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16. Abstract

This implementation project validates field test methods for checking the conformity of tire bales used in transportation applications. It also provides guidelines for instrumentation of installations involving tire bales. Specific components include field evaluation of tire bale dimensions, tire bale unit weight, tension in the bailing wires as well as field assessment of mechanical and thermal properties. New test methods for field application to test the bales are developed.

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Validation of Field Test Methods for Use of Tire Bales

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Chapter 1. Introduction

Tire bales have recently been used as an alternative fill material for highway structures. They consist of whole scrap passenger vehicle tires that are compressed into discrete blocks that can easily be placed into the structure. Utilizing the whole tires as bales provides a method to properly dispose of the whole scrap tires collected by the different state agencies without placing the tires in a landfill or stockpile. The tire bales can be used as a lightweight fill that provides both reinforcement within and drainage from the structure. Several laboratory and field testing programs have been conducted to determine the material properties of the bales needed for design. However, there is no quality control specification available that can be used to determine if tire bales delivered to the site are acceptable and have the same properties of the specified bale used for design.

This document outlines a series of quality control field testing procedures that can be used to characterize the basic properties of the tire bales delivered to the construction site. The quality control tests were developed and conducted at several tire bale sites to determine the expected variability of the tire bale properties, which is a results of the variability of the different scrap tires placed within the bales. The properties measured using the field tests were used to determine the acceptable range in tire bale properties, which represents the acceptable range of the properties for tire bales delivered to the site. The quality control field tests and data collected as part of this implementation program provides a set of quality control procedures and values that can be used to ensure that bales delivered to the construction site are acceptable (meet the criteria of the generic tire bale properties used for the design of the structure).

In addition to defining a set of field testing procedures and quality control specifications for tire bales, the performance of the tire bale structure was also a variable of interest. An instrumentation profile for a generic tire bale structure was developed to measure the performance of the tire bale structure and provide validation for the design procedures and material properties used in the design.

The main objective of the implementation program presented in this report is to identify the properties of the tire bales that are important to the construction and stability of the structure and develop a series of quality control field tests that could be used to characterize the properties. The field tests were developed and implemented at several tire bale sites to determine the range in properties of the bales. The range in tire bale properties was used to define a set of limitations that can be used in the field to determine if the bales are acceptable and meet the criteria of the tire bale used for the design of the structure. In addition to defining a series of quality control specifications, a set of instrumentation profiles for a generic tire bale structure were also developed to measure the performance of the tire bale structure.

The Quality Control (QC) procedures for field testing are provided in Chapter 2. The implementation of the proposed QC procedures in several locations as well as a discussion of the limitations on the measured tire bale properties are provided in Chapter 3. A field monitoring plan, including the instrumentation profile for a generic tire bale structure is provided in Chapter 4.

Chapter 2. Quality Control (QC) Procedures

To ensure that the tire bales delivered to a construction site are similar to the generic bale used for the design of the structure, a series of field quality control tests were developed. The main properties of interest include the as-received weight of the bale, the bale dimensions, and baling wire tensions. In addition, a field direct shear test procedure was developed to determine the interface strength of the bales. Field quality control tests were implemented at several tire bale sites to determine the range in the index and mechanical properties. Each of the field quality control test procedures and description of the different bales and the location of the tire bale sites are provided in this chapter.

2.1 Field Quality Control Test Methods

Testing tire bales delivered to a construction site requires that each test can be conducted quickly, can be easily implemented, and utilizes equipment that is already present at the site. A description of the four tests identified as potential quality control procedures is provided in this section.

2.1.1 As-Received Weight of the Tire Bales

The as-received weight of the tire bales is defined as the weight of the bales at the time of delivery to the site. Two as-received weights are defined for the tire bale: the specified weight and the actual weight. The specified weight is the weight of the tire bale used for the design of the tire bale structure. It should represent the average weight of all tire bales placed in the structure. The actual weight of the tire bale is the measured weight of the individual tire bale, which may be different than the specified weight due to the variability of the tire bales (variability of the tires used within the bales). The actual weight is determined by lifting the tire bale with a load cell system (as shown in Figure 2.1) with a capacity of at least 500 lbs. more than the specified weight.

The as-received dry weight of the tire bale is an important index property of the bales that indicates if the proper amount of tire material is present within the bale. If the weight is too low, there is not enough tire material and the unit weight of the structure will be too low. If the weight is too high, there is too much tire material within the bale which may result in higher baling wire tensions and a reduction the lifetime of the wires.

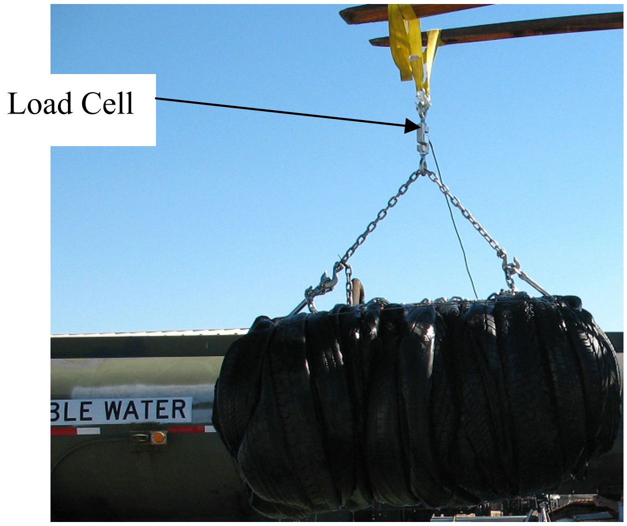

Figure 2.1: Lifting a Site 2 Block Tire Bale to Determine the As-Received Weight

2.1.2 Average Dimensions of the Tire Bales

The dimensions of the tire bale influences the unit weight of the structure, as well as the number of bales needed to complete the structure. Due to the irregular surfaces of the tire bales, the average dimensions of the bale, which represents the volume that the bale takes up within the structure, are used in the design of the structure. Two average dimensions are defined for the tire bale, the specified average dimensions and the actual average dimensions. The specified dimensions represent the dimensions of the bale used in the design of the structure, and should represent the average of all of the actual dimensions of the individual tire bales placed into the structure. The actual average dimensions are the measured average dimensions of the individual bale, and may be different than the specified dimensions due to the variability of the bales. The average dimensions of the tire bale are determined by taking the average of ten (10) measurements made along each axis of the tire bale (as defined in Chapter 2.2). A view of the standard measurements to be conducted with tape is shown in Figure 2.2.

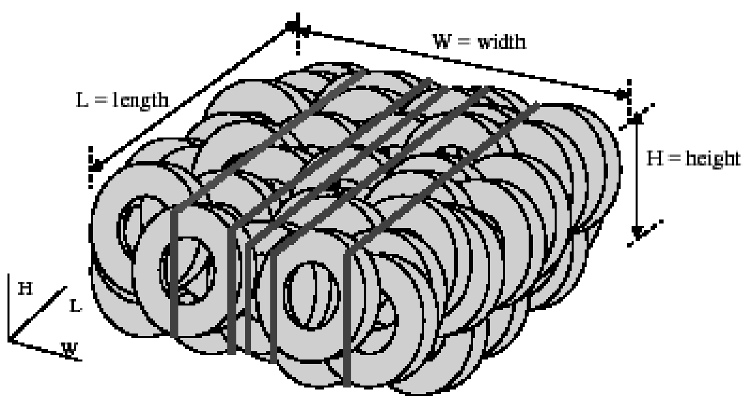

Figure 2.2: Standard Dimensions to be Measured

The average dimensions of the tire bales may be different for each project, as specified by the engineer, and therefore it is important to make sure that the bales used for construction are the same size and those used for the design.

2.1.3 Baling Wire Tension

The steel baling wires placed around the compressed tires confine the bale into the pre-defined geometry. The lifetime of the wires is controlled by the tension within the wires, which is a function of the confinement loads provided by the wires to the compressed tires and the loads applied to the tire bale (resulting in deformations of the tire bale). The tensions within the wires can be checked at the time of delivery to ensure that the tensions within the wires are less than that of the break strength of the wire. The tensions must be non-destructively determined using a tire bale tension meter shown in Figure 2.3.

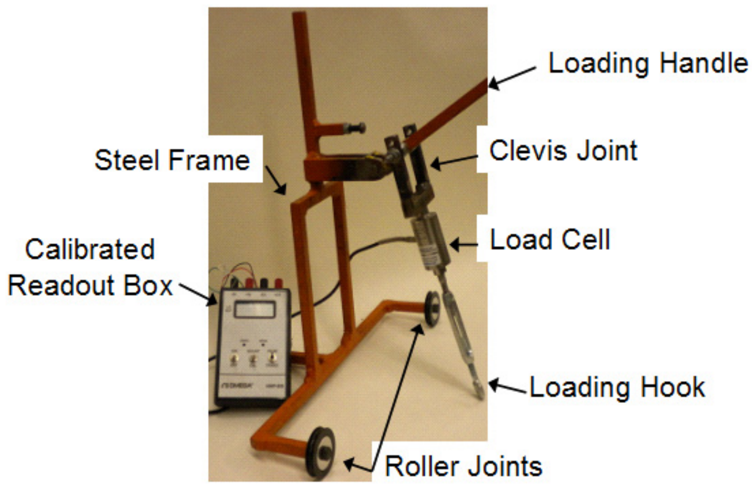

Figure 2.3: Tire Bale Tension Meter

The tire bale tension meter was designed to fit onto the baling wire and impose a deformation without requiring access to the bottom portion of the wire. The test procedure for the tension meter is as follows:

1. Locate a 14 in. space along the baling wire and place the frictionless roller joints on the top portion of the wire (Figure 2.4 a),
2. Rotate the loading handle into the down position and place the loading hook in contact with the wire using the turnbuckle connected to the tension load cell (Figure 2.4 b),
3. Rotate the loading handle into the up position and record the force (F) measured by the tension meter (Figure 2.4 c),
4. Rotate the loading handle into the down position and remove the tension meter.

The tension meter was developed so that the test did not damage the wire, was simple and easy to use, and did not require a significant amount of time to conduct. Measurement of the force readings (F) from the tension meter allows the determination of the baling wire tension (T_0). The measured variable from the tension meter is the force required to deform the wire (F), which can be related to the tension within the baling (T_0) wire using force equilibrium. The free body diagram for the wire before and after the imposed deformation is shown in Figure 2.5.

Force-equilibrium of the deformed wire results in a relationship between the tension meter force and wire tension, as follows:

$$F = 2 \cdot \sin\theta \cdot \left[T_0 + E \cdot A_C \left(\frac{1}{\cos\theta} - 1 - \frac{\Delta_W}{L_{TM}} \right) \right] \tag{2.1}$$

where F is the tension meter force, T_0 is the tension within the wire, θ is the deformation angle (2.3°), E is the Young's modulus for the steel wire (29,900 ksi), A_C is the cross sectional area of the wire, L_{TM} is the length of the tension meter (15.25 in.), and Δ_W is the rigid wire displacement. The rigid wire displacement (Δ_W) is the horizontal displacement of the wire due to the imposed tension meter deformation (ends of the wire are not rigidly restrained), and can be measured or assumed as discussed in Chapter 3.

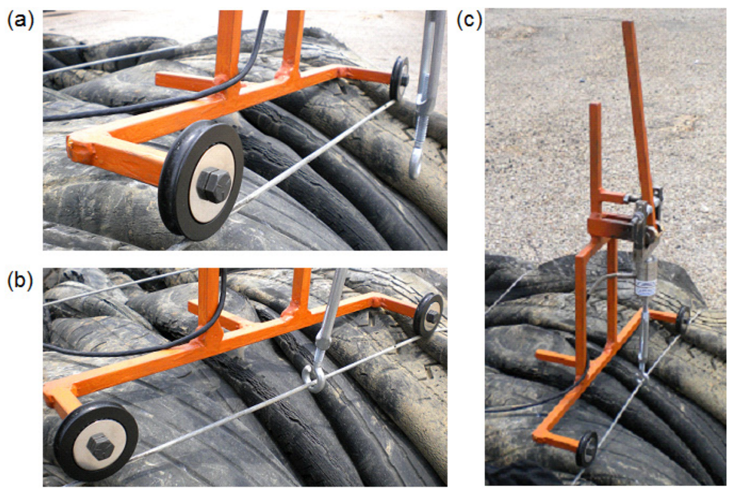

Figure 2.4: Tension Meter Procedure to Determine Wire Tensions: (a) Place Meter onto the Wire, (b) Place Loading Hook on the Wire, and (c) Lift Loading Handle

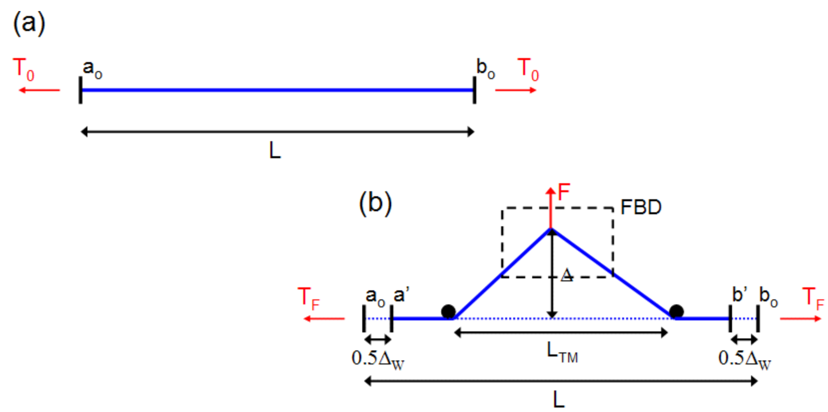

Figure 2.5: The (a) Initial Geometry and (b) the Deformed Shape of the Baling Wire

2.1.4 Field Estimation of the Interface Strength

The interface strength of the tire bale structure is controlled by the irregular and jagged surfaces of the tire bales. The interface shear strength of the bales can be determined in the field to determine if the bales are acceptable and not contaminated with any lubricants or other material that would influence the mechanical properties of the tire bale structure. The interface strength of the tire bales can be determined in the field using a direct shear test (Figure 2.6).

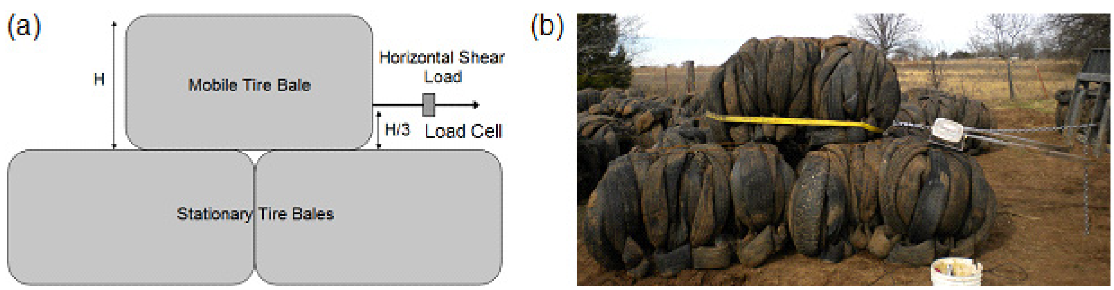

Figure 2.6: Field Quality Control Direct Shear Test for the Modified Block Tire Bales

The surfaces of the tire bales should be dry before the direct shear test is conducted. The normal load along the interface (N) is the weight of the tire bale, which is also measured as part of the field quality control testing program. A horizontal shear load (T) is applied to the tire bale at a distance of one-third the bale height using machinery present at the site (such as a forklift or front end loader) and measured with the load cell used to measure the tire bale weight. The top mobile tire bale is dragged along the stationary tire bale layer at the slowest rate the machinery can be operated. The maximum load measured during the test is the interface strength of the tire bales.

The maximum load measured with the field test is compared against the interface shear strength parameters determined utilizing the laboratory large scale direct shear tests reported in the literature (Simm et al. 2004, LaRocque 2005, Zornberg et al. 2005, Freilich 2009). The relationship between the applied horizontal shear load (T) and normal load is defined using the interface shear strength parameters as follows:

$$T = c \cdot A_F + N \cdot \tan\phi \qquad (2.2)$$

where c and ϕ are the interface shear strength parameters and A_F is the footprint area (product of the average dimensions of the bale along the sheared plane of the tire bales) of the tire bale.

2.2 Tire Bales used for the Field Quality Control Tests

Multiple tire bales were tested at different sites to characterize the range in properties of the bales. The range in properties measured for the bales were used to develop a series of quality control limitations on the tire bale properties. Two types of tire bales were tested as part of the field testing program, the block tire bale and the cylinder tire bale. The location of the tire bale sites, a description of the construction procedures, and the specified properties of the tire bales are provided in this section. The specified properties, as defined in the previous section, are those used to define the average properties of the bale used in design of the tire bale structure, and represents the average properties of all tire bales used in the structure.

2.2.1 Block Tire Bales

Block tire bales are constructed by placing whole scrap tires into a rectangular box and applying a compressive force to the tires. Galvanized steel wires are placed around the bales to confine the compressed tires into the block geometry (Figure 2.1 a). The dimensions of the bale are characterized with a length, width and height, as illustrated in Figure 2.1 b.

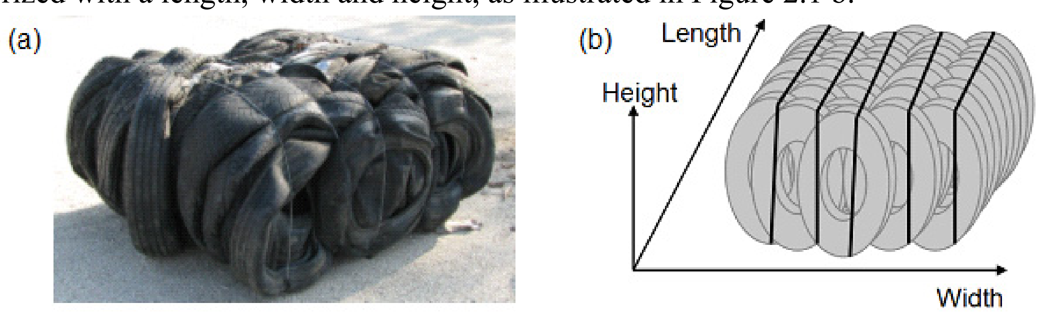

Figure 2.7: (a) Photograph of a Block Tire Bale and (b) Illustration of the Block Bale Dimensions

The three types of block tire bales measured as part of this implementation program are described in the following sections.

Block Bale Site 1: Block Tire Bale Data from United Kingdom

The first set of tire bale data was provided by Mike Winter and reported in Winter et al. 2006 and Simm et al. 2008. The specified dimensions of the bales were a length of 4.4 ft. (52.3 in.), a width of 5.1 ft. (61.2 in.), and a height of 2.7 ft. (32.4 in.). The specified weight of the tire bales was 1800 lbs. and contained approximately 100 to 115 whole scrap tires. Five steel baling wires, with diameter of 0.1496 in., were placed around the length of the bale to confine the tires into the block shape. Data for 74 block tire bales was provided via email by Dr. Winter.

Block Bale Site 2: Texas/Colorado Block Tire Bales

The second set of block tire bale data was obtained from a series of testing programs conducted for the Texas and Colorado Departments of Transportation (Zornberg et al. 2004, LaRocque 2005, Zornberg et al. 2005, and Freilich 2009). The specified dimensions and weight of the bales were identical, and therefore the data was combined to determine the influence of region, equipment, and personal on the properties of the tire bales. The specified dimensions for the tire bales were a length of 4.5 ft. (54 in.), and width of 5 ft. (60 in.), and a height of 2.5 ft. (30 in.). The specified weight of the tire bales was 2000 lbs. and contained between 71 to 85 whole scrap tires. The lower number of tires for the site 2 bales as compared to the site 1 bales provides evidence that the region in which the bales are constructed will influence the size of the scrap tires used, and therefore the number of tires within each bale. Five 7-gauge galvanized steel wires, with an approximate diameter of 0.1443 in., were placed along the length of the bale to confine the compressed tires. Data for 15 bales was obtained.

Block Bale Site 3: Modified Block Tire Bales from Trident Environmental Consulting

The third block tire bale site was located in north Texas (Contact: Tim Summers, Ph: 817-320-9009). The block bales were modified so that a series of tires were compressed along the base of the bale to provide a flat bottom interface (Figure 2.8).

(a) (b)

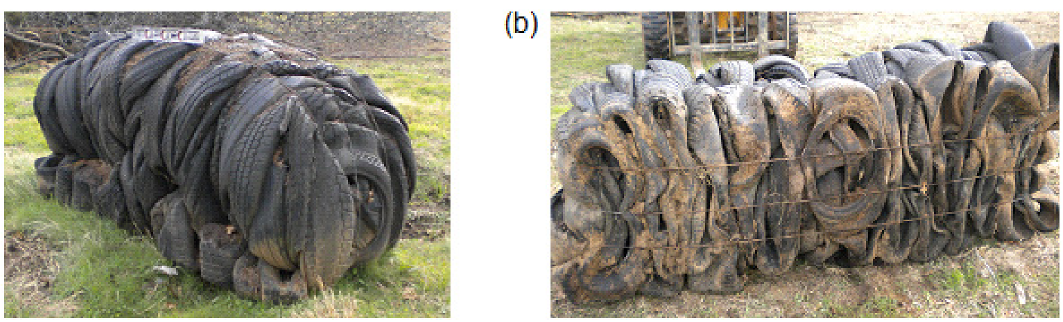

Figure 2.8: Photographs of the (a) Side and (b) Base of the Modified Block Tire Bales

The specified dimensions of the bales were a length of 5.2 ft. (62.4 in.), a width of 3 ft. (36 in.) and a height of 3 ft. (36 in.). The specified weight of the modified bales is approximately 1250 lbs. and contained 40 to 60 whole scrap tires. The compressed tires are confined with three 5-gauge steel wires wrapped around the length axis of the bales. Data for 12 modified block bales was obtained.

2.2.2 Cylinder Tire Bale Site

The cylinder tire bales used for the field testing program were constructed by placing whole passenger vehicle scrap tires into a cylindrical column and applying a compressive force to the tire mass (Figure 2.9). The cylinder bales were constructed at the Austin District location using mobile baling equipment provided by Nordmack Corporation (Ph: 877-379-7722). Four 11-gauge galvanized steel wires are placed around the bales to confine the tires into the cylinder geometry (Figure 2.10 a). The dimensions of the bale are characterized with an outer diameter and length, as illustrated in Figure 2.10 b.

Figure 2.9: Compression of the Whole Scrap Tires into the Cylinder Tire Bale

Figure 2.10: (a) Photograph of a Cylinder Tire Bale and (b) Illustration of the Cylinder Bale Dimensions

The specified dimensions for the passenger vehicle cylinder bale are an outer diameter of 2.3 ft. (27.6 in.) and a length of 3 ft. (36 in.). The specified weight of the cylinder bale is approximately 400 lbs. and contains 17 to 21 whole passenger vehicle tires. Data for 15 passenger vehicle cylinder tire bales was obtained.

In addition to the passenger vehicle cylinder tire bales, three truck tire cylinder bales were also manufactured (Figure 2.11). The specified dimensions for the truck tire cylinder bales are an outer diameter of 3.3 ft. (39.6 in.) and a length of 3 ft. (36 in.). The specified weight of the truck tire cylinder bale is 760 lbs. and contains approximately 10 whole truck tires. Data for 3 truck tire cylinder bales was obtained.

Figure 2.11: Photographs of the (a) Passenger Vehicle Tire and (b) Truck Tire Cylinder Bales

The benefit of the cylinder tire bale is that the internal voids of the bale are now accessible and the smaller (lighter) bales can be stacked in different arrangements depending on the required geometry of the tire bale structure.

2.3 Summary

A description of the field Quality Control (QC) test procedures and tire bales tested as part of this implementation program were provided in this chapter. The tire bale properties determined with the field tests include the tire bale weight, dimensions, baling wire tension, and interface strength. Each test was included so that the mechanical and index properties of the bale delivered to the site could be characterized and compared with the properties of the tire bale used for the design of the structure. The field QC procedures were used to determine the properties of tire bales located at four tire bale sites. The specified properties of the tire bales for each site were also provided in this chapter.

Chapter 3. Test Results obtained from use of Proposed QC Procedures

The field quality control tests presented in the previous chapter were conducted on different tire bales to determine the range in properties due to the variability of the bales. The range in the properties of the tire bales are an indication of the expected range in properties of the tire bales delivered to the construction site. The results from each of the field quality control tests is presented in this chapter, along with the recommended limitations on the range in properties for tire bales delivered to a construction site.

3.1 As-Received Weight of Tire Bales

The as-received weight of the tire bales was defined as the weight of the tire bale measured at the time of delivery. The variability of the as-received weights was characterized by defining a range that related the specified value of the weight to the maximum and minimum weights measured at each of the tire bale sites, as illustrated in Figure 3.1. The range therefore represents that largest measured deviation of the tire bale weight from the specified value, or the largest difference between the specified weight and the maximum/minimum value measured at the site. The specified, average, maximum and minimum values of the as-received weight of the tire bales measured as part of the field testing are provided in Table 3.1.

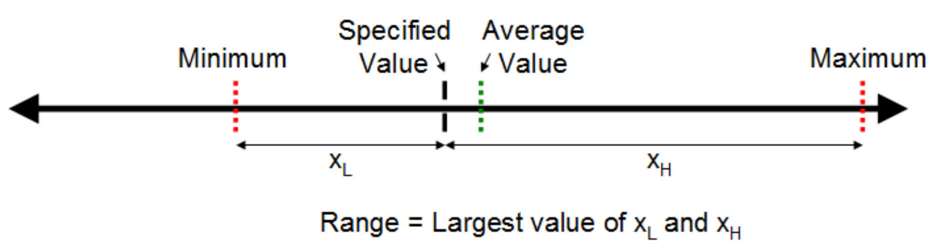

Figure 3.1: Specified, Average, Maximum and Minimum Measurements for the Tire Bale

The range was used to define the quality control limitations on the tire bale weight since it can be easily used to relate the specified weight to the expected range in weight of the tire bales delivered to the site. An example of using the data in Table 3.1 would be that the block tire bale weight used in the design (the specified weight) is 1800 lbs., but the expected range in weight for tire bales delivered to the site may be as high as 82 lbs.

Table 3.1: Specified, Average, Maximum and Minimum Values of the As-Received Weight of the Tire Bales

	Specified (lbs)	Average (lbs)	Max (lbs)	Min (lbs)	Range (lbs)
Block Bale Site 1	1800	1784	1863	1718	82
Block Bale Site 2	2000	2011	2350	1884	350
Modified Block Bales Site 3	1250	1273	1392	1210	142
Passenger Cylinder Bales	400	378	454	344	56
Truck Tire Cylinder Bales	760	761	834	652	108

3.2 Dimensions of Tire Bales

The variability of the tire bale dimensions was also characterized using the specified value and the range illustrated in Figure 3.1. The specified, average, maximum and minimum values of the block tire bale dimensions are provided in Table 3.2.

Table 3.2: Specified, Average, Maximum and Minimum Values of the Dimensions of the Block Tire Bales

		Specified (in.)	Average (in.)	Max (in.)	Min (in.)	Range (in.)
Site 1	Length	52	52	55.5	50	3.5
	Width	61.2	60.6	63.8	58.6	2.6
	Height	32.4	32.5	33.8	31.1	1.4
Site 2	Length	54	56.3	58.6	54.4	4.6
	Width	60	61.4	63.6	59.8	3.6
	Height	30	28.9	30.8	26.4	3.6
Site 3	Length	62.4	62.7	65	59.5	2.9
	Width	36	35.1	36.8	33.3	2.7
	Height	36	36.5	38.5	35.6	2.5

The range in tire bale dimensions can be used to define the quality control limitations for the bale delivered to the site. An example of using the data in Table 3.2 would be that the block tire bale length used in the design (the specified dimensions) is 52 in. (bales from the site 1 location), but the range in length for tire bales delivered to the site may be as high as 3.5 in.

3.3 Baling Wire Tensions

The data collected as part of the tension meter field quality control procedure was used to develop a method to estimate the baling wire tensions. The tire bale tension meter was only calibrated using the site 2 block tire bales and the passenger vehicle cylinder tire bales (Freilich 2009). The tension meter force (F) was measured for a series of baling wires, after which the wires were cut and strain gauges attached to the wires were used to determine the wire tension (T_0). Values of T_0 measured within the wires were less than half of the break strength of the wire attachments, 2,150 lbs. for the block baling wires (Jones 2009) and 830 lbs. for the cylinder baling wires (Yates 2009). The tension meter force was plotted against the wire tension, as shown for the site 2 block and cylinder bales in Figures 3.2 and 3.3, respectively.

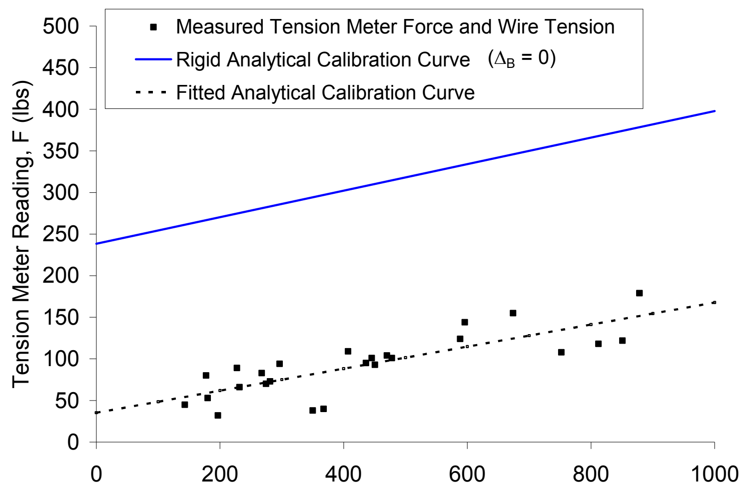

Figure 3.2: Tension Meter Forces and Corresponding Wire Tensions for the Site 2 Block Bales

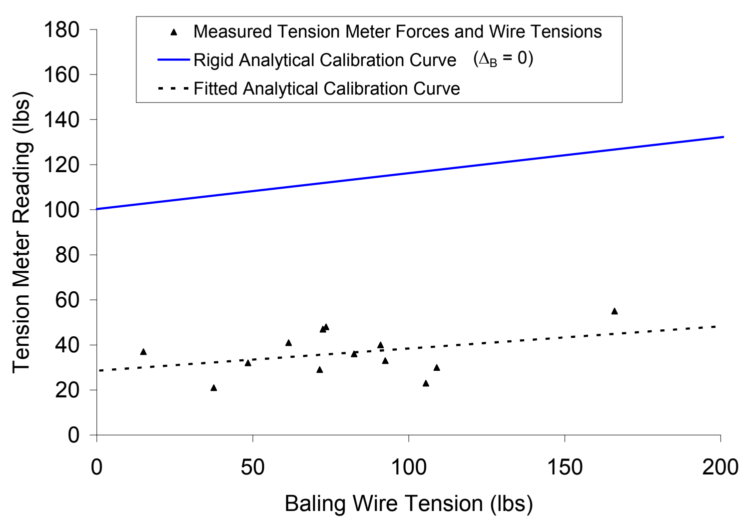

Figure 3.3: Tension Meter Forces and Wire Tensions for the Passenger Vehicle Cylinder Bales

The analytical calibration curve (Equation 2.1) was fitted to the measured data so that the values of Δ_W needed to estimate the wire tensions could be characterized. The resulting values of Δ_W were plotted against the tension meter force, as shown in Figure 3.4. Values of Δ_W for the site 2 block tire bales were also measured in the field to validate the fitted Δ_W curve. The small values of Δ_W made it difficult to measure in the field, and therefore Δ_W should be estimated using the fitted curves in Figure 3.4 and the measured tension meter force.

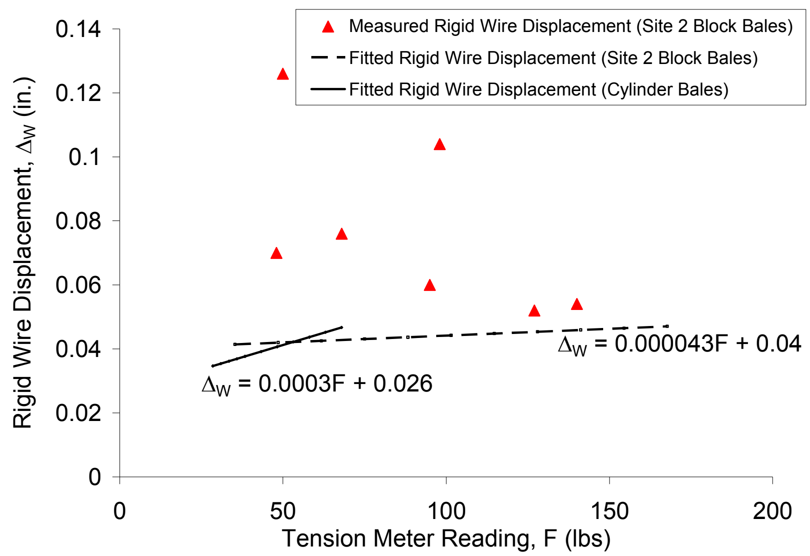

Figure 3.4: Rigid Wire Displacement (Δ_B) versus Tension Meter Reading for the Site 2 Block Bales and Passenger Vehicle Cylinder Bales

The analytical calibration curve and Δ_W curves provided in Figure 3.4 are used to determine the tensions within the baling wires, which may be required to be less than a specified value in the design of the tire bale structure. The design may specify a maximum tension meter force measured (F) in the field, or a maximum estimated tension within the wires (T_0). When a maximum tension meter force is specified, then values of F should be measured for each wire, and the maximum value measured for all wires must be less than the specified value. When a maximum tension value is specified, values of F are measured in the field and used with the DW curves in Figure 3.4 and with a re-arranged analytical calibration curve (Equation 3.1) to determine the tension.

$$T_0 = \frac{F}{2 \cdot \sin\theta} - \left[E \cdot A_C \left(\frac{1}{\cos\theta} - 1 - \frac{\Delta_W}{L_{TM}} \right) \right] \tag{3.1}$$

When checking the baling wire tensions after construction, the wire tension must be less than the break strength of the wire connection (which is provided by the wire manufacturer). Freilich (2009) collected wire tension data for cylinder bales immediately after construction which provided evidence that the tire tensions decreased after construction.

3.4 Field Determination of Interface Shear Strength

The interface strength of the tire bale structure is controlled by the irregular surfaces of the tire bale. Large scale direct shear tests conducted in the laboratory have provided a set of interface strength parameters for the different tire bales that can be used for the design of the tire bale structure (LaRocque 2005 and Freilich 2009). A series of field direct shear tests were also conducted to determine the interface strength in the field. Field direct shear tests were conducted for the site 2 (Figure 3.5) and site 3 (Figure 2.6) block tire bales.

Figure 3.5: Field Direct Shear Test for the Site 2 Block Tire Bales

The application of the horizontal shear load resulted in a rotation of the tire bales, rather than the sliding displacement needed to estimate the interface strength. Therefore, the field direct shear test is not a suitable way to measure the interface strength of the tire bales in the field. The one successful field direct shear test was conducted on a series of five (5) site 3 modified block tire bales.

3.5 Summary

The data collected as part of the field quality control testing program was provided in this chapter. The variability of the tire bale weight and dimensions were represented using the specified value and a range defined as the largest difference in the specified value and the values measured in the field. The data collected for the tension meter was used to determine values of Δ_W needed to estimate the baling wire tensions. The large scale field direct shear tests of the tire bales resulted in a rotation of the bales, and therefore the interface strength was not measured.

Chapter 4. Field Monitoring Plan Recommendations

A field monitoring plan for a generic slope stabilized using tire bales was developed as part of the implementation program. The most relevant variables are the external and internal stability (deformation measurements) of the slope, measurements of the flow out of the embankment coupled with relevant precipitation data, and the thermal response of the tire bale mass. Two instrumentation profiles were developed for the generic tire bale slope: the slope stability and thermal response instrumentation profiles.

4.1 Monitoring for Stability Assessment of a Tire Bale Slope

An illustration of the slope stability instrumentation profile for a generic tire bale structure is provided in Figure 4.1. The deformations of the tire bale slope are measured using a portable slope inclinometer (Model: Digitilt Portable Traversing Slope Inclinometer Probe, Supplier: Durham Geo Slope Indicator, Ph: 425-493-6200) that is manually positioned within a series of slope inclinometer casings (Model: Quick Connect Casing 2.75", Supplier: Durham Geo Slope Indicator). The casings are placed through the tire bale structure and into the foundation soils. Vertical movements of the tire bale slope are measured with steel settlement plates placed along the height of the tire bale structure. Surficial deformations of the soil cover along the tire bale mass are measured using survey markers placed along the surface of the tire bale structure. Atmospheric data around the tire bale slope, including precipitation and external temperature, is recorded using a weather station (Model: WXT520 Vaisala Weather Transmitter, Supplier: Campbell Scientific, Ph: 435-753-2342).

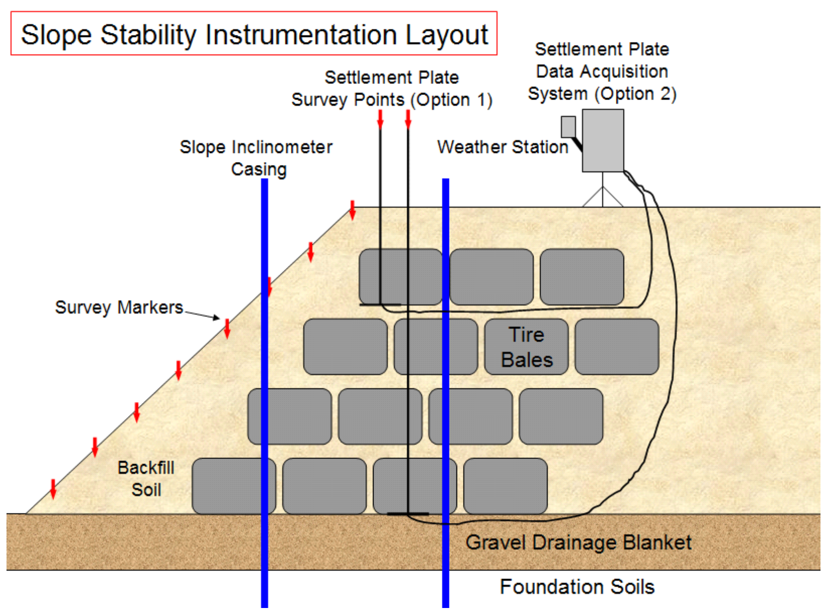

Figure 4.1: Instrumentation Profile for the Stability of the Tire Bale Slope

The estimated costs associated with the instrumentation layout options are provided in Table 4.1 (all costs were determined December 2009). Several options are available for the data acquisition systems required for the instrumentation profile, which will influence the cost of the final instrumented slope. The mobile inclinometer data acquisition and connection cable are required to lower the inclinometer into the casing and measure the corresponding casing angle with depth. The elevation of the settlement plates can be measured with survey equipment by attaching long steel tubes to the plates (Option 1), or using a data acquisition system provided by Durham Geo Slope Indicator (Option 2). The data acquisition system for the survey plates can be monitored with a mobile data logger (Option 2a), or by using a continuous data acquisition system provided by Campbell Scientific (Option 2b). The Campbell Scientific data acquisition system is already required for the weather station, and therefore would be easily implemented for the settlement plates.

Table 4.1: Cost Estimates for the Tire Bale Slope Stability Instrumentation Profile

	Units	Cost Per Unit	Quantity	Subtotal
Settlement Plates				
18"x18" steel settlement plate (3/4" thickness)	each	$35.00	2	$70.00
Hollow Steel Rod for Survey Analysis (1/2" outer diameter) OPTION 1	per foot	$0.50	60	$30.00
Vented VW Settlement Cell (Durham Geo Slope Indicator) OPTION 2	each	$660.00	2	$1,320.00
Liquid Reservoir and Desiccation Chamber (Durham Geo Slope Indicator) OPTION 2	each	$90.00	1	$90.00
Liquid Filled Cable (Durham Geo Slope Indicator) OPTION 2	per foot	$1.30	40	$52.00
Mobile Data logger* (Durham Geo Slope Indicator) OPTION 2	each	$1,200.00		
Slope Inclinometer				
Digitilt Portable Traversing Slope Inclinometer Probe (Durham Geo Slope Indicator)	each	$5,200.00	1	$5,200.00
Digitilt DataMate II, Mobile Data logger and Readout (Durham Geo Slope Indicator)	each	$2,900.00	1	$2,900.00
Measurement and Connection Cable	per 100 feet	$1,430	1	$1,430.00
Quick Connect Casing (2.75" diameter)	per 10 feet	$65.00	6	$390.00
Weather Station				
WXT520 Vaisala Weather Transmitter (includes 7.5 ft cable) (Campbell Scientific)	each	$3,047.00	1	$3,047.00
Survey				
Survey Hubs and Nails	per 25	$30	5	$150.00
Data Acquisition System for Weather Station (also used with Option 2)**				
CR1000 Data logger (Campbell Scientific)	Each	$1,440.00	1	$1,440.00
Power Option 1: SP20R 20-Watt Solar Panel (Campbell Scientific) - Requires Battery	Each	$500.00	-	
Power Option 2: PS100 12V Regulated Power Supply (Campbell Scientific)	Each	$245.00	-	
Power Option 2: SP10 10-Watt Solar Panel (Campbell Scientific)	Each	$230.00	-	
CN6 Tripod Stand for Enclosure	Each	$475.00	1	$475.00
ENC 12/14 Enclosure	Each	$305.00	1	$305.00

*Only need mobile data logger if data acquisition system is not used
**Same data acquisition system as for weather and temperature monitoring

The estimated total costs for the different slope stability instrumentation profile options are provided in Table 4.2. Option 1 of the instrumentation profile includes the costs settlement plates with hollow steep tube attachments (used to measure elevations as part of a survey). Option 2a includes the cost of the mobile data logger and data acquisition system for the settlement plates. Option 2b includes the costs of connecting the settlement plate data acquisition system to the continuous Campbell scientific data logger for the weather station (mobile data logger no longer required), which may require the purchase of a second CR1000 data logger. Two power supply options are available for the continuous data acquisition system, which are approximately the same price. A cost of $500.00 was added to the estimated costs in Table 4.2 to take into account the power supply.

Table 4.2: Estimated Costs for the Slope Stability Instrumentation Profile Options

Instrumentation Options	Estimated Total Cost
Option 1	$15,937.00
Option 2a (Mobile Data Logger)	$18,599.00
Option 2b (Continuous Data Logger)	$18,839.00

4.2 Thermal Response of the Tire Bale Slope

The thermal properties of the tire bale structure can be determined by measuring the internal and external temperatures of the structure. The thermal response instrumentation layout for the generic tire bale slope is provided in Figure 4.2. Temperature sensors (Model: 107-L, Supplier: Campbell Scientific, Ph: 435-753-2342) are placed along the height and depth of the tire bale structure to measure the temperature gradient. Two of the temperature sensors are combined with relative humidity sensors (Model: HMP50-L Vaisola Temperature and RH Sensor, Supplier: Campbell Scientific) to determine any relationship between moisture and heat generation. If soil layers are compacted within the tire bale mass, the water contents can be measured using water content reflectometers (Model: CS616-L, Supplier: Campbell Scientific). Atmospheric data for the tire bale slope, including precipitation and external temperature, is recorded using a weather station (Model: WXT520 Vaisala Weather Transmitter, Supplier: Campbell Scientific).

The costs associated with the temperature monitoring instrumentation profile are provided in Table 4.3. All instrumentation is measured using the continuous Campbell Scientific data logger. Two power supply options are available for the continuous data acquisition system, which are approximately the same price. A cost of $500.00 was added to the estimated costs in Table 4.4 to take into account the power supply.

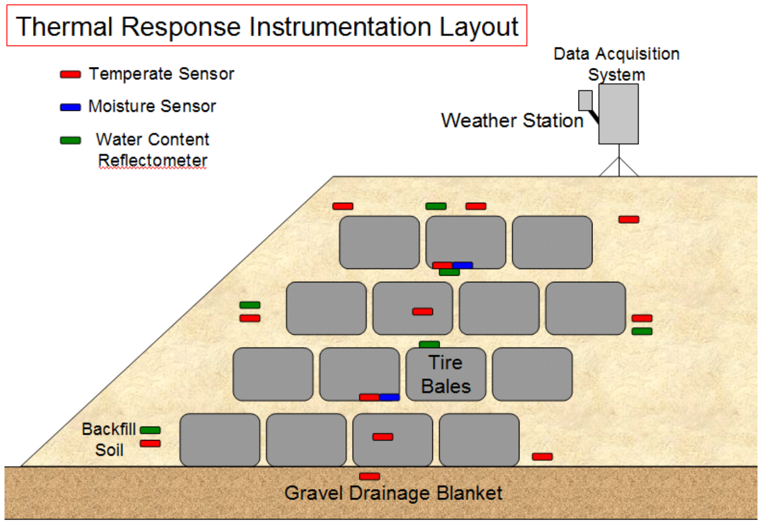

Figure 4.2: Instrumentation Profile for the Thermal Response of the Tire Bale Slope

Table 4.3: Cost Estimates for the Tire Bale Slope Thermal Response Instrumentation Profile

	Units	Cost Per Unit	Quantity	Subtotal
Temperature Monitoring				
Temperature Sensor 107-L (Campbell Scientific)	Each	$85.00	12	$1,020.00
WIR CA 22AWG Cable (Campbell Scientific)	per foot	$0.44	400	$176.00
Moisture Monitoring (ONLY IN SOIL LAYERS)				
CS616-L Water Content Refelctometer	Each	$150.00	-	
AM 16/32 relay Multiplexer (16 or 32 channel) Part #19232	Each	$645.00	-	
Sensor Cable	per foot	$0.74	-	
Relative Humidity and Temperature Monitoring				
HMP50-L Vaisola Temperature and RH Sensor (Campbell Scientific)	Each	$390.00	2	$780.00
WIR CA 22AWG Cable (Campbell Scientific)	per foot	$1.04	40	$41.60
Data Acquisition System				
CR1000 Data logger* (Campbell Scientific)	Each	$1,440.00	1	$1,440.00
6-Plate Gill Radiation Shield (Campbell Scientific) (for ambient temp. probe)	Each	$120.00	1	$120.00
Power Option 1: SP20R 20-Watt Solar Panel (Campbell Scientific) - Requires Battery	Each	$500.00		
Power Option 2: PS100 12V Regulated Power Supply (Campbell Scientific)	Each	$245.00	1	$245.00
Power Option 2: SP10 10-Watt Solar Panel (Campbell Scientific)	Each	$230.00	1	$230.00
CN6 Tripod Stand for Enclosure	Each	$475.00	1	$475.00
ENC 16/18 Enclosure	Each	$305.00	1	$305.00

* can record 16 temperature, moisture monitoring, or heat flux sensors or 8 temperature and RH sensors

The total estimated costs for the thermal response instrumentation layouts are provided in Table 4.4. When soil infill is included in the design of the structure, an additional CR1000 data logger is required, along with an AM multiplexer (16 channel) and 6 CS616-L water content reflectometers. Two power supply options are available for the continuous data acquisition system, which are approximately the same price. A cost of $500.00 was added to the estimated costs in Table 4.4 to take into account the power supply.

Table 4.4: Estimated Costs for the Thermal Response Instrumentation Profile Options

Instrumentation Options	Estimated Total Cost
No Soil Infill	$4,687.60
Soil Infill w/Moisture Measurement	$7,892.60

4.3 Summary of the Field Monitoring Program

A series of instrumentation profiles were developed for a generic tire bale slope. The main variables of interest are the deformations of the slope and the thermal response of the tire bale mass. Deformations can be measured using a series of slope inclinometers, settlements plates, and survey markers. The thermal response can be measured using temperature sensors placed along the tire bale slope surface and within the tire bale mass. The instrumentation profiles can be modified based upon the tire bale structure and the variables of interest for each project.

Chapter 5. Summary

The properties of the individual tire bale vary, due to the variability of the whole tires within the bale and the construction equipment and procedures used to manufacture the bale. A series of field quality control test procedures were developed and implemented to determine the range in the tire bale properties. The most pertinent properties of the tire bales were determined to be the as-received weight of the bales, the dimensions of the tire bales, the baling wire tensions, and the interface strength. Each of the properties were measured for tire bales located at different sites and constructed using different procedures to determine the feasibility of using the field tests and to determine the variability of the tire bale properties. In addition, a series of instrumentation profiles were developed to measure the behavior of the tire bale structure. The deformation and thermal response of the tire bale structure were the variables of interest. The specific conclusions from the implementation program presented in this document are as follows:

- Specified value and range are an appropriate method for the quality control specifications of the tire bales.
- The tension meter can be used to determined the interface strength using the tension meter force and the values of DW determine during the field testing program
- The interface strength could not be determined using the field direct shear test due to rotational deformations of the tire bales.

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