

# Testing and Analysis of Modified Rammed Earth Tire Walls

*Swarthmore College, E90 Project*

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## Abstract

This report tests modified rammed earth tires to determine coefficients of kinetic friction between tires and between tires and soil. The results are used to determine the largest allowable soil pressures that a free standing wall may receive as well as the largest pressures a wall receiving horizontal lateral support from a roof system may receive. A deflection test is carried out on a single modified rammed earth tire up to 1080 pounds, and a small scale wall is built and tested for resistance to transverse loads. Finally, a house is designed and structurally analyzed based on the results in this report. It is believed that modified rammed earth tires are a safe and dependable way to build single story homes after the testing and analysis done in this report.

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## Project Introduction

### Environmentally Sustainable Construction

Houses, buildings and structures are often made out of wood, metal, and concrete, but there are many different ways to construct these structures. There is a long history of searching for sustainable building alternatives, but in the past fifty years there has been an outburst of novel techniques and building approaches. One such approach is the rammed earth tire wall. Tire walls are made from two materials, recycled tires, and soil or dirt. If they are to be used for a house, they are usually covered in concrete or adobe to fill in the gaps. This yields internal and external walls that appear to be adobe-like in style.

Tire walls have many advantages over more standard building materials. Americans alone generate approximately two hundred and eighty-five million scrap tires a year.<sup>1</sup> Old and worn out tires are often thrown out, buried in a landfill, or burned. None of these options are particularly sustainable or environmentally friendly. On the other end of the spectrum, there are some ways in which tires may be re-used in a constructive fashion. This is a high priority because there are no organisms that feed on rubber, and tires may take hundreds if not thousands of years to decompose in a landfill. Clearly tire walls and structures are a way to use and reuse old tires instead of many of the environmentally harmful alternatives.

An issue with many alternative building structures, including rammed-earth tire walls, is that they are not specifically included within the building code. As a result, they also often lack documented formal testing procedures and guidelines and the results of any formal testing.

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<sup>1</sup> <http://www.epa.gov/waste/consERVE/materials/tires/tdf.htm>

Although these alternative construction methods support the sustainability of a structure, in terms of its accessibility, affordability, energy use, and environmental impact, the methods and technologies are often undocumented and undeveloped. This is the general case for rammed earth tire structures. It is important that alternative construction methods and technologies are researched, and through this research further developed to ensure that the opportunity to use these methods exists. Currently, many in the engineering and building communities, including building inspectors, lack faith in the strength and reliability of these alternative structures. This often makes building homes with tire walls as the main structural walls a difficult if not impossible goal.

In 1993 the International Union of Architects (UIA) signed the “Declaration of Interdependence for a Sustainable Future.” Through the signing of this document architects from around the world agreed to strive to follow the five following bullet points:

1. Place environmental and social sustainability at the core of our practices and professional responsibilities
2. Develop and continually improve practices, procedures, products, curricula, services, and standards that will enable the implementation of sustainable design
3. Educate our fellow professionals, the building industry, clients, students, and the general public about the critical importance and substantial opportunities of sustainable design
4. Establish policies, regulations, and practices in government and business that ensure sustainable design becomes normal practice
5. Bring all existing and future elements of the built environment - in their design, production, use, and eventual reuse - up to sustainable design standards.<sup>2</sup>

Although this project is not related to the UIA, these goals have been deemed worthwhile to a larger international and global community and this project strives to work towards these goals as well. This project aims to contribute to points 2, 3, and 5, by researching and developing a

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<sup>2</sup> <http://www.uia-architectes.org/texte/england/2aaf1.html>

sustainable construction technology, and by developing an engineering report that may be used by the larger architectural and construction world to implement a sustainable construction technology.

### **Motivation and Previous Studies**

Up until this point there has been one other engineering test performed on rammed earth tire structures. This report is titled, “Engineering Evaluation of Earth-Filled Tire Construction,” and was written under the supervision of the principal engineer, Thomas E. Griepentrog. The report was written in 1990 and the report was written for a building inspector to allow the building of the Dennis Weaver Tire House. Since then builders and architects have used this report around the country as proof to building inspectors that single story rammed earth tire homes are safe and structurally sound.

This project has been motivated by a need for further studies on the behavior of rammed earth tire walls. It is believed that by building walls using “topless” tires, the classic rammed earth tire structure can be manufactured much more efficiently, decreasing the construction time, and making the building of these structures considerably more feasible and economic. The goal of this project is to test and analyze modified rammed earth tire walls with the hope that they will be found appropriate to build single story homes. An additional goal of this project is to design it to meet the ABET realistic engineering constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.

## Background

### Rammed Earth Tire Structures

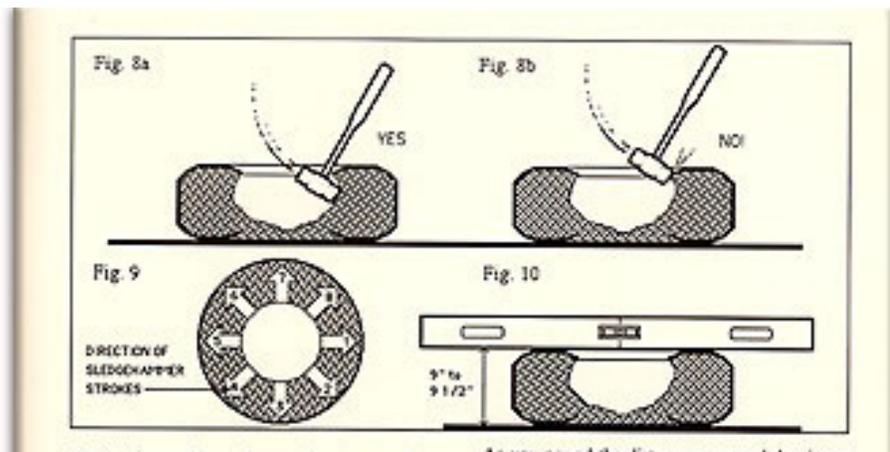
Rammed earth structures have been around for millennia and have been found dating back to over 200 BCE. Generally, rammed earth walls are simple to construct, requiring only a form to mold the dirt in and the soil itself. Other benefits of rammed earth structures are that they are incombustible, thermally massive, nearly soundproof, and often are quite strong and durable. In order to build a rammed earth structure, temporary forms are needed in which the soil may be compressed. This compression process essentially turns the soil into manmade sedimentary rock, which is compressed in minutes by human and mechanized compaction instead of in thousands of years of pressure in the ground.

Rammed earth tire walls are relatively new—they were not even conceivable one hundred years ago before the advent of the modern tire. In the 1970s, Michael Reynolds modified the typical rammed earth structure construction process to use bricks of tires filled with rammed earth instead of solid walls of rammed earth. To make his bricks, he filled used and otherwise junk tires as individual structures to hold the rammed earth. The tires experience the majority of the forces from the compacted soil in the horizontal direction (when lying flat on the ground), and the radial steel wires under the tires tread provide the tensile strength necessary to achieve the compaction of the soil without the bursting of the rubber.

### Standard Construction

The most common method of building rammed earth tire walls is to place a used tire on the ground, fill the tire with dirt and compress the dirt with a hammer. A double layer of

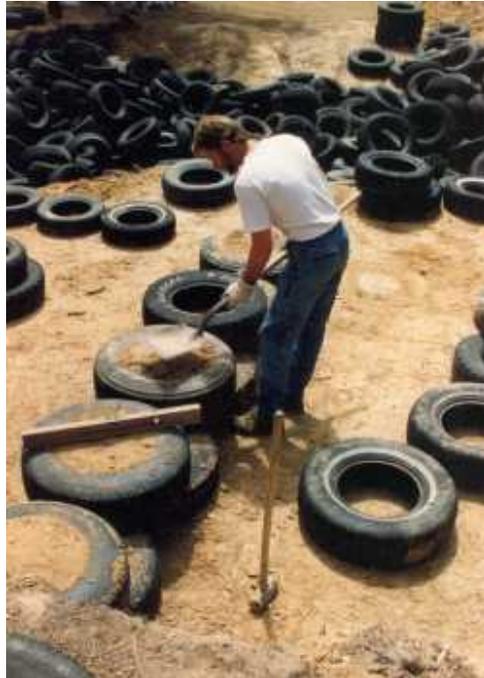
cardboard is often placed in the bottom of a tire before the dirt is placed in it to prevent the soil from falling out as it is compacted. This process is repeated until the tire is completely filled with compacted soil. The tires must be filled to at least 95 percent compaction. A schematic and image of the typical construction of a tire wall is shown below in Figures 1 and 2 and described in Table 1.



**Figure 1: Schematic detailing the standard construction and filling of a rammed earth tire,** <http://www.earthship.org>.

<ol style="list-style-type: none"> <li>1) Each tire takes about three or four wheelbarrows of dirt. When serious pounding begins, large amounts of dirt will be generated from the initial excavation.</li> <li>2) The tire will become full of dirt and begin to swell up.</li> <li>3) The sledgehammer strokes shown go <u>into</u> the casing. Do not hit the casing itself. (Fig. 8a and 8b)</li> </ol>	<ol style="list-style-type: none"> <li>4) As you pound the dirt, move around the tire to keep the tire pounded evenly. (Fig. 9)</li> <li>5) This is done until the tire has swelled to about 9 or 9.5 inches. After the outer casing is sufficiently packed and swollen, it will need to be leveled. Lay a 4' level across the tire, letting it rest on the swollen rubber casing. (Fig. 10)</li> <li>6) Make sure that the tire is level in all directions. Add more dirt to build up the tire if necessary.</li> </ol>
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**Table 1: Directions describing Figure 1, detailing the standard method to construct a rammed earth tire,** <http://www.earthship.org>.



**Figure 2: Image of a partially built tire wall and the construction process**

An individual tire is placed on the running axis of the wall; it is filled and compacted in that position. Other tires are then placed and filled next to the first tire. Once one row of tires is complete, another row is placed on top of the first row, but staggered in alternate lay from the first row, like bricks. In order for this to happen, half tires must be used. However, they cannot be filled cut in half because there would be no supporting structure to hold the dirt as it is compacted. Instead, tires are cut and screwed into whole tires. This may be seen in Figure 3 and the construction section below. It should also be noted that to avoid extra stress on the cut half-tire, it should be placed internally and the whole tire should be placed on the very end of the wall. This is particularly important in load bearing walls and may be seen Figure 4 below. The idea behind this method is that by placing the half-tire on the inside of the wall, it will allow it to be supported on both sides by whole tires, not allowing it to burst or pull away from the

tire that it is attached to. It should also be noted that the half tire is filled to at least 95 percent compaction, the same as all other tires.

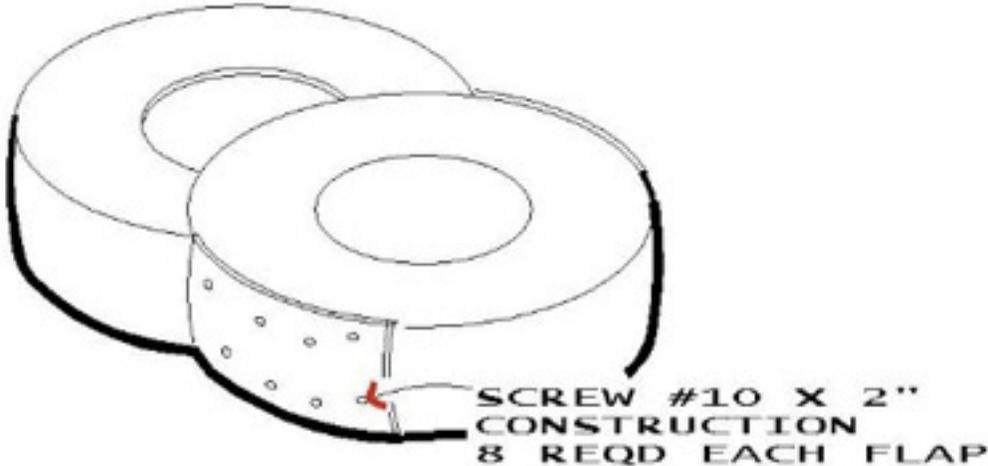


Figure 3: Schematic showing how a 'half-tire' is attached to a whole tire so the tire may be staggered in alternating layers, <touchtheearthranch.com>.

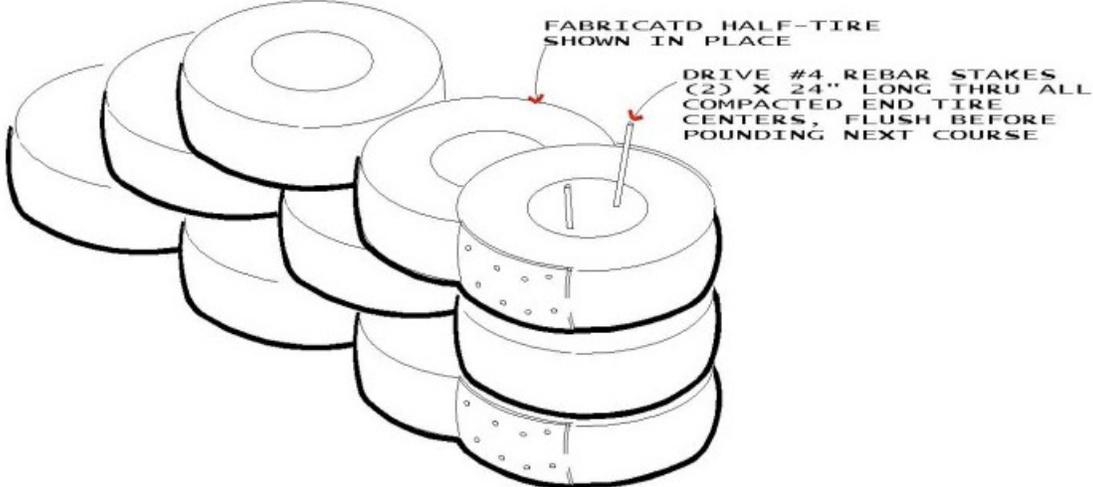


Figure 4: Schematic showing how the half tire is placed internally in the wall, <touchtheearthranch.com>.

## **Modified Construction**

As previously mentioned, this project and report are involved with a modified rammed earth tire structure. The modification involves cutting of one of the sidewalls of the tires. The extra rubber is then flipped over and placed inside the tire, not resulting in any extra rubber waste. The idea is that by cutting off one of the sidewalls, the tire may be completely filled by vertical compaction, instead by first compacting horizontally to fill the tire and then filling the center vertically (as shown in 1). It is the horizontal compaction of the tire that is most time consuming and difficult for the builder. It has been seen that by using the modified tires it is possible to increase a workers capacity from ~15 tires per day to ~50 tires per day.

It should also be noted that by implementing this method, the tire is no longer stretched vertically. As before, a double layer of cardboard is placed in the bottom of the tire before the soil is placed in the tire for compaction. Other than this modification, individual tires may be completed in the same way, and the walls may be built in the same fashion, using half-tires attached to whole tires at the ends of walls. More detail may be found in the construction portion of the report, below.

## **Objective and Constraints**

As mentioned previously, the purpose of this project is to investigate the structural integrity and feasibility of the modified rammed earth tire wall. In that sense, this project will follow the procedure of the Griepentrog report with modified tires as well as additional tests to further investigate the structural properties of the modified rammed earth tires and walls that are built from them. Specifically, friction tests will be performed for both R14 and R15 (tires with 14 inch and 15 inch radii respectively). Additionally, going further than the Griepentrog

report, a small scale wall will be built and tested, and the deflection of a modified tire will be studied. The wall will be three tires long, eight tires tall and will be tested under a uniform horizontal load centered on the centroid of the pressure that the wall would receive from the soil.

The project does not have many constraints that affect the rigorous study of the modified tires. The friction tests are well within the means of the project. The wall itself is where many of the constraints limit the feasibility of a larger project. The wall is being built within a college garage to protect it from the weather, to ensure that the project may be worked on throughout the parts of the winter, and to ensure the walls safety from harm as well as to prevent harm it may cause by falling on a person. The garage has dimensions of 9.5' by 17', but the length of the wall must be constrained to less than 9.5' so the horizontal loading for the friction tests and for the wall may occur by attaching the tires to a come-along which is fixed to a parked vehicle in the driveway. Additionally, as the length of the wall increases, the load needed to test the wall increases, and the project will be safer and more manageable by keeping the wall as short in length as possible. As mentioned above, the ends of walls are constructed out of half tires. By using a wall that has a length of three tires, it ensures that two half tires will not be attached to one whole tire, which will never happen in an actual structure. In this way, the wall, and thus the load needed to test it, will be kept as manageable as possible while maintaining a reasonable similarity to an actual structure.

For the ABET engineering criteria, economic, environmental, social, health and safety, manufacturability, and sustainability constraints were considered. Design and construction with modified rammed earth tires offers a cheaper alternative to standard building practices, and is

more time efficient than construction with unmodified rammed earth tires. The economic constraints of the project limited only the size of the wall that was built. The project uses scrap tires to remove tires from landfills, and environmentally friendly ways to dispose of them after the project were researched. The health and safety constraints are the utmost priority for the project considering the project is testing the safety of the walls for single story homes.

Additionally, the wall was built within a closed garage to ensure that in the case of unexpected failure, it would not be able to harm anything or anyone. The manufacturing processes of all aspects of the report are described in detail to ensure reproducibility.

## Theory

### Principles of Structural Modeling

Structural models are designed and manufactured for a variety of purposes to test a certain behavioral characteristics or types of strength. It is clear that the direct applicability of the results from the model to the actual material or structure depends on the objects being considered, the scaling, and the loading. Although reduced-size structural elements may be used as models, it is often the case that that similitude conditions are not then applied to large-scale research models. Instead, the design methods and equations are accepted as based on the model and what information can then be transferred, for instance through superposition, to larger scale models may then be accepted. (Harris, p.3)

Different classes of structural models include the Indirect, Direct, Wind Effects, Dynamic Model, Elastic Model, and the Strength Model. Direct models attempt to resemble the prototype in all geometrical and loading respects, while indirect models may not physically resemble the prototype are useful to develop information about material responses and the

general values that may be superimposed to the prototype situation. Superposition is only valid in the linear elastic range and thus this type of model is as well. Strength models, also known as ultimate strength models or realistic models are direct models that are made of similar materials to the prototype and may be tested to failure in order to gain an understanding of the actual way the prototype will behave. Conversely, elastic models are another form of direct model that are used to gain an understanding of how the geometry and load situation of the prototype will affect the elastic behavior without too much detail pertaining to the correct material. The dynamic model and wind effects are used to simulate the pressures and vibrations that the prototype may have to withstand due to forces of nature and the tests are used to observe the structural behavior of the prototype under these forces. (Harris)

Finally it should be noted that when modeling a structural system or component, there is often a phenomenon called a size effect that causes strength to often increase when the model size is decreased relative to the prototype. These size effects may be influenced by material curing, rate of loading, edge effects, or statistical variations in strength due to volume effects. (Harris, p.414)

### **Principles of Soil Mechanics**

In this project soil plays an important role as the primary structural element of the walls. As a result, it is important to consider the strength and deformation behaviors of soil. In particular, compaction and shear strength play a large role.

Compaction is the use of equipment or mechanical methods, instead of chemical methods, to stabilizing the soil by compressing it into a smaller volume. Compaction reduces compressibility; increases shear strength, decreases the void ratio, and decreases hydraulic

conductivity (Coduto, p.213). In particular, by decreasing the void ratio, compaction decreases the possible variance of the moisture content in the soil. As a result, compaction can and is characterized by the dry density and the water content of the soil.

The standard measure of optimal compaction is the Standard Proctor Test. This method was developed in the 1930s as a method of measuring compacted fills. The method generally consists of creating a compaction curve, as shown below in Figure 5, by compacting soil in a controlled setting using a set amount of energy for the compaction while varying the moisture content of the soil. These curves enable the technicians to determine the maximum dry unit weight of the soil from the peak of the curve. This is then a standard that is strived for when compaction is needed and a standard, such as 95% of the max. dry weight, must be reached in the field to ensure consistent and safe results.

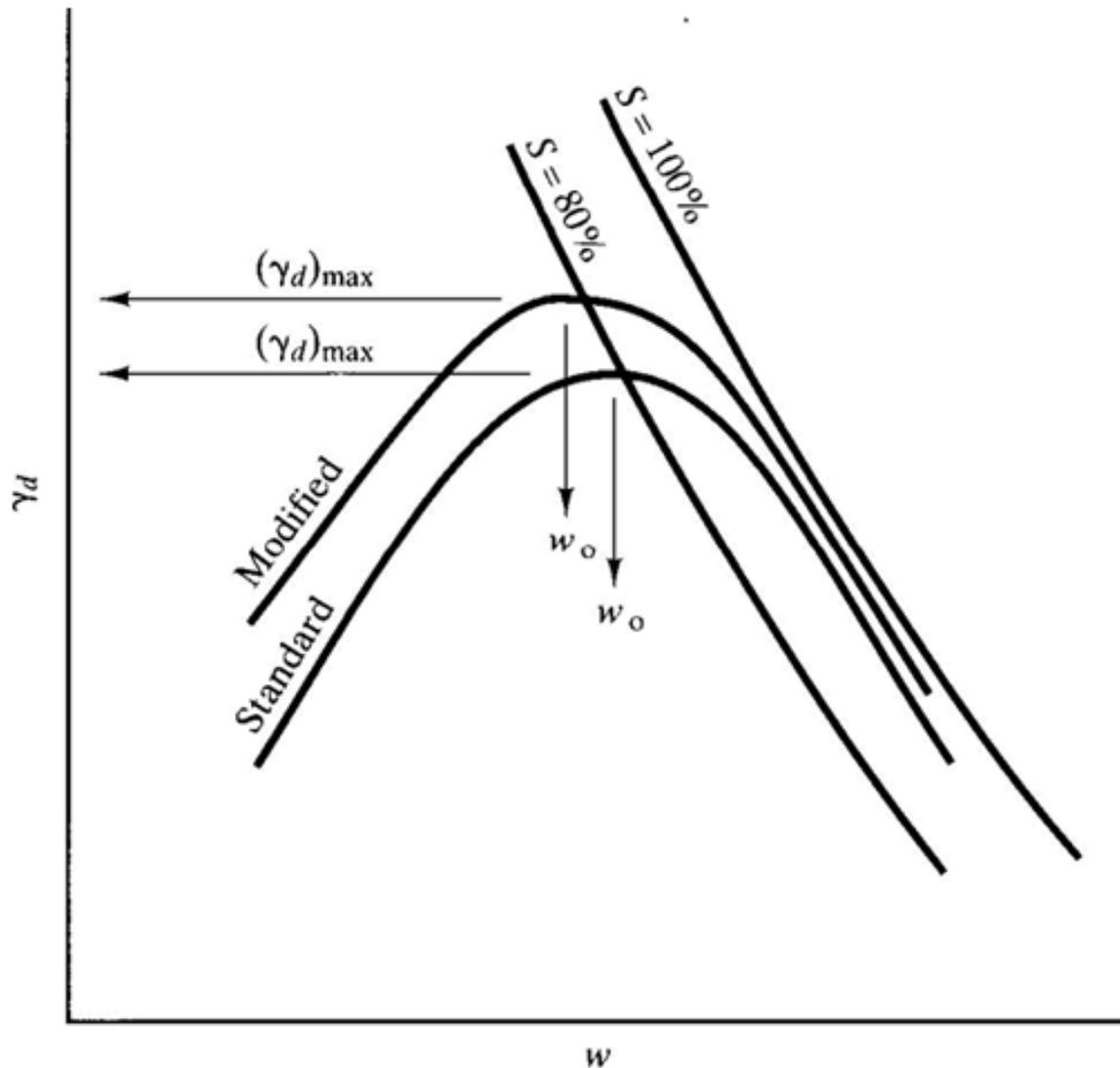


Figure 5: A sample compaction curve, <<http://www.fhwa.dot.gov>>

As mentioned above, compaction increases the shear strength of the soil, which is a positive trait in strength bearing soil structures. Increased shear strength enhances the soils capacity for supporting loads, and as a result, also is relevant to this project.

The shear strength of soil is given by the following equation:

$$\tau = c + \sigma \tan \phi$$

where the variables are defined to be,

$\tau$  = shear strength

$c$  = effective cohesion

$\sigma$  = effective normal stress acting on the shear surface

$\phi$  = effective friction angle, (Coduto, p.532)

## Project Design and Construction

### Design Constraints

As already mentioned, the largest constraint imposed on this project is the size of the wall when compared to the size of the garage that was used. Due to the constraints of the garage, a large wall could not be built and a wall that is three tires long was settled for. The pressure that the soil of a bearing wall would impart on an outside wall is triangular in nature. The resources available at the college could not handle both the size of the land and the shape of the load needed to correctly simulate the pressure the soil would cause. As a result, a uniform load is delivered at one third of the wall's height up from the ground. Similarly, due to the size of the wall, the loads necessary to represent the vertical loading realized by the wall were too large to simulate. Instead, a single modified rammed earth tire was evenly loaded using cinder blocks to determine the deflection of a single unit of the wall. Then, under assumption of linearity and super-positioning, the data from this test was used to determine the total deflection of a full-sized wall.

### Friction Tests

There are two types of friction tests that must be carried out. One set of friction tests must be completed to determine the friction between tires and the other friction tests must be

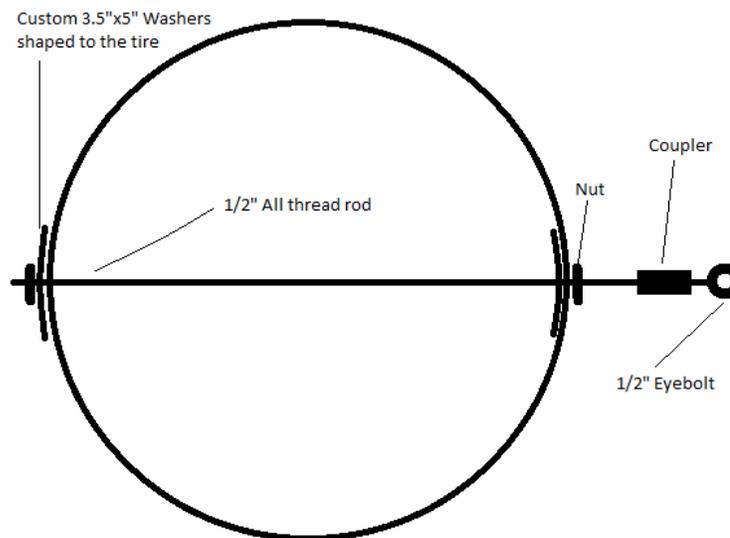
completed to determine the friction between the bottommost tire and the soil. It is assumed that the tire walls will be built on soil at the building site. The tests were all conducted within the garage at Whittier 6. In order to simulate a soil foundation, a wooden base was built and filled with the soil which was highly compacted. The filled foundation may be seen below in Figure 6. This foundation was used for all friction and wall tests.



**Figure 6: Wooden Frame foundation filled with compacted soil used for all friction and wall tests**

For the friction tests, the main components of the setup involved a way to attach the tire to a cable, a way to measure the force necessary to pull the tire, and a way to pull the tire. In order to make sure that the only movement that was occurring was at the tire, an additional goal was to ensure that there was as little possibility for stretch throughout the setup as possible. In the Griepentrog report, a thick rope was tied tightly around a tire and was used to pull the tires for the tests. This report, in order to avoid stretching, aimed to avoid any rope. In order to fasten the tire to the metal cables used to pull the tire, two holes were drilled through

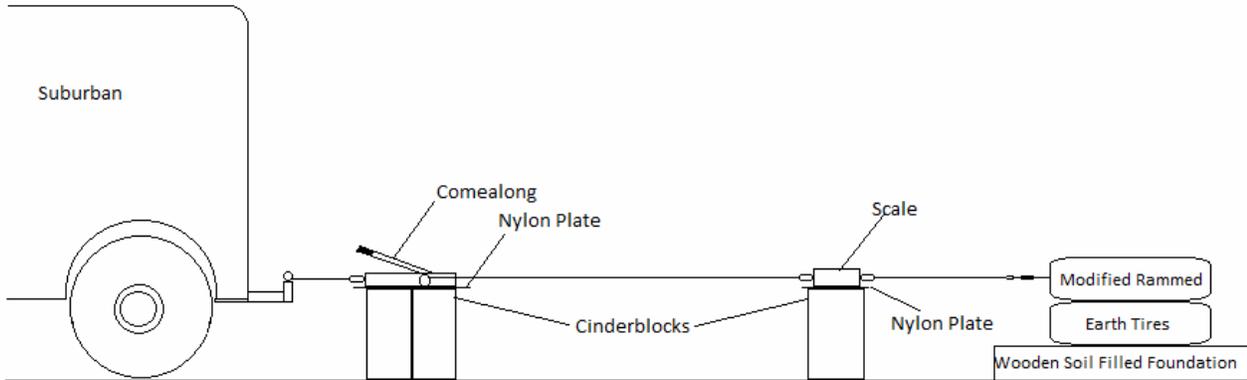
the centers of the treads of the tires. A 1/2" thick all-thread rod was screwed into these holes. Large, custom made 3.5"x5" washers were constructed and bent to fit the natural curve of the tire to minimize the deformation that the rod pulling on the tire would cause. A fastener was then constructed to attach an eyebolt to the rod so the cables could be easily attached to pull the tire. Figure 7 displays the construction of the pulled tire.



**Figure 7: Aerial display of the tire and rod setup**

An electronic scale was used to determine the force necessary to move the tires. The scale is capable of measuring forces up to 2000 lb, well under the expected force necessary to move the tires for the friction tests. A come-along was used to pull the tires. The come-along used is also capable of pulling forces up to 2000 lb. In order to ensure that no vertical force adding or subtracting from the normal force of the tires, it was important to design the setup such that the cables attaching the eyebolt on the tire to the scale and then to the come-along were horizontal. The expected height that the eyebolts would rest at for the tire on tire friction tests and the tire on soil tests was calculated and a combination of cinder blocks and planks of 2"x4"s were used to adjust the height of the scale and come-along accordingly.

Furthermore, to ensure that there was no friction between the scale and the come-along and their supports, a thin piece of nylon plate was placed under both the scale and the come-along. This low friction surface also decreased the likelihood of slippage under high pressures because the low friction allows the objects to slide at very low forces instead of jumping under higher forces. Finally, the come-along had to be fixed to some unmovable deadweight in order to pull the tires. The Engineering Department's Suburban with a hitch that could be oriented at two different heights was used as the deadweight. Pictures of the setup may be seen below in Figures 8 & 9. Figure 10 illustrates the basic principles of friction forces. As is clear from the diagram, in order to obtain enough data for a linear plot, the friction tests must be conducted with different weights and different normal forces



**Figure 8: Tire on Tire Friction Setup**

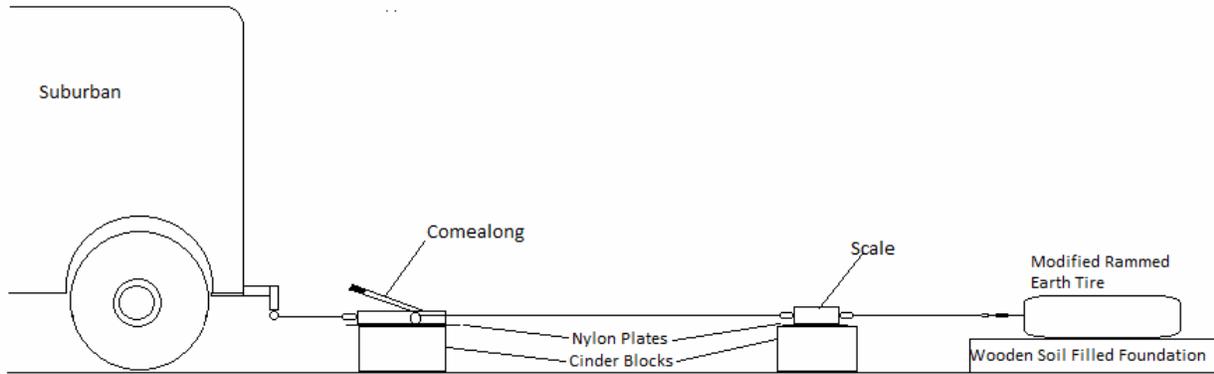


Figure 9: Tire on Earth Friction Setup

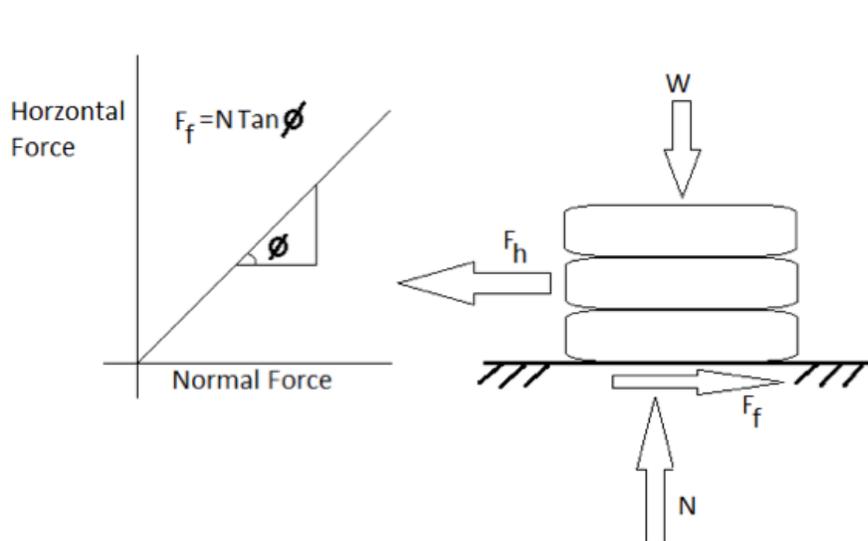


Figure 10: Schematic of Friction Force

## Deflection Tests

The purpose of the deflection test is to better characterize the way in which the modified rammed earth tires respond to loads. When a timber frame house is designed and the roof height is specified, the builders can cut the framing pieces to the height of the roof and not worry that they'll compress under a given load. The building codes prevent that sort of deflection or buckling. It is relatively standard to work to compress the soil in tires to 95% compaction while building one story homes. This still allows for some additional compaction

that should be considered when designing the height of the walls. For this test, a single modified tire was compressed under cinderblocks to develop a relationship between loading and deflection of the tire.

Simply, a tire is filled, a solid platform (a marble slab 1.5 inches thick was used) is placed above the tire and a gage is placed under the platform, near to the tire, to measure deflection. The plate is evenly loaded with 20 cinderblocks, and deflection readings are taken every time the load is symmetrical.

### **Wall Tests**

Based on the size of the garage, the largest wall that could be reasonably built was a wall three tires in length and eight tires in height. In order to build actual walls, tires are staggered on top of each other, row by row. In reality, this means that at the end of each alternating row of tires, there is a half tire space left over that must be filled. This typically accomplished by measuring and cutting off part of the tire leaving a half tire and flaps. See Figure 11 below for a picture. The flaps are then screwed into adjacent filled tires. Ten #10 x 3" screws were used per flap. It is often standard practice that the half tires are placed on the inside of the wall and whole tires are placed at the ends. This ensures that if there is failure in the weaker half tires, the wall will not fail because the whole tires surrounding them will hold them in place. For a wall that was three tires long, this would result in two half tires placed next to each other. It was decided to conservatively place the half tires on the outside of the rows. Figure 12 displays the wall that was built.



**Figure 11: Construction of half-tires**



**Figure 12: Constructed small-scale wall with no lateral support**

We assume that soil applies a triangular load to the wall, shown below in Figures 27 and 28. Due to material, time, and location constraints, it was not possible to apply a triangular load. Instead, a uniform load, centered on the centroid of the triangular load, was applied. To best approximate this, a frame was constructed out of four unistrut beams. The four beams were placed horizontally, at 7 inches center-to-center, and attached rigidly together with vertical beams placed at 16 inches center to center. The horizontal bars were placed over tire rows 2-5. Thus the centroid of this frame occurs at 3.5 tires up from the bottom, and the centroid from the soil pressure occurs at 3.75 tires up from the bottom. A picture of the setup may be seen in Figure 13.

Cable guides were included in the middle of the frame. Towing cables were wrapped around the entire wall and frame, passing through the cable guides on the frame. The cable ends were joined together with a U-fastener with a third cable which was used to pull the wall. A 5000 lb dynamometer was attached to the cable, and finally a cable was attached to the Suburban which was used to pull the wall over.

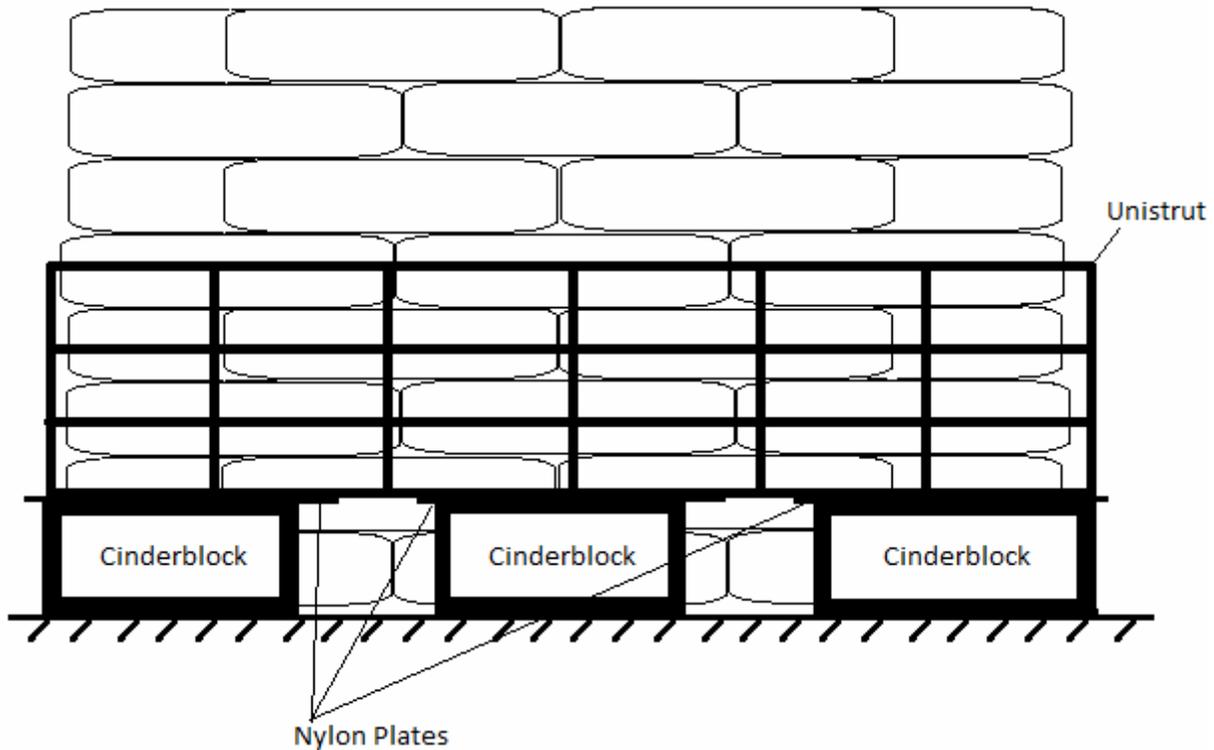


Figure 13: Wall testing setup displaying frame and its placement.

## Testing

### Friction Tests

The analysis requires is the coefficient of static friction between two tires and between a tire and the soil. In order to determine these coefficients of friction, the friction tests were repeated three different times, with various weights on top of the tires in order to find a linear curve fit. At each weight the friction test was completed three times yielding nine data points to make a linear plot. The slope of the graph represents the coefficient of friction for the test.

It should be noted that the coefficient of static friction may be found by recording the force necessary to move the tires for the first time. The force necessary to start moving an object only occurs for an instant. The scale that was used for the tests did not have a quick time resolution, and finding the peak force proved to be difficult. Instead, the tires were pulled

slowly, at a constant rate, and the stable force required for this was recorded. As a result, the coefficient of kinetic friction was in fact calculated. The coefficient of kinetic friction is always smaller than the coefficient of static friction so this result will yield a conservative analysis. This was corroborated by observing that there was a jump in the force displayed on the screen before the reading stabilized. Figures 14 and 15 display the actual tests.



**Figure 14: Picture of Tire to Tire Friction Tests**



**Figure 15: Pictures of Scale and Come-along Setup used for friction tests**

## Soil Mechanics

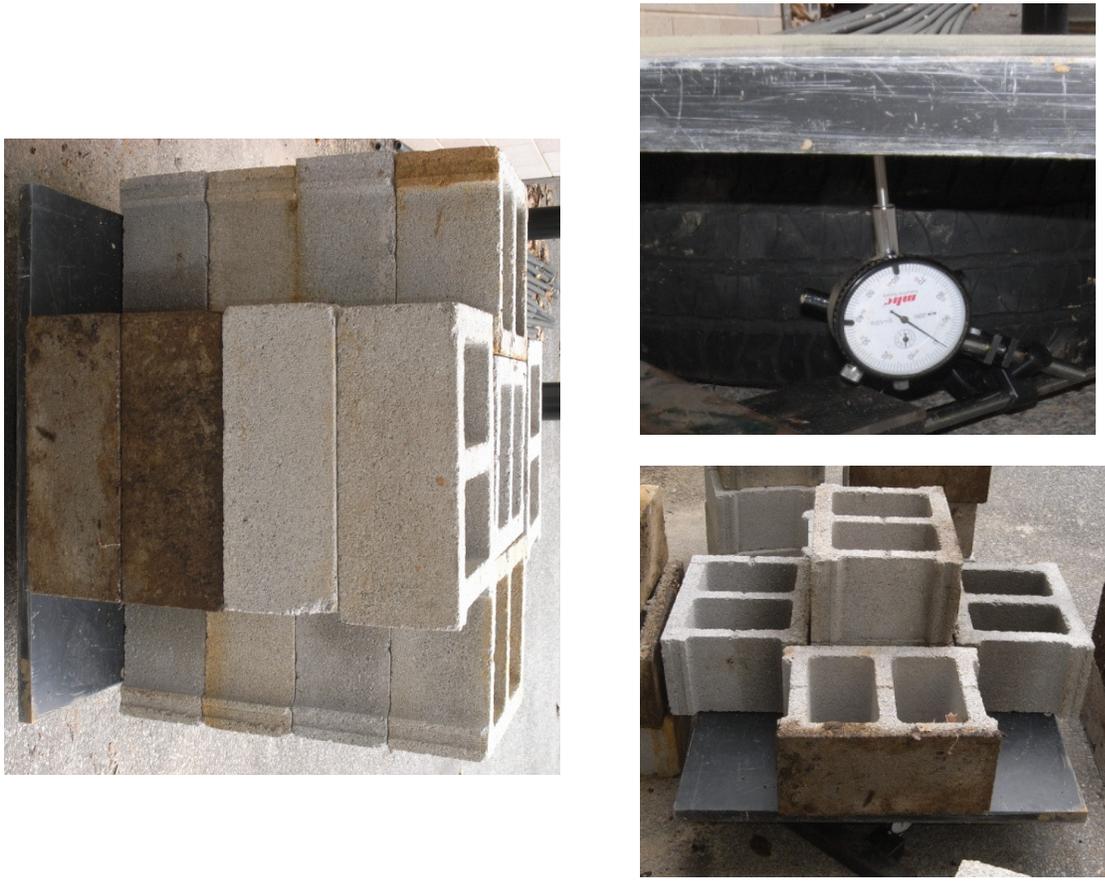
Moisture content tests were conducted by two other students, Duke Yeboah and Maher Shaban, on the soil that was used to fill the tires and to fill the wooden foundation platform. The purpose of these tests was to better characterize the soil use in this project. It is the goal that this report is fully reproducible, and identifying the soil moisture content is important for this reason. The tests were conducted by taking 50 random samples of approximately 50 grams of soil. The soil used for this project came from two different locations, a soil nursery on campus and worksite location near to the campus. As a result, it was important to determine the average moisture content of the soil over the whole pile. Defining the mass of the collecting can as  $M_c$ , the mass of the can and wet soil as  $M_1$ , and the mass of the can and dry soil as  $M_2$ , the moisture content was found for each of the fifty cans by the

following formula: 
$$\omega = \frac{M_1 - M_2}{M_2 - M_c} \times 100\%$$

## Deflection Tests

This test was carried by loading the tire with twenty cinderblocks. There was some nonlinearity in the results, most likely due to the non-uniform loading pattern. In total, twenty cinderblocks, each weighing 54 pounds were applied to the marble slab on top of the tire. The cinderblocks were applied in

four layers of five blocks. The first cinderblock was placed in the middle of the slab and a reading was taken. The next two blocks were placed above and below the first slab and then a reading was taken. Finally, the last two blocks of the layer were placed to the left and the right of the initial slab and a reading was taken. Figure 16 displays the actual tests.



**Figure 16: Pictures of the Deflection Tests**

### **Wall Test**

The cables were wrapped around the frame and wall, passing through the cable guides on the frame centered at 3.75 tire heights up from the bottom of the wall. These cables were attached to another cable, attached to a dynamometer, and attached by a final cable to the tow hooks on the suburban. Initially there was a frame that was used to direct the cables from the height of the wall cable guides to the height of tow hooks. As the load was increased, the frame started to twist and pull up. The

load was released, the frame was taken out, and the loading was recommenced. After approximately 800lb had been applied in the second loading, one of the cables slipped, but did not fail. The load was again taken off, the test setup was reexamined, and the load was applied for the third time. At this point, the wall had a slight tilt to it from the first two loadings. The wall was tested to failure in the third loading. Pictures of the testing setup may be seen below in Figures 17 and 18. It should be noted that a video of the failure was also recorded and may be obtained by request to the author.



**Figure 17: Picture of Wall and Testing Frame Setup**



Figure 18: Picture of the front of the Wall Testing Setup

## Results

### Friction Tests

The following tables display the results from the friction tests for both R14 and R15 tires.

Tire on Tire		Tire On Earth	
Normal Force (lb)	Force to Pull (lb)	Normal Force (lb)	Force to Pull (lb)
191.5	111	191.5	124
191.5	108	191.5	128
191.5	107	191.5	128
358.25	196	358.25	242
358.25	208	358.25	245
358.25	182	358.25	240
534.25	293	534.25	349
534.25	286	534.25	344
534.25	290	534.25	342

Table 2: Friction test results for R14 tires

Tire on Tire		Tire On Earth	
Normal Force (lb)	Force to Pull (lb)	Normal Force (lb)	Force to Pull (lb)
214	161	214	137
214	141	214	149
214	131	214	150
380.75	231.5	380.75	257
380.75	231	380.75	252
380.75	220	380.75	257.5
556.75	320	556.75	406
556.75	315.5	556.75	403
556.75	318.5	556.75	380

Table 3: Friction test results for R15 tires

The following graphs display the friction coefficient slopes for the tire on tire friction and the tire on soil friction for both R14 and R15 tires.

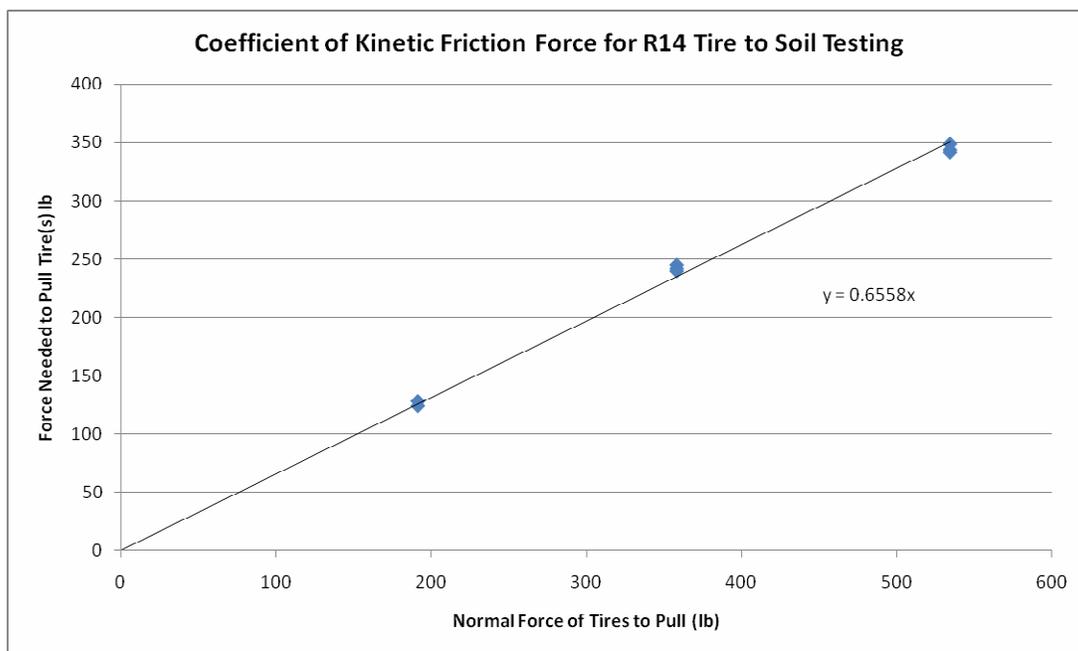


Figure 19: Graph displaying the coefficient of kinetic friction for R14 tire to soil testing. The coefficient of friction is 0.6558. The  $R^2$  value for the fit is 0.9958.

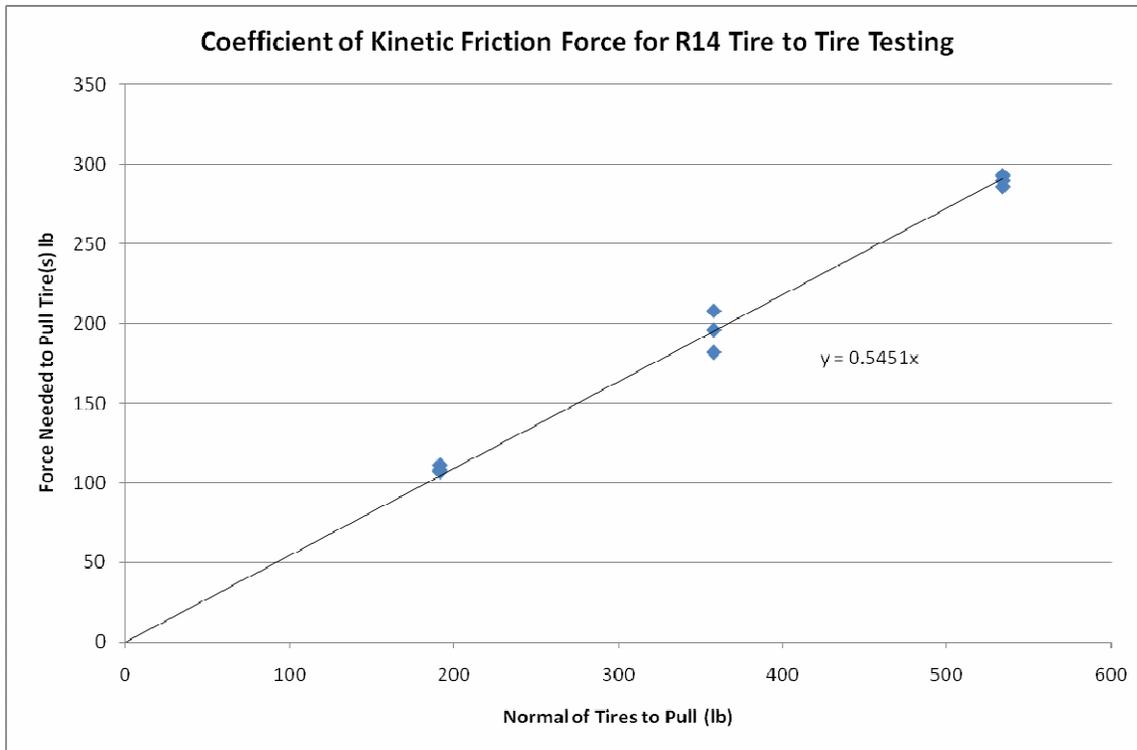


Figure 20: Graph displaying the coefficient of kinetic friction for R14 tire to soil testing. The coefficient of friction is 0.5451. The  $R^2$  value for the fit is 0.9912.

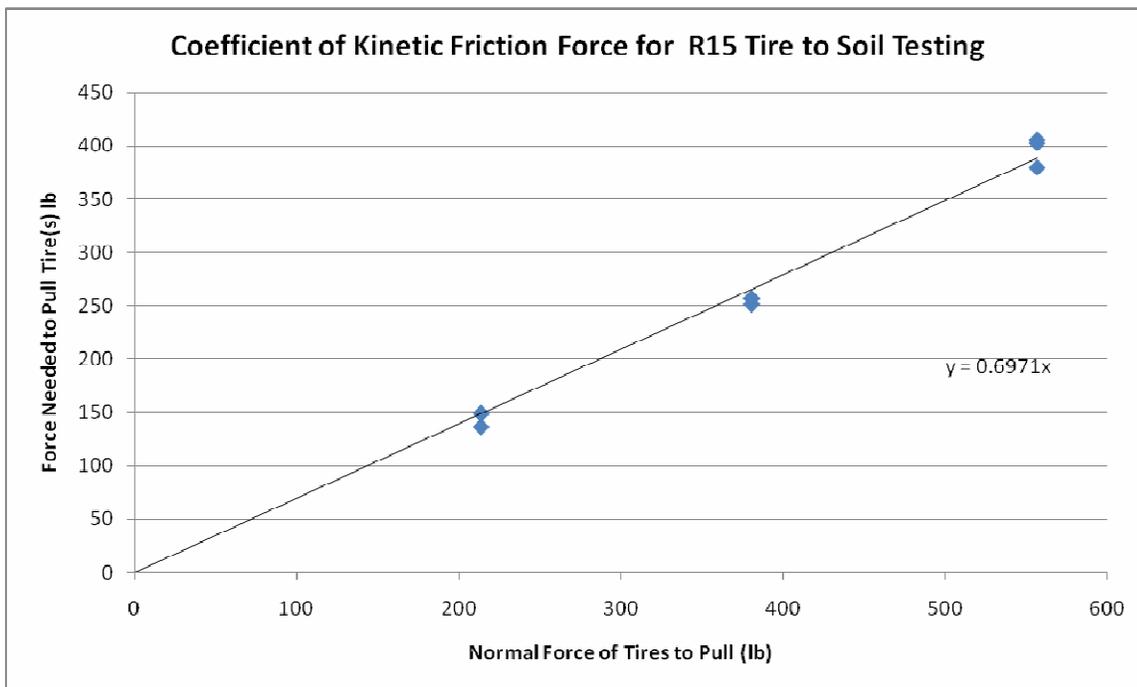


Figure 21: Graph displaying the coefficient of kinetic friction for R15 tire to soil testing. The coefficient of friction is 0.6971. The  $R^2$  value for the fit is 0.9888.

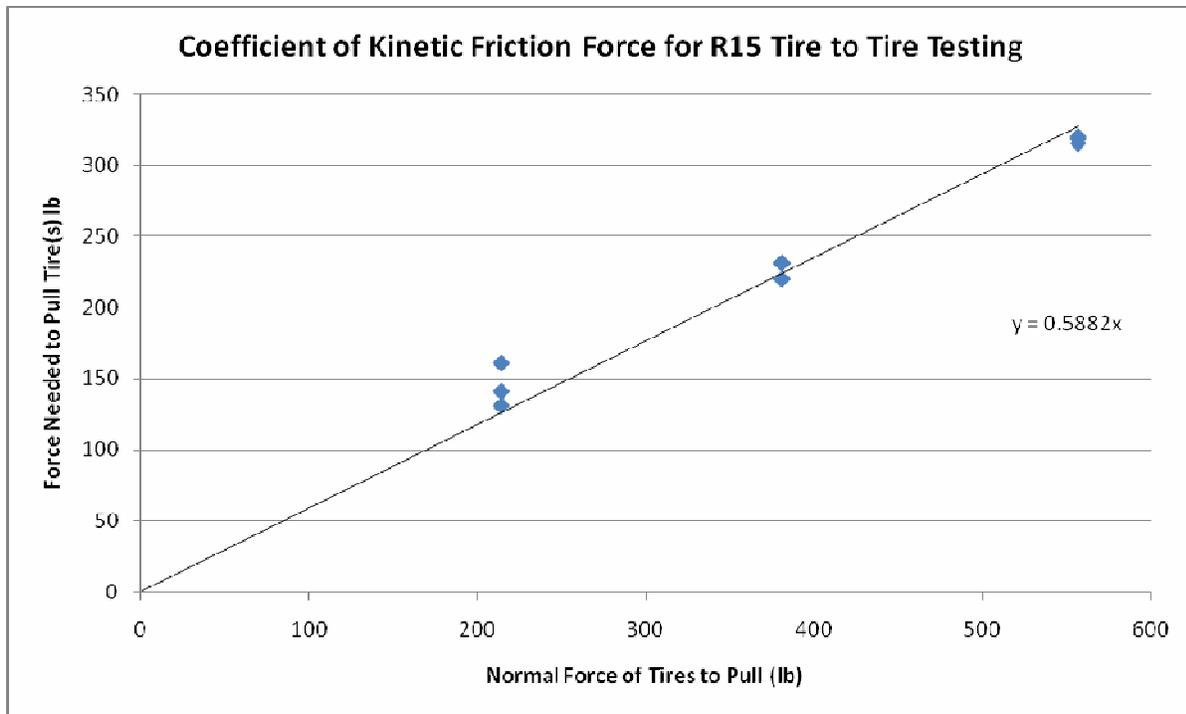


Figure 22: Graph displaying the coefficient of kinetic friction for R15 tire to soil testing. The coefficient of friction is 0.5882. The  $R^2$  value for the fit is 0.9587.

The following table displays the coefficients of friction for the four situations.

	R14	R15
Tire on Soil	0.6558	0.6971
Tire on Tire	0.5451	0.5882

Table 4: Coefficients of Kinetic Friction for tire to tire friction and tire to soil friction for both R14 and R15 tires.

## Soil Mechanics

The entire soil moisture tests may be found in Appendix B. Table 5 summarizes the results from the test and Figure 23 displays the distribution of the found moisture content.

Statistic	Moisture Content (%)
Mean	26.62
Median	26.51
Variance	7.043
Standard Deviation	2.654

Table 5: Characteristics of soil moisture content

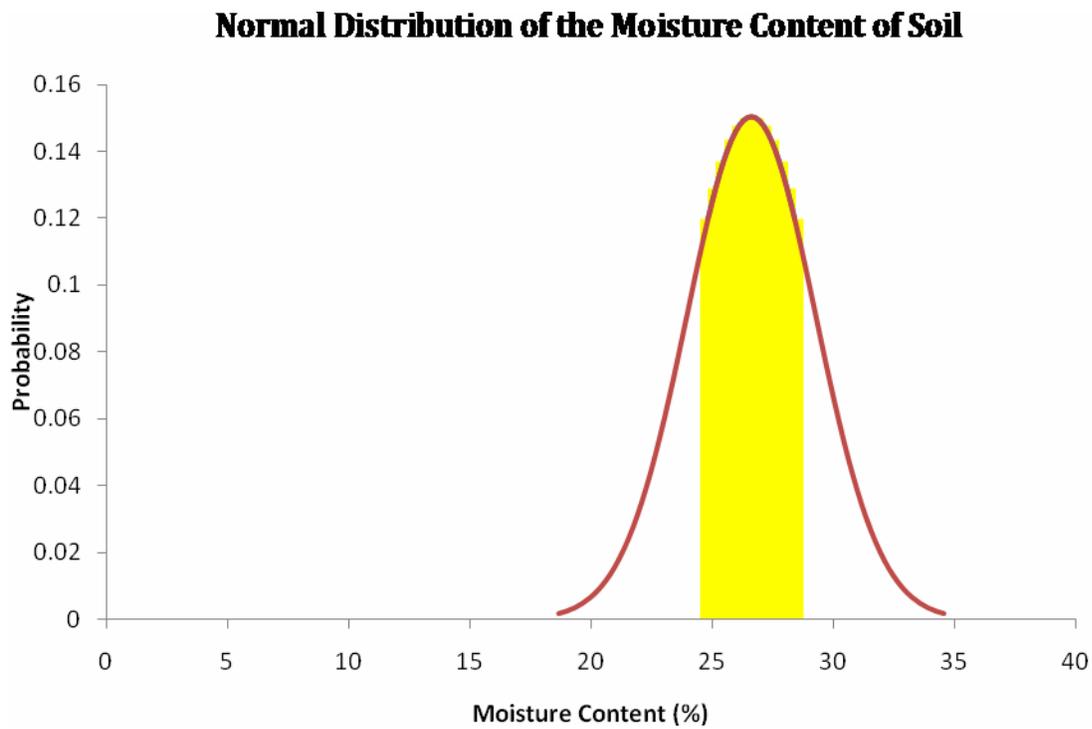


Figure 23: The distribution of the soil moisture content. The characteristics of the distribution may be seen in Table 5. The middle 50% of the density is highlighted in yellow.

## Deflection Tests

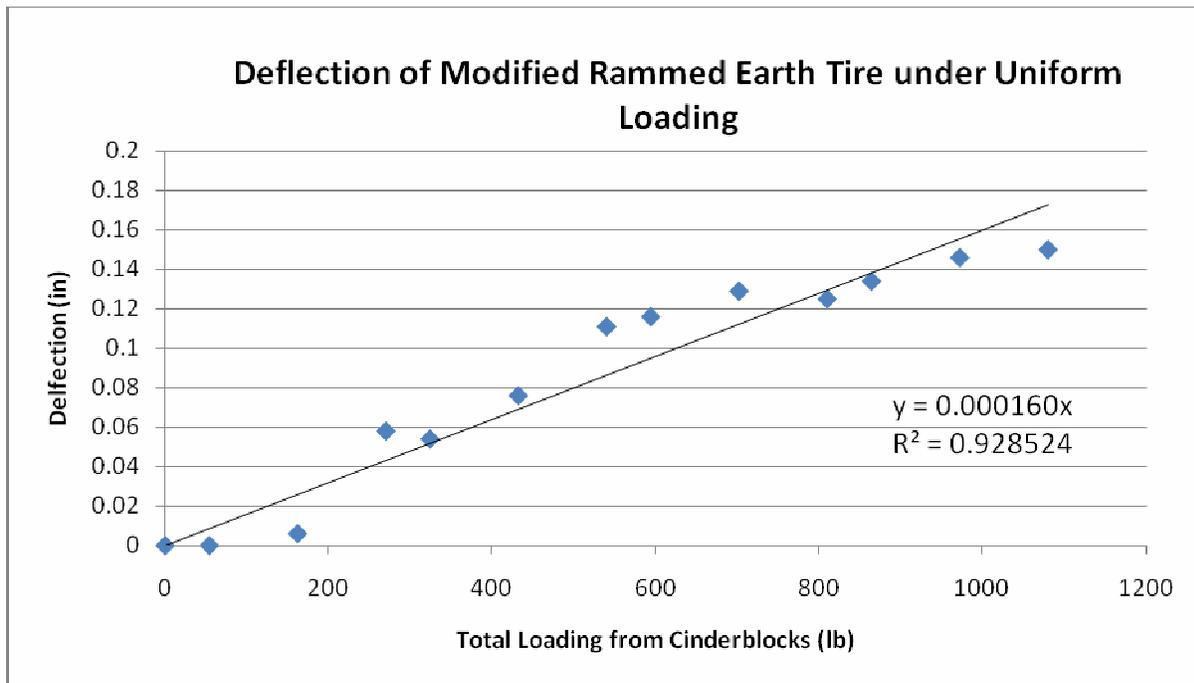


Figure 24: Results from the deflection tests using a linear fit. Under a load of 1080lb, the tire deflected .14 inches.

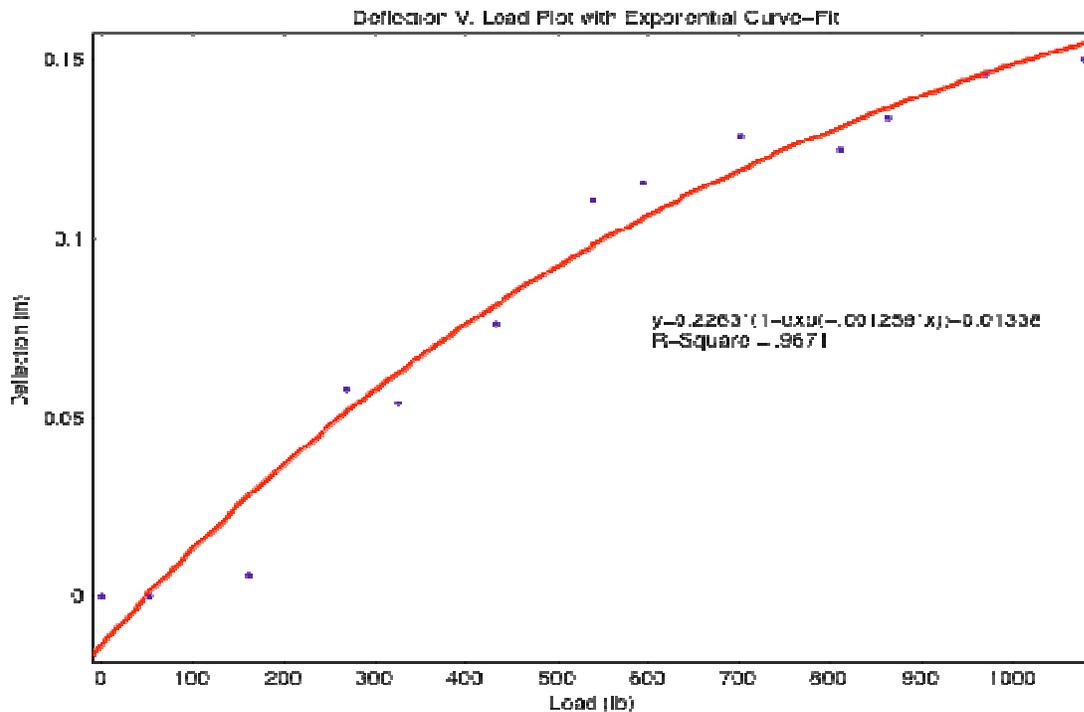


Figure 25: Results from the deflection tests using an exponential fit in Matlab.

## Wall Tests

The freestanding wall failed at approximately 1200 pounds (the dynamometer used has a capacity of 5000 pounds with an error of 150 pounds.) The wall was built out of both R14 and R15 tires. Using an average weight of 200 pounds, a wall with no lateral support that is three tires long and 8 tires in height will fail by overturning (see analysis section below). A wall this size will take a moment of approximately 4800 lb-ft to fail, or a load of approximately 2250 pounds applied at 3.75 tires up from the bottom of the wall. The discussion section includes possible reasons for the early failure.

## Analysis

### Friction Tests

In order to complete the analysis, some simple assumptions were made, and they may be seen below:

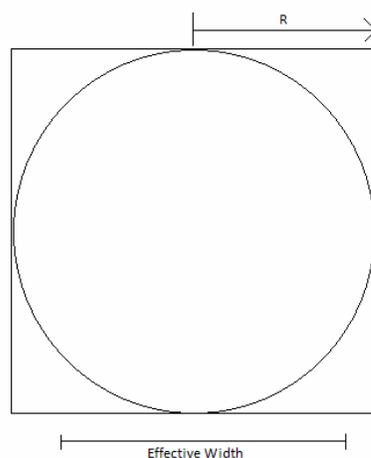
1) The wall will not buckle or fail from its own weight combined with the weight of the roofing.

This assumption is safe in a rammed earth structure and the deflection that the wall might undergo is analyzed in the vertical loading test.

2) As a result of Assumption 1, the wall will only fail from horizontal loading. If a house was built in the middle of a flat site, the wall would certainly be safe. Many rammed earth tire wall homes are built into the side of a hill to add extra thermal insulation to the house. As a result, the walls built into the soil will receive earth pressures from the soil and it is these pressures that may cause the walls to fail. Additionally, an earthquake analysis is later performed.

The analysis of the friction tests consists of two portions. The first analysis is simply of a freestanding tire wall, with no lateral support. The second analysis assumes that the wall is laterally braced at the top. The second analysis is more realistic and more closely represents the conditions that a wall in a house will be under. Note that the second analysis only assumes that the wall receives lateral support from the roof whereas many walls in houses will also receive lateral support from adjacent walls. There are two possible modes of failure in each analysis. One mode of failure is caused by the wall failing by overturning, rotating as a unit around the base due to the earth pressures. The other mode of failure is due to sliding between the tires and other tires, or between the bottommost tire and the soil.

In order to perform the analysis, some basic calculations are first performed on the tires to find their effective widths and the weight per height of wall per length of wall. In order to calculate the effective tire width, a fillet correction is performed to account for variability in tread and the rounded corners of the tires. As a result we take two inches off the radius of the tires. See Figure 26.



**Figure 26: Fillet Correction and Effective Area diagram**

### Fillet Correction for R14 Tires

Area of a R15 tire,  $Area = 13 * 13 = 169 \text{ in}^2$ . The area of a quarter circle of R15 tire is

then  $A = \frac{\pi(169)}{4} = 132.73 \text{ in}^2$ . Thus, the percent reduction is  $\frac{169 - 132.72}{169} = 21.46\%$ , and

the effective width is *effective area for R15*,  $a_{15} = 2 * 13 - (2 * 13) * .2146 = 20.42''$ .

Similarly, *effective area for R14*,  $a_{14} = 2 * 12 - (2 * 12) * .2146 = 18.85''$ .

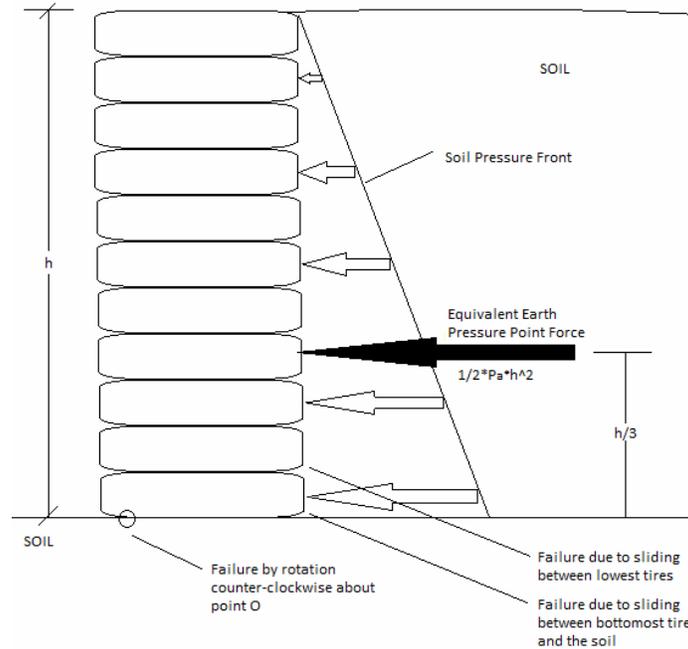
Assuming the tires are seven inches tall, the weight of a fully compacted R15 tire per length of wall per height of wall is:

$$w_{15} = 214 * \frac{12}{8} * \frac{12}{30} = 128.4 \text{ lb per foot of ht per foot of length}$$

Similarly,  $w_{14} = 191.5 * \frac{12}{8} * \frac{12}{28} = 123.1 \text{ lb per foot of ht per foot of length}$ .

### No Lateral Support

Figure 27 displays the possible modes of failure for a modified rammed earth tire which receives no lateral support. Note that  $P_{\text{allow}}$  is the allowable pressure in pounds per square foot.



**Figure 27: Analysis model displaying the different possible modes of failure and their locations for a wall with no lateral support**

For this model, first consider failure by counter clockwise rotation about point O. Let  $a$  be the effective width of the tire. Summing the moments yields

$$\sum M_O = \frac{1}{2} * P_{allow} * h^2 * \frac{h}{3} - w * h * \frac{a}{2} = 0$$

. Thus, the equation for  $P_{allow} = \frac{3wa}{h^2}$ . Altering  $h$

yields the different pressures in pound per square foot that it would take to knock over the wall for a given  $h$ . Note that  $w$  and  $a$  represent the effective area and the weight of the wall per area as found above.

For failure by sliding, horizontal forces are summed. There are two cases of possible failure, sliding at the foundation and sliding between the first and the second tire. Summing forces and solving for  $P_{allow}$  yields the following two cases:

For failure above the first tire: 
$$P_{allow} = \frac{2w \left( h - \frac{8}{12} \right) f_{tt}}{h^2}$$

For failure at the foundation:  $P_{allow} = \frac{2Wf_{te}}{h}$

Where  $f_{tt}$  represents the tire to tire coefficient of kinetic friction and  $f_{te}$  represents the tire to earth coefficient of kinetic friction.

### With Lateral Support

Figure 28 displays the possible modes of failure for a modified rammed earth tire which receives lateral support from a roof system located above the wall.

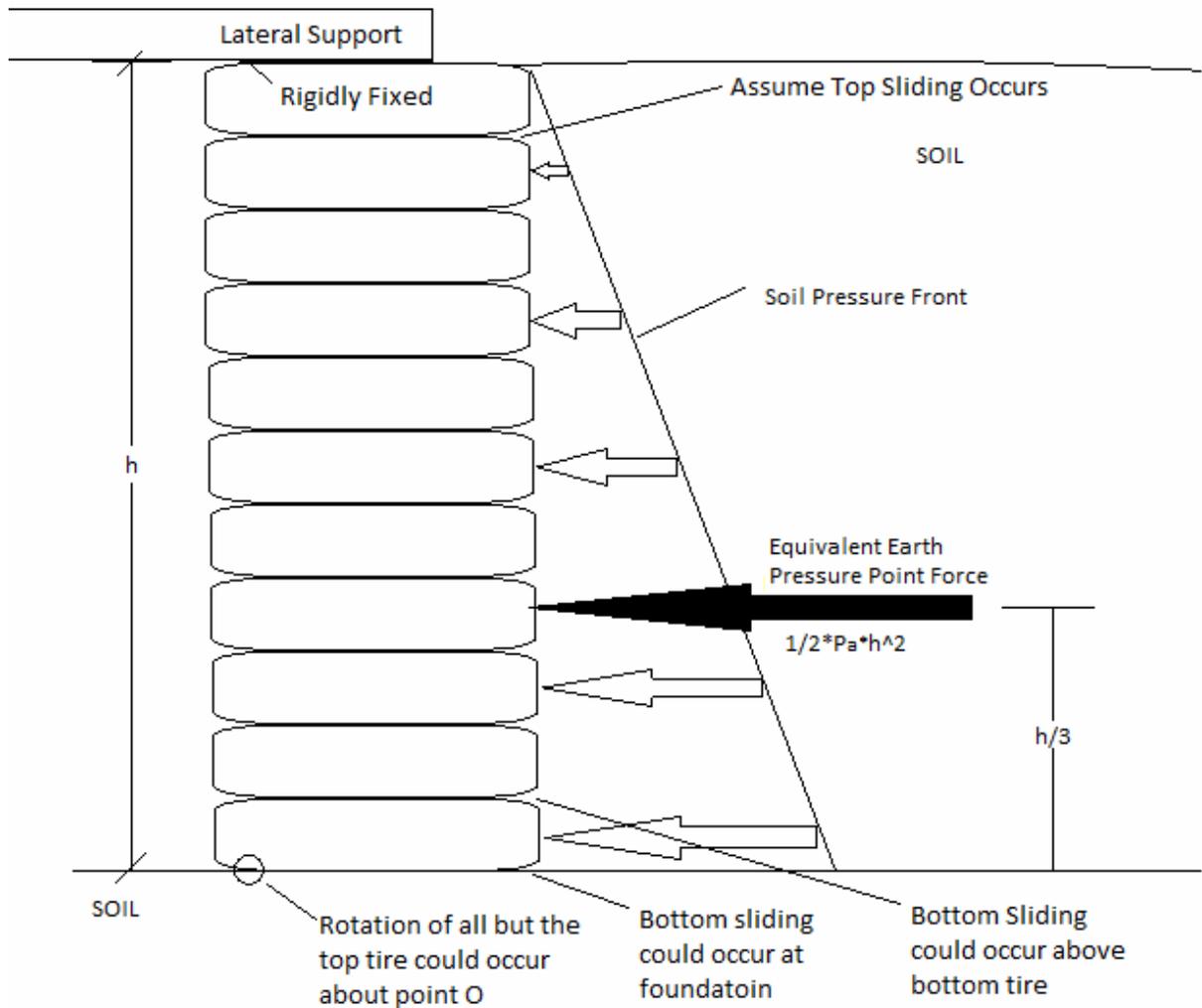


Figure 28: Analysis model displaying the different possible modes of failure and their locations

In this model, first consider rotation about point O in a counter clockwise direction. If this occurs, we assume that all of the tires stay rigidly connected from the bottom tire to the tire second from the top. These tires all rotate together as one column. This results in the top tire slipping inside the house and the lower tires slide towards the point of failure. Summing the moments about point O yields the following formulas:

$$\sum M_O = \frac{1}{2} * P_{allow} * h^2 * \frac{h}{3} - \frac{wha}{2} - \frac{1}{2} w_{ft} h^2$$

$$P_{allow} = \frac{3wa}{h^2} + wf_{tt}$$

Similarly, for failure by sliding, horizontal forces are summed. There are two cases of possible failure, sliding at the foundation and sliding between the first and the second tire. It is assumed that the top-most tire will slide and that the tires in between the points of slippage will move as a column. Summing forces and solving for  $P_{allow}$  yields the following two cases:

$$\text{For failure above the first tire: } P_{allow} = \frac{2wf_{te}}{h} + \frac{wf_{tt} \left(h - \frac{8}{12}\right)^2}{h^2}$$

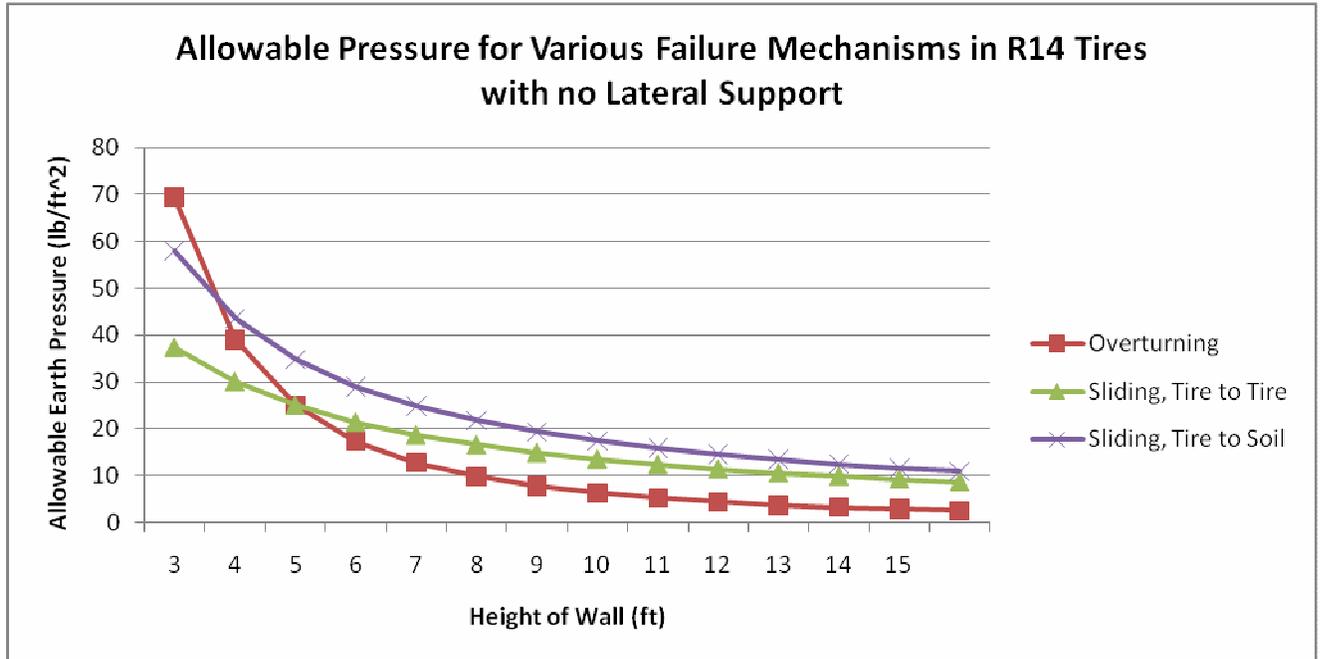
$$\text{For failure at the foundation: } P_{allow} = \frac{wf_{tt} \left(h - \frac{16}{12}\right)^2}{h^2} + \frac{2wf_{tt} \left(h - \frac{8}{12}\right)^2}{h^2}$$

#### Friction Test Results

The following tables and figures represent the allowable soil pressure for R14 tires with no lateral support.

Resistance to Overturning		Resistance to Sliding		Resistance to Sliding	
		Failure at Tire to Tire		Failure at Tire to Soil	
h (ft)	$P_{allow}$ (lb/ft <sup>2</sup> )	h (ft)	$P_{allow}$ (lb/ft <sup>2</sup> )	h (ft)	$P_{allow}$ (lb/ft <sup>2</sup> )
3	69.394	3	37.47865333	3	57.97272
4	39.034125	4	30.116775	4	43.47954
5	24.98184	5	25.0571568	5	34.783632
6	17.3485	6	21.41637333	6	28.98636
7	12.74583673	7	18.68469306	7	24.84545143
8	9.75853125	8	16.56422625	8	21.73977
9	7.710444444	9	14.87248148	9	19.32424
10	6.24546	10	13.4923152	10	17.391816
11	5.16153719	11	12.34538876	11	15.81074182
12	4.337125	12	11.37744833	12	14.49318
13	3.695538462	13	10.54978154	13	13.37832
14	3.186459184	14	9.83404898	14	12.42272571
15	2.77576	15	9.209040533	15	11.594544
16	2.439632813	16	8.658572813	16	10.869885

**Table 6: Allowable pressure for a modified rammed earth tire wall with R14 tires and no lateral support. From the table Resistance to sliding occurring above the bottommost tire dominates the failure method until after 5 ft at which point failure occurs by overturning.**



**Figure 29: Graph displaying the allowable pressure an R14 rammed earth tire wall with no lateral support may receive before failure by different mechanisms.**

The following tables and figures represent the allowable soil pressure for R14 tires with lateral support.

Resistance to Overturning		Resistance to Sliding		Resistance to Sliding	
		Failure at Tire to Tire		Failure at Tire to Soil	
h (ft)	Pallow (lb/ft <sup>2</sup> )	h (ft)	Pallow (lb/ft <sup>2</sup> )	h (ft)	Pallow (lb/ft <sup>2</sup> )
3	141.67426	3	104.8768085	3	65.81073056
4	111.314385	4	96.21526789	4	67.13531094
5	97.2621	5	91.18231265	5	68.0237558
6	89.62876	6	87.89532962	6	68.65509264
7	85.02609673	7	85.58094768	7	69.12516929
8	82.03879125	8	83.86346135	8	69.48818398
9	79.99070444	9	82.53848316	9	69.77672562
10	78.52572	10	81.48533266	10	70.01146295
11	77.44179719	11	80.62818113	11	70.20610194
12	76.617385	12	79.91699365	12	70.37007566
13	75.97579846	13	79.31742471	13	70.51008269
14	75.46671918	14	78.80511728	14	70.63100804
15	75.05602	15	78.36231874	15	70.73649642

16	74.71989281	16	77.97578502	16	70.82932162
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Table 7: Allowable pressure for a modified rammed earth tire wall with R14 tires and lateral support. From the table Resistance to sliding occurring at the foundation dominates the failure method.

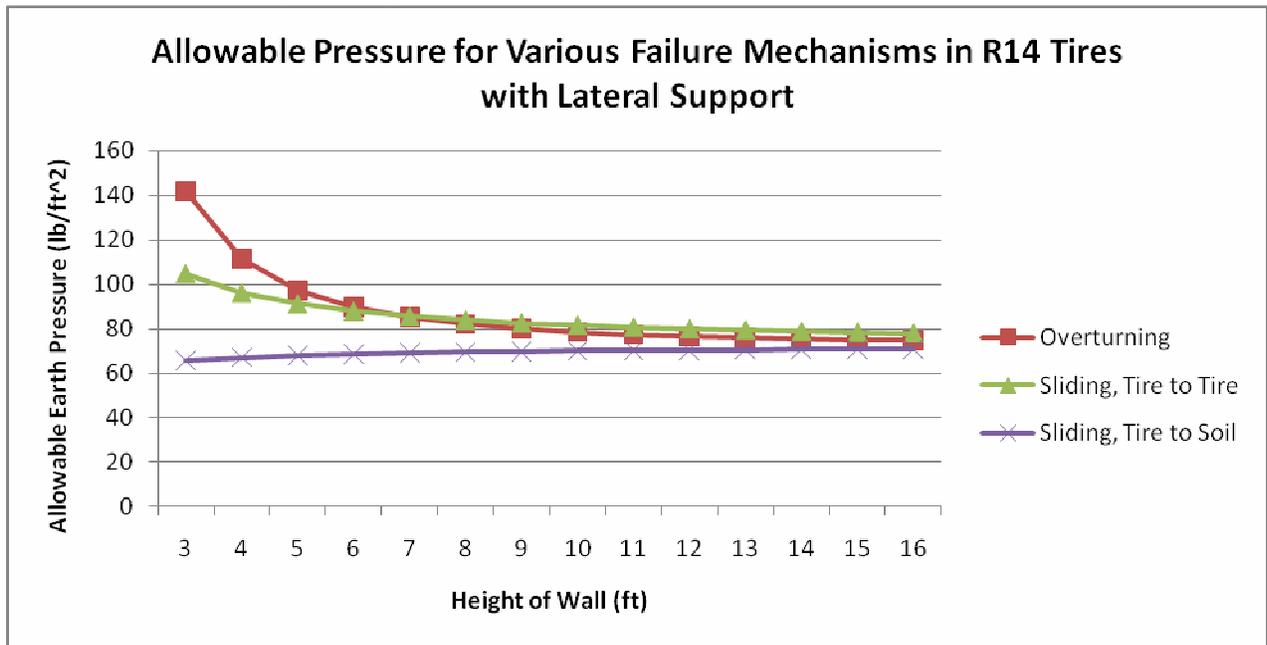


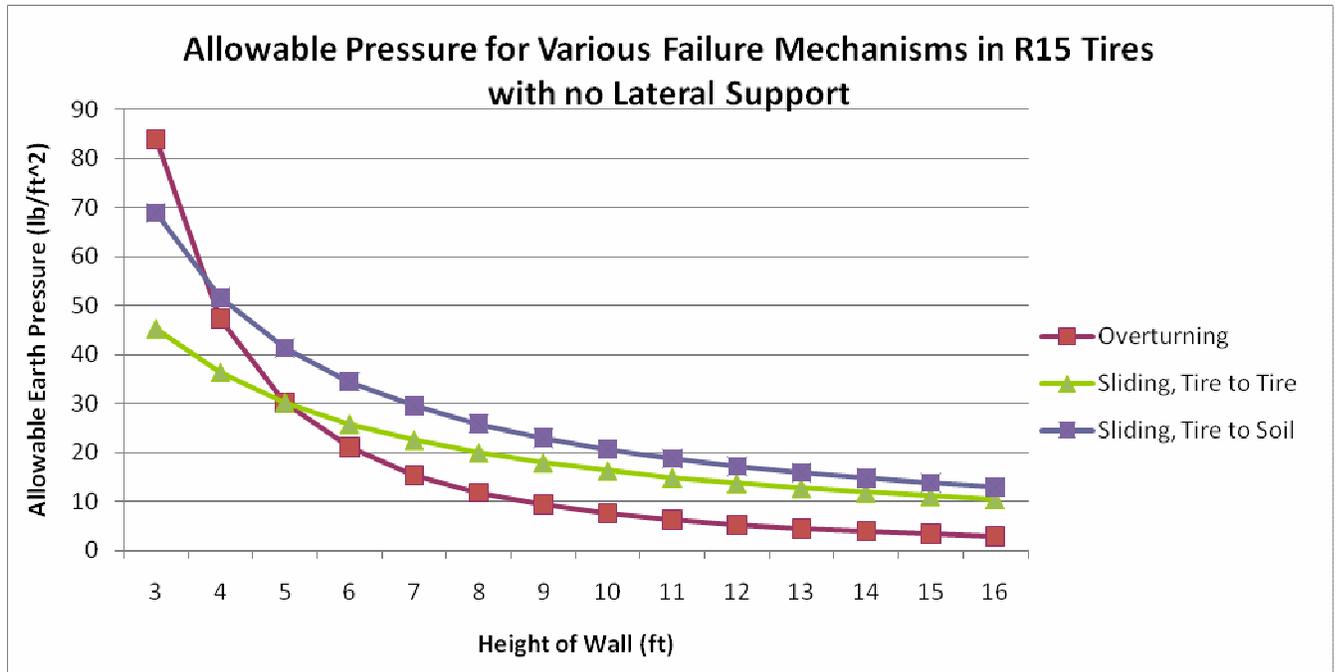
Figure 30: Graph displaying the allowable pressure an R14 rammed earth tire wall with lateral support may receive before failure by different mechanisms.

The following tables and figures represent the allowable soil pressure for R15 tires with no lateral support.

Resistance to Overturning		Resistance to Sliding		Resistance to Sliding	
		Failure at Tire to Tire		Failure at Tire to Soil	
h (ft)	Pallow (lb/ft <sup>2</sup> )	h (ft)	Pallow (lb/ft <sup>2</sup> )	h (ft)	Pallow (lb/ft <sup>2</sup> )
3	83.98	3	45.18453333	3	68.8636
4	47.23875	4	36.309	4	51.6477
5	30.2328	5	30.209088	5	41.31816
6	20.995	6	25.81973333	6	34.4318
7	15.42489796	7	22.5264	7	29.51297143
8	11.8096875	8	19.96995	8	25.82385
9	9.331111111	9	17.93037037	9	22.95453333
10	7.5582	10	16.266432	10	20.65908
11	6.246446281	11	14.88368926	11	18.78098182
12	5.24875	12	13.71673333	12	17.2159
13	4.472307692	13	12.71889231	13	15.8916
14	3.85622449	14	11.856	14	14.75648571
15	3.3592	15	11.10248533	15	13.77272

16	2.952421875	16	10.4388375	16	12.911925
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**Table 8: Allowable pressure for a modified rammed earth tire wall with R15 tires and no lateral support. From the table Resistance to sliding occurring above the bottommost tire dominates the failure method until after 5 ft at which point failure occurs by overturning.**



**Figure 31: Graph displaying the allowable pressure an R15 rammed earth tire wall with no lateral support may receive before failure by different mechanisms.**

The following tables and figures represent the allowable soil pressure for R15 tires with lateral support.

Resistance to Overturning		Resistance to Sliding		Resistance to Sliding	
		Failure at Tire to Tire		Failure at Tire to Soil	
h (ft)	Pallow (lb/ft <sup>2</sup> )	h (ft)	Pallow (lb/ft <sup>2</sup> )	h (ft)	Pallow (lb/ft <sup>2</sup> )
3	171.1216	3	125.4115056	3	79.34188889
4	134.38035	4	115.2262719	4	80.9388125
5	117.3744	5	109.312814	5	82.009928
6	108.1366	6	105.4528764	6	82.77107222
7	102.566498	7	102.7361214	7	83.3378
8	98.9512875	8	100.720618	8	83.77545313
9	96.47271111	9	99.1660784	9	84.12332099
10	94.6998	10	97.9306835	10	84.406322
11	93.38804628	11	96.92535165	11	84.64098017
12	92.39035	12	96.0913191	12	84.83866806
13	91.61390769	13	95.38825769	13	85.00746154
14	90.99782449	14	94.78757321	14	85.15325

15	90.5008	15	94.26842822	15	85.28042756
16	90.09402188	16	93.81527949	16	85.39233828

Table 9: Allowable pressure for a modified rammed earth tire wall with R15 tires and lateral support. From the table Resistance to sliding occurring at the foundation dominates the failure method.

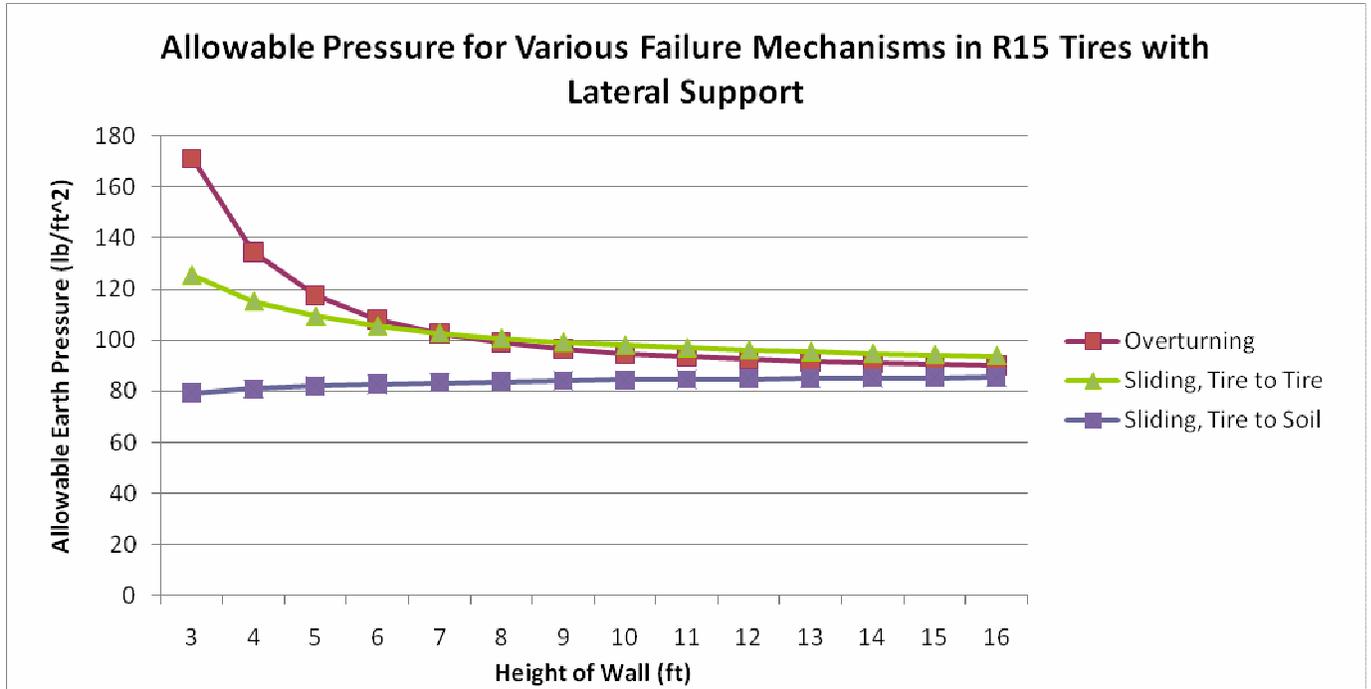


Figure 32: Graph displaying the allowable pressure an R15 rammed earth tire wall with lateral support may receive before failure by different mechanisms.

## Discussion of Results and Analysis

### Friction Tests

The analysis of the friction tests are the most relevant results pertaining to the safety of using these modified rammed earth tires in single story homes. Figures 29 and 30 and Tables 6 and 7 display the results from the analysis of a free-standing wall. It is hoped that these results will help to classify these structures and may be useful in some situations, such as building small retaining walls for gardens or similar structures.

Figure 31 and 32 and Tables 8 and 9 display the results of the friction analysis when the wall is assumed to receive lateral support from a roofing system. It can be seen that for both R14 and R15 tires, walls are more likely to fail from overturning as opposed to sliding. It may also be seen that in either case, for realistic sized walls of 7.5 feet or higher, it would take over 60psf to cause failure. From the Griepentrog report, active soil pressures around the Weaver site were expected to be in the 30-40 psf range. The factor of safety is then at least 1.5, which is standard.

It should also be noted that these results are very conservative. As already mentioned, the coefficient of kinetic friction has been used instead of the coefficient of static friction. Although the coefficients may not differ drastically, small changes may carry through the equations for large effect.

More importantly, in many rammed earth style homes, the retaining walls are U-shaped which should add extra strength to the structure. Furthermore, in almost all rammed earth style homes, the retaining walls are connected to walls that resist the earth pressure laterally, as opposed to the transverse resistance that the actual retaining walls provide. In the models assuming lateral support, only horizontal lateral support from the roof system is assumed. The additional vertical lateral support from the walls adjacent to the retaining walls will significantly increase the strength of the retaining walls. Given that the factor of safety is already at 1.5, allowing for the increased strength of the walls due to the conservative nature of the model will ensure that these structures are capable of providing dependable support for one-story homes. As discussed in the Griepentrog report, these walls receive their strength from their massive size and large friction coefficients.

## **Deflection Tests**

The deflection results were fit using two different formulas, a linear fit, and an exponential decay fit. It is clear from Figures 24 and 25 and the associated  $R^2$  values that the exponential fit defines the data better. This conclusion further makes sense because as the already highly compacted soil experiences additional loading, it has a limited amount that it can further be compacted. Additionally, the radial reinforcing steel wires under the treads of the tires ensure that the tire cannot continue to stretch horizontally. As a result, there is an upper limit on the deflection the tires can experience. From the best-fit curve equation in the exponential model, it can be assumed that each row of tires will not deflect more than .215 inches. Thus, if a house design called for 8-foot tall ceilings, and assuming 7 inches per row of tire, it would be conservative to assume 14 rows of tires to create a ceiling height of 8 feet 2 inches. At most there will be 3 inches of deflection due to loadings on the tires, resulting in a minimum 7 foot 11 inch ceiling. This is the case which is assumed in the house design below.

## **Wall Tests**

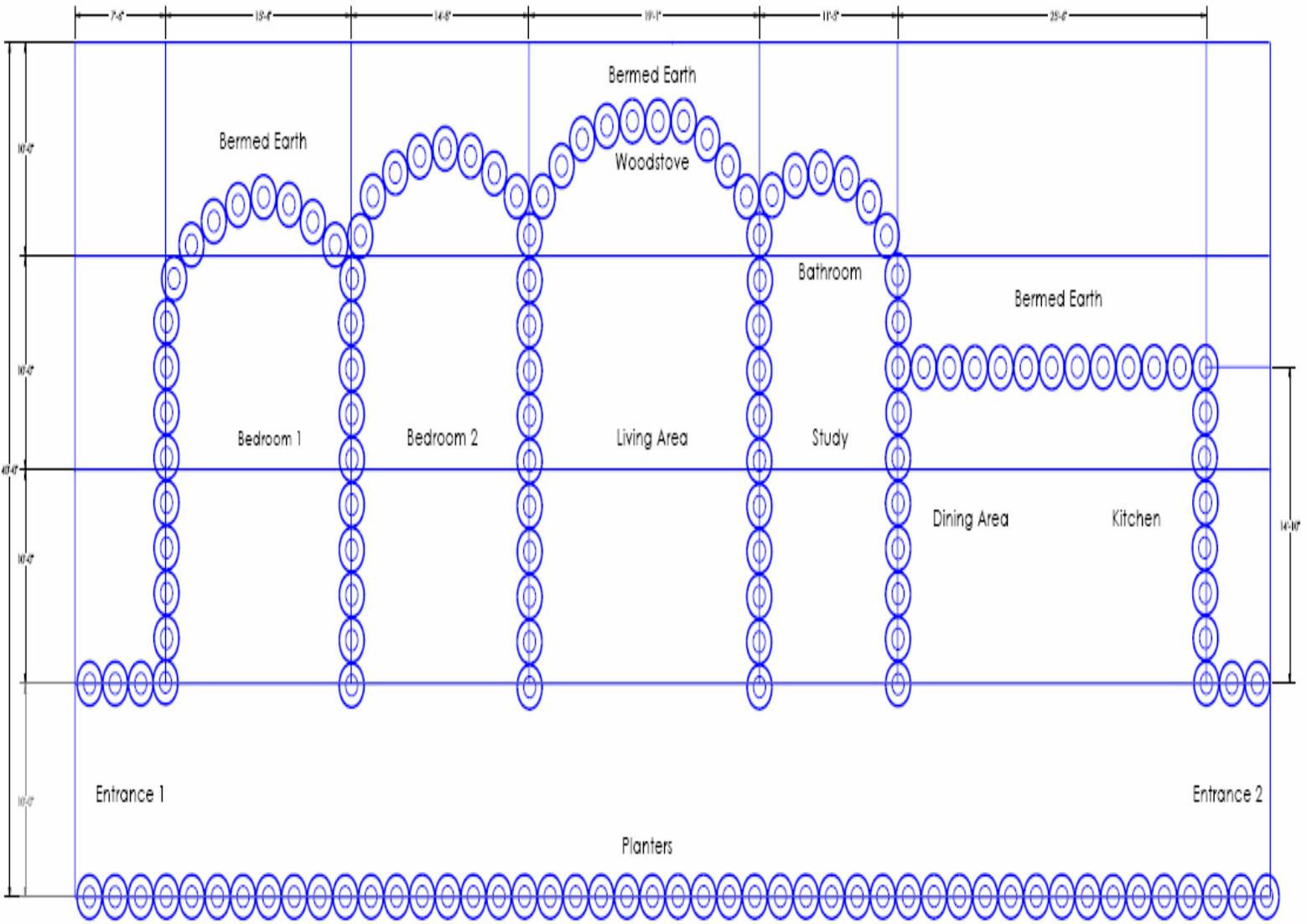
As already mentioned, the wall failed under a load of approximately 1200 pounds and was expected to fail around 2250 pounds. There are many reasons that this failure may have been early. As mentioned previously, the wall was constructed with the half tires on the outside of the rows as opposed to standard building practice which places them on the inside of rows. Secondly, the uniform load applied over four rows of tires may have contributed to partial local failures as opposed to the global failure the models are based on. Finally, the wall was loaded

twice to over 800 pounds and fully relaxed before the final load of 1200 pounds. This may have in fact tested the wall for a failure closer to fatigue failure than to the ultimate strength test that the wall was designed for. It is believed that due to these reasons the test is not conclusive or representative of the actual strength of modified rammed earth tire walls.

## House Design

For the last part of the project, a single story home built out of modified rammed earth tires was designed and analyzed. Figure 33 displays the design of the house. The house was analyzed for both the soil pressure on the retaining walls as well as the resistance of the walls to earthquake loads. The calculations may be found in Appendix A. It was already found that the factor of safety for an eight-foot retaining wall is 1.5 or greater. It was found that conservatively using R14 tires, the factor of safeties involved in both resistance to sliding and resistance to overturning in Swarthmore, PA and in Taos, NM were not lower than 2.3. This suggests in a real world example that single story homes made from modified rammed earth tires will be safe under all regular loadings that they might incur.

Please note that the earthquake analysis was done to best represent an earthquake loading. It is often assumed that parts of building higher off the ground receive larger earthquake loads. To perform the EQ analysis, it was assumed that the roof load acted at the roof, contributing a large point load to the top of the wall. Additionally, it was assumed that the earthquake load on the wall acted as an inverse triangular load, smallest at the bottom and largest at the top.



Modified Rammed Earth Tire

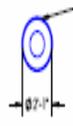


Figure 33: Single story home designed to be built out of modified rammed earth tires with eight foot ceilings

## **Conclusion**

Based on the tests and analysis of R14 and R15 rammed earth tire walls, it is believed that they are capable of providing safe and reliable support in single story homes. Although some of the factors of safety approach a lower limit of 1.5, it should again be noted that the models used in this report are quite conservative and the structures will be capable of withstanding larger forces than are computed within this report. Furthermore, from the Griepentrog report it has been concluded that loads applied to foundation soils suggest that it is acceptable to construct these homes directly on undisturbed soil, assuming specific site based investigation are carried out.

Finally, many of the ABET constraints discussed in the introduction were considered throughout the project. It is believed that these homes offer environmentally sustainable alternatives to standard building practices that may be built more economically than many other standard constructions.

## **Future Work**

The most meaningful future work that could be carried out would be continued testing of walls. Tests of both laterally supported and un-laterally supported walls in both transverse and longitudinal loading would further characterize the strength of these structures. Furthermore, based on the wall testing in this report, fatigue-loading tests on the walls could also yield meaningful results.

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# Appendices

## Appendix A – House Design Analysis Calculations

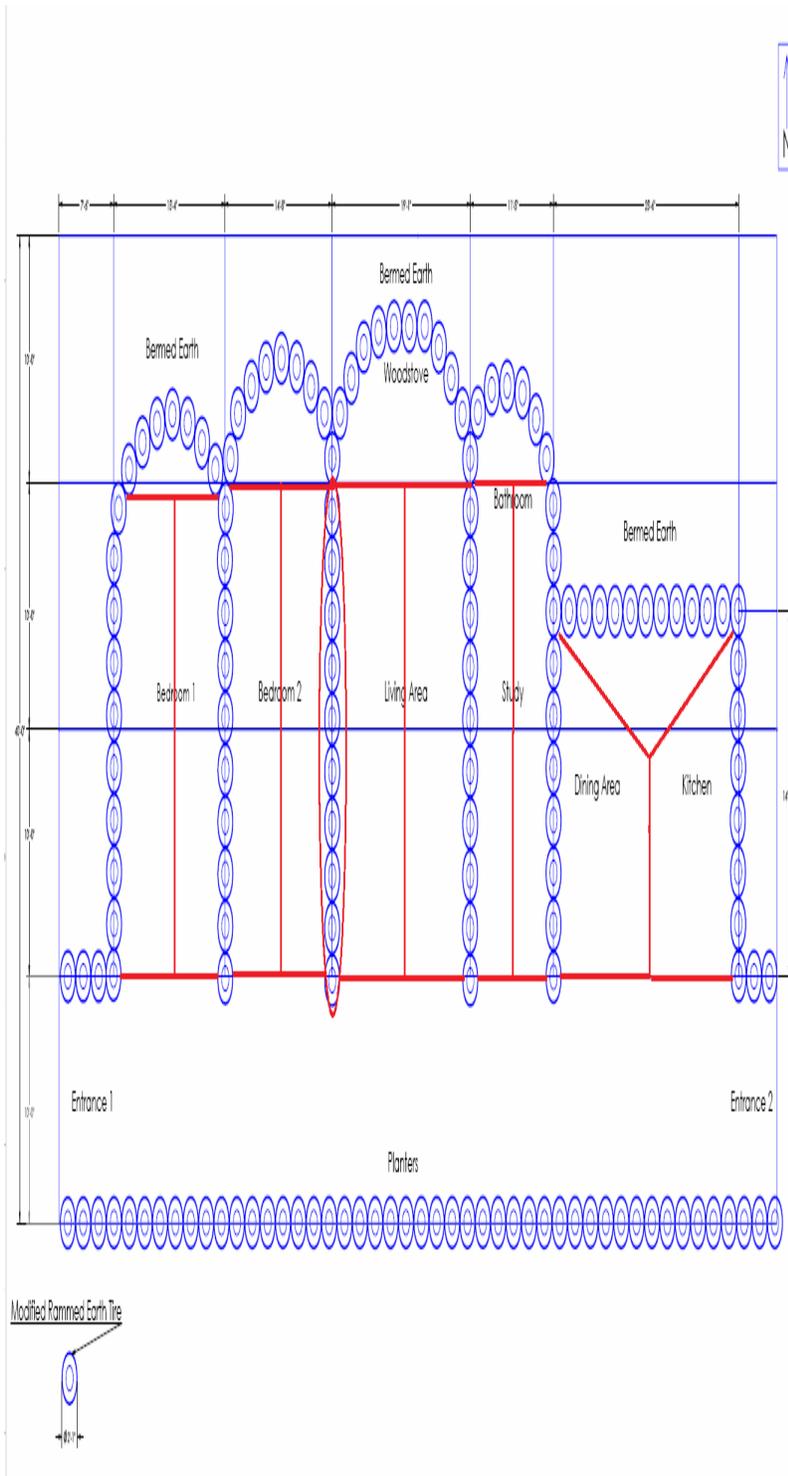
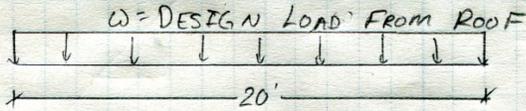


Figure 34: Tributary areas of house. Circled wall is critical wall due to largest tributary area.

# CRITICAL NON-RETAINING WALL



TRIBUTARY AREA:  
 $A_T = 20 \cdot \left( \frac{19+19}{2} + \frac{19+12}{2} \right) \cdot \frac{1}{2}$   
 $= 335 \text{ ft}^2$

SWARTHMORE, PA  
 SNOW LOAD  
 ROOF DEAD LOAD

30 PSF  
 40 PSF

TAOS, NM  
 40 PSF  
 40 PSF

ROOF LIVE LOAD

$L_R = 20 R_1 R_2$       $12 \leq L_v \leq 20$   
 $R_1 = 1.2 - .001 A_T = .865$   
 $R_2 = 1$   
 $L_R = 17.3 \text{ PSF}$

$L_R = 17.3 \text{ PSF}$

SEISMIC ZONE  
 EQ LOAD

2A  
 .15g

2B  
 .2g

W      $(17.3 + 30 + 40)(16.75) = 1462 \text{ lb/ft}$

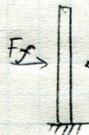
$(17.3 + 40 + 40)(16.75) = 1630 \text{ lb/ft}$

ROOF LOAD      $(1462)(20) = 29240 \text{ lb}$

$(1630)(20) = 32600 \text{ lb}$

EXPECTED WT. OF WALL:  $(20 \cdot \frac{7}{25}) \left( \frac{8 \cdot 7}{12} \right) \cdot 200 = 8960 \text{ lb}$

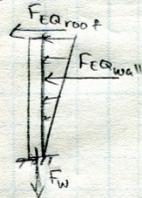
## LATERAL FORCE FROM EQ



$F_{E0} = (29240 + 8960) \cdot .15 = 5730 \text{ lb}$

$(32600 + 8960) \cdot .2 = 8312 \text{ lb}$

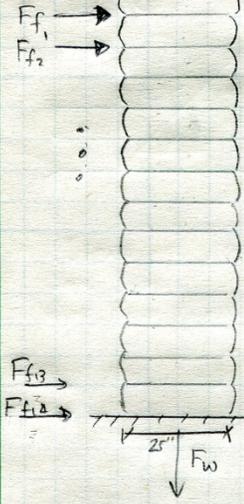
## OVERTURNING MOMENT FROM EQ



$M_{E0} = (29240)(.15)(8) + (8960)(.15)(\frac{2}{3})(8)$   
 $= 42,256 \text{ lb-ft}$

$(32600)(.2)(8) + (8960)(.2)(\frac{2}{3})(8)$   
 $= 61718 \text{ lb-ft}$

LATERAL SUPPORT FROM ROOF  
 → FIXED



SLIDING RESISTANCE TO EQ  
 (CONSERVATIVELY ASSUME R14 TIRES)

$$F_{RES_i} = \text{Min}(F_f + F_{f_i}) \quad \text{for } i=2, \dots, 14$$

CALCULATIONS ARE PER FOOT OF WALL

SWARTHMORE, PA

TAOS, NM

ROOF LOAD 1462 lb

1630 lb

TIRE LOAD 123.1 lb/TIRE

123.1 lb/TIRE

$$F_{RES_2} = (1462 + 123.1)(.545) = 863.9$$

$$(1630 + 123.1)(.545) = 955.4$$

$$F_{RES_{WALL}} = (863.9)(20) = 17278 \text{ lb}$$

$$(955.4)(20) = 19109 \text{ lb}$$

FACTOR OF SAFETY  $\frac{17278}{5730} = \underline{3.01} > 1.5$  OK

$\frac{19109}{8312} = \underline{2.3} > 1.5$  OK

OVERTURNING RESISTANCE TO EQ  
 (AGAIN ASSUME R14 TIRES)

$$M_{RES_i} = M (F_w \cdot \frac{25}{12} + F_{f_i} \cdot (8 - \frac{3.5}{12}))$$

$$F_w \quad F_{f_i} = 1462 + 123.1(14) = 3185.4 \text{ lb}$$

$$1630 + 123.1(14) = 3353.4 \text{ lb}$$

$$M_{RES_{\#1}} = (3185.4)(\frac{25}{12}) + (1462 + 123.1)(.545)(7.417) = 13043 \text{ lb-ft}$$

$$(3353.4)(\frac{25}{12}) + (1630 + 123.1)(.545)(7.417) = 14072 \text{ lb-ft}$$

$$M_{RES_{WALL}} = 13043 \cdot 20 = 260860 \text{ lb-ft}$$

$$14072(20) = 281440 \text{ lb-ft}$$

FACTOR OF SAFETY  $\frac{260860}{42256} = \underline{6.2} > 1.5$  OK

$\frac{281440}{61718} = \underline{4.6} > 1.5$  OK

1723.9

## Appendix B – Soil Moisture Content Data

	Mass of Container (g)	Initial Mass of Soil in Container (g)	Initial Mass of Soil (g)	Final Mass of Soil in Container (g)	Final Mass of Soil (g)	Mass of Evaporated Water (g)	Moisture Content
1	11.24	54.07	42.83	45.28	34.04	8.79	25.8
2	11.09	52.66	41.57	43.78	32.69	8.88	27.2
3	11.44	62.8	51.36	52.51	41.07	10.29	25.15
4	10.91	52.44	41.53	43.52	32.61	8.92	27.4
5	10.9	50.22	39.32	41.53	30.63	8.69	28.4
6	11.08	54.69	43.61	45.51	34.43	9.18	26.7
7	11.12	59.24	48.12	48.52	37.4	10.72	28.7
8	11.14	58.68	47.54	47.81	36.67	10.87	29.6
9	11	52.02	41.02	42.25	31.25	9.77	31.3
10	10.84	57.44	46.6	47.69	36.85	9.75	26.5
11	10.98	54.97	43.99	45.38	34.4	9.59	27.9
12	10.83	52.41	41.58	44.14	33.31	8.27	24.8
13	10.97	53.14	42.17	46.58	35.61	6.56	18.4
14	11.15	47.74	36.59	40.3	29.15	7.44	25.5
15	11.08	66.81	55.73	53.2	42.12	13.61	32.3
16	11.13	52.08	40.95	43.67	32.54	8.41	25.8
17	11.38	54.75	43.37	45.86	34.48	8.89	25.8
18	11.15	53.08	41.93	44.05	32.9	9.03	27.4
19	11.23	60.05	48.82	49.07	37.84	10.98	29.0
20	11.03	53.07	42.04	43.38	32.35	9.69	30.0
21	10.92	57.9	46.98	48.48	37.56	9.42	25.1
22	11.03	52.13	41.1	43.05	32.02	9.08	28.4
23	10.99	59.15	48.16	47.76	36.77	11.39	31.0
24	11.26	61.15	49.89	50.42	39.16	10.73	27.4
25	11.19	53.92	42.73	44.53	33.34	9.39	28.2
26	11.24	62.43	51.19	51.05	39.81	11.38	28.6
27	11.09	59.81	48.72	49.55	38.46	10.26	26.7
28	11.44	52.62	41.18	42.37	30.93	10.25	33.1
29	10.91	71.67	60.76	59.72	48.81	11.95	24.5
30	10.9	58.34	47.44	49.54	38.64	8.8	22.8
31	11.08	55.35	44.27	47.07	35.99	8.28	23.0
32	11.12	52.41	41.29	44.45	33.33	7.96	23.9
33	11.14	58.03	46.89	48.19	37.05	9.84	26.6
34	11	41	30	33.99	22.99	7.01	30.5
35	10.84	61.29	50.45	50.37	39.53	10.92	27.6
36	10.98	53.23	42.25	44.51	33.53	8.72	26.0
37	10.83	56.47	45.64	47.4	36.57	9.07	24.8
38	10.97	53.69	42.72	44.71	33.74	8.98	26.6
39	11.15	56.77	45.62	47.27	36.12	9.5	26.3
40	11.08	54.83	43.75	45.47	34.39	9.36	27.2
41	11.13	55.58	44.45	47.08	35.95	8.5	23.6
42	11.38	56.33	44.95	47.34	35.96	8.99	25.0

43	11.15	55.88	44.73	46.22	35.07	9.66	27.5
44	11.23	59.72	48.49	50.1	38.87	9.62	24.7
45	11.03	43.84	32.81	37.37	26.34	6.47	24.6
46	10.92	50.91	39.99	42.54	31.62	8.37	26.5
47	11.03	50.07	39.04	42.53	31.5	7.54	23.9
48	10.99	48.29	37.3	40.67	29.68	7.62	25.7
49	11.26	57.07	45.81	48.48	37.22	8.59	23.1
50	11.19	50.24	39.05	42.54	31.35	7.7	24.6

**Figure 35: Soil moisture content results**