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16. Abstract

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REVIEW OF UNDRAINED SHEAR STRENGTH TESTING METHODS USED BY THE TEXAS STATE DEPARTMENT OF HIGHWAYS AND PUBLIC TRANSPORTATION

by

Edward S. O'Malley
Stephen G. Wright

Research Report 446-1F

Shear Strength for Embankment and Retaining Wall Design
Research Project 3-5-85-446

conducted

Texas State Department of Highways
and Public Transportation

in cooperation with the
U.S. Department of Transportation
Federal Highway Administration

by the

Center for Transportation Research
Bureau of Engineering Research
The University of Texas at Austin

November, 1987

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

PREFACE

Reliable estimates of the undrained shear strength of foundation soils are needed for design of embankments and retaining wall foundations on soft clay soils. The Texas State Department of Highways and Public Transportation (SDHPT) has employed a variety of test procedures for estimating shear strengths for such design purposes. The SDHPT has performed Texas Triaxial, Texas Transmatic, and field vane shear tests. None of the laboratory test procedures are used in geotechnical engineering practice outside the Department and limited data has shown that at least some type of correction should be applied to the strengths measured in the Texas Triaxial test, although it does not appear that such a correction has been used in actual practice. The SDHPT has also utilized consultants outside the Department for the purpose of determining undrained shear strengths. These outside consultants have generally used conventional unconsolidated-undrained (UU, Q-type) triaxial shear tests to determine undrained shear strengths. Accordingly, the SDHPT has employed undrained shear strengths determined in a variety of ways, at least some of which are known to introduce errors and require some form of correction.

Research Project 446 was undertaken to review and evaluate various test methods employed by the Texas SDHPT as well as by outside consultants to determine undrained shear strengths of clays. The objectives of the study were to recommend appropriate test procedures for this purpose and to recommend any corrections or changes in the existing procedures and methods employed by the Texas SDHPT.

ABSTRACT

This report presents the results of a study conducted to evaluate the various laboratory test methods used by the Texas State Department of Highwyas and Public Transportation for determining the undrained shear strengths of clays. Shear tests were performed using the Texas Triaxial, Texas Transmatic, conventional (ASTM) unconsolidated-undrained, and vane shear apparatus. Tests were performed on a variety of specimens including: (1) soft remolded specimens prepared by packing soil into specially fabricated tubes, (2) stiffer, remolded specimens prepared by a "vacuum extrusion" process, (3) specimens prepared by compaction using Standard Proctor Compactive effort, (4) undisturbed specimens obtained from the north approach embankment of the proposed State Highway 87 bridge over the Neches River in Port Arthur, Texas, and (5) artificial specimens cast from polyurethane. Strengths measured by the various test procedures were compared and recommendations are made regarding appropriate procedures for use by the Texas SDHPT.

SUMMARY

Several series of laboratory shear tests have been performed using devices and test procedures employed either by the Texas State Department of Highways and Public Transportation or in conventional geotechnical engineering practice to measure the undrained shear strength of clays. The test methods include: Texas Triaxial, Texas Transmatic, unconsolidated-undrained triaxial shear, laboratory vane, and Torvane. Tests were performed on several types of specimens prepared by: packing soil into a mold, using a vacuum extrusion device, and compaction. Additionally, tests were performed on undisturbed specimens and artificial specimens cast of polyurethane. At the outset of this study, it was recognized that the procedures commonly employed by the SDHPT differed from those employed in conventional geotechnical engineering practice and often required that substantial correction be applied to obtain meaningful results. Accordingly, the purpose of most of the tests performed in this study was to evaluate the suitability of existing SDHPT laboratory test procedures for measuring the shear strength of clays and to provide suitable recommendations for modification and improvements.

The results of this study showed that the Texas Triaxial test may substantially overestimate the shear strength of soft clays in comparison to other procedures which are commonly used and accepted as being reliable in geotechnical engineering practice. The overestimate is especially pronounced for shear strengths below 1000 psf and any corrections to the data are impractical. One of the major reasons for the overestimate in shear strength in the Texas Triaxial test appears to be the heavy rubber membrane used to surround the sample. The heavy membrane is necessitated by the design of the apparatus. Attempts were made to develop either theoretical or empirical corrections for the membrane; however, these were not successful due to the dominant effects of the membrane. Significant difficulties were encountered using the Texas Transmatic apparatus provided for this study. Although most of

the difficulties could probbably be eliminated by minor modifications to the design and fabrication of a new Texas Transmatic device, the effort was not judged to be warranted; adoption of the relatively simpler and standardized conventional unconsolidated-undrained triaxial test apparatus is preferred. The vane shear tests all produced shear strengths in excess of those that would be recommended for design based on other tests. This confirmed Bjerrum's (1972) suggestion that the strengths measured in vane shear tests should be adjusted before using them for design.

IMPLEMENTATION STATEMENT

It is recommended that the Texas State Department of Highways and Public Transportation adopt the unconsolidated-undrained test as described in American Society for Testing and Materials Designation D-2850-82 for all cases requiring the determination of undrained shear strength in the laboratory. Use of corrected or uncorrected shear strengths obtained from Texas Triaxial tests is not recommended. Modification of the Texas Transmatic device to correct deficiencies identified in this study could be more costly than acquisition of a conventional, commerically-available triaxial cell. Thus, modification of the Texas Transmatic device in lieu of acquiring a conventional triaxial cell is not recommended. Vane shear tests are suitable for at least preliminary estimates of undrained shear strength; however, strengths measured in vane shear tests should not be used for design unless they have been adequately corrected.

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CHAPTER 1. INTRODUCTION

The Texas State Department of Highways and Public Transportation (SDHPT) has recently experienced a number of problems involving embankments and retaining walls constructed on soft clays. Failures in the form of sliding in embankment foundations have occurred in Districts 12, 16, and 20. A retaining wall has failed in District 20 by sliding in the foundation. Reliable measurements of the undrained shear strength of the foundation soils are needed for proper design under these circumstances.

Undrained shear strength is considered to be the shear strength of soil under conditions where there is no change in water content during loading. In the field, undrained shear strengths are assumed to apply to most clayey soils during the normal period of construction. "Undrained", rather than "drained" shear strengths are typically the governing (lowest) strengths for soils comprising the foundations of retaining walls and embankments; these foundation soils will consolidate under the applied loads and become stronger with time. In the laboratory, undrained conditions are maintained either by placing the specimen inside an impervious membrane sealed at both ends to impervious platens or by performing the test at a rate where the specimen will have insufficient time to drain. Prevention of drainage during the application of both the confining pressure and the axial load has led to these tests being termed "unconsolidated-undrained" tests.

The SDHPT has employed at least four procedures for determining the undrained shear strength of foundation soils: (1) the Texas Triaxial test (Test Method Tex-118-E), (2) a type of triaxial device referred to as the "Texas Transmatic" apparatus, (3) the miniature vane test, and (4) the field vane test. In other cases, outside consultants have been employed to perform laboratory tests. The consultants typically employ conventional triaxial devices and unconsolidated-undrained shear test procedures conforming more closely to American Society for Testing and Materials (ASTM) standards.

The four test methods mentioned above have all been used by the SDHPT at one time or another; however, each of the types of tests is known to have potentially important deficiencies. In the case of the Texas Triaxial test, some drainage of water from the specimen may occur during the test. Thus, the measured shear strength may not represent the undrained shear strength. Additionally, the Texas Triaxial test involves the use of a heavy rubber membrane for confinement. The stiffness of this membrane should have some effect on the test results.

The Texas Transmatic apparatus available for use in this study employed a stiff proving ring for measurement of load, which made accurate determination of the shear strength of soft specimens impossible. Although this problem could have been eliminated by use of another proving ring, it is not clear that this has been done in practice. The Texas Tranxmatic apparatus also exhibited significant friction between the upper and lower portions of the cell. Although the friction did not affect the measurement of loads, because the loads were measured inside of the cell, the friction led to difficulties in performing the test and keeping the apparatus in proper alignment with the specimen.

The miniature and field vane tests both contain inherent errors. Differences among vane dimensions, strain rates, insertion techniques, as well as accuracy and frequency of equipment calibration will probably all influence measured shear strengths.

Hamoudi, et al., (1974) compared results of Texas Triaxial tests and unconsolidated-undrained triaxial tests on specimens with undrained shear strengths in the 1000 to 5000 psf range. A correction factor was developed as a result of these tests to apply to Texas Triaxial test results to bring them into agreement with unconsolidated-undrained triaxial test results. However, this correction factor is not applicable to the results of Texas Triaxial tests on soft clays having shear strengths below 1000 psf.

The objective of this study was to examine the various test methods employed by the SDHPT to determine their validity for measuring the undrained shear strength of soft clays and to develop recommendations for determination of undrained shear strengths using existing, revised or new shear test procedures. The unconsolidated-undrained triaxial test was included in the study because it is one of the most common methods used in geotechnical engineering practice for the determination, in the laboratory, of the undrained shear strength of soft clays. A second type of vane test, the Torvane test, was included because of its virtually universal use in the field. Several series of laboratory tests were performed using the various types of test equipment and procedures for comparison.

Five different types of specimens were prepared and tested as part of this study in an effort to compare shear strengths over a range from soft to stiff. One series of specimens was prepared by molding soil at a high water content into tubes fabricated for this purpose. Another series of specimens was prepared using a vacuum extrusion device. A third series of specimens was prepared by compacting soil using Standard Proctor compactive effort. The fourth series of specimens was formed (cast) from polyurethane. Finally, a fifth series of specimens was obtained from undisturbed samples of soft clay from a site in Port Arthur, Texas.

The following chapter contains a review of the test apparatus and procedures examined. The third chapter describes material selection and specimen preparation. The results of triaxial and vane shear tests are presented in the fourth and fifth chapters, respectively. The sixth chapter summarizes the study and presents recommendations.

CHAPTER 2. UNDRAINED SHEAR STRENGTH TEST APPARATUS AND PROCEDURES

INTRODUCTION

Apparatus and procedures for each of the five tests (Texas Triaxial, Texas Transmatic, unconsolidated-undrained, laboratory vane, and Torvane) considered in this study are briefly reviewed and discussed in this chapter.

TEXAS TRIAXIAL TEST

The Texas Triaxial test apparatus and procedure are described as Test Method Tex-118-E of the Texas State Department of Highways and Public Transportation, Materials and Tests Division (SDHPT,1962). The Texas Triaxial cell, shown in the photograph in Figure 2.1 and in the drawing in Figure 2.2, consists of a hollow steel cylinder, four-and-one-half inches in diameter and eight-and-one-half inches high, with a wall thickness of five one-hundredths of an inch. A heavy rubber membrane, sixty-five one-hundredths of an inch thick, is positioned inside the cylinder. The ends of the membrane are wrapped over the ends of the cylinder and clamped. Confining stress is applied by pressurizing the annulus between the cylinder wall and the membrane with air. The Texas Triaxial cell used in this study was purchased from the Rainhart Company, Austin, Texas. A Wykeham-Farrance load press (Model Number 12001) rated to 2,200 pounds force, was employed. This load press was set to load at the highest rate possible: six one-hundredths of an inch per minute. Loads were measured using one of two different load cells: 1) Lebow Products (Model Number 3169) rated to 500 pounds force, and 2) MTS Systems Corporation (Model Number 661.21A-01) rated to 5,500 pounds force. Two load cells were required due to the wide range of specimen strengths. Deformation readings were obtained using a TransTek (Model Number 243-000-K4) linearly variable differential

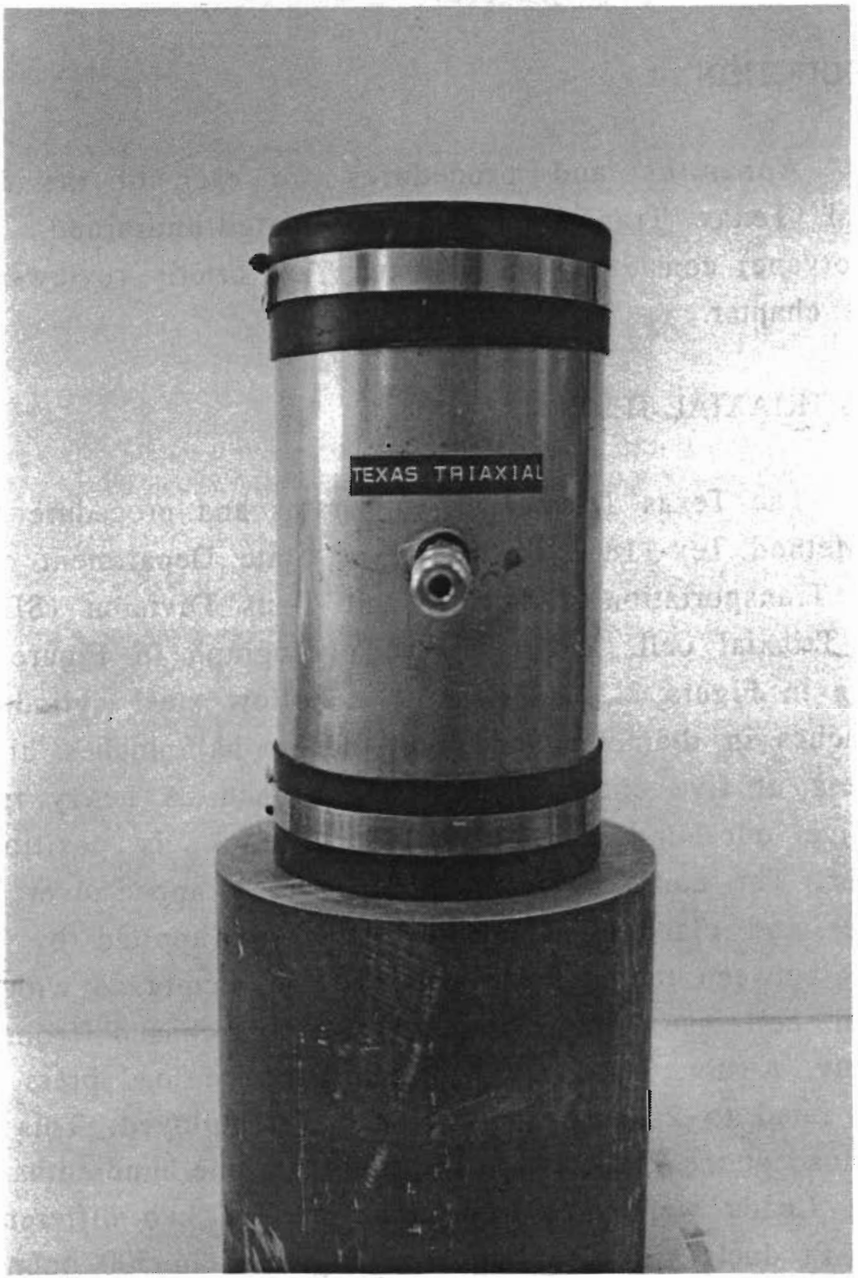

Figure 2.1. Photograph of Texas Triaxial Test Apparatus.

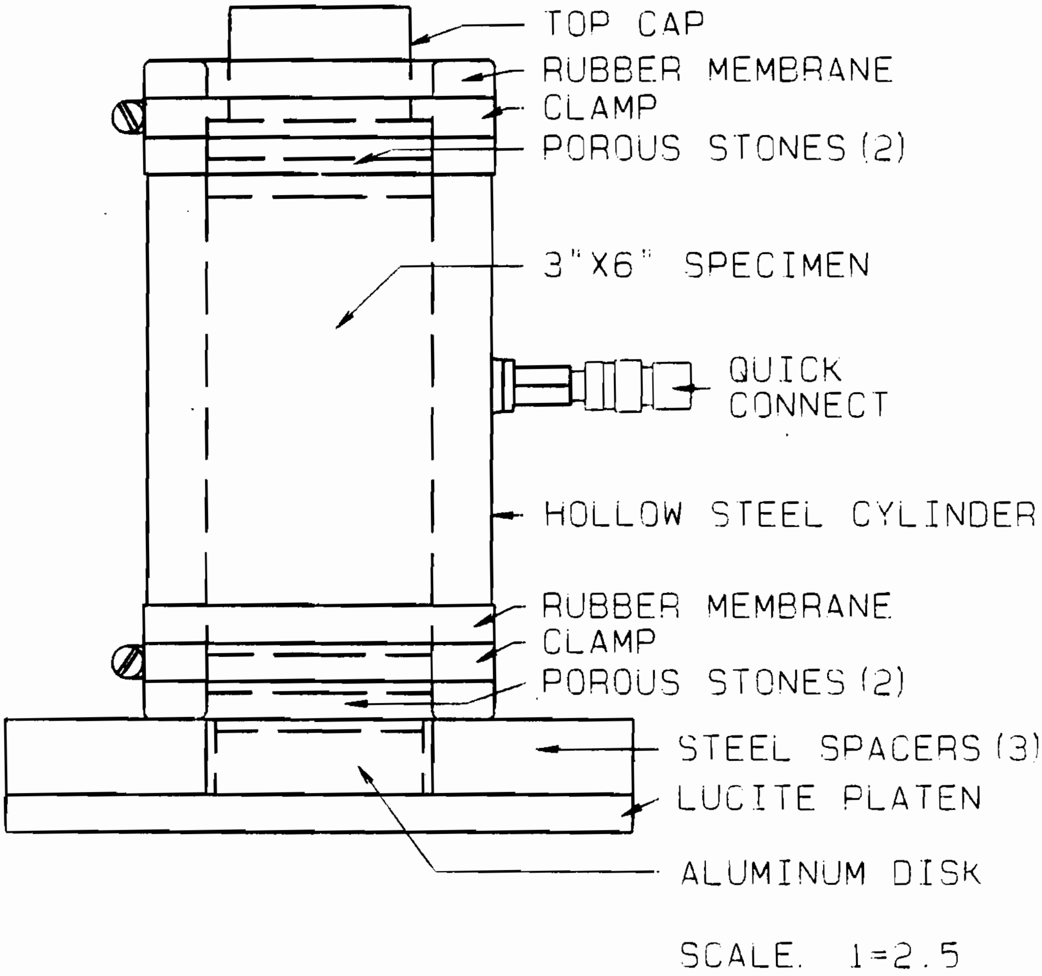

Figure 2.2. Drawing of Texas Triaxial Apparatus.

transformer (LVDT). Signals from the load cell and LVDT were recorded using a Hewlett-Packard data acquisition system consisting of a Model 3478A digital multimeter and Model 3488A multiplexer. A Hewlett-Packard microcomputer was used for all data storage and reduction.

The procedure outlined in Test Method Tex-118-E (SDHPT, 1962). was followed as closely as possible in performing tests in this study. A specimen was set up on a pedestal consisting of an aluminum disk and porous stones as shown in Figure 2.2. Porous stones, an acrylic top cap and a stainless steel ball bearing were placed on top of the specimen. A vacuum was placed on the cell in order to pull the membrane back against the cell wall. Steel spacers, one inch in thickness, were used to temporarily elevate the cell above the platen. The cell was then placed around the specimen. The platen with the specimen/cell assembly was placed on the load platform. The platform elevation was raised until the stainless steel sphere made contact with the bottom of the load cell. Initial load and deformation readings were recorded. Confining pressure was applied; the spacers were removed from beneath the cell; a second set of load and deformation readings to reflect changes due to confining pressure were recorded and loading was started. A deformation rate of six one-hundredths of an inch per minute was used. Loading was stopped when an axial strain in the specimen of 17 percent was achieved, which corresponded to one inch of deformation and the limit of the linear range of the LVDT. In some cases, peak load was achieved prior to reaching 17 percent axial strain. Strengths were determined either using the axial stress on the specimen at ten percent axial strain, or the peak axial stress, whichever was greater. This is in accordance with the procedure described in Test Method Tex-118-E (SDHPT, 1962). A sample was taken from the center of the specimen for water content determination.

Problems observed while performing Texas Triaxial tests mainly involved the membrane used. In the Texas Triaxial test, the heavy rubber membrane is clamped to the cell cylinder wall and comes in contact with the specimen when confining pressure is applied. The ends of the specimen are not sealed and drainage of water from the specimen may occur as a result. Also, the heavy rubber membrane used in the Texas Triaxial cell may contribute significantly to the measured undrained shear strength of the specimen being tested. An additional problem is the method by which confining pressure is applied. When confining pressure is applied, the rubber membrane is forced against the specimen, causing lateral deformation. Application of the confining pressure in the lateral direction induces stress in the axial direction, causing the axial loading apparatus to provide axial confinement in a passive sense. The application of confining pressure in the Texas Triaxial test often resulted in excessive inflation (bulging) of the membrane at the bottom of the cell. During several tests using confining pressures of 15 pounds per square inch, inflation of the membrane at the bottom of the cell was excessive and those tests had to be aborted. In one case, the clamped end of the membrane slipped off the end of the cylinder during a test using a confining pressure of 30 pounds per square inch.

TEXAS TRANSMATIC TEST

Dodson (1951) reported that the Texas Transmatic device was originally designed and built in 1949 for the Houston Interurban Expressway office of the Texas Highway Department by Mr. Frederick Harris. The Texas Transmatic apparatus, shown in the photograph in Figure 2.3 and in the drawing in Figure 2.4, consists of two acrylic cylinders which form the main housing of the device. The upper cylinder is six inches in diameter and sixteen inches in height. One end of the upper cylinder is closed and has attached the proving ring through which load is applied to the specimen and measured. The lower cylinder is eight inches in diameter, six inches in height, and is open at the top allowing the upper cylinder to be inserted into it during the test. The upper cylinder is held in place by an acrylic ring which is secured with wing nuts. The lower cylinder contains the specimen pedestal on which the

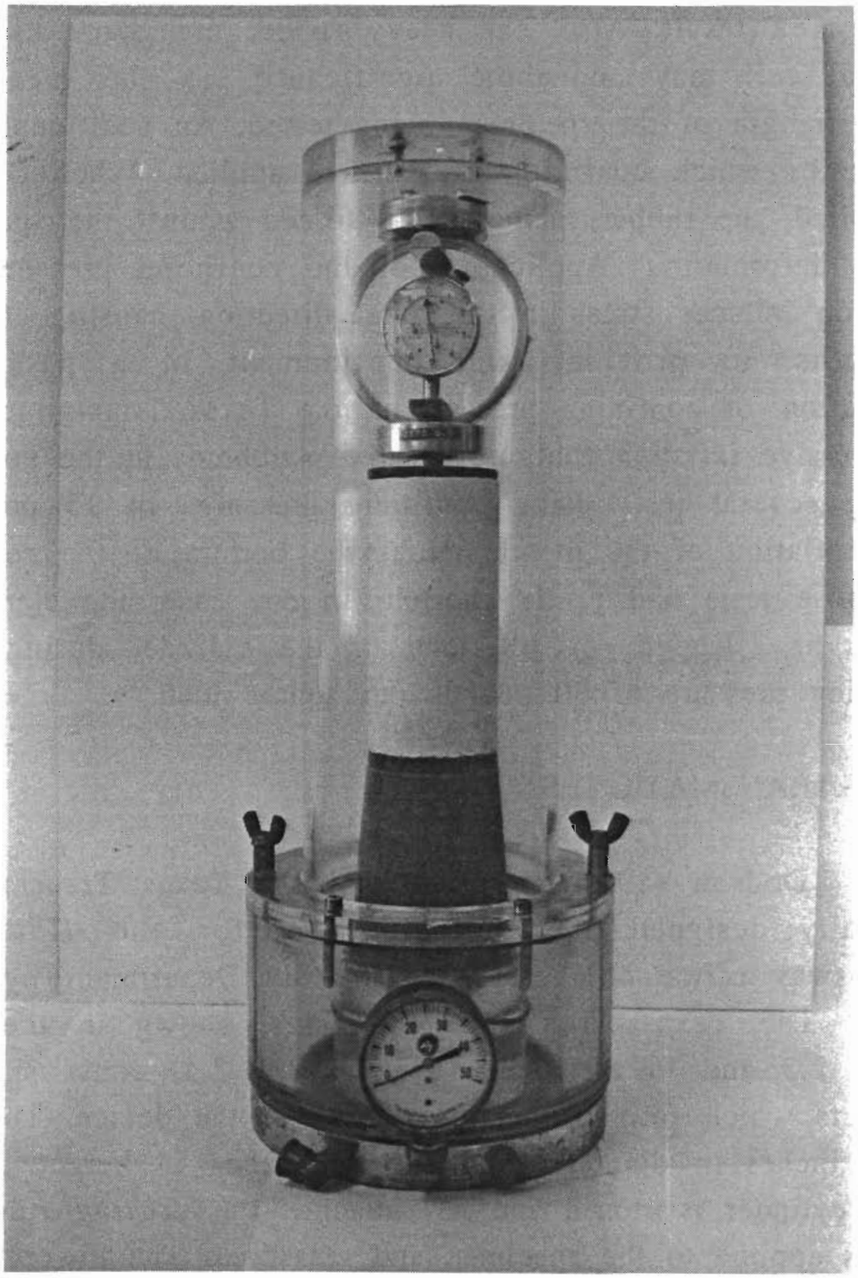

Figure 2.3. Photograph of Texas Transmatic Apparatus.

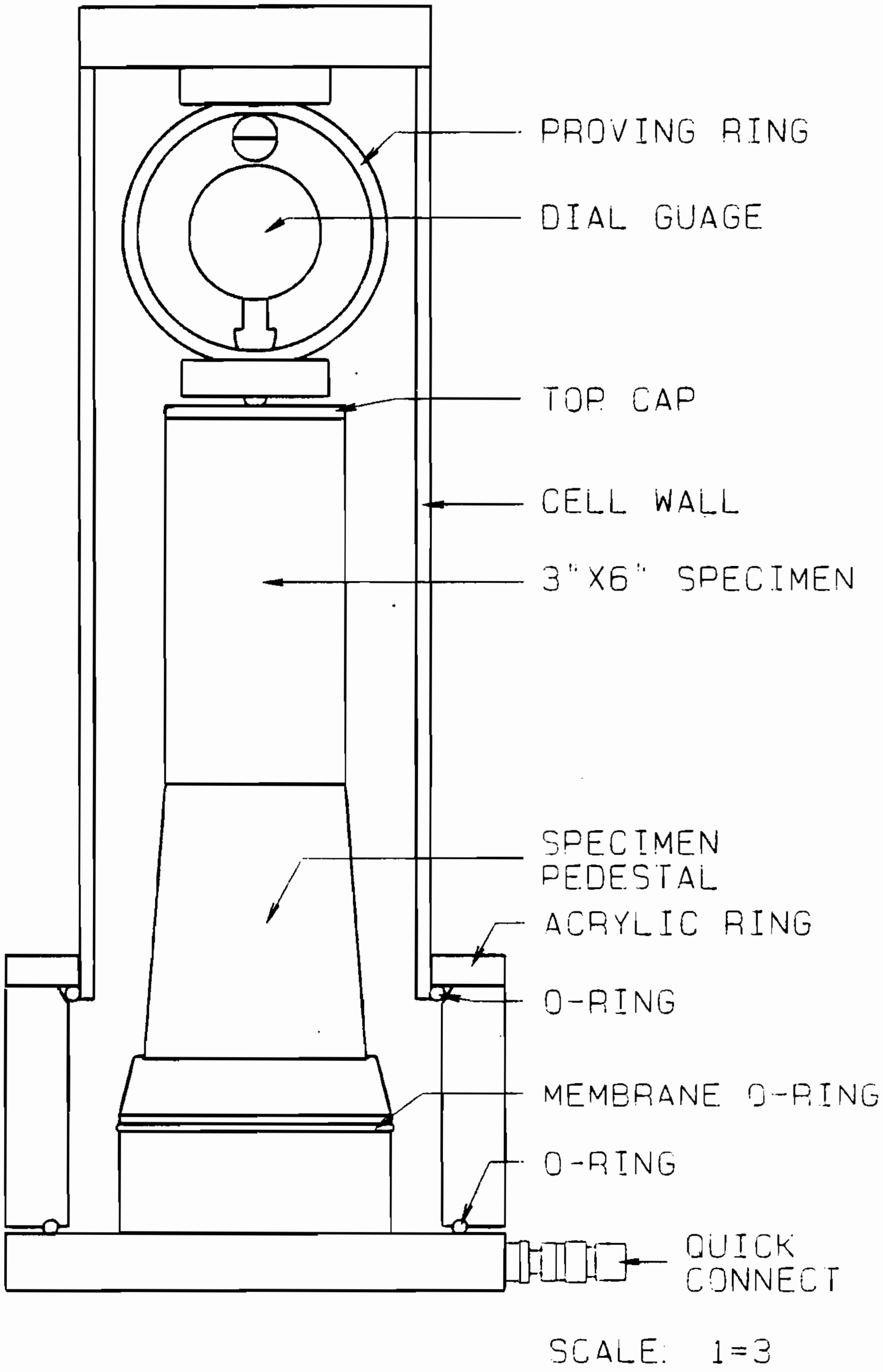

Figure 2.4. Drawing of Texas Transmatic Apparatus.

specimen is placed. The Texas Transmatic device is configured to test three-inch diameter, six-inch high specimens. The proving ring in the device obtained for this study was calibrated and the calibration factor was calculated as seven and sixty-one one-hundredths of a pound per per division, a division being equal to one ten-thousandth of an inch of proving ring deflection. A thin plastic membrane (sandwich bag), five-and-one-half inches wide, sixteen inches long and sealed at one end, is employed to prevent drainage of water from the specimen during the test. The membrane is placed over the specimen and secured with an o-ring placed in a groove in the specimen pedestal. O-rings provide seals between the upper and lower portions of the cell and between the lower portion of the device and the steel base. To apply load to the specimen, the loading platform and lower portion of the cell, including the o-ring between the upper and lower portions of the cell, are raised. The upper cylinder of the cell is held stationary by the loading press crossbar and the specimen is forced upward until it contacts the proving ring. The device used as part of this study was loaned to the University of Texas by the Houston Urban office of the SDHPT.

The procedure used in this study to perform tests with the Texas Transmatic device is as follows: a specimen was placed on the pedestal. A steel top cap and plastic membrane were placed over the specimen and secured. The upper cylinder of the cell was inserted into the lower cylinder and secured. The entire assembly was placed on the loading press platform. The elevation of the load press platform was raised until the top of the cell made contact with the loading press crossbar. It is necessary that this step be accomplished without prematurely loading the specimen. Confining pressure, in the form of compressed air, was applied. The initial proving ring dial gauge and deformation readings were recorded and the test was started. The same LVDT and data acquisition, storage, and reduction equipment described previously were employed. Load and deformation readings were recorded until an axial strain of 17 percent was achieved. The test was stopped at that point.

Several problems were observed during attempts to perform preliminary tests on artificial specimens using the Texas Transmatic device. The first problem observed was a leak in the seal between the lower portion of the cell and the steel base. As a result, confining pressure could not be maintained inside the cell. Attempts to seal the leak, including the use of vacuum grease on the o-ring between the lower portion of the cell and the base, were unsuccessful. Meaningful tests on other specimens were not attempted as a result. Other problems concerning the mechanics of the apparatus were observed. It was difficult to maintain proper alignment between the upper cylinder and the lower cylinder due to excessive friction caused by the rubber O-ring. During tests, loading could become eccentric. Additionally, the proving ring suplied by the SDHPT with the Texas Transmatic apparatus used in this study was very stiff, making determination of undrained shear strength of soft clays difficult. Although these deficiencies in the apparatus could all have been overcome by construction of a new device similar to the one examined, the effort required to do so would not be appropriate for the present study.

UNCONSOLIDATED-UNDRAINED TEST

Apparatus and procedures for conventional unconsolidated-undrained triaxial tests are described in ASTM Designation D-2850 (ASTM,1985). In the present study, two different size triaxial cells were used, one for one-and-one-half inch diameter by three-inch high specimens and one for three-inch diameter by six-inch high specimens. Drawings of these two cells appear in Figures 2.5 and 2.6.

The ASTM procedure was followed closely in performing unconsolidated-undrained tests. A specimen was set-up in the appropriate cell and the cell was placed in the loading press described previously. The desired confining pressure in the form of compressed air

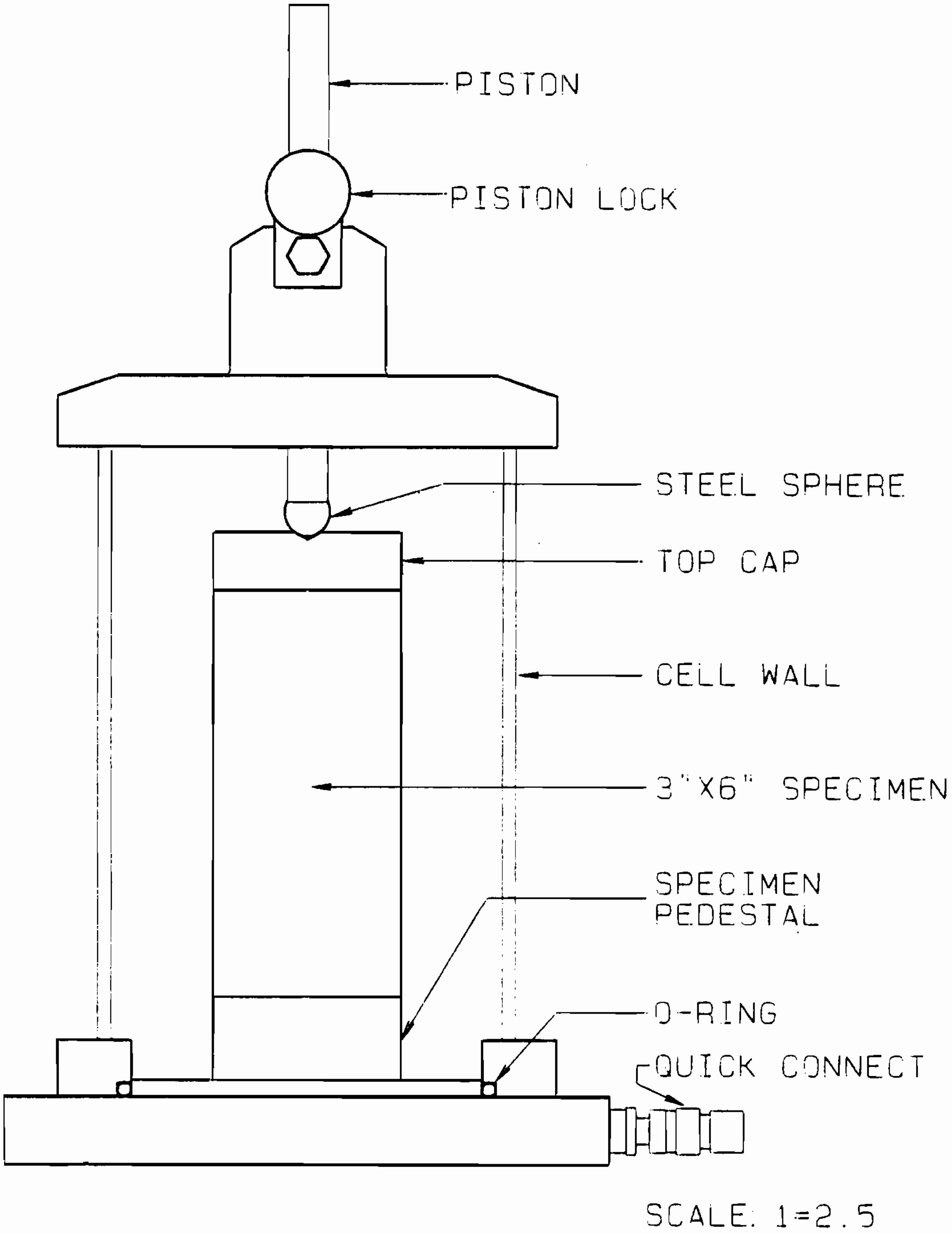

Figure 2.5. Unconsolidated-Undrained Apparatus (3" x 6" specimens).

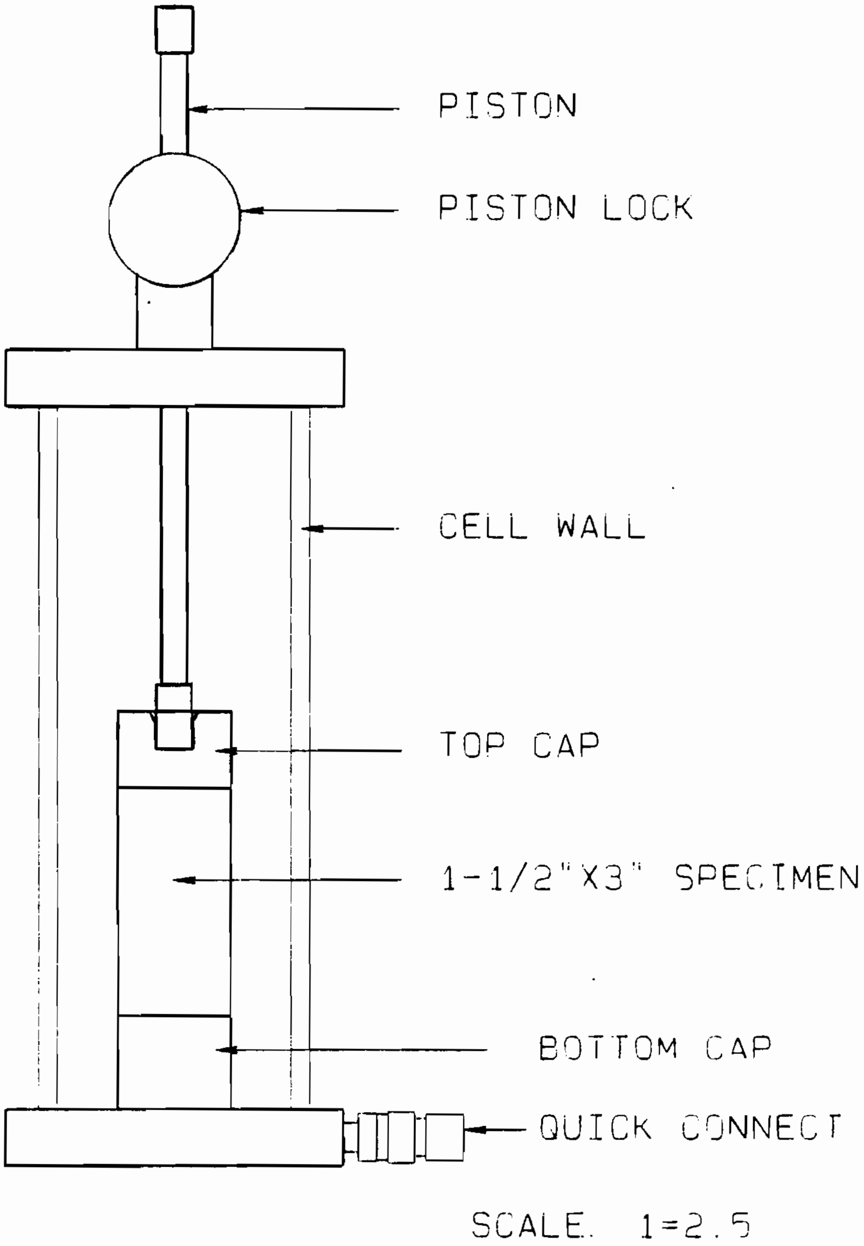

Figure 2.6. Unconsolidated-Undrained Apparatus (1-1/2" x 3" specimens).

for three-inch diameter specimens or water and an air/water interface for one-and-a-half-inch diameter specimens was applied, the loading platform was adjusted until the piston made contact with the top cap, the LVDT was zeroed and the loading was started. The same data acquisition, storage, and reduction equipment described previously was used except that a Transducers, Incorporated load cell (Model Number BTC-FF62-CS-100) rated to 100 pounds force was used due to the relatively low loads applied in the unconsolidated-undrained test. Loading continued until an axial strain in the specimen of 17 percent was achieved in three-inch diameter, six-inch high specimens or 20 percent when testing one-and-one-half-inch diameter, three-inch high specimens. The slightly lower axial strain was used as a stopping point for tests performed on three-inch diameter, six-inch high specimens in order to stay in the operating range of the deformation-measuring device. After loading was stopped, the specimen was removed from the cell and a sample from the center of the specimen was retained for water content determination.

LABORATORY VANE TEST

All laboratory vane tests were performed using a Wykeham-Farrance (Model Number WF23500) laboratory vane test device with electric motor drive. The device, shown in the photograph in Figure 2.7 and in the drawing in Figure 2.8, is geared to provide a rotation rate of one-tenth of a degree per second. Two sizes of vane blades were used: one-inch diameter by one-inch height and one-half-inch diameter by one-half-inch height. Torque applied to the soil was obtained by measuring the angle of rotation of a calibrated spring prior to failure.

The test procedure employed in performing laboratory vane tests is as follows: a specimen contained in a three-inch diameter tube was placed in the device and secured. The vane blades were lowered into the center of the specimen. The initial spring rotation reading was recorded and the test was started. Spring readings were monitored until the torque transmitted to the specimen by the vane blades reached a

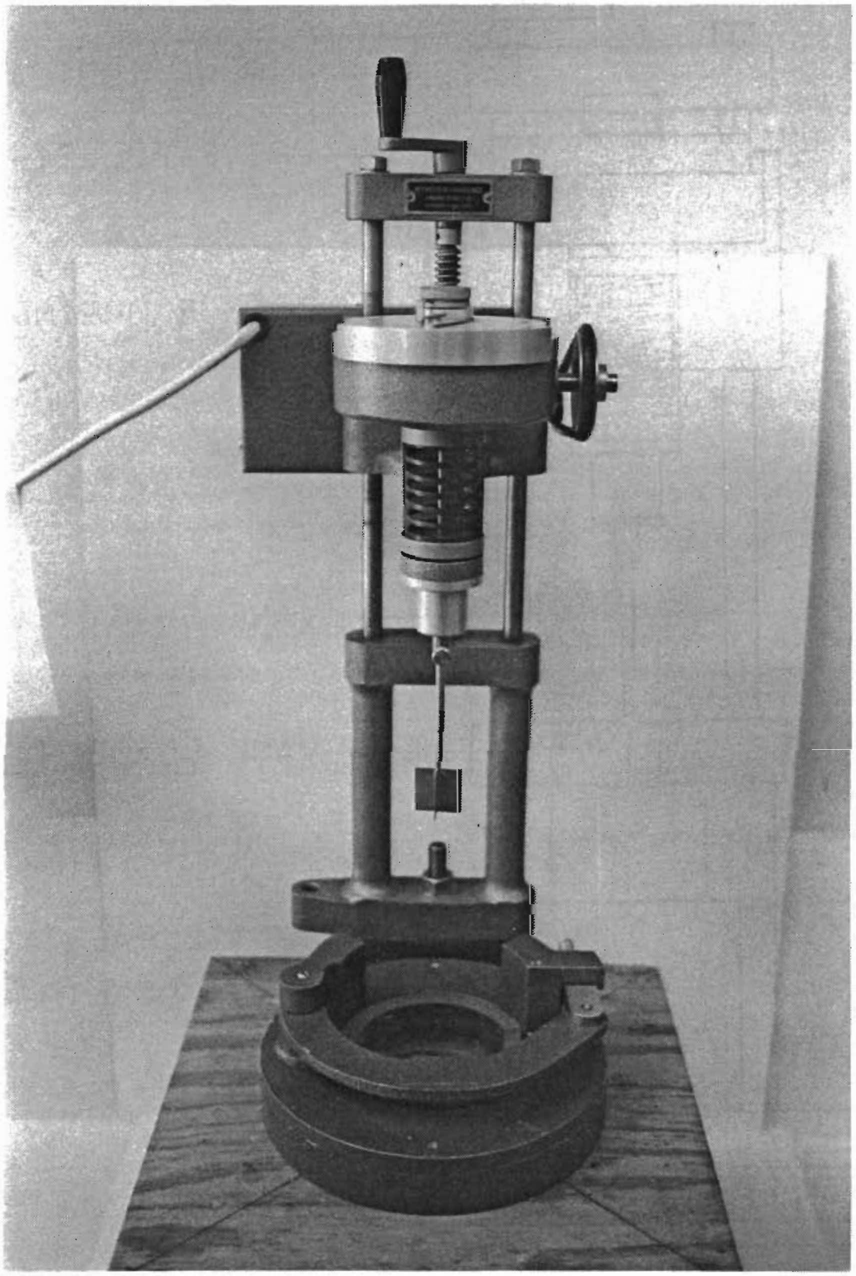

Figure 2.7. Photograph of Laboratory Vane Apparatus.

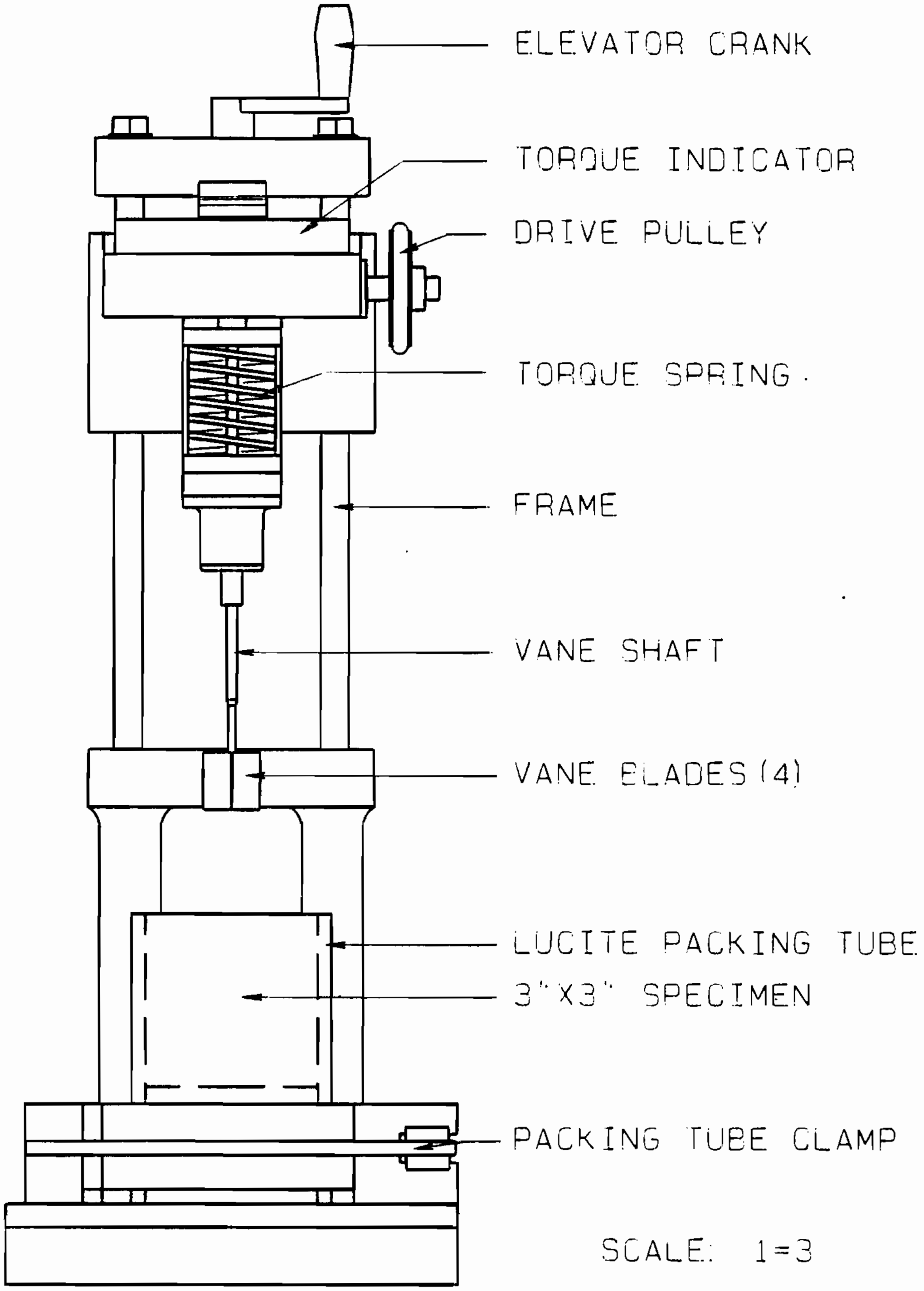

Figure 2.8. Drawing of Laboratory Vane Apparatus.

maximum value. The time required to reach this point varied from approximately five minutes for softer specimens to approximately eight minutes for stiffer specimens. Immediately after the test was completed, a sample was taken from the center of the specimen for water content determination. A calibration sheet provided by the test device manufacturer was used to correlate the total spring rotation and the maximum torque resisted by the soil. From maximum torque resisted, undrained shear strength was calculated from the following formula:

$$c_u = \frac{T}{P(1/2(d^2h))(1 + 1/3(d/h))}$$

where:

c_u = undrained shear strength

T = maximum applied torque

d = vane diameter

h = vane height

A variety of factors exist which may lead to differences between the strengths measured in laboratory vane tests and those measured in triaxial shear tests. These factors include: rate effects, vane dimension effects, disturbance due to vane insertion, calibration errors, and loading the specimen in a manner that does realistically model loading in the field. Some of these factors represent sources of error while others reflect fundamental features of soil behavior. Disturbance due to vane insertion and calibration errors are examples of error sources. Anisotropy, discussed by Aas (1965), is an example of possible reflection of true soil properties. Some factors could reflect both sources of error and soil behavior. Effects of loading rate could constitute error regarding drainage of water or could reflect true soil behavior because soils show a rate effect under purely undrained loading.

TORVANE TEST

The Torvane test employs a small hand-operated device, manufactured by Slope Indicator Company, Seattle, Washington, and marketed by Soiltest Company, Evanston, Illinois. The device, shown in Figure 2.9, consists of a round steel plate with thin steel vane blades projecting from it. The vane is connected to a torsional spring which, in turn, is connected to a handle. The Torvane incorporates two different sets of vane blades shown in Figure 2.9. The smaller diameter set of blades is typically used for stiff and stronger clays. The larger diameter set of blades, which fits over the smaller set, is typically used on soft-to-medium clays.

Torvane tests were performed by first pushing the vane blades into the surface of the specimen. The handle was then rotated until a maximum torque was reached. The duration of each test was approximately five seconds. Each Torvane test performed in the laboratory as part of this study was performed immediately prior to a laboratory vane test on the same specimen.

The Torvane has most of the limitations associated with the laboratory vane test discussed previously. The differences between either the laboratory vane or Torvane and any other type of undrained shear test would be expected to be similar. However, in the case of the Torvane, the ratio of the shear surface area perpendicular to the axis of rotation to the shear surface area which is parallel to the axis of rotation is 2.4 for the large plate and 1.2 for the small plate. The corresponding ratio for the laboratory vane test used in this study is 0.5. Accordingly, the shear strength measured using the Torvane will be more significantly affected by the shear strength on horizontal planes than the shear strength measured with the laboratory vane test. This is an important difference between the Torvane and laboratory vane test devices.

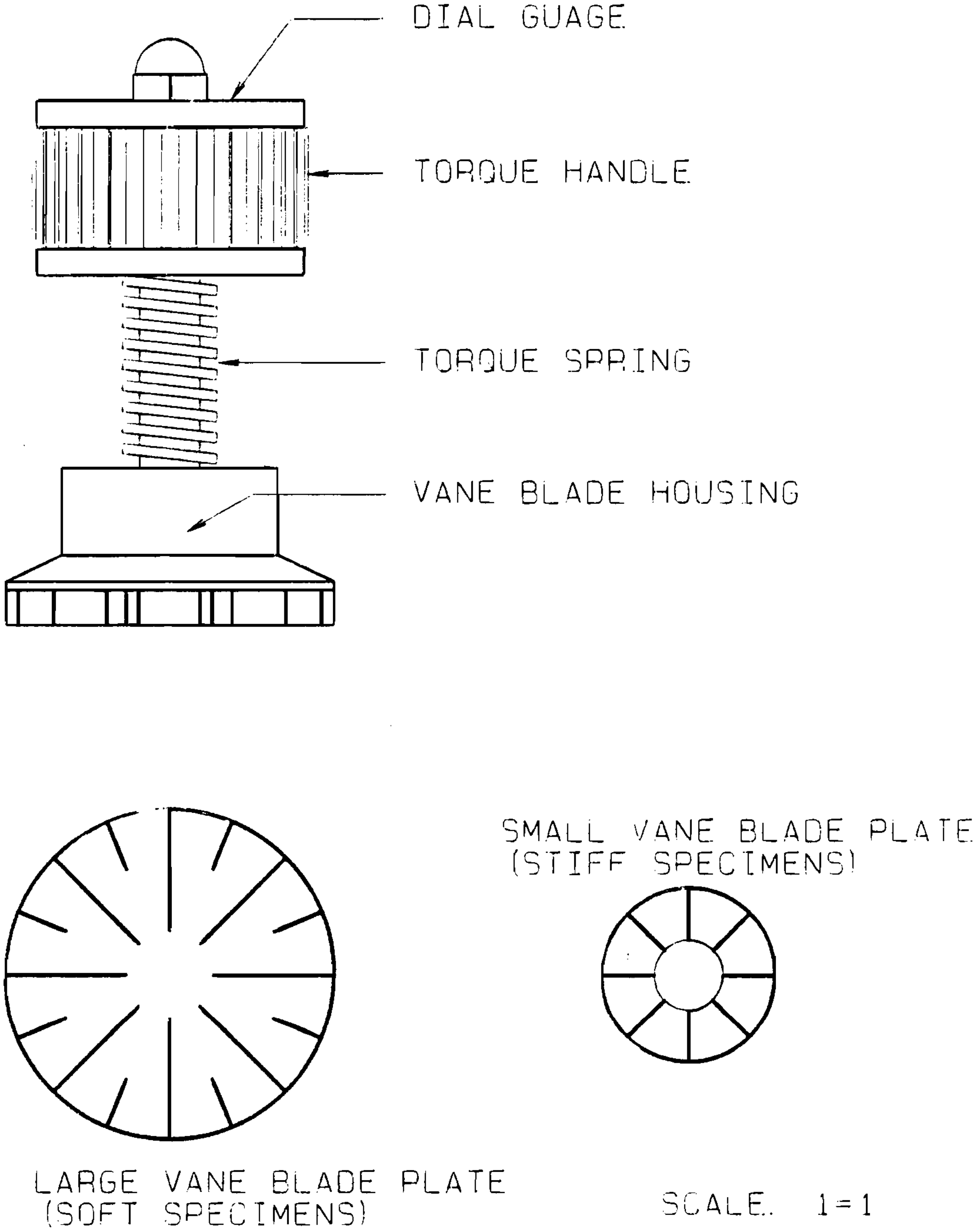

Figure 2.9. Torvane Apparatus.

CHAPTER 3. PROCEDURES FOR PREPARING SPECIMENS IN THE LABORATORY

INTRODUCTION

Four types of laboratory-prepared specimens were used in the testing program. The first type of specimen was prepared by "packing" (molding) soil into specially-fabricated tubes. The second type of specimen was prepared by passing soil through a vacuum extrusion device. Specimens prepared by either packing or vacuum extrusion will be referred to as "nearly-saturated" specimens. A third type of remolded soil specimen was prepared by compaction and are referred to as "compacted" specimens. The fourth type of specimens were artificial, cast from polyurethane. The preparation of these four types of specimens is discussed in this chapter.

SOIL SELECTION AND PROCESSING

A locally available, natural clay, known as Taylor clay was selected for preparation of all laboratory soil specimens. Taylor clay was selected because of its relatively low permeability which should limit problems associated with drainage of water from specimens during preparation and handling. Further, relatively large, uniform quantities of Taylor clay were available locally at no cost.

Approximately 750 pounds of Taylor clay were obtained from the City of Austin Landfill on Burleson Road approximately one mile east of the intersection of Burleson Road and U.S. Highway 183 in southeast Travis County, Texas. The clay was air-dried, crushed, pulverized and sieved through a U. S. Standard Number 40 (0.0165 inch) sieve in an effort to increase uniformity. The fraction of soil passing the Number 40 sieve was retained for use. Individual batches of soil were prepared starting with ten pounds of dry soil. The soil was placed in a commercial mixing device and anywhere from two-and-one-half to seven-and-one-half pounds of distilled water were added, depending on the desired water content. A spray bottle was used to add the water uniformly. Completely blended soil was removed from the mixer. Soil to be used for packed or vacuum extruded specimens was carefully wrapped in plastic wrapping, and stored in a humidity room for a minimum of 24 hours in order to enhance uniform hydration of the soil. Soil to be used for compacted specimens was not stored, but was used immediately after preparation.

PREPARATION OF NEARLY-SATURATED SPECIMENS

For the first several series of tests, it was considered desirable to test specimens of saturated or very nearly-saturated soil for several reasons. First, such soils are typically the weakest soils encountered and were judged to be representative of the "problem" foundation soils encountered along the Gulf coast regions of Texas. Secondly, the vane shear tests, which were of interest in this study, are theoretically only valid for saturated soils where the Mohr-Coulomb failure envelope is horizontal and the well known "$\phi = 0$" condition can be assumed. Initially, consideration was given to preparing specimens by consolidating soil in tubes from a slurry state; however, previous work by Green (1986), suggested that consolidation times might be excessive, especially for three-inch diameter, six-inch high specimens. Accordingly, two procedures, "packing" and vacuum extrusion, were considered and adopted.

Packing Procedure

"Packed" specimens were prepared by packing soil into specially-fabricated tubes. Three different sizes of specimens were prepared by packing. One-and-a-half-inch diameter, three-inch high specimens were prepared for unconsolidated-undrained tests. Three-inch diameter, six-inch high specimens were prepared for Texas Triaxial tests using the molding tube shown in Figure 3.1. Three-inch diameter, three-inch high specimens for testing using the laboratory vane and Torvane tests were also packed using the tube shown in Figure 3.1. The procedure for preparing all of the specimens by packing is the same as the one presented and discussed by Green (1986). The smaller one-and-a-half inch diameter specimens were used in the unconsolidated-undrained tests on packed specimens in an effort to save time in specimen preparation and reduce the quantity of soil that needed to be prepared. The ASTM standard pertaining to unconsolidated-undrained triaxial tests, ASTM Designation D-2850 (ASTM, 1985), only requires that the height-to-diameter ratio of specimens to be tested be no less than two and no greater than three. No other specimen size limitations are presented in ASTM Designation D-2850 (ASTM, 1985).

To prepare a packed specimen, soil at a water content closest to the desired water content was removed from the humidity room and brought into the laboratory. The packing tube piston was locked in its initial position. Soil was packed in layers with a small stainless steel spatula, from the tube walls inward toward the longitudinal axis of the specimen and from the piston head upward until the soil surface was flush with the top of the tube. After a layer of soil was placed, the piston in the packing tube was unlocked and an acrylic piston was used to force the packed soil and tube piston downward so that the next layer could be placed. The process was continued until a specimen of the final desired height was completed. Eight lifts of three-eighths of an inch thickness were used to prepare each three-inch high specimen. Eight lifts of three-quarters of an inch thickness were used in the preparation of each six-inch high specimen. Four lifts of three-quarters of an inch thickness were used to pack three-inch high specimens for the laboratory vane and Torvane tests. Packed specimens were extruded by forcing the molding tube piston and specimen up and out of the tube. The extruded specimen was "caught" and handled with a sling made of plastic wrapping.

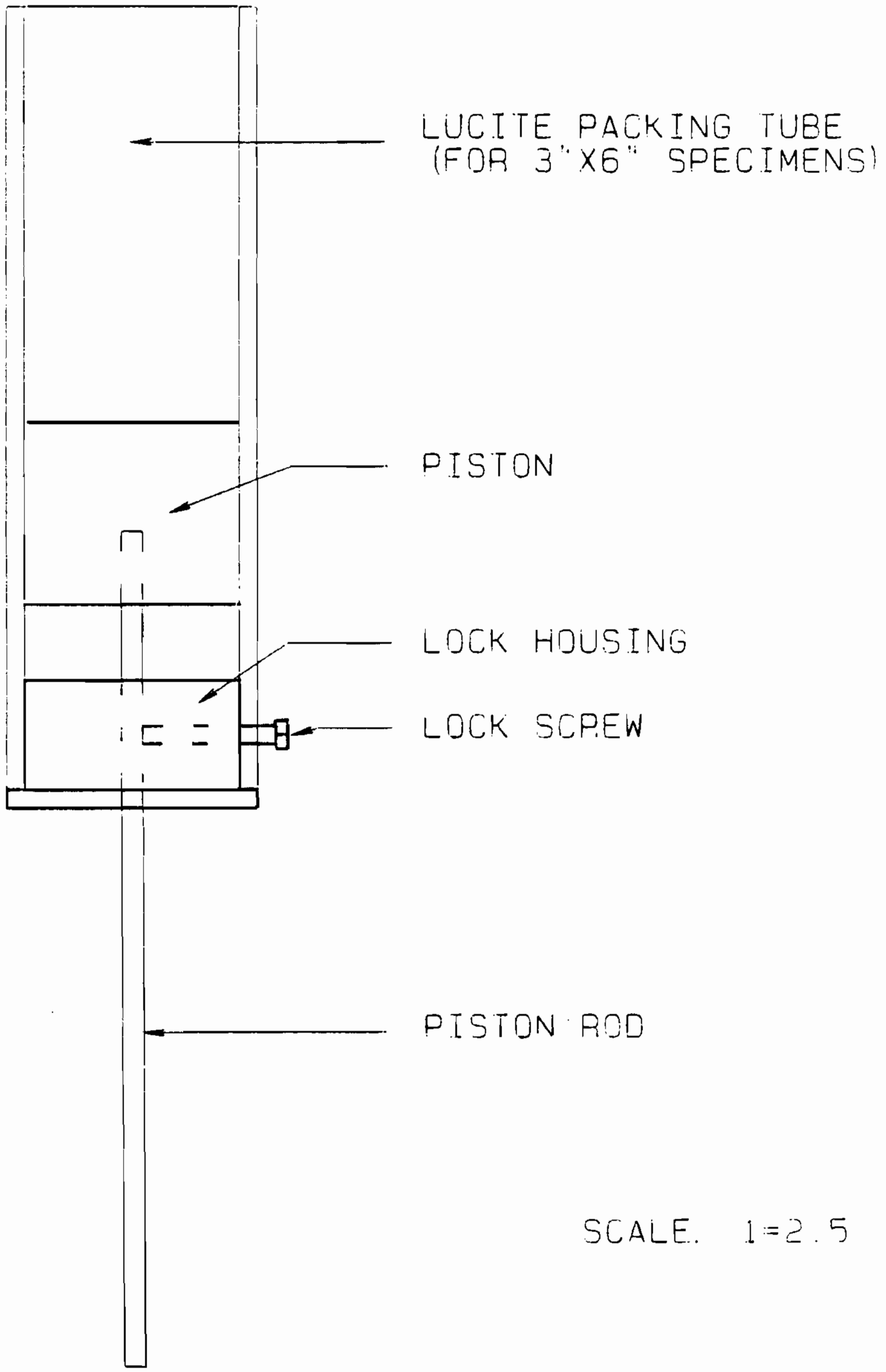

Figure 3.1. Soil Molding Tube for Three-inch Diameter Specimens.

Vacuum Extrusion Procedure

After initial tests of specimens prepared by packing soil into tubes had been completed, it was determined that specimens needed to be prepared at water contents as low as 40 percent to obtain strengths that were sufficiently high to cover the range of interest. However, preparation of these specimens by packing at 40 percent water content and at the associated stiffness was difficult to accomplish without developing air voids in the specimens which may affect test results. Accordingly, preparation of remolded specimens using a vacuum extrusion procedure discussed by Matlock, et al., (1951) was selected as an alternative to packing. Soil was prepared at a water content of approximately 40 percent as discussed previously. The soil was removed from the humidity room and brought into the room containing the vacuum extrusion device. Soil was manually forced into the device through the intake port. A continuous flight auger then forced the soil through a vacuum chamber and out the extrusion port. Specimen diameter was easily controlled by using extrusion templates with openings of the desired specimen diameter. Specimens slightly longer than required were extruded and trimmed to the correct lengths, weighed, and carefully wrapped in plastic wrapping. One-and-a-half-inch diameter, three-inch high and three-inch diameter, six-high specimens were prepared using vacuum extrusion.

Degrees of Saturation

Degrees of saturation were calculated for each specimen prepared by packing and vacuum extrusion. The average degrees of saturation for each specimen size and test method are shown in Table 3.1. Average values range from 94 percent for one-and-a-half inch diameter specimens prepared by vacuum extrusion to 98 percent for three-inch diameter specimens prepared by vacuum extrusion.

TABLE 3.1. AVERAGE DEGREES OF SATURATION OF NEARLY-SATURATED SPECIMENS.

Specimen Size (inch)	Preparation Method	Average Degree of Saturation (percent)	Standard Deviation
1-1/2 x 3	Packing	95.9	1.6
1-1/2 x 3	Vacuum Extrusion	94.0	3.6
3 x 6	Packing	94.9	1.3
3 x 6	Vacuum Extrusion	97.9	1.9
Overall		95.7	2.4

Thixotropic Effects

Initially, it was anticipated that several days might elapse between the time of specimen preparation and testing. Thus, strength gains due to thixotropy might need to be considered. To investigate the effects of thixotropy on measured shear strengths, 35 one-and-one-half-inch diameter by three-inch high specimens were prepared at three different water contents and stored for various periods of time before testing. Storage times prior to testing were: one hour, four hours, twenty-four hours, seven days, and twenty-eight days. After the specified storage times, unconsolidated-undrained tests were performed using a confining pressure of 20 psi.

At the completion of testing, all test results were grouped according to storage time and shear strengths were plotted versus corresponding water contents on the semi-logarithmic plot shown in Figure 3.2. A regression line was fit through each of the five sets of data representing the five storage times considered. Although there is noticeable scatter among the trends indicated by the various regression lines, they were used primarily as an aid in interpolating strengths for a given storage time to a common water content for comparison purposes. Two water contents, 62 percent and 72 percent, were selected for comparison. Strengths corresponding to the selected water contents were determined from each regression line. Strengths for the various storage times along with strengths determined from tests performed immediately after preparation are listed in Table 3.2 and shown in Figure 3.3. According to Figure 3.3, significant thixotropic gains in strength were observed in specimens stored longer than approximately 24 hours. However, thixotropy later proved to be not a problem for the tests performed in this study because storage times were held to less than one hour in all cases.

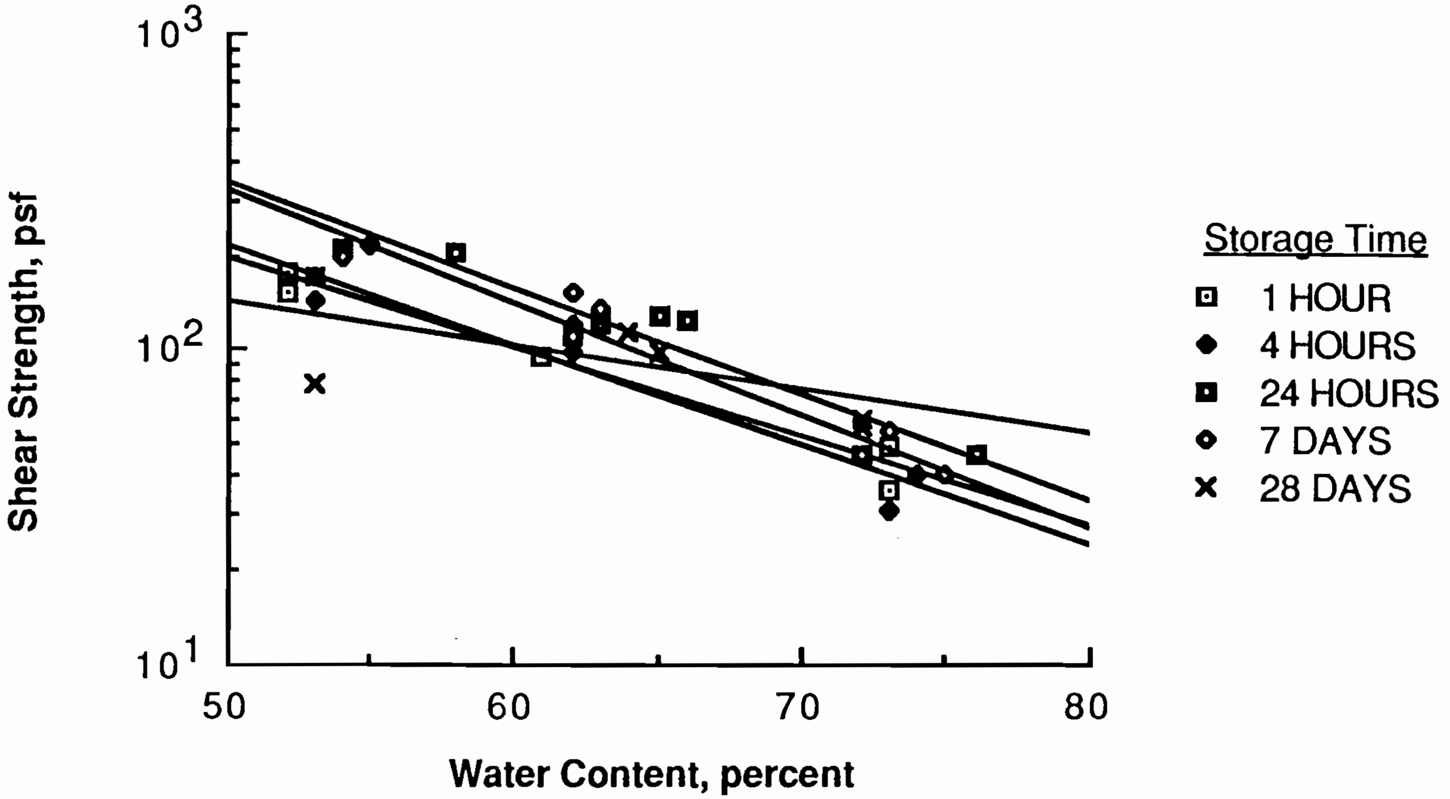

Figure 3.2. Variation in Undrained Shear Strength with Water Content from Unconsolidated-Undrained Tests for Specimens Stored for Various Periods of Time Prior to Testing.

TABLE 3.2. SHEAR STRENGTH FOR STORAGE TIME PRIOR TO TESTING FOR WATER CONTENTS OF 62 AND 72 PERCENT.

	Water Content	
	62 %	72 %
Storage Time	Shear Strength, psf	Shear Strength, psf
0	100	56
1 hour	90	45
4 hours	110	41
24 hours	130	56
7 days	137	51
28 days	132	58

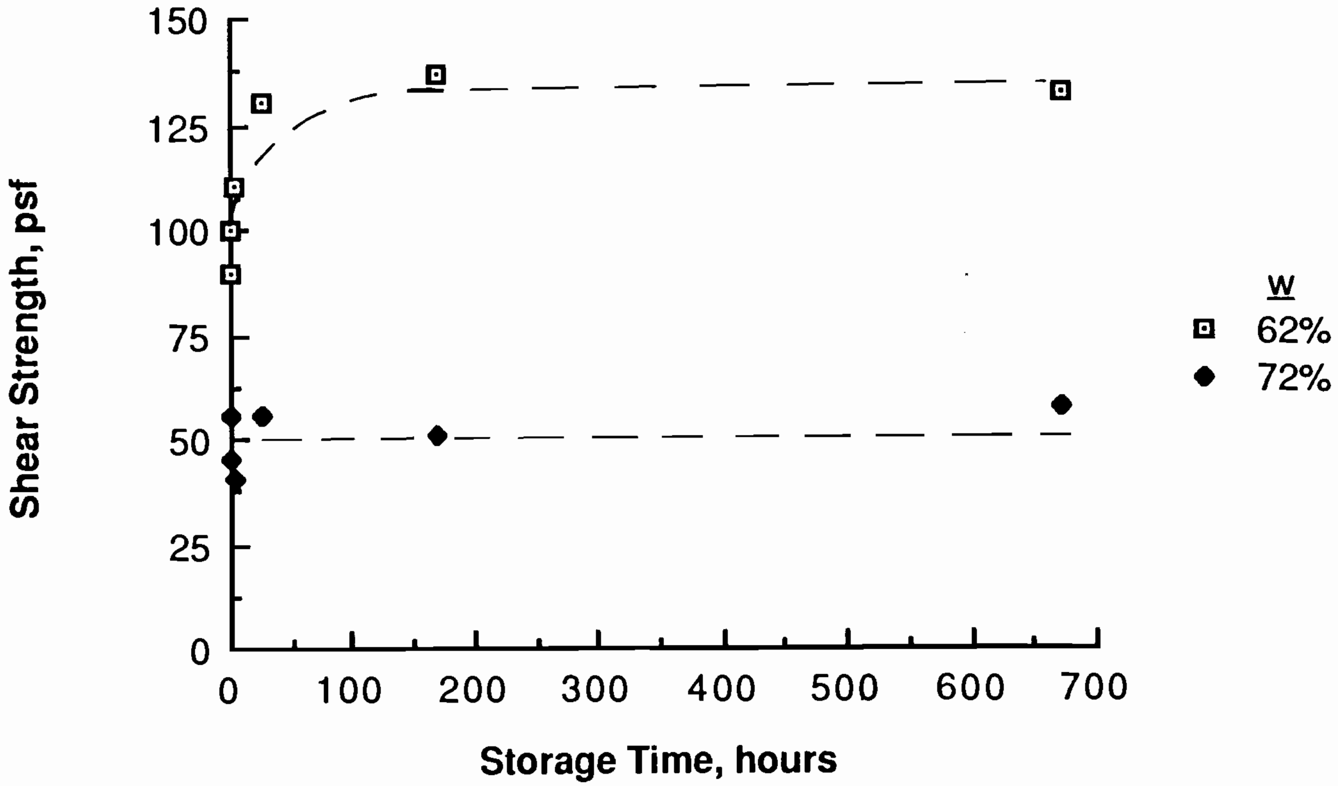

Figure 3.3. Variation in Undrained Shear Strength with Storage Time Prior to Testing for Water Contents of 62 and 72 Percent.

PREPARATION OF COMPACTED SPECIMENS

Specimens prepared by both packing and vacuum extrusion all had relatively low strengths, generally not exceeding 400 psf. In order to obtain stronger specimens for testing, compaction was used to prepare stiff specimens. Although the specimens were not saturated and meaningful vane shear tests could not be performed, vane shear tests were not considered to be of great interest when considering stiff specimens and compaction was the most feasible method for preparing stiff specimens in the laboratory.

Twenty-four specimens were prepared by compaction, using Standard Procter compactive effort employing 12,400 foot-pounds of energy per cubic foot of material per ASTM Designation D-698-78 (ASTM,1985). Compacted specimens were prepared in groups of three in an effort to limit variation of water content and dry density. An optimum water content and maximum dry density of 22 percent and 103 pounds per cubic foot, respectively, were obtained for Taylor clay by Kayaal (1985) using a specially-fabricated mold and compaction hammer. These values of water content and dry unit weight were used as an initial estimate of soil parameters needed to ensure that compacted specimens prepared for this study demonstrated adequately high shear strengths. Compacted specimens were prepared by mixing sufficient amounts of soil and distilled water to prepare three specimens at a time. Each specimen was compacted in a three-inch diameter, seven-inch high mold using Standard Procter compactive effort and three lifts of slightly over two inches in final thickness. Specimens were extruded from the mold using a hydraulic extrusion device and any small voids were carefully filled. The specimens were trimmed to six inches in length, weighed, and wrapped in plastic. A summary of specimen properties appears in Table 3.3.

TABLE 3.3. SUMMARY OF MOISTURE-DENSITY DATA FOR COMPACTED SPECIMENS OF TAYLOR CLAY.

Specimen	Total Unit Weight (pcf)	Water Content (percent)	Dry Unit Weight (pcf)
UCOM1	110.2	27.9	86.2
UCOM2	112.6	27.0	88.7
UCOM3	110.4	26.8	87.1
UCOM4	112.0	26.3	88.9
UCOM5	112.6	25.9	89.4
UCOM6	110.2	28.6	85.7
UCOM7	113.4	26.9	89.3
UCOM8	111.3	27.3	87.4
UCOM9	112.3	27.4	88.1
UCOM10	111.8	28.1	87.2
UCOM11	110.7	28.1	86.4
UCOM12	111.2	27.4	87.3
TCOM1	111.8	29.4	86.4
TCOM2	112.2	26.0	89.0
TCOM3	112.0	27.0	88.2
TCOM4	112.4	28.0	87.8
TCOM5	112.8	28.7	87.7
TCOM6	111.3	27.4	87.4
TCOM7	111.8	27.5	87.7
TCOM8	112.7	27.4	88.4
TCOM9	111.8	27.7	87.5
TCOM10	112.0	28.0	87.6
TCOM11	110.2	27.8	86.2
TCOM12	111.2	27.8	87.0
AVER.	111.7	27.5	87.6
S.D	0.9	0.8	1.0

PREPARATION OF ARTIFICIAL SPECIMENS

Artificial specimens were prepared in an effort to isolate effects of the membranes used in the various triaxial tests. Several criteria were established as desirable for artificial specimens: linear deformation under repeated loading and unloading, no change in properties with time or due to changes in confining pressure (an angle of internal friction of zero), negligible shrinkage or heat generation during curing, controllable stiffness similar to a soft clay, and ease in preparing specimens in the laboratory.

Material Selection

A material found to be suitable for preparing artificial specimens was an elastomer known as Polyurethane Mold Compound PMC-744 supplied by Smooth-On, Inc., Gillette, New Jersey. Artificial rubbers such as Neoprene and Styrene and other elastomers such as epoxy, polysulfide and silicon were considered. Artificial rubbers satisfy most of the essential criteria but cannot be formed easily. Epoxy cannot be formed into large specimens due to excessive heat build-up during curing. The elastic modulus of polysulfide is difficult to adjust and the material tends to degrade by bleeding with time. Silicon elastomers are preferable over polyurethane due to their non-reactive nature, but they are more expensive than polyurethane by a factor of four to five.

The polyurethane mixture used in this study is composed of three components: polyurethane elastomer, hardening agent, and flexibilizing agent. The elastomer-to-hardening agent ratio is required to be ten-to-one by weight for proper curing; however, the amount of flexibilizing agent can be adjusted to vary the stiffness. Several different ratios of elastomer to flexibilizing agent were tried and a ratio of one part elastomer to one part flexibilizing agent was found to produce a sufficiently soft specimen. Use of larger amounts of flexibilizing agent was not recommended by the supplier due to curing problems. A second specimen possessing higher stiffness was prepared by excluding the use of any flexibilizing agent.

Specimen Preparation

The components discussed in the previous section were carefully placed in a glass beaker and mixed in a manner that limited the entrapment of any air bubbles. After complete blending, the mixture was poured into a steel mold which had been treated with a silicon releasing agent. A curing period of 24 hours was required for the specimen to harden completely. At the end of the curing period, the specimen was removed from the mold. No shrinkage was observed during the curing period.

The manufacturer of the materials used to prepare artificial specimens recommends that caution be used during preparation of the polyurethane specimens. Mixing and curing should take place under a vented hood. Contact with skin should be avoided until the compound has completely cured. The completed specimens should be stored in a cool, dark, and dry location to prolong their usable life. During the course of preparing specimens, it was observed that materials other than metal and glass should not be used for mixing as the liquid polyurethane may react with them. Generally, it is preferable to use disposable mixing containers and tools; however, if the mixing equipment is to be cleaned, then it was found to be desirable to allow the polyurethane to cure first.

A summary of artificial specimen properties is presented in Table 3.4.

TABLE 3.4. SUMMARY OF STIFFNESS PROPERTIES OF ARTIFICIAL SPECIMENS.

Specimen	Axial Stress at 5 Percent Axial Strain (psi)	Axial Stress at 10 Percent Axial Strain (psi)	Young's Modulus (psi)
Soft	1.31	2.64	26.6
Stiff	11.79	24.14	247.0

CHAPTER 4. TRIAXIAL SHEAR TESTS

INTRODUCTION

Unconsolidated-undrained and Texas Triaxial shear tests were performed on five types of specimens: packed Taylor clay, vacuum extruded Taylor clay, compacted Taylor clay, undisturbed soil, and synthetic specimens. The results of unconsolidated-undrained and Texas Triaxial tests on these four series of specimens are discussed in this chapter.

TESTS ON NEARLY-SATURATED SPECIMENS

Twenty-eight unconsolidated-undrained tests and 26 Texas Triaxial tests were performed on nearly-saturated specimens prepared by packing or vacuum extrusion. Four Texas Triaxial tests out of the 26 attempted had to be aborted due to excessive membrane inflation at the bottom of the cell. In general, the stiffer specimens in this series were prepared by vacuum extrusion; the softer specimens were prepared by packing soil into tubes as previously described. The majority of unconsolidated-undrained tests were performed on packed specimens while roughly equal numbers of Texas Triaxial tests were performed on packed and vacuum extruded specimens. Difficulty was encountered in handling the larger, three-inch by six-inch, specimens used in the Texas Triaxial test when the specimens were prepared at water contents of 70 percent or greater. Specimens packed at these high water contents deformed under their own weight at a rate that made testing impossible. Accordingly, Texas Triaxial tests were not performed on specimens as soft as some of those on which unconsolidated-undrained tests were performed.

Initially, unconsolidated-undrained and Texas Triaxial tests were planned using confining pressures of 10, 20 and 30 psi in an effort to identify any effects of confining pressure inherent to the specimens or to either test. Unconsolidated-undrained tests were performed using these confining pressures. However, confining pressures of 15 psi were found to cause excessive membrane inflation and bulging in the Texas Triaxial test; confining pressures as high as 30 psi sometimes caused the membrane to slip off the cylinder. As a result, Texas Triaxial tests on soft remolded specimens were performed using confining pressures of 5, 10, and 12.5 psi.

Strengths from the Texas Triaxial and unconsolidated-undrained tests are plotted on a logarithmic scale versus water content in Figure 4.1. The semi-logarithmic plot was selected because the shear strength-water content relationship can typically be approximated by a straight line in this type of plot which facilitates data interpretation and smoothing to reduce scatter effects. Linear regression lines were fit to the data corresponding to each test method. The two test methods can be seen to yield significantly different shear strengths at any given water content. For example, at a water content of 40 percent, the Texas Triaxial tests indicate a shear strength of approximately 870 psf; whereas, the unconsolidated-undrained tests yield a shear strength of approximately 360 psf. The ratio of these two shear strengths is 2.4. This ratio varies with water content. As the water content is increased, and the measured shear strengths decrease, the ratio of shear strength measured by the Texas Triaxial test to shear strength measured by the unconsolidated-undrained test increases. At a water content of 70 percent, the Texas Triaxial and unconsolidated-undrained tests yielded shear strengths of 289 psf and 49 psf, respectively. The corresponding ratio of shear strengths increased to 5.9.

Confining pressure was not expected to significantly affect the shear strength of the specimens due to their relatively high degrees of saturation (summarized previously in Table 3.1). Texas Triaxial and unconsolidated-undrained shear strengths are plotted with different symbols for each confining pressure in Figures 4.2 and 4.3, respectively. Linear regression lines were fit through each set of data corresponding to a common confining pressure used. Although there is noticeable random

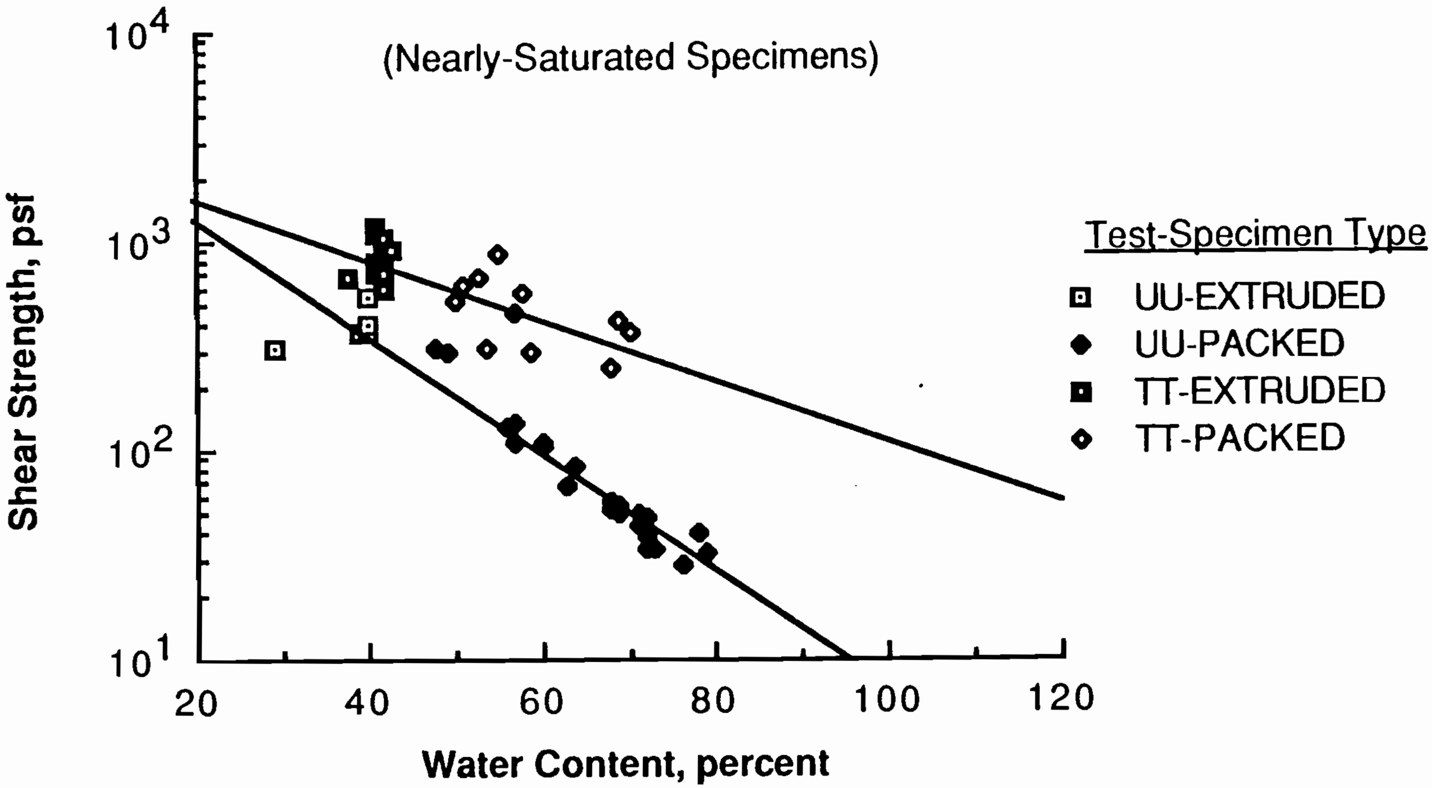

Figure 4.1. Variation in Undrained Shear Strength with Water Content from Texas Triaxial and Unconsolidated-Undrained Tests on Nearly-Saturated Specimens.

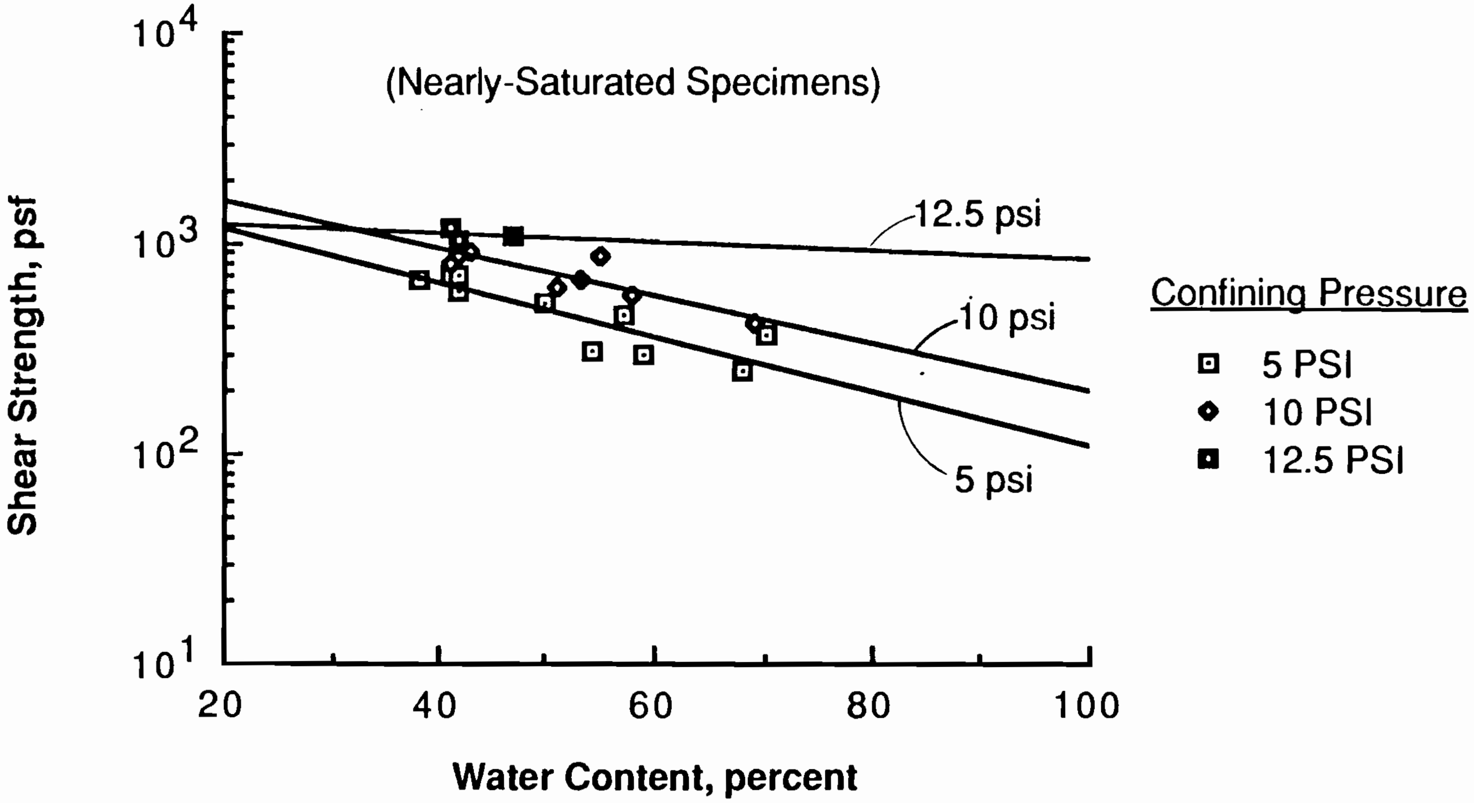

Figure 4.2. Variation in Undrained Shear Strength with Water Content from Texas Triaxial Tests on Nearly-Saturated Specimens.

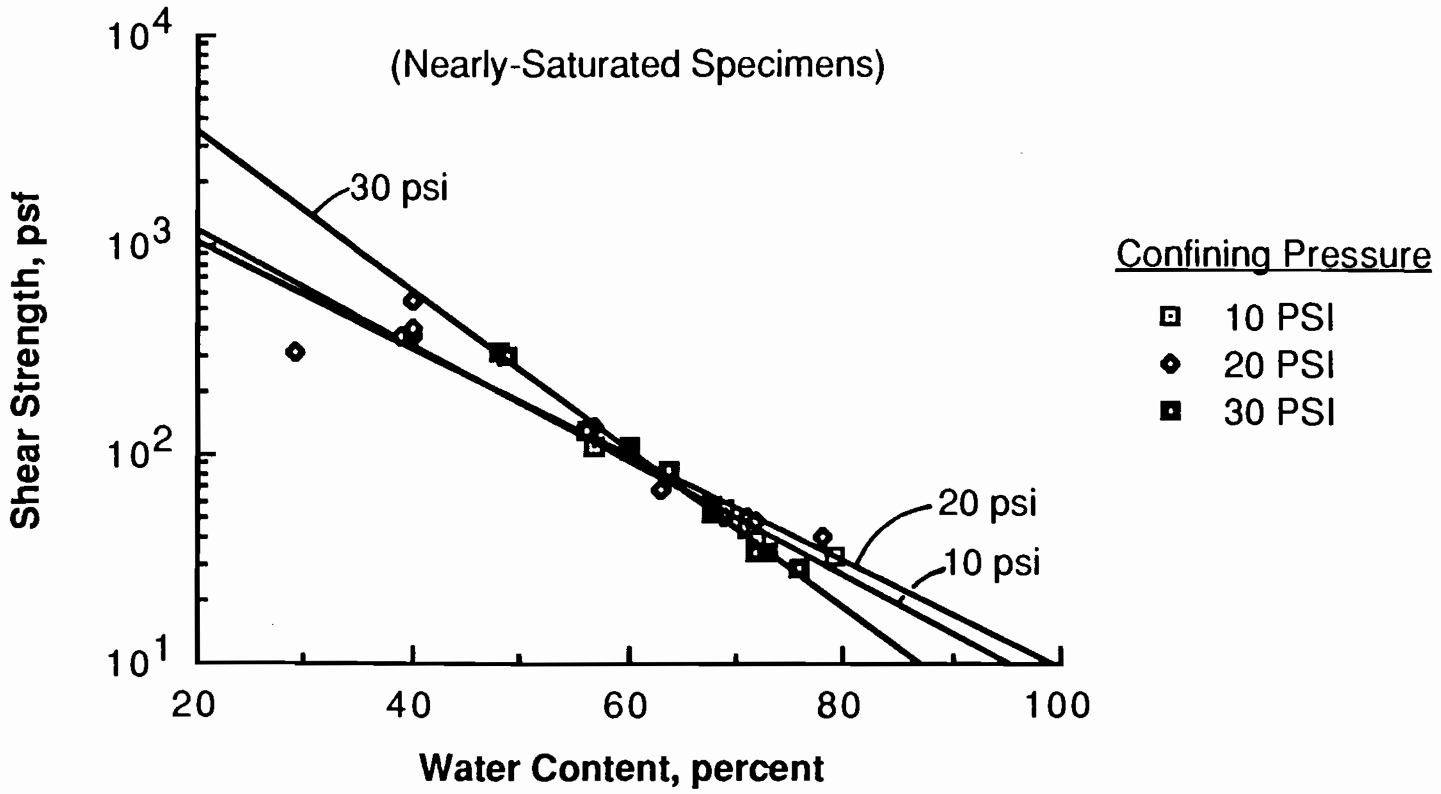

Figure 4.3. Variation in Undrained Shear Strength with Water Content from Unconsolidated-Undrained Tests on Nearly-Saturated Specimens.

variation in the strengths measured in the unconsolidated-undrained tests, no discernible effects of confining pressure were observed. The effects of confining pressure on the strengths measured in the Texas Triaxial tests are more pronounced, especially in view of the fact that a narrower range of confining pressure was used in the Texas Triaxial tests than in the unconsolidated-undrained tests. The most probable reason for confining pressure having an effect in the Texas Triaxial test is the use of the heavy rubber membrane. Apparently, as confining pressure is increased, the portion of the measured shear strength contributed by the membrane increases.

TESTS ON COMPACTED SPECIMENS

Twelve unconsolidated-undrained tests and 12 Texas Triaxial tests were performed on compacted specimens. Specimens were prepared in groups of three as discussed in Chapter Three.

Each set of three specimens was tested using confining pressures of five, 10, and 15 psi. The use of 15 psi confining pressure in the Texas triaxial test did not present any problems associated with excessive membrane inflation for these stiffer specimens. The measured shear strengths from the Texas Triaxial and unconsolidated-undrained tests are shown in Figures 4.4 and 4.5, respectively. Linear regression lines were fitted to the data as shown. Average correlation coefficients of linear regression, calculated from values corresponding to data grouped by confining pressure, are 0.86 and 0.72 for the Texas Triaxial and unconsolidated-undrained test data, respectively.

A water content of 27.5 percent was selected as typical and ratios of strengths measured in the Texas Triaxial and unconsolidated-undrained tests were calculated for each of the confining pressures used. These strengths and ratios are shown in Table 4.1. The strength obtained from the Texas Triaxial test results at 15 psi confining pressure corresponding to the unconsolidated-undrained test strength at the same confining pressure had to be estimated due to the large difference in strengths measured in the Texas Triaxial test using 15 psi confining pressure. The data point representing a measured strength of 3800 psf at a water content of 27 percent using 15 psi confining pressure in the Texas Triaxial test was excluded and another linear regression line was fit through the remaining data points to estimate strength measured at 15 psi. The ratio of Texas Triaxial-to-unconsolidated-undrained strength appears to increase slightly with increasing confining pressure. This is probably due to increasing membrane effects in the Texas Triaxial test with increasing confining pressure. The average ratio is 1.5.

Cohesion intercepts (c) and angles of internal friction (ϕ) were calculated from the Mohr-Coulomb envelopes for each series of tests on three specimens. Summaries of these calculations appear in Tables 4.2 and 4.3. The results of these calculations yield average cohesion intercepts of 8 and 12 psi from the results of the Texas Triaxial and unconsolidated-undrained tests, respectively. Average angles of internal friction obtained from the Texas Triaxial and unconsolidated-undrained tests are 23 and 5 degrees, respectively.

Shear strengths were calculated at 5, 10, and 15 psi confining pressure using the eight sets of cohesion and friction parameters. The summaries of these calculations appear in Tables 4.2 and 4.3. The ratio of average calculated shear strength using cohesion and friction parameters for Texas Triaxial and unconsolidated-undrained tests is 1.2 at a confining pressure of five psi but increases to 1.6 at a confining pressure of 15 psi. The ratio is expected to increase with confining pressure due to the use of significantly larger friction angles from the Texas Triaxial test results.

TESTS ON UNDISTURBED SPECIMENS

A total of 20 unconsolidated-undrained tests and 19 Texas Triaxial tests were performed on specimens obtained from undisturbed samples

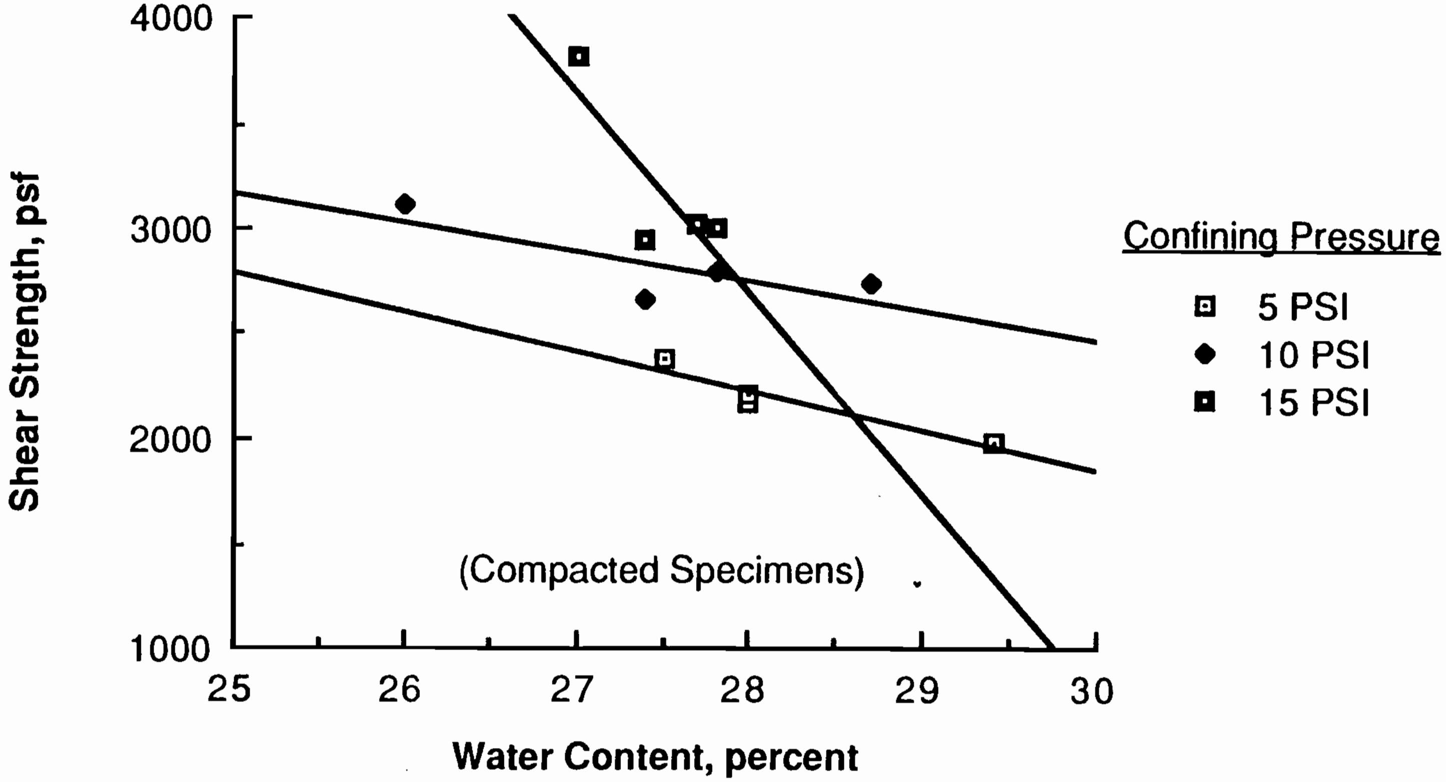

Figure 4.4. Variation in Undrained Shear Strength with Water Content from Texas Triaxial Tests on Compacted Specimens.

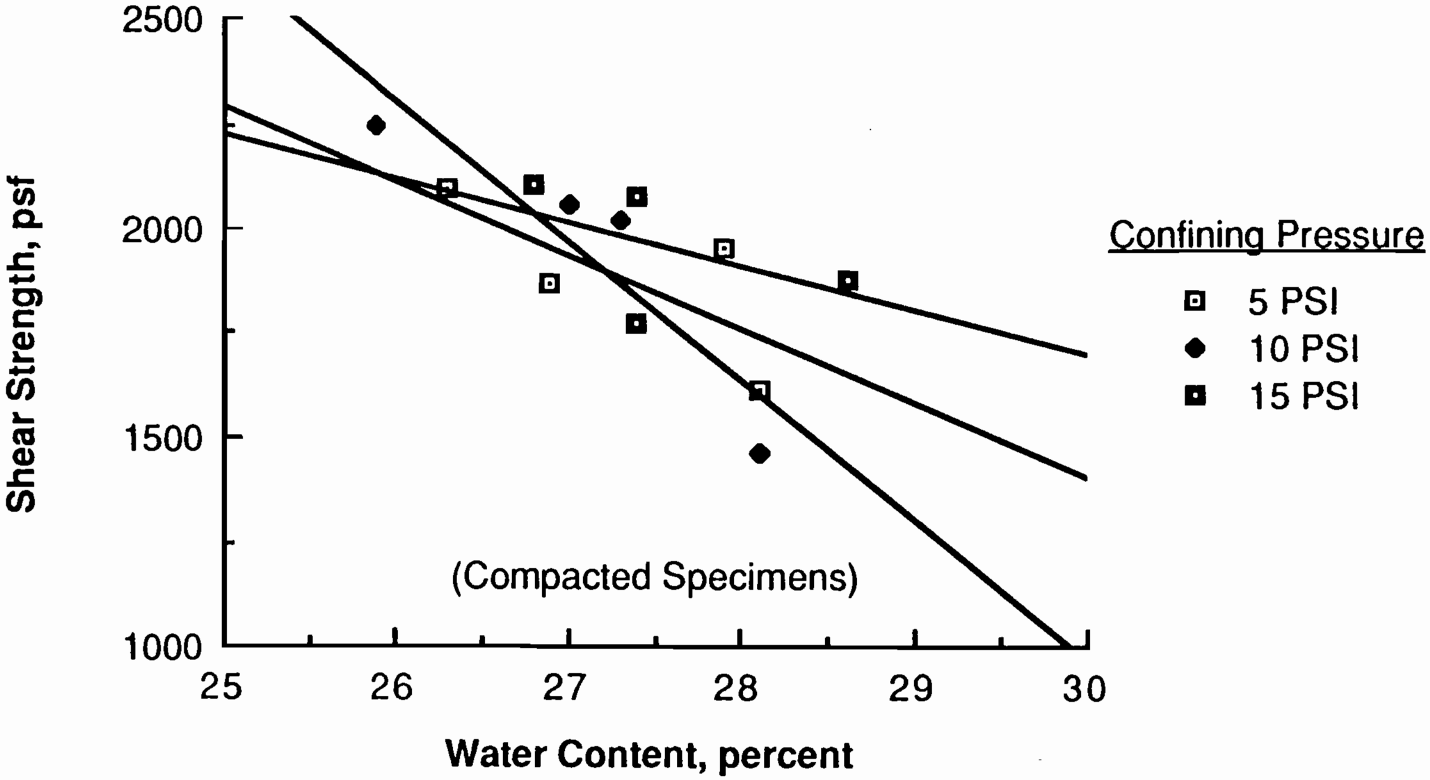

Figure 4.5. Variation in Undrained Shear Strength with Water Content from Unconsolidated-Undrained Tests on Compacted Specimens.

TABLE 4.1. COMPARISON OF TEXAS TRIAXIAL AND UNCONSOLIDATED-UNDRAINED SHEAR STRENGTHS FROM COMPACTED SPECIMENS.

Confining Pressure, psi	UU Shear Strength, psf	TT Shear Strength, psf	Ratio TT to UU Strength, psf
5	1750	2350	1.3
10	1600	2800	1.7
15	1950	3200	1.6

TABLE 4.2. COHESION AND FRICTION PARAMETERS AND RESULTING STRENGTHS CALCULATED FROM TEXAS TRIAXIAL TESTS ON COMPACTED SPECIMENS.

Specimen	c (psi)	ϕ (degrees)	Principal Stress Difference/2 at Confining Stress, psi		
			5.0	10.0	15.0
UCOM1 UCOM2 UCOM3	11.8	5.7	13.6	14.1	14.7
UCOM4 UCOM5 UCOM6	14.4	0.0	14.4	14.4	14.4
UCOM7 UCOM8 UCOM9	11.0	7.1	13.2	13.9	14.6
UCOM10 UCOM11 UCOM12	9.2	5.8	10.7	11.3	11.8
Average	11.6	4.6	12.9	13.4	13.9
Standard Deviation	2.2	3.2	1.6	1.4	1.4

TABLE 4.3. COHESION AND FRICTION PARAMETERS AND RESULTING STRENGTHS CALCULATED FROM UNCONSOLIDATED-UNDRAINED TESTS ON COMPACTED SPECIMENS.

Specimen	c (psi)	ϕ (degrees)	Principal Stress Difference/2 at Confining Stress, psi		
			5.0	10.0	15.0
TCOM1	4.7	33.9	15.1	21.4	27.7
TCOM2					
TCOM3					
TCOM4	8.8	20.6	15.4	18.1	20.9
TCOM5					
TCOM6					
TCOM7	10.4	17.8	16.5	18.7	20.9
TCOM8					
TCOM9					
TCOM10	9.0	20.8	15.8	18.6	21.3
TCOM11					
TCOM12					
Average	8.2	23.3	15.7	19.2	22.7
Standard Deviation	2.5	7.2	0.6	1.5	3.3

taken from the site of the proposed State Highway 87 bridge embankment on the north bank of the Neches River in Port Arthur, Texas. The procedures used to obtain and prepare specimens for testing and associated boring data are described in Appendix A. Initially, tests were planned using three confining pressures of 5, 10, and 15 psi; however, use of 15 psi was abandoned for the Texas Triaxial tests due to problems associated with excessive membrane inflation. Three unconsolidated-undrained tests were performed using 15 psi confining pressure.

Measured shear strengths from both types of tests are shown in Figure 4.6. The results of two unconsolidated-undrained tests were considered non-typical due to water contents of 190 and 225 percent. These two data points were not plotted.

There was significant scatter in the shear strengths measured using both types of tests with no discernable variations in strength with water content shown by the data in either type of test. The correlation coefficients of linear regression for the unconsolidated-undrained and Texas Triaxial test results are 0.04 and 0.06 respectively, verifying the negligible trend in strength versus water content. However, the data clearly show that the Texas Triaxial test yields consistently higher strengths than the unconsolidated-undrained test. The ratio of average shear strengths measured in the Texas Triaxial and unconsolidated-undrained test is approximately four.

The possibility of drainage in the Texas Triaxial test during shearing was initially discussed in Chapter Two. Drainage was observed on several occasions during Texas Triaxial tests on undisturbed specimens. Water contents were recorded from the top and bottom of specimens obtained from one boring prior to testing with the Texas Triaxial apparatus. At the completion of each test, water contents were recorded from the top, center, and bottom of each specimen. A summary of water contents for these specimens appears in Table 4.4. The average decreases in water content in the top and bottom of the specimens are 8.7 and 13.8 percent, respectively. In some cases, the decrease in water

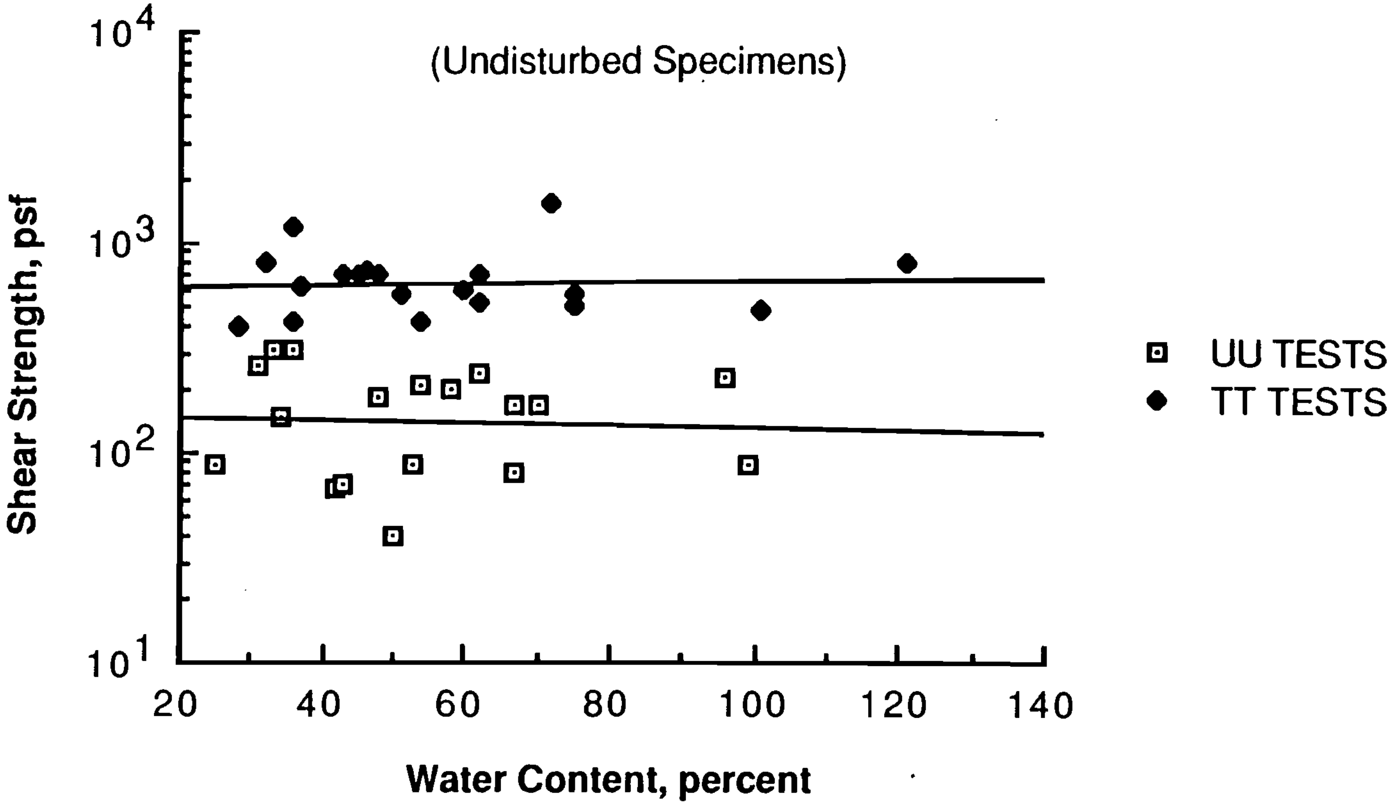

Figure 4.6. Variation in Undrained Shear Strength with Water Content from Texas Triaxial and Unconsolidated-Undrained Tests on Undisturbed Specimens.

content was over 40 percent. In other cases, negligible decreases or very small increases in water content were observed. The standard deviations of changes in water contents in the top and bottom of the specimens examined are 14.7 and 13.9, respectively. These standard deviations are high, reflecting significant scatter in the data.

TESTS ON ARTIFICIAL SPECIMENS

Unconfined compression tests, Texas Triaxial tests and unconsolidated-undrained tests were performed on artificial (polyurethane) specimens in an effort to compare the effects of the membranes employed in the Texas Triaxial and unconsolidated-undrained test. One soft and one stiff specimen were used.

Initially, unconsolidated-undrained tests were performed on specimens with no membranes and at confining pressures of 5, 10, and 15 psi to determine if different confining pressures would affect the stress-strain behavior of the specimens. Plots of principal stress difference versus axial strain at different confining pressures for both the soft and stiff specimens are shown in Figure 4.7. It can be seen that, in the absence of membranes and any effect they might produce, confining pressure had a negligible effect on the stress-strain behavior of either the soft or stiff specimen.

Membrane effects were determined in the following manner. Texas Triaxial and unconsolidated-undrained tests were performed on each specimen using 5, 10, and 15 psi confining pressures. The effects of the rubber membrane used in the Texas Triaxial test on each specimen were determined by subtracting the stresses applied to the specimens in the unconfined compression tests from the stresses applied in the Texas Triaxial tests at selected values of axial strain. The differences in axial stresses obtained are shown in Figures 4.8 and 4.9 for soft and stiff specimens, respectively. The effects of the membrane used in the unconsolidated-undrained tests were obtained by subtracting the stresses

TABLE 4.4. WATER CONTENT CHANGES IN UNDISTURBED SPECIMENS TESTED IN TEXAS TRIAXIAL TESTS.

	Water Content, percent						
Specimen	Top Before Test	Top After Test	Water Content Change	Center After Test	Bottom Before Test	Bottom After Test	Water Content Change
BTT7	39.5	35.0	4.5	42.8	50.6	41.4	9.2
BTT8	71.8	77.2	-5.4	61.7	75.6	46.0	29.6
BTT10	77.8	30.3	47.5	27.8	78.9	33.9	45.0
BTT11	38.0	30.5	7.5	31.7	32.2	29.7	2.5
BTT15	49.5	44.2	5.3	45.2	50.3	44.7	5.6
BTT16	50.8	46.2	4.6	47.8	62.5	55.7	6.8
BTT17	69.0	61.4	8.6	58.0	78.7	67.4	11.3
BTT19	74.8	59.8	15.0	46.3	68.1	58.9	9.2
BTT21	85.0	83.4	1.6	101.3	97.3	78.0	19.3
BTT23	69.4	70.7	-1.3	61.9	35.8	36.1	-0.3
Average			8.7				13.8
Standard Deviation			14.7				13.9

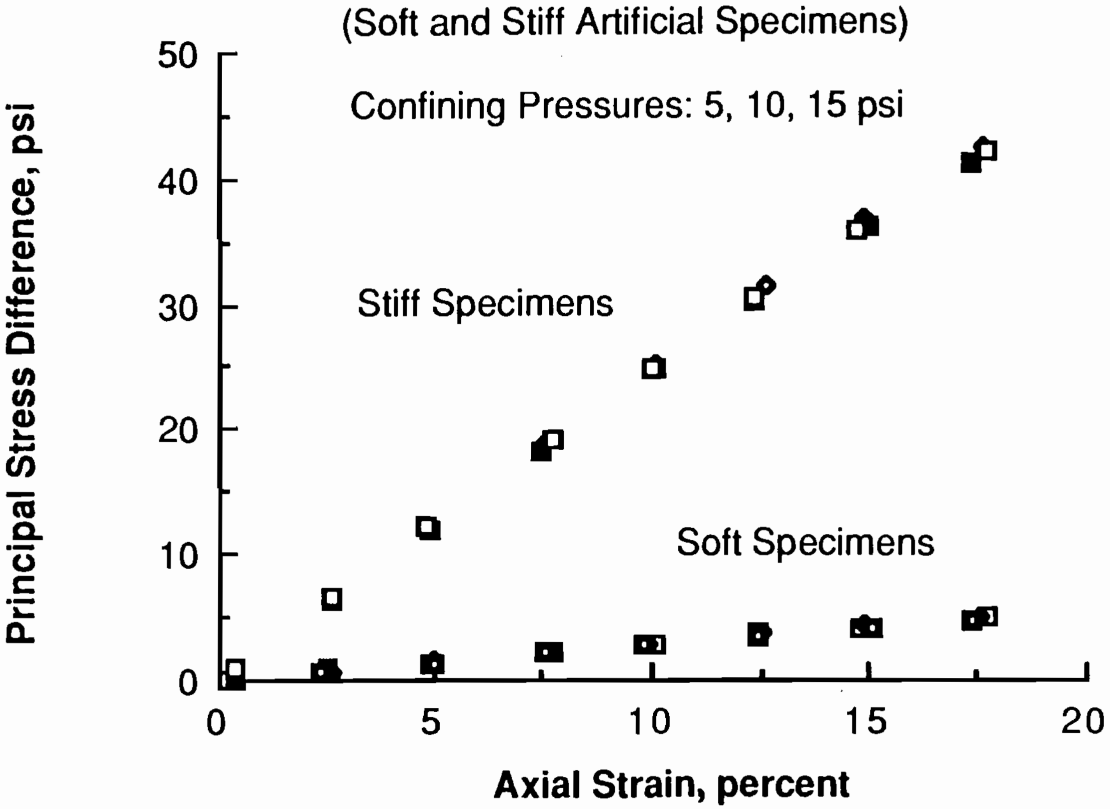

Figure 4.7. Principal Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Soft and Stiff Artificial Specimens Without Membranes.

applied to the specimens in the unconsolidated-undrained tests without using membranes from the stresses applied to the specimens in the unconsolidated-undrained tests using membranes at selected values of axial strain. The results of the calculations are shown in Figure 4.10 for soft specimens. Attempts to calculate membrane effects from unconsolidated-undrained tests using the stiff artificial specimen were unsuccessful. The axial stress increase due to the membrane used was too small a fraction of the total axial stress applied to the specimen to produce meaningful results; even small amounts of scatter in the data obscured membrane effects.

Duncan and Seed (1965) developed equations to estimate stress increases due to the use of membranes in triaxial tests. Their equations are based in part on previous work done by Bishop and Henkel (1962). Axial stress increases were calculated for axial strains of one to ten percent using properties of a typical membrane used in this study. The values of axial stress increase due to membrane are shown in Table 4.5 and in Figure 4.10. The axial stress increase calculated using the Duncan and Seed (1965) approach agreed with axial stress increases calculated using the soft artificial membrane.

The effect of the membrane used in the Texas Triaxial test with the soft artificial specimen ranged from 238 to 468 psf in terms of shear strength measured at ten percent axial strain. These measured membrane effects exceed the average strengths measured on nearly-saturated and undisturbed specimens in the unconsolidated-undrained test by up to a factor of three. The effect of the membrane in the Texas Triaxial test using the stiff artificial specimen ranged from 468 to 612 psf at an axial strain of ten percent. This range is 24 to 32 percent of the average strengths measured in unconsolidated-undrained tests on compacted specimens.

The effect of the membrane employed with the unconsolidated-undrained test at ten percent axial strain was an average of 10 psf in tests using the soft artificial specimen. This is seven percent of the

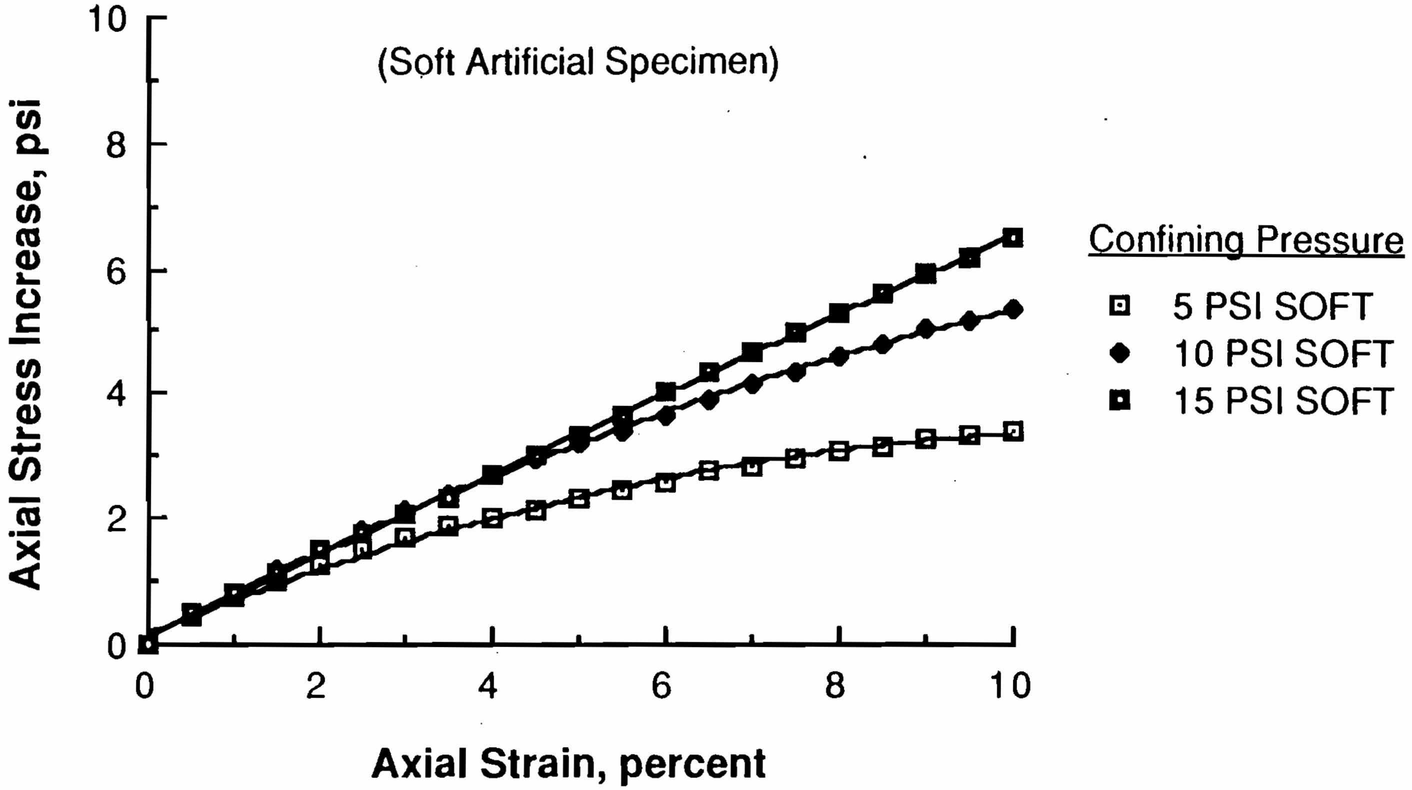

Figure 4.8. Axial Stress Increase Versus Axial Strain in a Soft Artificial Specimen During Texas Triaxial Tests.

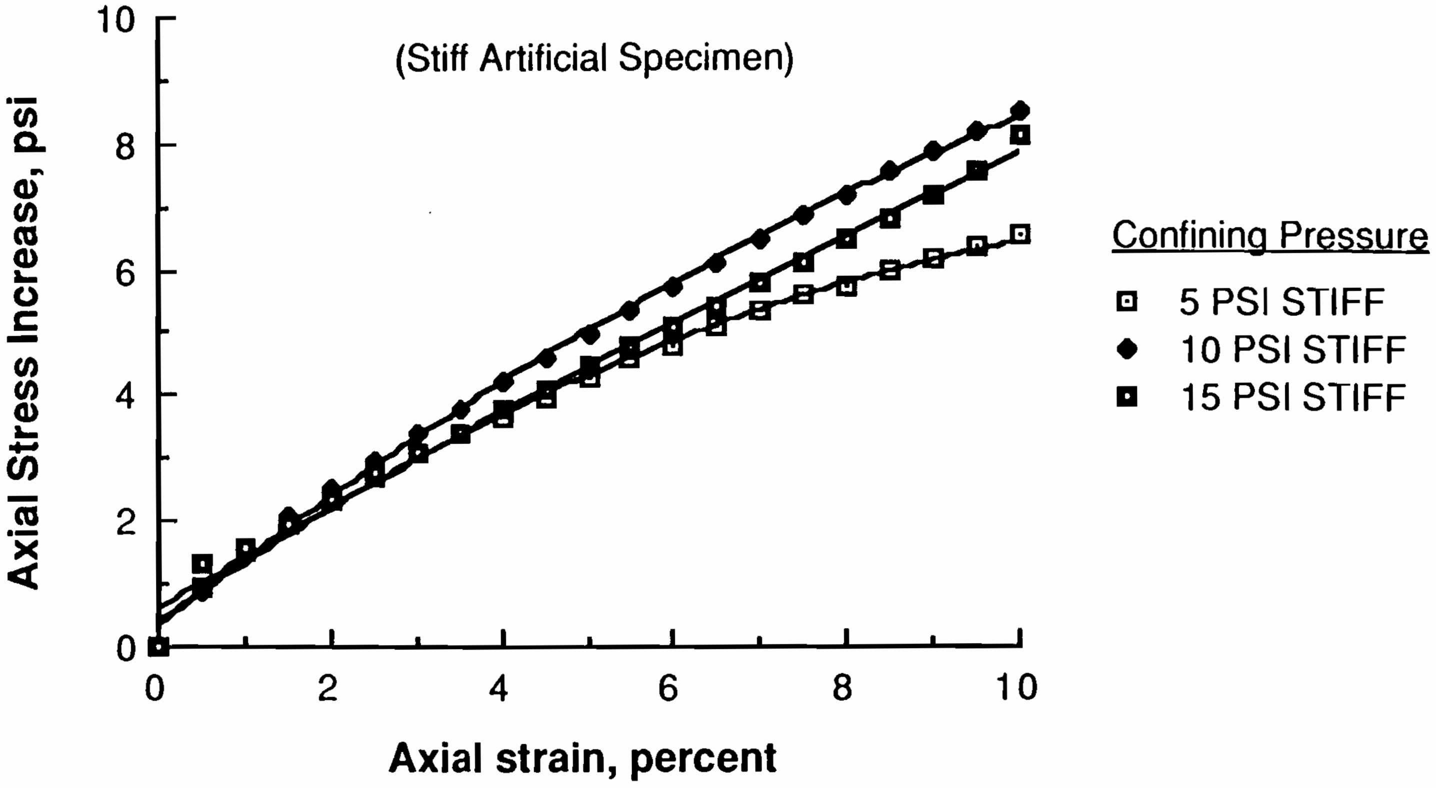

Figure 4.9. Axial Stress Increase Versus Axial Strain in a Stiff Artificial Specimen During Tests Triaxial Tests.

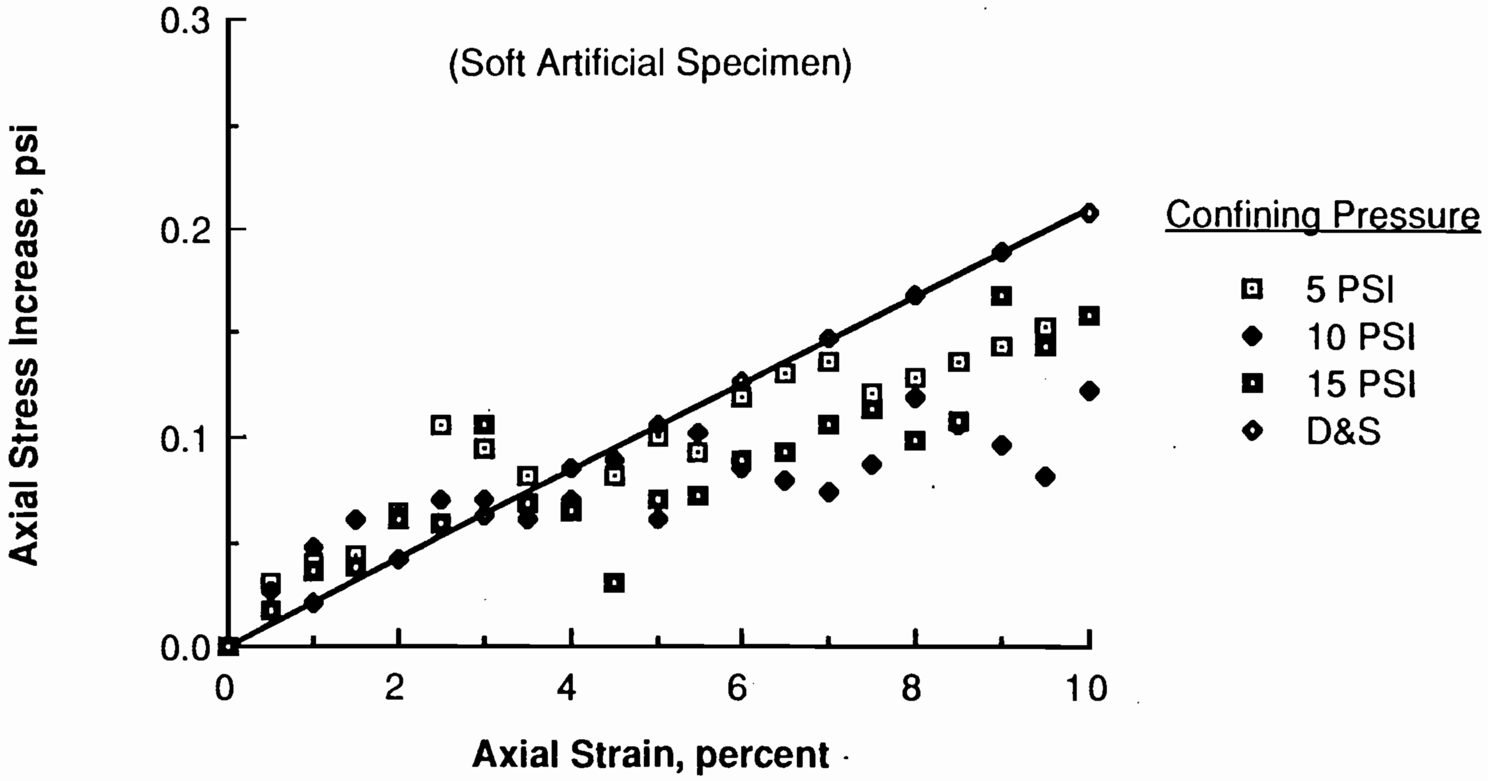

Figure 4.10. Axial Stress Increase Versus Axial Strain in a Soft Artificial Specimen During Unconsolidated-Undrained Tests.

TABLE 4.5. DUNCAN AND SEED AXIAL STRESS CORRECTION DUE TO MEMBRANE IN UNCONSOLIDATED-UNDRAINED TESTS.

Axial Strain, percent	Axial Stress Correction, psi
1	0.021
2	0.042
3	0.063
4	0.084
5	0.105
6	0.126
7	0.147
8	0.167
9	0.188
10	0.208

average shear strength measured on nearly-saturated and undisturbed specimens using the unconsolidated-undrained test.

CHAPTER 5. DISCUSSION OF TRIAXIAL AND VANE SHEAR TEST RESULTS

INTRODUCTION

Results from the various series of triaxial tests are compared and discussed in this chapter. In addition, several series of vane shear tests are described and the results are compared with those from the triaxial tests.

DISCUSSION OF TRIAXIAL TEST RESULTS

Ratios obtained by dividing the shear strengths measured in the Texas Triaxial tests by the corresponding shear strengths measured in the unconsolidated-undrained triaxial tests are plotted versus nominal shear strengths based on unconsolidated-undrained tests in Figure 5.1. As can be seen from Figure 5.1, all data seem to plot along a single curve labeled "UT Curve" in Figure 5.1. It is clear from this plot that the Texas Triaxial test can substantially overestimate the shear strength of clays having shear strengths lower than 1000 psf and should not be used to test soils at or below this shear strength. The "UT Curve" is shown as a broken line for strengths above 1000 psf for the relative values of Texas Triaxial and unconsolidated-undrained shear strengths above 1000 psf to reflect uncertainty about Texas Triaxial strengths obtained from stronger specimens.

Strengths measured in Texas Triaxial and unconsolidated-undrained tests have previously been compared by Hamoudi, et al., (1974) for undisturbed specimens having strengths ranging from 1000 to 5000 psf. A correction factor of 0.58 was developed by Hamoudi, et al., (1974) to apply to Texas Triaxial test results to bring them into reasonable agreement with unconsolidated-undrained test results. The inverse of the correction factor (1/0.58=1.7) is shown in Figure 5.1 as a horizontal line extended over the range of strengths examined by Hamoudi, et al., (1974). This line is marked as "Hamoudi, et al." It is clear

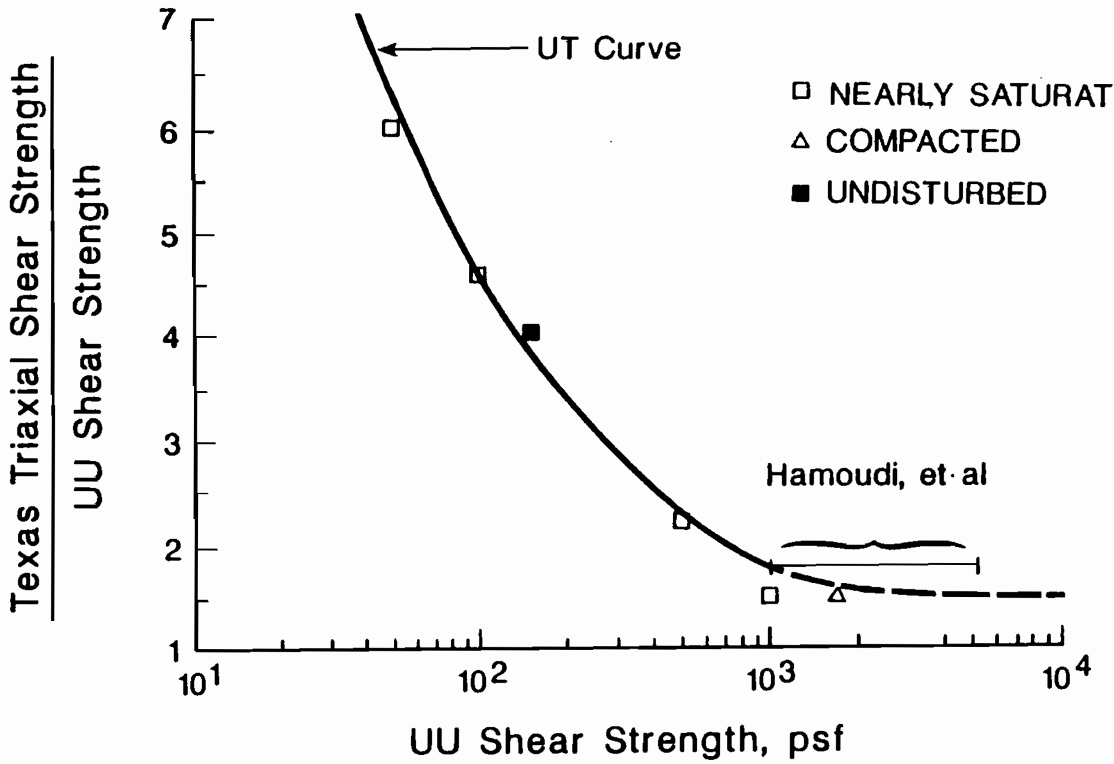

Figure 5.1. Variation in Texas Triaxial Shear Strength Divided by Unconsolidated-Undrained Shear Strength with Unconsolidated-Undrained Shear Strength.

that the correction factor developed by Hamoudi, et al. will not apply to soft clays having shear strengths lower than 1000 psf, although it does appear to lead to conservative strengths in the 1000 to 5000 psf range. Shear strengths measured in the current study using Texas Triaxial tests have been corrected using the factor suggested by Hamoudi, et al. and are plotted with the corresponding shear strengths determined from unconsolidated-undrained tests. Tests on nearly-saturated specimens are shown in Figure 5.2; tests on compacted specimens are shown in Figure 5.3; tests on undisturbed specimens are shown in Figure 5.4.

In an effort to develop a simple correction which might apply to data for a wide range of strengths, the data from tests on artificial specimens was re-examined. It seemed evident that a correction expressed in units of stress, which might be subtracted from the measured axial stresses, might be more applicable to a wider range of stresses than a correction which is expressed as a dimensionless multiplication factor as developed by Hamoudi, et al.,(1974). It was also evident from the tests on artificial specimens, as well as fundamental considerations, that the correction would depend on the axial strain to which the specimen was subjected at the point where failure was considered to occur, the point where the strength was measured. Accordingly, the stresses carried by the membrane and shown previously in Figures 4.8 and 4.9 were determined at strains of 1 through 10 percent, in increments of 1 percent, converted into a stress per percent strain value by dividing each by its corresponding strain and then averaged for all strains. This was done using the data for tests at 5, 10 and 15 psi confining pressure for both soft and stiff specimens and the values obtained were averaged to produce a single value. The overall average value determined by this method is 0.8 psi per percent axial strain. The total range of values extends from 0.5 psi per percent axial strain at one percent strain in the soft specimen to 0.86 psi per percent axial strain at 10 percent axial strain and 10 psi confining pressure in the stiff specimen. The standard deviation of the single average value of 0.8 psi per percent axial strain is 0.3.

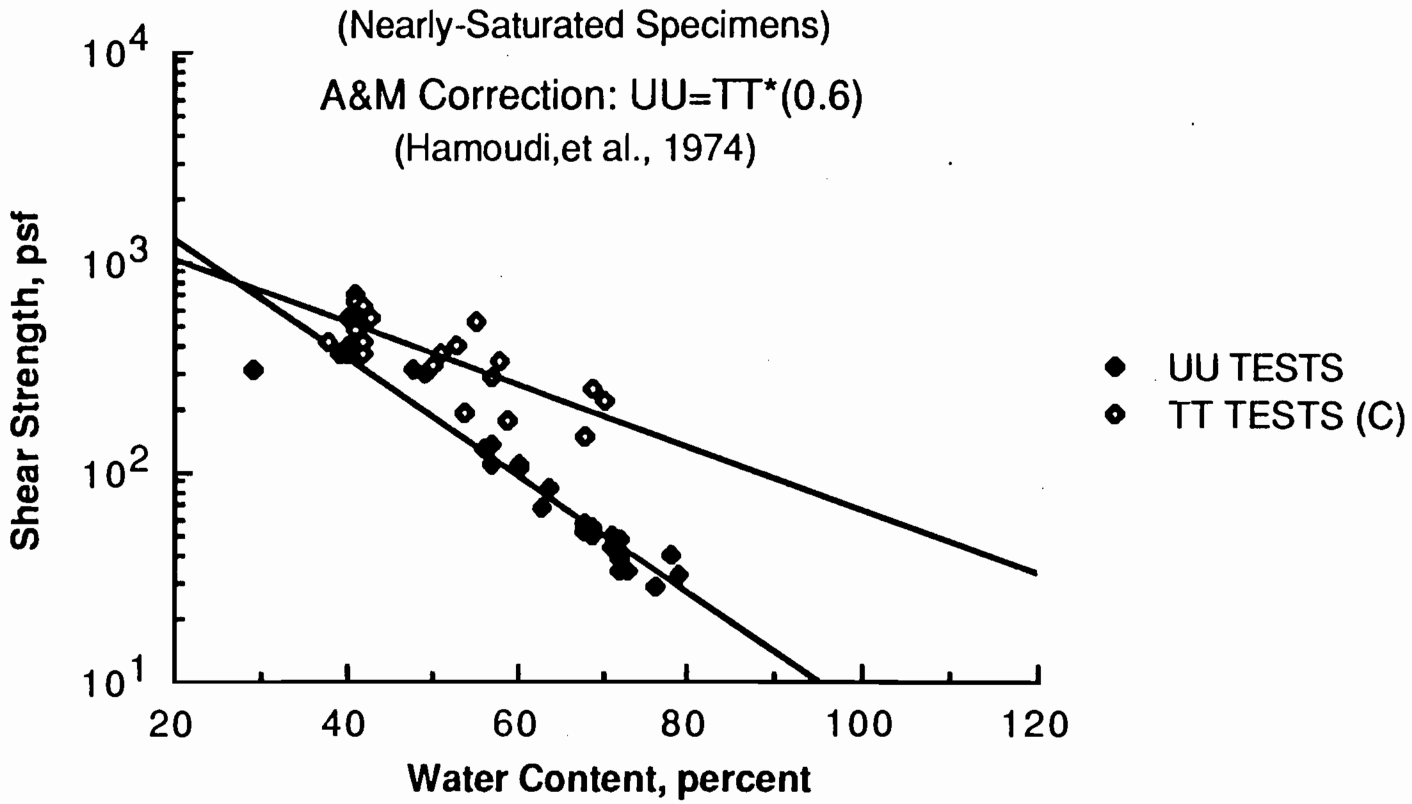

Figure 5.2. Variation in Undrained Shear Strength with Water Content from Corrected Texas Triaxial and Unconsolidated-Undrained tests on Nearly-Saturated Specimens.

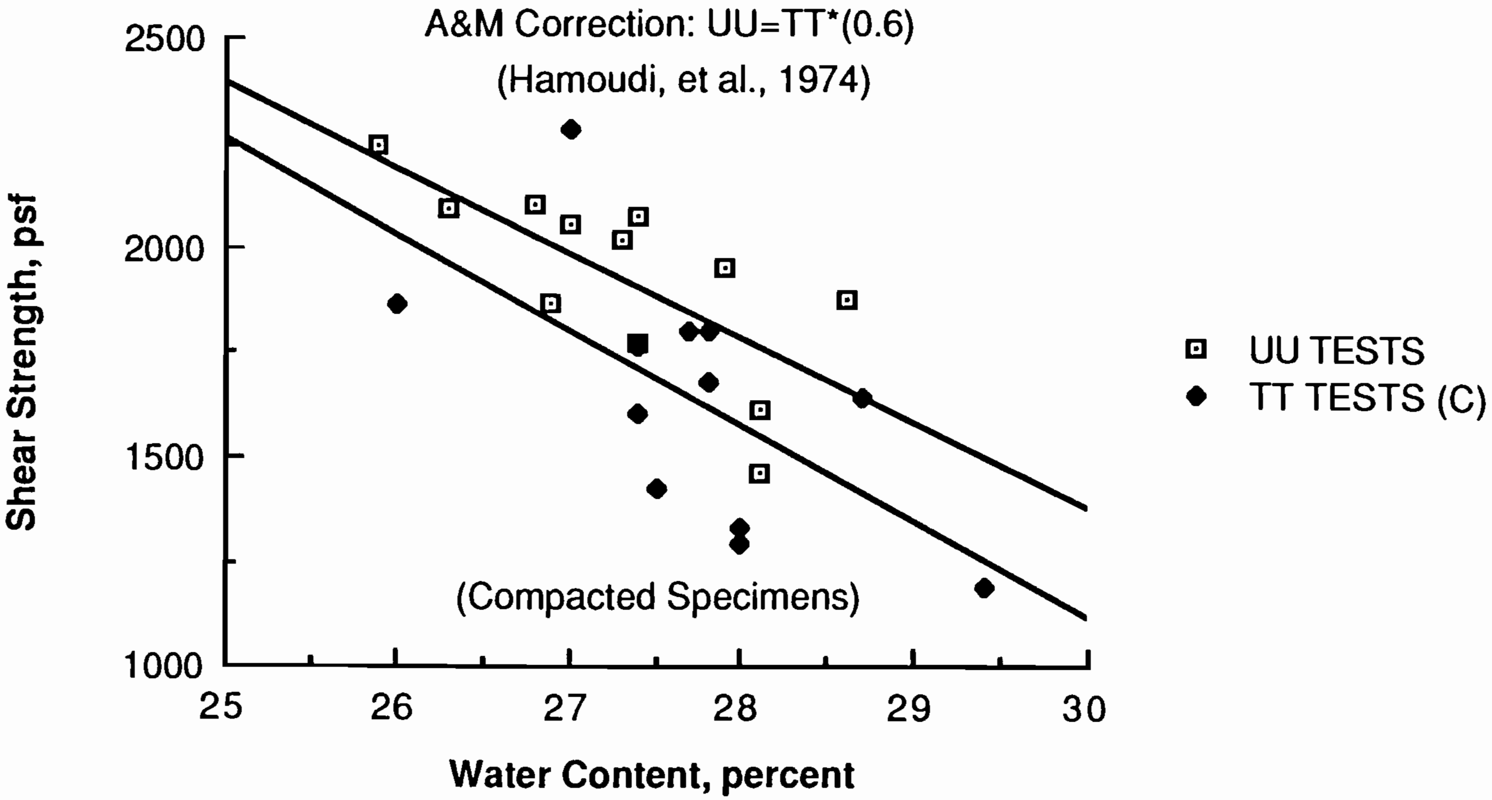

Figure 5.3. Variation in Undrained Shear Strength with Water Content from Corrected Texas Triaxial and Unconsolidated-Undrained Tests on Compacted Specimens.

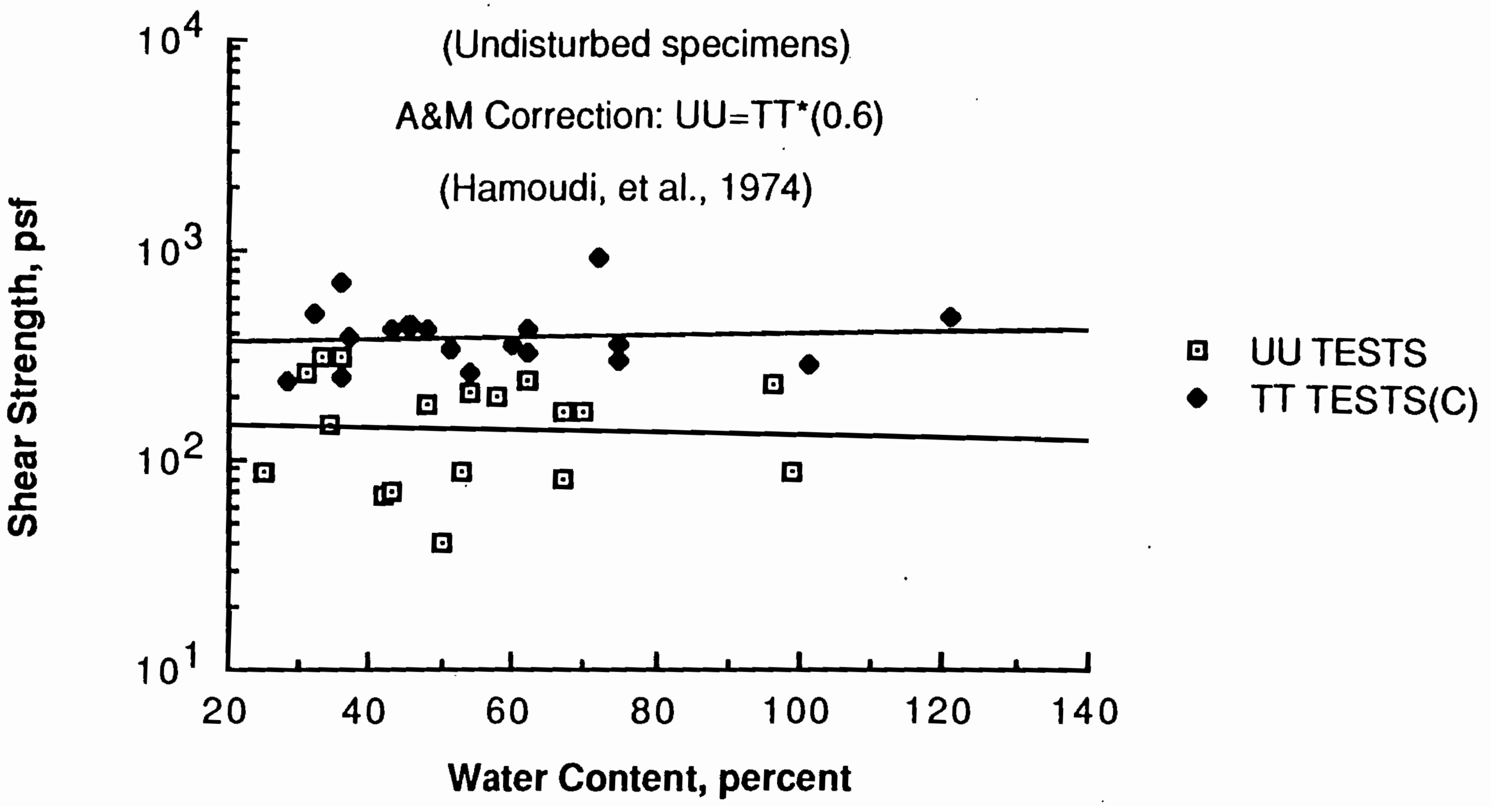

Figure 5.4. Variation in Undrained Shear Strength with Water Content from Corrected Texas Triaxial and Unconsolidated-Undrained Tests on Undisturbed Specimens.

The correction factor of 0.8 psi per percent axial strain was applied to axial stresses at failure measured using the Texas triaxial test for a range of strengths. Shear strengths were recalculated using the corrected axial stresses at failure. It was found that in many cases the corrected shear strengths were either close to zero or were negative, indicating that the correction exceeded the measured strength. It should be clear that any attempt to develop and apply corrections to Texas Triaxial test results would have to incorporate both axial strain and confining pressure in each application.

LABORATORY VANE TESTS

Vane shear tests provide a convenient alternative to triaxial tests for estimating the undrained shear strength of soft clays. However, Bjerrum (1972) showed that the vane shear test overestimated the undrained shear strength in some cases and underestimated it in other cases. Others, including La Rochelle, et al., (1974), Flaate, (1966), Kimura and Saitoh, (1983), and Schmertmann, (1975) have presented problems with the vane test that could affect its ability to accurately predict undrained shear strength. It is clear that some correction should be applied to vane shear test results prior to use in design.

A total of 47 laboratory vane tests were performed as part of this study. Twenty-three tests were performed using a four-bladed vane with a diameter and height of one inch and 24 tests were performed using a second vane with a diameter and height of one-half inch. Both vane sizes were employed to check for possible size effects. The test results for both vane sizes are shown in Figure 5.5.

Two linear regression lines are fit to the data, one for one-inch vanes and one for half-inch vanes, however, distinguishing between the two regression lines is difficult, and the lines indicate no meaningful size effect for the two vanes used.

Linear regression analyses were performed for the relationship between shear strength and water content for both the one-half-inch and

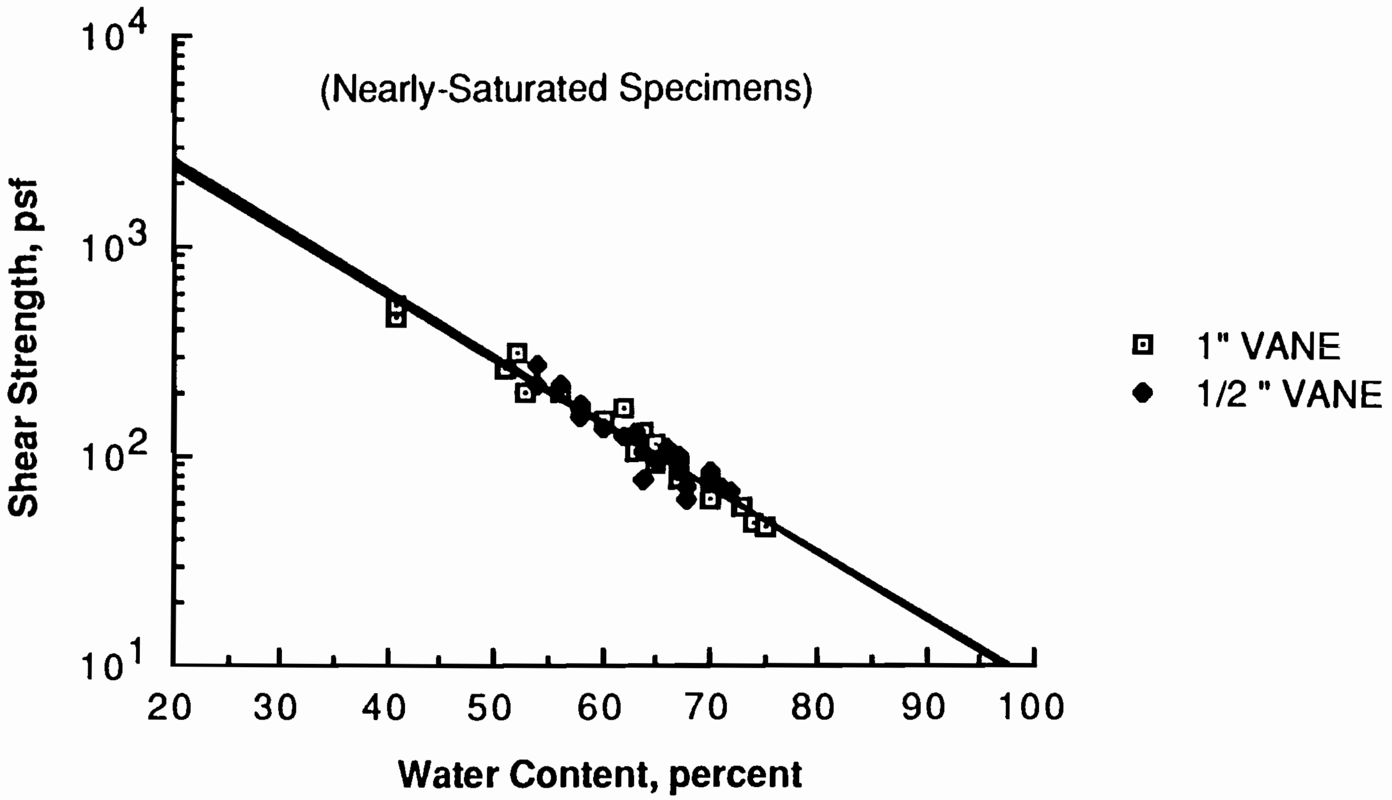

Figure 5.5. Variation in Undrained Shear Strength with Water Content from Laboratory Vane Tests on Nearly-Saturated Specimens.

one-inch laboratory vane test results. The correlation coefficients were found to be 0.95 and 0.98, respectively. The high correlation coefficients and close grouping of data about the regression lines suggests little scatter in the data.

Comparison With Triaxial Test Data

Shear strengths of nearly-saturated specimens measured using unconsolidated-undrained triaxial tests, discussed in Chapter Four and plotted in Figure 4.1, have been plotted with the laboratory vane strengths discussed above and are shown in Figure 5.6. Two water contents, 40 and 70 percent, were selected to illustrate conditions of relatively high and low strength. At a water content of 40 percent, vane tests yielded a shear strength of approximately 590 psf; whereas, the unconsolidated-undrained tests indicate a shear strength of approximately 360 psf. The ratio of laboratory vane shear strength to unconsolidated-undrained shear strength at a water content of 40 percent is 1.6. This ratio varies slightly with water content. At a water content of 70 percent, this ratio of laboratory vane shear strength to unconsolidated-undrained shear strength is 1.4. Over the range water contents from 40 to 70 percent, the average ratio of laboratory vane shear strength to unconsolidated-undrained vane shear strength is 1.5.

Bjerrum (1972) developed a correction to apply to shear strengths obtained from vane tests in an effort to bring them into better agreement with "actual" (field) shear strengths. The correction was developed from a series of case histories involving failures of embankments on soft clays. The correction factor, which is a function of plasticity index, is shown in Figure 5.7.

The correction factor of 0.8 corresponding to a plasticity index of 47 for the Taylor clay used in this study was applied to the vane shear strengths shown in Figure 5.6. The corrected vane shear strengths are plotted with unconsolidated-undrained shear strengths in Figure 5.8.

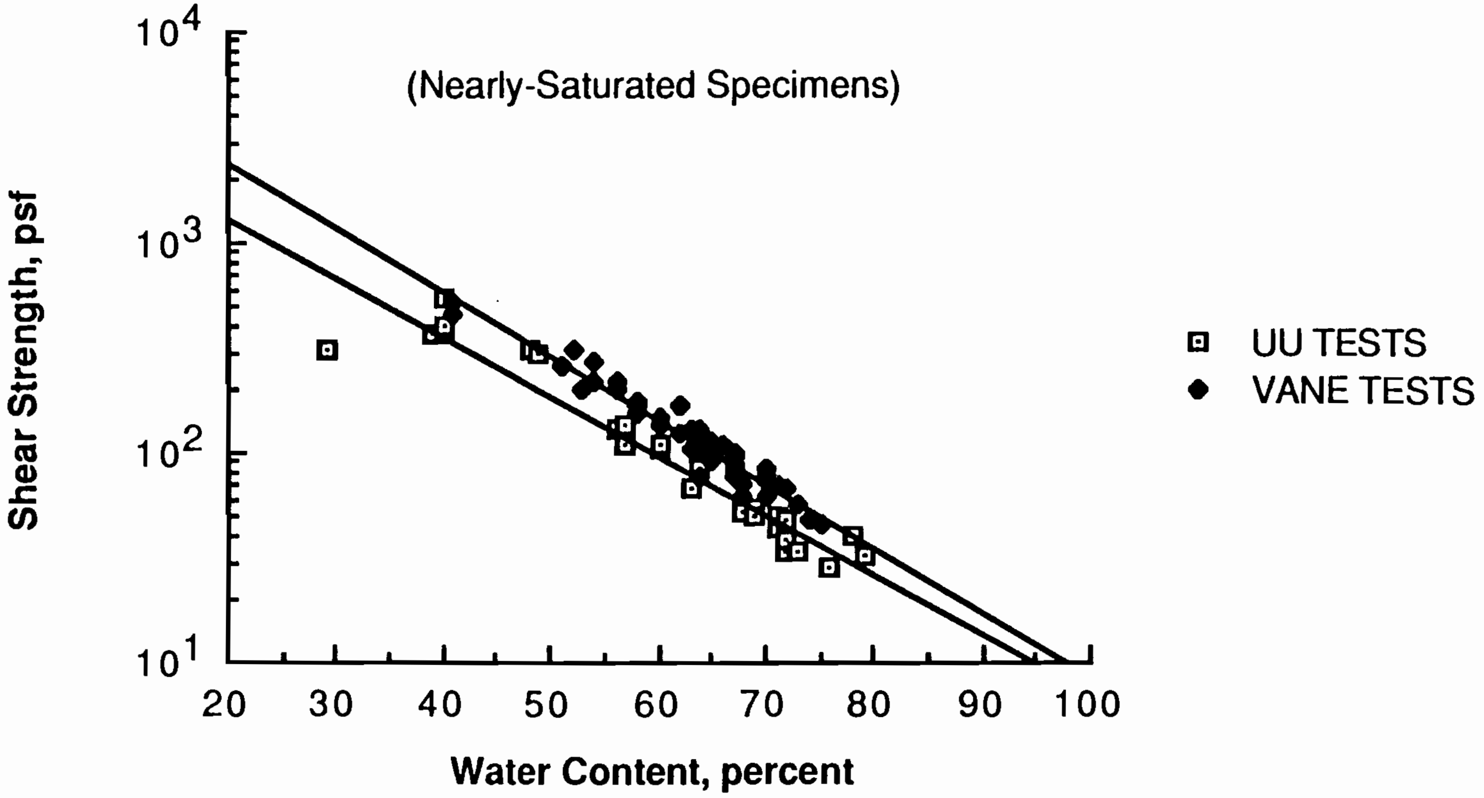

Figure 5.6. Variation in Undrained Shear Strength with Water Content from Laboratory Vane and Unconsolidated-Undrained Tests on Nearly-Saturated Specimens.

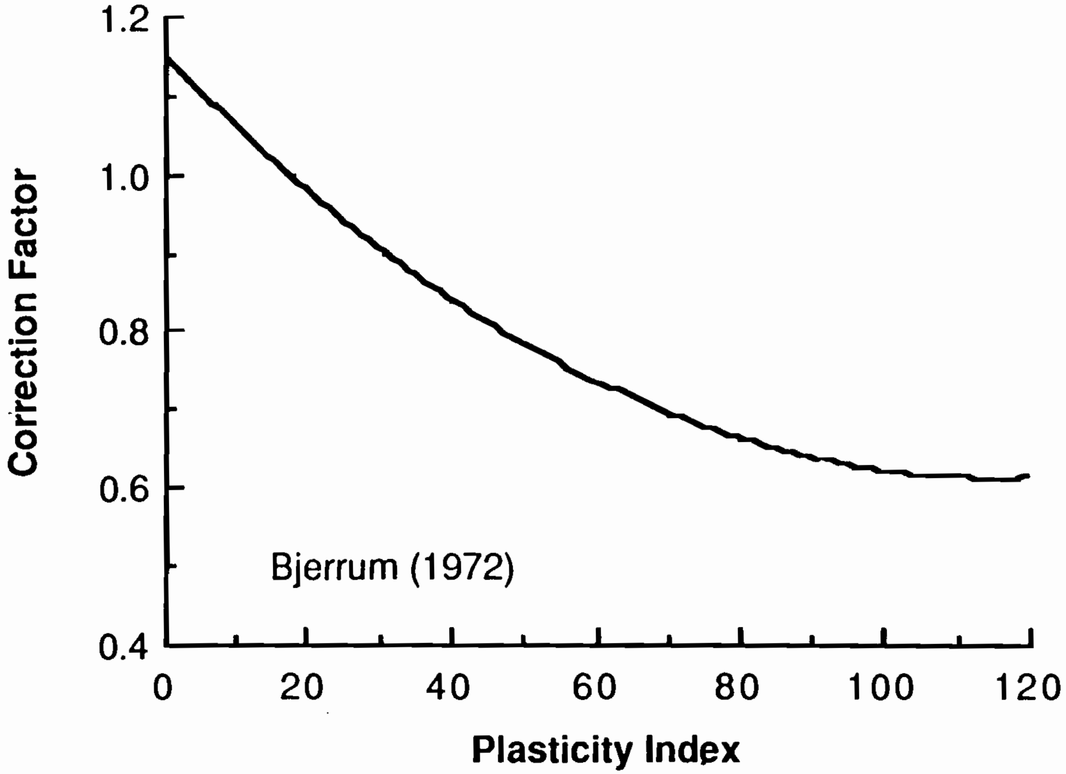

Figure 5.7. Variation in Bjerrum's Vane Strength Correction with Plasticity Index.

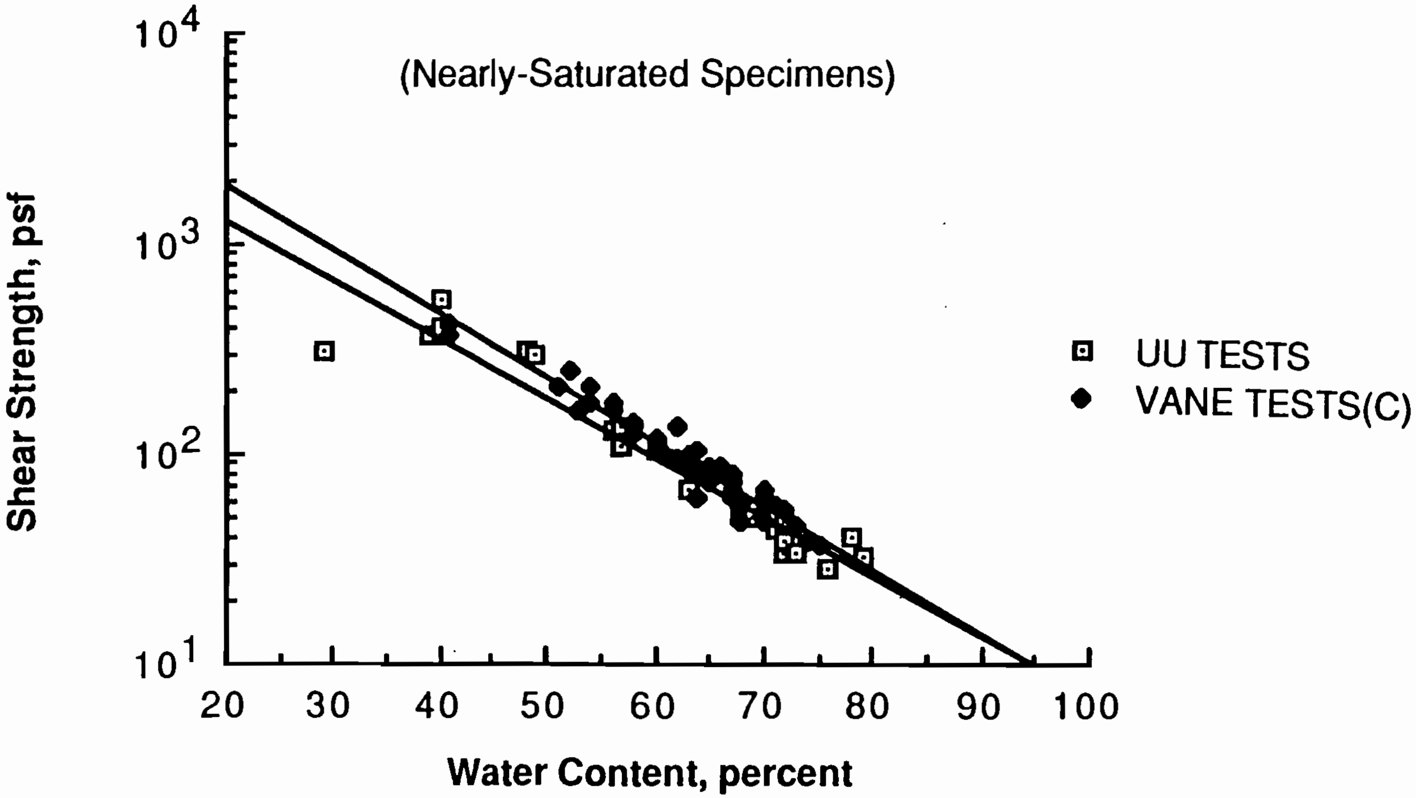

Figure 5.8. Variation in Undrained Shear Strength with Water Content from Corrected Laboratory Vane and Unconsolidated-Undrained Tests on Nearly-Saturated Specimens.

TORVANE TESTS

Nearly-Saturated Specimens

Twenty-four Torvane tests were performed on nearly-saturated specimens as part of this study. The shear strengths obtained from these tests are shown in Figure 5.9. The correlation coefficient of linear regression is 0.99, indicating that scatter of the measured shear strengths is low.

Comparison With Triaxial Test Data from Nearly-Saturated Specimens

The Torvane and unconsolidated-undrained triaxial test shear strengths are plotted together in Figure 5.10. Two water contents, 40 and 70 percent, were selected to illustrate conditions of relatively high and low shear strengths. At a water content of 40 percent, the regression lines fitted through the unconsolidated-undrained triaxial and Torvane data each yielded shear strengths of approximately 360 psf. At a water content of 70 percent, the shear strengths obtained from the Torvane and unconsolidated-undrained triaxial tests are 70 psf and 50 psf, respectively. The corresponding ratios of Torvane-to-unconsolidated-undrained triaxial shear strengths are 1.0 and 1.4 for water contents of 40 and 70 percent, respectively. The average of the two ratios calculated for 40 and 70 percent water content is 1.2.

Undisturbed Specimens

Torvane tests were performed on undisturbed soil at the tip of each Shelby tube immediately after it was recovered in the field and prior to sealing. Torvane shear strengths are plotted versus depth in Figures A.1 and A.2 in Appendix A. Torvane strengths are plotted versus water content in Figure 5.11. The correlation coefficient of linear

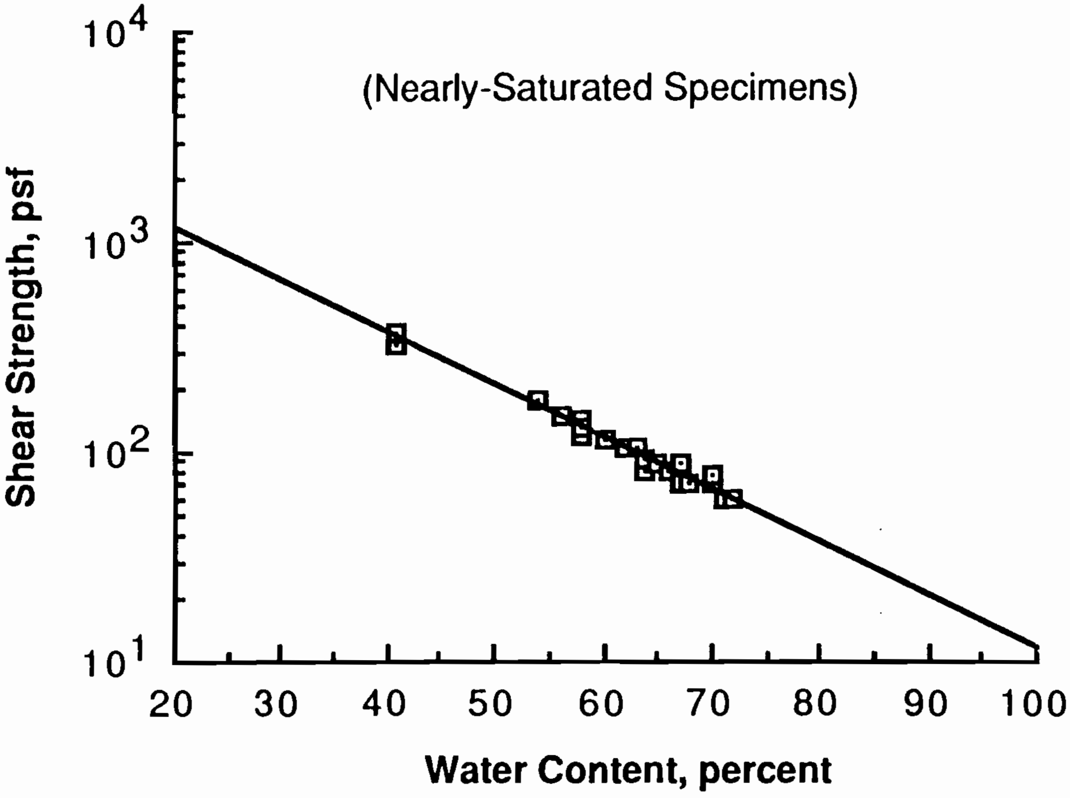

Figure 5.9. Variation in Undrained Shear Strength with Water Content from Torvane Tests on Nearly-Saturated Specimens.

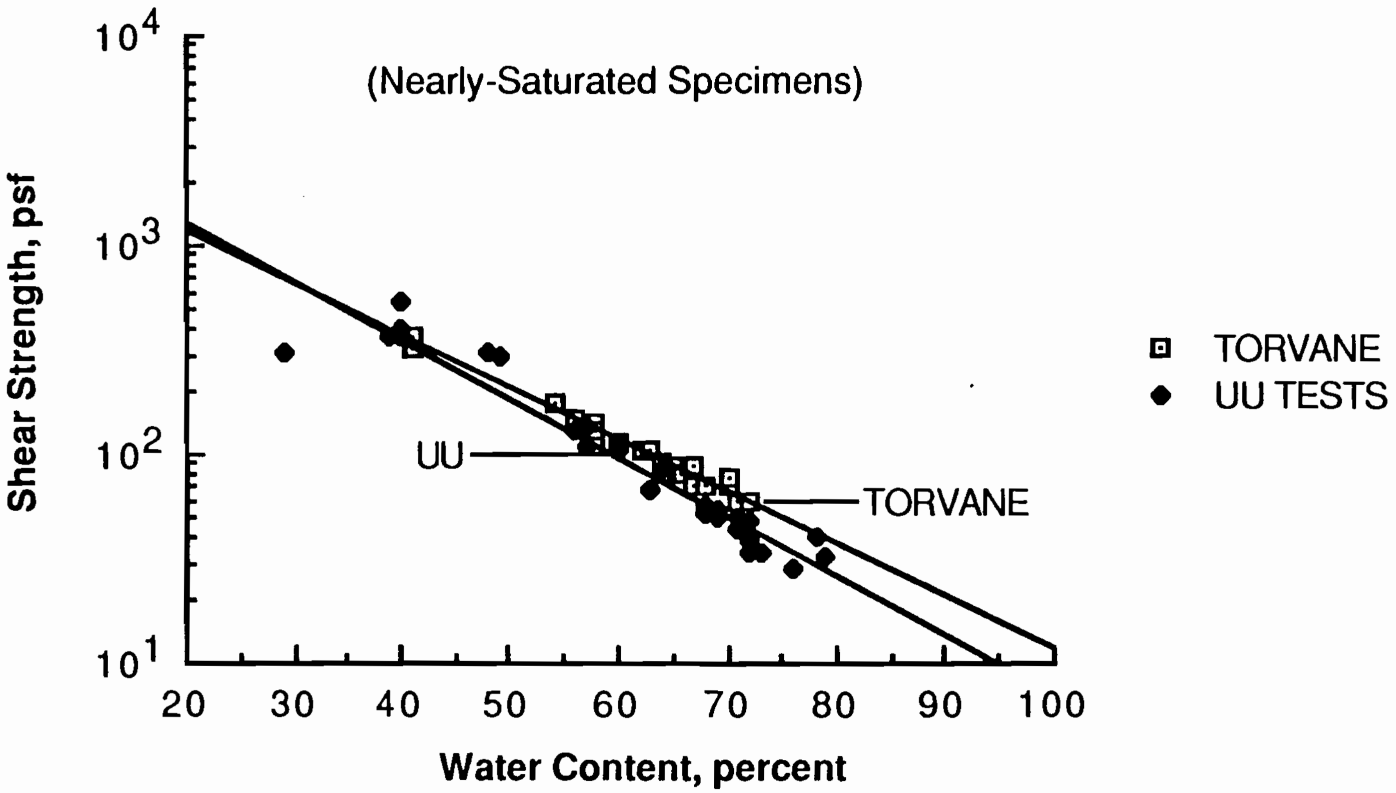

Figure 5.10. Variation in Undrained Shear Strength with Water Content from Torvane and Unconsolidated-Undrained Tests on Nearly-Saturated Specimens.

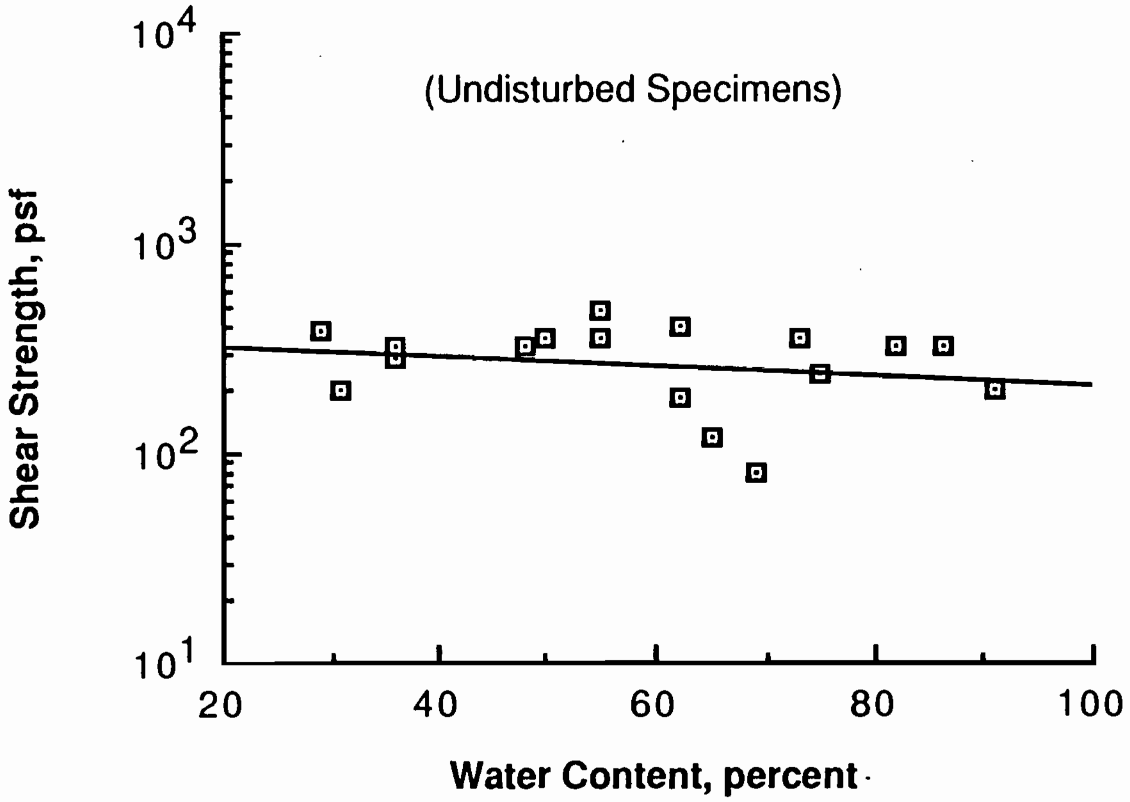

Figure 5.11. Variation in Undrained Shear Strength with Water Content from Torvane Tests on Undisturbed Specimens.

regression is small (0.21), indicating that the Torvane shear strengths of undisturbed specimens vary considerably. This variation is due most likely to natural variations in soil deposits.

Comparison With Triaxial Test Data from Undisturbed Specimens

Due to the lack of apparent trends for the strengths to vary with water content, average values of shear strength at all water contents from each Torvane and unconsolidated-undrained test were compared. The average undrained shear strength measured in the unconsolidated-undrained triaxial tests is 165 psf; the average strength measured with the Torvane is 300 psf. Thus, the ratio of average Torvane shear strength to average unconsolidated-undrained triaxial shear strength is 1.8. This ratio is higher than those calculated in comparisons of laboratory vane and Torvane tests with unconsolidated-undrained triaxial tests on nearly-saturated specimens, but may be affected by either scatter in the data or a difference in soil type. The average plasticity index of undisturbed specimens tested is 62, indicating the presence of clay that is more plastic in nature than the Taylor clay used to prepare the nearly-saturated specimens. This could possibly explain the bigger difference in strengths of undisturbed specimens measured with the Torvane and unconsolidated-undrained tests and could lend additional validity to Bjerrum's correction method.

DISCUSSION OF VANE TEST RESULTS

It is clear from the data presented that while laboratory vane and Torvane tests are convenient alternatives to triaxial shear tests, some correction of shear strengths obtained from these tests is necessary. Bjerrum's method is probably the most widely accepted method used in practice for correcting vane shear strengths. It should be noted, however, that this vane shear strength correction method was originally intended to correct vane shear strengths to "actual" (field) shear strengths and not to some other laboratory-determined shear strength. Corrected vane shear strengths will probably differ from shear strengths measured in laboratory triaxial tests for this reason. Despite the specific intent behind the development of the method, it appears to provide an adjustment in the right direction and should be used to adjust vane strengths in the absence of any better method which provides specific reduction factors.

CHAPTER 6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

Several series of laboratory shear tests have been performed using a variety of test apparatus and procedures to measure the shear strength of soft clays. The apparatus and procedures represent most of those used either by the Texas State Department of Highways and Public Transportation or in conventional geotechnical engineering practice and include: Texas Triaxial, Texas Transmatic, unconsolidated-undrained triaxial shear, laboratory vane, and Torvane. Tests were performed on several types of specimens prepared by: packing soil into a mold, using a vacuum extrusion device, and compaction. Additionally, tests were performed on undisturbed specimens and artificial specimens cast of polyurethane. At the outset of this study, it was recognized that the procedures commonly employed by the SDHPT differed from those employed in conventional geotechnical engineering practice and often required that substantial correction be applied to obtain meaningful results. Accordingly, the purpose of most of the tests performed in this study was to evaluate the suitability of existing SDHPT laboratory test procedures for measuring the shear strength of clays and to provide suitable recommendations for modification and improvement.

The results of this study showed that the Texas Triaxial test may substantially overestimate the shear strength of soft clays, especially for shear strengths below 1000 psf and that corrections to the data may be nearly impossible. Additionally, a combination of unconfined compression, Texas Triaxial, and unconsolidated-undrained tests were performed on laboratory-prepared polyurethane specimens in an effort to isolate effects of the membrane used in each test empirically. Duncan and Seed's (1965) correction was calculated for the membrane used in the unconsolidated-undrained tests. Significant difficulties were encountered using the Texas Transmatic apparatus provided for this study; however, based on the experience with the device, several recommendations are made in the following sections of this Chapter. The vane shear tests all produced shear strengths in excess of those that would be recommended for design based on other tests and confirmed Bjerrum's (1972) suggestion that the strengths should be adjusted before using them for design. Specific recommendations based on the findings of this study are presented in the next section.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are suggested based on examination of the test devices and procedures and of test data developed as part of this study.

Texas Triaxial Test

The Texas Triaxial test consistently overestimates the shear strength by an amount that makes the test generally unsuitable for use in measuring the undrained shear strength of clays. The correction factor developed by Hamoudi et al., (1974) appears to be conservative for shear strengths above 1000 psf; however, no suitable correction factor could be found for shear strengths below 1000 psf. Based on the errors in the tests and the lack of suitable correction factors, use of the Texas Triaxial device is not recommended for determining the undrained shear strength of clays.

Texas Transmatic Test

Significant difficulties were encountered in using the Texas Transmatic device in this study. Specific problems encountered included: (1) the apparatus leaked excessively due to poor sealing of the o-ring seal between the two main sections of the test cell; (2) excessive friction and binding in a secondary o-ring seal made it difficult to set up specimens without disturbing them; (3) the proving ring for measuring loads was excessively stiff and did not provide the sensitivity needed to reliably measure loads when testing soft clays; (4) the base pedestal on which the specimen rested contained a hole which would allow drainage and the potential for soil to be extruded through the base at certain confining pressures. Fundamentally, the Texas Transmatic device should produce measured shear strengths comparable to those measured in conventional unconsolidated-undrained triaxial tests; however, the specific device used in this study was unsuitable. A new device would need to be fabricated to eliminate the deficiencies noted above. It seems likely that the cost and effort to construct such a device might be comparable to what is required to construct or purchase commercially a conventional triaxial cell for unconsolidated-undrained shear tests. Consequently, except for cases where there may already be suitable, existing equipment, there seems to be little incentive for using the Texas Transmatic test in preference to conventional unconsolidated-undrained tests, which are much more widely used and for which there is already considerable practical experience.

Unconsolidated-Undrained Test

Unconsolidated-undrained triaxial shear tests performed in accordance with the ASTM standard are universally accepted for measuring undrained shear strengths of clays. Shear strengths measured employing unconsolidated-undrained tests probably require the least correction for application to field problems. Unconsolidated-undrained shear tests should be the primary type of laboratory test adopted by the Texas SDHPT for determination of undrained shear strength of soft clays.

Unconfined compression tests may in some cases be considered as an alternative to unconsolidated-undrained tests. However, unconfined compression tests should only be used in instances where the soil is saturated. In the case of stiff-fissured clays and shales, unconfined compression tests may significantly underestimate the shear strength due to the opening of fissures or joints. Accordingly, in such materials, use of unconfined compression tests could cause excessive conservatism if the confinement in the field would have prevented such features from opening.

Laboratory Vane Test

Laboratory vane tests are theoretically and practically valid only for use in saturated soils. Even for saturated soils, vane tests generally overestimate the shear strength and require that some correction be made. Bjerrum's correction is perhaps the best available for this purpose; however, based on the limited comparisons in this study, it may still result in a higher shear strength than that measured in conventional unconsolidated-undrained tests. Laboratory vane tests may be used to supplement data from other types of tests, but generally should not be the only type of test used.

Torvane Test

Generally, the same precautions discussed for the laboratory vane tests will apply to the Torvane test. In addition, added caution may be required since the tests are typically performed in the ends of sample tubes or on exposed surfaces of samples, which are likely to be affected more by sample disturbance. The principal advantage of the Torvane test is its relative simplicity and low cost. Further, it provides a useful means of obtaining data for making preliminary estimates of undrained shear strength in the field and verifying results of other types of laboratory tests.

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APPENDIX A

UNDISTURBED SOIL SAMPLING AND SPECIMEN PREPARATION

APPENDIX A. UNDISTURBED SOIL SAMPLING AND SPECIMEN PREPARATION

Appendix A contains the procedures used to obtain undisturbed samples and prepare undisturbed samples for testing as part of this study. Undisturbed samples were taken from the proposed State Highway 87 bridge embankment under construction on the north bank of the Neches River in Port Arthur, Texas and returned to the University of Texas for testing.

UNDISTURBED SOIL SAMPLING

Undisturbed Shelby tube samples were obtained from an area approximately 150 feet east of the centerline of the proposed Rainbow Bridge approach embankment at station 373+00. Southwestern Laboratories, Incorporated performed the drilling and sampling on August 29, 1986 under the supervision and direction of personnel from the University of Texas.

The drill rig used was a Failing Model 250 mounted on an Ardco four-by-four all terrain vehicle. The drill rig was levelled by hydraulic jacks where necessary.

The Shelby tubes used to recover the samples conformed to ASTM specifications as descibed in ASTM designation D-1587 (ASTM, 1985). The tubes were three inches in outside diameter and had a wall thickness of 0.075 inches. It should be noted that these tube dimensions varied slightly among the tubes measured but that the variation was within ASTM tolerances. These tubes had an area ratio of 11 percent based on the nominal dimensions stated.

Two borings were made approximately ten feet apart. Depths of penetration of 29.5 and 30 feet were accomplished for Boreholes A and B respectively. Both borings encountered sand at approximately 26 feet of depth and were terminated at the depths stated.

All tubes were logged and sealed with paraffin on both ends prior to being transported back to the University of Texas for extrusion and testing. The logging process included Torvane shear strength testing as well as other standard field classification parameters.

SOIL PROFILES

The soil profiles for borings A and B are shown in Figures A.1 and A.2, respectively. In both borings, the soil color ranges from greenish gray to dark gray. Aside from slight differences in the depths that color changes occur and the presence of traces of sand, the soil profiles are virtually identical when considering color.

Water content and Torvane shear strength readings shown in Figures A.1 and A.2 indicate general similarities between the two boreholes. In each case, the Torvane shear strength appears to decrease considerably as the water content increases with depth.

SPECIMEN PREPARATION

Prior to extrusion, the tube was cut with a hacksaw slightly above the top of the paraffin seals on both ends to reduce the distance that the soil would have to travel on extrusion. The paraffin was carefully removed from both ends of the tube. The tube was placed vertically in the extrusion device and a hand-operated hydraulic jack with a 2.7-inch diameter plate attached to the piston was used to push the soil out of the tube. The soil was extruded in the same direction as it was pushed into the tube. As the soil was being extruded, six-inch lengths were carefully measured and cut with a wire saw. Each specimen was lifted off the top of the extrusion device, carefully wrapped in cellophane, and weighed. This process was continued until the tube was empty. No more than five specimens were extruded and tested at one time.

A summary of recovery lengths per tube is presented in Table A.1.

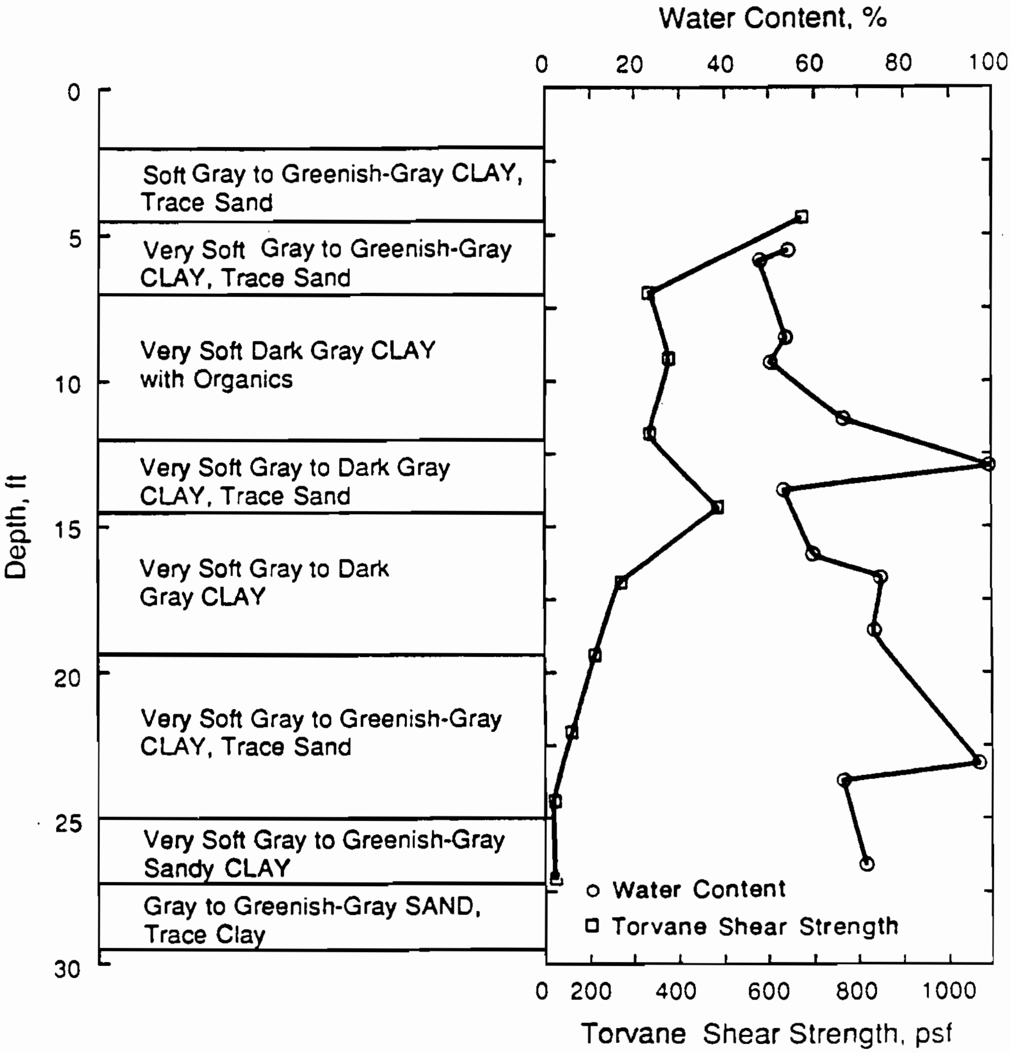


Figure A.1. Soil Profile for Boring A.

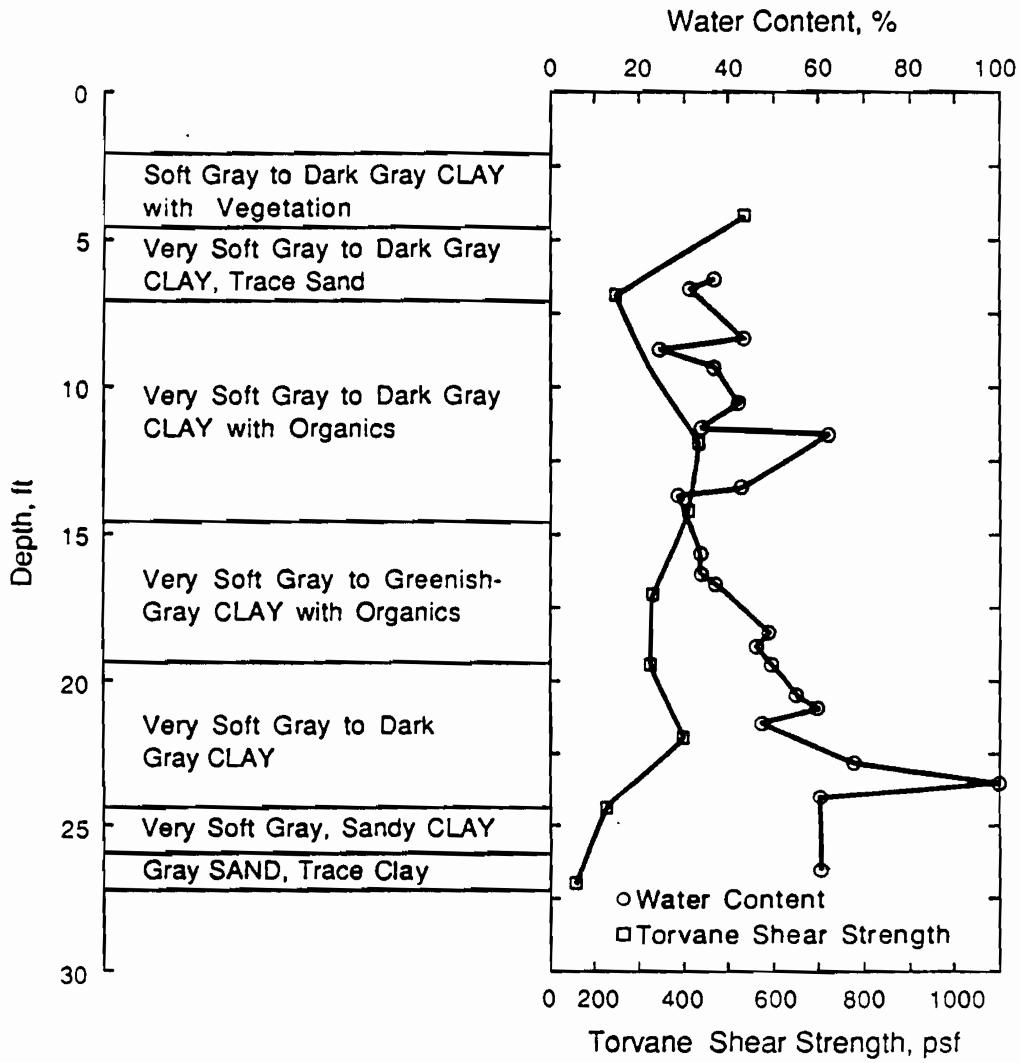


Figure A.2. Soil Profile for Boring B.

TABLE A.1. RECOVERED UNDISTURBED SAMPLES EXAMINED IN THE LABORATORY.

Boring	Tip Depth of Shelby Tube (feet)	Length of Recovery (feet)
A	4.5	1.0
	7.0	2.1
	9.5	1.9
	12.0	1.8
	14.5	2.2
	17.0	2.0
	19.5	2.1
	22.0	0.0
	24.5	2.1
	27.0	2.3
	29.5	2.1
B	4.5	1.2
	7.0	1.2
	9.5	1.9
	12.0	1.8
	14.5	1.8
	17.0	1.8
	19.5	1.8
	22.0	2.4
	24.5	2.4
	27.0	1.5

APPENDIX B

SUMMARY PLOTS FOR TEXAS TRIAXIAL TESTS

APPENDIX B. SUMMARY PLOTS FOR TEXAS TRIAXIAL TESTS

Appendix B contains the summary plots of stress versus strain over the full range of strains for the Texas Triaxial tests performed as part of this study. These include tests on the specimens prepared by packing, vacuum extrusion, and compaction. Additionally, summary plots of tests on undisturbed and artificial specimens are included.

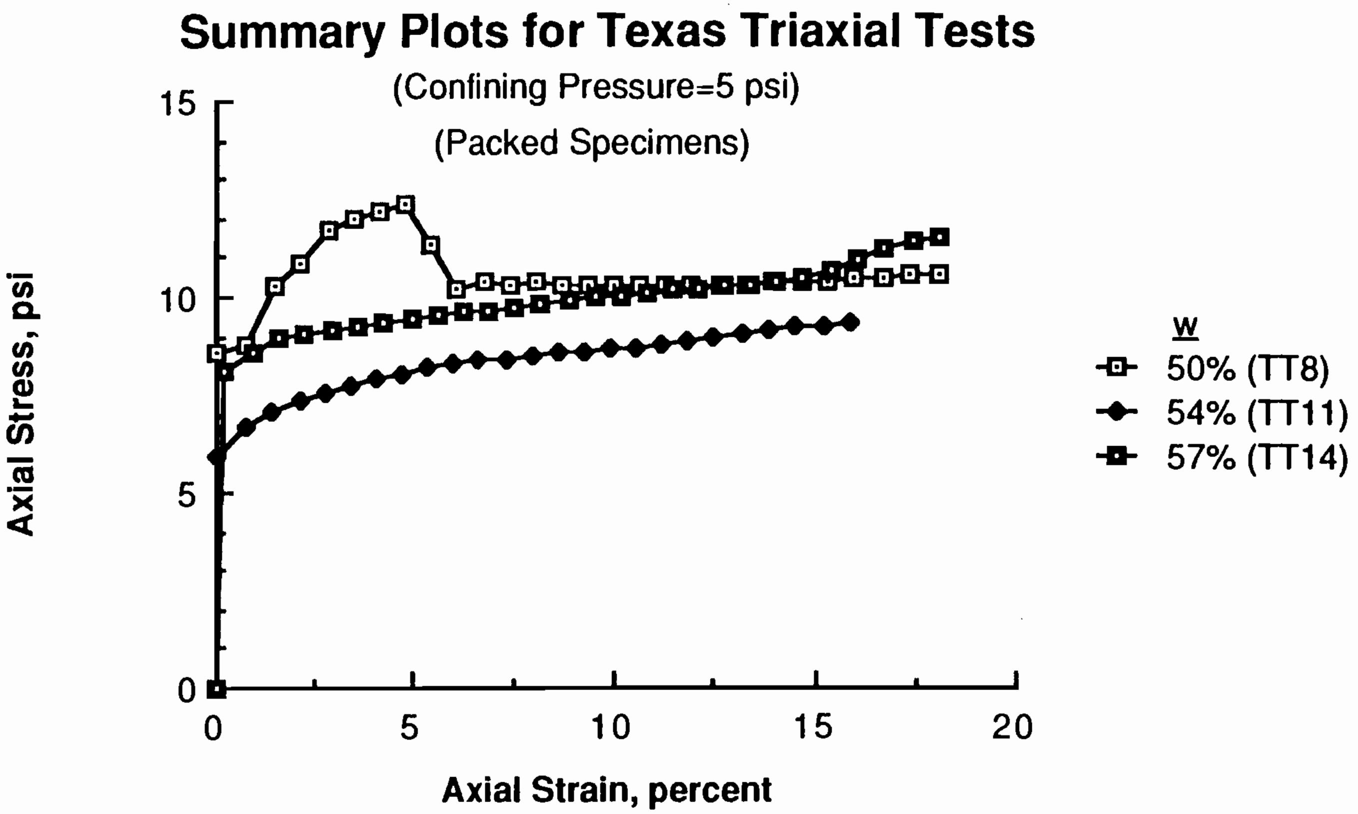


Figure B.1.1. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Packed Specimens.

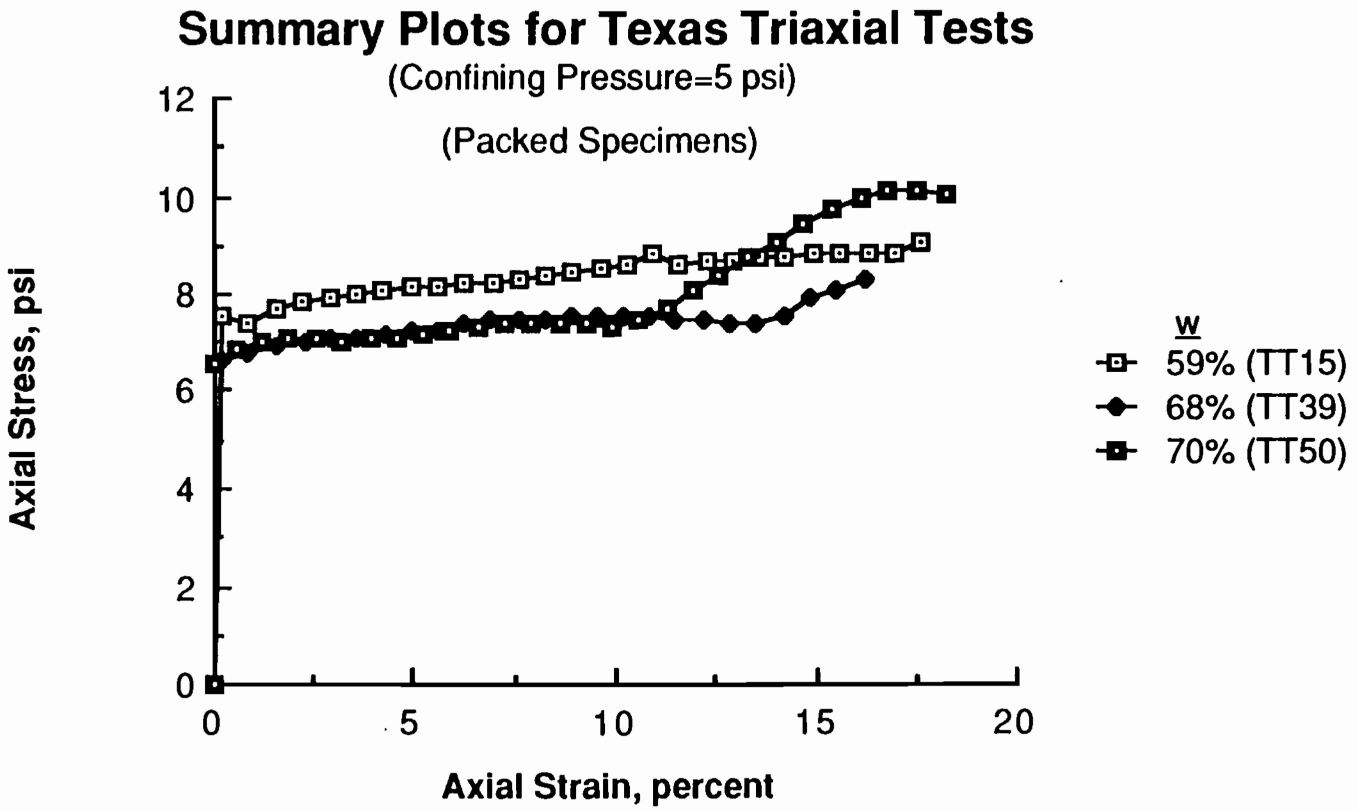


Figure B.1.2. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Packed Specimens.

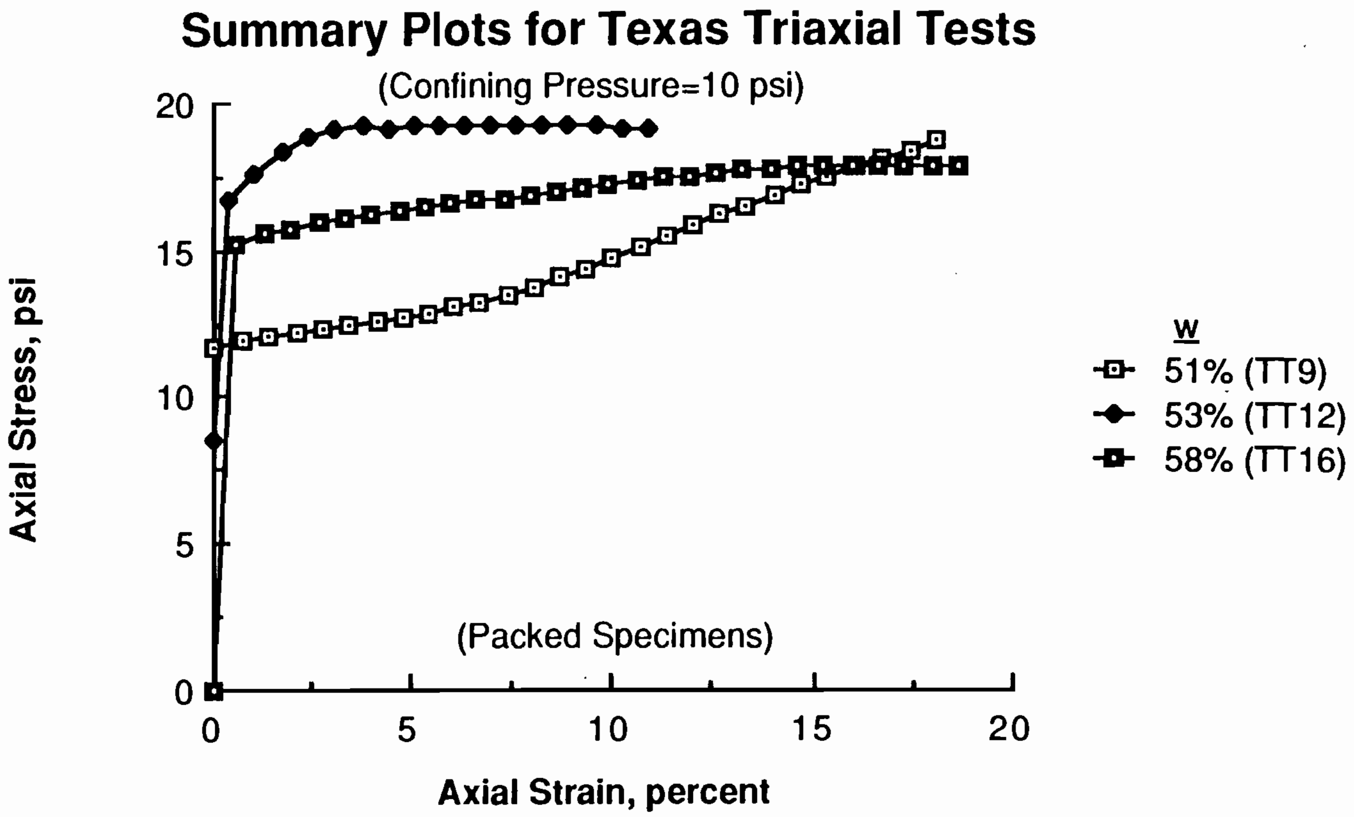


Figure B.1.3. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Packed Specimens.

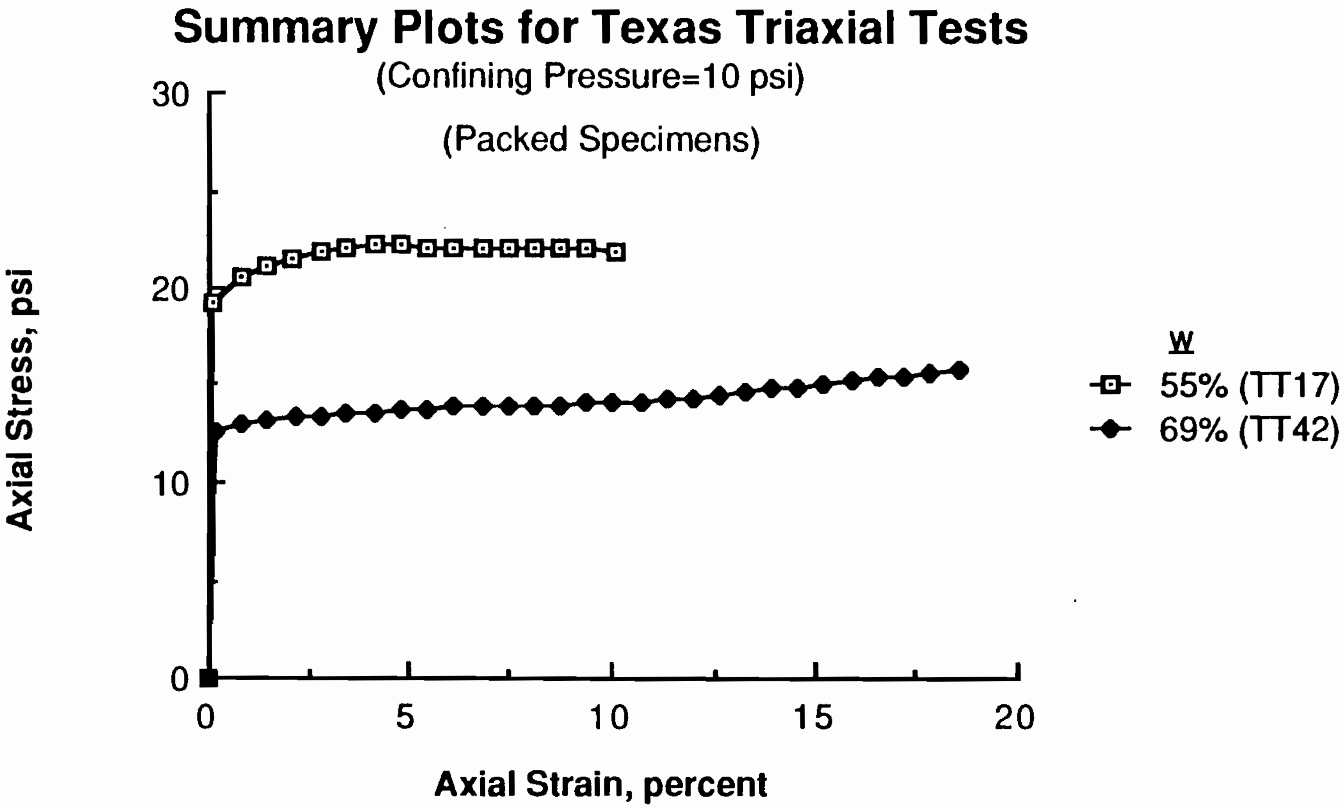


Figure B.1.4. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Packed Specimens.

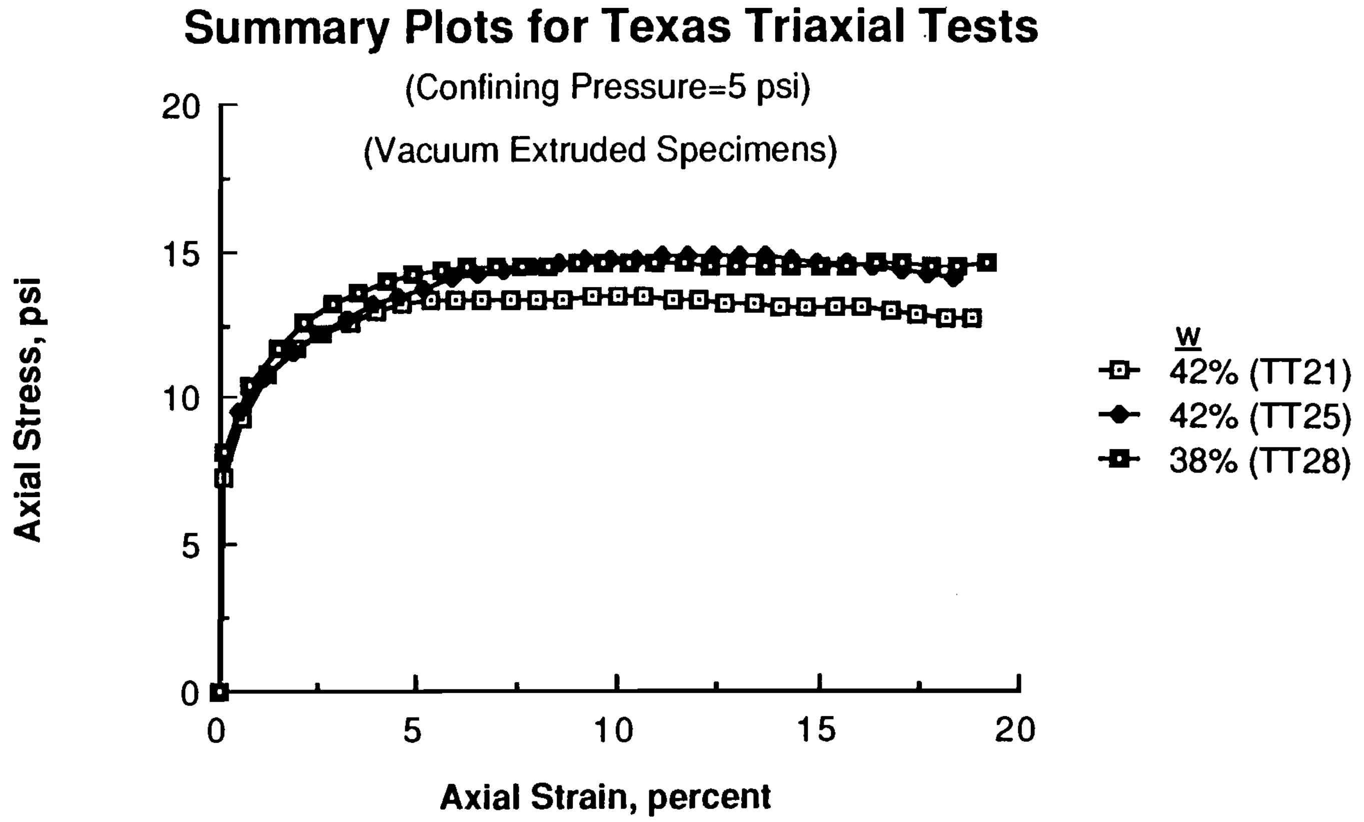


Figure B.2.1. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Vacuum-Extruded Specimens.

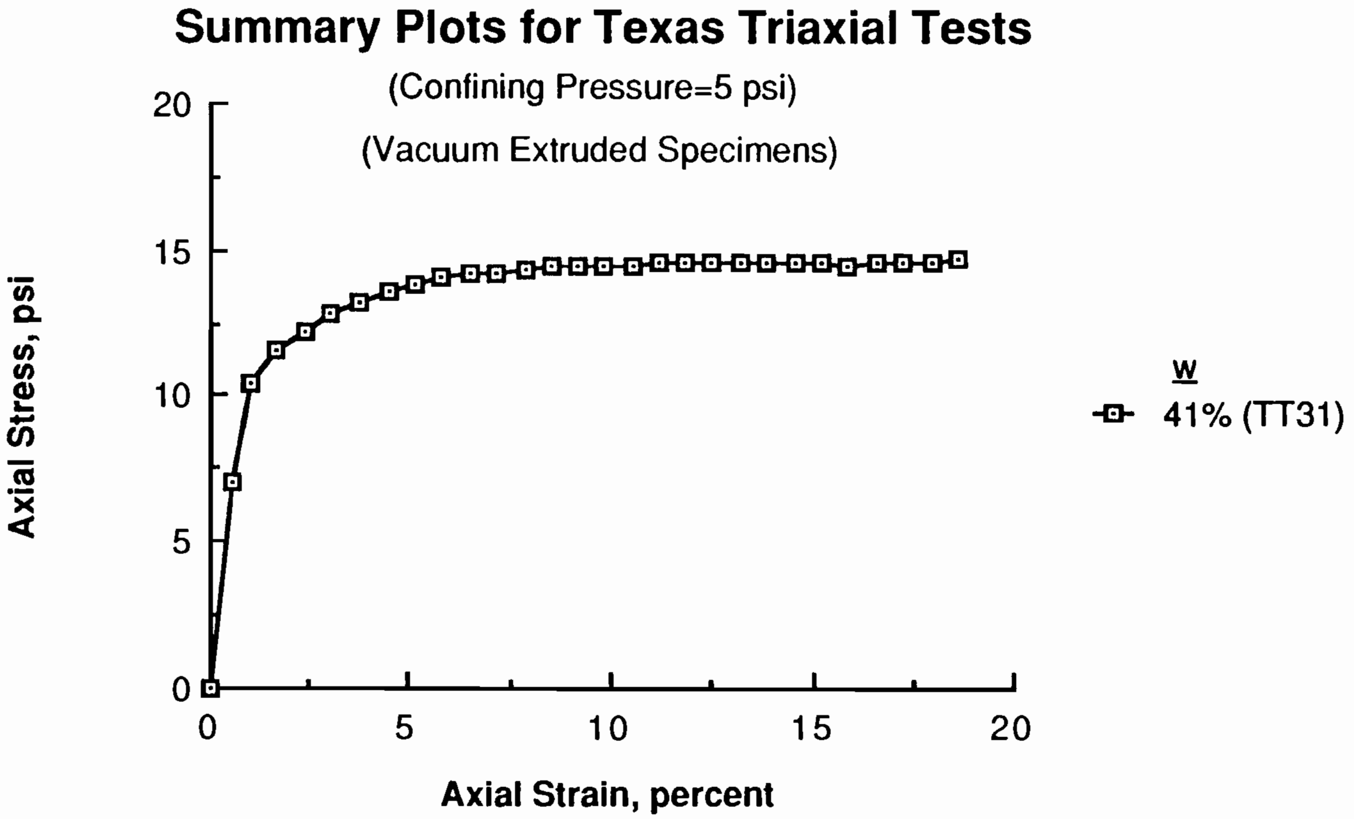


Figure B.2.2. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Vacuum-Extruded Specimens.

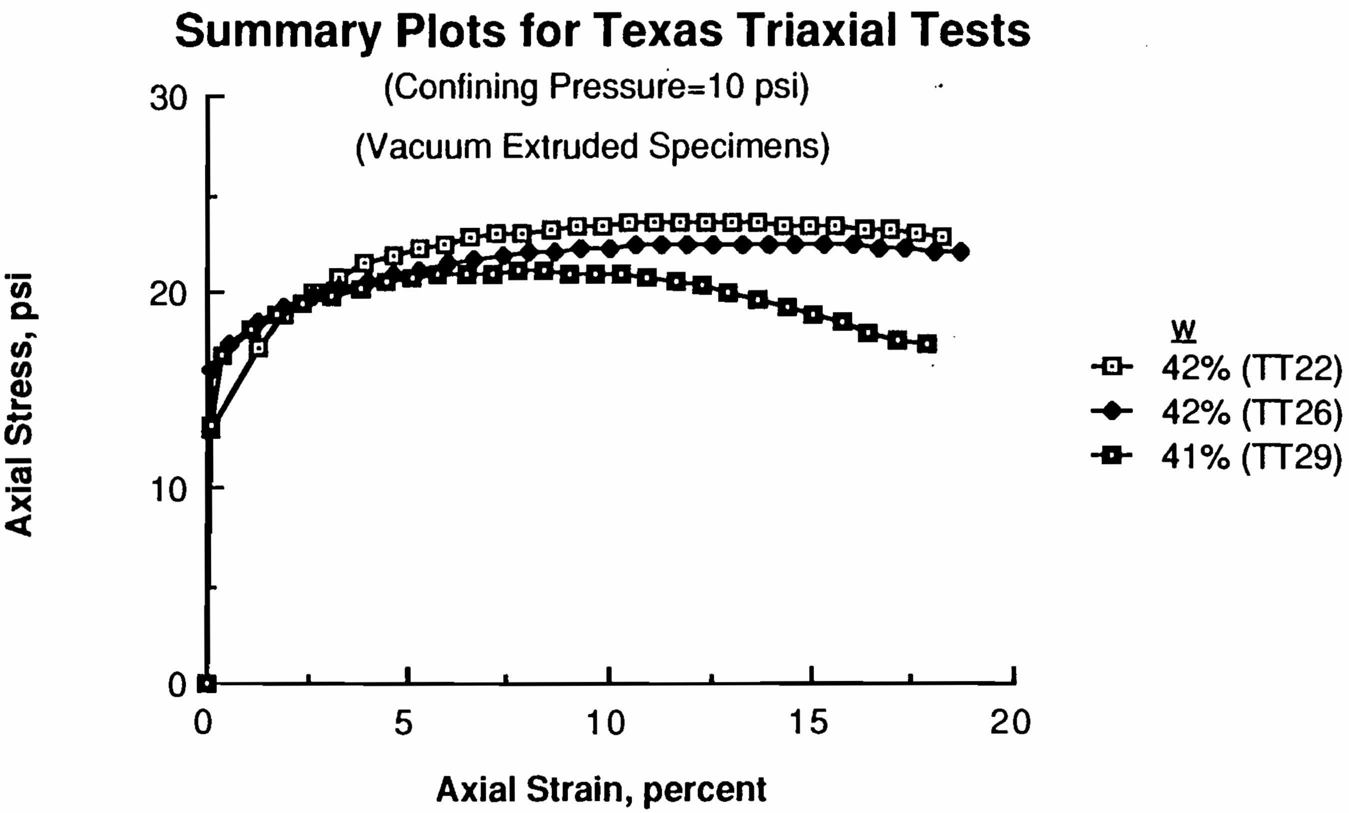


Figure B.2.3. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Vacuum-Extruded Specimens.

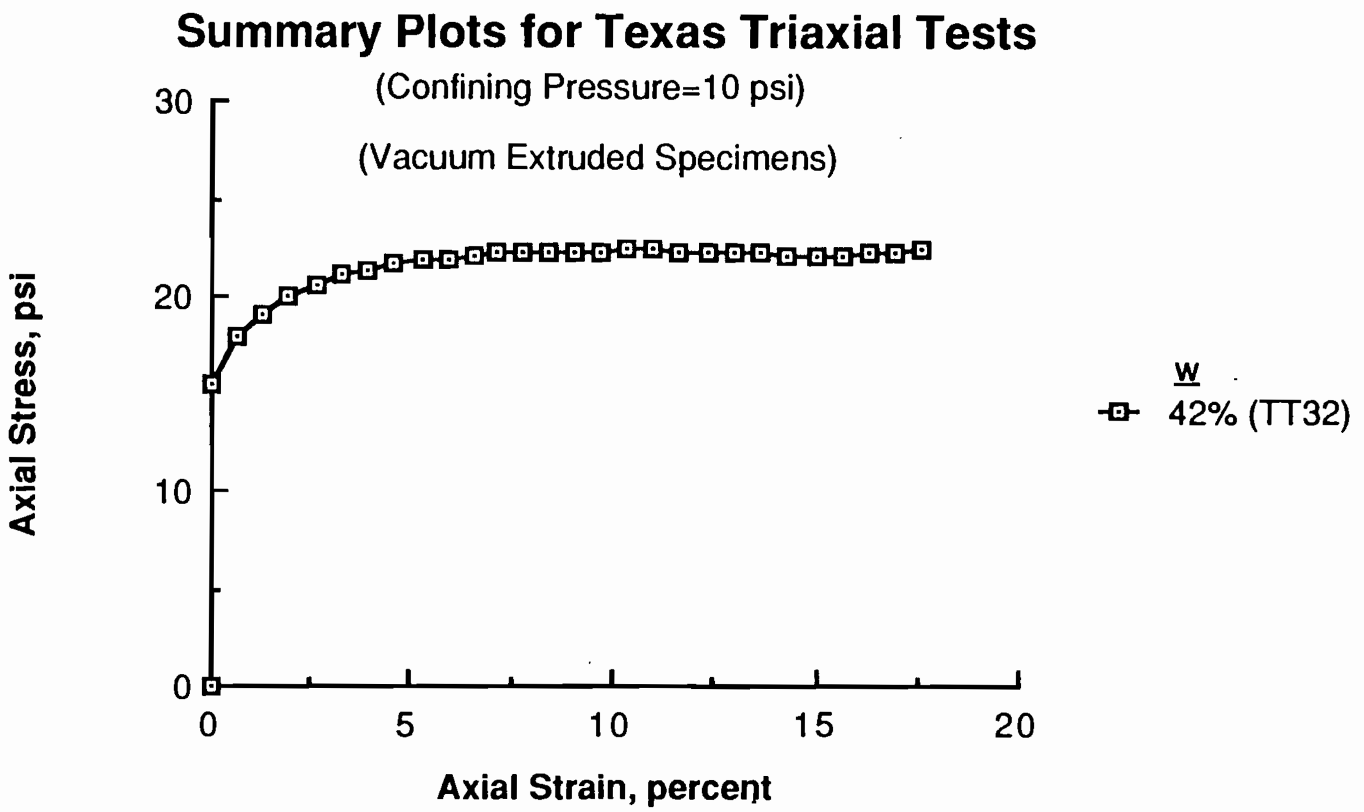


Figure B.2.4. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Vacuum-Extruded Specimens.

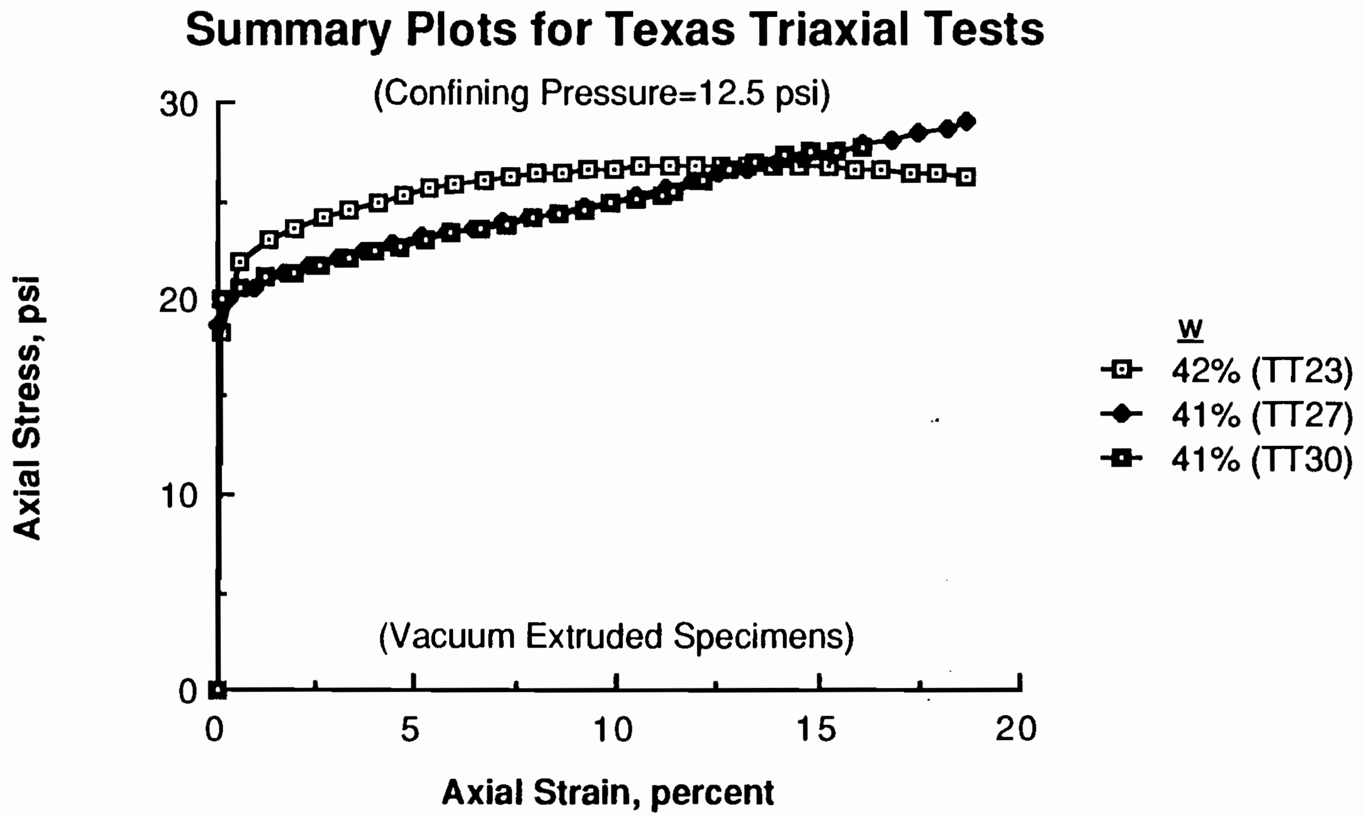


Figure B.2.5. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Vacuum-Extruded Specimens.

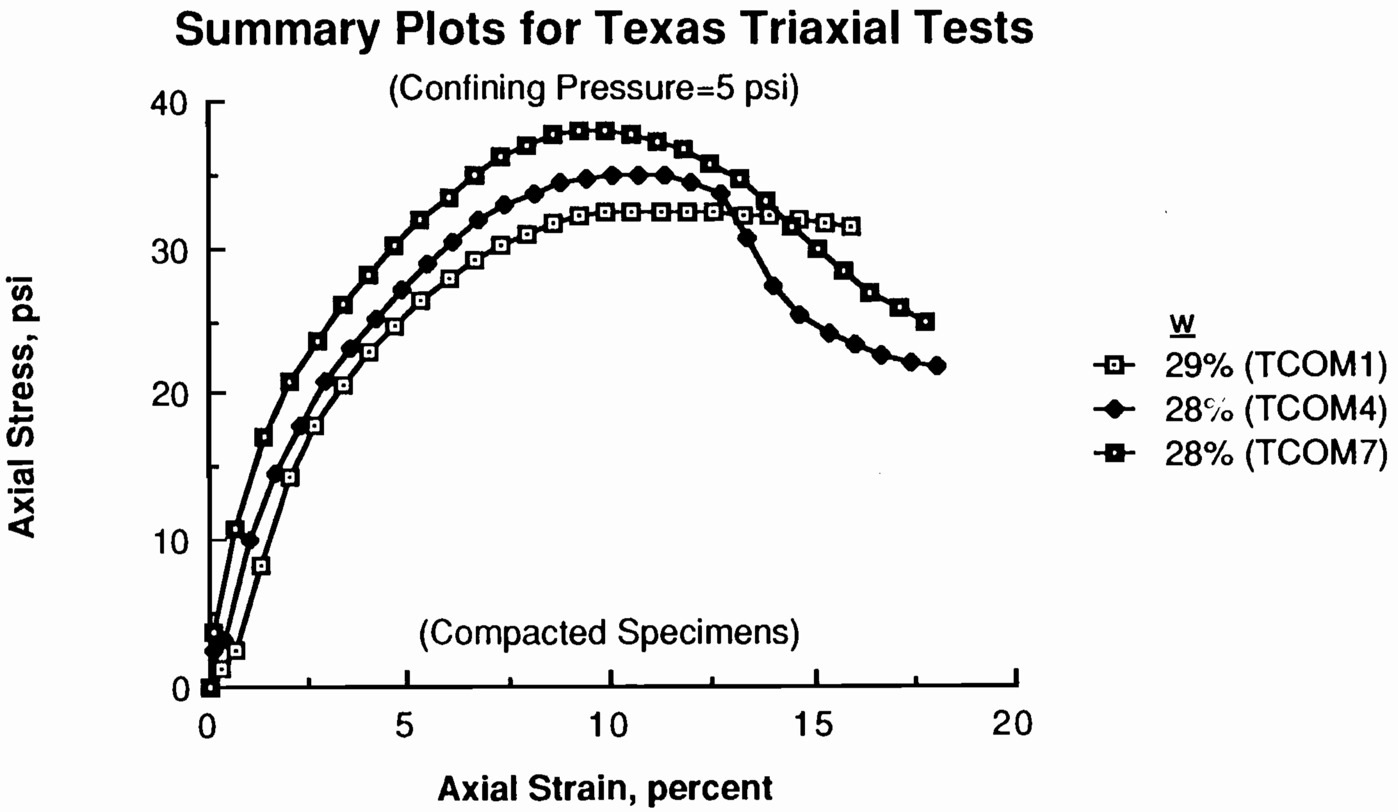


Figure B.3.1. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Compacted Specimens.

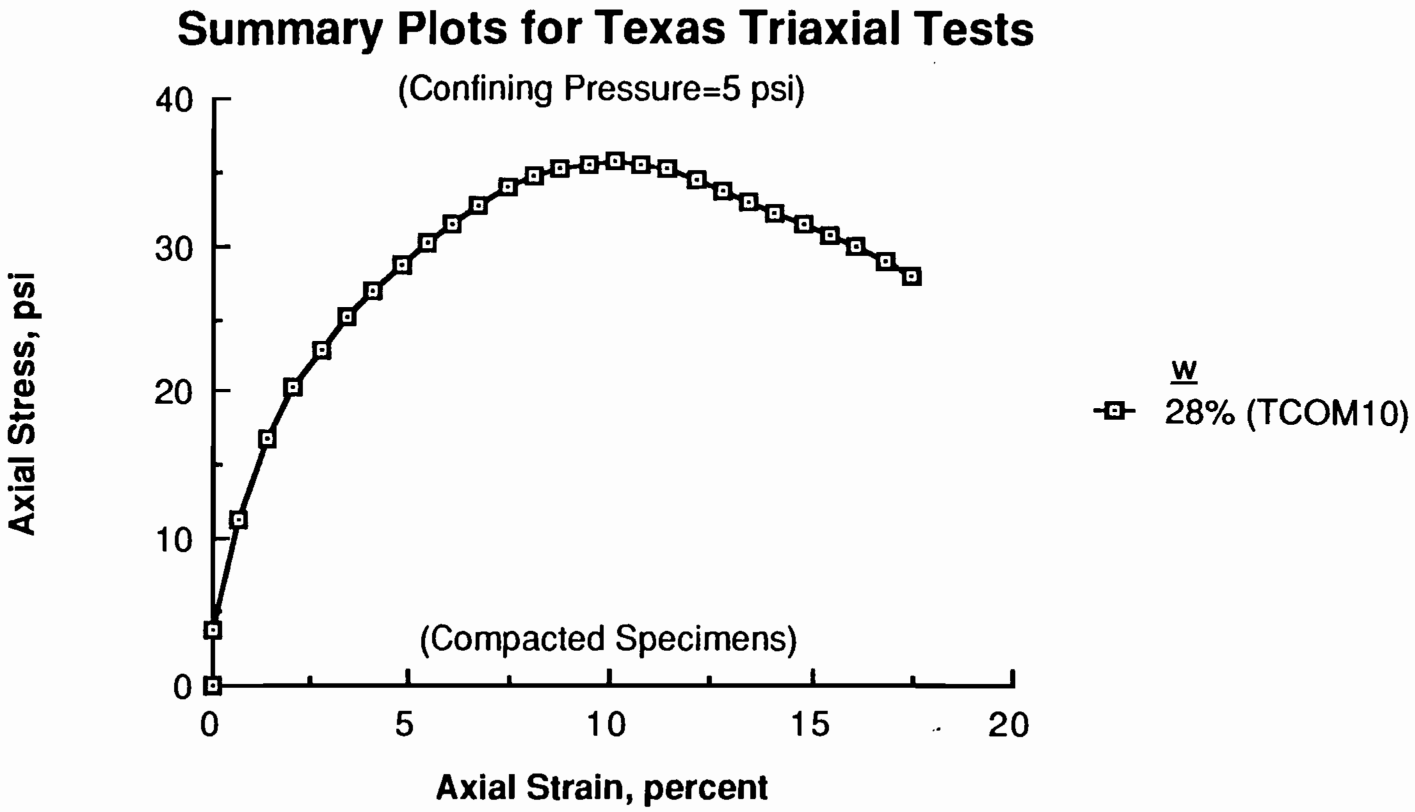


Figure B.3.2. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Compacted Specimens.

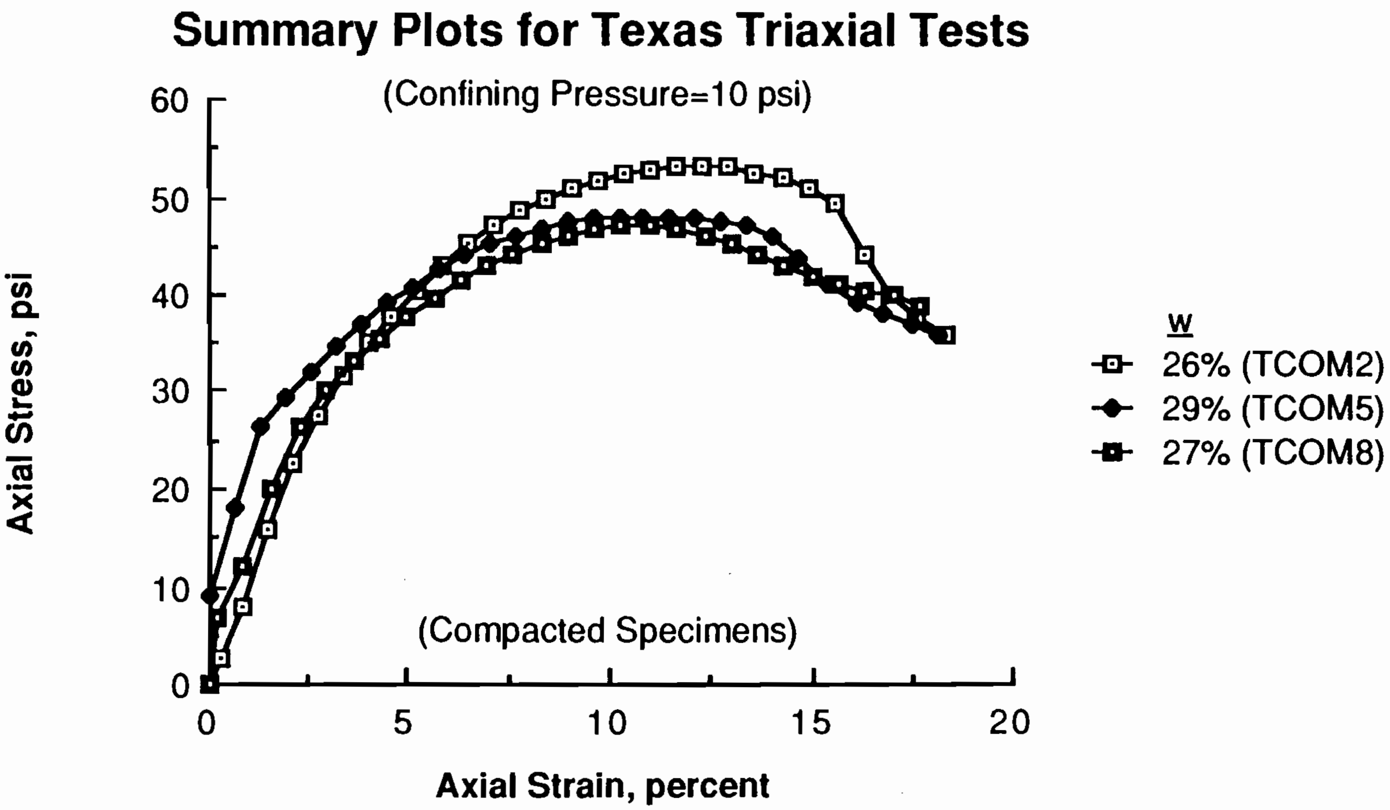


Figure B.3.3. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Compacted Specimens.

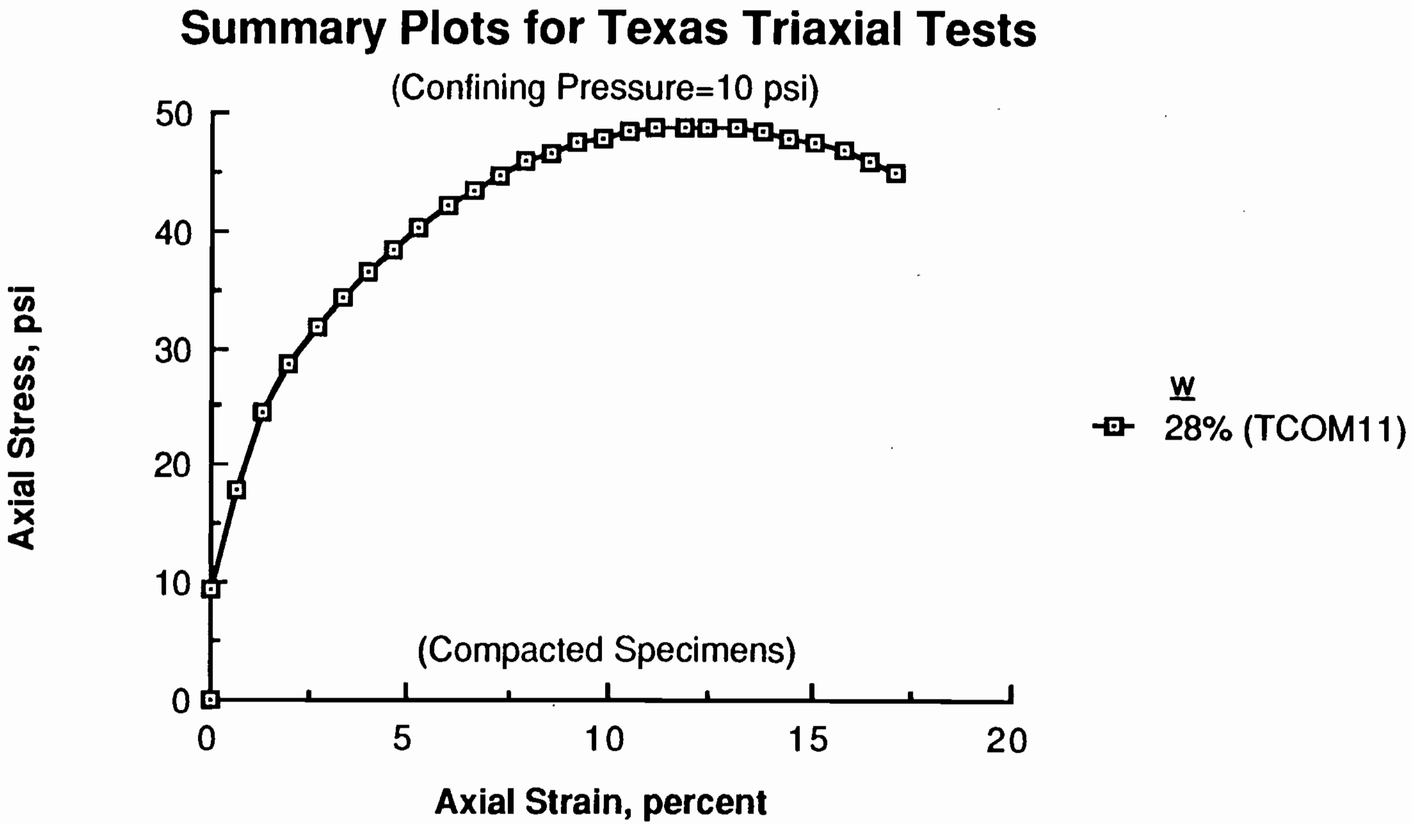


Figure B.3.4. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Compacted Specimens.

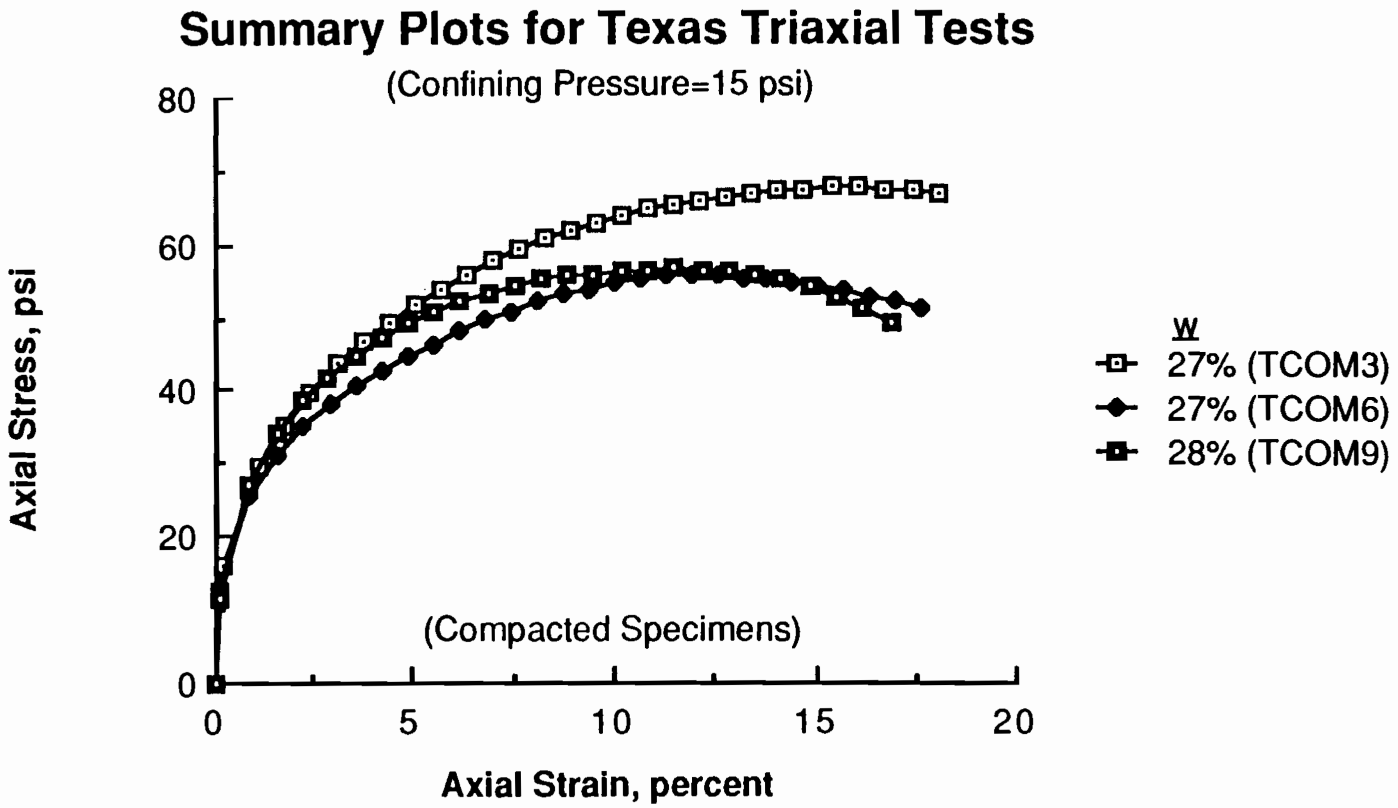


Figure B.3.5. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Compacted Specimens.

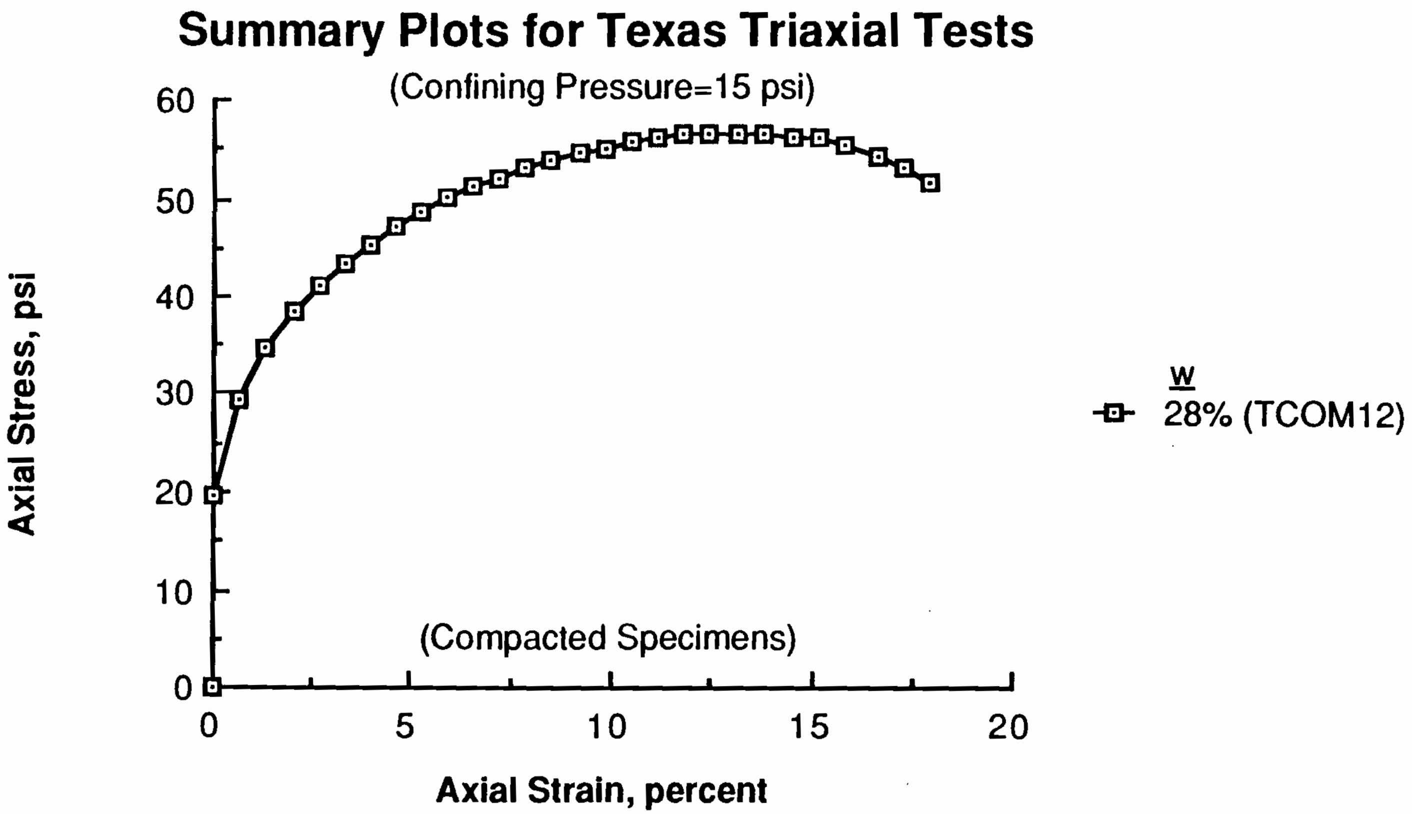


Figure B.3.6. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Compacted Specimens.

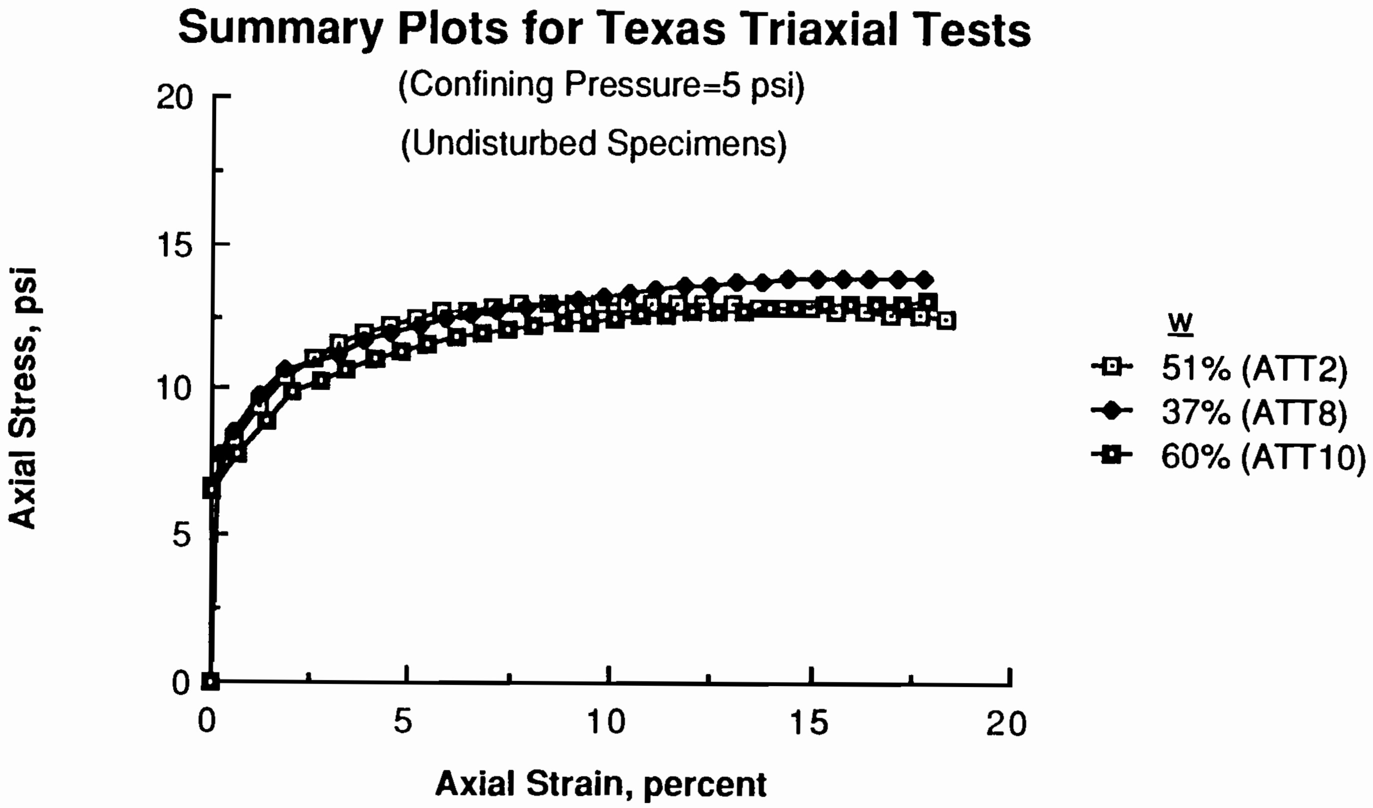


Figure B.4.1. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Undisturbed Specimens.

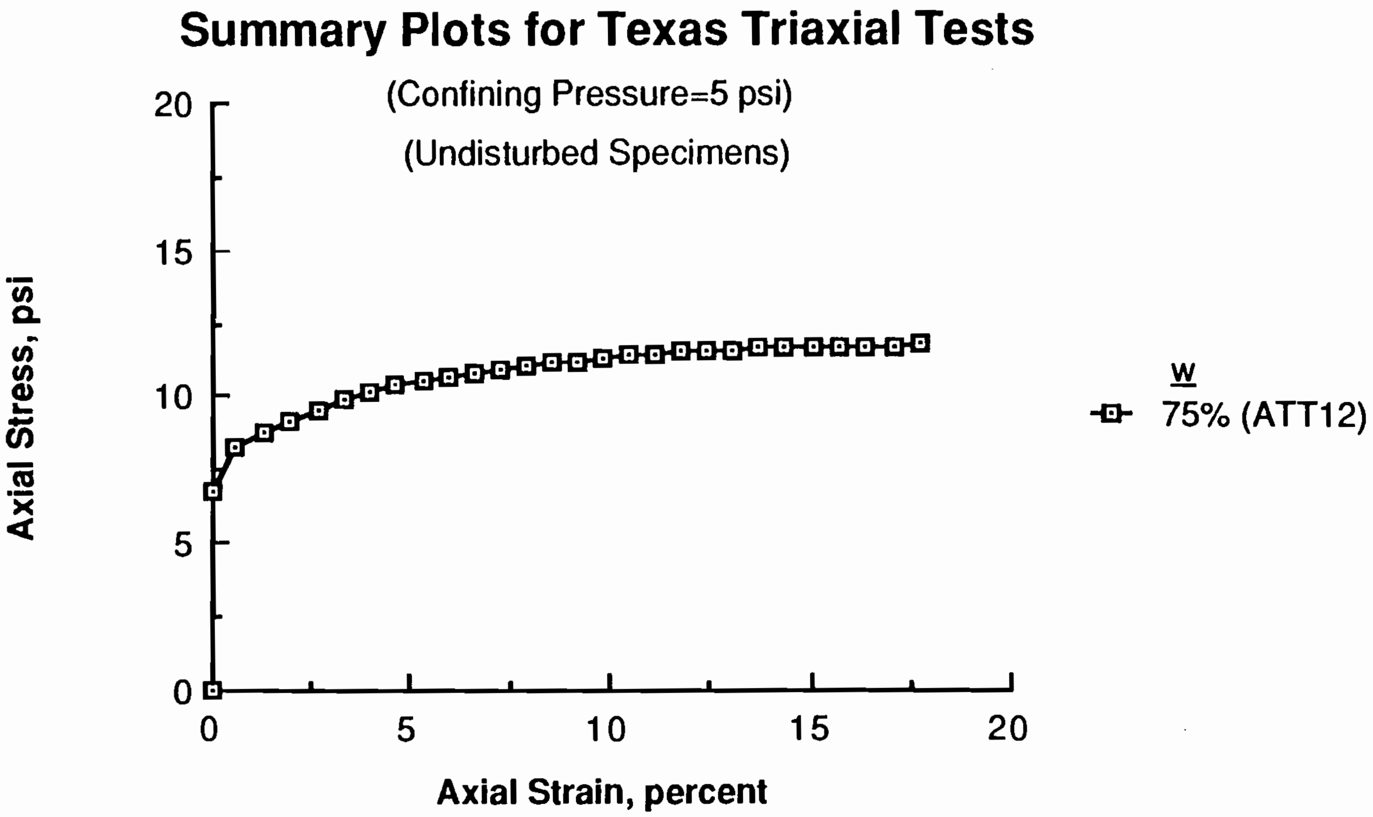


Figure B.4.2. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Undisturbed Specimens.

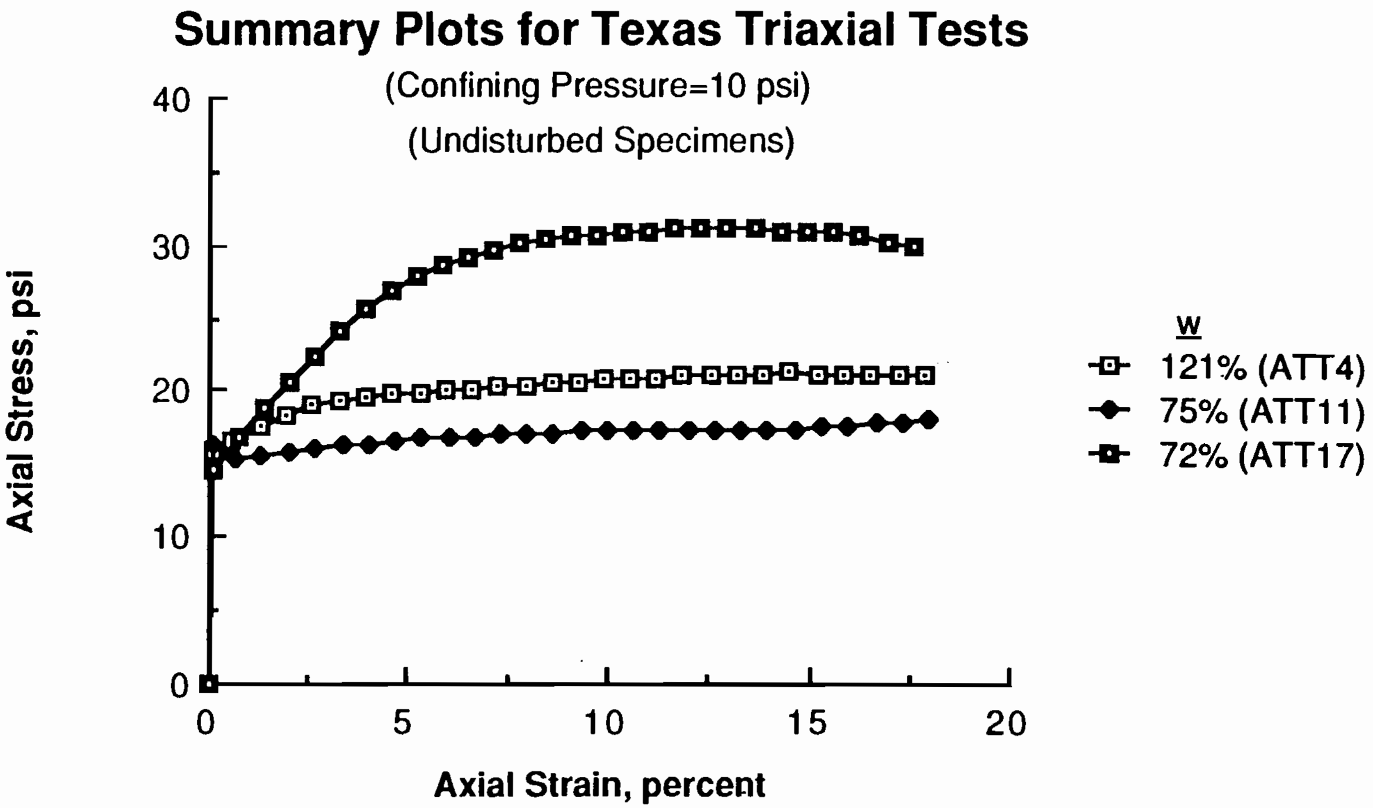
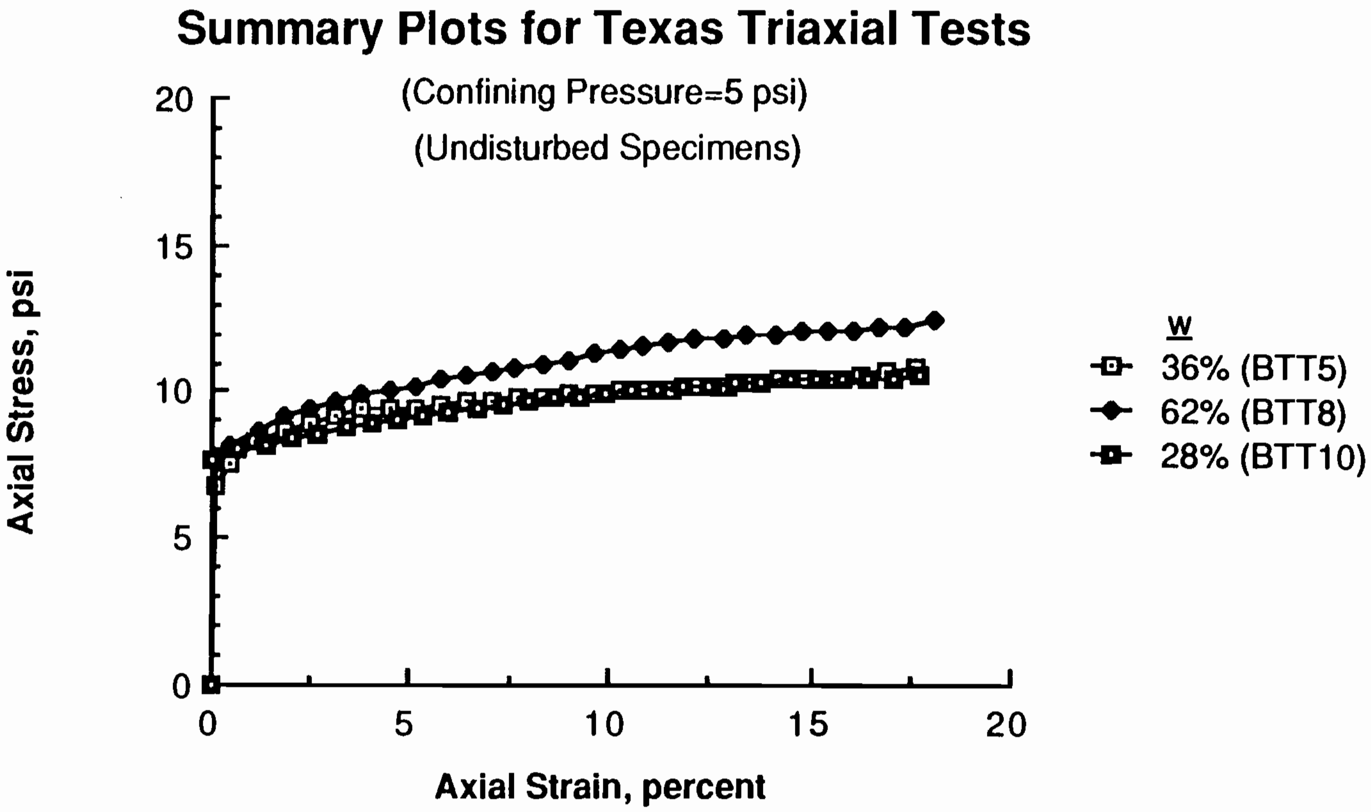


Figure B.4.3. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Undisturbed Specimens.



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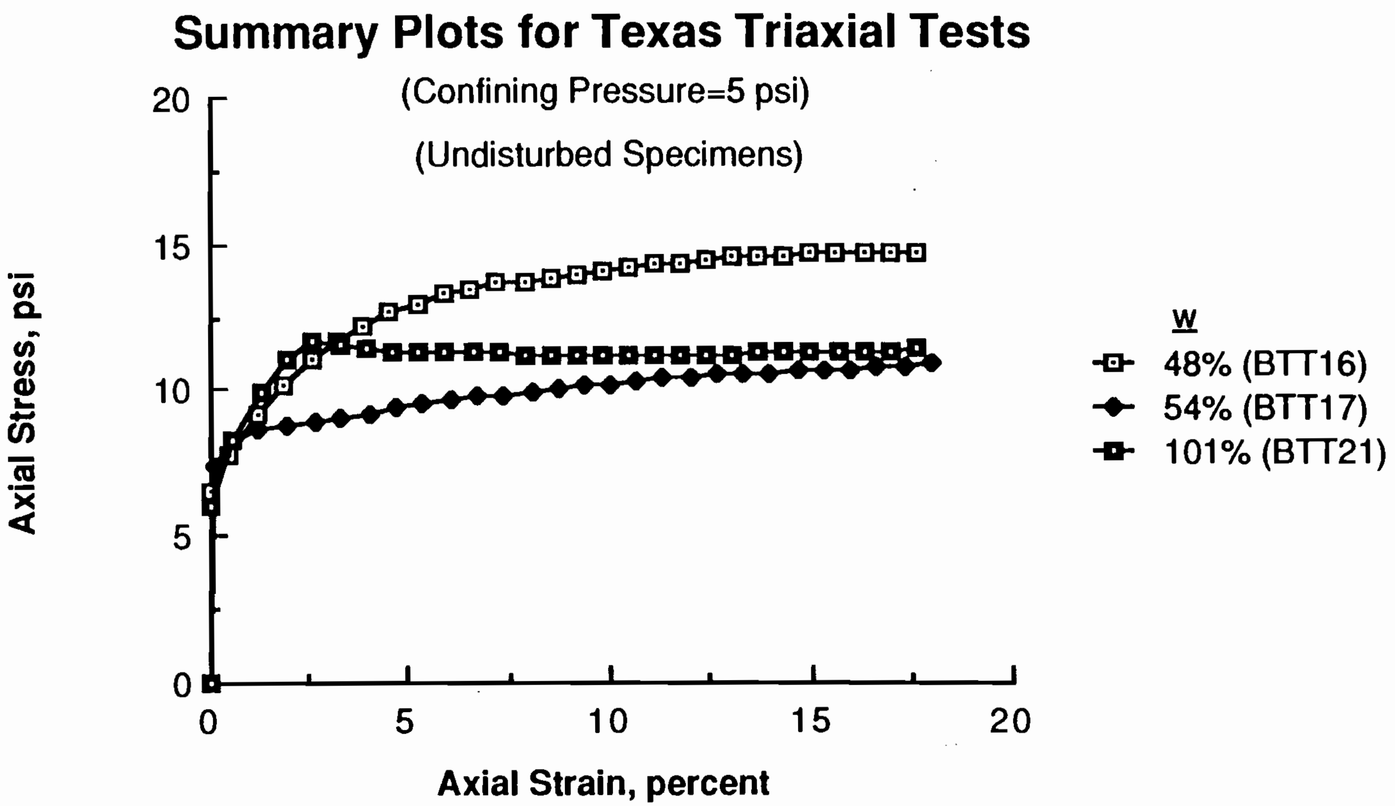


Figure B.4.5. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Undisturbed Specimens.

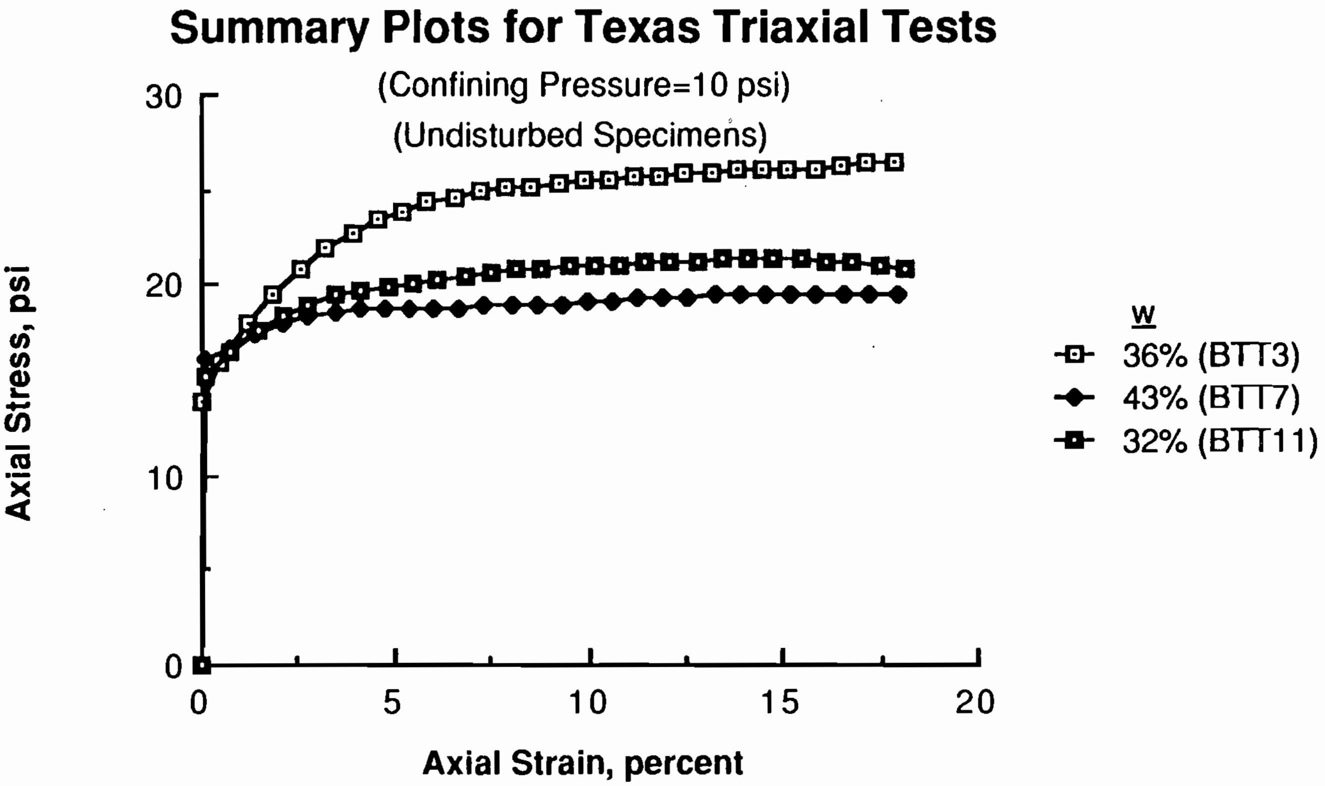


Figure B.4.6. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Undisturbed Specimens.

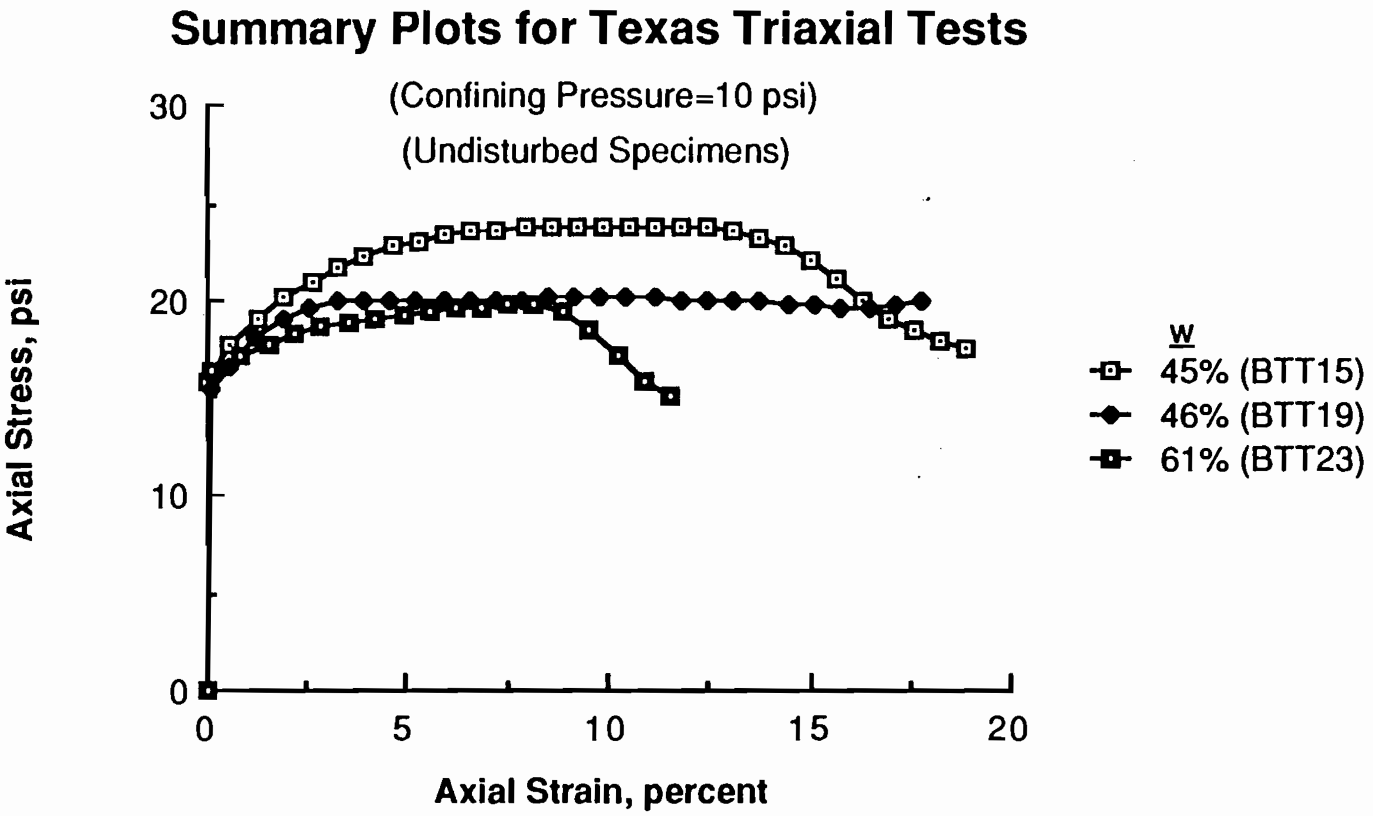


Figure B.4.7. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Undisturbed Specimens.

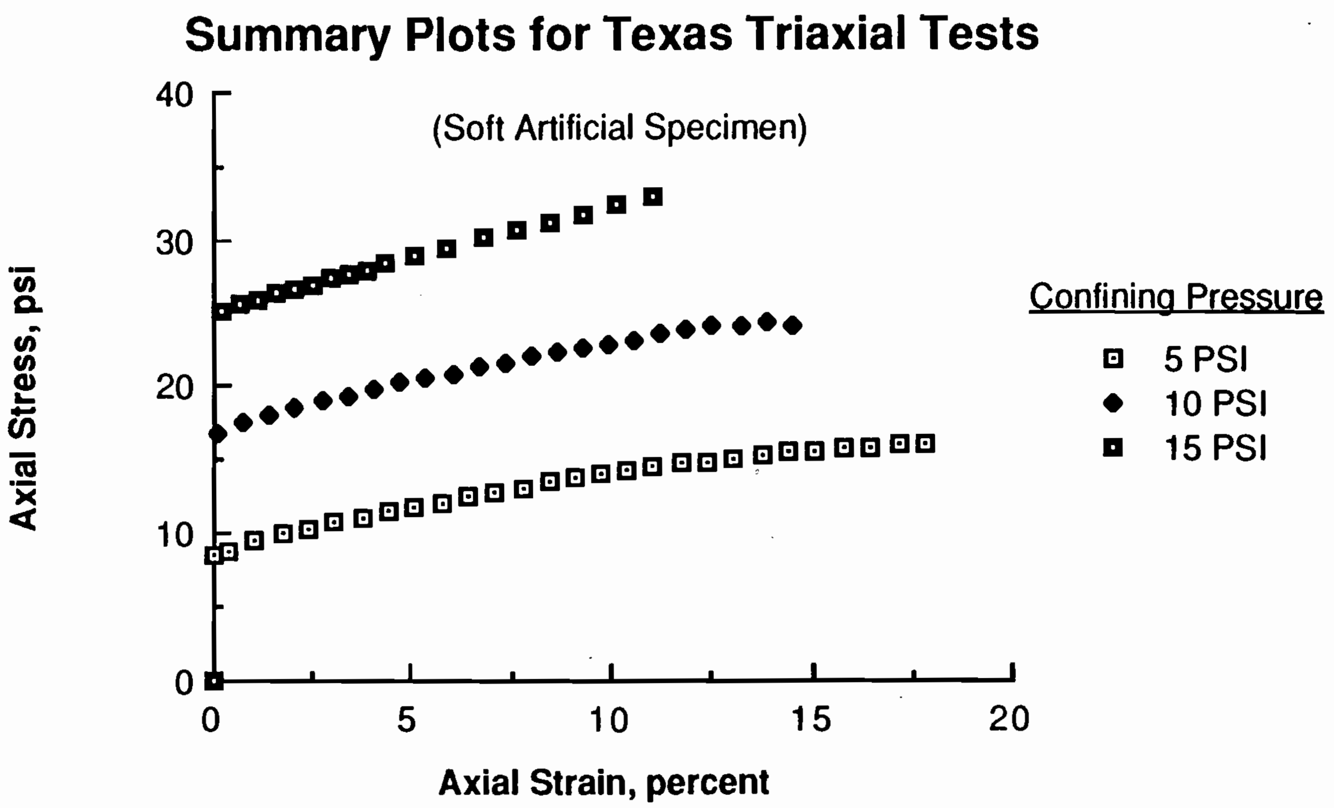


Figure B.5.1. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Artificial Specimens.

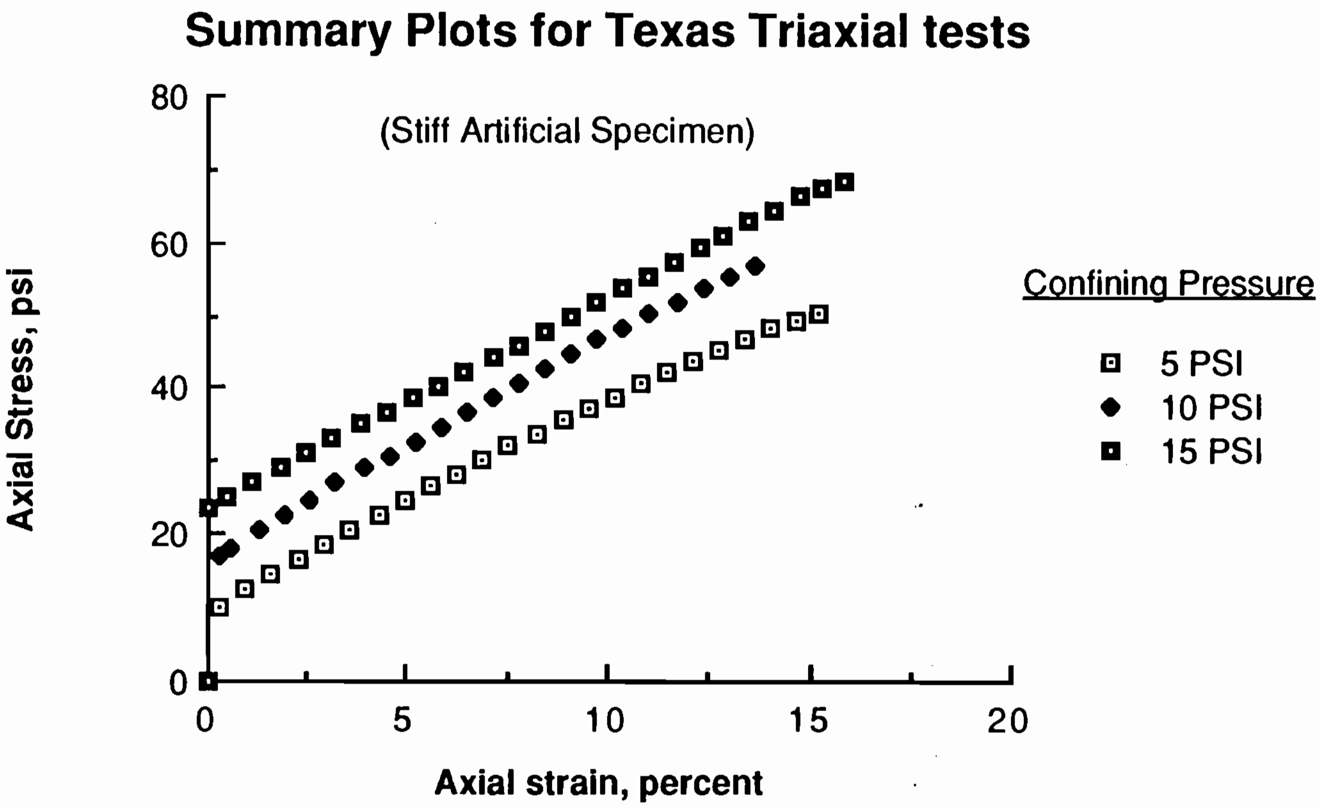


Figure B.5.2. Summary Plots of Axial Stress Versus Axial Strain for Texas Triaxial Tests on Artificial Specimens.

APPENDIX C

SUMMARY PLOTS FOR UNCONSOLIDATED-UNDRAINED TESTS

APPENDIX C. SUMMARY PLOTS FOR UNCONSOLIDATED-UNDRAINED TESTS

Appendix C contains the summary plots of stress versus strain over the full range of axial strains for the unconsolidated-undrained triaxial tests performed as part of this study. These include tests on specimens prepared by packing, vacuum extrusion, and compaction. Tests on undisturbed and artificial specimens are included. The stresses shown are not corrected for membrane effects.

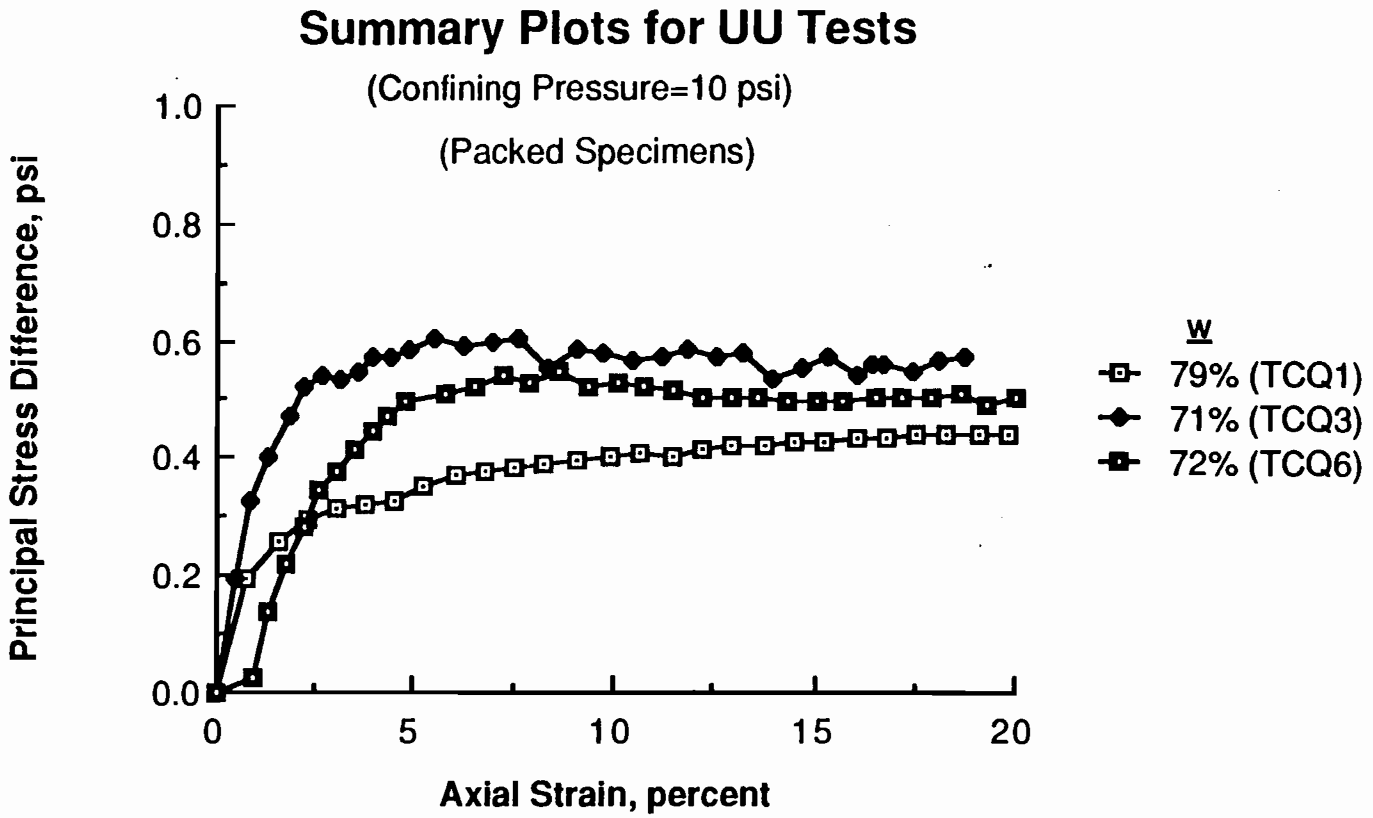


Figure C.1.1. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Packed Specimens.

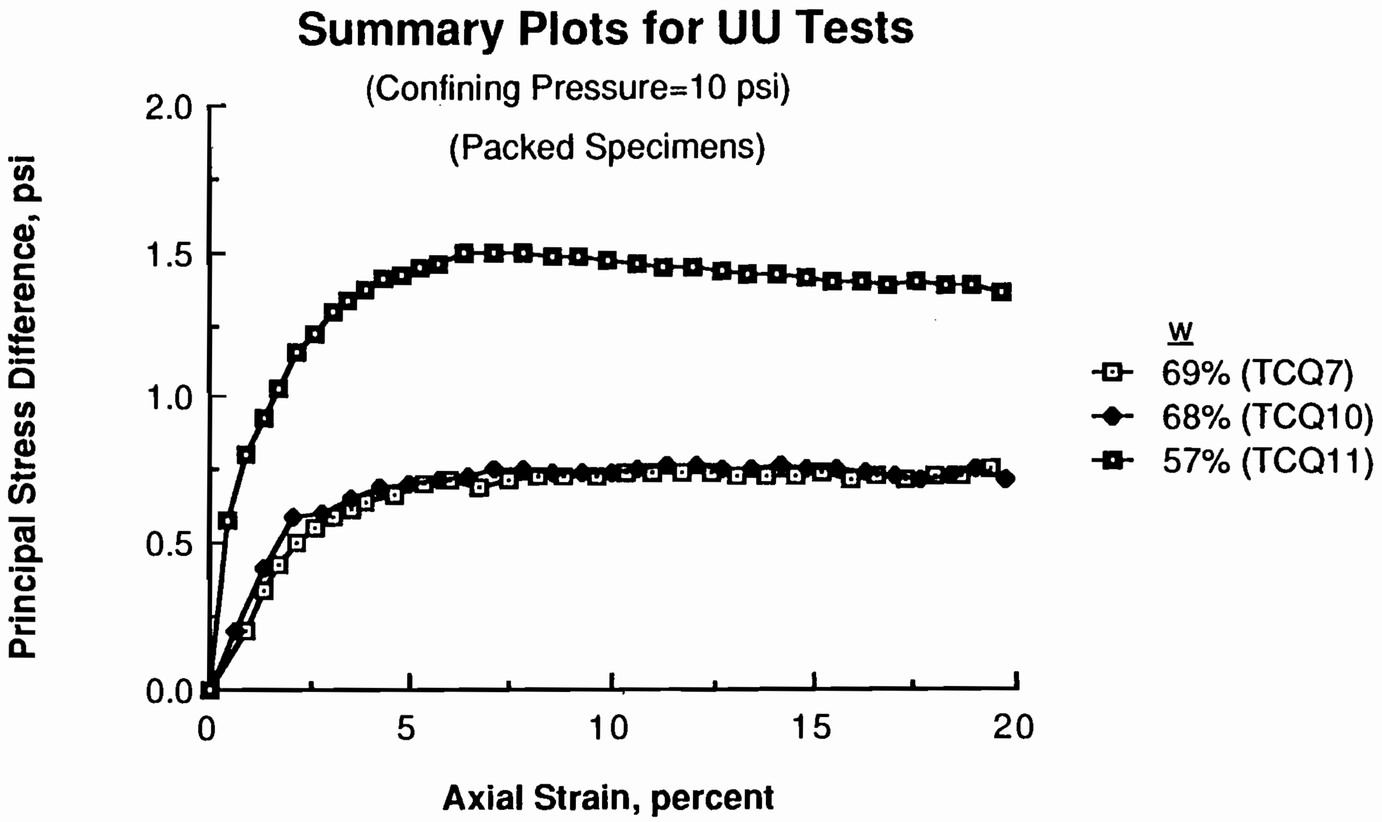


Figure C.1.2. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Packed Specimens.

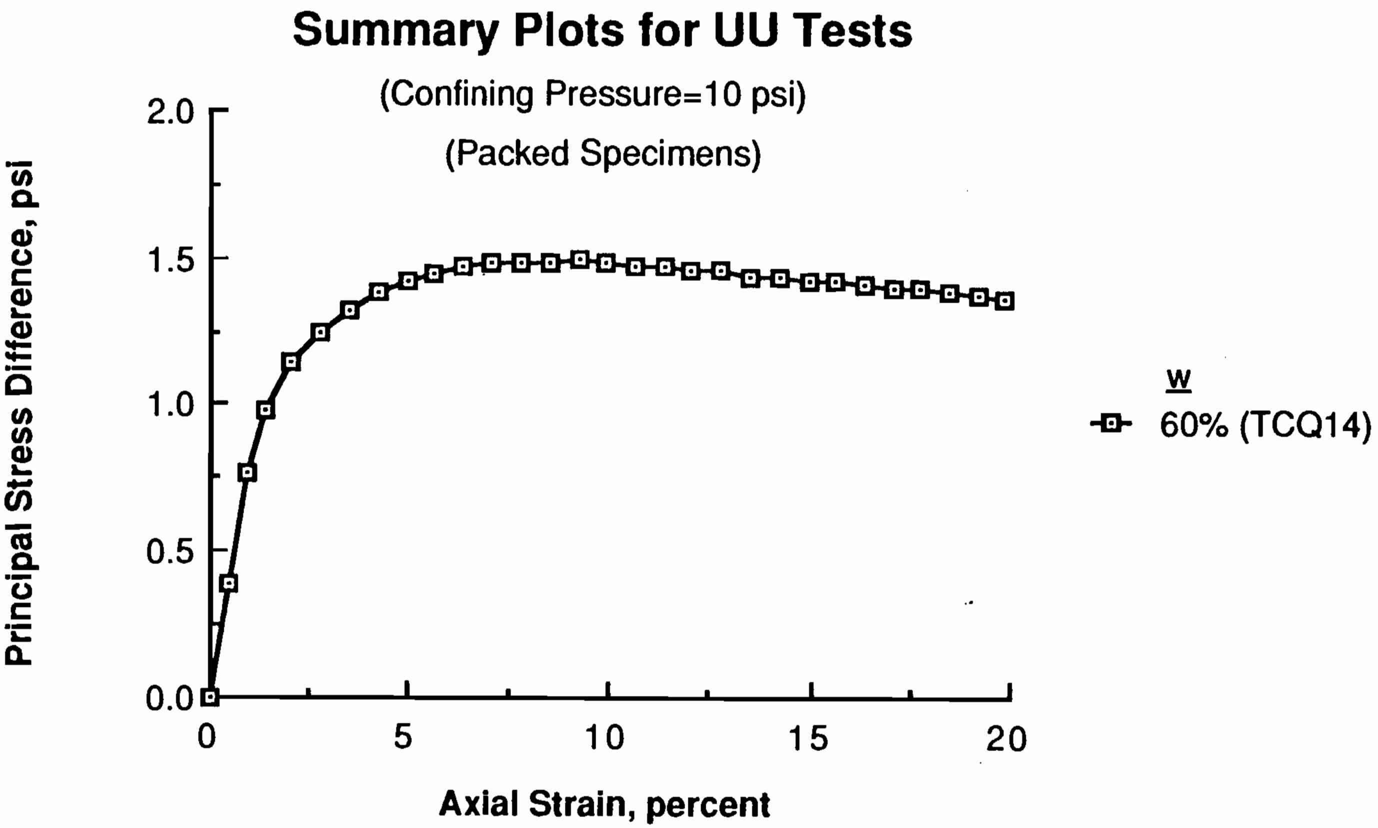
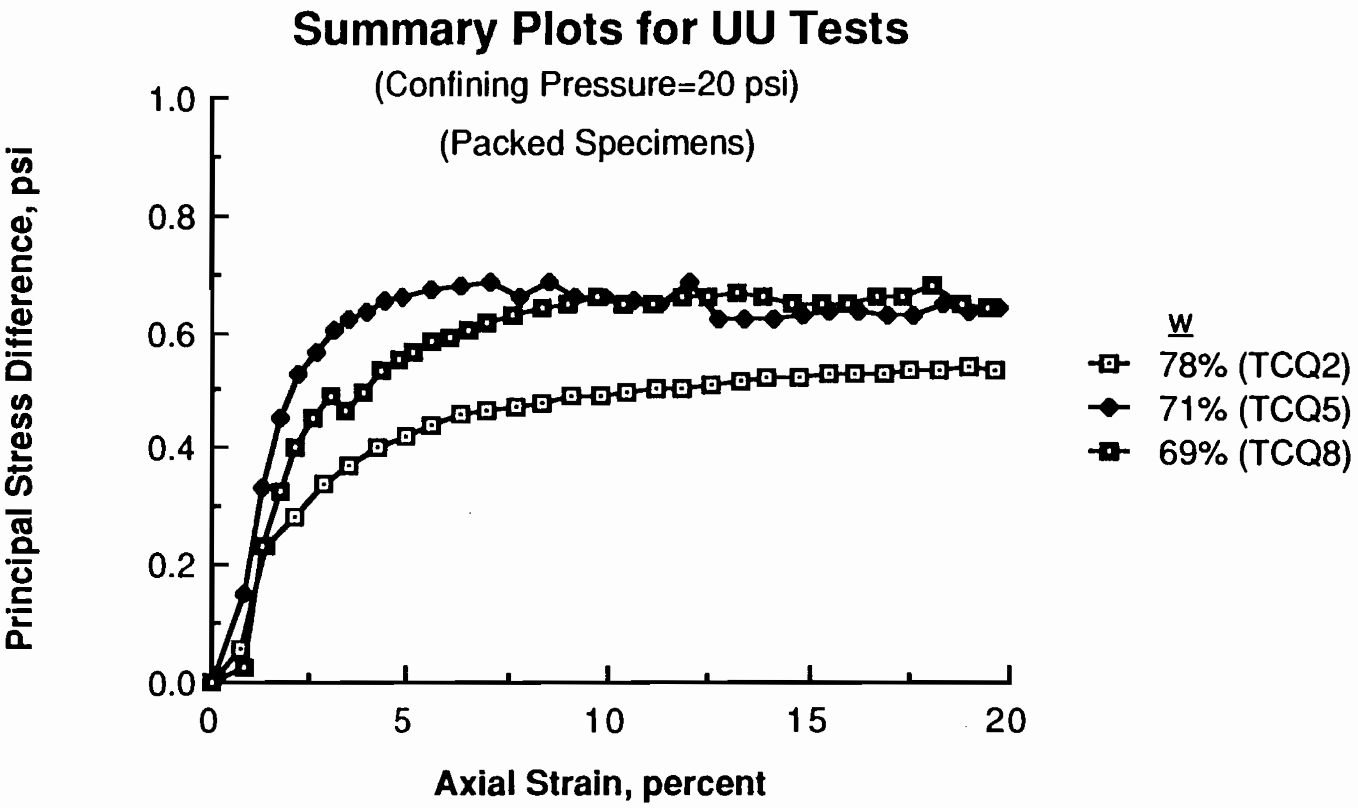


Figure C.1.3. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Packed Specimens.



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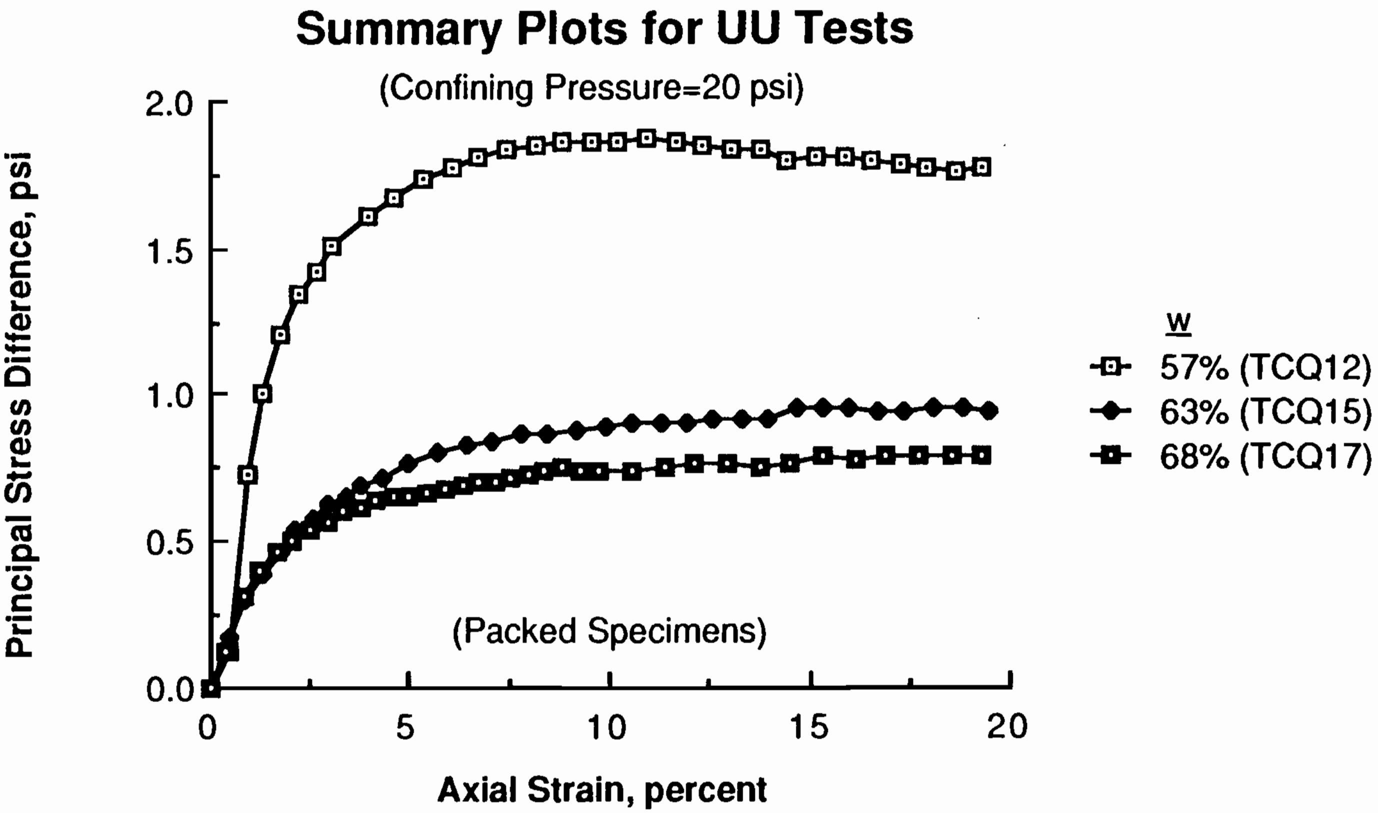

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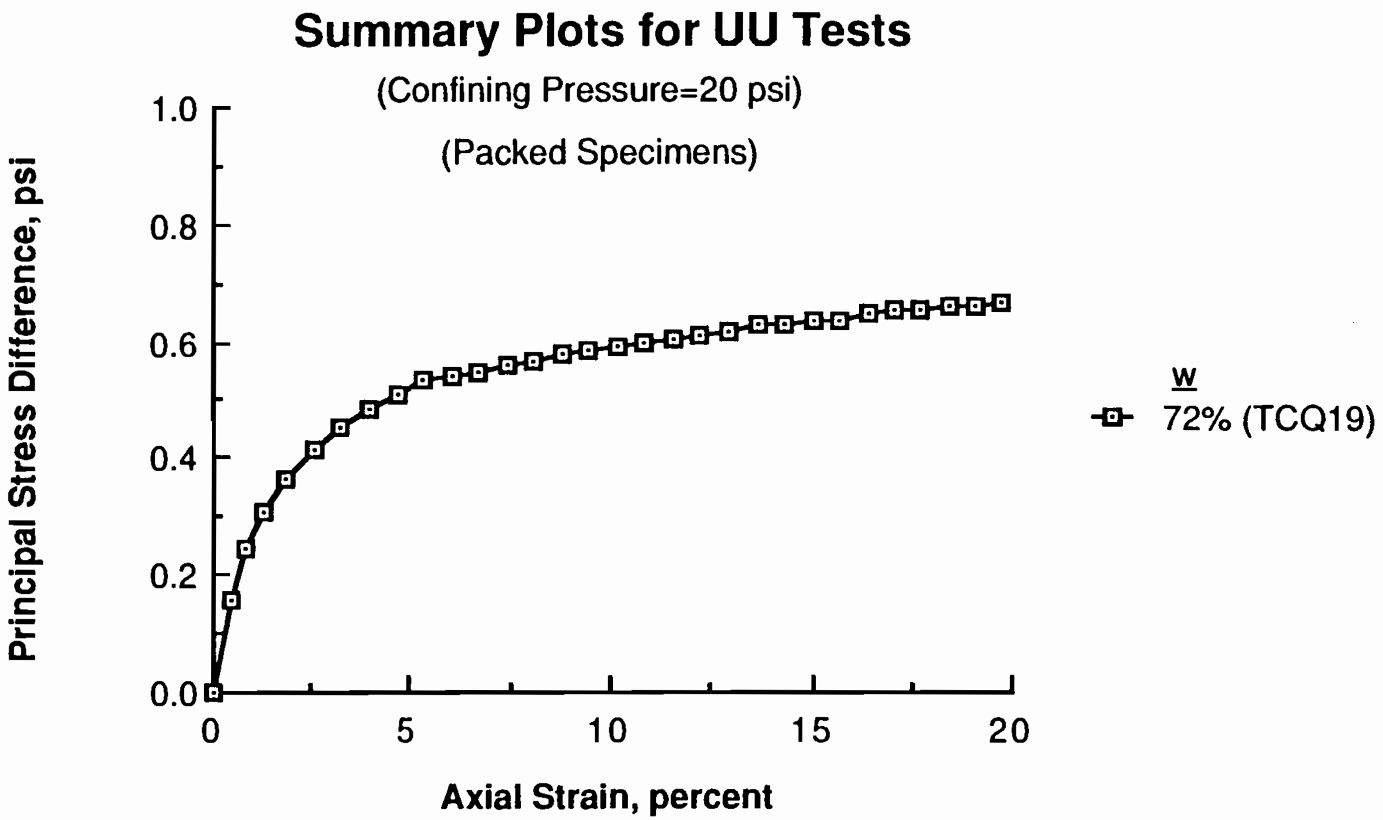

Figure C.1.6. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Packed Specimens.

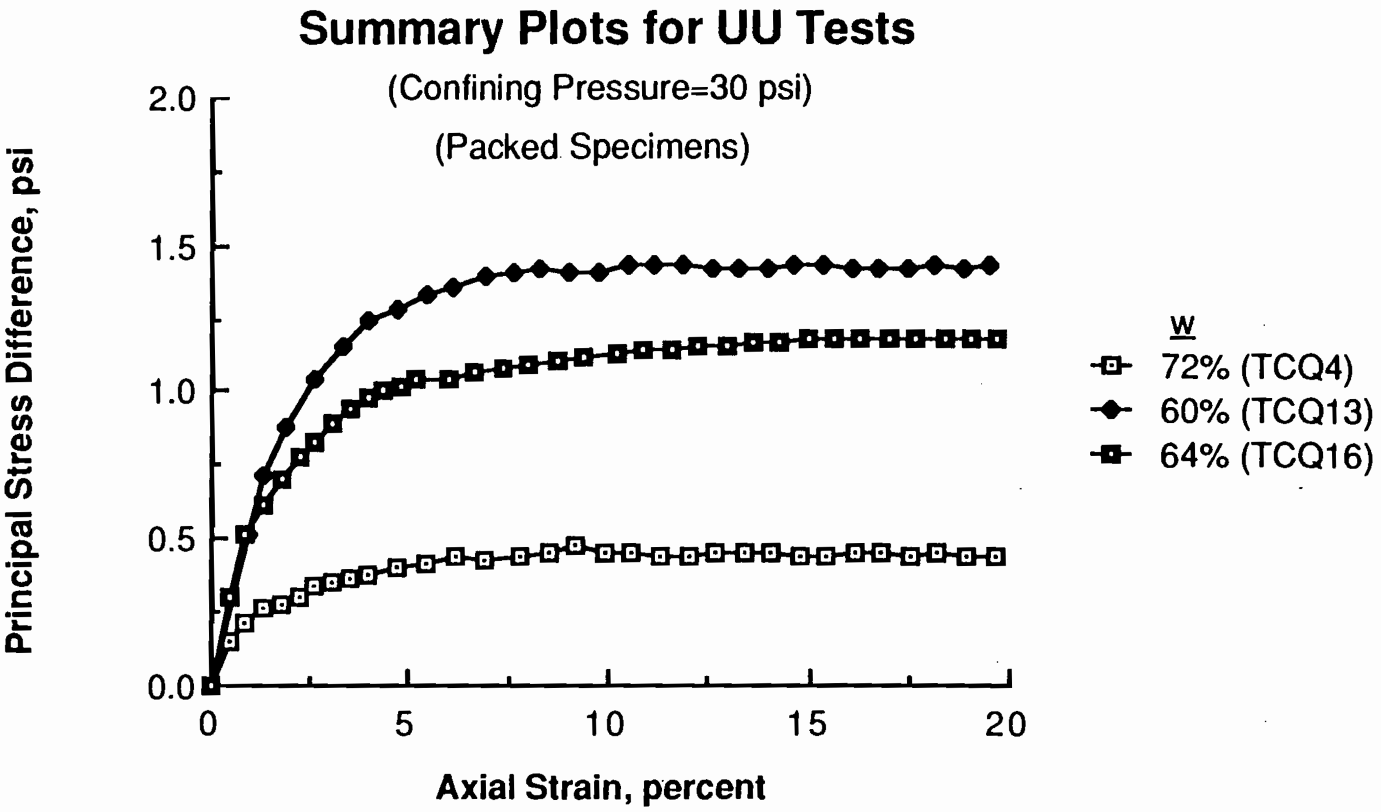

Figure C.1.7. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Packed Specimens.

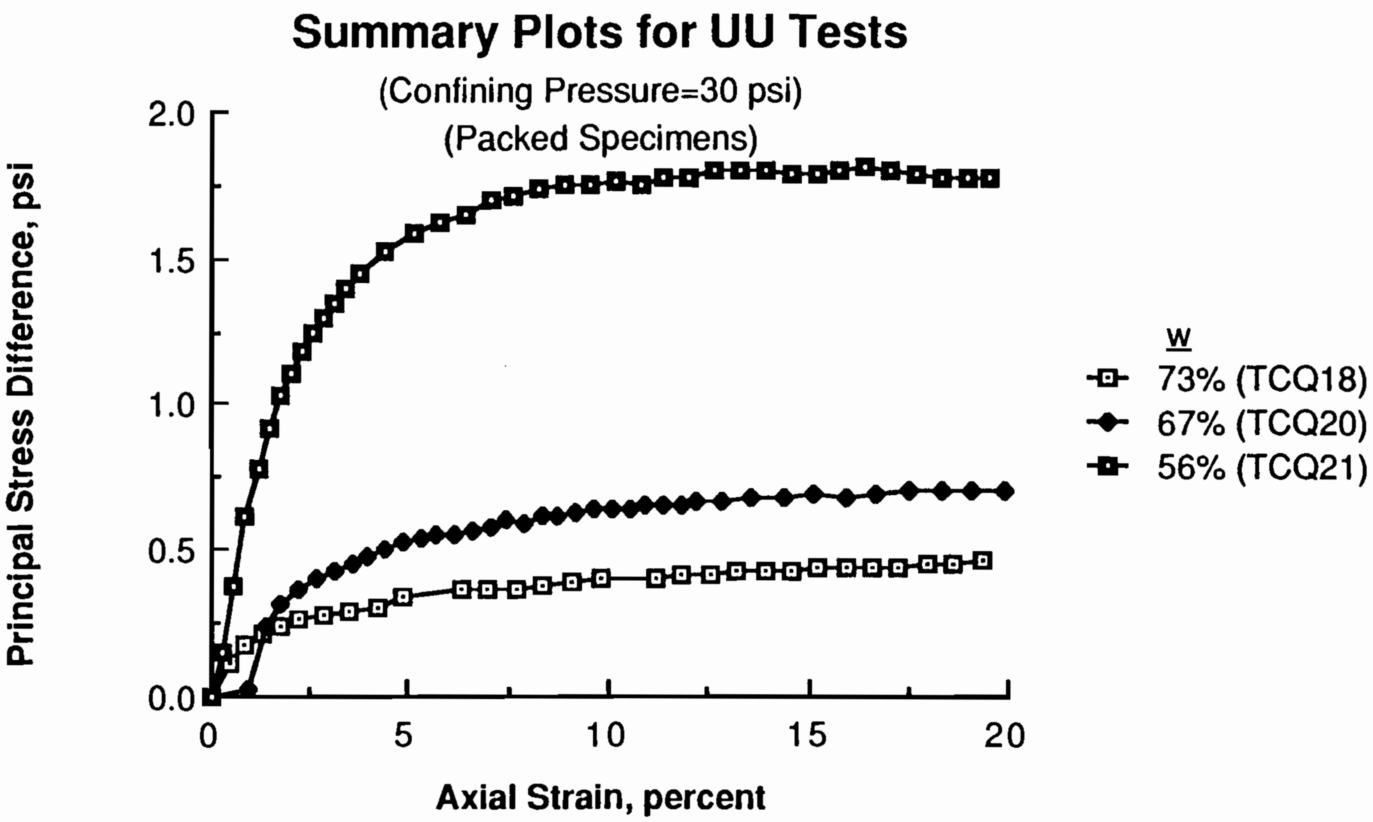

Figure C.1.8. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Packed Specimens.

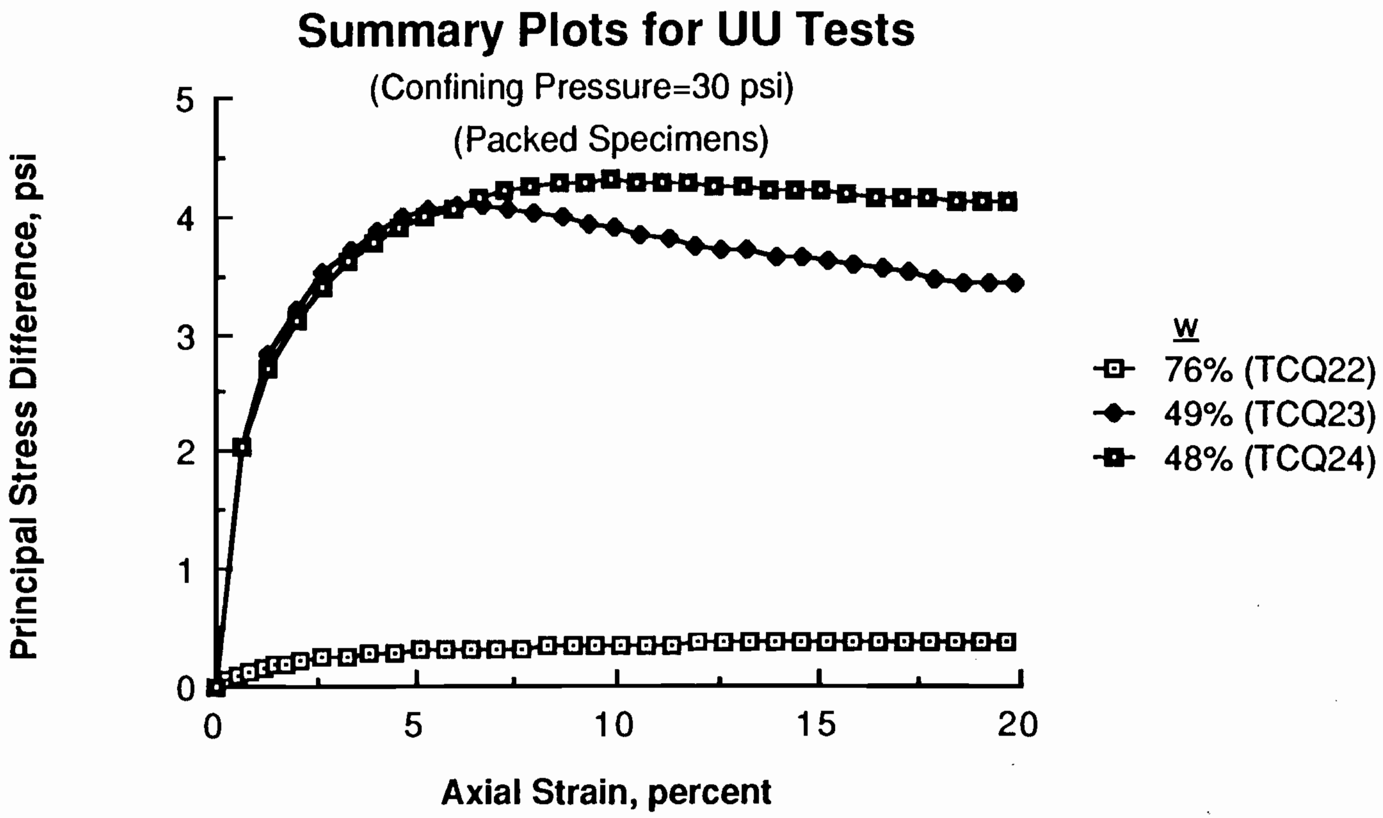

Figure C.1.9. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Packed Specimens.

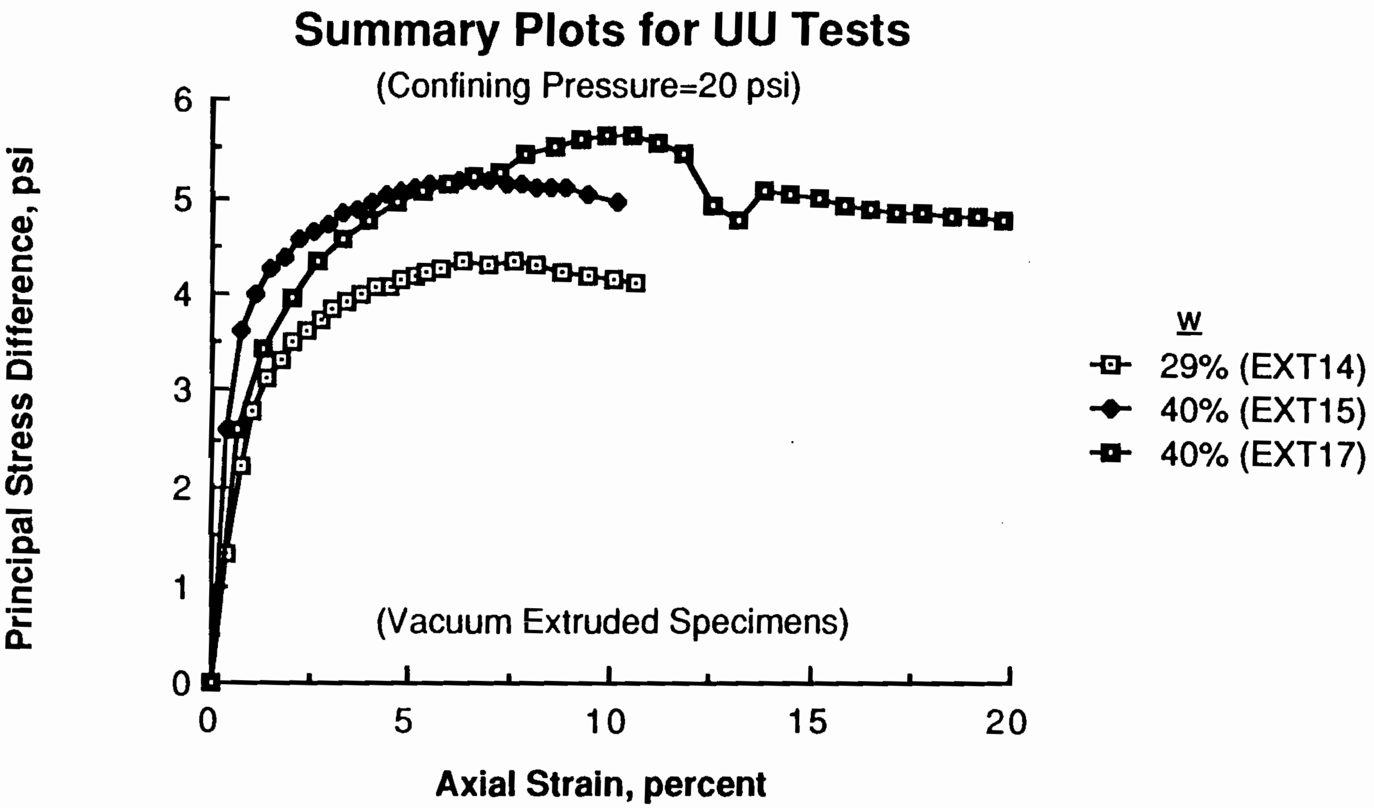

Figure C.2.1. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Vacuum-Extruded Specimens.

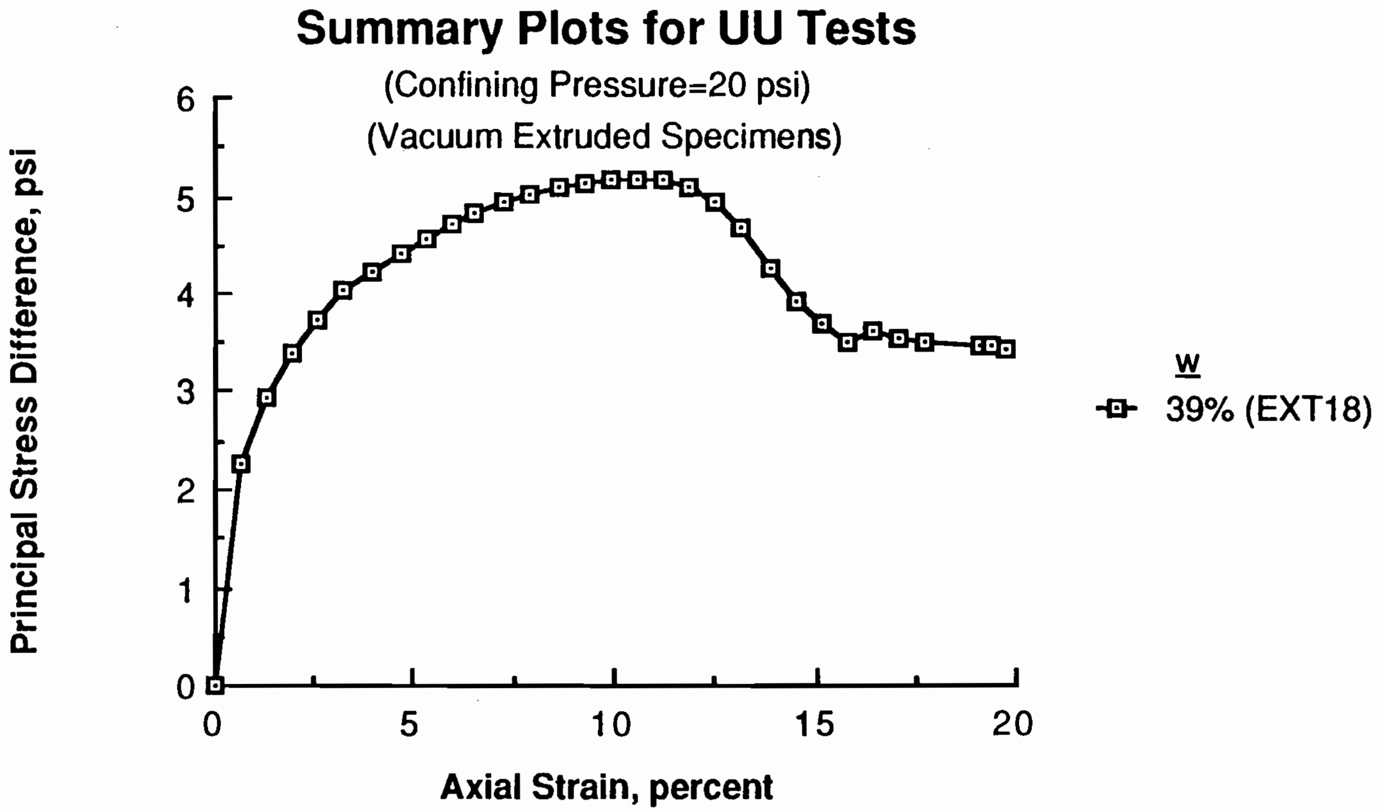

Figure C.2.2. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Vacuum-Extruded Specimens.

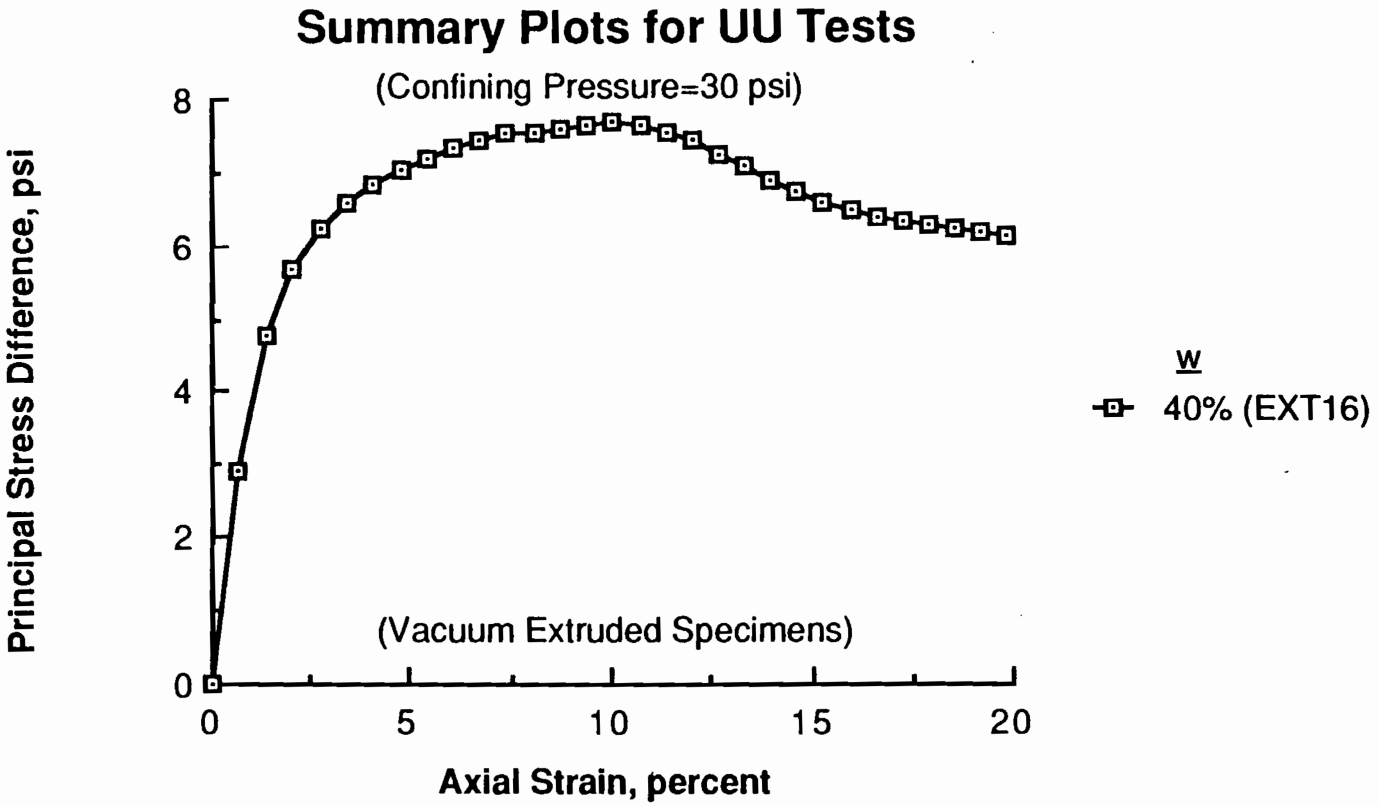

Figure C.2.3. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Vacuum-Extruded Specimens.

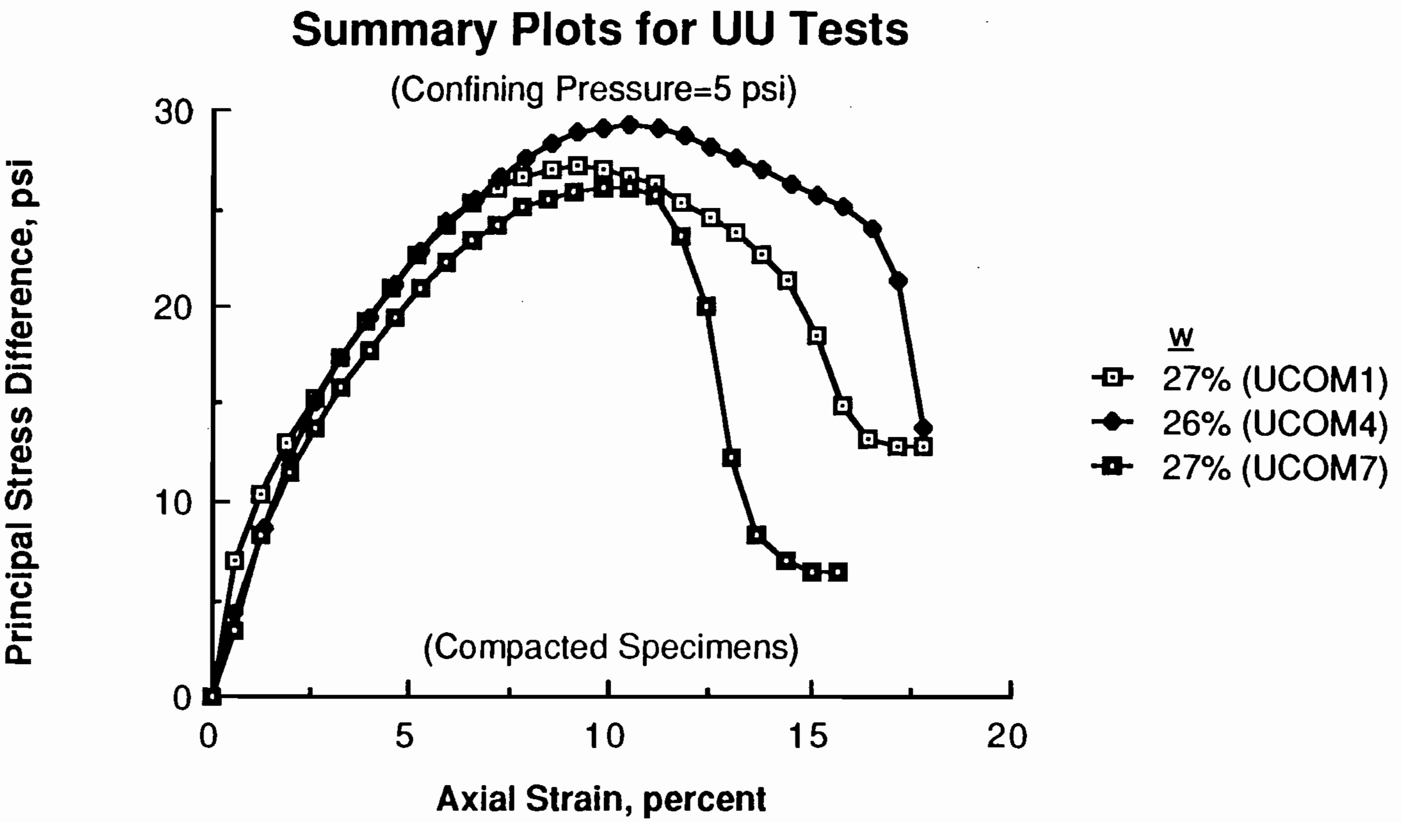

Figure C.3.1. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Compacted Specimens.

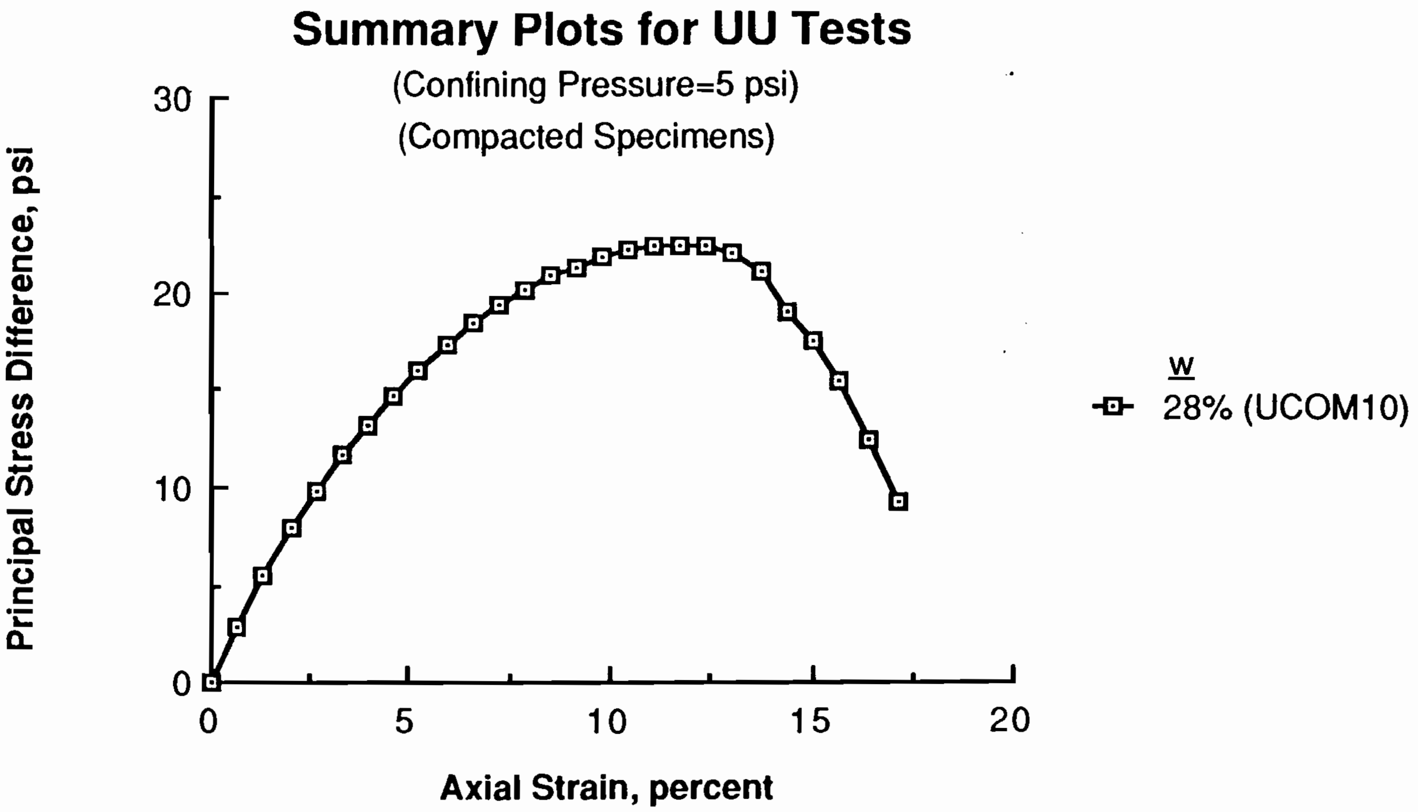

Figure C.3.2. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Compacted Specimens.

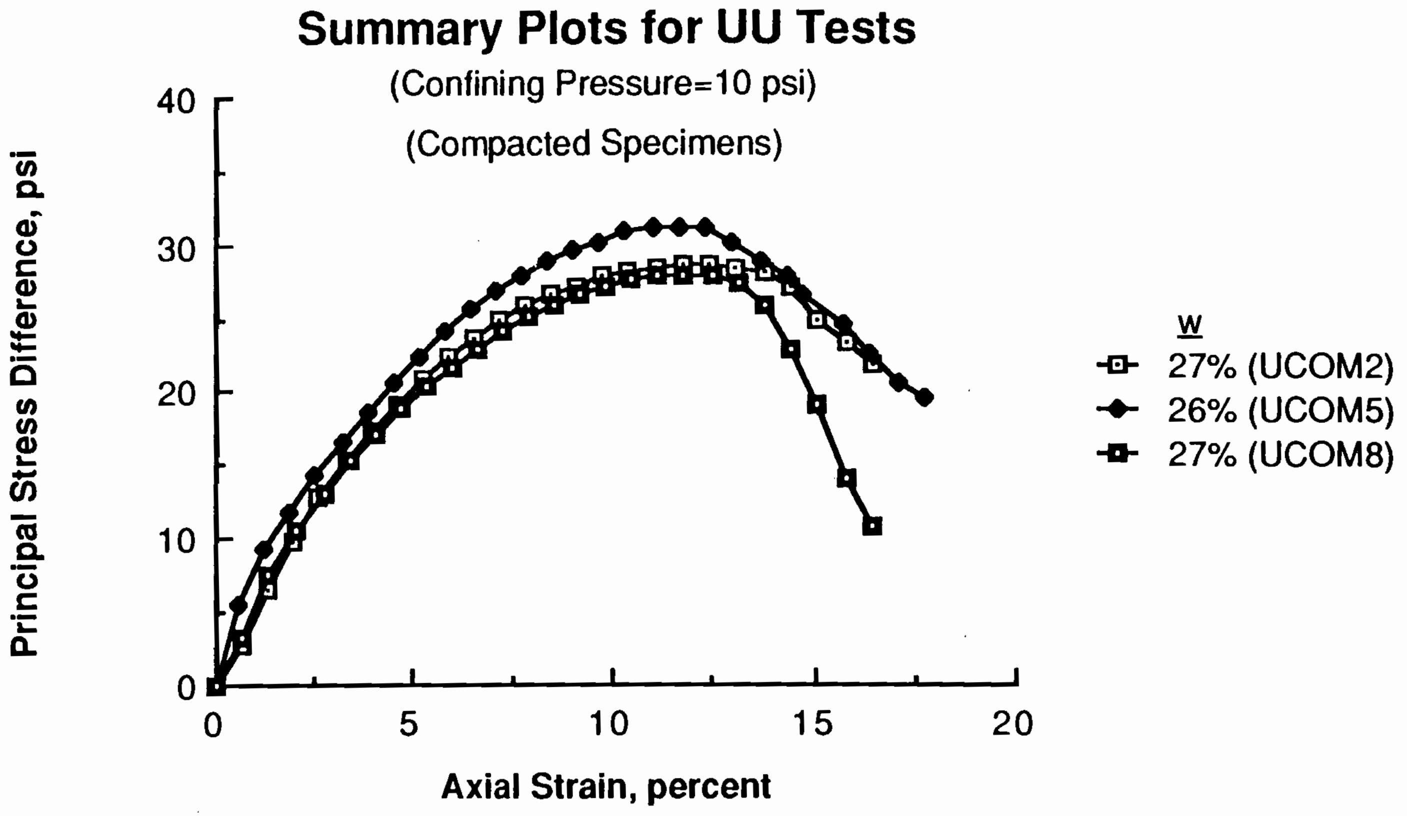

Figure C.3.3. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Compacted Specimens.

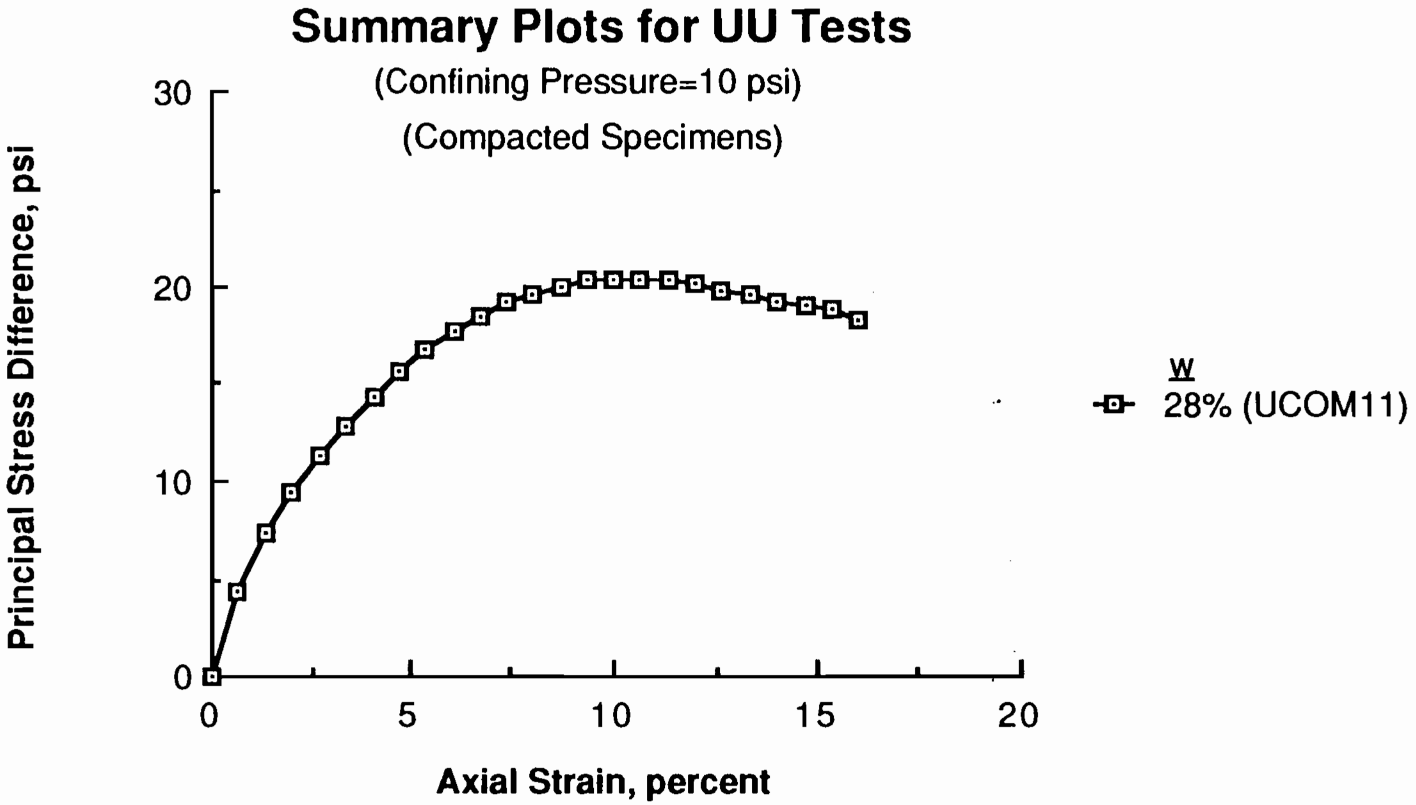

Figure C.3.4. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Compacted Specimens.

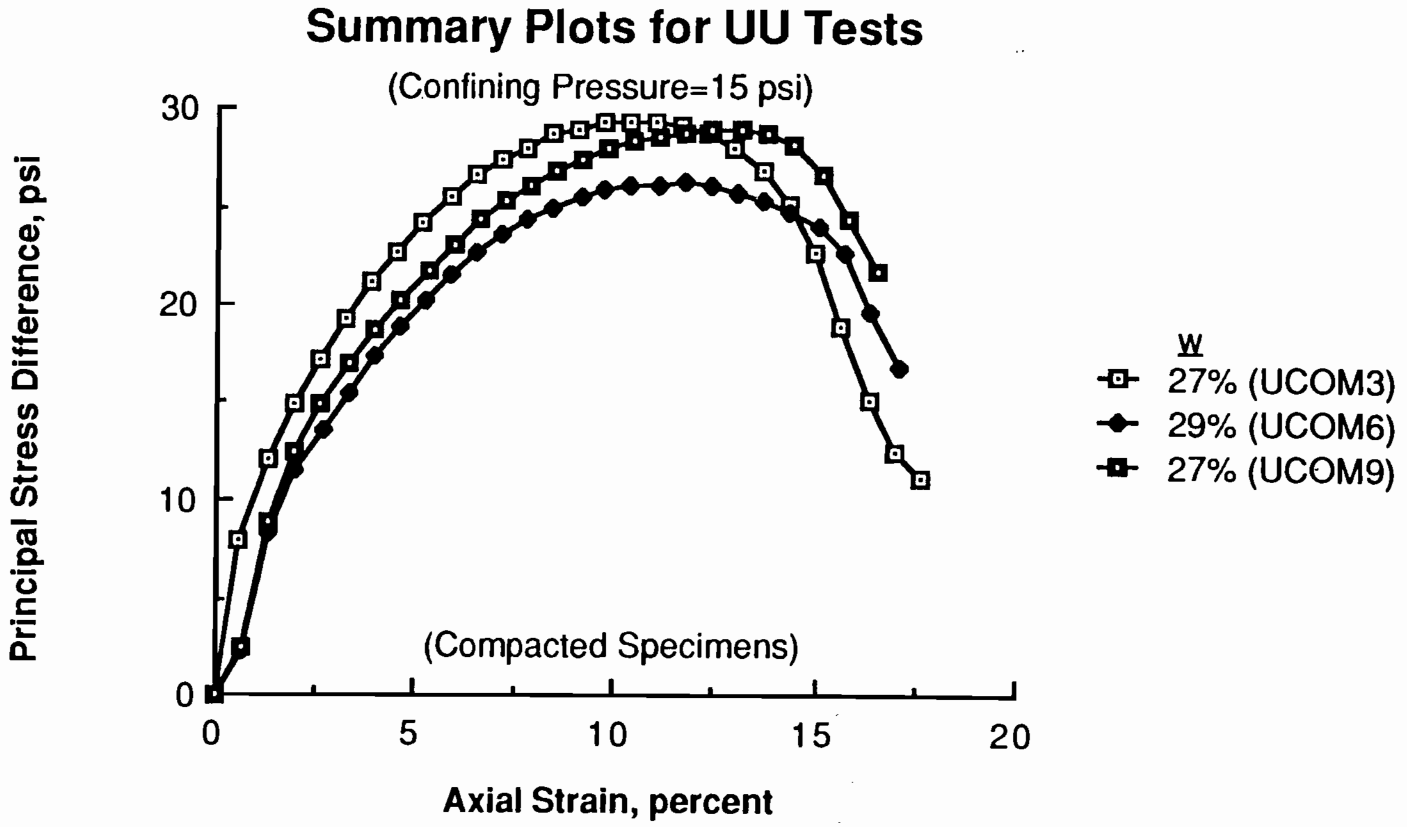

Figure C.3.5. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Compacted Specimens.

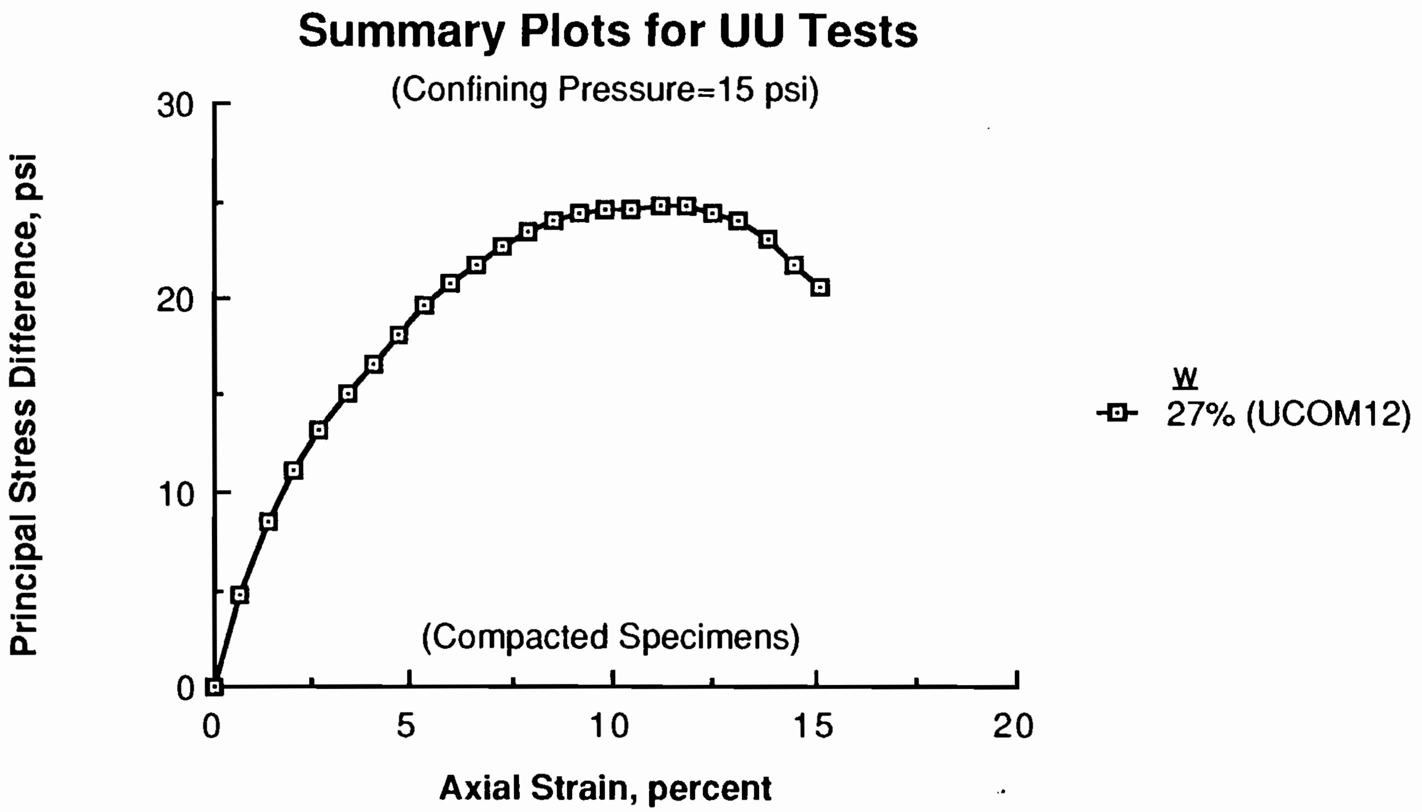

Figure C.3.6. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Compacted Specimens.

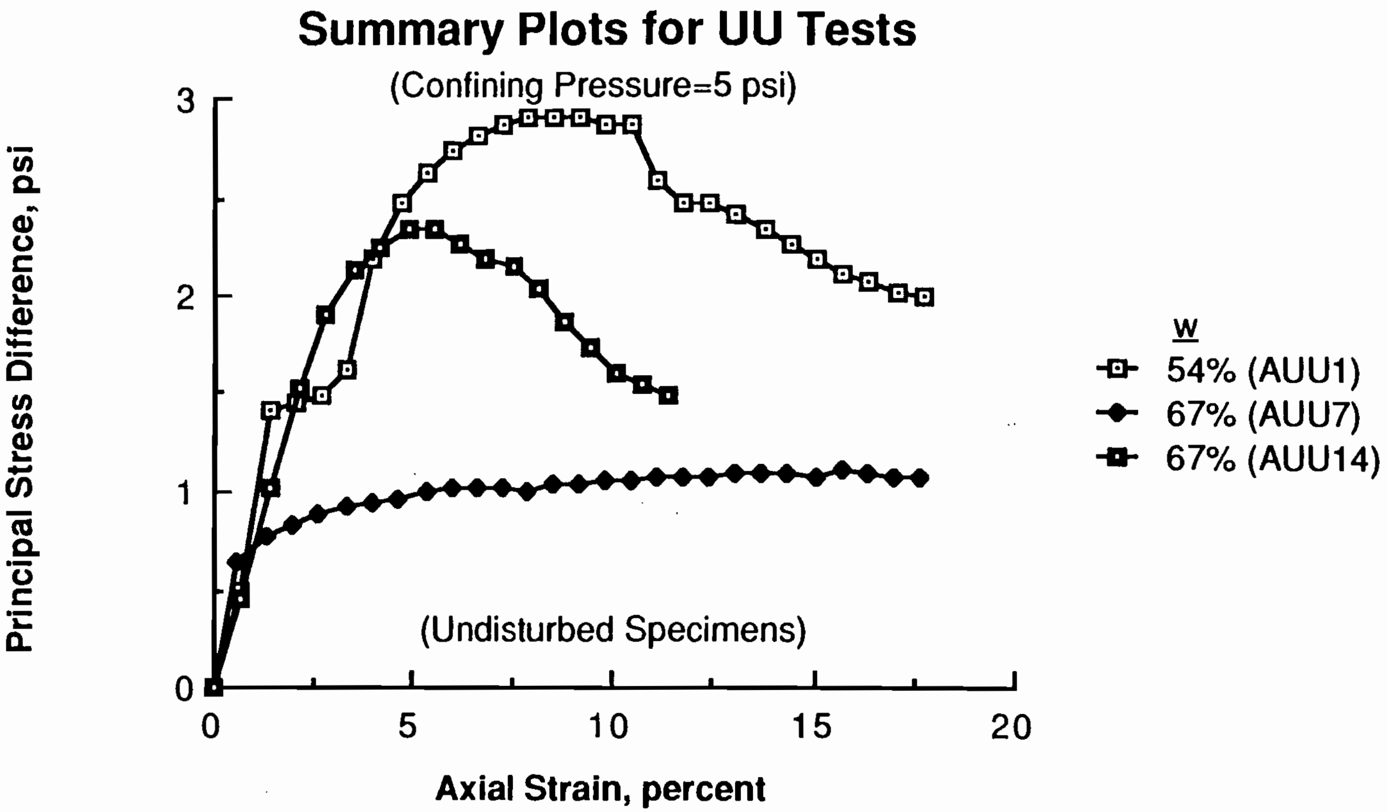

Figure C.4.1. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Undisturbed Specimens.

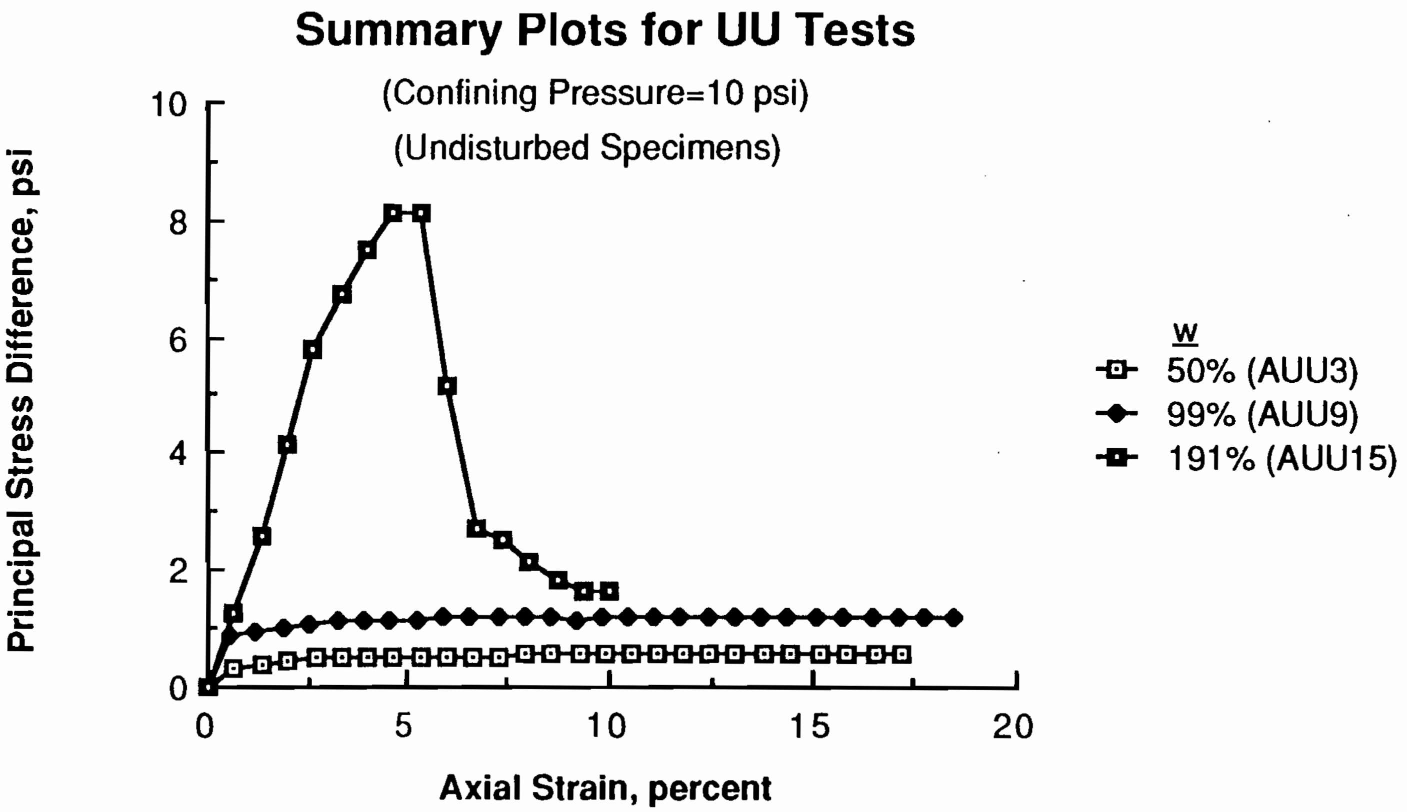

Figure C.4.2. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Undisturbed Specimens.

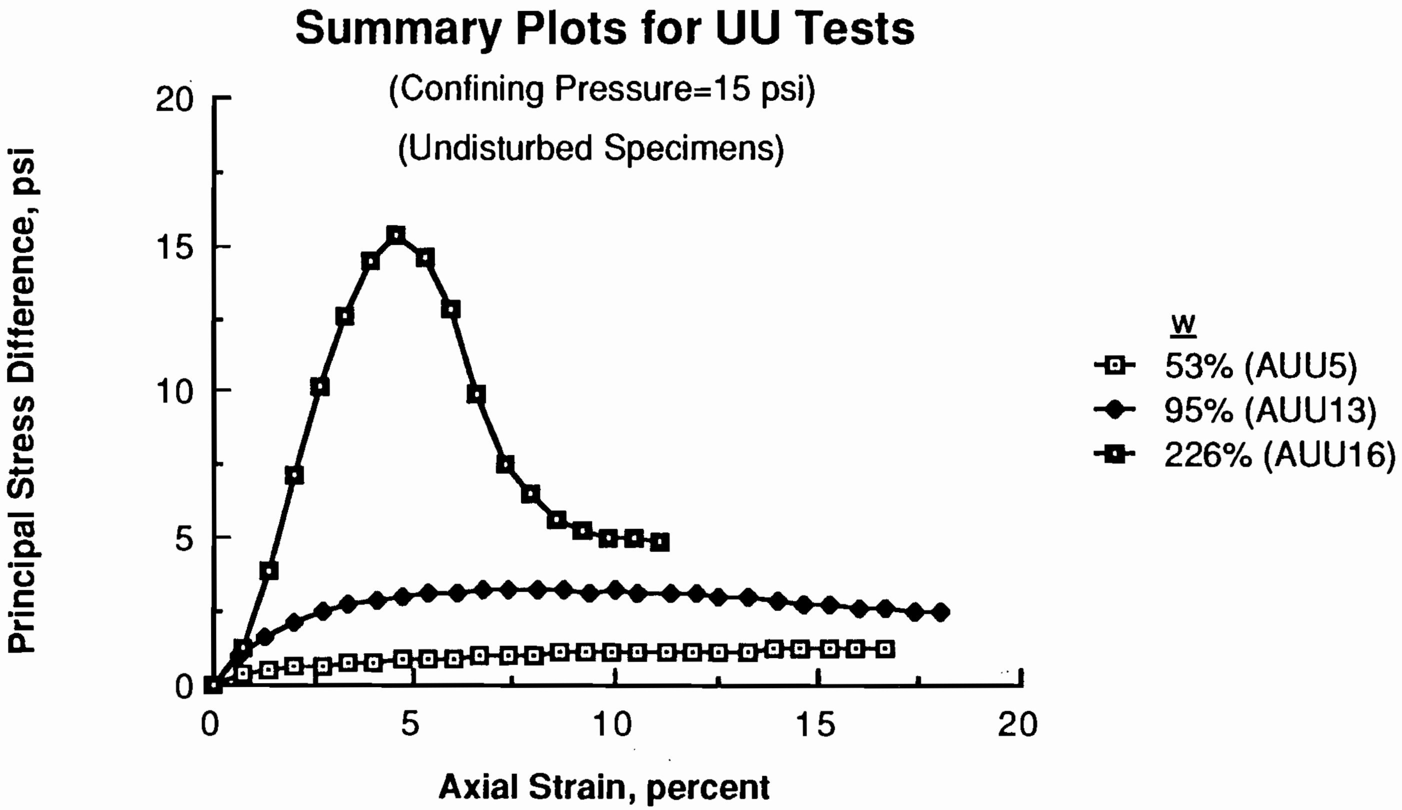

Figure C.4.3. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Undisturbed Specimens.

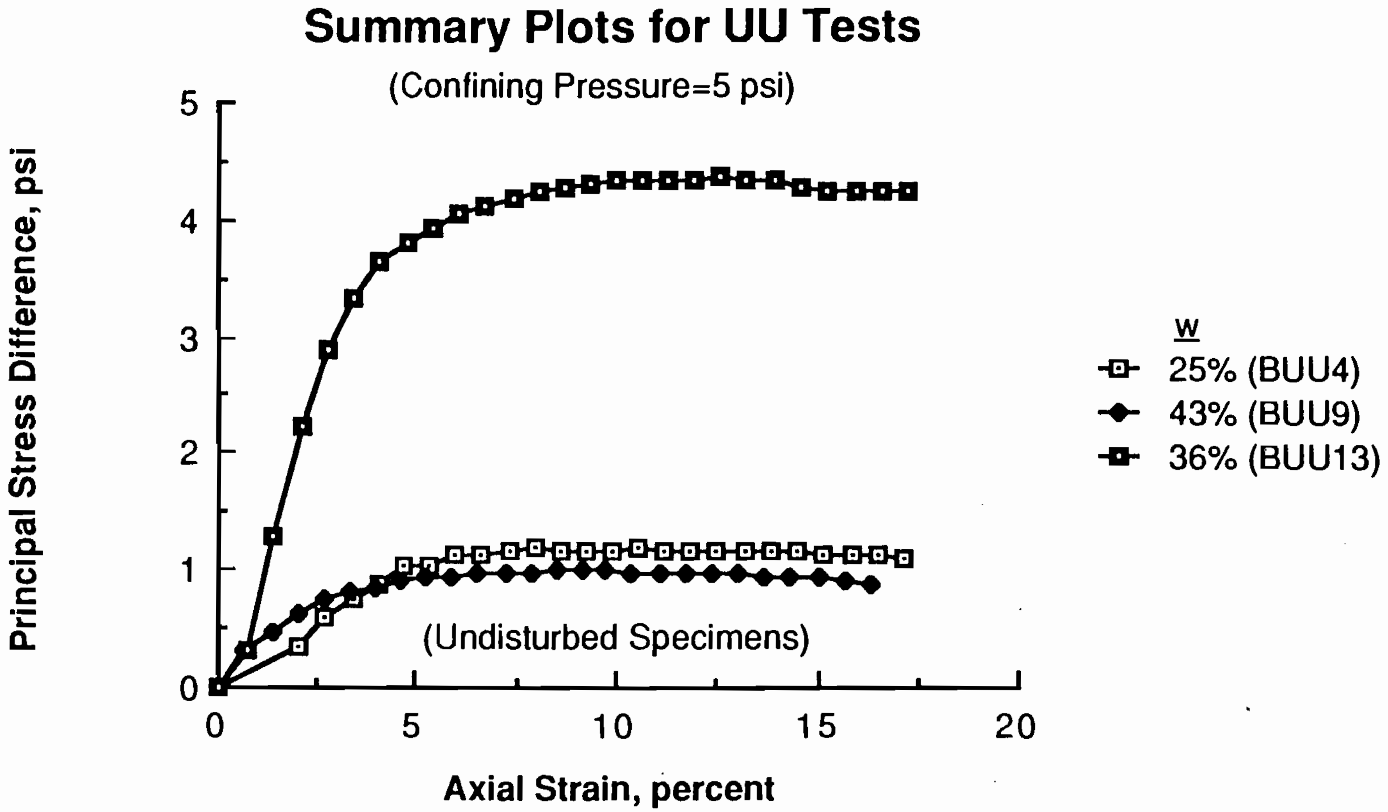

Figure C.4.4. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Undisturbed Specimens.

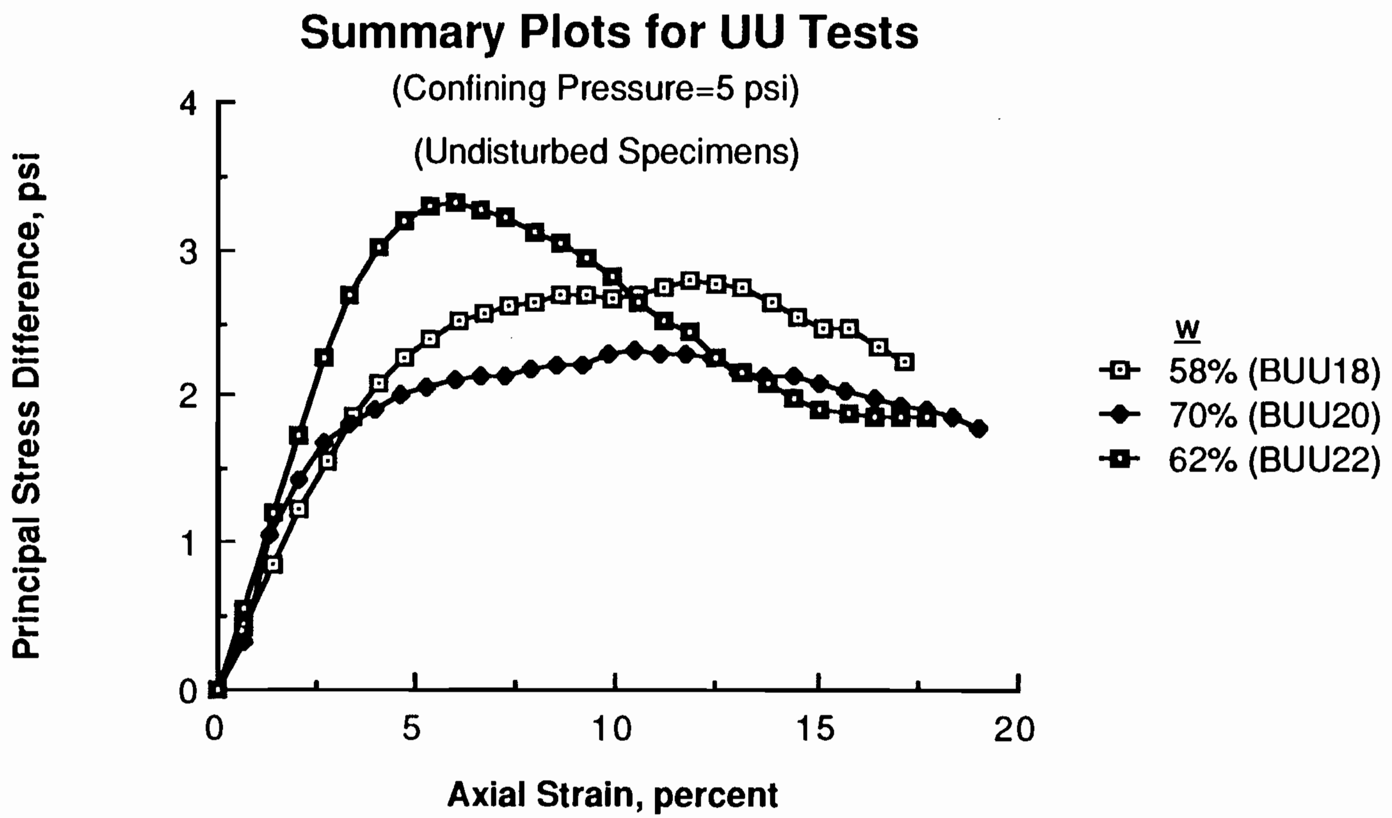

Figure C.4.5. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Undisturbed Specimens.

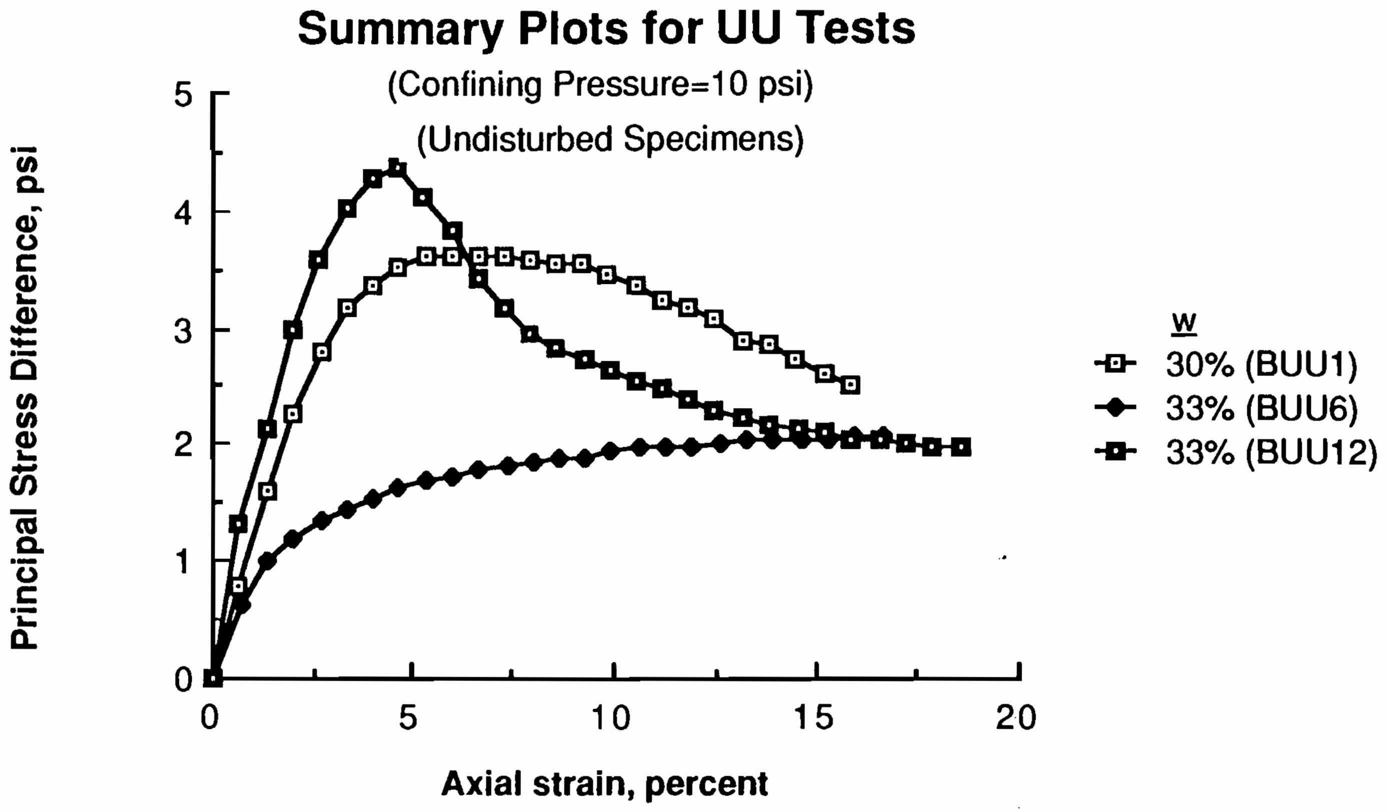

Figure C.4.6. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Undisturbed Specimens.

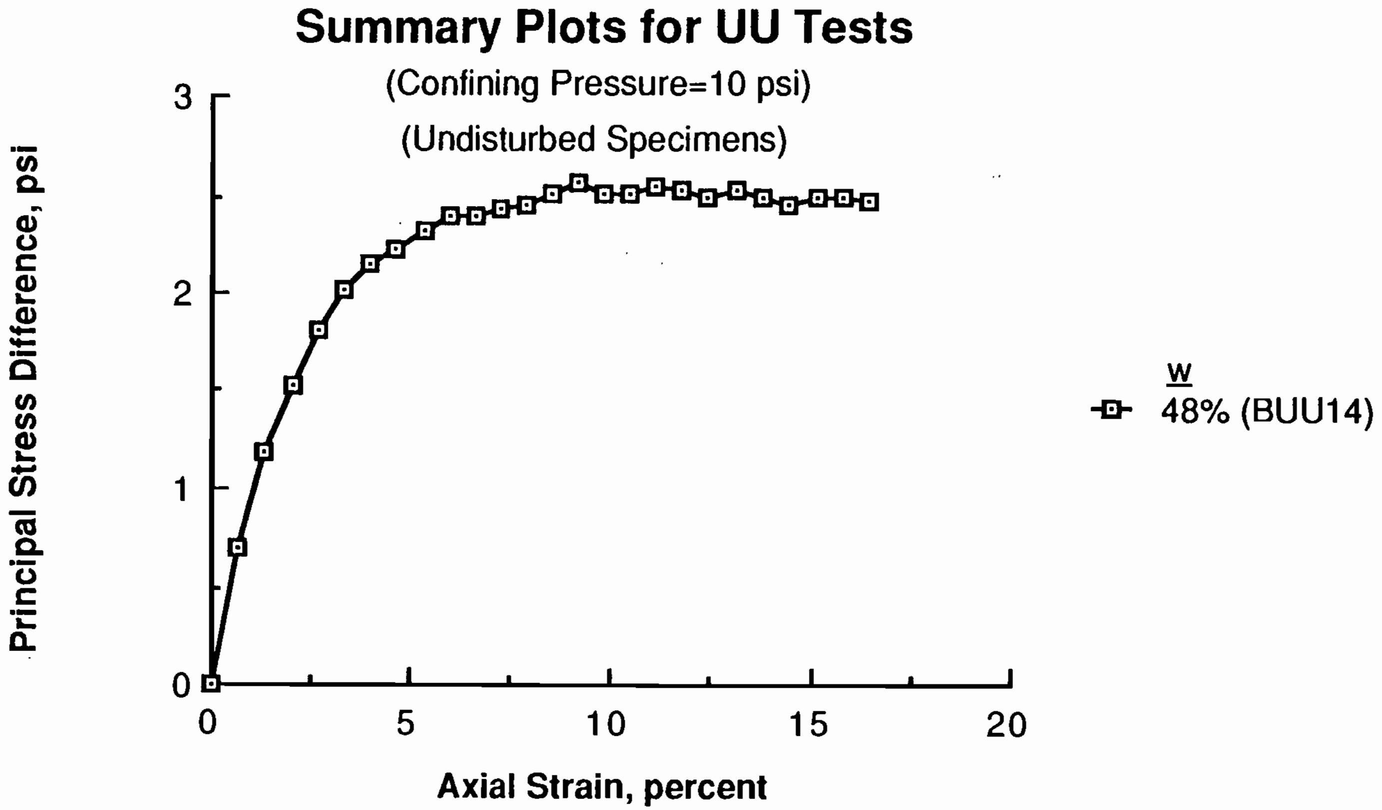

Figure C.4.7. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Undisturbed Specimens.

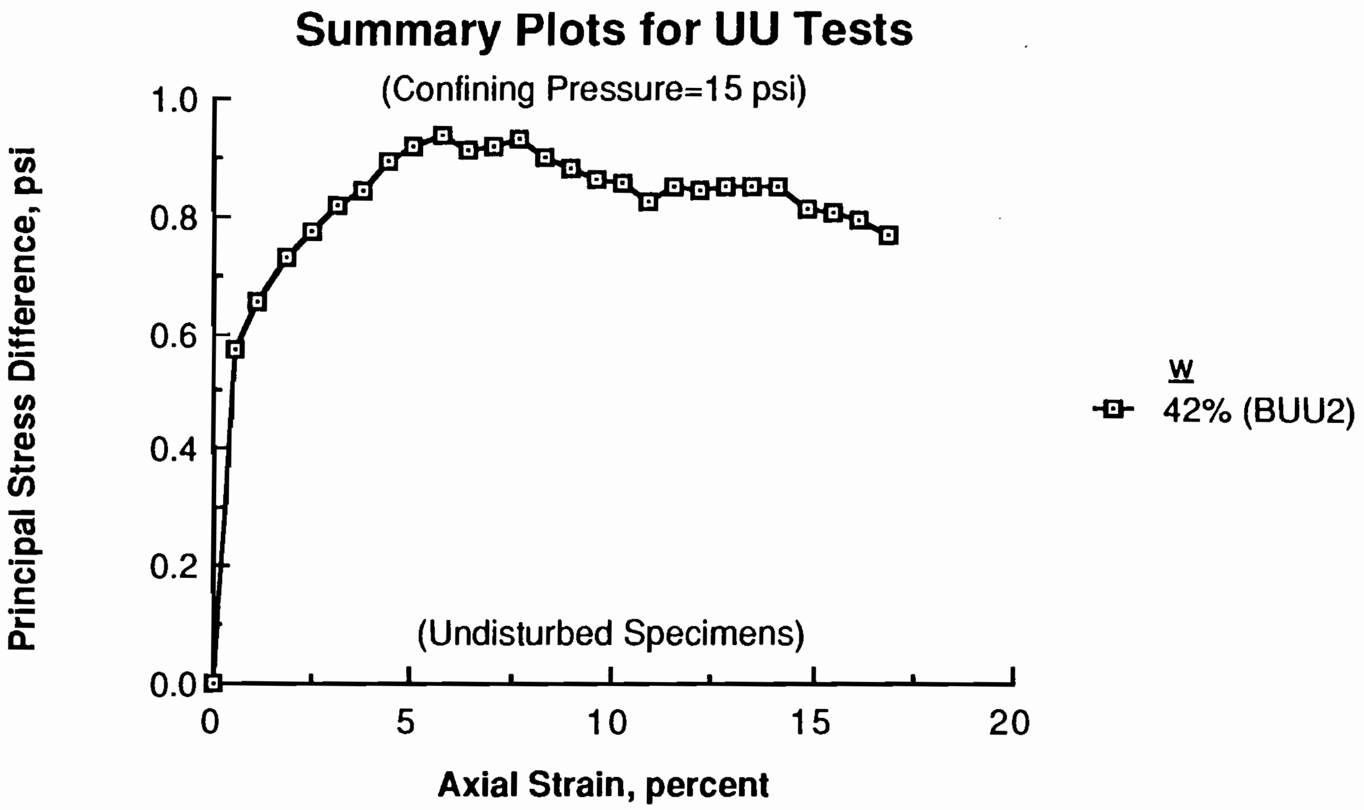

Figure C.4.8. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Undisturbed Specimens.

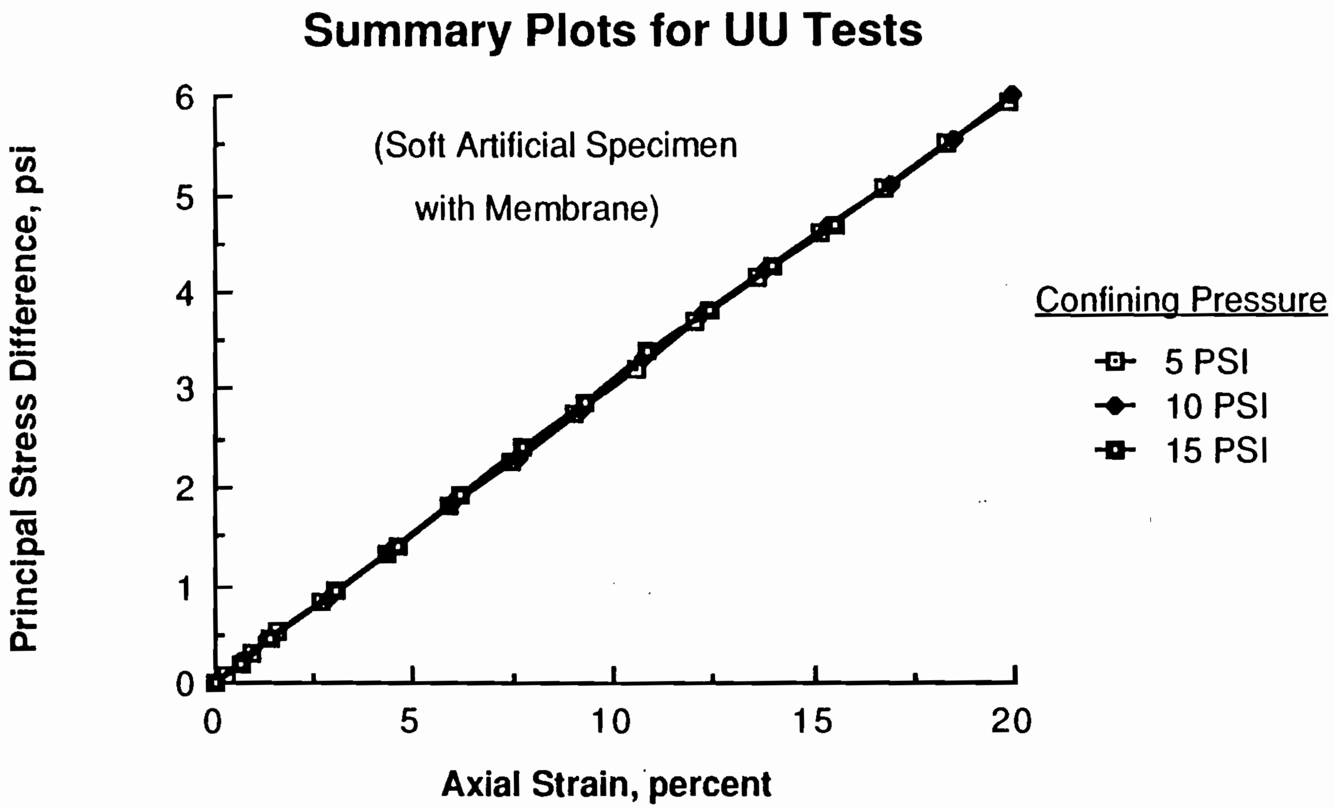

Figure C.5.1. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconsolidated-Undrained Tests on Artificial Specimens.

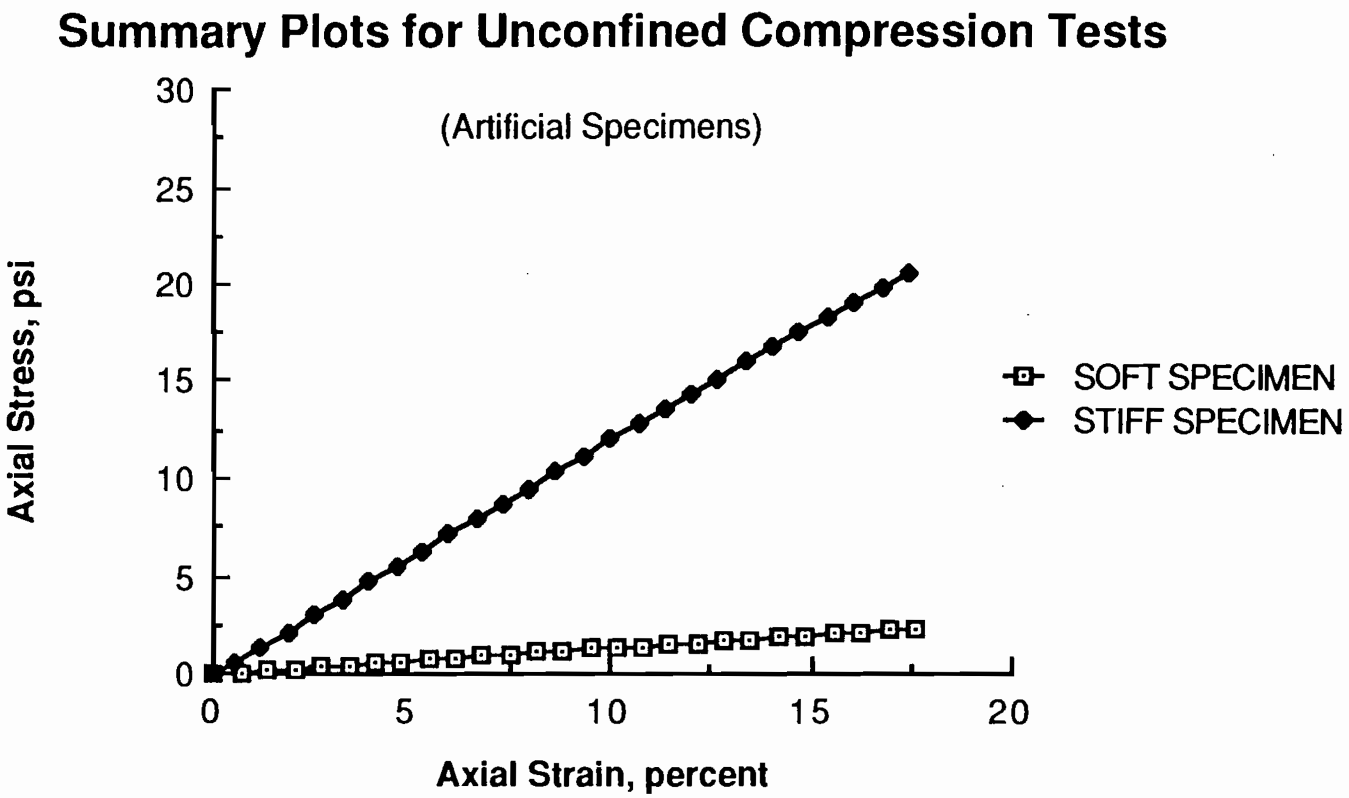

Figure C.6.1. Summary Plots of Principle Stress Difference Versus Axial Strain for Unconfined CompressionTests on Artificial Specimens.

APPENDIX D

SUMMARY OF CALCULATIONS FOR TEXAS TRIAXIAL CORRECTION FACTOR

APPENDIX D. SUMMARY OF CALCULATIONS FOR TEXAS TRIAXIAL FACTOR

Appendix D contains the summary of calculations performed to obtain a single correction factor for strengths measured using the Texas Triaxial test. Table D.1 contains the summary of calculations performed pertaining to the soft artificial specimen. Table D.2 contains the summarized calculations pertaining to the stiff artificial specimen.

TABLE D.1. SUMMARY OF CALCULATIONS FOR AXIAL STRESS INCREASE IN A SOFT ARTIFICIAL SPECIMEN USING THE TEXAS TRIAXIAL TEST.

Confining Pressure, (psi)	Axial Strain, (percent)	Axial Stress Increase, (psi)	Axial Stress Increase/Axial Strain, psi/ percent axial strain
5	1	0.740	0.7
	2	1.279	0.6
	3	1.692	0.6
	4	2.029	0.5
	5	2.298	0.5
	6	2.601	0.4
	7	2.832	0.4
	8	3.053	0.4
	9	3.262	0.4
	10	3.419	0.3
10	1	0.837	0.8
	2	1.518	0.8
	3	2.132	0.7
	4	2.679	0.7
	5	3.209	0.6
	6	3.656	0.6
	7	4.121	0.6
	8	4.574	0.6
	9	5.004	0.6
	10	5.357	0.5
15	1	0.825	0.8
	2	1.483	0.7
	3	2.066	0.7
	4	2.686	0.7
	5	3.337	0.7
	6	3.997	0.7
	7	4.644	0.7
	8	5.277	0.7
	9	5.913	0.7
	10	6.497	0.6

TABLE D.2. SUMMARY OF CALCULATIONS FOR AXIAL STRESS INCREASE IN A STIFF ARTIFICIAL SPECIMEN USING THE TEXAS TRIAXIAL TEST.

Confining Pressure, (psi)	Axial Strain, (percent)	Axial Stress Increase, (psi)	Axial Stress Increase/Axial Strain, psi/ percent axial strain
5	1	1.497	1.5
	2	2.306	1.2
	3	3.058	1.0
	4	3.641	0.9
	5	4.302	0.9
	6	4.788	0.8
	7	5.317	0.8
	8	5.723	0.7
	9	6.167	0.7
	10	6.535	0.7
10	1	1.512	1.5
	2	2.542	1.3
	3	3.413	1.1
	4	4.191	1.0
	5	4.991	1.0
	6	5.721	1.0
	7	6.500	0.9
	8	7.189	0.9
	9	7.881	0.9
	10	8.495	0.8
15	1	1.588	1.6
	2	2.345	1.2
	3	3.099	1.0
	4	3.766	0.9
	5	4.448	0.9
	6	5.067	0.8
	7	5.778	0.8
	8	6.457	0.8
	9	7.190	0.8
	10	8.120	0.8

APPENDIX E

ONE-DIMENSIONAL CONSOLIDATION TEST RESULTS

APPENDIX E. ONE-DIMENSIONAL CONSOLIDATION TEST RESULTS

Appendix E contains the results of a one-dimensional consolidation test performed on Taylor clay packed into the consolidation ring. Included in Figure E.1 are the undrained shear strengths obtained from unconsolidated-undrained tests on nearly-saturated specimens. These strengths are included for comparison.

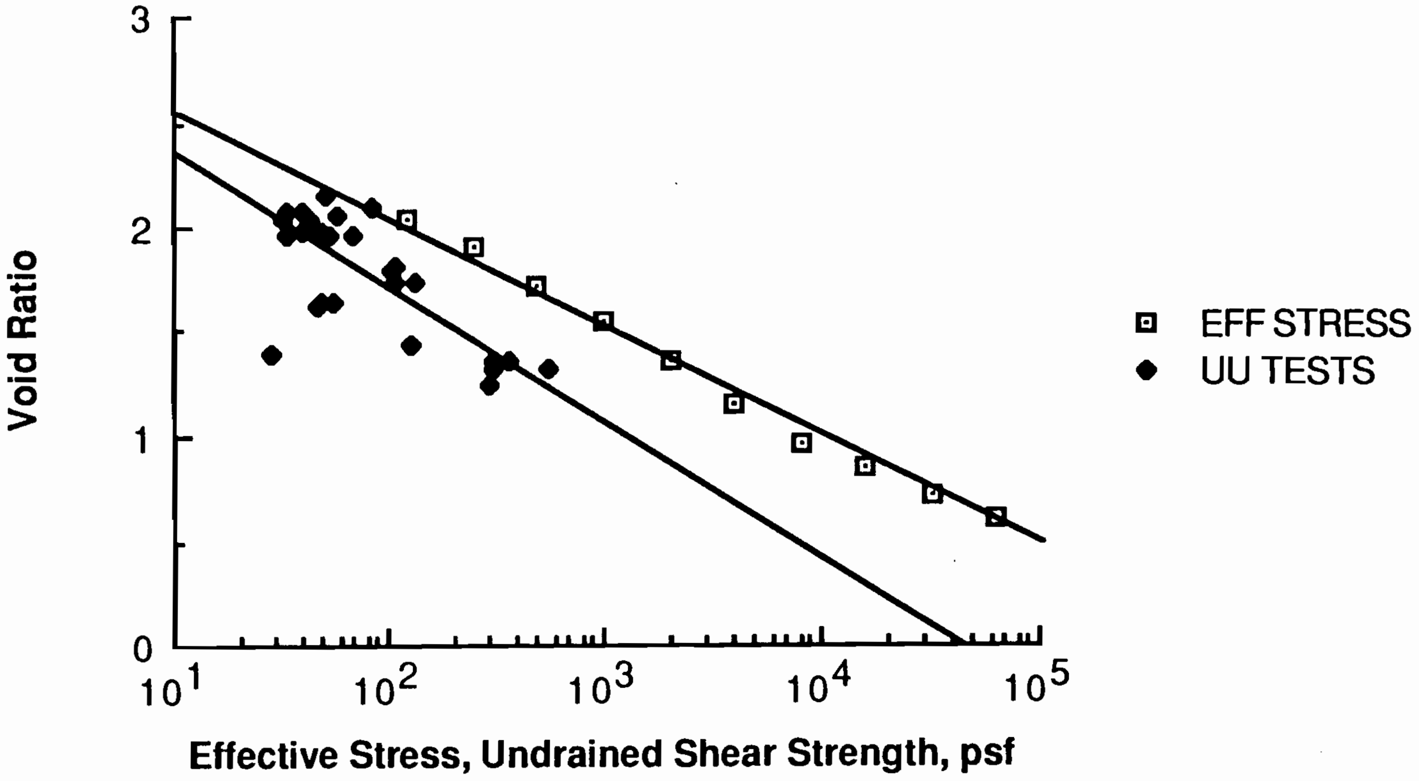

Figure E.1. Effective Consolidation Pressure and Undrained Shear Strength Versus Void Ratio for Nearly-Saturated Taylor Clay.