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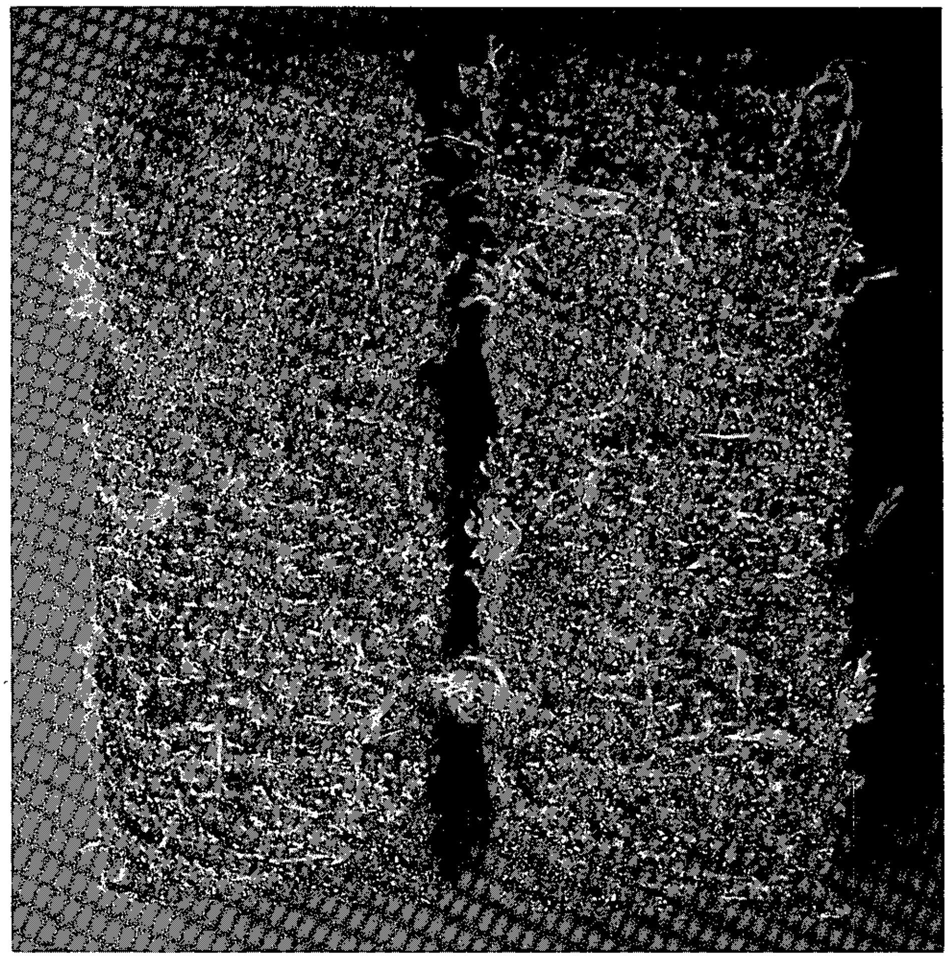
YARN REINFORCED SOIL

FINAL REPORT #FHWA/CA/TL-91/07
CALTRANS STUDY #F87TL19



STATE OF CALIFORNIA

DEPARTMENT OF TRANSPORTATION
DIVISION OF NEW TECHNOLOGY,
MATERIALS AND RESEARCH

YARN REINFORCED SOIL

FINAL REPORT

FINAL REPORT # FHWA/CA/TL-91/07

CALTRANS STUDY #F87TL19

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TECHNICAL REPORT STANDARD TITLE PAGE

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CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quality	English Unit	Mutiply By	To get Metric Equivalent
Length	inches (in) or (")	25.40	millimetres (mm)
		.02540	metres (m)
	feet (ft) or (')	.3048	meters (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2)	6.432×10^{-4}	square metres (m^2)
	square feet (ft^2)	.09290	square metres (m^2)
	acres	.4047	hectares (ha)
Volume	gallons (gal)	3.785	litre (1)
	cubic feet (ft^3)	.02832	cubic metres (m^3)
	cubic yards (yd^3)	.7646	cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s)	28.317	litres per second (l/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph)	.4470	metres per second (m/s)
	feet per second (ft/s^2)	.3048	metres per second (m/s)
Acceleration	miles per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity (G)	9.807	metres per second squared (m/s^2)
Density	(lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lb)	4.448	newtons (N)
	kips (1000 lb)	4448	newtons (N)
Thermal Energy	British thermal unit (Btu)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb)	1.356	joules (J)
	foot-kips (ft-k)	1356	joules (J)
Bending Moment or Torque	inch-pounds (in-lb)	.1130	newton-metres (Nm)
	foot-pounds (ft-lb)	1.356	newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (°F)	$\frac{°F - 32}{1.8} = °C$	degrees celsius (°C)
Concentration	parts per million (ppm)	1	milligrams per killogram (mg/kg)

NOTICE

The contents of this report reflect the views of the Division of New Technology, Materials and Research which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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DISCLAIMER NOTICE

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Test Fibers were provided by:

John Minor, Western Regional Manager, Phillips Fiber Corp.; Bob Klyne, Market Development Engineer, Phillips Fiber Corp.; Bill Martin, Market Development Manager, Hercules Inc.; Diana Robertson, Marketing Manager, Hoechst/Celanese Corp.

This was a unique research project. It required considerable mechanical engineering in development of the test hardware and modification of the existing compaction machine. During the course of the research project the modifications included: revising the tamper weight from 10 to 40 pounds, installing safety features, designing a 6-inch steel mold which holds a special PVC liner and revising the existing controller system from micro-switches to a solid-state system.

Also, during the course of this research, special yarn feeding equipment (yarn rack to hold the spools of yarn, a yarn feed system to distribute the yarn and yarn mixing chamber) was designed to uniformly feed yarn into the soil sample. This special equipment was fabricated by the Machine Shop Staff under the direction of Mr. Gene Weyel.

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1. INTRODUCTION

Project Overview

There are numerous locations on the California highway system where surface stability is a problem. Many roadways in mountainous areas have cuts and fills of decomposed granite or other granular noncohesive soils. The granular soils have two types of problems associated with their lack of fine cohesive soil particles.

The first type of problem is instability when cut slopes intrude into the drainage paths used by the existing groundwater. Seepage pressures increase to the point where the remaining cover soil cannot resist the pressures and a slide or slump of soil occurs.

Normally construction occurs during the summer low groundwater season, so the instability does not become apparent until after construction. Even if the instability is apparent during construction, few suitable correction schemes exist. The solutions to this problem have been horizontal drains or stabilization trenches, as slope flattening is normally not practical due to the steep terrain.

The second problem is that of high erodibility. Granular soils are easily eroded, because they have little or no cohesive attraction. Normal slope angles generate highly erosive water velocities for non-cohesive soils. Typically, attempts to provide cohesion by some type of binding together of soil particles decrease the soil permeability. Lower permeability results in higher pore pressures, thus, resulting in rapid saturation flows and mud slides.

The establishment of vegetation to bind the surface particles together is very difficult. These soils are deficient in nutrient value and susceptible to leaching during rainy periods. The yarn reinforcing concept should allow surface stabilization without significantly altering permeability.

In 1987, the FHWA approved a proposal to study the feasibility of combining yarn with soil in order to obtain a less erodible psuedocohesive material that could be utilized to buttress steep highly erodible highway cuts and fills. The inception of this concept occurred in Europe. The yarn reinforced soil concept is similar to work done by LeFlaiv at the French Government's Highway and Bridges Laboratory in France. The theory is similar to the central theme of the French "TEXOL" system.

Most natural soil has either high internal friction or high cohesion, but not both. A high friction - high cohesion material is a new concept in soil mechanics. It appears to permit relatively high embankments with steep faces. Additionally the slope faces have low surface erodibility due to the exposed threads which shield the surface. This technology can be used to construct steep slopes where flatter ones require excessive right-of-way or are too expensive to construct.

Granular soils, such as sands and decomposed granitics, are highly erodible, normally exhibit minimal, if any, cohesion and require long slopes flatter than 1.5 to 1. The addition of cohesive soils to provide greater stability and reduce erodibility provides lower permeabilities and destabilizing of the slopes from excess pore pressures or seepage pressures behind the less permeable layer. A granular soil stabilized with approximately 0.2% yarn fibers will permit building steeper, less erodible slopes while maintaining high permeabilities.

The cost of building these buttresses should average between $70 and $100 per cubic yard. This may seem excessive. However, considering the cost of laying back the slopes, extra right-of-way, ditches, stabilization trenches, highway cleanup and horizontal drains, this becomes a potentially viable solution.

To investigate the potential of high friction - high cohesion soils, research was planned in three phases.

First - Develop laboratory capabilities to test and compare samples of yarn and soil mixtures in 6 x 14 inch samples and perform triaxial compression testing of the samples to determine the materials' apparent cohesion and internal friction values.

Second - Develop a laboratory evaluation of yarn soil samples' resistance to erosion by rain, simulated by exposure in the laboratory rainfall generation facility.

Third - Construct test embankments and/or buttresses at several sites throughout the state.

This project was to address only the first phase.

Objective

The objective of this research was to provide a laboratory evaluation of a new concept "Yarn Reinforced Soil". The concept is to provide small-scale widely-distributed reinforcement to noncohesive soils by including a random distribution of small threads or yarns. Triaxial testing of the 6 x 14 inch core samples could provide design values of cohesion and internal friction.

Hypothetically, various soils' strength can be increased while maintaining permeability by randomly mixing yarn with the soil. To evaluate this concept a subobjective of this research was to develop an air dispersal system and conveyor system on a laboratory scale. These systems were used fabricate samples for strength evaluation of granular soils stabilized with yarn. These tests could possibly lead to design methods and the development of field construction methods which would facilitate the use of yarn-stabilized soil. This phase of the research was to be pursued through the following steps:

1. Fabricate and evaluate samples made from graded sands with and without the commingling of polypropylene or polyester fibers.

2. Upon analysis of the preliminary sand and sand/yarn samples, the research would continue with highly erodible decomposed granitic soil samples, and some testing of the effects of yarn inclusion in a moderately cohesive soil.

3. Evaluate the samples by testing in triaxial compression for cohesion and internal friction values, and permeability testing of the different types of materials with and without yarn inclusion.

2. CONCLUSIONS

The results of this research indicate yarn reinforced soil could possibly be a viable solution for stabilizing highly erodible soils. The research indicated an increase in apparent cohesive strength regardless of what sand or yarn was commingled. The observed strength increase was not as great as anticipated; therefore, additional laboratory work may be necessary before design concepts can be formulated.

Inclusion of yarn fibers does not appear to significantly alter the soil permeability. The fabrication of consistent representative soil/yarn test cylinders is feasible, as is the fabrication of soil/yarn permeability samples. Many more samples need to be made and the testing procedure evaluated.

3. RECOMMENDATIONS

Caltrans should begin the second phase of this research, by exposing open 4 ft x 8 ft samples to rain from the laboratory rain generator. Starting with samples of Monterey and Silica Sands with 0.2% polypropylene yarn, sample sections should be tested in the rain tower to provide additional information on surface erosion, rills, gullies and slippage related to yarn reinforced soil.

Further laboratory investigations should be undertaken in an attempt to develop design guidelines, refine the testing procedure, and develop a large enough data base to more accurately define the true effects of yarn inclusion.

It is also recommended that further research into various types of yarns and soils be considered as well as the method of strength evaluation, in order to provide control testing to determine the appropriate types of soils, and the volumes and types of yarns required. The information from further research can provide the control required for the actual material being used in the construction of yarn reinforced soil.

4. IMPLEMENTATION

Yarn reinforced soil is a viable concept for altering granular soils. The Texol Co. (France) is presently marketing a similar technique in the United States on a small scale. Caltrans should construct some Texol reinforced fill buttresses where there are presently erosion problems. The actual implementation of this research is limited to subsequent research needed to develop application techniques and criteria.

5. BENEFITS

The development of this technology could well provide an aesthetically pleasing system of slope stabilization that will minimize soil encroachment on many of the mountainous highways throughout California and the nation. Many of these highways are in terrain where the soil is highly erodible. Stabilizing these slopes with yarn reinforced soil would assist in the establishment of vegetation and provide stable slopes that otherwise require constant maintenance. The value of accident prevention by not having sediment on the pavement cannot be readily estimated nor can the value of the ability to rapidly revegetate slopes in environmentally sensitive areas.

It may allow for a reduction in right-of-way cost by enabling steeper slopes using less right-of-way in new construction.

In areas where we now use rock fences to protect the motorist from eroding slopes and falling rocks, yarn reinforced soil could be used as a cover buttress to prevent further erosion of the supporting matrix in some slopes, thus minimizing rock fall and providing a safer traveled way by eliminating that hazard along the travel way.

6. MECHANICAL COMPACTOR

6.1 Description

A fully automatic, hydraulically operated compactor was fabricated according to specifications prepared by researchers in 1973, Photo 1. For use on this project, this device was modified to provide more flexibility/versatility and maintain a constant compaction energy. Some of the features of the modified compactor include: a soil loading conveyer, use of a 10 or 40 pound tamper with variable drop heights of 12 to 18 inches, and the use of 3 and 6 inch diameter molds. Additionally, the turntable oscillates in a 3/8 to 5/8 inch random pattern during rotation of the compaction sample to provide complete soil area impact compaction. The compactor is shown in Photo 2.

The California test for density and moisture, method 216, requires that the soil be compacted in a mold in five equal layers. The conveyor belt feed system is hand loaded so that each of the five lifts has an equal amount of soil, thus eliminating variations between increments. A yarn mixing chamber was added to the machine to facilitate soil/yarn commingling.

Midway through the research, it became necessary to repair the electrical control systems on this seventeen-year-old compaction machine. Since parts for the machine were unavailable, the existing electrical system was stripped from the machine and it was rewired with a new solid-state controller (See Photo 3). An operator can now fabricate samples approximately twice as fast as before the repair.

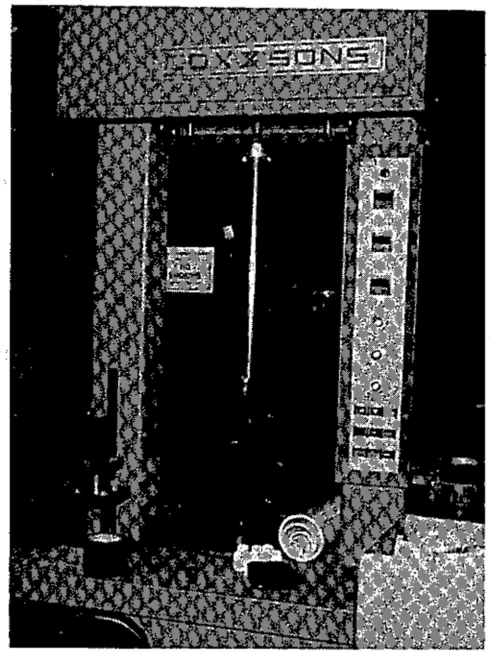


Photo 1 - Original Compactor

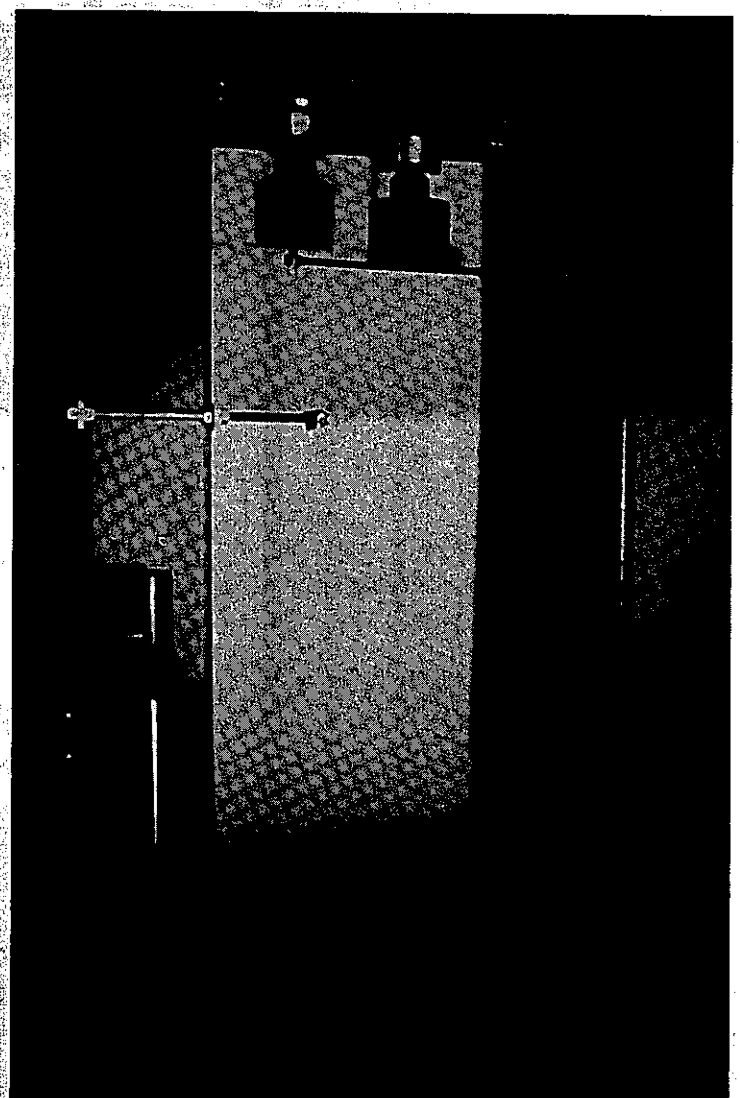


Photo 2 - Redesigned compactor
Note larger compaction foot.

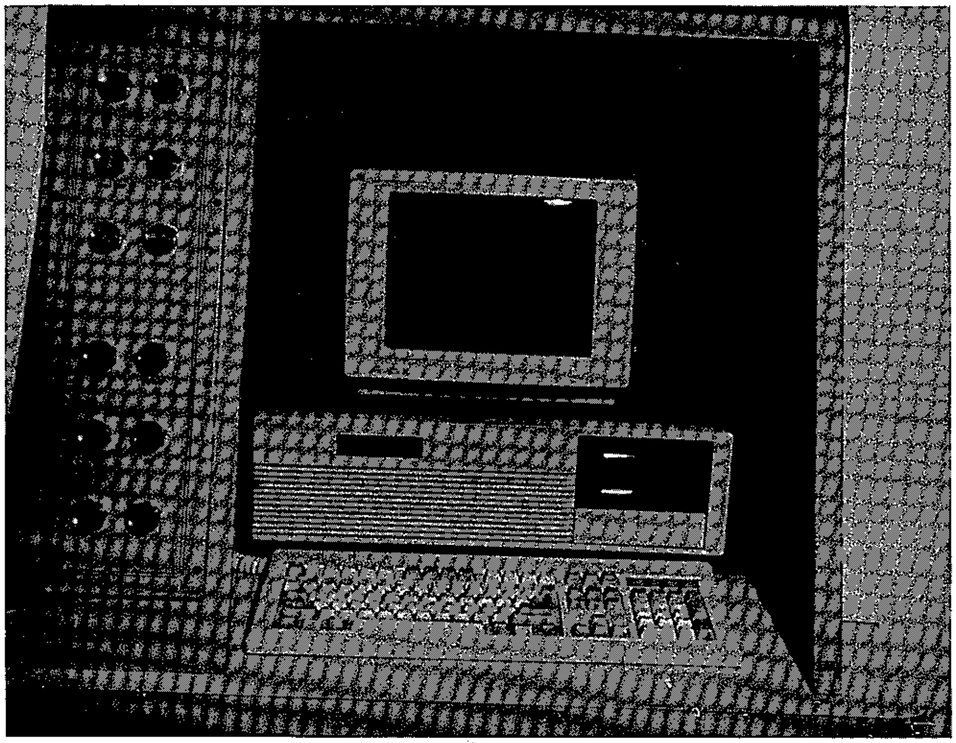


Photo 3 - Electronic Controller Installed in 1989

6.2 Tamper

The bottom section of the tamper shaft, the compaction foot, is a 3-inch high by 4-inch diameter steel cylinder, Photo 4. It is connected to a 1-inch diameter by 72-inch long steel shaft that extends to a 5-inch by 4-inch diameter steel cylinder affixed at the top, Figure 1. The total weight of the bottom section, shaft and top section is 40 pounds

The tamper action can be set for impact numbers ranging from 0 to 99 tamps. Empirically, the material at 100% compaction requires 25 tamps per lift from a free fall height of 18 inches regardless of the height of the sample. At 95% compaction the requirement is 12 tamps from the height of 18 inches. With the total volume predetermined in the sample, the sample is capped with the steel piston and compacted until the specified volume of material is compressed into the liner.

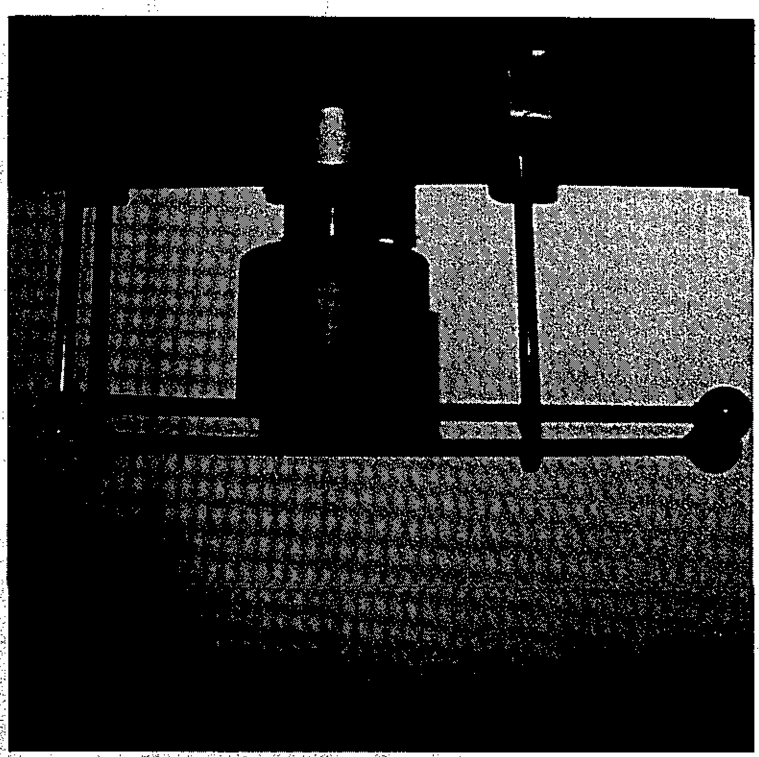


Photo 4 - Compaction foot

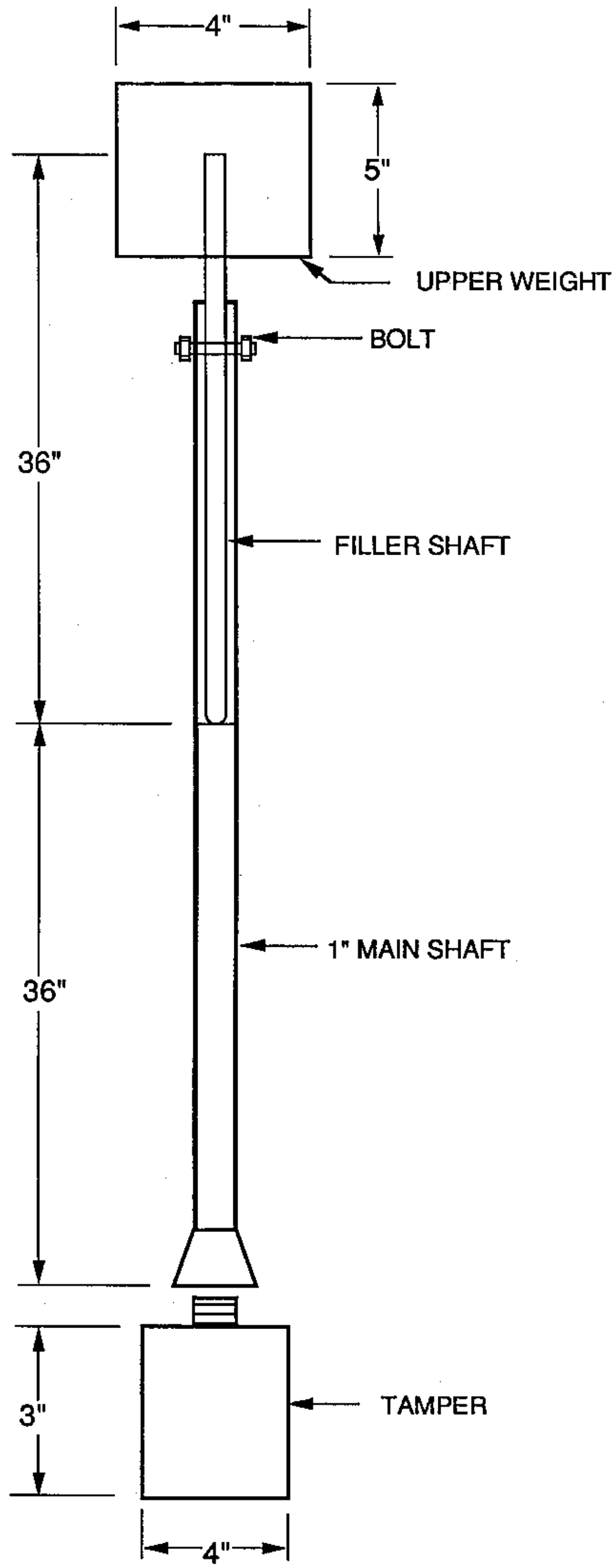


FIGURE 1 - Tamper

6.3 Conveyer

The soil conveyer system is a belt loader attached to the compaction apparatus. The conveyor belt is 2 1/2 inches wide by 36 inches long and moves in increments of 1.42 inches per signal, Photo 5. The conveyer can be set to 25 increments. It requires hand-loading of the soil onto the belt. The material is spread throughout the length of the conveyer belt and during this operation the material drops into the mold along with the air-blown yarn at a predetermined rate.

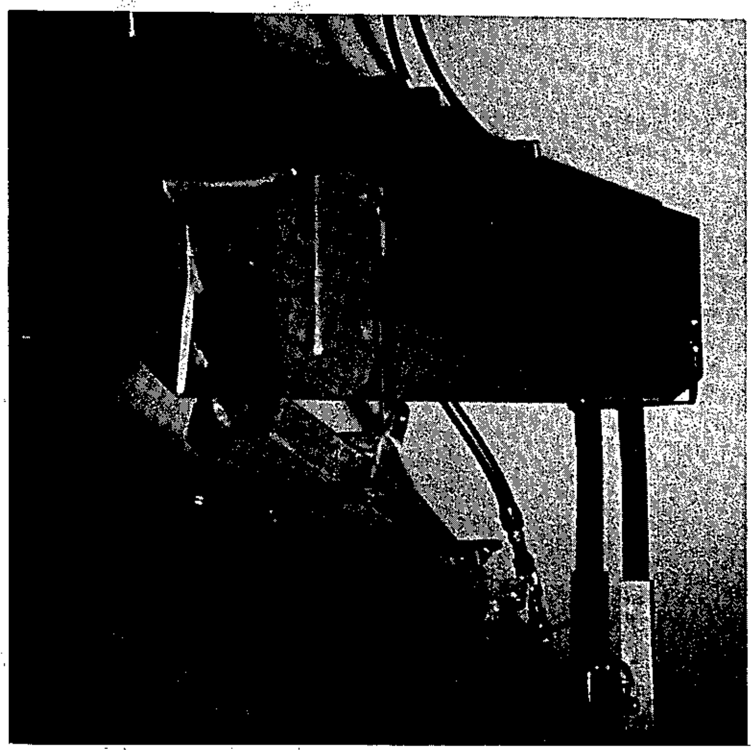


Photo 5 - Conveyer

6.4 Yarn Mixing Chamber

The mixing chamber is mounted on the top of the conveyer in order to permit both the yarn and soil to mix as they drop into the mold, Photo 6.

The yarn mixing chamber feeds the yarn into the mold at a rate predetermined by the operator. The chamber is made up of four aluminum channels with air fed from a four-nozzle manifold, Photo 7. The nozzle feed system in each channel separates the fibers as they pass through the unit. Slightly before the yarn reaches the outlet, there are two additional air nozzles which further mix and push the yarn from the chamber, Figure 2.

The chamber operates using 90 psi air for maximum distribution. The system separates the yarn into varying amounts facilitating commingling with the soil at the outlet of the mixing chamber and conveyer, Photo 8, where both converge and drop into the mold.

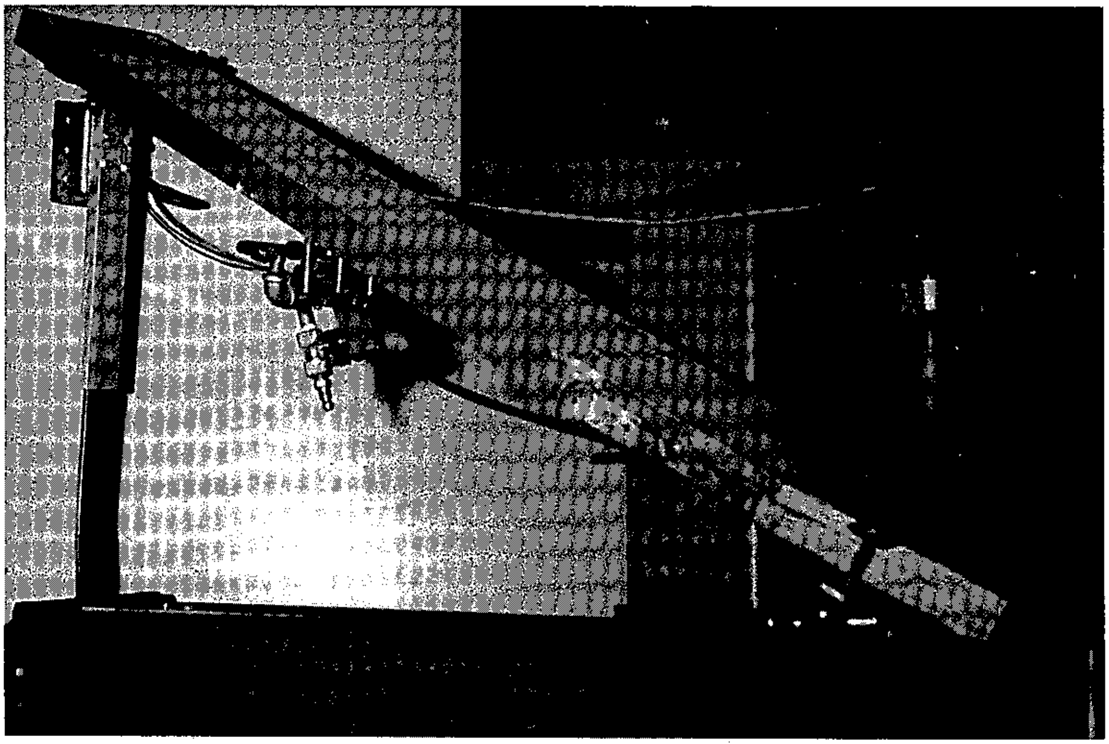


Photo 6 - Yarn Mixing Chamber

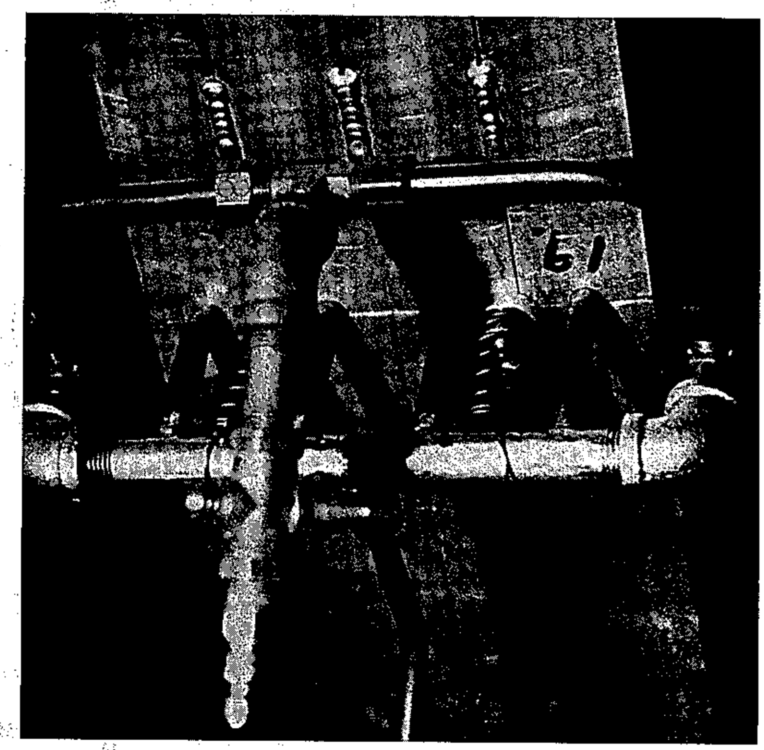


Photo 7 - Air Manifold on Mixing Chamber

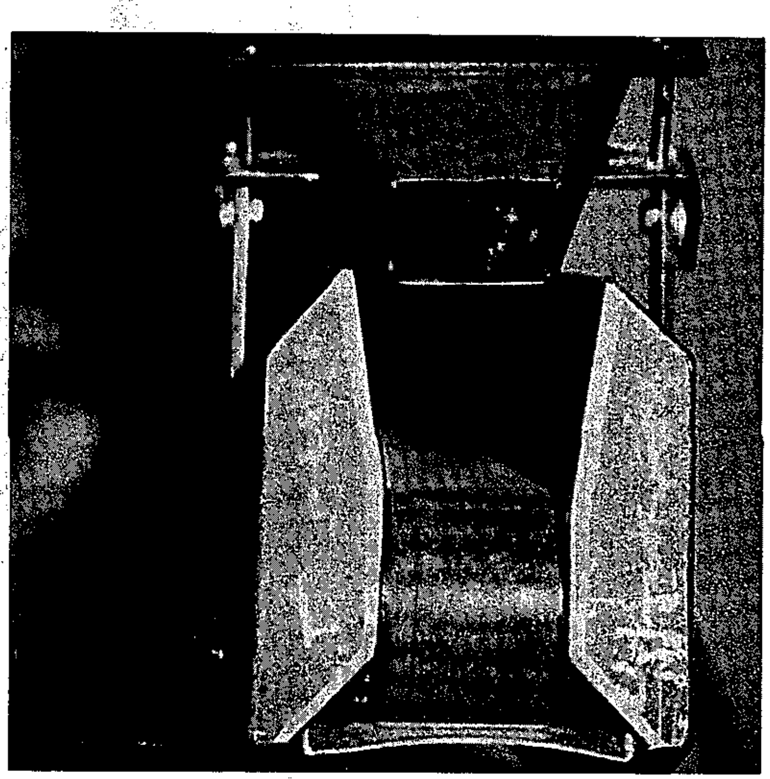


Photo 8 - Outlet of Mixing Chamber and Conveyer

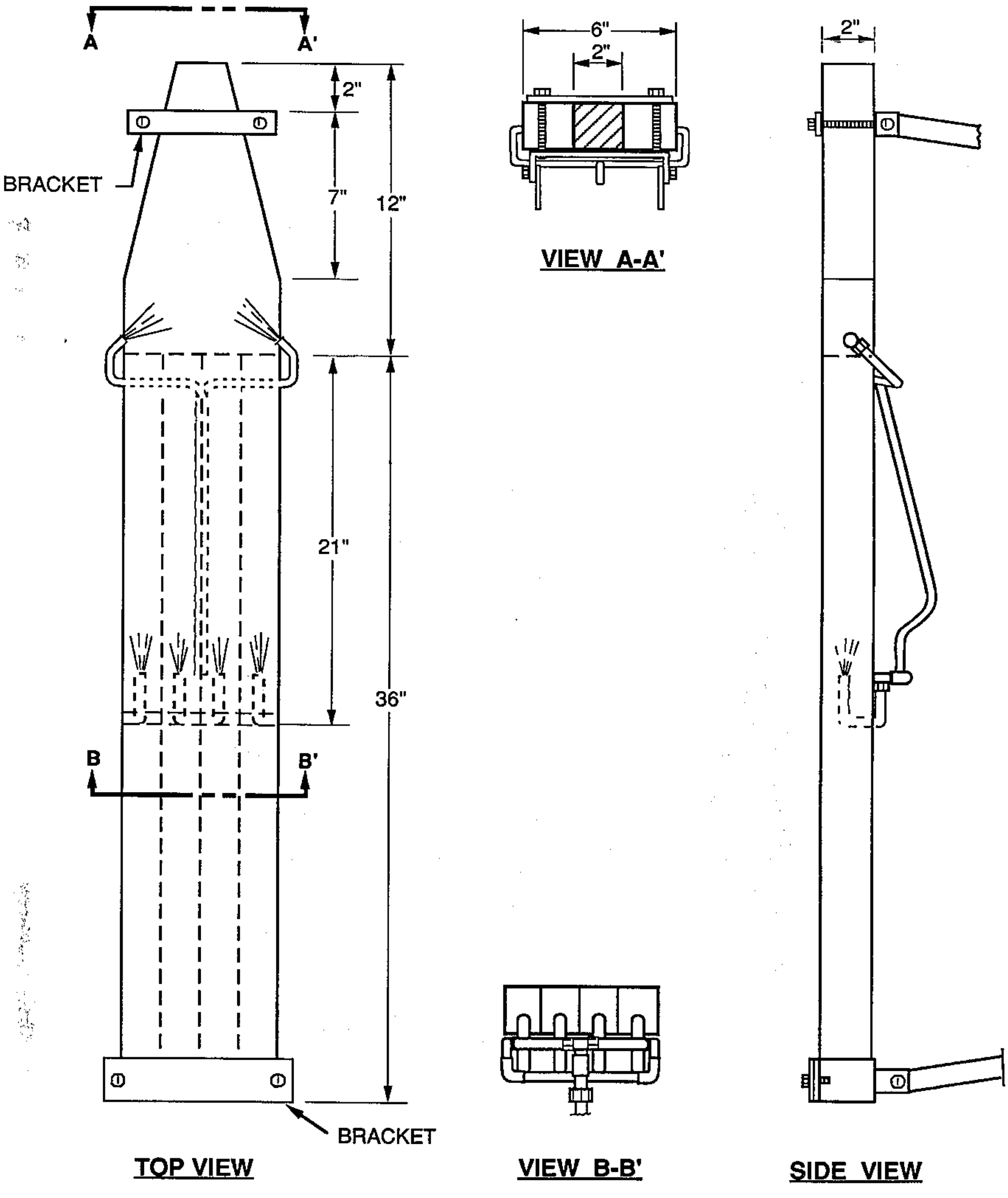


FIGURE 2 - Yarn Mixing Chamber

6.5 Turntable

The turntable is a 1-inch thick, 10-inch diameter steel plate, Photo 9, and is capable of receiving and fastening securely a 6-inch diameter by 18-inch high mold. It makes seven stops during each revolution. The turntable oscillates a maximum of 5/8 inch to provide a uniform distribution of blows by the tamper over the entire surface of the sample. The blows of the tamper are timed to the revolution of the turntable. The turntable can be adjusted to rotate at various rates other than one complete rotation for each seven tamps of the tamper.

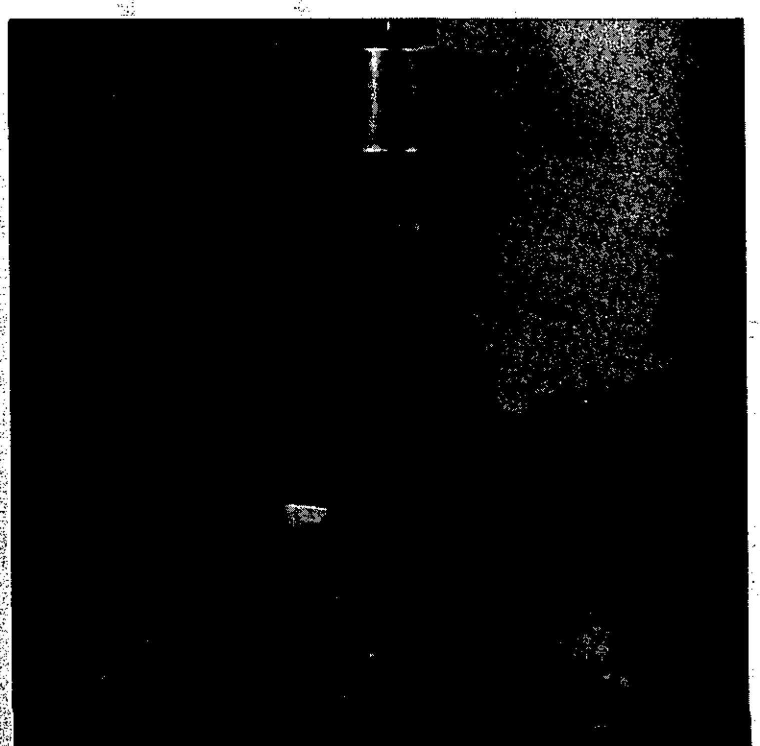


Photo 9 - Turntable

6.6 Yarn Distribution

The yarn distribution system is a composite of the yarn rack that holds up to four spools of yarn, a yarn feed system, Photos 10 and 12, which mechanically feeds the four tows of yarn into the yarn mixing chamber, and the mixing chamber, which distributes the four tows of yarn into the mold at the same time as the soil is deposited.

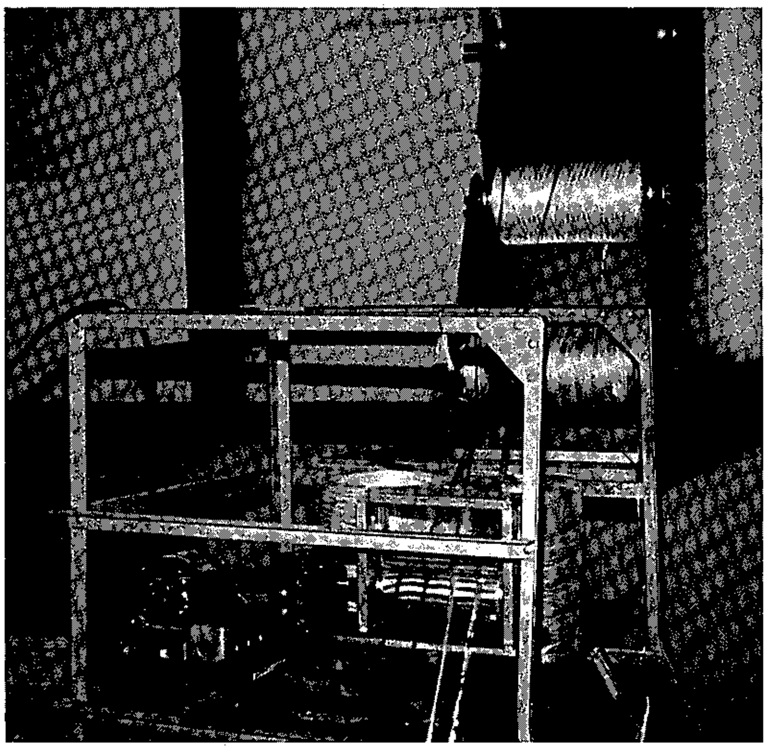


Photo 10 Yarn Rack and Yarn Feed System

6.7 Yarn Rack

The yarn rack holds up to four spools of yarn weighing approximately 20 pounds each. The yarn is supplied on various sizes of disposable cardboard spools. The spools of yarn are installed in the rack by inserting a 3/4-inch shaft through the spool and capping the ends with ballbearing support caps. The cap ends are then inserted into slots in the rack which hold the yarn assemblies, Photo 11 and Figure 3. The spools are free flowing as the yarn is pulled from the spools by the yarn feed system.

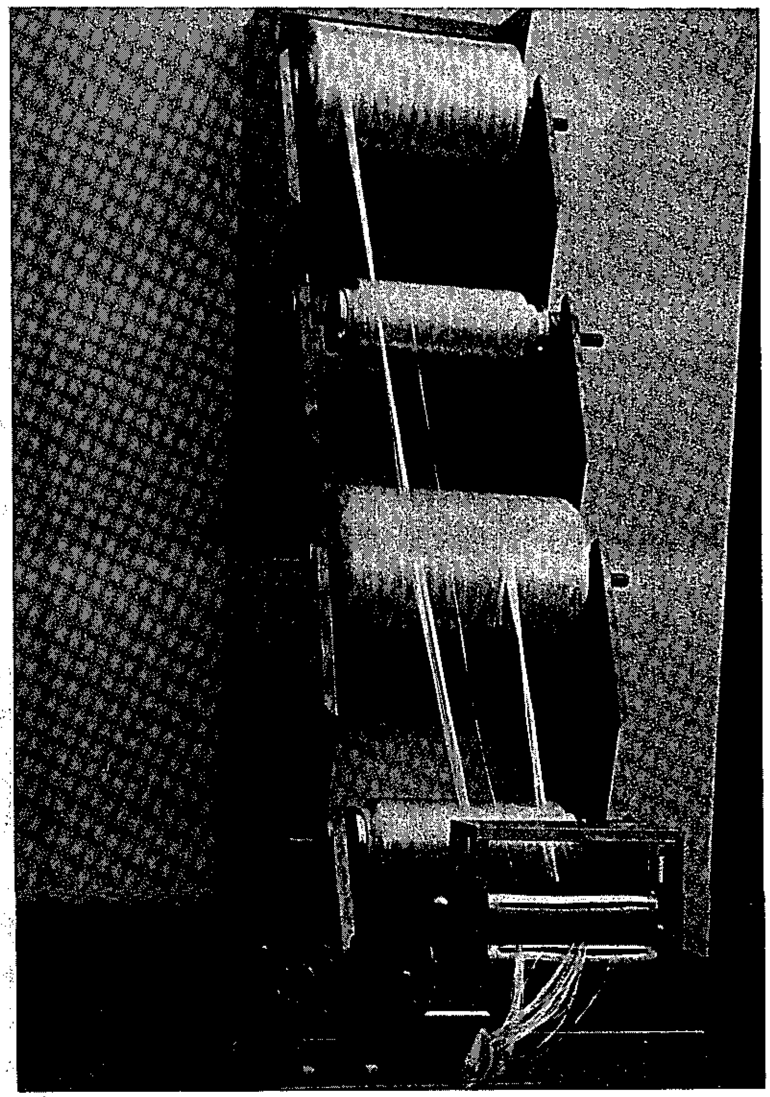


Photo 11 - Yarn Rack

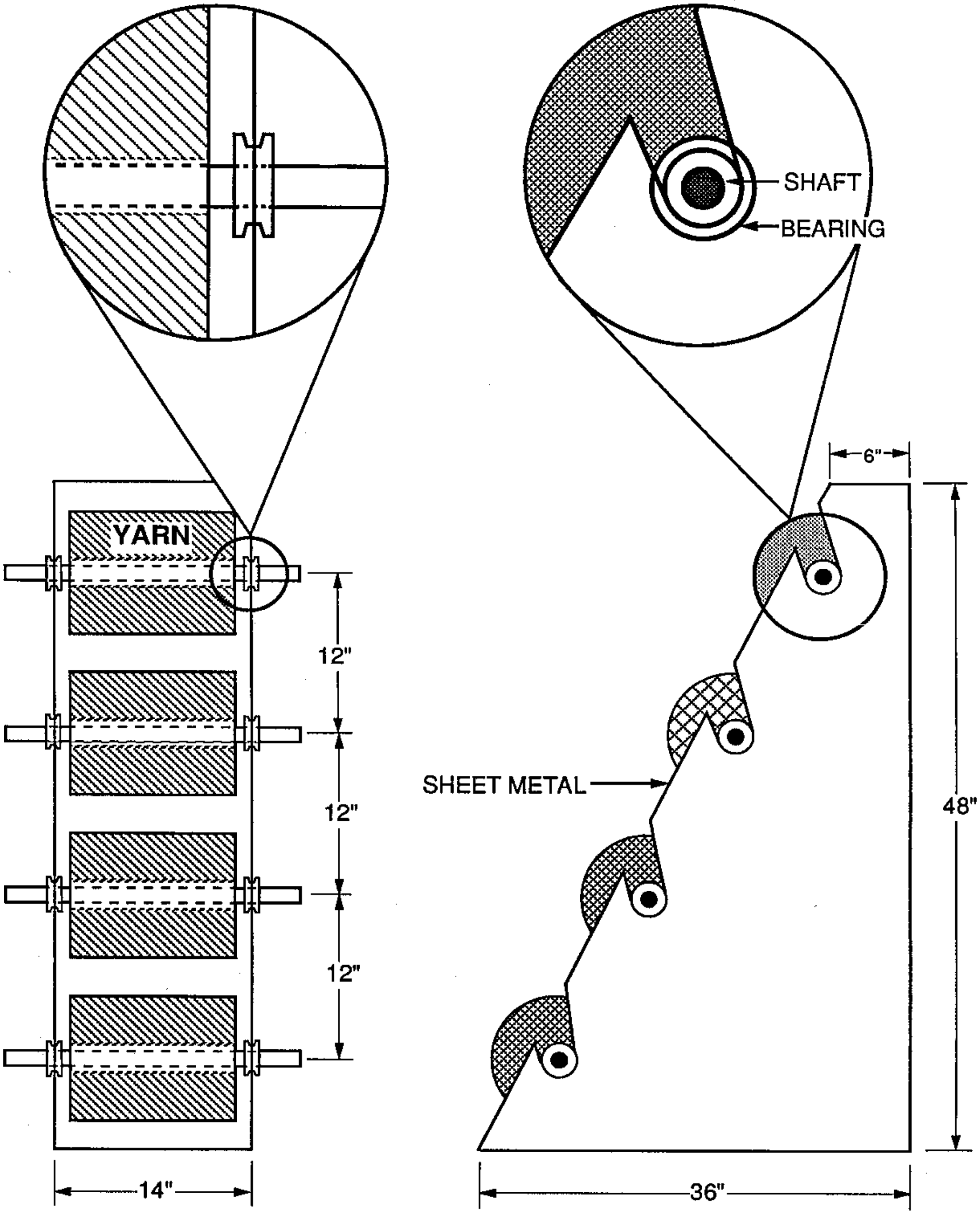


FIGURE 3 - Yarn Rack

6.8 Yarn Feed System

The yarn feed system is a two roller device designed to accept up to four tows of yarn at one time, Photo 12 and Figures 4a and 4b. The two 2-inch diameter by 7-inch long rubber coated aluminum rollers are driven by a 1/250 HP motor through a torque converter. The rollers are rubber-coated to prevent slippage of the yarn through or on the aluminum rollers. This system can feed various yarns from cardboard spools or internally wound packages.

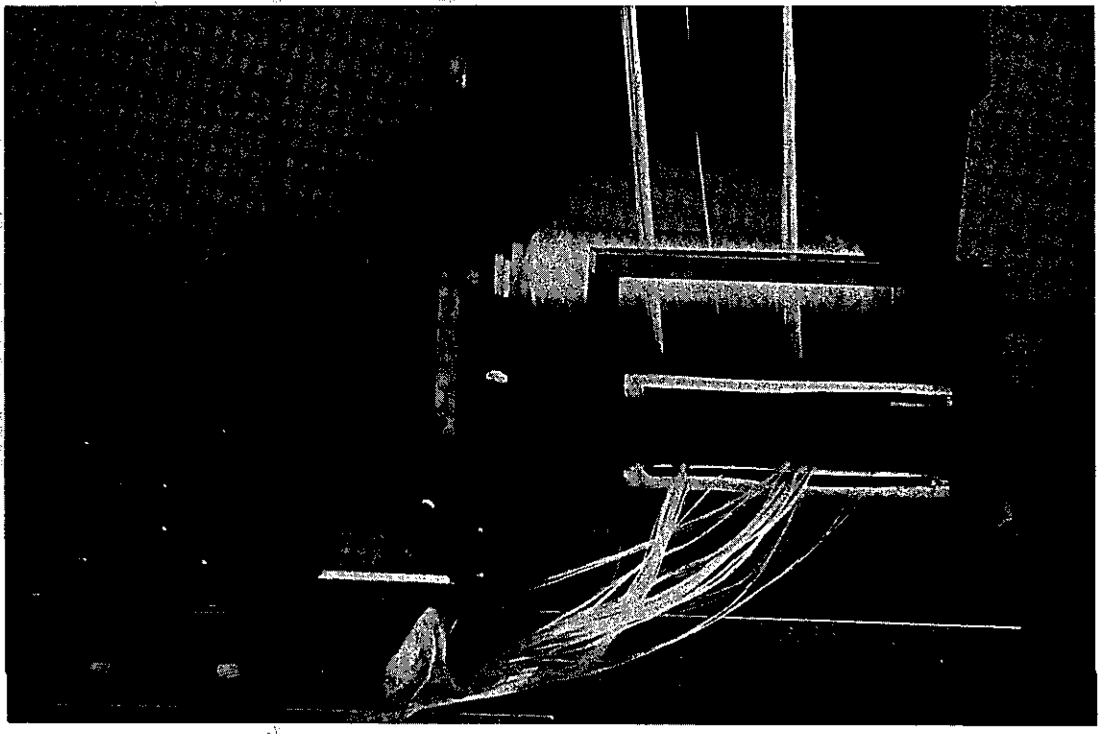


Photo 12 - Yarn Feed System

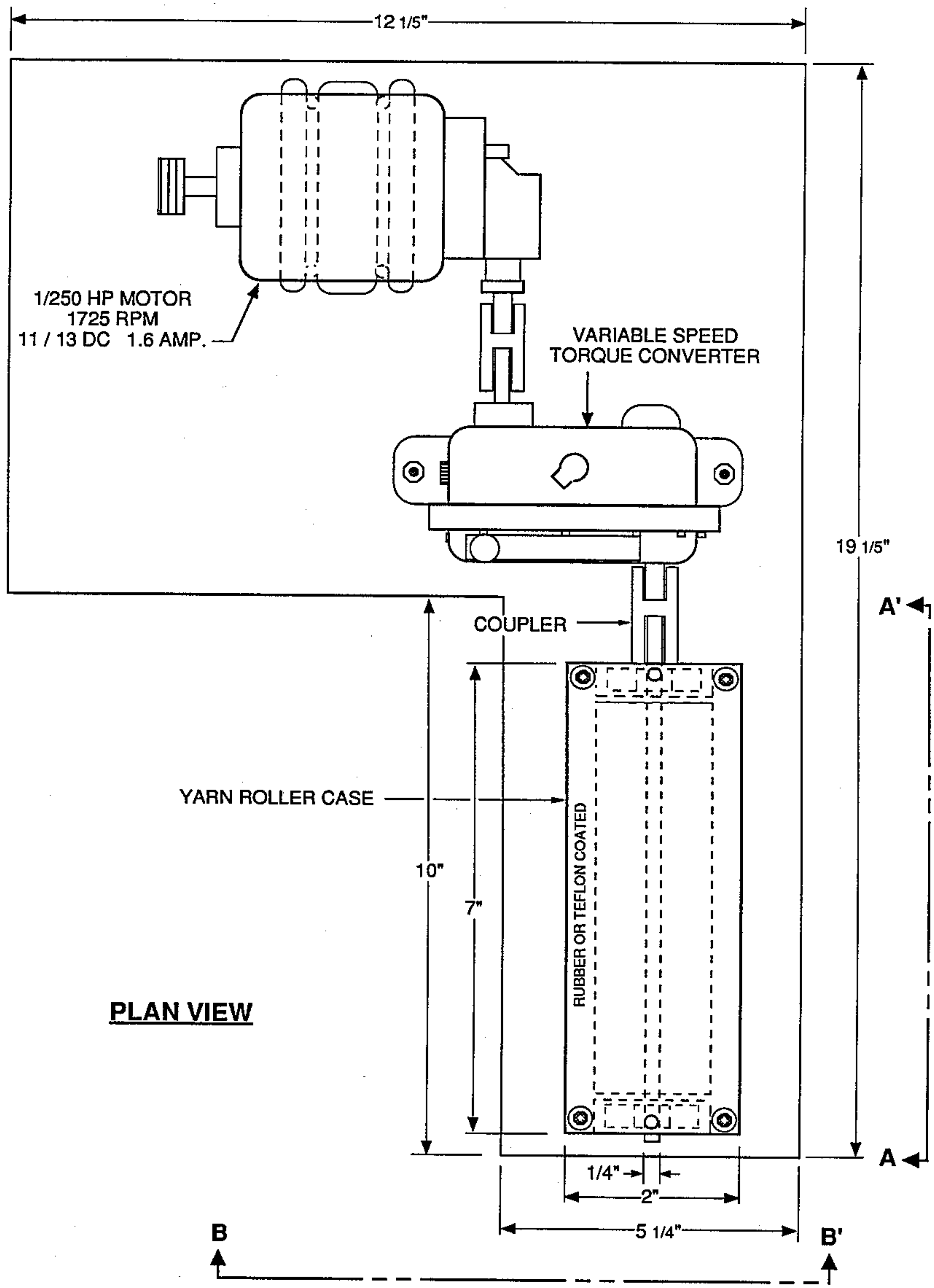
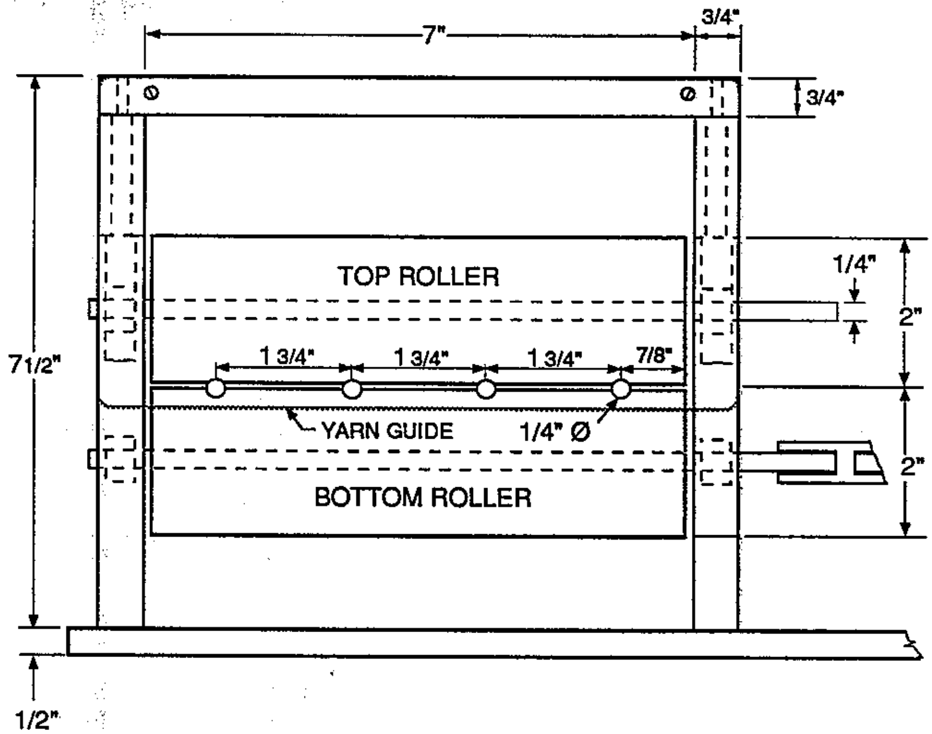
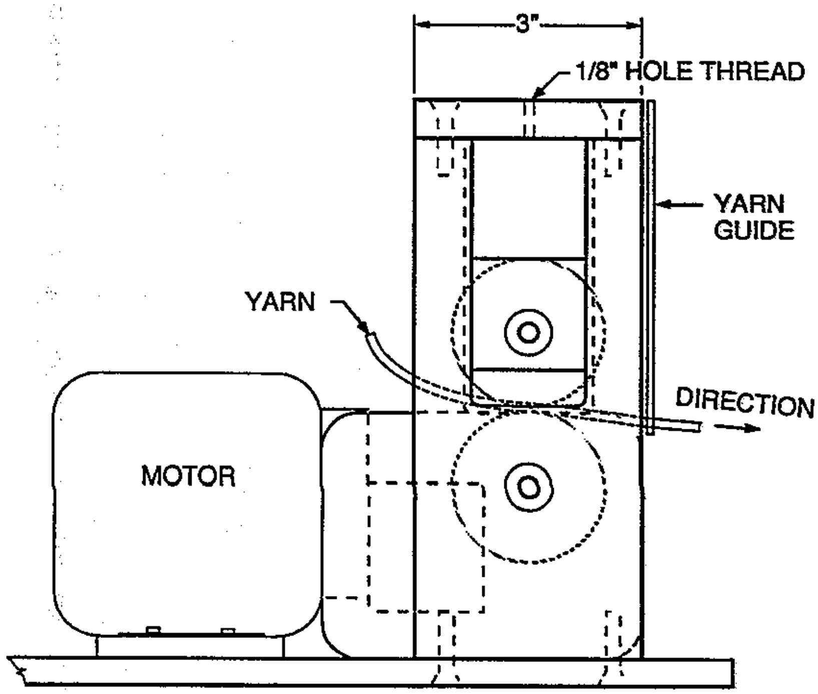


FIGURE 4a - Yarn Feed System



VIEW A-A'



VIEW B-B'

FIGURE 4b - Yarn Feed System

7. TRIAXIAL TESTING - 6-inch Core Fabrication Test Equipment

7.1 Mold

The steel mold consists of a 3/4-inch thick by 18-inch high steel annulus. It sits on a baseplate 1 inch thick and 10 inches in diameter, Photo 13. The base plate bolts to the machine's turntable, Figure 5. The inside walls of the 18-inch mold are inset 3/8 inch to receive the 6-inch ID PVC liner. Enough tolerance was provided, 1/16 inch, to allow room for the overlap of the butyl membrane used inside the PVC liner. The base protrudes into the mold 3/4 of an inch on the bottom and the piston protrudes into the top of the mold 3 1/4 inches, Photo 18. This produces a 6-inch x 14-inch finished core sample.

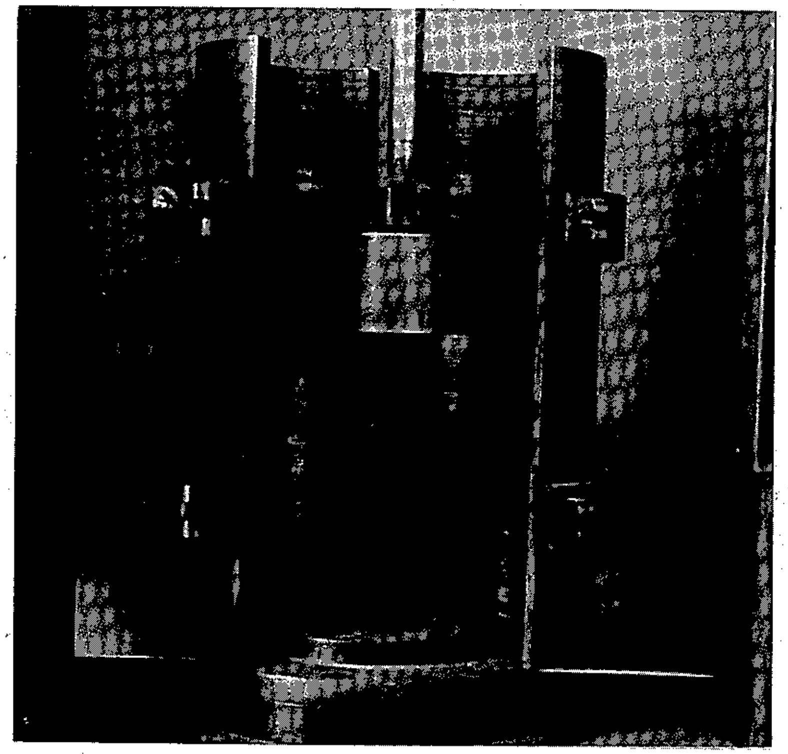


Photo 13 - Steel Mold to Retain PVC Liner During Compaction.

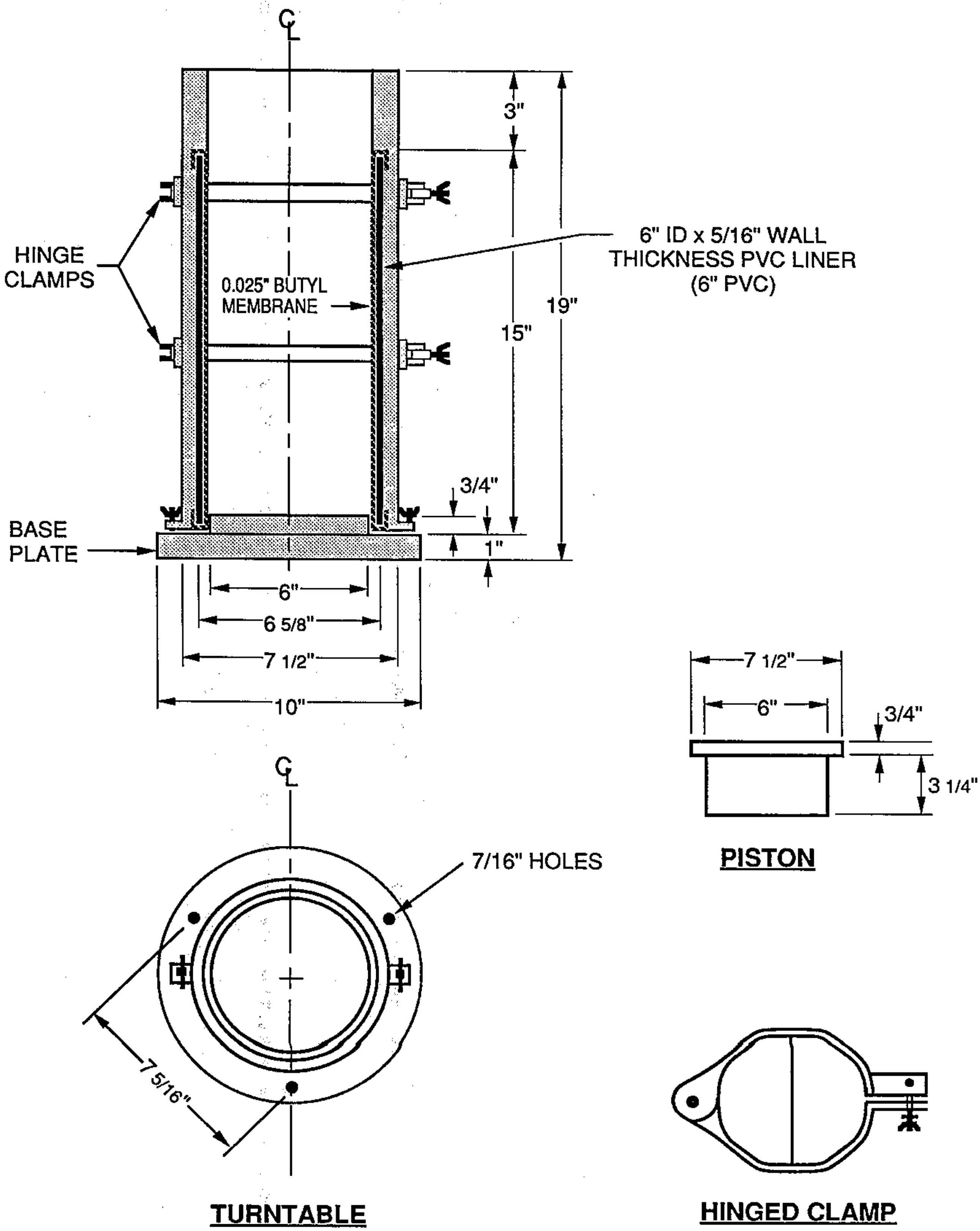


FIGURE 5 - Impact Compaction Apparatus

7.2 PVC Liner and Its Preparation

The 6-inch x 18-inch mold holds a 6-inch ID x 15-inch PVC liner which is fabricated from a standard 6-inch PVC molded water pipe, Photo 14. The calibration of these liners is described in Appendix B. The liner serves as a separator between the wall of the mold and the core sample inside, as well as providing a containment cylinder for the core sample during fabrication and storage before triaxial testing.

The PVC liner is prepared by inserting the rubber membrane and securing it to the liner with plastic tape, Figure 6. The liner is then reversed and talcum powder is applied between the membrane and the PVC liner to create a slip surface that allows the sample to be freely removed from the liner during the extraction process, Photo 15. The membrane is then secured to the bottom of liner with plastic tape. It is now ready for insertion into the mold.

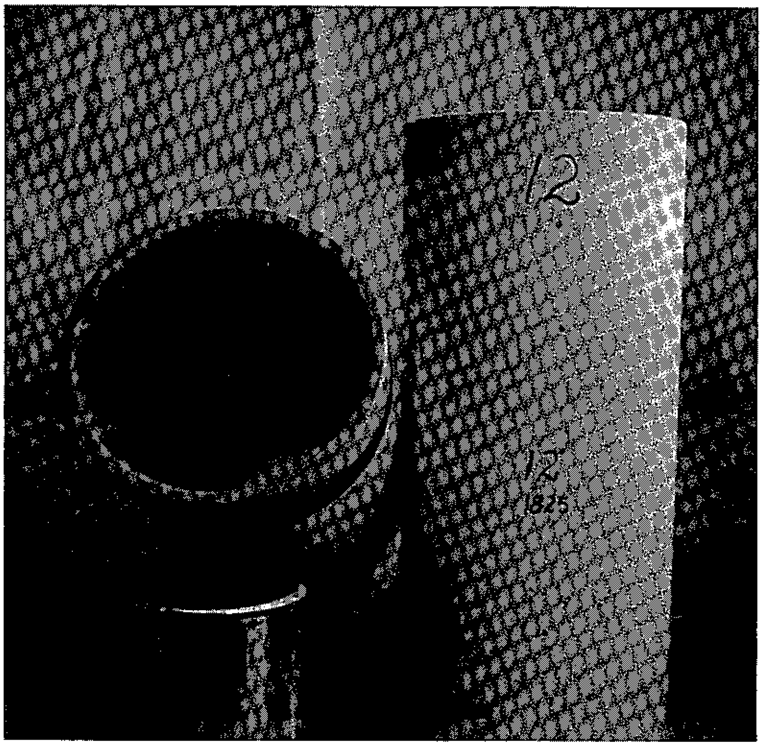


Photo 14 - PVC Liner and Liner with Membrane Installed

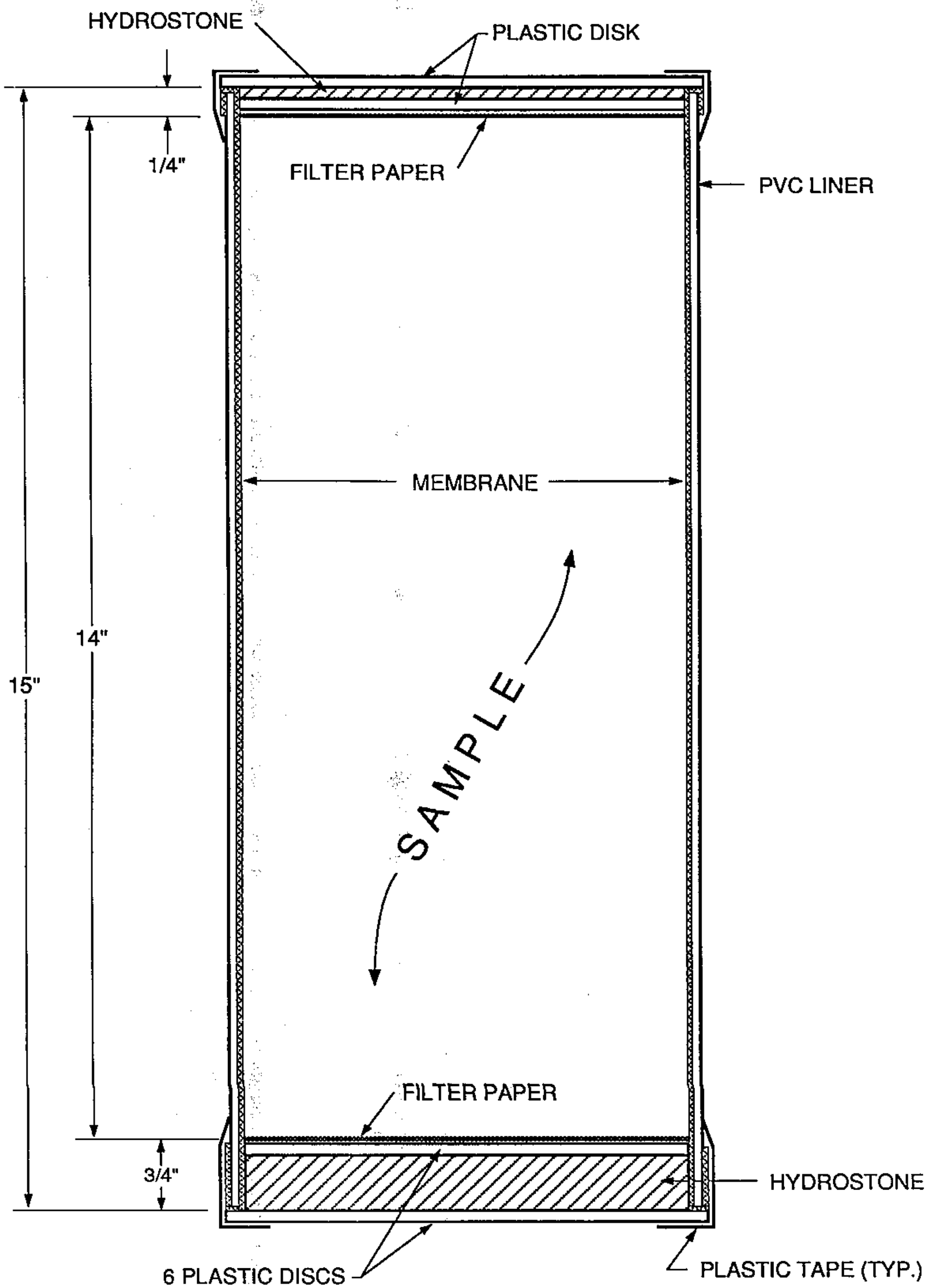


FIGURE 6 - PVC Liner and Core Sample

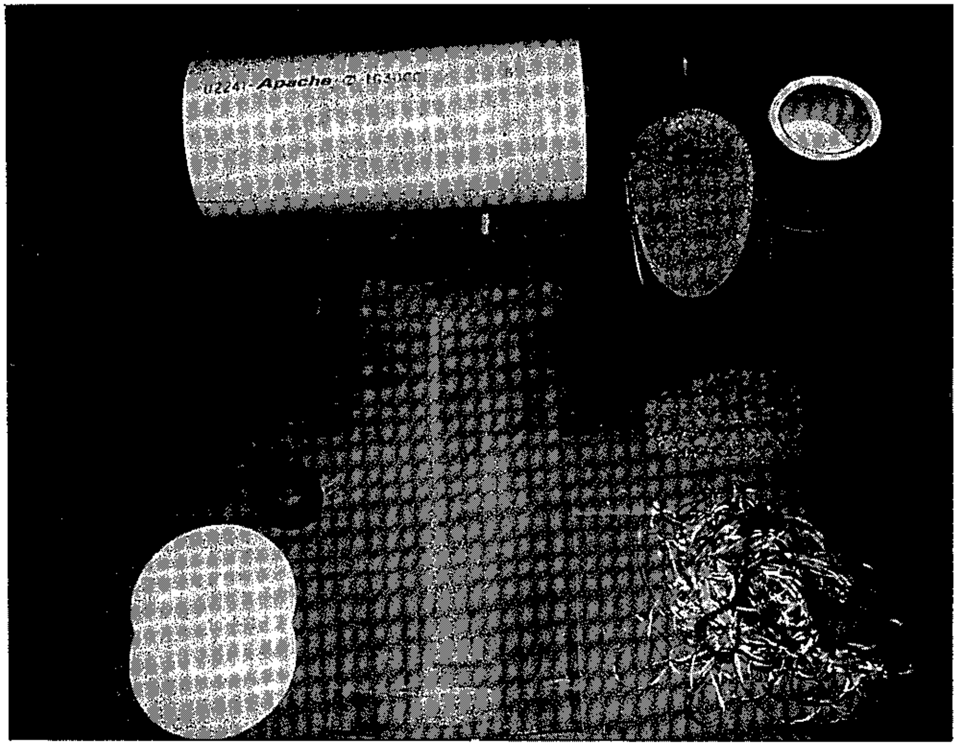


Photo 15 - PVC LINER PREPARATION,
Sand and Yarn,Liner, Membrane, Talcum Powder,
Plastic Disc, Filter Paper and Plastic Tape

7.3 Membrane

The butyl rubber membrane is used in the liner to contain the compacted sample during triaxial compression testing, Photo 16. It and the PVC liner protect the core sample in transporting and storage prior to being extracted from the liner before triaxial testing. The volume of the liner with the rubber membrane is 0.233 cubic foot.

Talcum powder is used as a lubricant between the PVC liner wall and the membrane. This allows easier extraction of the sample prior to triaxial testing. An additional membrane is used on the core sample during triaxial testing.

Liner, a membrane, plastic disc, filter paper, hydrostone (not shown) and plastic tape are used to seal the reinforced soil samples for transport and storage.

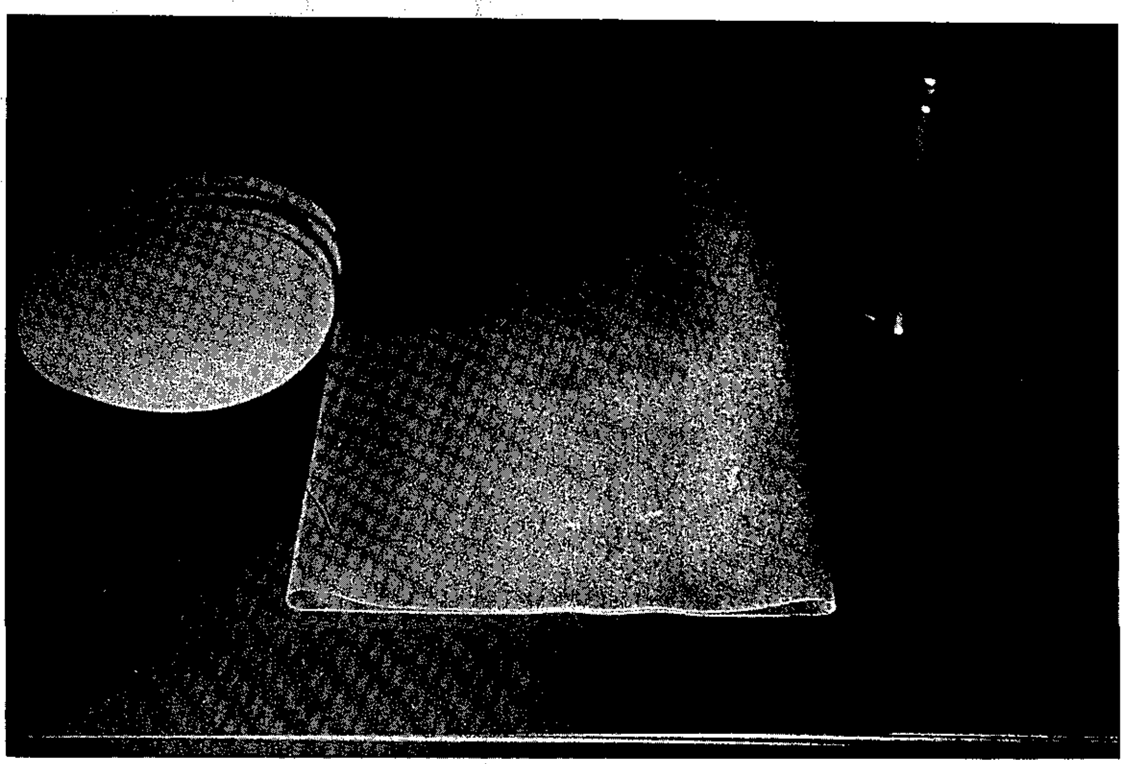


Photo 16 - Membrane, Plastic Disc and Filter Paper.

7.4 Filter Paper and Plastic Disc.

Filter Paper

Six-inch diameter filter paper, Photo 16, is placed on the top and bottom of the sample prior to placing the plastic disc inside the liner. The filter paper prevents the escape of fine material and also prevents adhesion between the sample sand and the sealing hydrostone. The filter paper is removed prior to triaxial testing.

Plastic Disc

The plastic discs are 6 inches in diameter and are used to seal the ends of the core samples for transporting and storing the samples, Photo 16. These discs were used for sealing the samples and worked satisfactorily.

After applying hydrostone to the ends of the samples, plastic discs are secured to the mold with plastic tape on both the top and bottom of the sample. They are removed when the sample is ready for extraction for triaxial testing.

There are three sizes of plastic disc. The first is a 5 1/2-inch diameter disc used to seal the 14-inch test core sample. The second disc is slightly larger having the same diameter as the outside diameter of the liner, 6 inches, and is used to cap the sample prior to transport. The third size is a 6 1/2 inch plastic disc used to cap the entire triaxial test core prior to transport.

7.5 Deflection Screen

The removable deflection screen is attached to the top of the mold. Its main purpose is to deflect the yarn and soil mixture and direct it into the mold while allowing the air to pass through. This prevents blowback of the soil and yarn from within the mold, Photo 17.

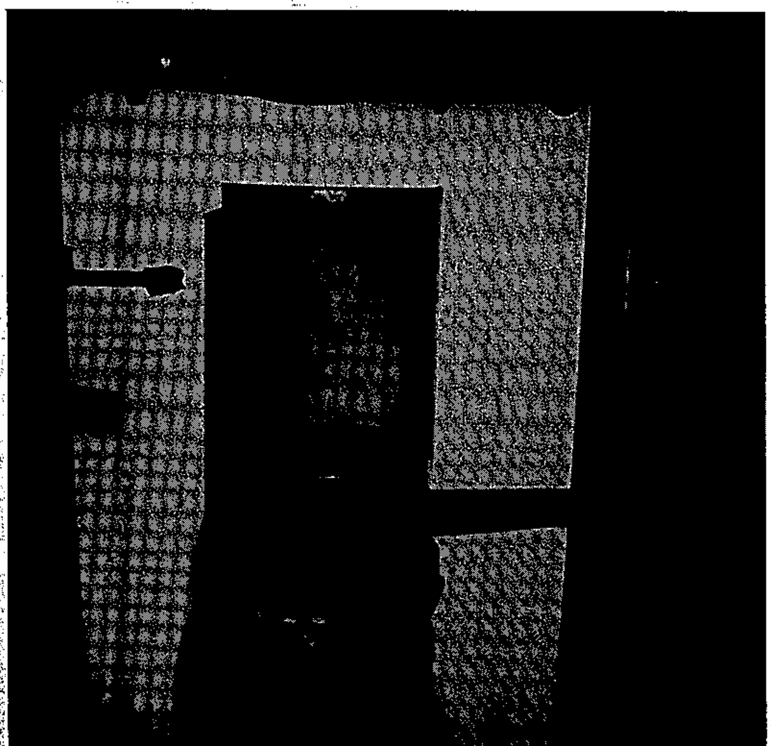


Photo 17 - Deflection Screen

7.6 Piston

The piston is a 4-inch high by 6-inch diameter steel cylinder with a 1-inch flange on top. It is used to smooth the surface of the sample and compact the predetermined volume of material in the mold, Photo 18.

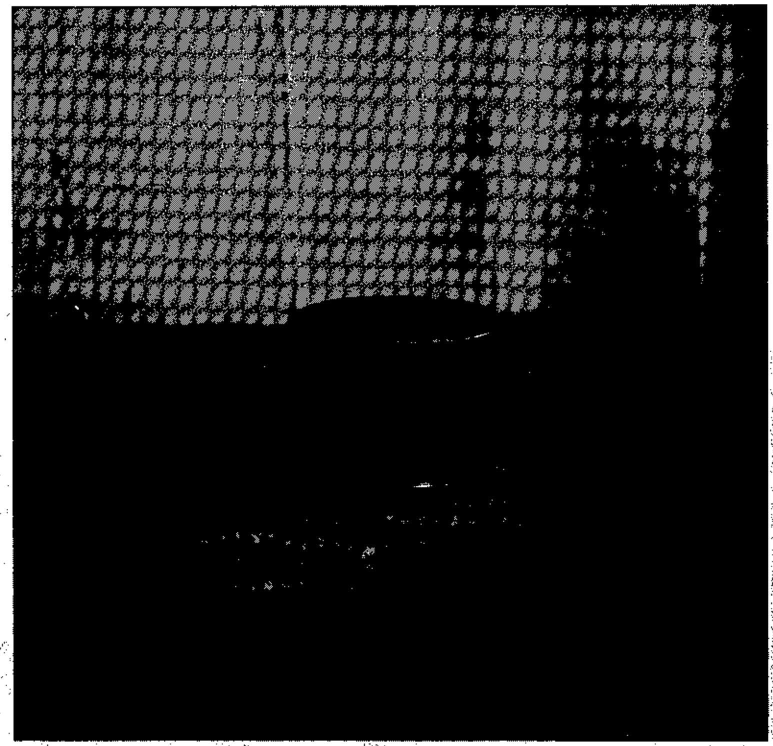


Photo 18 - Piston

8. PERMEABILITY - CORE FABRICATION TEST EQUIPMENT

8.1 Permeability Core Fabrication Equipment

Six-inch high by 6-inch diameter metal sample cans, for concrete, are used in preparation for the permeability test. The bottom of the can is removed. The can is then placed inside a PVC liner that has been split lengthwise. A metal shim slightly smaller than the can is used to fill the space around the can that was created by the bead on the bottom of the can, Figure 7.

The can with shim is inserted into the PVC liner, then placed on the turntable and secured in the mold, Photo 19. It is now ready for compaction of the sample. Two lifts of material are compacted, 12 blows per lift (95% compaction). This sample is now comparable to the 6-inch diameter triaxial core sample. The sample is removed from the mold and liner, but stays in the metal can. The bottom of the sample is sealed with a plastic disk, the sample is reversed, and the top is sealed with hydrostone and a plastic disk.

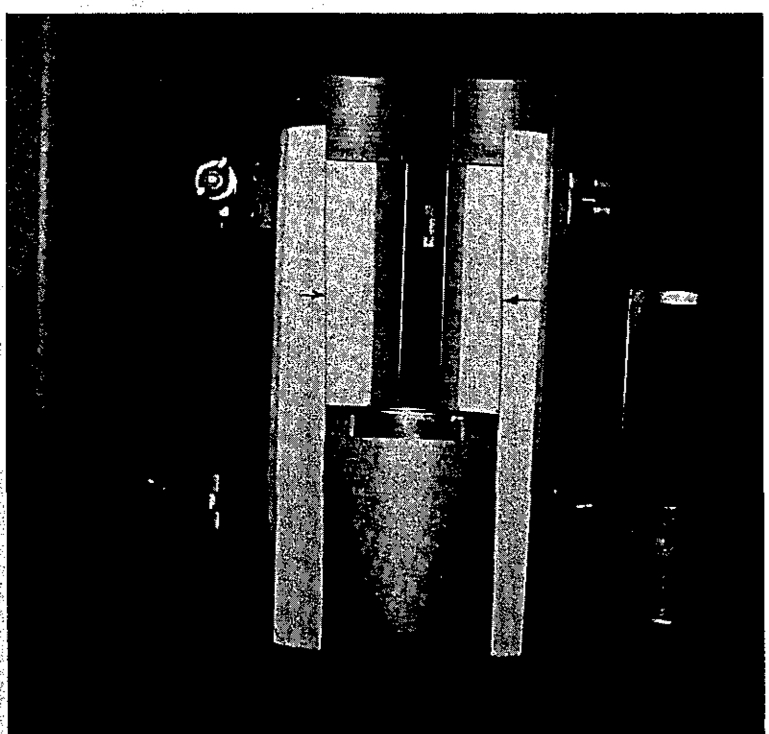


Photo 19 - 6x6 Sample Ready for Compaction

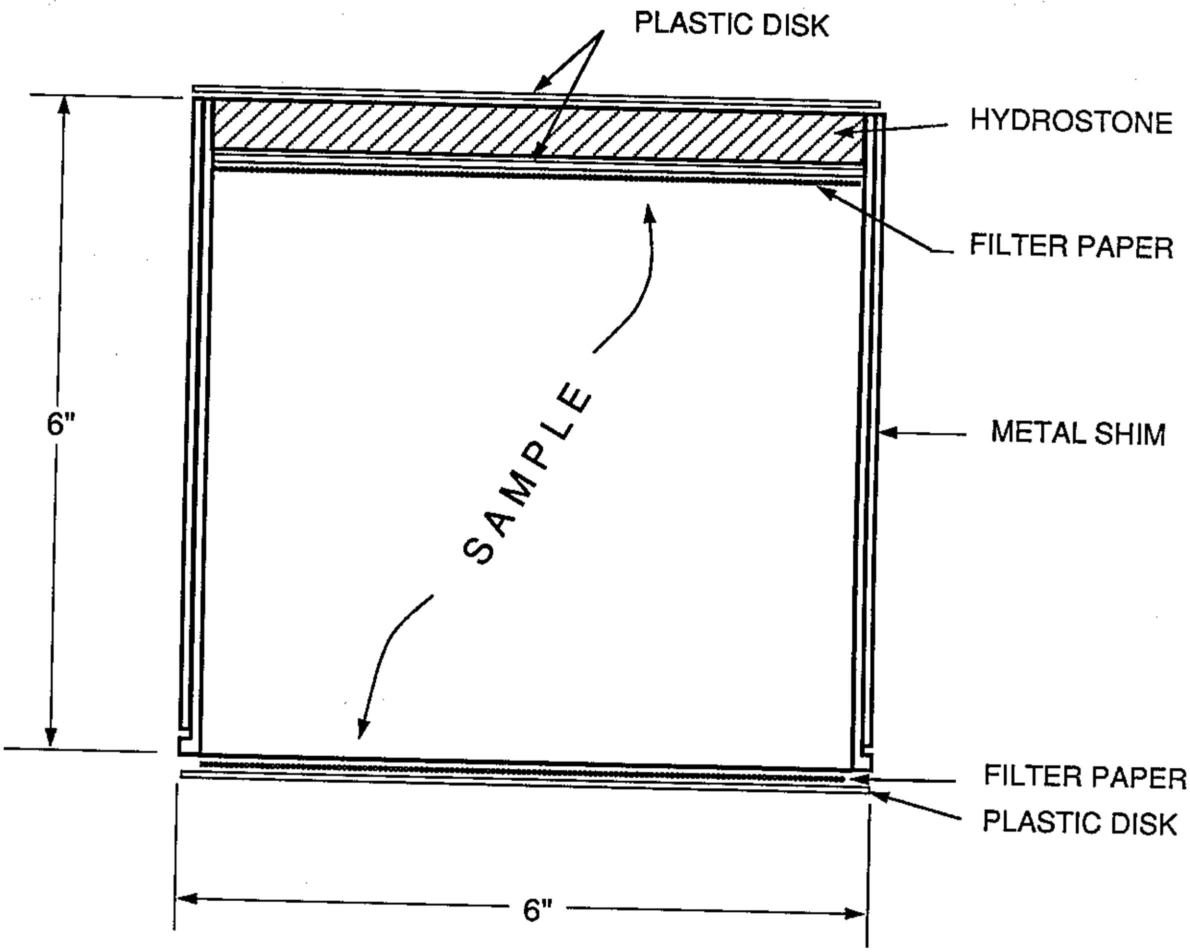


FIGURE 7 - Permeability Sample

8.2 Split Liner

A split PVC liner is used for the permeability test sample fabrication. In order to prepare a 6-inch high sample, a 6-inch x 15-inch PVC cylinder was split into two sections to receive the 6-inch x 6-inch sample can, Photo 20. The sample can, split liner, and shim are installed into the mold as shown in Photo 19.

8.3 Shim

The shim consists of a piece of 8-gauge metal stock. It surrounds the can to fill the void which results from the bead on the bottom. The shim is placed on the can as it is being installed in the split liner mold. The split liner, can, and shim are installed into the steel mold, Photo 20.

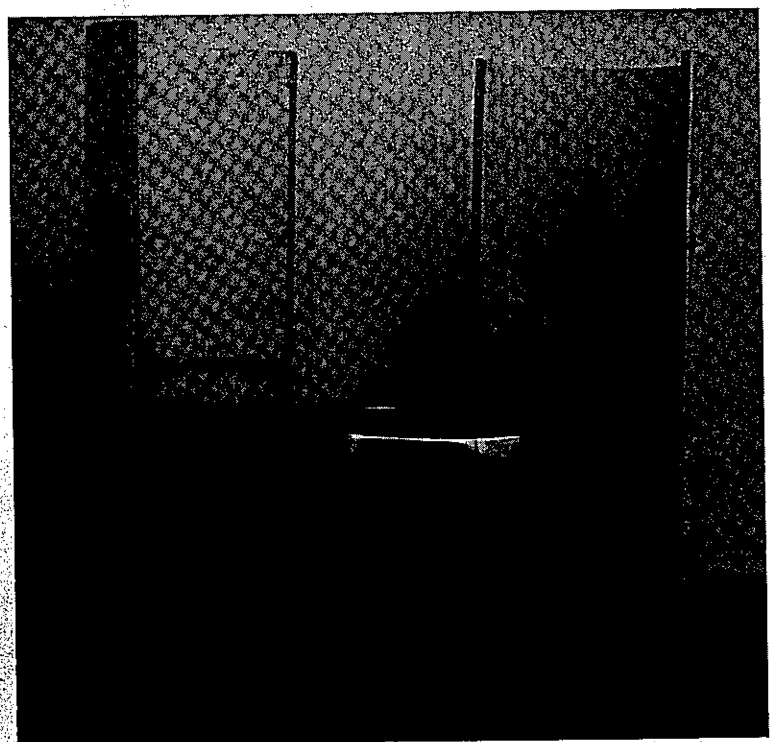


Photo 20 - Split Liner and Can with Shim

9. EXPERIMENTALLY VARIED MATERIALS

9.1 Soil Types and Sources

Two different types of sand were purchased from vendors in California. They were Silica Sand from Cal Silica Products Company in San Juan Capistrano and Monterey Sand from Lone Star Industries Incorporated, in Monterey. Also decomposed granite material was obtained from a local borrow source on Highway 50 in El Dorado County. All three of these materials were used in this research, Photo 21.

9.1.1 Silica Sand

The Silica Sand is from the California Silica Products Company in San Juan Capistrano, California. The company provides a wide choice of gradations for the selection of various types of sands for use in yarn reinforced soil samples. They provide eight different gradations of Silica Sand to the construction industry. The following three sands were blended for this research: #12, #30 and #60.

The Silica Sand has round smooth particles that are white to gray in color.

Gradations used for this research were 40% of the #12, 40% of the #30, and 20% of the #60. See the attached gradation chart in Table 1. The blending of the three sizes provided a gradation similar to the pervious type materials found along much of our State highway system.

9.1.2 Monterey Sand

This sand is processed in Monterey, California by Lone Star Industries in various sizes. Three sizes of sand were selected for the gradation for this research project: #3, #0/30 and the #LSI30.

Monterey Sand as provided by Lone Star Industries is obtained by screening ocean driven sands near Monterey. The sand is tan to brown in color and has angular but smooth particles. The sand blend used was 40% of the #3, 30 % of the #0/30, and 30% of the #LSI30.

9.1.3 Decomposed Granite, Highway 50 Site

The decomposed granite, obtained from a borrow site in El Dorado County in California, was a clean granular soil with gradation as indicated in Table 1.

MECHANICAL ANALYSIS

Sieve Size	Monterey Sand	Silica Sand	Decomposed Granite
	Passing	Passing	Passing
4	100%	100%	100%
8	99%	98%	92%
16	65%	62%	73%
30	58%	60%	53%
50	12%	22%	34%
100	2%	3%	21%
200	0%	1%	13%

TABLE 1

The sand materials used in this research were individually blended to produce a consistent comparable gradation for all samples. However, the decomposed granite was used as obtained from the borrow site and contained more fines than the two sands.

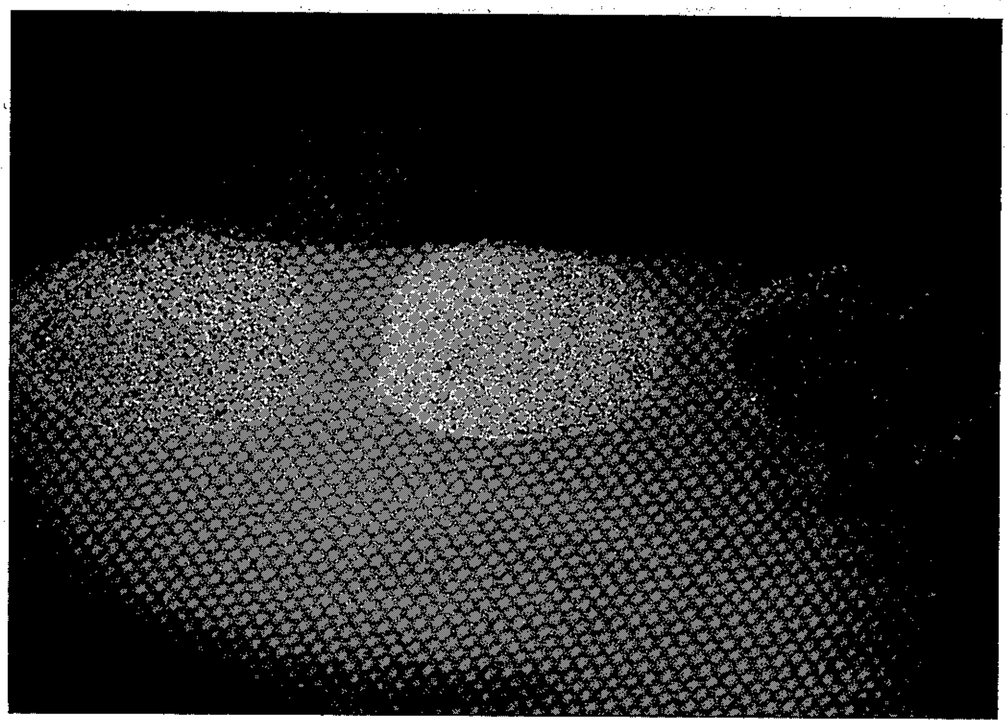


Photo 21 Sands - Left to Right - 1. Monterey Sand, 2. Silica Sand, 3. Decomposed Granite

9.2 Yarns - Type and Source

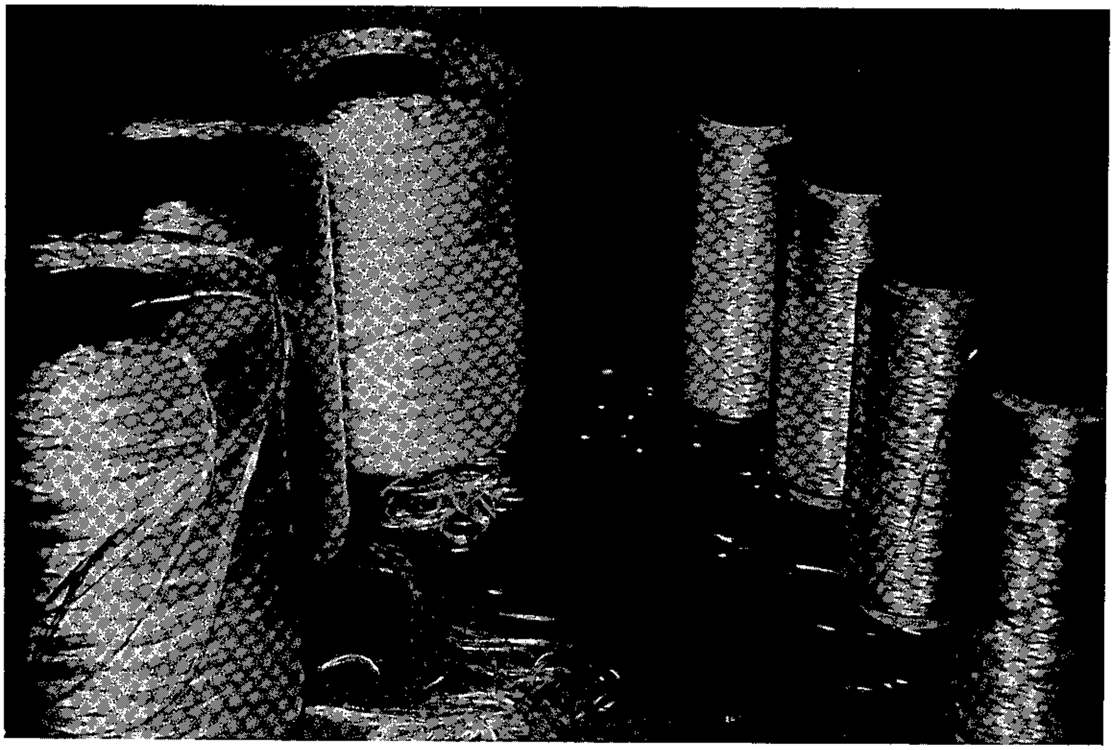
Various fibers and yarns from numerous companies were investigated for this research project including fiberglass roving, monofilaments, chopped yarn, continuous polypropylene yarn and continuous polyester yarns. Continuous yarns of polypropylene and polyester were selected for this research project.

9.2.1 Polypropylene

The Phillips Corporation supplied the polypropylene yarn used in this research, Photo 22. The yarn had fibers of from 4.5 to 6.5 denier per filament (dpf) with 100, 200, and 400 filaments per yarn. These yarns were bundled into 24 ply for the 100 filament yarn, 12 ply for 200 filament yarn, and 8 ply for the 400 filament yarn.

9.2.2 Polyester

Hoechst/Celanese Corporation provided polyester yarn at 1000 denier containing 192 filaments per yarn with a dpf of 5.2, Photo 22. Hoechst/Celanese had difficulty combining the yarns into plys, so we accepted the 1000 denier yarn with 192 filaments per yarn and increased the number to obtain an equivalent sample. Being able to adjust the speed of the yarn feed provided a greater range of the type and denier of yarn we could use.



Polypropylene (Phillips) Polyester (Hoechst/Celanese)
Photo 22 Yarns

10 TESTING - SAMPLE INFORMATION

10.1. Core Preparation

10.1.1 Procedure to Test Maximum Density and Optimum Moisture

Prior to the yarn testing, the maximum density and optimum moisture for each material were determined by California Test 216, "Method of Test For Relative Compaction of Untreated and Treated Soils and Aggregates".

TABLE 2 -Test for Maximum Density

6 x 14 inch core sample maximum density

Material	100% Comp. (grams)	95% Comp. (grams)
Monterey Sand	11,938	11,341
Moisture 9.5%	1,134	1,077
Total	13,072	12,418
Silica Sand	11,727	11,141
Moisture 10%	1,173	1,114
Total	12,900	12,255
Decomposed Granite	11,938	11,341
Moisture 13%	1,551	1,474
Total	13,489	12,815

Maximum Density

Material	Moisture	Maximum Density (pounds per cubic foot)
Monterey Sand	9.5%	113
Silica Sand	10%	111
Decomposed Granite	13%	111

10.1.2 Tests

In order to develop a data base for comparison in this study, a series of five triaxial cores was fabricated for each variable. For the Monterey and Silica sands, five cores were prepared with and five cores without polypropylene yarn; and five cores with and five cores without polyester yarn. Also five cores with polypropylene yarn and five cores without were prepared for the decomposed granite sample. Similarly, five permeability samples were prepared for each soil with and without yarn for all three materials. .

Two densities were evaluated without yarn, 95% and 100%. Only the 95% relative density was used with yarn. The assumption was made that 100% relative density was not a practicality in the field.

10.1.3 Test Core Fabrication Procedures

1. Prepare a liner by inserting the rubber membrane and securing it to the liner with plastic electrical tape. The rubber membrane extends down the outside of the liner approximately 2 inches.

2. Mount the liner in the mold and secure it and the mold to turntable.

3. Place the plastic disc in the bottom of the mold.

4. Prepare 12,000 gram sample plus or minus as dictated by density requirements, with optimum moisture.

5. Divide the sample into five equal parts.

6. Set load cycle: turntable time and loader time.

7. Set tamp cycle: turntable time, oscillation time, drop height, delay after limit; number of loads, number of tamps and number of layers always equals one for this system.

8. Place sample on conveyer.

9. Activate programs, twenty-five loader increments and yarn distribution in one minute and fifteen seconds. The tamper then activates for the number of selected blows with the tamper dropping, the turntable revolving seven increments, totaling one revolution of the turntable, and the oscillation of the turntable moving 1/8 inch with each increment of the turntable. A total of five layers are compacted in this manner for triaxial samples.

10. The top of the sample is smoothed off to a level plane without soils loss or removal. The piston is now placed in the top of mold. The final five blows are added to the sample to bring the core to the predetermined volume derived from California Test 216.

11. The piston is removed and a filter paper and plastic disc are placed on the top of the core sample. The remaining volume is filled with hydrostone cement. The top of the liner or final sample is sealed with an additional plastic disc fastened with plastic electrical tape. The sample is them removed from the turntable and the bottom is sealed in the same fashion as the top, Photo 23.

12. The sample is now ready for triaxial testing. The sample is either tested or stored in a fog room until it is ready for triaxial testing. Even though some samples are tested immediately, the sealing procedure is essential for transport, and to prevent introduction of an uncontrolled variable.

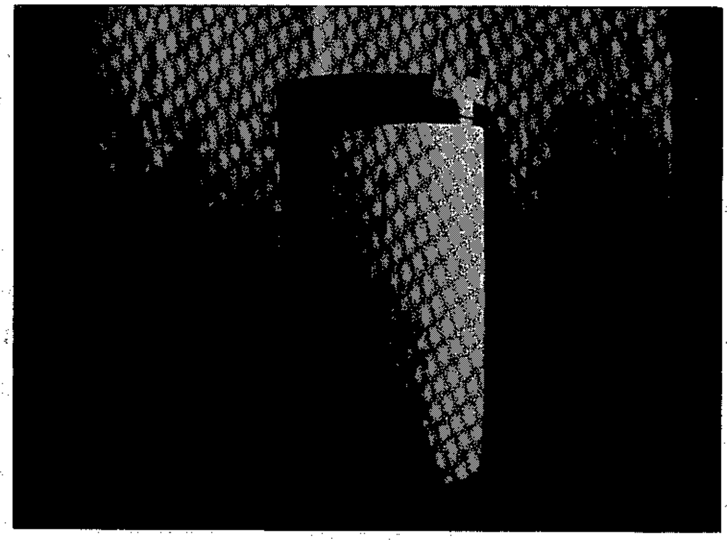


Photo 23 - Test Core Sample

10.2 TRIAXIAL TESTING

10.2.1 Equipment

See California Test 230 "Method of Test For Triaxial Compression of Soils"

10.2.2 Testing - Consolidated Undrained Triaxial Test with Pore Pressure

The consolidated undrained test with pore pressure is used to predict the in-place strength of soils after consolidation under known loads. The effective stress envelope may be produced by subtracting the effects of pore water pressure. This test is conducted at a relatively slow rate of strain.

When the sample is ready for triaxial testing the sample is removed from the fog room, the seals are removed from the top and bottom of the sample and the core sample is extracted from the PVC insert liner still encased in the membrane, Photo 24.

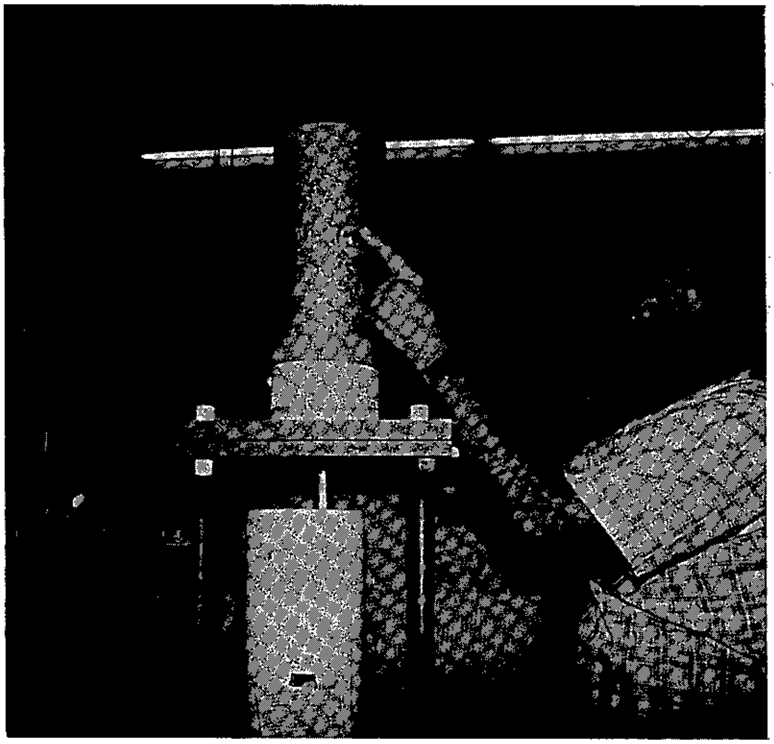


Photo 24 - Extracting Core for Triaxial Testing

10.2.3 Results

Complete results of triaxial testing are shown in Tables 4 through 6 along with the tabulation of values for the variables in Appendix A. The total data package is available at The Division of New Technology, Materials and Research, 5900 Folsom Blvd, Sacramento, CA 95819. A completed test core is shown in Photos 25 and 26.

When blending fibers into the soil mass, the continuous yarn typically separates to form networks of very small diameter fibers. Thus, the incidence of fiber per unit cross section within the soil was increased beyond that of any single fiber tested, Photo 25. Some specific fibers, surface textures and diameters could be better suited to specific applications.

The observed degree of enhancement in geotechnical parameters resulting from adding fibers does not suggest universal application in compacted fills. The increases are significant enough to suggest that a resultant design could be used for solving site-specific problems and to obtain desired performance characteristics. The anticipated substantial apparent cohesion increase was not observed.

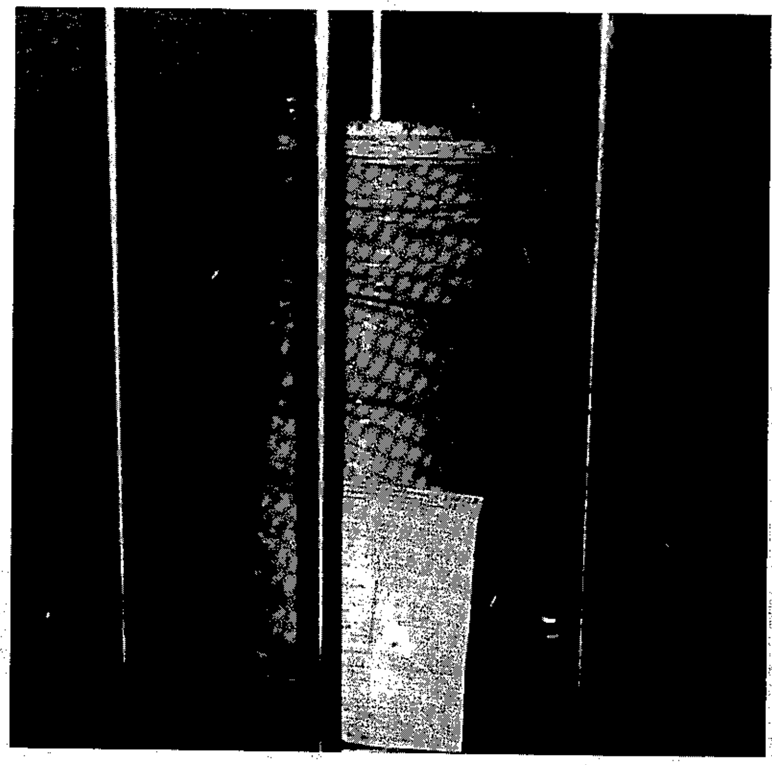


Photo 25 - Tested Triaxial Core

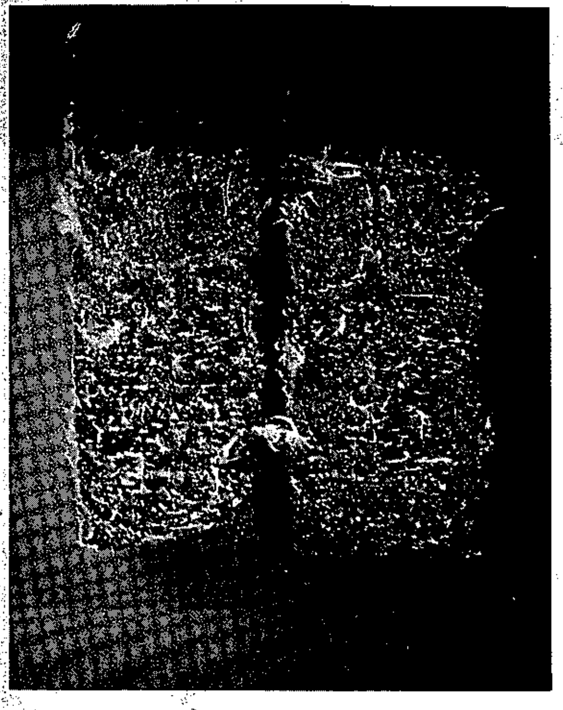


Photo 26 - Reinforced Yarn Sample

The Mohr envelope from effective stress path for Monterey Sand with 0.2% polypropylene yarn without pore pressure resulted in 0 pounds per square foot apparent cohesion increase. With Silica Sand the results show 200 pounds and with decomposed granite with 0.2% polypropylene, the results show 700 psf cohesion.

With the samples of each material using 1% polypropylene, the results show a significant increase in the apparent cohesion. Monterey Sand showed 1600 psf as did the Silica Sand samples. The higher quantity of polypropylene in the sample did increase the strength; however, experience from field installations by the French indicates that additional yarn does not significantly increase strength. If anything, the soil tends to lose strength as greater amounts of yarn are used. French experience has indicated that 0.2% is the optimum quantity that should be used. However, their experience is primarily with polyester, not polypropylene. Our results, as indicated in Tables 4 through 6, indicate a slightly greater strength increase with polyester fibers over that obtained with polypropylene.

An investigation into the testing methods and strain rates may reveal procedures or apparatus that mask the anticipated strength increases at low yarn volumes.

10.3 Permeability Testing

Permeability testing was used to compare the soils' ability to drain both with and without yarn inclusions, a potentially important characteristic when buttressing in place soils.

10.3.1 Equipment:

It was determined early in the research to utilize 6-inch diameter permeability testing to match existing lab equipment. To facilitate this, 6-inch diameter by 6-inch tall concrete sample cans were used to compact permeability core samples in the same manner as the 6 x 14 inch core samples for triaxial testing. The cans provided an undisturbed compacted sample for testing. The 6-inch diameter by 6-inch high core specimen was selected to provide consistent samples of the material, Figure 7, as well as to be compatible with the existing fabrication equipment. During the course of the research there were three samples for each variable. The range of results is shown is Table 3.

The first step in preparation of the permeability test samples is to remove the bottom from the 6-inch concrete sample can. This, provides an acceptable form that will hold the sample and can be ejected easily from the liner, slipped into the permeability chamber, sealed and tested. The 6-inch cans are slightly smaller than the liner thus requiring a 1/8-inch thick by 4.5-inch high shim that is designed to encompass the can during compaction and fill the void between can beads. The can, shim, and split PVC liner, which separates into two parts are shown in Photo 27. They are all installed into the mold and the sample is fabricated in the same manner as the triaxial samples, except quantities which reflect a shorter sample. (See Section 8.)

After fabrication the sample is removed from the compactor and both ends sealed in the same manner as the 6-inch triaxial core samples, Photo 28. The samples are then conveyed to the fog room to await permeability testing.

The same compactive effort is applied to the permeability test sample as applied to the triaxial samples in the 6-inch core sample series. The samples were set for compaction of 95% and 100% to evaluate their relative permeabilities.

10.3.2 Testing

See California Test 220 "Method of Test for Permeability of Soils", Photo 29.

10.3.3 Results

There was very little difference in the permeability rate from the basic sand and those samples with yarn at different percentages. There is considerable difference between the 100% and the 95% compaction permeabilities, substantiating that, as the particles tend to move closer together with the additional compactive effort they pass less water. Samples compacted at 100% compaction had approximately half the permeability of those compacted at 95%.

Adding 0.2% yarn to both the sands slightly increased the permeability. However, when the yarn was increased to 1% the permeabilities tended to drop. This indicates that small amounts of yarn do not reduce soil permeability significantly. See the results tabulated in Table 3.

The permeability of the decomposed granite showed a drop in rate from 1.14 feet per day in the samples without yarn to .95 feet per day with yarn. This indicates a possibly significant variability in permeability with the combination of decomposed granite and yarn, suggesting that soils high in fines cannot accept the yarn inclusions without an effect.

Photo 27 - Permeability Preparation,
Mold, Liner and Can

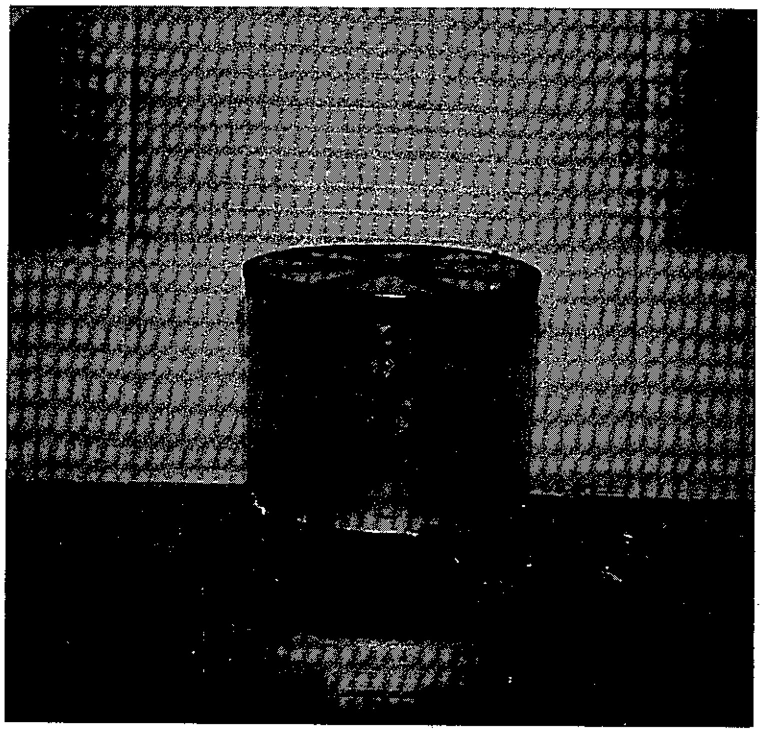


Photo 28 - Sealed Permeability Test Core

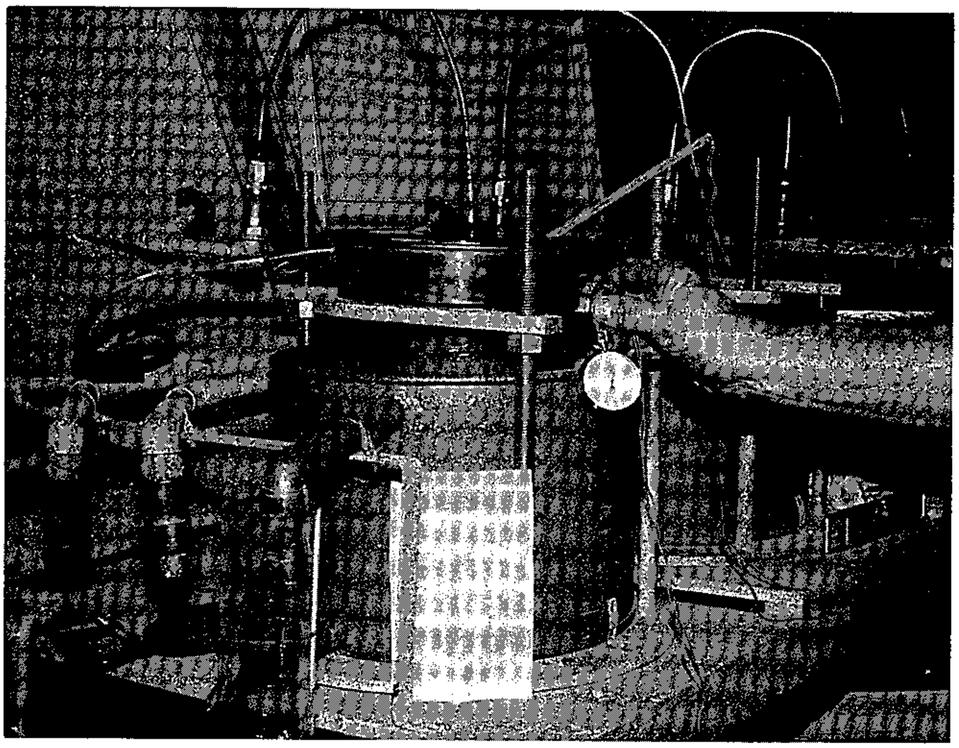


Photo 29 - Permeability Test in Progress

PERMEABILITY RATES

Rate (Cu/Ft per day)

Material	Compaction	Rate
Silica Sand	95% Compaction	25
" "	" " w. 0.2% yarn	26
" "	" " w. 1% yarn	22
" "	100% Compaction	11
Monterey Sand	95% Compaction	41
" "	" " w. 0.2% yarn	49
" "	" " w. 1% yarn	39
" "	100% Compaction	25
Decomposed Granite	95% Compaction	1.4
" "	" " w. 0.2% yarn	.9

TABLE 3

11 DATA DISCUSSION

The triaxial testing effective stress paths were used to determine Mohr envelopes for Monterey Sand, Silica Sand and the decomposed granite with no negative pore pressure, Charts 1-7. The samples with 0.2% polyester yarn did result in slightly higher strengths. However, the different yarn did not appear to have a significant effect upon the sample.

All samples were saturated for approximately 12 hours. Higher values may have been obtained if the samples had been saturated at a slower rate, possibly a 24 hour saturation rate . Both the Monterey and Silica Sands with 1% polypropylene show an apparent cohesion of 1600 PSF, Charts 2 and 5. This higher cohesion is inconsistent with the general experience of the French. However, their experience is with polyester rather than with polypropylene. Our data also indicates a potential for higher strengths with polyester.

The rate of strain during the triaxial testing over a 12-hour period may not have provided sufficient time for the sample to respond. In future testing a 24-hour strain period is recommended so that a more definitive result may be achieved.

The soils were tested for relative compaction at 100% compaction and 95% compaction. This was used to determine the volume of material required for compacting 95% compaction yarn soil samples.

The yarn did not appear to displace additional volume in the core samples. The yarn tended to be included in the volume of air space in the sample. The relative effect of yarn inclusion was evaluated by comparing the apparent cohesion of the Mohr enveloped developed from the effective stress path at zero negative pore pressure.

The sample of Monterey Sand with 0.2% polypropylene yarn and the decomposed granite increased from zero for the Monterey Sand with 0.2% polypropylene (Chart 1 - Appendix A) to 700 # for the decomposed granite (Chart 7). The Silica Sand was at 200 PSF for both the 0.2% polypropylene and the 0.2% polyester samples. Tests with the 1% polypropylene in both sands resulted in much higher Mohr envelope intercepts.

12. REFERENCES

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2) Freliag D. R. (1986) "Soil Randomly Reinforced with Fibers" J. of Geotechnical Division, ASCE, 112 (8) August pp 823-826.

3.) Gray, D. G., and T. Al-Refeai, 1986 "Behavior of Fabric versus Fiber-Reinforced Sand", J. of Geotechnical Divisions, ASCE, 112 (8) pp 804-819.

4.) Gottschall, C., Special Report of a Texsol Retaining Wall, FHWA, July 6, 1989

13. APPENDIX

APPENDIX A - TEST VARIABLES AND MOHR ENVELOPES TRIAXIAL TESTS - MONTEREY SAND

Pressure Test I	Date	Moist	Compaction	* % Yarn	** % Yarn	Pseudo Cohession
129	1-4-90	9.5%	100%			
101	12-20-80	9.5%	100%			
102A	1-24-89	9.5%	100%			
103A	1-24-89	9.5%	100%			
130	1-4-90	9.5%	100%			
131	1-4-90	9.5%	95%			
104A	1-24-89	9.5%	95%			
105	12-20-88	9.5%	95%			
106	12-20-88	9.5%	95%			
132	1-4-90	9.5%	95%			
133	1-10-90	9.5%	95%	.2%		
117	3-9-89	9.5%	95%	.2%		
118	3-9-89	9.5%	95%	.2%		0 psf
134	1-10-90	9.5%	95%	.2%		
135	1-10-90	9.5%	95%	1%		
120	3-9-89	9.5%	95%	1%		
121	3-9-89	9.5%	95%	1%		1600 psf
122	3-9-89	9.5%	95%	1%		
136	1-17-90	9.5%	95%	1%		
137	2-6-90	9.5%	95%		.2%	
138	2-6-90	9.5%	95%		.2%	
139	2-6-90	9.5%	95%		.2%	100 psf
140	3-21-90	9.5%	95%		.2%	
141	3-21-90	9.5%	95%		.2%	

TABLE 4

* Polypropylene by weight

** Polyester by weight

Note: (102A) "A" after test number indicates a supplemental sample, resulting from operational problems during the testing of the original sample.

TRIAXIAL TESTS - SILICA SAND

Pressure Test #	Date	Moist.	Compaction	* % Yarn	** %Yarn	Pseudo Cohession
147	1-9-90	11%	100%			
109	2-8-89	11%	100%			
110	2-8-89	11%	100%			
111A	2-8-89	10%	100%			
148	1-9-90	10%	100%			
149	1-9-90	10%	95%			
113	2-8-89	10%	95%			
114A	5-5-89	10%	95%			
115	2-8-89	10%	95%			
150	1-9-90	10%	95%			
151	1-18-90	10%	95%	.2%		
123	3-14-89	10%	95%	.2%		
124	3-14-89	10%	95%	.2%		200 psf
125	3-14-89	10%	95%	.2%		
152	1-18-90	10%	95%	.2%		
153	1-17-90	10%	95%	1%		
126	3-14-89	10%	95%	1%		1600 psf
127	3-14-89	10%	95%	1%		
128	3-14-89	10%	95%	1%		
155	3-21-90	10%	95%		.2%	
156	3-21-90	10%	95%		.2%	
157	3-21-90	10%	95%		.2%	500 psf
158	3-21-90	10%	95%		.2%	
159A	3-21-90	10%	95%		.2%	

TABLE 5

* Polypropylene by weight

** Polyester by weight

Note: (111A) "A" after test number indicates a supplemental sample, resulting from operational problems during the testing of the original sample.

TRIAXIAL TESTS - DECOMPOSED GRANITE

Test #	Date	Moist.	Compaction	* % Yarn	Pseudo Cohession
165A	1-25-90	9.5%	95%		
166	1-25-90	9.5%	95%		
167	1-25-90	9.5%	95%		
168	1-25-90	9.5%	95%		
169	1-25-90	9.5%	95%		
170	1-26-90	9.5%	95%	.2%	
171	1-26-90	9.5%	95%	.2%	
172	1-26-90	9.5%	95%	.2%	700 psf
173	1-26-90	9.5%	95%	.2%	
174	1-26-90	9.5%	95%	.2%	

* Polypropylene by weight

Note: (165A) "A" after test number indicates a supplemental sample, resulting from operational problems during the testing of the original sample.

TABLE 6

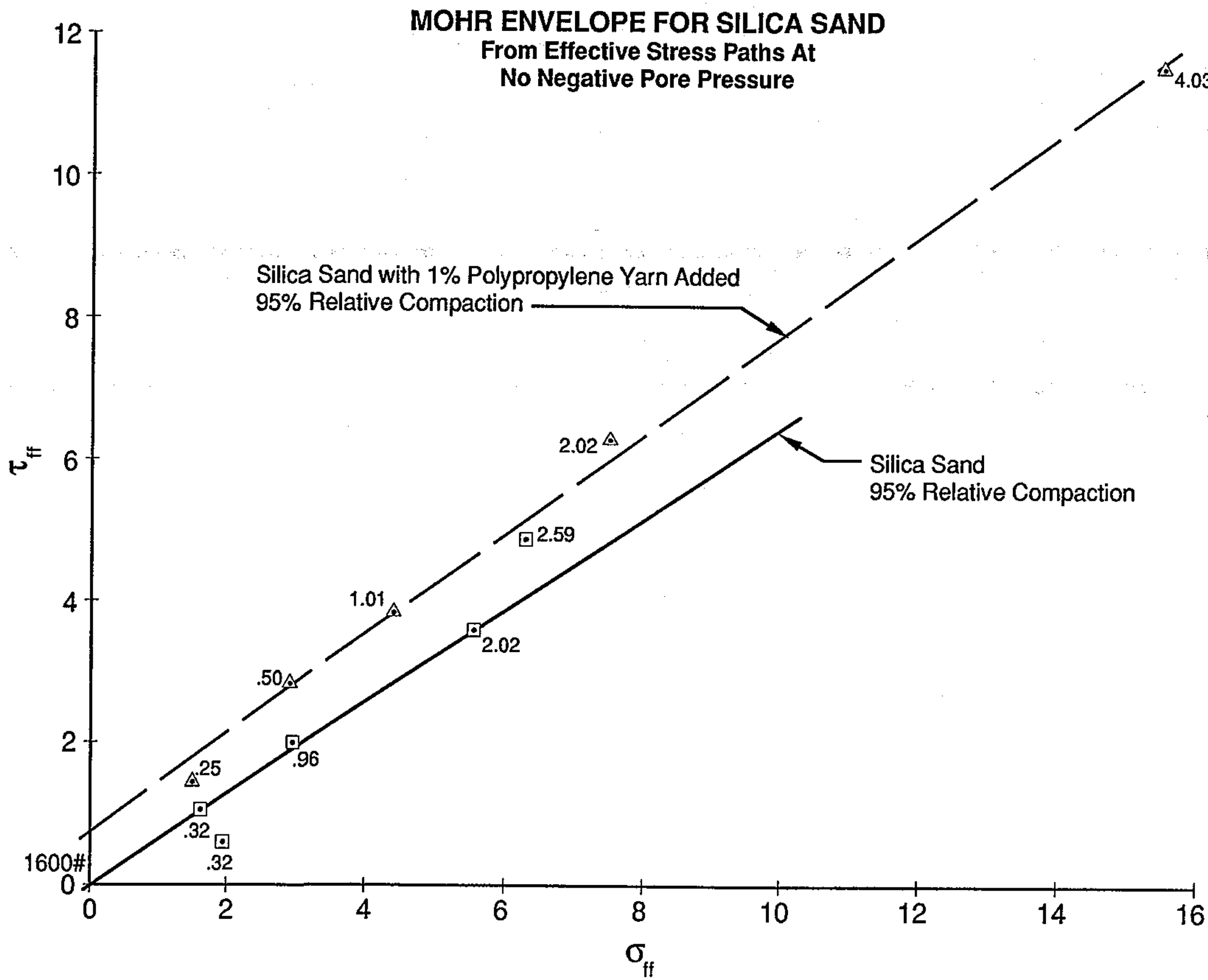

MOHR ENVELOPE FOR SILICA SAND
From Effective Stress Paths At
No Negative Pore Pressure
Silica Sand with 1% Polypropylene Yarn Added
95% Relative Compaction
Silica Sand
95% Relative Compaction
4.03
2.02
2.59
1.01
2.02
.50
.96
.25
.32
.32
1600#
0
2
4
6
8
10
12
14
16
12
10
8
6
4
2
0
τ_{ff}
σ_{ff}

Chart 1

MOHR ENVELOPE FOR SILICA SAND
From Effective Stress Paths At
No Negative Pore Pressure

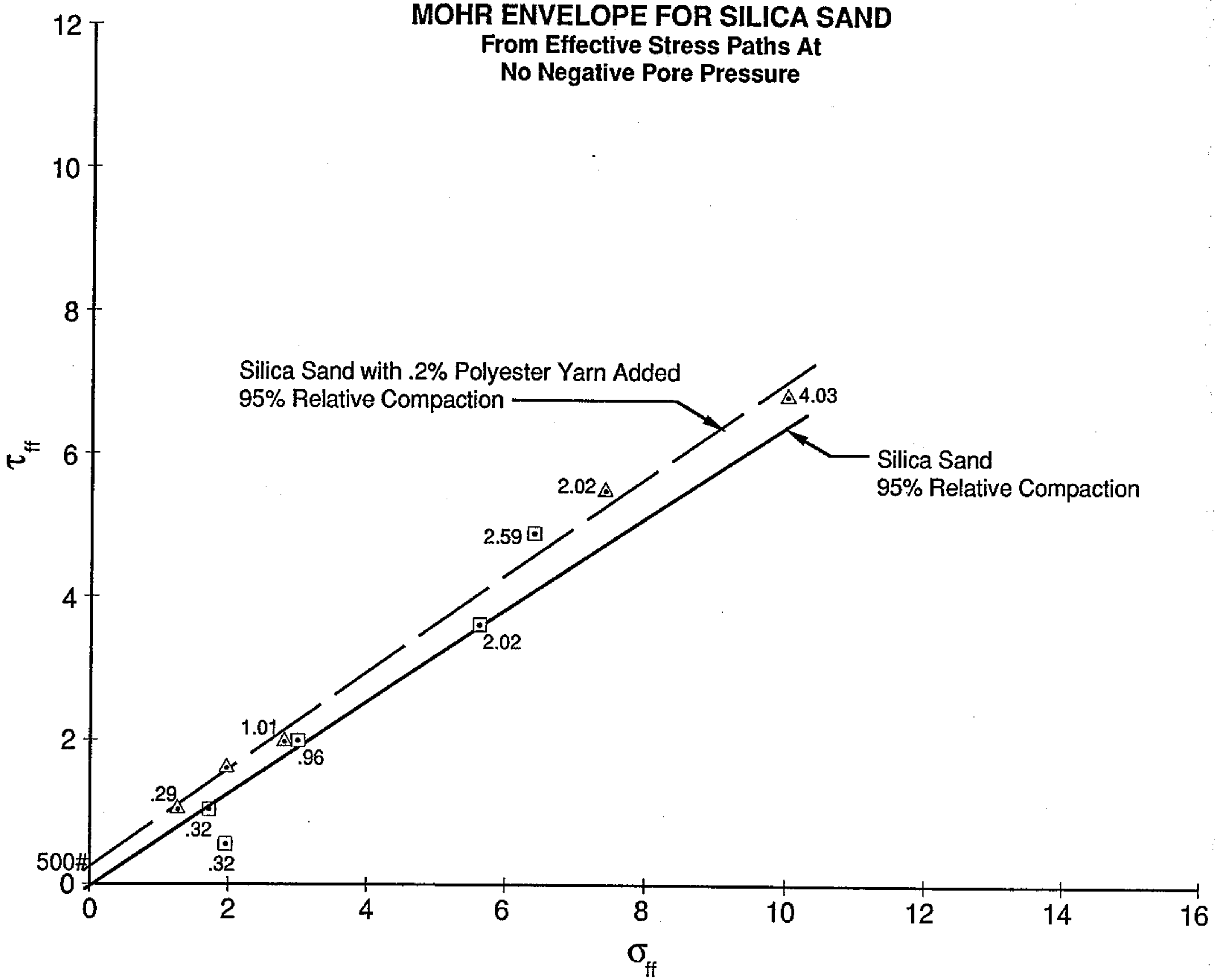
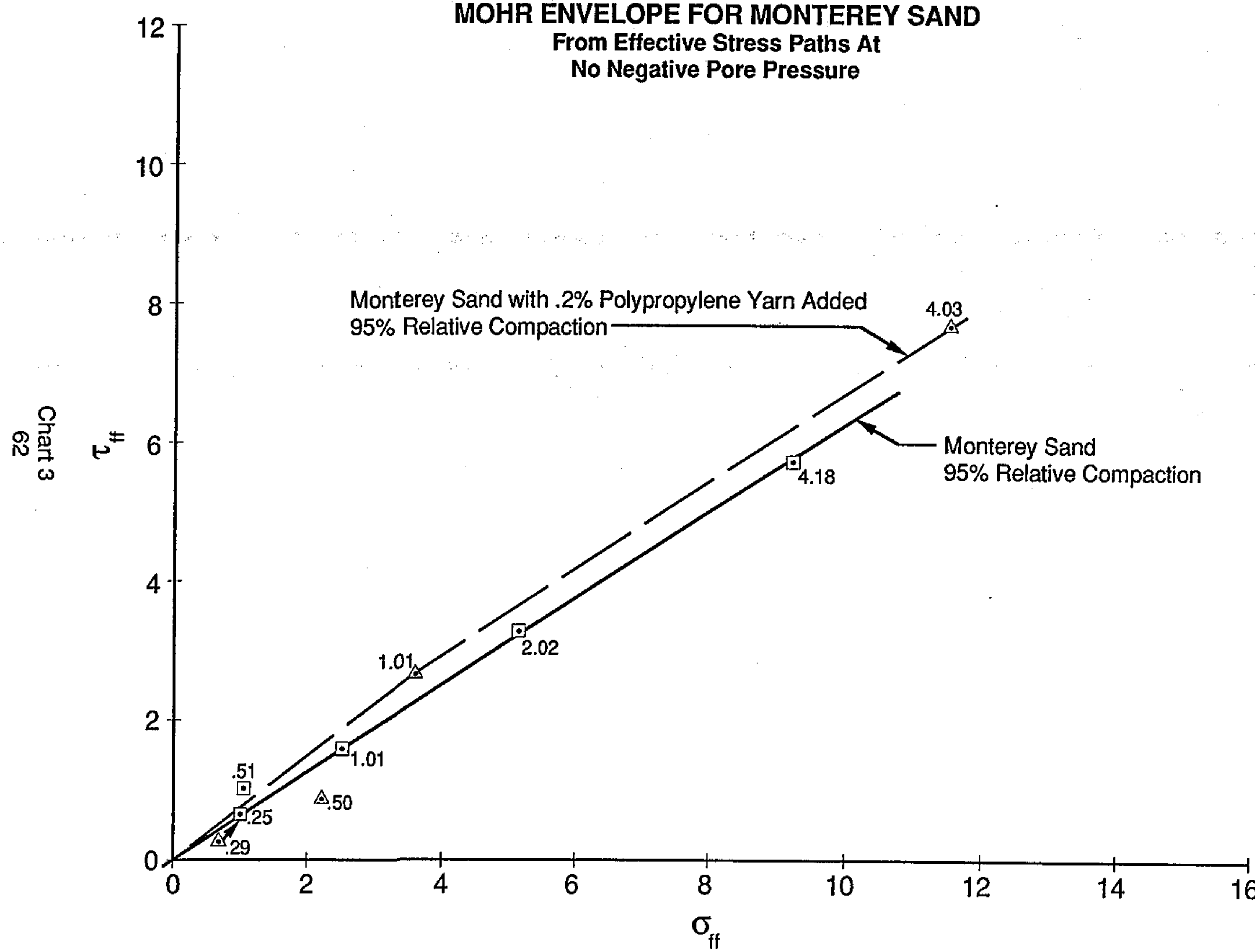


Chart 2

MOHR ENVELOPE FOR MONTEREY SAND

From Effective Stress Paths At No Negative Pore Pressure



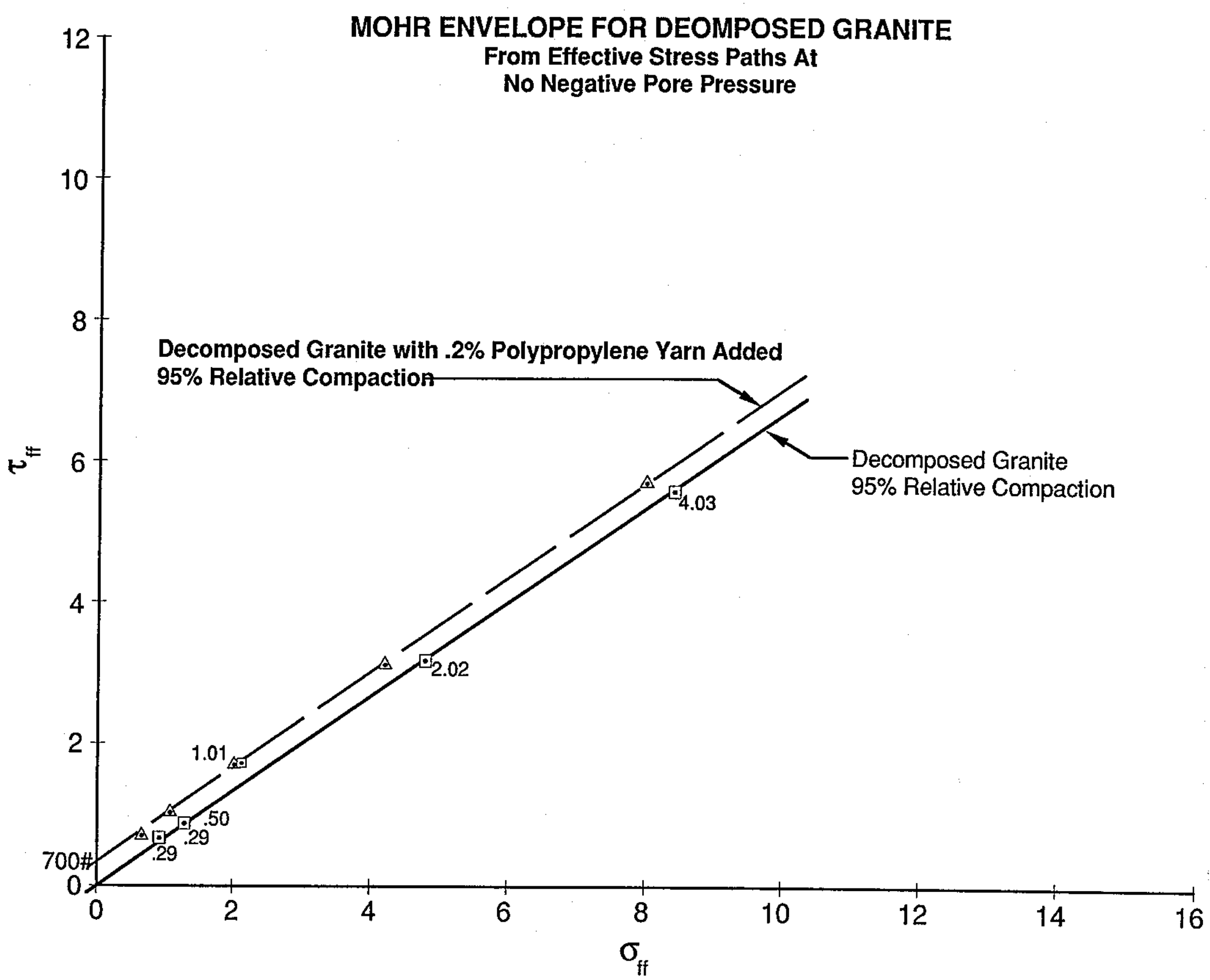

MOHR ENVELOPE FOR DEOMPOSED GRANITE
From Effective Stress Paths At
No Negative Pore Pressure
Decomposed Granite with .2% Polypropylene Yarn Added
95% Relative Compaction
Decomposed Granite
95% Relative Compaction
12
10
8
6
4
2
0
700#
τ_{ff}
0
2
4
6
8
10
12
14
16
σ_{ff}
1.01
.50
.29
.29
2.02
4.03

Chart 4

MOHR ENVELOPE FOR MONTEREY SAND
From Effective Stress Paths At
No Negative Pore Pressure

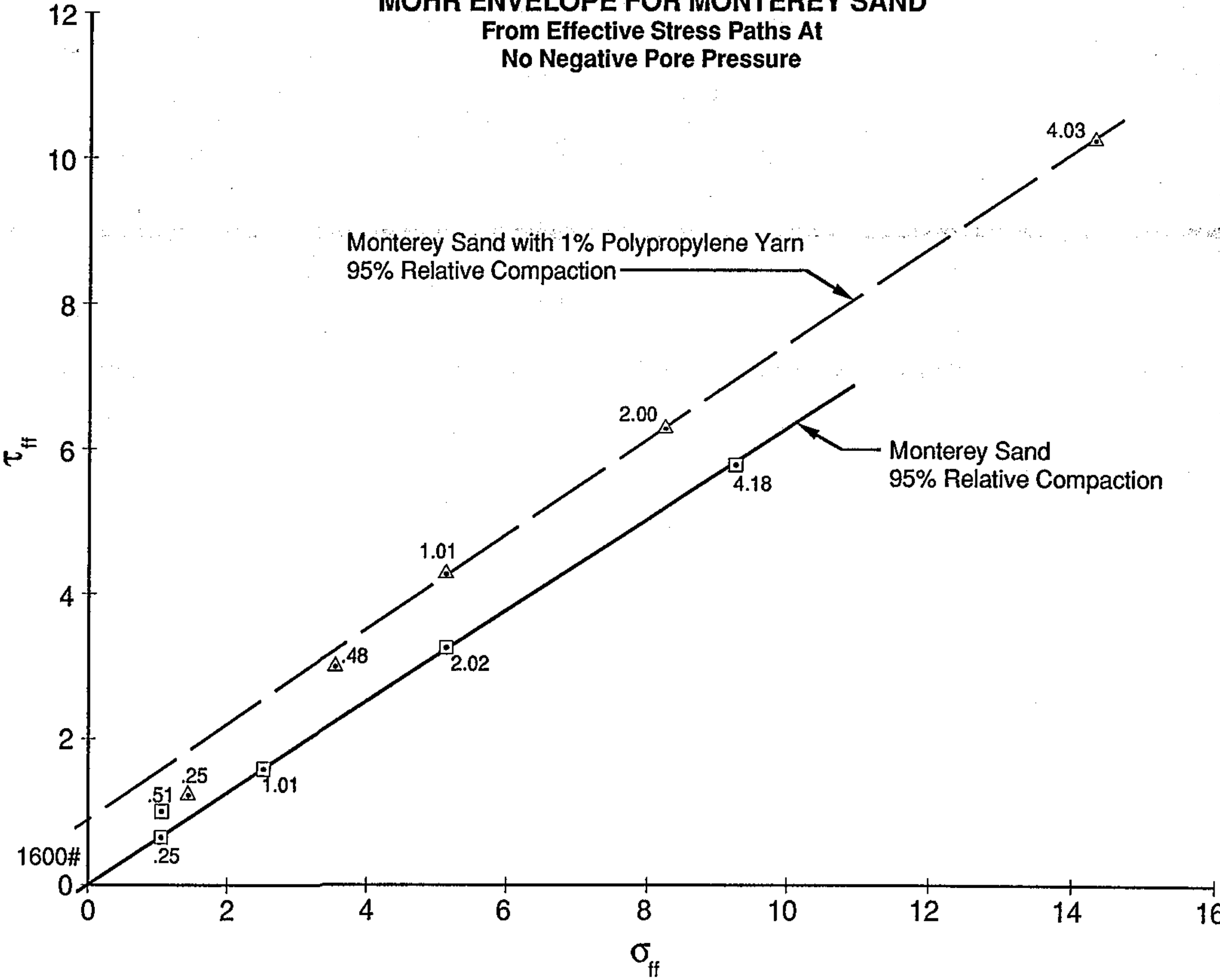


Chart 5

MOHR ENVELOPE FOR SILICA SAND

From Effective Stress Paths At
No Negative Pore Pressure

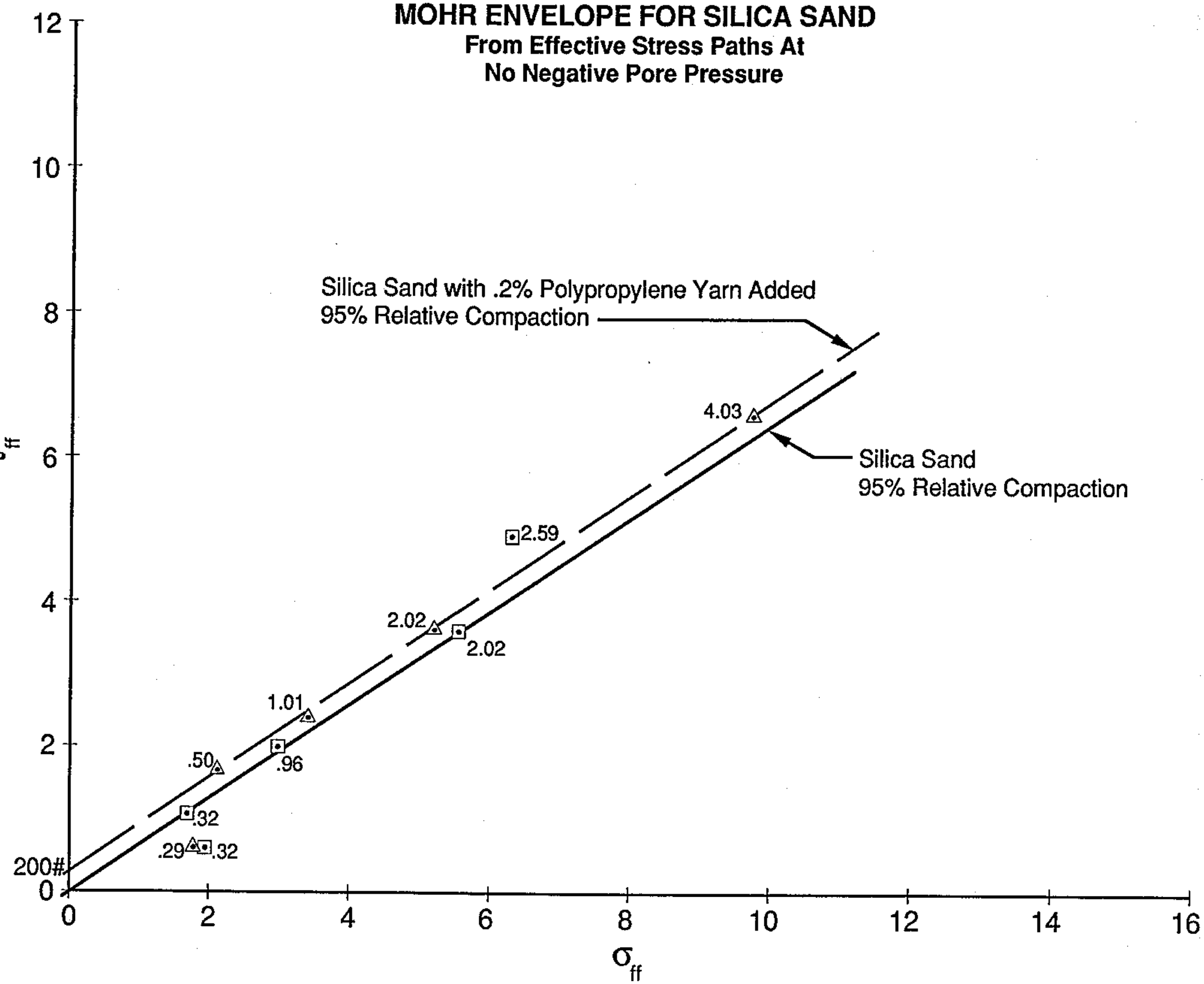
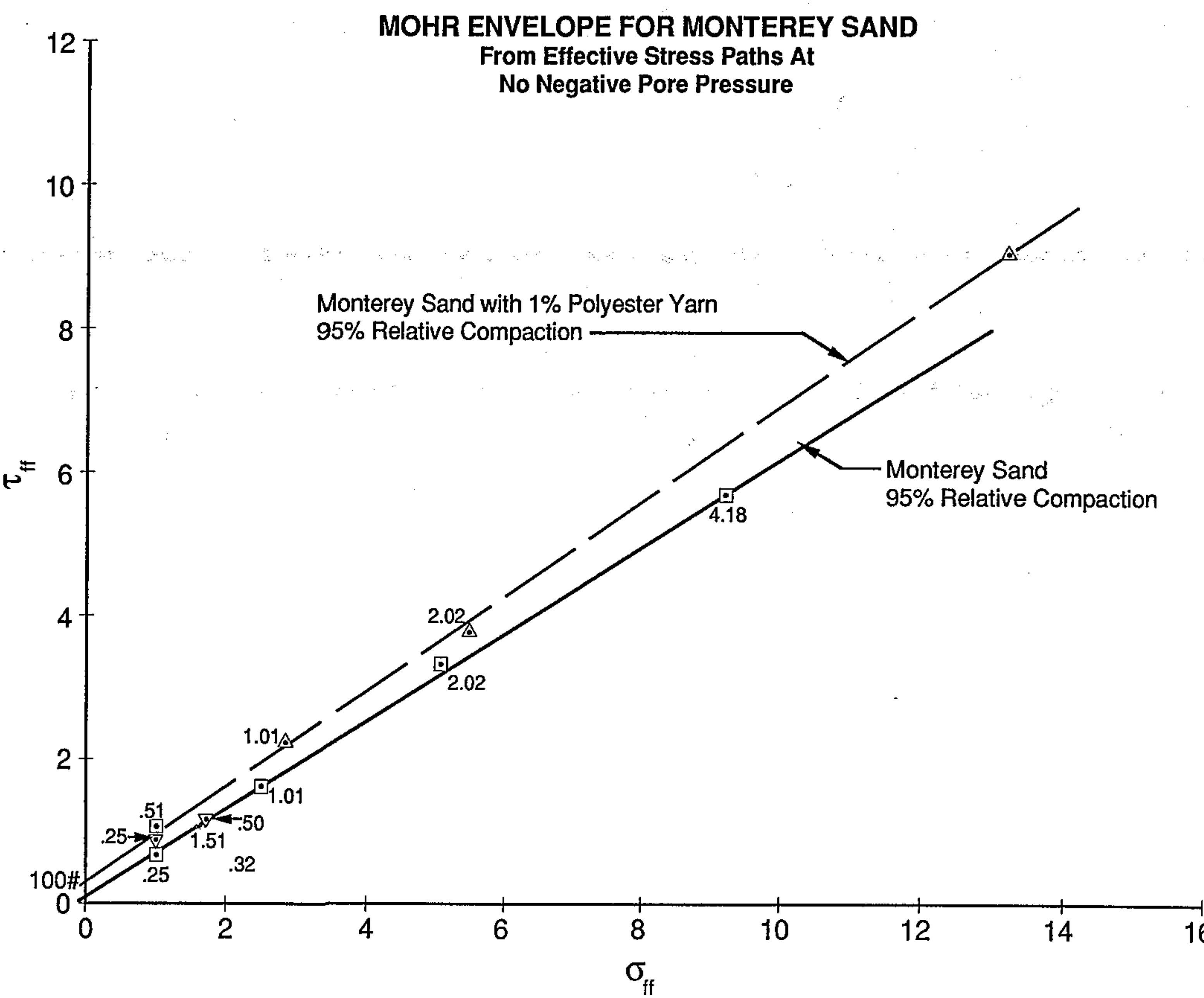


Chart 6


MOHR ENVELOPE FOR MONTEREY SAND
From Effective Stress Paths At
No Negative Pore Pressure
Monterey Sand with 1% Polyester Yarn
95% Relative Compaction
Monterey Sand
95% Relative Compaction
4.18
2.02
2.02
1.01
1.01
.51
.25
.50
1.51
.25
.32
100#
τff
σff
0
2
4
6
8
10
12
14
16

APPENDIX B - SAMPLE LINER CALIBRATION METHOD

Method for Calibration of 6-inch PVC Compaction Test Liners.

SCOPE

The procedure for calibration of test liners is described and outlined in this method. The equipment is used for determining the volume of test core liners used in the test for maximum density of 6-inch samples of yarn reinforced soils.

PART I Method of Calibrating the Test Liner.

A. Apparatus, Photo 30

1. A PVC cylindrical mold liner.
2. Weighing scale of minimum 10 kilogram capacity, sensitive to 1 gram.
3. Pouring containers for water 8 kg capacity.
4. Eyedropper
5. Six-inch PVC compaction liner clamp, Photo 30
6. Unbreakable flat transparent nonpliable plate about 7 inches square, two each, part of liner clamp system
7. Water insoluble heavyweight grease.
8. Thermometer
9. Small level
10. Metal shims
11. Two hold-down bolts 18 inches long with wing nuts.
12. Ancillary liner calibration test equipment, Photo 31:

Procedure for Calibrating

1. Place liner clamp in position and level with shims

2. Examine joints and machined surfaces of liner, baseplate and piston to insure that they are smooth and do not show visible openings. Examine the hold-down bolts and wing nuts. Repair or replace them if necessary.

3. Examine the liner to see if it is out of round. Measure the inside diameter of the liner at 2 points 90 degrees to each other. Measure both at the same distance from the end of the liner. The difference between two corresponding measurements at any point in the liner shall not exceed 0.064 inch (1.6mm). If the liner cannot be brought within these tolerances, discard the liner.

4. Place a thin bead of grease on the rim of the liner. This grease bead seals the seam between the liner and the plastic base. Place the greased end of the liner on the plastic base in the clamp. Remove any excess grease. Grease the top rim of the liner.

5. Fill the water container with approximately 8000 grams of water. Weigh the water, containers, and eyedropper to the nearest gram. Record this gross initial weight.

6. Carefully pour the weighed water into the sealed liner to a point near the top. Place the plastic top on the pregreased rim and secure finger tight with washers and nuts. Add additional water with the eyedropper though the hole in the center of the plastic top. Above all, do not spill or lose any of the water.

7. Gently tap the edge of the mold to allow the air to escape the sealed vessel. This technique aids in determining whether the liner is completely filled with water. If the liner shows air bubbles, tap the cylinder until only water can be seen and the air has escaped the liner. Be careful not to lose any water.

8. The difference between the initial and final weight of water is the volume in cubic centimeters of the liner. Temperature corrections are made according to the values shown Table B-1.

9. Use this volume to calculate the soil volume needed for desired relative compaction.

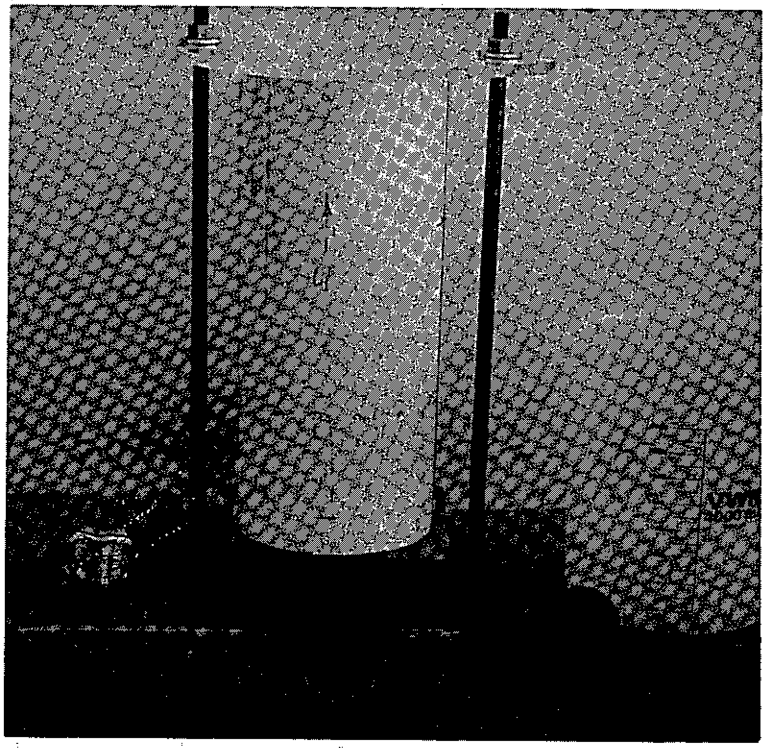


Photo 30 - Liner Calibration Test Equipment

TABLE B-1

VOLUME OF WATER PER GRAM BASED ON TEMPERATURE*

Deg C	Deg F	Volume of H_2O, ml/g
12	53.6	1.00048
14	57.2	1.00073
16	60.8	1.00103
18	64.4	1.00138
20	68.0	1.00177
22	71.6	1.00221
24	75.2	1.00268
26	78.8	1.00320
28	82.4	1.00375
30	86.0	1.00435
32	89.6	1.00497

* Values other than shown may be obtained by referring to the Handbook of Chemistry and Physics, Chemical Rubber Publishing Company, Cleveland Ohio.

Example: If the weight of water is 944 grams and the temperature is 86° F, the product of 944 and 1.00435 is 948 cc.