UCKHORN GEOTECH
Consulting Engineers & Geologists
245 So. Cascade Ave. Montrose, Colo. 81401
(303) 249-6828 FAX (303) 249-2768

# ENGINEERING EVALUATION OF EARTH-FILLED TIRE CONSTRUCTION

## DENNIS WEAVER RESIDENCE

## RIDGWAY, COLORADO

### Introduction

In the same tradition as the thick adobe walls southwestern Indians built centuries ago, the walls of this massive solar home are designed to keep the interior cool during the day by absorbing the sun's rays until nightfall when the energy begins to penetrate the walls and heat the home. Non-traditional, however, is the use of tires to support the adobe walls. These tires are packed with adobe earth and stacked flat in a brick-like manner. A sand, straw, and adobe mix is then used as mortar between the tires and as a plaster to cover the wall surface. The walls serve an ecological purpose by providing a use for otherwise discarded tires and an economic purpose in creating the needed mass for passive solar heating and energy conservation.

## Purpose

The unique building methods and materials have made it necessary to determine the walls' structural integrity. Tests were conducted to determine the tire-to-tire friction, tire-to-earth friction, resistance to failure through sliding, resistance to overturning, and theoretical distribution of soil pressures under a tire wall. All testing was conducted at the building site using actual construction materials and conditions. Two samples of the adobe plaster were also collected and laboratory tested to measure basic strength parameters.

## Testing Procedure

The walls are constructed by placing the tires flat, hand filling with moist earth and packing with a sledge hammer. To determine the lateral stability of the wall, two tests were conducted. First, the tire-to-tire coefficient of friction between packed tires was experimentally determined and secondly, the coefficient of friction between a packed tire and the ground typical of the work site was found. The attached photographs (Appendix A) show how the tire walls are constructed and some of the apparatus used in field testing.

## Tire-to-Tire Testing

A wooden frame pulley and cable apparatus was used for the field testing. The frame served to transfer a known vertical load into a horizontal force on the tire. Two bags of cement whose weight was known to be 94 pounds each and two plastic five-gallon buckets filled with water in one-gallon increments were used to apply the vertical load. The load was gradually increased until movement between the two tires was induced. This experiment was performed on two typical tires, one 14 inches and one 15 inches in diameter. The tires were handled, filled, and compacted using the same methods and procedures as were being used for the actual construction. No mortar or adobe plaster was used between the tires to imitate a worst-case scenario. The coefficients of friction determined from these tests ranged from 0.728 to 0.877 as shown in the following table.

TABLE 1

| Size Tire | Load (Fm) | Weight of Tire (N) | Tire-To-Tire Coef. of Friction (Ms) |
|---|---|---|---|
| 15" | 282.0 lbs. | 350 lbs. | .806 |
| 15" | 254.8 lbs | 350 lbs | .728 |
| 14" | 263.1 lbs | 300 lbs | .877 |
| 14" | 229.7 lbs | 300 lbs | .766 |

## Tire-to-Earth Testing

A hand winch and spring scale were used to measure the horizontal force necessary to initially move two different 14-inch tires. The tires were filled and compacted in a typical manner on a level area of soil that was similar in composition and consistency to the foundation soil at the residence. The winch was then used to exert a measured horizontal force on the tire until movement occurred.

The coefficients of friction determined from the two tests were 0.485 and 0.651. These coefficients are significantly less than those measured in the tire-to-tire tests. This shows that it is the properties of the underlying earth rather than the properties of the tire that govern the tire-to-earth frictional resistance to sliding at the Weaver site. The following table shows typical values for coefficients of friction between various dry surfaces. The tire-to-tire and tire-to-earth coefficients of friction determined in these field tests appear to be reasonable in comparison with these typical values.

TABLE 2

Approximate Values of Coefficient of Static Friction for Dry Surfaces for Comparison*

| | |
|---|---|
| Metal on Metal | .15 - .60 |
| Metal on Wood | .20 - .60 |
| Metal on Stone | .30 - .70 |
| Wood on Wood | .25 - .50 |
| Stone on Stone | .40 - .70 |
| Earth on Earth | .20 - 1.0 |
| Rubber on Concrete | .60 - .90 |

*Vector Mechanics for Engineers, 5th Edition, F.P. Beer, E.R. Johnston, Jr., McGraw-Hill Book Co., 1988.

## Tire Weighing Procedure

Both a 14-inch diameter and a 15-inch diameter tire were filled and compacted using the typical methods and procedures of construction. The tires were then weighed one at a time via two 200-pound spring scales set in parallel. The 14-inch diameter tire was found to weigh 241 pounds while the 15-inch tire weighed 378 pounds.

## Sources of Error

Any error inherent in the spring scales would have created error in both experiments. However, the scales were tested against the known weights of the cement sacks and were found to be within 3 pounds. It is therefore concluded that the scales were of sufficient accuracy for the intent of the experiment. The weight of the hand winch and scales was estimated at 5 pounds. This amount was added to the load applied during each experiment as compensation for the apparatus.

Small errors may have been introduced by friction in the pulley, weight of the stand, force from pouring the water in the five-gallon buckets, and small inaccuracies in measuring the water and cement bags. These possible errors are considered irrelevant in view of the inherent variability of the construction method. That is, irregularities in the tires and inadvertent sand or dust between the tires would cause larger variation in friction values then would errors resulting from the testing procedures. No attempt was made to quantify these possible variations. Since the tires were "constructed" using the same procedures and methods as employed in construction of the Weaver home, it is felt that results of the tests are representative.

## Stability Calculations

After the weights and frictional properties of the tires had been determined, two sets of calculations were made to evaluate the stability of a tire wall. These calculations are attached hereto as an appendix. The first set analyzed a free standing wall constructed of earth-filled tires stacked in overlapping tiers, like bricks. The wall was assumed to retain an earth bank on one side but no lateral bracing was provided on the other side. The second set looked at a similar wall with the addition of lateral bracing at the top, such as would be derived from a roof system, and vertical bracing at each end of the wall, as would be provided through an intersecting wall or a wall return.

The first set of calculations quantified the basic properties of a tire stacked wall in its simplest form. While walls of this type are not used in the Weaver house, the analysis has merit for several reasons. It provides a basis of comparison for understanding the method of analysis, it emphasizes the advantages of lateral bracing and the inherent weaknesses of the free standing wall, and it provides a quantification of the soil bearing pressures beneath the wall that are also applicable to the laterally braced wall system.

The second set of calculations is based on a wall system braced horizontally at the top and vertically at the ends. This represents the conditions at the Weaver house.

Prior to making the stability calculations, the effective width of the tires was determined. This entailed reducing the tire diameter to allow for tread wear and side taper, and then subtracting the fillets between adjoining tires. The net result was a simulated square tire with a width of 18.85 inches for 14-inch tires and 20.42 for 15-inch tires. The weights of the tires were also adjusted to a value expressed in pounds per foot of height per linear foot of wall. The adjusted weight of a 14-inch tire was found to be 123.9 pounds/foot of height/linear foot and the 15-inch tire was 181.4.

Free Standing Tire Wall

Two mathematical models of a free-standing tire wall retaining earth on one side have been established. The models represent equilibrium between active earth pressures behind the wall which act to cause the wall to overturn or slide, and the forces of gravity and friction which cause the wall to resist the sliding and overturning forces. The results of the calculations are shown as curves in Figure 1. The curves represent the amount of lateral earth pressure, expressed as a fluid equivalent, that will just cause a wall of the corresponding height to overturn or slide. It was found that walls under 5-feet high made of 14-inch tires will fail by sliding while walls over 5-feet in height are more apt to overturn. Walls made with 15-inch tires hold the same relationship but the crossover height is about 6 feet. The lateral earth pressures developed by soil can be determined by a soils testing laboratory. They can vary considerably with a general range of 25 to 30 pounds per cubic foot (pcf) for coarse sand and gravel to over 75 pcf for soft silts and clays. The curves of Figure 1 show that a 14-inch tire wall would generally be suitable for a height of up to 4 feet while a wall constructed with 15-inch tires may be stable to a height of 6 feet.

The weight of a tire wall and the overturning moment imparted to the wall by lateral earth pressures create a load on the soil beneath the wall. These soil bearing pressures have been calculated for a free standing wall and are shown in Figure 2. Two curves are shown for both 14-inch and 15-inch tires. They represent the maximum pressure under the outside edge or toe of the tire wall and the average pressure under the wall. Both curves assume that the lateral earth pressures are at a maximum for the various wall heights shown. Therefore, they represent the upper range of values to be expected under stable walls. The safe bearing pressure of a soil can be established through field and laboratory testing. At the Weaver house, the safe bearing pressure is over 2500 pounds per square foot (psf). However, it can vary in the Ridgway area from as little as 500 psf for soft silts and clays to as high as 5000 psf for gravels and dense soil mixtures.

## Laterally Restrained Tire Walls

The mathematical models developed for the free standing walls were modified to incorporate the additional resistance to sliding and overturning afforded due to lateral bracing. The Weaver house has horizontal lateral bracing from the roof system and vertical bracing from the wall curve at the back of the U-shaped cells and the wall return at the corners of the two outermost walls at the open ends of the U's. This lateral bracing is transferred through the tire wall via the tire-to-tire friction developed through the overlapping tiers of tires. That is, in order for the wall to fail, movement must occur at each tire between the area of lateral bracing and the point of failure. Therefore, the frictional forces along each of those planes of movement must be overcome. This adds dramatically to the strength of the wall as shown in Figure 3. It can be seen from the curves of Figure 3 that the laterally braced walls of the Weaver house will not slide or overturn.

Although both 14-inch and 15-inch laterally restrained walls are more likely to slide than overturn, it would take lateral pressures in excess of 80 pcf to move a 14-inch tire wall and pressures of over 120 pcf to cause failure of a 15-inch tire wall. The active earth pressures at the Weaver site are expected to be in the 30 to 40 pcf range.

As stated earlier, the soil bearing pressures developed for the free standing tire wall are considered representative for the laterally restrained wall system. The only difference is that the roof contributes an additional axial load to the wall which causes an increase in the soil bearing pressures. At the Weaver house, the full live and dead load to be added would vary from 353 pounds per linear foot of wall for a 10-foot wide cell to 635 pounds per linear foot for an 18-foot wide cell. These loads added to the loads applied through the tire wall are well within the safe bearing pressure of the soils at the Weaver site.

## Adobe Plaster

The final analysis conducted at the Weaver house was the sampling and testing of the adobe plaster which was being used to fill the gaps in the tire wall. This plaster consisted of a mixture of native soil (sifted through 1/4" hardware cloth), an equal amount of sand, and about 2 handfuls of straw per wheel barrow load. The dry adobe was found to have a cohesive strength of over 2000 psf. However, the cohesion of the saturated plaster was only about 150 psf. When dry, the plaster can increase the strength of the tire walls by adding up to 21% to the effective tire width. However, should the adobe become wet, the plaster will probably fail under its own weight and all of its strength benefits will be lot. It is recommended, therefore, that no structural strength be assigned to the adobe plaster.

## CONCLUSIONS

Based on the tests conducted for this analysis and the calculations performed, it is felt that the rammed earth-filled tire walls used in construction of the Dennis Weaver residence near Ridgway, Colorado, will provide safe and dependable support for the structure. The laterally braced walls have sufficient strength from their massive structure and internal tire-to-tire friction to resist the sliding and overturning pressures imparted to the walls from the outside. Additionally, the loads applied to the foundation soils have been found to be well within the estimated safe bearing capacity of the undisturbed soil at the site.

Respectfully submitted,

April 30, 1990

Thomas E. Griepentrog

Thomas E. Griepentrog, P.E.

TEG:dc

# APPENDIX A

BUCKHORN GEOTECH
Consulting Engineers & Geologists
245 So. Cascade Ave. Montrose, Colo. 81401 303-249-6828

NAME ALLISON CONSTRUCTION
PROJECT WEAVER TIRE HOUSE
JOB #
DATE 4/28/90



EFFECTIVE TIRE WIDE

OVERALL RADIUS

14" TIRE = 14"

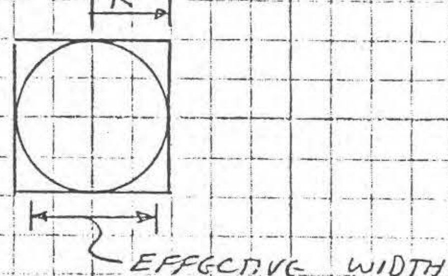
15" TIRE = 15"

EFFECTIVE RADIUS - REDUCE ACTUAL BY 2" AS COMPENSATION FOR TREAD WEAR & TAPER

14" TIRE = 14 - 2" = 12" RADIUS

15" TIRE = 15 - 2" = 13" RADIUS

FILLET CORRECTION




AREA OF SQUARE

14" TIRE

A = 12 x 12 = 144 $in^2$

15" TIRE

A = 13 x 13 = 169

AREA OF QUARTER CIRCLE = $\frac{1}{4}\pi r^2$

14" TIRE $A = \frac{\pi \cdot 12^2}{4} = 113.10$

15" TIRE $A = \frac{\pi \cdot 13^2}{4} = 132.73$

% REDUCTION = $\frac{144 - 113.10}{144}$ = 21.46% BOTH 14" & 15" TIRES

EFFECTIVE WIDTH OF TIRE WALL

14" TIRE = 2 x 12 - 0.2146 x 24 = 18.85"

15" TIRE = 2 x 13 - 0.2146 x 26 = 20.42"

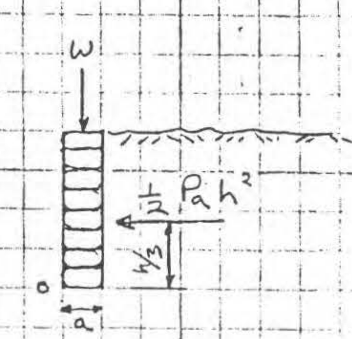
BUCKHORN GEOTECH
Consulting Engineers & Geologists
245 So. Cascade Ave. Montrose, Colo. 81401 303-249-6828

NAME ALLISON CONSTRUCTION
PROJECT WEAVER TIRE HOUSE
JOB #
DATE 4/28/90



FREE-STANDING TIRE WALL RETAINING EARTH

RESISTANCE TO OVERTURNING




$$\Sigma M_o = \frac{1}{2} P_a h^2 \cdot \frac{h}{3} - wh \cdot \frac{a}{2} = 0$$

where $P_a$ = ACTIVE EARTH PRESSURE (FLUID)
$h$ = WALL HEIGHT
$a$ = EFFECTIVE WALL WIDTH
$w$ = WEIGHT OF TIRE / L.F. / FT of HT.

SOLVE IN TERMS OF $P_a$

$$P_a \cdot \frac{h^3}{6} = \frac{w h a}{2}$$

$$P_a = \frac{3 w a}{h^2}$$

14" TIRE

$w = 241 \times \frac{12}{10} = 289.2$ Lbs / FT of HT / TIRE WIDTH

$WT / L.F. = \frac{289.2 \times 12}{28} = 123.9$ Lbs / FT of HT / L.F.

$a = 18.85'' = 1.57'$

15" TIRE

$w = 378 \times \frac{12}{10} = \frac{453.6 \times 12}{30} = 181.4$ Lbs / FT of HT / L.F.

$a = 20.42'' = 1.70'$

| 14" TIRE | |
|---|---|
| h | $P_a$ |
| 4' | 36.5 |
| 5' | 23.3 |
| 6' | 16.2 |
| 7' | 11.9 |
| 8' | 9.1 |
| 9' | 7.2 |
| 10' | 5.8 |
| 11' | 4.8 |
| 12' | 4.1 |
| 13' | 3.5 |
| 14' | 3.0 |

| 15" TIRE | |
|---|---|
| h | $P_a$ |
| 4' | 57.8 |
| 5' | 37.0 |
| 6' | 25.7 |
| 7' | 18.9 |
| 8' | 14.5 |
| 9' | 11.4 |
| 10' | 9.3 |
| 11' | 7.6 |
| 12' | 6.4 |
| 13' | 5.4 |
| 14' | 4.7 |

BUCKHORN GEOTECH
Consulting Engineers & Geologists
245 So. Cascade Ave. Montrose, Colo. 81401 303-249-6828

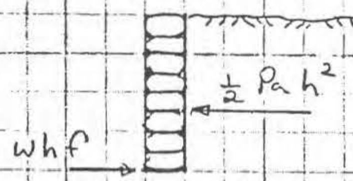
NAME ALLISON CONSTRUCTION
PROJECT WEAVER TIRE HOUSE
JOB #
DATE 4/28/90



FREE STANDING TIRE WALL RETAINING EARTH

RESISTANCE TO SLIDING

TIRE TO EARTH COEF. of FRICTION = 0.485




$$\frac{1}{2} P_a h^2 = whf$$

$$P_a = \frac{2wf}{h}$$

WHERE:

$w$ = TIRE WT IN LBS/FT of HT/L.F.
$h$ = HEIGHT OF WALL
$f$ = COEF. of FRICTION

| 14" TIRE | |
|---|---|
| $h$ | $P_a$ |
| 4' | 30.0 |
| 5' | 24.0 |
| 6' | 20.0 |
| 7' | 17.2 |
| 8' | 15.0 |
| 9' | 13.4 |
| 10' | 12.0 |
| 11' | 10.9 |
| 12' | 10.2 |
| 13' | 9.2 |
| 14' | 8.6 |

| 15" TIRE | |
|---|---|
| $h$ | $P_a$ |
| 4' | 44.0 |
| 5' | 35.2 |
| 6' | 29.3 |
| 7' | 25.1 |
| 8' | 22.0 |
| 9' | 19.6 |
| 10' | 17.6 |
| 11' | 16.0 |
| 12' | 14.7 |
| 13' | 13.5 |
| 14' | 12.6 |

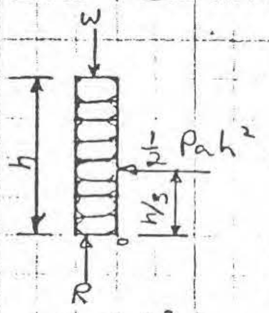
BUCKHORN GEOTECH
Consulting Engineers & Geologists
245 So. Cascade Ave. Montrose, Colo. 81401 303-249-6828

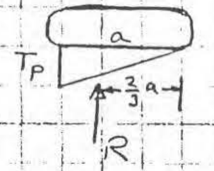
NAME ALLISON CONSTRUCTION
PROJECT WEAVER TIRE HOUSE
JOB #
DATE 4/28/90



# FREE STANDING TIRE WALL RETAINING EARTH

## SOIL BEARING PRESSURES




$R = \frac{1}{2} T_P \cdot a$

$$\Sigma M_o = \frac{1}{2} P_a h^2 \cdot \frac{h}{3} + Wh \cdot \frac{a}{2} - R \cdot \frac{2}{3} a = 0$$

$$T_P = \frac{h}{2a}\left(\frac{P_a h^2}{a} + 3W\right) \quad \text{OR} \quad T_P = \frac{P_a h^3}{2a^2} + \frac{3Wh}{2a}$$

where

- $T_P$ = MAX TOE PRESSURE
- $a$ = EFFECTIVE TIRE WIDTH
- $W$ = TIRE WT IN LBS/FT of HT/L.F.
- $h$ = HEIGHT OF WALL

$$\text{AVERAGE SOIL PRESSURE} = \frac{MAX}{2} = \frac{T_P}{2}$$

14" TIRE

| h | $P_a$ | $T_P$ | $P_{AVE}$ |
|---|---|---|---|
| 4' | 36.5 | 947 | 474 |
| 6' | 16.2 | 1420 | 710 |
| 8' | 9.1 | 1892 | 946 |
| 10' | 5.8 | 2360 | 1180 |
| 12' | 4.1 | 2858 | 1429 |
| 14' | 3.0 | 3327 | 1664 |

15" TIRE

| h | $P_a$ | $T_P$ | $P_{AVE}$ |
|---|---|---|---|
| 4' | 57.8 | 1280 | 640 |
| 6' | 25.7 | 1920 | 960 |
| 8' | 14.5 | 2565 | 1282 |
| 10' | 9.3 | 3210 | 1605 |
| 12' | 6.4 | 3834 | 1917 |
| 14' | 4.7 | 4472 | 2236 |

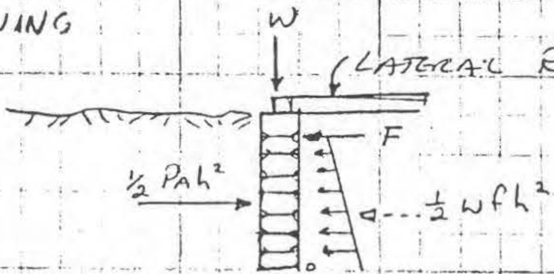
BUCKHORN GEOTECH
Consulting Engineers & Geologists
245 So. Cascade Ave. Montrose, Colo. 81401 303-249-6828

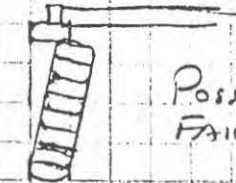
NAME ALLISON CONSTRUCTION
PROJECT WEAVER TIRE HOUSE
JOB #
DATE 4/28/90



WALL W/ LATERAL RESTRAINT AT TOP & WALL ENDS

OVERTURNING




TO FAIL, TIRE AT TOP MUST SLIDE INWARDS AND INTERLOCKING TIRES ON LOWER TIERS MUST SLIDE TOWARD POINT OF FAILURE

$$\Sigma M_o = \tfrac{1}{2} P_A h^2 \cdot \tfrac{h}{3} - wha/2 + \tfrac{1}{2} wfh^2 \cdot \tfrac{h}{3} = 0$$

$$P_A = \frac{3wa}{h^2} + wf$$

where
w = wt of TIRE / FT of HT / L.F.
a = Effective width
f = Coef. of Friction, Tire to Tire
h = Ht of WALL

| 14" TIRES | |
|---|---|
| h | Pa |
| 4 | 126.7 |
| 6 | 106.4 |
| 8 | 99.3 |
| 10 | 96.0 |
| 12 | 94.3 |
| 14 | 93.2 |

| 15" TIRES | |
|---|---|
| h | Pa |
| 4 | 189.9 |
| 6 | 157.8 |
| 8 | 146.5 |
| 10 | 141.3 |
| 12 | 138.5 |
| 14 | 136.8 |

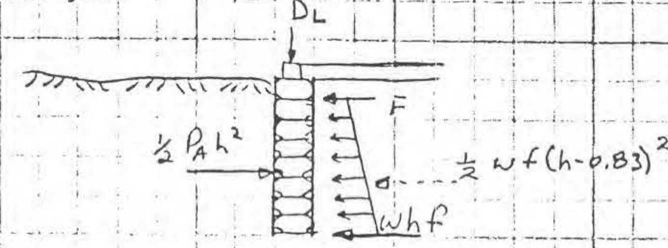
BUCKHORN GEOTECH
Consulting Engineers & Geologists
245 So. Cascade Ave. Montrose, Colo. 81401 303-249-6828

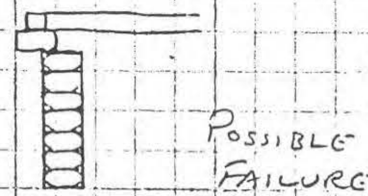
NAME ALLISON CONSTRUCTION
PROJECT WEAVER TIRE HOUSE
JOB # ______ DATE 4/23/90



WALL W/LATERAL CONSTRAINT AT TOP & WALL ENDS

SLIDING




TO FAIL, TIRE AT BOTTOM MUST SLIDE INWARDS AND INTERLOCKING TIRES, IN UPPER TIERS MUST SLIDE TOWARDS POINT OF FAILURE

$$\tfrac{1}{2} P_A h^2 - whf_{T/G} - \tfrac{1}{2} wf_{T/T} (h-0.83)^2$$

$$P_A = \frac{0.97\,w}{h} + \frac{0.728\,w\,(h-0.83)^2}{h^2}$$

where $h$ = wall height
$w$ = wt of tire/FT of ht/L.F

| 14" TIRE | |
|---|---|
| h | Pa |
| 4 | 86.7 |
| 6 | 87.0 |
| 8 | 87.5 |
| 10 | 87.9 |
| 12 | 88.2 |
| 14 | 88.4 |

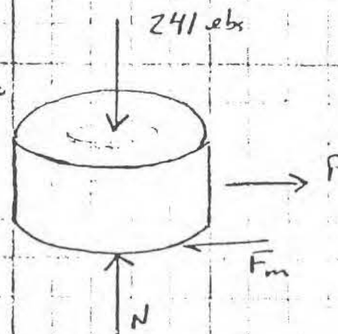
| 15" TIRE | |
|---|---|
| h | Pa |
| 4 | 126.9 |
| 6 | 127.4 |
| 8 | 128.1 |
| 10 | 128.6 |
| 12 | 129.1 |
| 14 | 129.4 |

BUCKHORN GEOTECH
Consulting Engineers & Geologists
245 So. Cascade Ave. Montrose, Colo. 81401 303-249-6828

NAME
PROJECT
JOB # DATE

# Tire to Earth Friction Test Calculations

14" Tire




Σ Vertical Forces $N = 241^{\#}$

Σ Horiz Forces $P = F_m$

Assume: weight of winch, scale and cable is 5 l

## 14" Tire

Test I

$F_m = P = 112 + 5 = 117$ lbs

$\mu_s = \frac{F_m}{N} = \frac{117}{241} = .485$

Test II

$F_m = P = 152 + 5 = 157$

$\mu_s = \frac{F_m}{N} = \frac{157}{241} = .651$

## Conclusions

| Size Tire | load ($F_m$) | Weight of Tire (N) | Tire to Earth Coef of Friction |
|---|---|---|---|
| 14" | 117# | 241# | .485 |
| 15" | 157# | 241# | .651 |

**BUCKHORN GEOTECH**

Consulting Engineers & Geologists

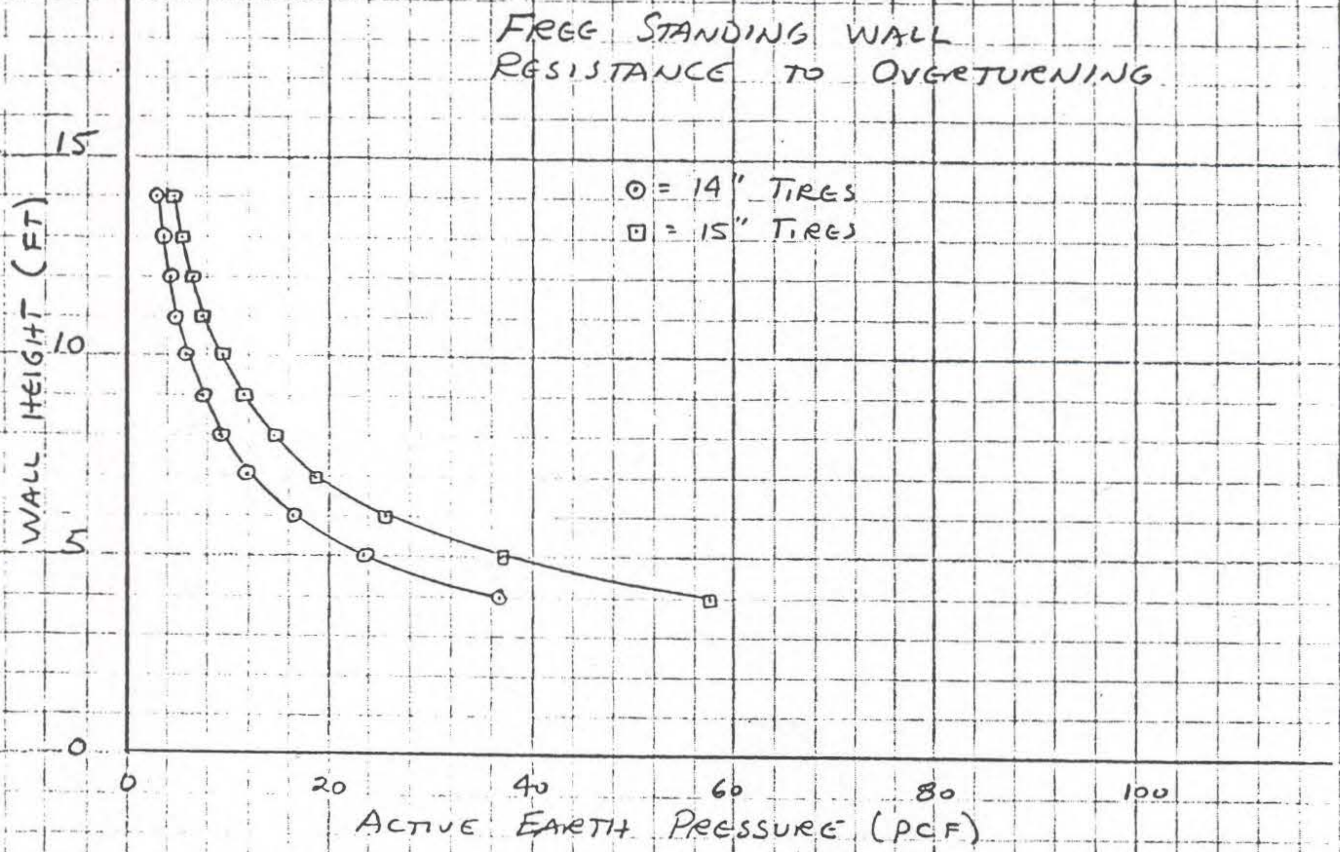
245 So. Cascade Ave. Montrose, Colo. 81401 303-249-6828

NAME ALLISON CONSTRUCTION

PROJECT WEAVER TIRE HOUSE

JOB # ______ DATE 4/28/90

7/



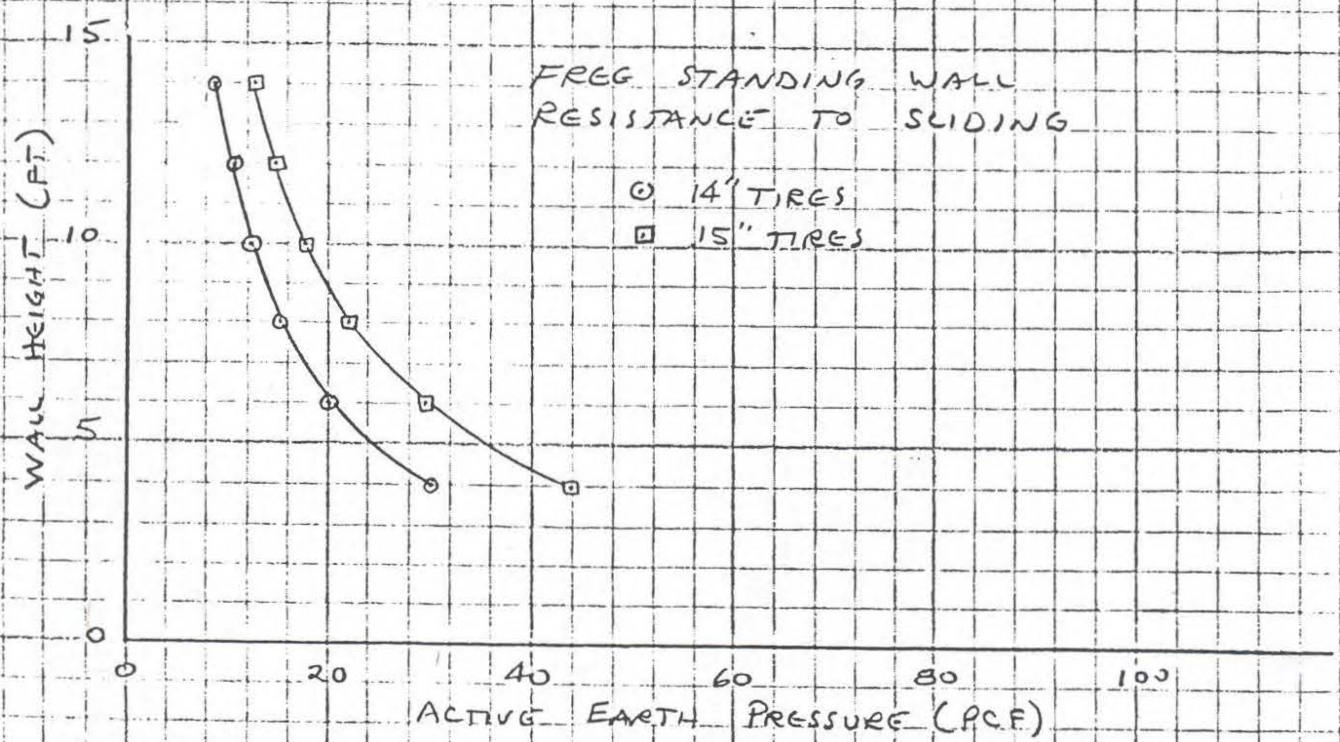




FIGURE 1.

**BUCKHORN GEOTECH**

**Consulting Engineers & Geologists**

245 So. Cascade Ave. Montrose, Colo. 81401 303-249-6828

NAME ALLISON CONSTRUCTION

PROJECT WEAVER TIRE HOUSE

JOB # ________ DATE 4/28/90

8/

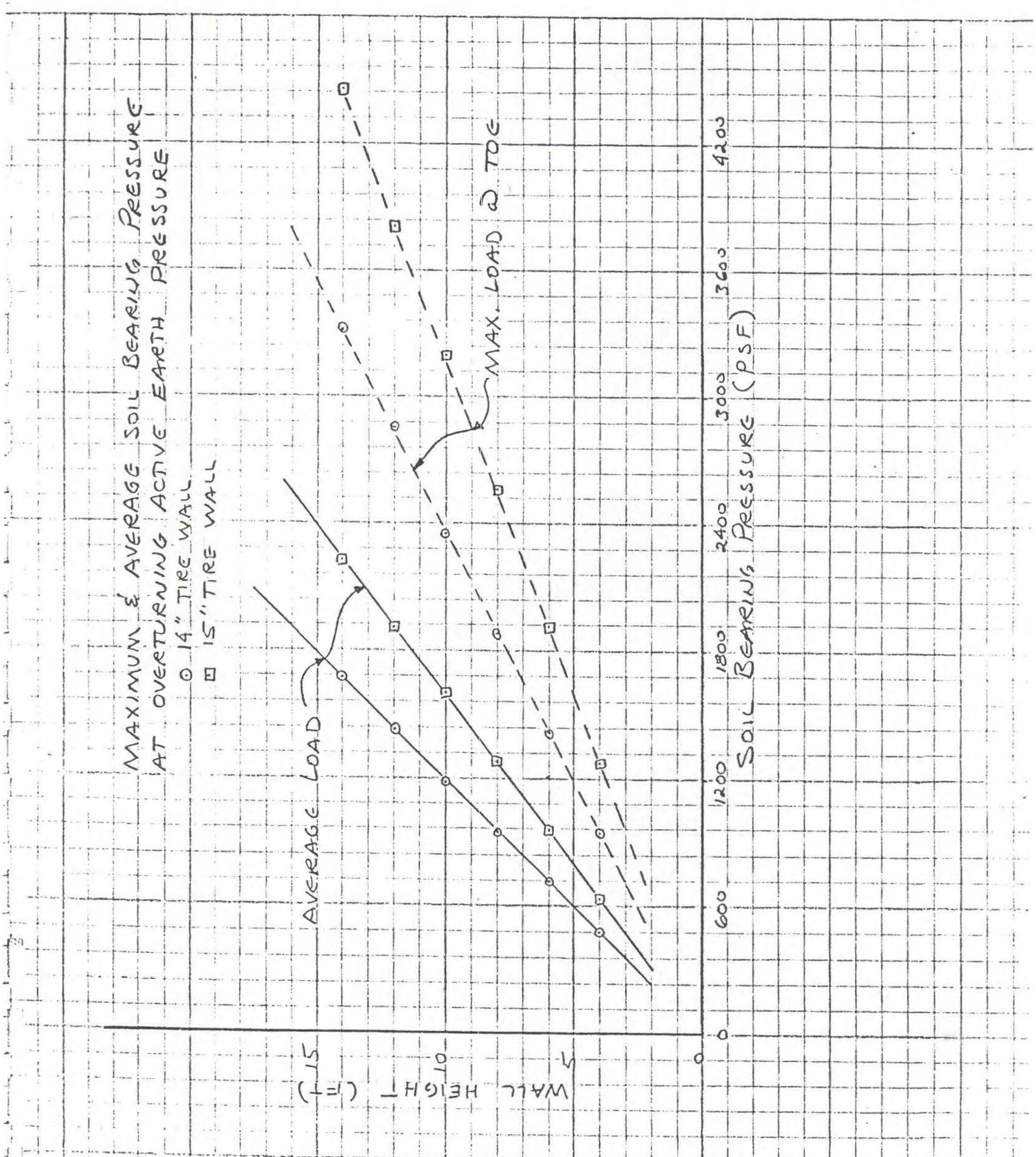



FIGURE 2

**BUCKHORN GEOTECH**

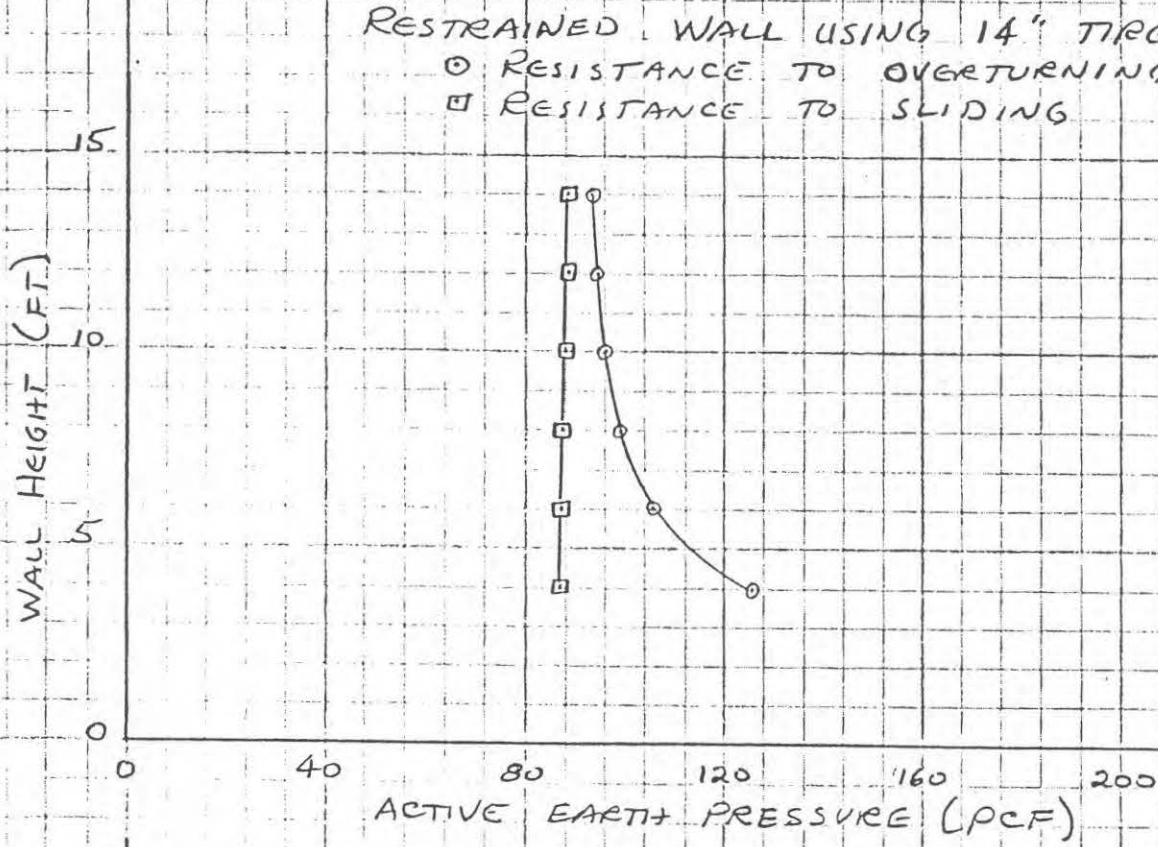
Consulting Engineers & Geologists

245 So. Cascade Ave. Montrose, Colo. 81401 303-249-6828

NAME ALLISON CONSTRUCTION

PROJECT WEAVER TIRE HOUSE

JOB # DATE 4/28/90



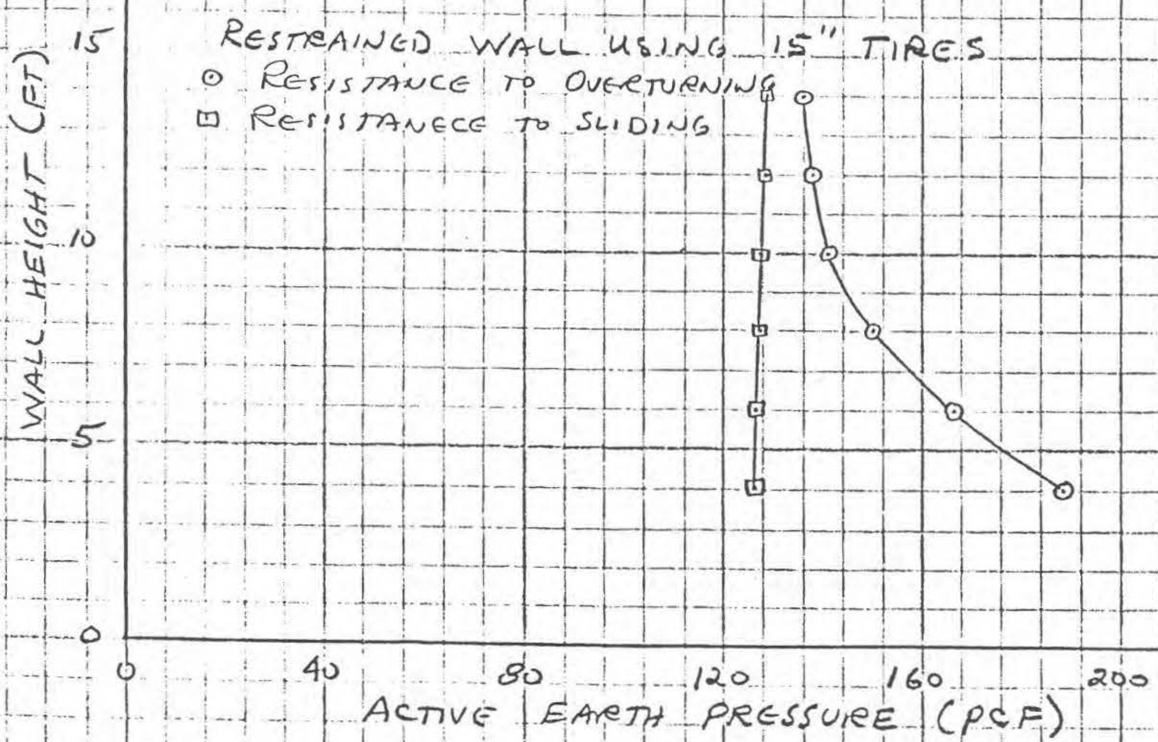
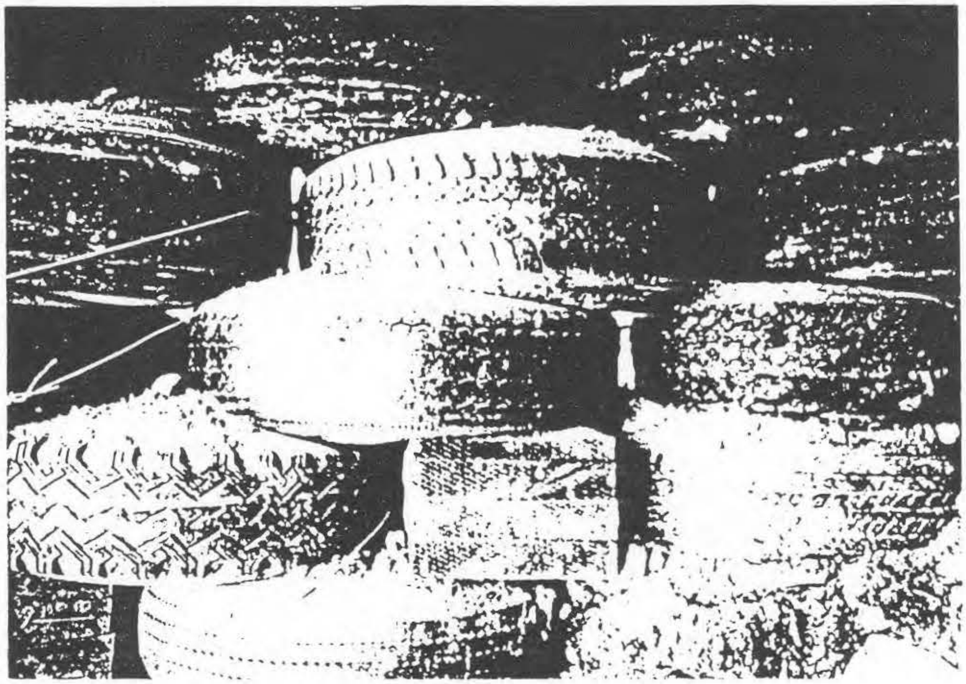
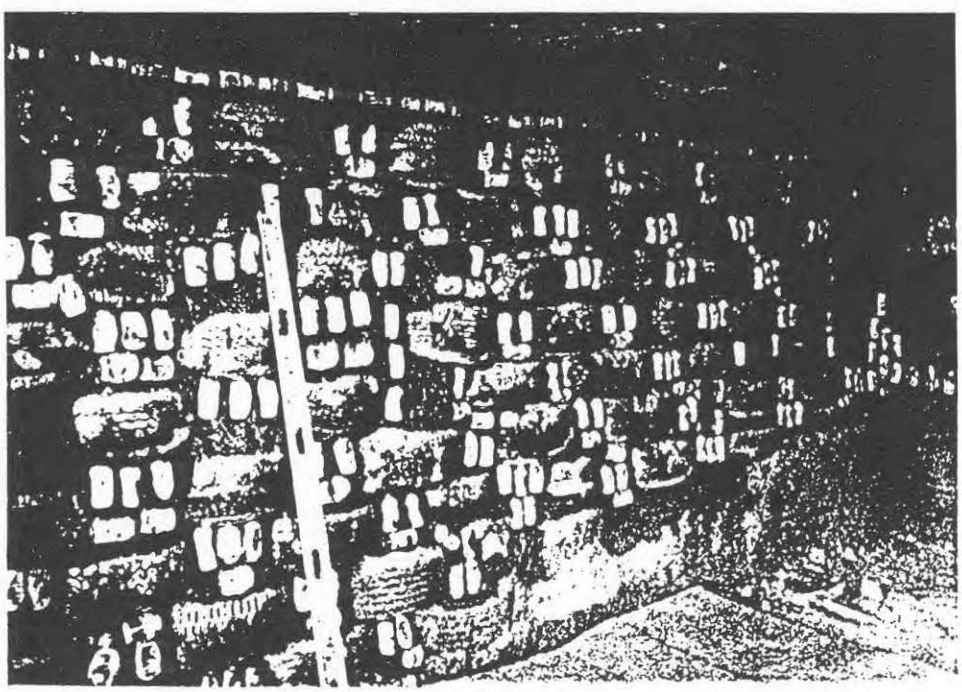




FIGURE 3

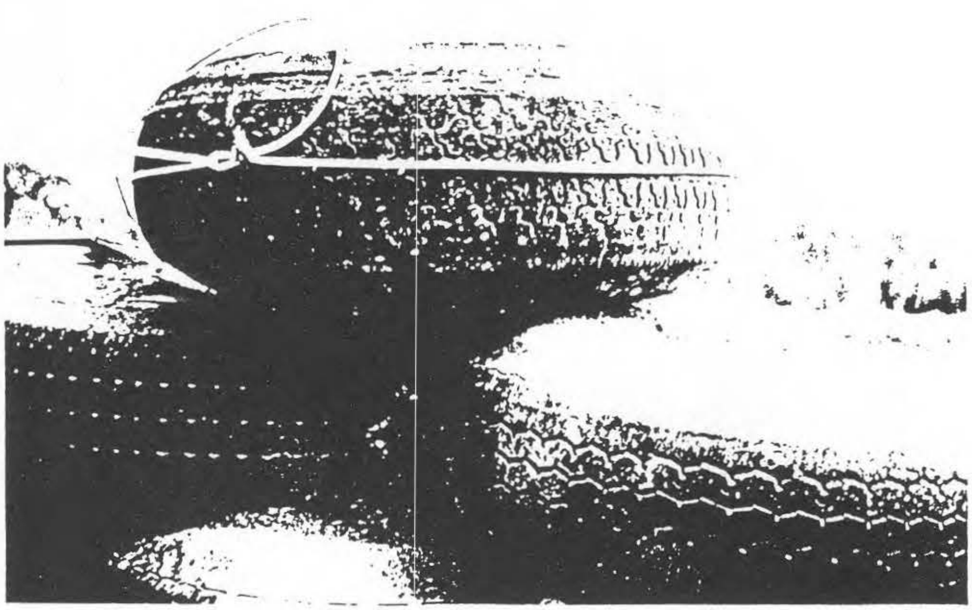


Typical Completed Wall.



Typical Wall Before Mortar Application.

Frame With Weights.



Close-up of Tire Being Tested.