fabrication and storage	Important	Requires additional testing and evaluation
Tire bale permeability	Moderately important	Moderately Important	Tire bales were found to be permeable (see lab test App. F) but requires additional quantification
Requirements for soil buffer layers:			Requires monitoring field test sections
a) to support roadways above tire bale embankment	Important	Very Important	
b) reduce temperature increase and exothermic reaction in untreated tire bales	Important	Important	
c) below side slopes, and	Important	Important	
d) limit thickness of tire bale embankments.	Important	Important	
Requirements for geotextile separation/filters to minimize soil movement (loss of ground) into internal voids in tire bales.	Very Important	Very Important	Requires monitoring field test sections
Exterior Protection	Not important	Important	Depends on application
Exterior Facing	Important	Important	Depends on application

9 VIABILITY AND FUTURE EFFORTS

Based on the current understanding of the properties of waste tires, as well as on the apparent satisfactory performance of a limited number of embankment projects constructed so far using tire bales, it may be concluded that the use of tire bales as embankment materials is technically and economically feasible and offers significant potential applications in many transportation systems. In addition to the obvious environmental benefit of using recycled waste materials, the lightweight and inherent mechanical strength of tire bales offer advantages over normal fill in terms of reduced stress to the subgrade and improved internal strength of the structure. Based on rebates for recycling scrap tires in Colorado, tire bales are essentially free except for hauling costs. Other normal construction cost for handling and installation should be no greater than conventional embankment construction and the time of construction could possibly be could be accelerated (especially winter construction).

The current understanding of tire bale feasibility is based on:

1. The quantification of material properties involving the use of waste tires processed as tire shreds, keeping in mind that tire shreds are much different from a tire bale composed of compressed whole tires.
2. Visual inspection of transportation applications that did use tire bales but did not incorporate comprehensive monitoring programs necessary to adequately define long-term performance required for engineered transportation facilities.
3. The results of a companion laboratory testing program to define basic engineering properties of tire bales. (See Section 4.3 and Appendix D of this report).
4. A draft tire bale specification, which outlines many of the design and construction requirements.

Although a significant amount of testing was performed in the companion laboratory test performed as part of this study, the limited amount of test data is not extensive enough to develop reliable statistical relations that adequately describe the variance of the measured properties. It is likely that properties of tire bales fabricated using a different tire baler, or prepared with the same equipment but different procedures, will show somewhat different results. It is also pertinent that performance of in-service tire shred fills often have a better physical performance than would be predicted by the observed laboratory behavior of small specimens.

In order to integrate tire bales into a recognized standard of Civil Engineering practice, future projects must include laboratory tests and prototype field test sections that will allow development of reliable statistical relations that describe the variance of the measured properties and the real in-service performance. As indicated in Section 8.4, a comprehensive standardized product specification for fabrication of tire bales should be developed for consistence of the delivered materials. For projects using standardized products, a limited amount of testing (e.g., dimensional variation and unit weight) is required to characterize the materials and verify conformance to the draft tire bale specifications. If tire bales are produced by an alternate method, then more extensive test should be performed (e.g., compressive strength and creep in addition to the conformance testing). As discussed in the specification Section 6.3 Manufacturer's Quality Assurance (MQA) should include the requisite tire bale tests to provide data that adequately describes the tire bales used to construct the prototype test sections.

9.1 Recommended field testing

As discussed in Section 8.4, several design and performance-related issues require further evaluation. In the authors' opinion, use of tire bales as a core fill in embankments can be best evaluated in an instrumented prototype embankment structure, ideally as part of an actual project.

The field prototype should be constructed with at least two sections, each at least 15 m (50 ft) long. In one test section the tire bale portion of the embankment should be in filled with sand (or flowable fill) and in the other test section a geotextile separator should be placed above and beneath the tire bale section with no infill material placed inside or between the tire bales. A possible third test section could be constructed using the alternate infill material (i.e., either flowable fill or sand) that was not used in the first test section to provide a constructability and performance comparison of the infilling procedures.

For the primary test sections, tire bales should be placed a minimum of three layers deep and placed in a stacked brick arrangement. Other sections could be constructed to evaluate the impact of different layer thickness. For example, a ramp could be constructed at one end of the test embankment with an increasing number of tire bale layers to evaluate the maximum number of tire bale layers that could be practically used in an embankment. Similarly, the thickness of a compacted soil buffer layer above the tire bales could be evaluated by increasing the thickness of the buffer layer from each end of the test embankment to the middle. Constructing the thickest soil buffer above the middle test section will allow transition from one tire bale test section to the next and provide some insight into the behavior of the soil buffer layer and long-term compression and rebound of varying layers (thicknesses) of the tire bale zones.

The instrumentation program for each section is outlined in Table 9.1, and includes the tire bale issues to be monitored along with the appropriate instrumentation for making the measurements. The specific type and location of the instruments will depend on the specifics of the prototype test embankment including the location in relation to accessibility and power sources, purpose (e.g., roadway support or temporary construction access, and dimensions (i.e., length, width, and height).

The cost of the instrumentation for each section is anticipated to be basically the same, regardless of the prototype. However, there will be some anticipated savings if the prototypes are staged such that data acquisition equipment can be shared. Based on the monitoring program outlined in the table, the instrumentation for each test section should cost on the order of $20,000 including procurement, installation and calibration. An additional $20,000 should be budgeted for onsite instrumentation specialist and support personnel for each prototype section to provide on site consultation during construction and reading, reporting, interpreting and maintain the instrumentation program. The estimated costs do not include the costs of embankment design, construction, and associated material costs, nor do they include the cost of data interpretation and a final research report.

Table 9.1 Instrumentation program to monitor tire bale issues for embankment fill applications.

Tire Bale Issues	Measurement	Magnitude	Potential Instruments
Confirmation of fabrication requirements for the "Standard Type I tire bales"	Must document the fabrication & characteristics of a "Standard" tire bale.	N/A	Eyes, photographs and lab tests to document conformance with specification requirements.
Deformation during construction	Compression during construction and subsequent traffic loading	15% of tire bale thickness or approximately 150 mm (6 in.) during construction & short-term settlement	- Survey during construction after placement of each lift. - Settlement plates below and above tire bales extended to the surface. - LVDT's with data acquisition to monitor deformation during traffic loading. - Compression with depth could be evaluated with settlement plates also placed between tire bale layers. - Horizontal profilers could also be used if cost is not an issue
Creep during service life	Long-term monitoring of vertical settlements	25 to 50 mm (1 to 2 in.) (depends on thickness of tire bale embankment)	Settlement plates above and below tire bales extended to the surface with LVDT's and remote data acquisition to evaluate movement during temperature change and check surface deformation.
Relaxation or vertical expansion and lateral pressure exerted by tire bales if confining tie wires break or relax.	Vertical heave and lateral pressure between bales (cut bale wires at a min. of 2 locations after construction)	50 mm (2 in.) 9kN (2 kips)	Settlement plates below and above tire bales extended to the surface. Place load cells with large seating plates between bale to be cut and adjacent bale(s)
Internal and external shear strength values as function of tire bale interlock, surface asperities, separation materials, and unit weight.	Measure by pullout tests on tire bales in the field	N/A	N/A
Tire bale permeability	Observe water flow through tire bale section in field during rain events	N/A	Visual, on site rain fall measurements and outflow measurements from drainage system.
Requirements for soil buffer layer thickness	Visual and evaluation based on other measurements	N/A	Visual and surveyed response.

Table 9.2 Instrumentation program to monitor tire bale issues for embankment fill applications (continued)

Influence of soil buffer on pavement design	Load and deflection response	CDOT subgrade requirements for pavements	FWD and plate load test performed on buffer layer.
Requirements for geotextile separation/filters to minimize soil movement (loss of ground) into internal voids in tire bales	Use Class I geotextiles in test section with no in fill and excavate after construction	Holes in geotextile and loss of strength	Visual and surveyed response. Take samples and run wide width test ASTM D 4595.
Exterior protection	Evaluate alternative soil, rock and vegetation cover	N/A	Eyes, photographic, and survey techniques to provide accurate response records and data.
Exterior facing	Not required for embankments, but could evaluate vegetation growth	N/A	Eyes, photographic, and survey techniques to provide accurate response records and data
Temperature effects and fire protection	Thermal monitoring of the system	5 to 60º C (40 to 140º F)	- Strings of thermisters located every 300 mm (1 ft) vertical placed during construction on tires or after installation (through embankment into underlying soil). - Thermocouples placed (during construction) internal and external of tires, also monitor ambient temperature.
Long-term moisture absorption (and associated weight gain)	Long-term monitoring of humidity and moisture level within the tire bale system	0 to 10 % moisture content and 50 to 100% relative humidity	- Moisture sensors (TDR, gypsum blocks, etc) - relative humidity gage - Drill hole and sample (periodically)
Frost protection (If site location permits)	Long-term monitoring of frost penetration with depth in the tire bale system	-20 to 40º C (0 to 100º F)	- String(s) of thermisters placed vertically after construction at 100 mm (4 in) intervals to monitor temperature with depth. - Surface survey of road.
Long-term performance of pavement constructed over tire bale embankments	Ride quality and load/deflection response	Standard pavement requirements	- Periodic FWD and Benkelman beam tests (consult with pavement group). - Periodic distress surveys

10 CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

This research study concludes that compacted tire bales systematically placed as the core of highway embankments is another technically and economically feasible use of scrap tires. The steady development and sales of tire balers, as well as the small-scale installations completed in the past 15 years, indicates there are a wide range of applications for properly fabricated tire bales. Compacted tire bales are considered a lightweight engineered fill, with properties similar to, and often better than the typical lightweight materials which have been successfully used by Civil Engineers for the past 30 years. Tire bales, as listed in Table 2.1, have been used in wall systems, slope repair systems, lightweight embankments, drainage zones, erosion protection walls, and rockfall and crash barriers. The Case Studies in Appendix B illustrate recent uses in transportation applications.

Typical tire bales weigh approximately 8.9 kN (2,000 lb), the dimensions range from 0.7 m to 1.5 m (2.5 ft to 5 ft), and the unit weights range from 5.5 to 8.8 kN/m^3 (35 to 50 pcf). The compacted tire bale is typically bound by several wire tires to maintain the block form and provide the inherent strength and properties of each tire bale. This size, weight, and tie system provides reasonable dimensions, and weights that can quickly handled by small wheeled / tracked fork lift equipment.

The tire bale properties include low unit weight, specific gravity greater than 1.0 (sinks in water), modest compressibility (2 to 10 % strain at working stress levels) and creep values, high internal and external shear strength, relatively high permeability, low thermal conductivity, low leaching potential, low potential for developing exothermic reactions, and high chemical and physical durability as described in Section 4 and listed in Table 4.1.

The laboratory test program, conducted as a companion study to the feasibility analysis and report, was very successful and provided a number of property values that had not been previously measured and reported for typical tire bales. The test results in Appendix D, and the presentation of typical test results in Section 4, provide a starting point for an engineered design approach for tire bale embankments. Additional Quality Assurance and Quality Control testing should be conducted for each instrumented prototype field tire bale test section in order to relate measured performance to the measured characteristics of the tire bales fabricated for each test embankment. Similar tests should be conducted on tire bales fabricated for routine embankment projects to develop a statistical evaluation of the standard deviation values and variability of the important properties of tire bales.

The preliminary estimates of the net cost of \$3.70 to \$9.70 /m^3 (\$2.80 to \$7.40 /cy) indicate a tire bale embankment zone could result in a cost savings as compared to the use of embankment backfill. Embankment backfill was found to have an average cost of \$12.60 /m^3 (9.60 /cy) on approximately 50 percent of the 125 Colorado projects in the 2001 to 2003 time period where the volume of the embankment fill ranged from 3,270 to 38,210 m^3 (2,500 to 50,000 cy). The estimated cost of a tire bale fill is at the low end of the range of costs reported for other lightweight materials, such as EPS blocks, foamed concrete, shredded tires, and fly ash / slags.

However, there are some fabrication, design, construction, and performance issues that must be addressed in order to develop an established basis for engineered approach to design and construct a tire bale embankment that will provide satisfactory performance for the service life of the project. This situation is typical of the engineering process for any new material or application where manufacturing and fabrication requirements must be established, followed by laboratory and field testing to determine the material properties the designer must use to develop the project plans and specifications. Finally, prototype structures must be instrumented and monitored to measure a structure's performance in comparison to the design expectation.

The important issues that must be addressed are listed in Table 8.1 and summarized below. The issues include:

- understanding the appropriate level of fire protection required, commensurate with the level of risk and costs associated with use of tire bale embankment zones in transportation applications.
- developing specifications for consistent fabrication of tire bales with the desired properties.

- understanding product variability resulting from changes in fabrication procedures and the use of different tire balers.
- defining the short-term and long-term requirements for bale ties and the potential impact of broken wire tires on the lateral restraint requirements for the embankment.
- understand variations in internal and external shear strength, and compressibility and creep rates, as a function of fabrication procedures and applied loadings.
- developing properties and dimensions for Class I and Class II Tire Bale Embankments
- developing requirements for geotextile separation layers.
- selecting type and thickness of buffer layers between tire bales and the overlying pavement.
- interactions with existing and future utility penetrations.
- selecting soil / rock covers, facing, and protection on variable angle side slopes for specific site and service conditions.

10.2 Recommendations

The continuing evaluation of tire bales in transportation embankments is strongly recommended. Previous sections of this report have outlined and tabulated in detail the “state of practice” and the feasibility of using tire bale embankments, in comparison to other lightweight fill materials and in contrast to, the conventional CDOT use of embankment backfill. The previous sections outlined recommendations that are “next steps” to implement and improve the state of practice for tire bale embankments. These next steps are intended to provide additional information on the relation of fabrication procedures to tire bale properties (see Section 4.3), design guidelines (see Table 6.2), specifications (see Section 6.3), costs (see Table 7.1 to 7.3), fire protection issues (see Table 8.3), and in-service issues such as creep (see Table 9.1).

The following tasks are recommended by the authors as an efficient and effective sequence to follow in implementing the recommendations developed by this study to obtain the information required to develop the state of practice for this application of recycled scrap tires.

Task 1 Construct several prototype tire bale embankment with different cross-sections as part of a highway embankment on a secondary highway. (See Section 9) This would involve:

- (a) selecting an appropriate site.
- (b) preparing a comprehensive tire bale specification, including fabrication and QC guidelines.
- (c) testing selected tire bales for basic mechanical and chemical properties.
- (d) developing design guidelines and formulas, performance requirements, and safety factors.
- (e) selecting instrumentation as recommend in Table 9.1.
- (f) preparing design drawings and cost estimates.
- (g) constructing instrumented cross-sections as recommended in Section 9.
- (h) conducting FWD evaluations of soil buffer layers and pavement system.
- (i) preparing as-built plans and reports of the construction monitoring.
- (j) monitoring in-service performance of the prototype sections (a five-year program is recommended, including FWD testing at 3 month intervals for the first year and once a year thereafter.
- (k) preparing annual reports on in-service performance

After constructing the prototype test sections, and simultaneously with monitoring the performance of the test sections, address geotechnical engineering design methodology and fire protection engineering.

Task 2.1 Conduct **e**ngineering studies that develop a comprehensive design methodology for constructing tire bale embankments, including:

- (a) fabrication procedures in relation to tire bale properties.
- (b) prepare documented case histories of the prototype sections along with other successful and problematic tire bale installations, including design assumptions, construction details, and measured performance.
- (c) quality control requirements and responsibilities.
- (d) design methods, analyses, details, and examples.
- (e) construction practices and requirements.

(f) impacts on pavement design.

(g) use of ancillary materials, such as bale ties, soil / rock slope covers, and facing options.

(h) cost studies and estimates to optimize costs v. benefits in the design construction process.

(i) specifications and related AASHTO / ASTM standards, for Class I, Class II tire bale embankments, (including fire protection requirements developed in Task 2.2.)

(j) monitoring long-term in-service performance.

(k) guidelines for use of tire bales in other applications,(such as slope stability, erosion protection for lakes, rivers, streams, and rock-fall barriers.)

Task 2.2 Simultaneously with Task 2.1, conduct a fire engineering study to evaluate the potential in-service fire risks associated with tire bale embankments. This could involve:

(b) selection of experienced and qualified fire engineering consultants.

(c) review and report of pertinent literature that assesses the fire risks and protection required for in-service tire bale embankments.

(d) review temperature data obtained from the prototype tire bale embankments test sections to determine if observed temperature changes are (1) similar to the temperature observations in fresh tire shred fills, and (2) indicate the possibility of that significant exothermic reaction could develop and initiate tire bale fires.

(e) develop a report, including appropriate recommendations (as required) and cost estimates for field fire tests of selected materials and tire bales to replicate in-service conditions.

(f) prepare a report with recommendations for fire protection requirements for in-service tire bale embankments.

(g) prepare fire protection requirements for tire bale embankment specifications, based on the work described in Task 2.2 (a) to (e)

Task 3 Ultimately, it may be appropriate to develop a national oversight panel consisting of the stakeholders in the tire recycling industry that are interested in and can champion the continued development of tire bale applications. The panel could include 1) tire baler manufacturers, experienced geotechnical design engineers familiar with tire bales and lightweight fills, instrumentation, and transportation applications, 2) transportation contractors, 3) experienced academic researchers familiar with behavior of rubber materials and fire protection requirements, 4) governmental agencies, and 5) industry agencies, such as Rubber Manufacturer's Association and Waste Recyclers. This group would solicit funding, select outside consultants, and guide the process of rapidly developing the "state of practice" to a point where tire bale materials are routine in Civil Engineering practice and quality materials are readily available at a reasonable cost.

REFERENCES

AASHTO M288, (1997). “Standard Specifications for Geotextiles – M288”, Standard Specifications for Transportation Materials and Methods of Sampling and Testing, 18th Edition, American Association of State Transportation and Highway Officials, Washington, D. C.,

ASTM, (1998). ASTM D 6270-98, “Standard Practice for Use of Scrap Tires in Civil Engineering Applications,” American Society of Testing and Materials, West Conshohocken, PA

Baker, T. E., T. M. Allen, D. V. Jenkins, Mooney, D. T., Pierce, L. M., Christie, R. A., Weston, J. T., (2003). “Evaluation of the Use of Scrap Tires in Transportation Related Applications in the State of Washington”, Report to the Legislature as Required by SHB 2308, Environmental and Engineering Programs Division, Materials Laboratory, Olympia, WA.

Benson, C.H., M.A. Olson, and W.R. Bergstrom, (1996). Temperatures of an Insulated Landfill Liner, Transportation Research Board, 75th annual meeting, Washington, D.C.

Blumenthal, M., Rubber Manufacturer’s Association, (2004). Personal Communication

Bosscher, P.J., T.B. Edil, and N. Eldin, (1993). “Construction and Performance of Shredded Waste Tire Test Embankment,” Transportation Research Record No. 1345, Transportation Research Board, Washington, D.C., pp. 44-52.

Bosscher, P.J., T.B. Edil, and S. Kuraoka, (1997). “Design of Highway Embankments Using Tire Chips,” Journal of Geotechnical and Geoenvironmental Engineering, Vol. 123, No. 4, April 1997, pp. 295-304.

Caltrans (1988) “The Use of Discarded Tires in Highway Maintenance”, Translab Design Information Brochure No. TI/REC/1/88, California Department of Transportation, Sacramento, CA

Chautauqua County, (2001). “Utilization of Scrap Tires in Baled Form Used in Roadbed Construction in Conjunction with the Tire Amnesty Program.” Chautauqua County Department of Public Facilities, Division of Transportation.

Chautauqua County Department of Public Works, New York, (2002). “Where the Rubber Really Meets the Road, Chautauqua County New York Scrap Tire Reduction Program, Using Scrap Tires in Roadbed Construction, Tire Amnesty Program”, CD-ROM.

Christopher, B.R., (2002). Personal photo.

Edil, T.B., and Bosscher, P.J., (1992). “Development of Engineering Criteria for Shredded or Whole Tires in Highway Applications,” Report No. WI 14-92, Department of Civil and Environmental Engineering, University of Wisconsin, Madison, WI,

Edil, T.B., and Bosscher, P.J., (1994). “Development of Tire Shreds and Soil Mixtures,” Geotechnical Testing Journal, Vol. 17, No. 4, December, pp. 453-464.

Encore Systems, (2003, 2004). Personal communication. Photo courtesy of Encore.

Enviroblock, www.enviro-block.com

EPA, (1991). “Summary of Markets for Scrap Tires,” Report No. EPA/530-SW-90-0748B, US Environmental Protection Agency, Washington D.C., pp. 1-12.

Eaton, R. A., Roberts, R.J., and Humphrey, D. N.,(1994). “Gravel Road Test Sections Insulated with Scrap Tire Shreds,” Special Report 94-21, U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory, Hanover, NH August 1994.

Northern Tyre (UK) Limited, Inverness, Scotland, (2004). www.northerntyre.co.uk/projects.htm

Integrated Waste Management Board, (2002). “Tire Pile Fires Prevention, Response, Remediation”, prepared by Environmental Engineering and Contracting, Santa Anna, CA.

Foose, G.J., C.H. Benson, and P.J. Bosscher, (1996). “Sand Reinforced with Shredded Waste Tires,” Journal of Geotechnical Engineering, Vol. 122, No. 9, September 1996, pp. 760-767.

GeoTesting Express, (2004). “Laboratory Testing of Tire Bales,” A report prepared for the Colorado Department of Transportation by GeoTesting Express of Georgia, Roswell, Georgia.

Geisler, E., W.K. Cody, and M.K. Niemi, (1989). “Tires for Subgrade Support,” Annual Conference on Forest Engineering, Coeur D’Alene, ID 5 pp.

Hoppe, E.J., (1998). “Field Study of Shredded-Tire Embankment,” Transportation Research Record No. 1619, Transportation Research Board, Washington D.C., pp. 47-54.

Humphrey, D.N., (1996). Investigation of Exothermic Reaction in Tire Shred Fill Located on SR 100 in Ilwaco, Washington, Prepared for Federal Highway Administration, Washington, D.C.

Humphrey, D., and W. Manion, (1992). “Properties of Tire Chips for Lightweight Fill,” Proceedings of the 1992 ASCE Specialty Conference on Grouting, Soil Improvement and Geosynthetics, Vol. 2, No. 30, ASCE, New York, N.Y., pp. 1344-1355.

Humphrey, D.N, (1998), “Highway Applications of Tire Shreds”, Sponsored by: New England Transportation Consortium, Worcester, MA, December 1, 1998.

Humphrey, D.N., Katz, L.E., (2001), “ Five-Year Study of the Water Quality Effects of Tire Shreds Placed Above the Water Table”.

Liu, H.S., Mead, J.L., and Stacer, R.G., (1998). “Environmental Impacts of Recycled Rubber in Light Fill Applications: Summary and Evaluation of Existing Literature,” Chelsea Center For Recycling and Economic Development, Massachusetts.

Masad E, Taha R, Ho C, Papagiannakis T. (1996) “Engineering Properties of Tire/Soil Mixtures as a Lightweight Fill Material” ASTM Geotechnical Testing Journal, ASTM International, West Conshohocken, PA.

NFPA 231 D, (1998) “Standard for Storage of Rubber Tires – 1998 Edition”, prepared by Technical Committee on Rubber Tires, effective August 5, 1998, National Fire Protection Association, Inc., Quincy, MA.

Oosterbaan, M.D. (1963) “Investigation of Foamed Plastic as an Insulating Layer in Highway Pavements, M.S. Thesis, Purdue University, Lafayette, IN.

O’Shaughnessy, V. and V.K. Garga, (2000). “Tire-Reinforced Earthfill. Part 2: Pull-Out Behavior and Reinforced Slope Design,” Canadian Geotechnical Journal, Vol. 37, pp. 97-116.

RMA, (2002). “U.S. Scrap Tire Markets 2001,” Rubber Manufacturers Association, Washington, D.C.

Rooke, L., (2001). “Building Dams From Baled Scrap Tires,” Biocycle, Vol. 42, p. 74.

Scraptires www.scraptirenews.com

Senadheera, Sanjay. (TxDOT, 2002). http://www.ce.ttu.edu/centers/techmrt/home/researchproj/Geotech/Scraptires.html

Shock, A., R. Zeck, R. Sandusky, and D. Hudson, (2001). “Thermal Modeling of Tire Bales,” submitted to Dr. Robert Knecht, Colorado School of Mines, June 13th, 2001.

Stark T.D, D. Arellano, J.S. Horvath, and D. Leshchinsky, (2000), “Guidelines for Geofoam Applications in Embankment Projects”, by National Cooperative Highway Research Program, Project No. 24-11, Final Report, August 2002.

Touch the Earth Construction, “Tire-house Builders: No More Pounding!!!” (2004), www.touchtheearthranch.com/tires.htm

TXDOT (2004) “Validate the Effectiveness of Tire Bale Use in Slope Repairs and Embankment Construction,” Project No. 5-9023-01, Texas Department of Transportation.

TXDOT, TCEQ, (2001). “Progress Report on Using Scrap Tires and Crumb Rubber in Highway Construction Projects,” 76th Legislative Session TCEQ-Rider 24 and TXDOT-Rider 47. Texas Department of Transportation, Texas Commission on Environmental Quality.

TXDOT, TCEQ, (2003). “Progress Report on Using Scrap Tires and Crumb Rubber in Highway Construction Projects,” 77th Legislative Session TCEQ-Rider 19 and TXDOT-Rider 44. Texas Department of Transportation, Texas Commission on Environmental Quality.

Tirebaler http://tirebaler.com

Transportation Research Board: http://rip.trb.org

U.S. Fire Administration, “Scrap and Shredded Tire Fires, Special Report”, Report 093 of Major Fires Investigation Project, researched by Stanley L. Poole, Jr. and edited by Hollis Stambaugh and Peter Banks, conducted by Varley-Campbell and Associates, Inc./TriData Corporation under contract EMW-94-4423 to the Federal Emergency Management Agency, (1998).

Welle, R., (2004) Front Range Recycling, personal communication.

Williammee, R., (2004) Personal communication

Williamson, R. B., (2004) Personal communication

Williamson, R.B. and Schroeder, R.A., “Fire Safety Assessment of the Scrap Tire Storage Methods”, Interdisciplinary Graduate Program in Fire Safety Engineering Science, Civil and Environmental Engineering, University of California, Berkeley, CA in proceedings INTERFLAM ’96, Interscience Communications, London, England pp 89-101 (1996).

Wu, W.Y., C.C. Benda, and R.F. Cauley, (1997). “Triaxial Determination of Shear Strength of Tire Chips,” Journal of Geotechnical and Geoenvironmental Engineering, Vol. 123, No 5, pp. 479-482.

Zornberg, J.G., A. Cabral, and C. Viratjandr, (2003). “Behaviour of Tire Shred-Soil Mixtures.” Accepted for publication in the Canadian Geotechnical Journal.

Zornberg, J.G., Costa, Y., and Vollenweider, B. (2004). “Mechanical Performance of a Prototype Embankment Backfill Built with Tire Shreds and Cohesive Soil.” Proceedings of the 83rd Annual Meeting, *Transportation Research Board*, January 11-15, Washington, D.C.

World Wide Web Sites , relevant information on scrap tires

http://www.epa.gov/jtr/jtrnet/tire_conv.htm

www.epa/gov/recycle.measure/conversn.htm

www.tfhrc.gov/hnr20/recycle/waste/index.htm

www.cwc.org/tirest954.htm
(scrap tire density)

www.co.chautauqua.ny.us

http://www.scraptirenews.com
(571.258.0500)

www.wasteage.com

http://www.scraptirenews.com/99apr3.html
(Iowa landfills use tire chips)
(Rubber core sound wall for I-675, Centerville, Ohio)

http://www.ciwmb.ca.gov/Publications
(CA landfills use tire shreds)

www.tirebaler.com
(Encore tire baler, 218.328.0023)

http://www.northerntyre.co.uk

http://www.ecoflex.com.au

http://useit.umeciv.maine.edu/.
(Beneficial Use of Solid Waste in Maine, University of Maine)