

THE EFFECTS OF FREEZING ON A COMPACTED WINNIPEG CLAY

By

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SYNOPSIS

It was undertaken to determine the effect of a single freezing and thawing on the strength and compressibility characteristics of a compacted local clay. The soil samples were frozen in a closed system so that during the freezing process no external source of water was available to the soil. Of particular interest were the results obtained when the moulding moisture content was less than, equal to, or exceeded the optimum moisture content for the compactive efforts used. Two different compactive efforts were considered.

Sufficient samples were compacted using standard Proctor compactive effort, and also using modified Proctor compactive effort, to permit identical tests on sets of samples subjected to the one cycle of freezing and thawing, and on sets of samples not subjected to the freezing, for the two compactive efforts.

One dimensional consolidation and undrained triaxial tests including unconfined compression tests were used to indicate the changes in strength and compressibility characteristics caused by the freezing.

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CHAPTER I

INTRODUCTION

With the increase in knowledge of the influence of compaction on soil properties has come a better appreciation of the advantage of its use.¹

Such factors as size and shape of mould, support of mould, magnitude and distribution of compactive effort and method of sample preparation etc., have been shown to have an effect on the properties of a compacted clay.

Work done by Proctor² demonstrated the effect that the size of mould has on compaction results. The variables in Proctor's study were:

1. A 5½ lb. tamper dropped 18 inches for 25 blows on each of 3 equal soil layers in a 1/20 cu. ft. container. (12,375 ft./lb. per cu. ft.)
2. A 5½ lb. tamper dropped 12 inches for 25 blows on each of 3 equal soil layers in a 1/30 cu. ft. container. (12,375 ft./lb. per cu. ft.)

Using the 1/20 cu. ft. container gave a maximum dry density of 92.5 lb. per cu. ft. at a moisture content of 25.0 percent. Values for the 1/30 cu. ft. container were 98.0 and 21.0 respectively.

Ray and Chapman³ performed a series of tests to measure the influence of the type of support on the resulting maximum dry unit weight and optimum moisture content. The tests were made with the mould (a) resting on a concrete floor, (b) resting on the middle of a stout wooden table, (c) resting on a steel plate placed on the table

and (d) resting on a 213 lb. weight. Ray and Chapman concluded that the results of the standard compaction test for a given soil depend to a small extent on the effective mass of the base on which the test is performed. With greater compactive effort the difference in results increases.

Lambe⁴ showed that differences in compactive effort affect the maximum dry density and optimum moisture content of a compacted soil. The results of Lambe's work indicate that with increasing compactive effort the maximum dry density increases and optimum moisture content decreases.

The effect of the type of compactive effort has been investigated by Seed and Chan⁵. Seed and Chan limited most of their investigation of a compacted clay to static and kneading compaction as these are the common methods of compacting a clay soil. The results of Seed and Chan's work, as regards method of compaction, are too lengthy to discuss in this thesis, but it can be said that the method of compaction affects to some extent the properties of a compacted clay, and could be significant for the properties investigated in this study.

The method of preparing the compaction sample has been investigated and the results published by the Highway Research Board, Bulletin No. 316. The effect of air drying compared to oven drying the soil, and the effect of recompaction versus the use of separate portions of the sample for each point on the compaction curve, were studied. The results of these studies indicate that for the soil tested there is little difference between recompacting air-dried and oven-dried samples with regard to the moisture-dry unit weight relationship. It also shows that the continued recompacting results in greater maximum unit weights

and lower optimum moisture contents than were obtained from a single run.

Although only a few factors affecting the moisture-dry unit weight relationship have been discussed, and even though some factors have little effect on final values, it must be realized that an accumulation of the effects of these factors can greatly influence the final moisture-dry unit weight relationship and make repeatability of results difficult.

Discussions of the properties of a compacted clay usually center around the term "clay structure". The term "clay structure" is used to describe the arrangement of soil particles and the electric forces between adjacent particles. The structure theory of soil behaviour helps considerably in explaining measured soil properties. According to Leonards⁶, the direct evidence to support this theory is unfortunately scanty.

Differences in structure resulting from compaction can have a pronounced effect on the engineering properties of a compacted clay. Seed and Chan⁵, investigated the effect of structure on shrinkage, swelling, swell pressure, stress deformation characteristics, undrained strength, pore water pressures, etc.

It was observed by Lambe⁸ that samples compacted dry of optimum shrink less than samples compacted wet of optimum.

Unfortunately the influence of structure alone on shrinkage is not made apparent by Lambe's work, since samples of equal densities compacted wet and dry of optimum have both different structures and different water contents. However, Seed and Chan clarified this effect by allowing the compacted samples to soak at constant volume

before measuring shrinkage. The results of this type of test have shown that samples compacted dry of optimum exhibited less shrinkage than samples compacted wet of optimum.

Seed and Chan⁵ have observed that samples compacted dry of optimum show higher swelling pressures and greater swell percentages than do samples of the same density compacted wet of optimum. The reason is that some of the water entering a compacted specimen during swelling is required to simply fill the voids, as distinct from water absorbed by the soil during the swelling process. Thus samples compacted wet and dry of optimum (and having different structures) will show different increases in water content due to both of these effects. Samples compacted dry of optimum will show increases in water content due to both water being absorbed by the soil and by water that is entering the voids. Samples compacted wet of optimum will show an increase in water content that is mainly due to water entering the voids. Seed and Chan⁵ state that a marked increase in swelling tendencies of samples compacted dry of optimum is readily detectible.

The influence of soil structure on swelling pressure has also been studied by Seed and Chan⁵. Results of these investigations show samples compacted dry of optimum exhibit greater swell pressures than samples of the same final composition compacted wet of optimum.

Structure affects stress-deformation characteristics to the following extent. Samples compacted dry of optimum have initially a steep stress-strain curve with only a slight increase in stress being developed after about 5 percent strain. For samples compacted wet of optimum, a much flatter curve with a generally consistent increase in

resistance to deformation up to strains as high as 25 percent is observed according to Seed and Chan⁵.

The influence of structure on the undrained strength of soils depends on the deformation criterion adopted as a basis for strength determination. Seed and Chan⁵ prepared two samples at the same water content and density (after soaking) but with different structures. At 25 percent strain both samples reached about the same ultimate strength. However, at 10 percent strain, samples compacted wet of optimum were evidently weaker than samples compacted dry of optimum.

Research into the effect of structure on pore water pressures has indicated that during the early stages of a test particularly, the samples compacted wet of optimum generated greater pore pressures than samples compacted dry of optimum. However, at high strains both structures exhibit approximately the same pore pressures⁵.

Although the work of Seed and Chan and others is more extensive than the above mentioned, only certain aspects have been touched on because they are the most pertinent to this thesis.

This thesis extends some of the work done by Seed and Chan by examining the effect of frost action on the strength and compressibility properties of a compacted clay.

Previous laboratory investigation usually consisted of a soil sample being frozen uniaxially in a frost cell and being supplied with an external source of water, and subsequently thawed. Haley⁹, Takagi¹⁰, and Kaplar¹¹ showed the above noted freezing procedure resulted in the forma-

tion of ice lenses due to moisture redistribution during freezing and strength loss upon thawing.

The method of freezing the soil samples in this thesis program was to freeze them triaxially in a closed system. This particular method of freezing was adopted for expediency of the testing program. Also, freezing triaxially in a closed system is the simplest type of freezing process. By freezing the samples in the manner stated (triaxially in a closed system), the effect of freezing and subsequent thawing is studied. If samples were frozen in the customary manner, the effect of moisture redistribution, freezing and subsequent thawing is examined. Freezing samples triaxially in a closed system eliminates the effect of moisture redistribution due to water migrating into the sample.

Because of the important effect of soil structure on the properties of a compacted clay associated with different compactive efforts, two sets of soil samples, compacted to different compactive efforts, were studied. The details of the different compactive efforts are given in Chapter III.

Since the effect of frost action on the strength and compressibility properties of a compacted clay were to be studied, it was necessary to conduct triaxial and consolidation tests. Two sets of consolidation tests were required for each compactive effort. One set of tests was performed on samples in the "as compacted state" (unfrozen samples), and another set of tests was performed on identical samples that had undergone one freeze-thaw cycle (frozen samples). The moisture content of a compacted clay also affects its properties and therefore samples at different moisture contents were examined. The moisture contents were 2 and 4 percent dry of optimum, optimum, and 2 to 4 percent wet of optimum

for each set of samples. This gave a total of 20 consolidation tests.

Triaxial tests were run on samples (frozen and unfrozen) at the same moisture contents and compactive efforts as mentioned above with cell pressures of 0, 15, 30, 45 and 60 PSI. This resulted in a total of 100 triaxial tests for the compactive efforts studied.

Since the number of combinations of influencing factors such as compactive effort, subjection to one freeze-thaw cycle or no subjection to a freeze-thaw cycle, moisture content and cell pressure result in such a large number of tests being run (100 triaxial and 20 consolidation tests for 2 compactive efforts) the author decided to examine only one type of soil.

CHAPTER II

PROPERTIES OF SUBJECT SOIL

The soil used in this study was obtained from a highway construction site located at Highways No. 8 and No. 101 on the outskirts of Winnipeg, Manitoba.

This particular soil was selected because it was being used in an actual earth fill structure, that would be subject to frost action. The results of this paper could be used in a future evaluation of the earth fill performance.

The soil showed the following properties as obtained according to Procedures for Testing Soils, A.S.T.M.¹².

Specific Gravity - 2.75 (A.S.T.M. Reference Number D584¹²)

Liquid Limit - 82.5 (A.S.T.M. Reference Number D423¹²)

Plastic Limit - 28.5 (A.S.T.M. Reference Number D424¹²)

Plastic Index - 54 (A.S.T.M. Reference Number D424¹²)

M.I.T. Classification	Grain Size Limits (Millimeters)	Percentage of Subject Soil Within Grain Size Limits
Gravel	2 - 100	0
Sand	0.06 - 2	0
Silt	0.002 - 0.06	22
Clay	Less than 0.002	78

Using the Unified Classification System and the Plasticity Chart, Figure 1, the soil would be classified as a CH type soil, or a highly plastic inorganic clay.

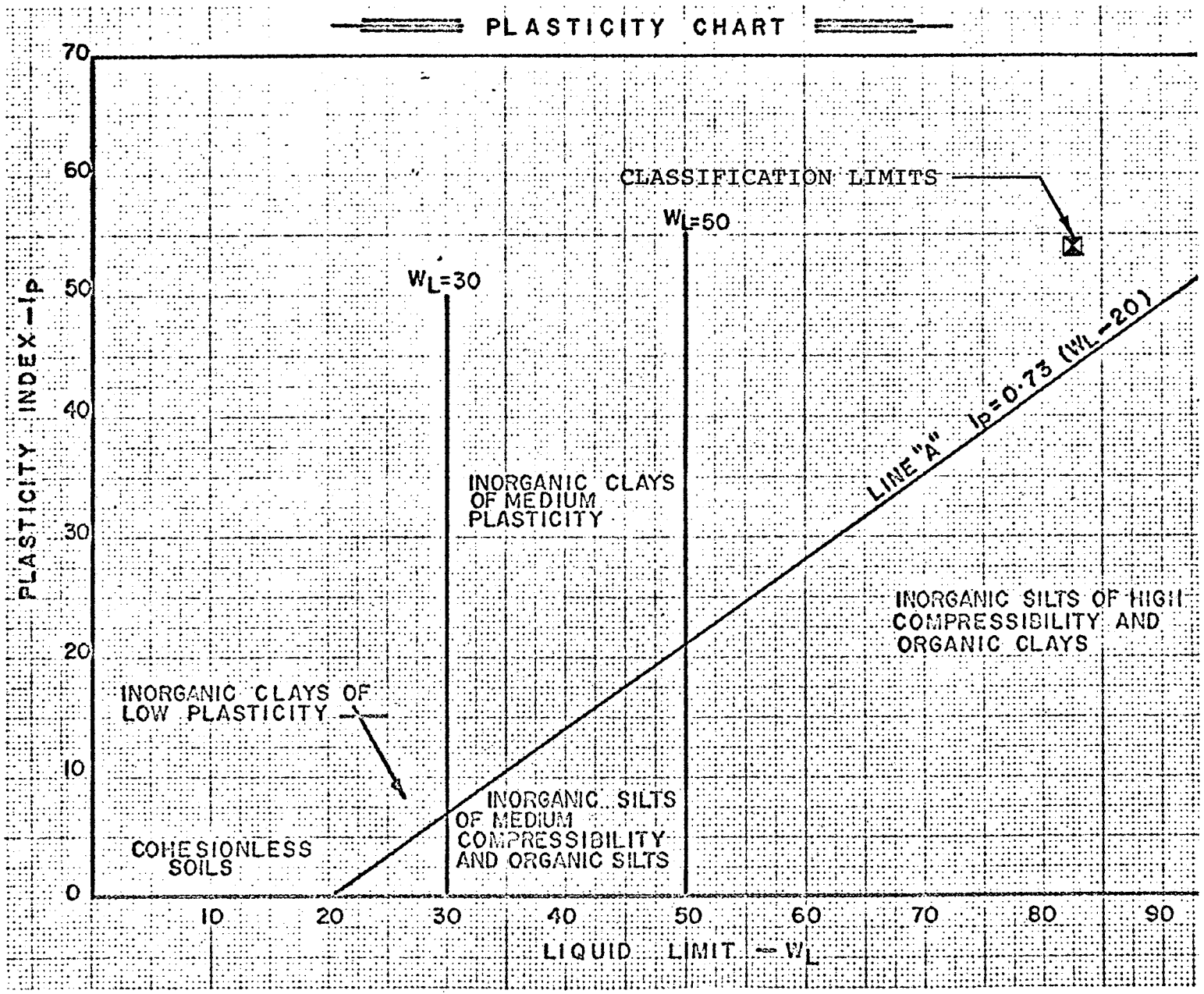


FIGURE 1
 PLASTICITY CHART SHOWING THE CLASSIFICATION
 LIMITS OF THE SOIL UNDER INVESTIGATION

CHAPTER III

EXPERIMENTAL PROCEDURE

It should be noted that "frozen" in this thesis denotes all-round freezing in a closed system. Zero cell pressure denotes an unconfined compression test. The author found that to reproduce samples of a given moulding moisture content and dry density, the following sample preparation technique had to be strictly followed.

A. SAMPLE PREPARATION

Approximately 450 pounds of air dried soil was prepared for the standard Proctor compaction test samples. An additional 450 pounds of air dried soil was prepared for samples compacted with 4.5 times the compactive effort used in the standard Proctor test. For the purpose of this paper, the 4.5 times standard Proctor compactive effort samples will be referred to as modified Proctor samples, although the compaction technique for the latter differed from that of A.S.T.M. D1557.

Following the air drying of the soil, it was crushed to 3/8 inch size and smaller using a Braun Chipmonk crusher. After crushing, the air dried soil was sieved for not less than 15 minutes on a No. 4 size U.S. sieve, using a mechanical sieve shaker. Only material passing No. 4 sieve size was used in the compaction test. The material retained on the No. 4 sieve was discarded. The material passing the No. 4 sieve was quartered in 4 bins, A, B, C and D. After quartering 450 pounds of soil, approximately 475 grams of material was taken from each bin, A through D, giving a total of 1800 grams of soil per sample. Each 1800 gram sample was then further dried for 24 hours at a temperature of approximately 84°F. The sample was then sieved for 5 minutes on a No. 20 size U.S. sieve using the sieve shaker. The percent passing No. 20 was recorded as a means of ensuring that the samples were relatively homogeneous. After 10 trials,

the average percent passing No. 20 sieve size was found to be approximately 33 percent. Therefore, all samples used in the testing procedure contained approximately 33 percent material passing No. 20 sieve size. It should be noted that the percent material passing a given sieve size refers to clusters of particles, not to individual particles. The use of the No. 20 sieve size and the 5 minutes sieving time were an arbitrary choice by the author, but found necessary to ensure uniformity of material.

Distilled water was then added by means of an applicator consisting of a bottle and perforated cap to each 1800 gram sample of air dried soil in the appropriate amount to give the desired moisture content. Allowances were made for the moisture content of the soil remaining after the drying at 84°F.

The mixture of dried soil and distilled water was then allowed to cure for approximately 16 hours in a moist room, then compacted by either standard Proctor compactive effort or modified Proctor compactive effort (4.5 times standard Proctor compactive effort). For the standard Proctor samples, A.S.T.M. procedure D-698-70 Method A was followed, utilizing a 4 inch tapered mould and a Rainhart mechanical tamper. A 3.14 square inch sector-face rammer was used in conjunction with the Rainhart mechanical tamper. For samples compacted to modified Proctor compactive effort, the A.S.T.M. procedure D-1557-70 Method A was used, but with several changes being employed. Firstly, the Proctor sample was compacted in 3 lifts not 5, and secondly each layer received 42 blows as opposed to 25 as detailed in A.S.T.M. D-1557 Method A. Using the 10 pound ram and 42 blows per layer for each of 3 layers resulted in a compactive effort of 55,700 foot pounds per cubic foot, as compared with 12,375 foot pounds per cubic foot for the standard Proctor compactive effort, or 56,250 foot pounds per cubic foot for the modified Proctor, A.S.T.M. procedure D-1557-70 Method A.

The purpose of using three lifts per mould for the modified Proctor

samples, compared to five as called for by A.S.T.M. D-1557-70 Method A, was to facilitate sample preparation for the triaxial and consolidation tests. For the modified Proctor samples compacted dry of optimum, it was found that the lifts separated upon extrusion from the Proctor mould. The separated lifts were too short, when 5 lifts were used, to give triaxial samples of at least 2.80 inches required for testing.

The consolidation samples used in the testing program were initially approximately 0.75 inches in height (the height of the cutting ring was 0.75 inches). The lift from which the consolidation sample was cut had 0.20 to 0.30 inches of soil trimmed from both top and bottom to eliminate any extraneous effects that might possibly have been generated at the intersection of two adjacent lifts.

If the soil samples were compacted in 5 lifts, a lift thickness of 0.9 inches would result. Subsequent trimming would yield a consolidation sample of 0.275 inches in thickness. Although a sample of 0.275 inches in height is not impossible to work with, it is much more difficult to use than a sample 0.625 inches in height, and less accuracy is obtained using the thinner sample.

For the previously stated reasons the author opted for a 3 lift specimen rather than a 5 lift specimen for the modified Proctor samples.

After the compaction process the moisture content of each specimen was determined using A.S.T.M. procedure D-2216. It should be noted that for each mould 15 to 20 grams of soil was taken from the edge of the sample when the moisture content was determined. The dry density was then calculated using A.S.T.M. procedure D-698-70. Moulding water content versus dry density curves were then drawn.

The compacted samples were then wrapped in Saran Wrap, waxed and stored in the moist room until they were used for either triaxial or consolidation tests.

B. TRIAXIAL COMPRESSION TEST

The strength parameters C and ϕ are important in many analyses and can be obtained relatively easily and quickly by using unconsolidated, undrained triaxial compression tests. Therefore, these tests were used in this study.

The triaxial samples tested in the undrained unconsolidated state were prepared by simultaneously pressing three 1.4 inch diameter (0.07 inch wall thickness), brass cutting tubes into the top of a specimen. The soil sample was extruded from the cutting tube by forcing a 1.360 inch diameter piston through the cutting tube.

Cutting tubes were used as opposed to cutting the samples with a wire saw because at the lower moisture contents crumbling became a problem if a wire saw was used. By employing greased cutting tubes, three samples could be obtained simultaneously from one Proctor mould in a relatively short period of time, thereby reducing any possible moisture loss. Trimming by means of a wire saw could introduce the possibility of the samples losing moisture during this process. Immediately after extrusion from the cutting tubes, the samples were wrapped in Saran Wrap, waxed and stored in a moist room for not less than 5 days to allow dissipation of stresses possibly brought about by the compaction and extrusion processes.

The cutting tubes were 4 inches in length, resulting in all three lifts initially being part of the triaxial sample. The final lengths of the samples were 2.80 inches \pm 0.050 inches. There are two reasons for choosing a length of 2.80 inches. Firstly, it is generally recognized that the length to diameter ratio (L/D ratio) affects the strength characteristics of a triaxial sample since long samples, that is, samples with a large L/D ratio, may fail by buckling. In view of the buckling

phenomena, Bishop and Henkel¹³ state that a range of L/D ratios of 1.5 to 2.5 is usually satisfactory to minimize the buckling effect. Therefore, triaxial samples used in this testing program had L/D ratios of approximately 2:1 $\frac{(2.8 \text{ inches})}{(1.4 \text{ inches})}$ which is within the stated range of L/D ratios to minimize the possibility of failure by buckling. The second reason for choosing a sample length of 2.80 inches is related to the densities of the individual lifts. It was found that the average density of the top and center lifts was closer to the average density of the Proctor sample than was the average density of center and bottom lifts. Therefore, the four inch cutting tubes were forced completely through the top and center lifts and partially penetrated the bottom lift giving a sample initially about 4 inches in length. Immediately prior to a sample being tested, 0.5 inches of soil was trimmed from the top lift and 0.7 inches trimmed from the bottom lift, resulting in a specimen approximately 2.80 inches in length. Such a specimen was composed of approximately 90 percent soil from the top and center lifts and 10 percent soil from the bottom lift, which resulted in a density best approximating the average Proctor sample density.

After the soil sample had been trimmed to length, its dimensions and weight were recorded. The sample was then placed on the base pedestal of a triaxial cell. It should be noted that a nonporous metal spacer separated the soil sample from the pedestal. The spacer was used to eliminate the possibility of soil being forced into the drainage grooves in the pedestal, thus fouling the cell. Also, without the use of the spacer, the sample could be considered to be partially drained and partially consolidated by the fact that air in the drainage paths could be compressed by air or water escaping from the sample upon application of sufficient deviator stress. The triaxial sample was then covered with two greased membranes. The second membrane was employed because of the crumbly nature of the samples. A single membrane could be

easily punctured by a particle of soil during testing. The membranes were held securely against the cap and pedestal by means of rubber O rings and elastic bands. The triaxial cell was fitted on the base, and the loading piston was then brought into contact with loading cap and ball. The entire triaxial cell was then placed in a loading frame.

The loading frame was a Leonard and Farnell variable strain rate hydraulic drive unit. It was noted that this unit did not provide a constant rate of strain, but rather a rate of strain which increased with time. To ensure that every sample tested was examined at approximately the same strain rate, the initial rate of strain was the same for each sample. This initial strain was 0.167×10^{-4} inches/second. The average strain rate was found to be $.481 \times 10^{-3}$ inches/second. It was important that the loading yoke was brought into contact with the piston and the test started as soon as possible after the initial strain rate was established. Load dial readings were taken at strain increments of 0.01 inches until the load dial readings peaked and then decreased in magnitude. If the load dial readings did not peak but increased at a decreasing rate of increase, the test was continued until the percent strain reached approximately 26 percent (0.72 inches).

Samples were tested at different confining pressures of 0, 15, 30, 45, 60 PSI. The samples tested at zero cell pressure (unconfined) did not require rubber membranes, and these were omitted.

The desired cell pressure was maintained by the use of compressed air. Since the samples were tested in an undrained condition, the duration of the test was in the order of 10 to 20 minutes, depending upon the cell pressure and type of sample, (standard or modified compactive effort).

Both unfrozen samples and samples that had been subjected to one freeze-thaw cycle were prepared and tested in the manner previously described. The method of freezing the triaxial samples was the same as that described in Section B of this chapter with one exception. The individually prepared triaxial samples were frozen, not the entire Proctor mould as was the case with the samples frozen for the one dimensional consolidation test.

C. CONSOLIDATION TEST

The purpose of performing consolidation tests was to provide a means by which to detect changes in a compacted clay caused by freezing. The changes caused by the freezing and subsequent thawing will be reflected in such parameters as coefficient of permeability, coefficient of compressibility and coefficient of consolidation, etc. These parameters are suitable only for comparison purposes because one of the governing assumptions for consolidation theory as derived by Terzaghi¹⁴, was violated. This was the assumption that the porous media (the compacted clay) must be fully saturated.

The following sample preparation procedure was followed for the consolidation test on unfrozen samples.

After having a sample compacted to the desired moulding water content and dry density, the center lift of the mould was cut out and 0.2 to 0.3 inches of soil trimmed from both the top and bottom of the lift. The purpose of trimming the lift was explained in Part A of this chapter. The selection of the center lift of the Proctor mould resulted from the finding that the bottom, center and top lifts did not generally have the same densities. The center lift was found to have a density less than the bottom lift and more than the top lift. A second reason for choosing the center lift is that it is bounded on both faces by a

soil-soil interface as opposed to the bottom lift which has one soil-soil interface and one soil-air interface after extrusion from the Proctor mould; or one soil-soil interface and one soil-metal interface during the compaction process. Similarly the top lift has one soil-soil interface and one soil-air interface. It should also be noted here that the top lift of each mould was subjected to a form of remoulding that neither the center or bottom lifts were subjected to; namely the trimming of approximately 1/8 inch of soil from the top of the lift prior to extrusion from the Proctor mould. For these reasons it was decided to use the center lift of any appropriate Proctor mould for use in the one dimensional consolidation tests because the author believed that the center lift had been subjected to the most uniform compaction process.

Following the preliminary trimming of the center lift, a lightly greased cutting ring was centered on the lift and the lift circumferentially wrapped with masking tape. The purpose of wrapping the lift with tape was to provide lateral restraint for the soil so it would not tend to crumble in front of the advancing edge of the cutting ring. If the sample were allowed to crumble, it was found that large air voids were created adjacent to the inside edge of the cutting ring. Although these air voids could be "patched" with soil from the trimmings, patching could be affected only on the surface of the consolidation sample and large voids would still exist along the sides of the sample. The existence of these air voids due to crumbling would give rise to erroneous subsequent calculations such as initial wet density and initial void ratio. Crumbling was found to be most prevalent in samples compacted dry of optimum, particularly in the modified sample compacted 4 percent dry of optimum.

The top of the cutting ring was covered by a circular metal plate and the ring was slowly advanced to its full height into the soil by means of a mechanical piston pushing on the cover plate. Soil was then trimmed from the top and bottom of the cutting ring to facilitate seating of the porous stones. The above noted trimming process resulted in a sample that had both top and bottom faces trimmed and therefore both faces exposed to the same remoulding process brought about by the trimming. The ring and wet soil were then placed immediately over a saturated porous stone which was centered in a consolidation dish. The top of the sample was fitted with a porous loading cap and steel ball. This resulted in the soil sample being drained from both top and bottom. A strain dial (0.001 inch divisions) was attached to the consolidation dish via a loading yoke and set to some initial reading on the frame.

A load of 0.5 lb. (0.083 tons/ft^2) was then applied through a lever system to the sample by means of a weight placed on the hanger. After 2 minutes from the time the weight was put on the hanger, distilled water was added to the dish in sufficient quantity to only partially submerge the sample. The distilled water used to partially submerge the sample came from the same source as the distilled water used to obtain the moulding water content. After the sample had completed the swelling process, which occurred after the partial submergence, it was completely submerged with distilled water. Pressures of 0.154, 0.297, 0.574, 1.156, 2.302, 4.593, 0.574 ton/ft^2 were then subsequently applied. Since different loading frames, with different lever arm factors were employed, varying pan loads (hanger weights) were used to obtain the above mentioned pressures. After the application of the first pan load, subsequent pan loads were twice the previous pan load.

Subsequent pressures were applied only after the sample had reached 100 percent consolidation under the previous pressure. The condition of 100 percent consolidation was ascertained from the usual plots of strain dial readings versus time as detailed in Leonards Foundation Engineering⁷. Strain dial readings were taken at the following intervals after the application of any one pressure, 15, 30, 60 seconds, 2, 4, 8, 15, 30, 60, minutes 2, 4, 8, 24 hours and then once per day until the sample reached 100 percent consolidation.

After consolidation had been completed under the final pressure the soil sample was removed from the consolidation ring and oven dried. Following removal from the drying oven, the ring and dry soil were weighed. Having the necessary weights and measures, and the time for 50 percent consolidation as calculated using the Casagrande logarithm of time method based on plots of strain dial readings versus log of time as detailed in Leonards Foundation Engineering⁷, the following consolidation characteristics (as customarily defined) were evaluated for the various moulding water contents and corresponding dry densities: void ratio, coefficient of consolidation, coefficient of compressibility, coefficient of permeability and preconsolidation pressure.

Sample preparation for the samples tested after one freeze-thaw cycle was identical to the procedure used for the unfrozen samples. The method of freezing the samples was to suspend the entire waxed Proctor mould sample in a burlap sling in a conventional freezer for a period of 24 hours. The purpose of the burlap sling was to ensure circulation of air around the mould and therefore guarantee three dimensional freezing. The temperature in the freezer was +6^oF. After the 24 hour freezing period, the frozen moulds were allowed to thaw.

Three dimensional freezing, that is all around freezing as compared to uniaxial freezing, in a closed system was employed for the following reasons. Three dimensional freezing was the simplest form of freezing and the most expedient to use in this study. If uniaxial freezing were used in either an open or a closed system, moisture redistribution would affect the results. Since the purpose of this paper was to explore the effect of freezing on a compacted clay, not the effect of moisture redistribution and subsequent freezing, uniaxial freezing was not appropriate as a method of freezing the samples.

CHAPTER IV

OBSERVATIONS AND RESULTS

In the following text, the results of the one dimensional consolidation tests and the undrained triaxial compression tests are examined and pertinent observations made regarding the strength and compressibility characteristics of the compacted soil under investigation.

Due to the large number of one dimensional consolidation tests and undrained triaxial compression tests, the author has, in some instances, presented a typical example of a particular relationship or characteristic being examined, and the change in this property due to one freeze-thaw cycle. If certain properties were studied for each individual test, the time required to compile representative diagrams and tables would prove prohibitive.

The reader should note that the term "frozen sample", when used in this transcript, refers to a soil sample that has been subjected to one freeze-thaw cycle and not to a sample in the frozen state.

A. GENERAL

The dry density moulding moisture content curves for the two different compactive efforts are shown in Figures 2 and 3. These curves were determined by running a series of compaction tests. Utilizing the optimum moisture contents obtained from the two sets of compaction tests, the moisture contents at 2 and 4 percent wet and dry of optimum were determined and plotted as shown in Figures 2 and 3. Figure 2 shows that the soil, when compacted to standard Proctor compactive effort, has a maximum dry density of 86.9 lb/ft^3 at an optimum moisture content of 29.6 percent. Figure 3 demonstrates that the same soil when compacted

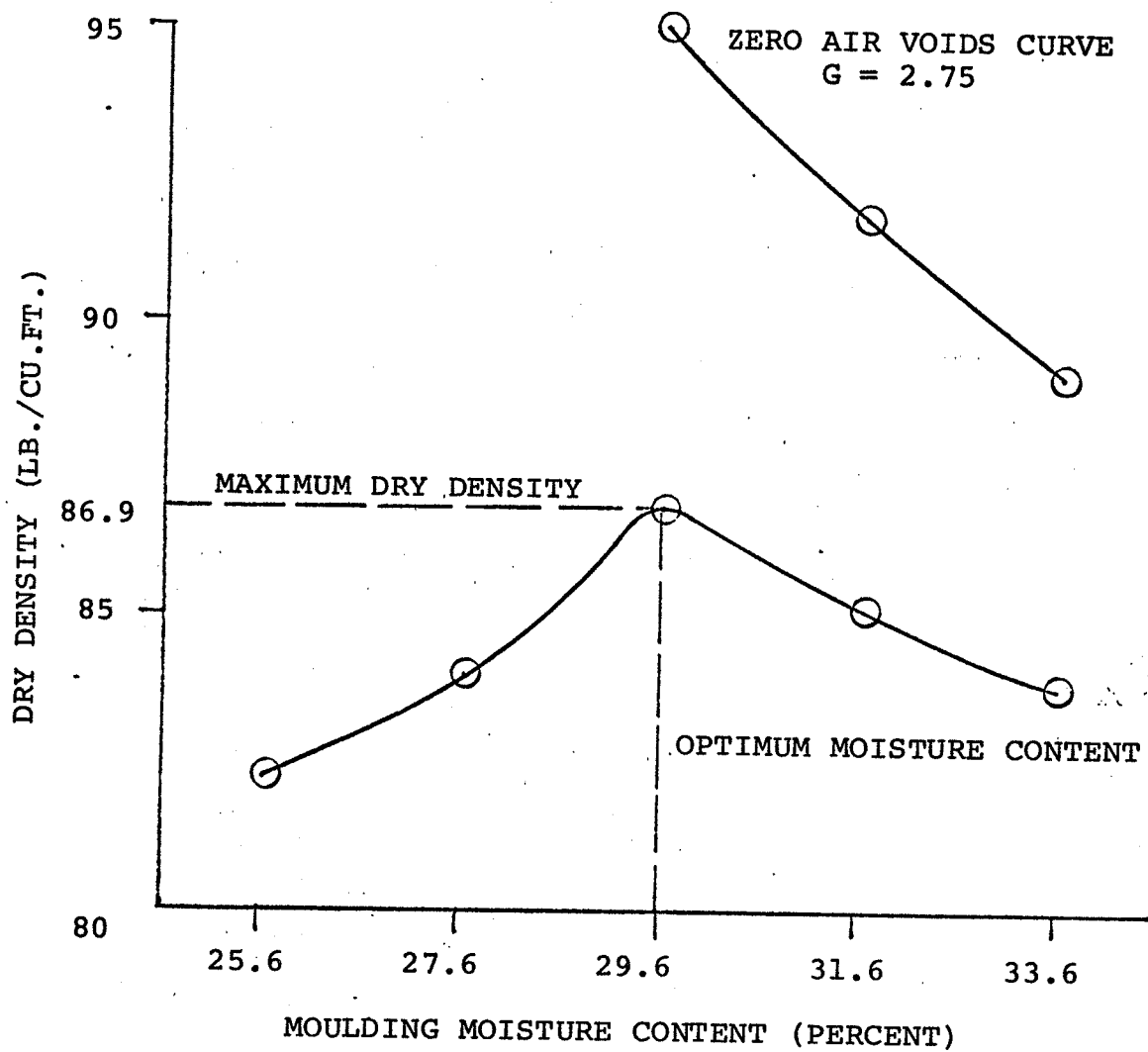


FIGURE 2
DRY DENSITY-MOULDING MOISTURE RELATIONSHIP FOR
SAMPLES COMPACTED TO STANDARD PROCTOR COMPACT-
IVE EFFORT.

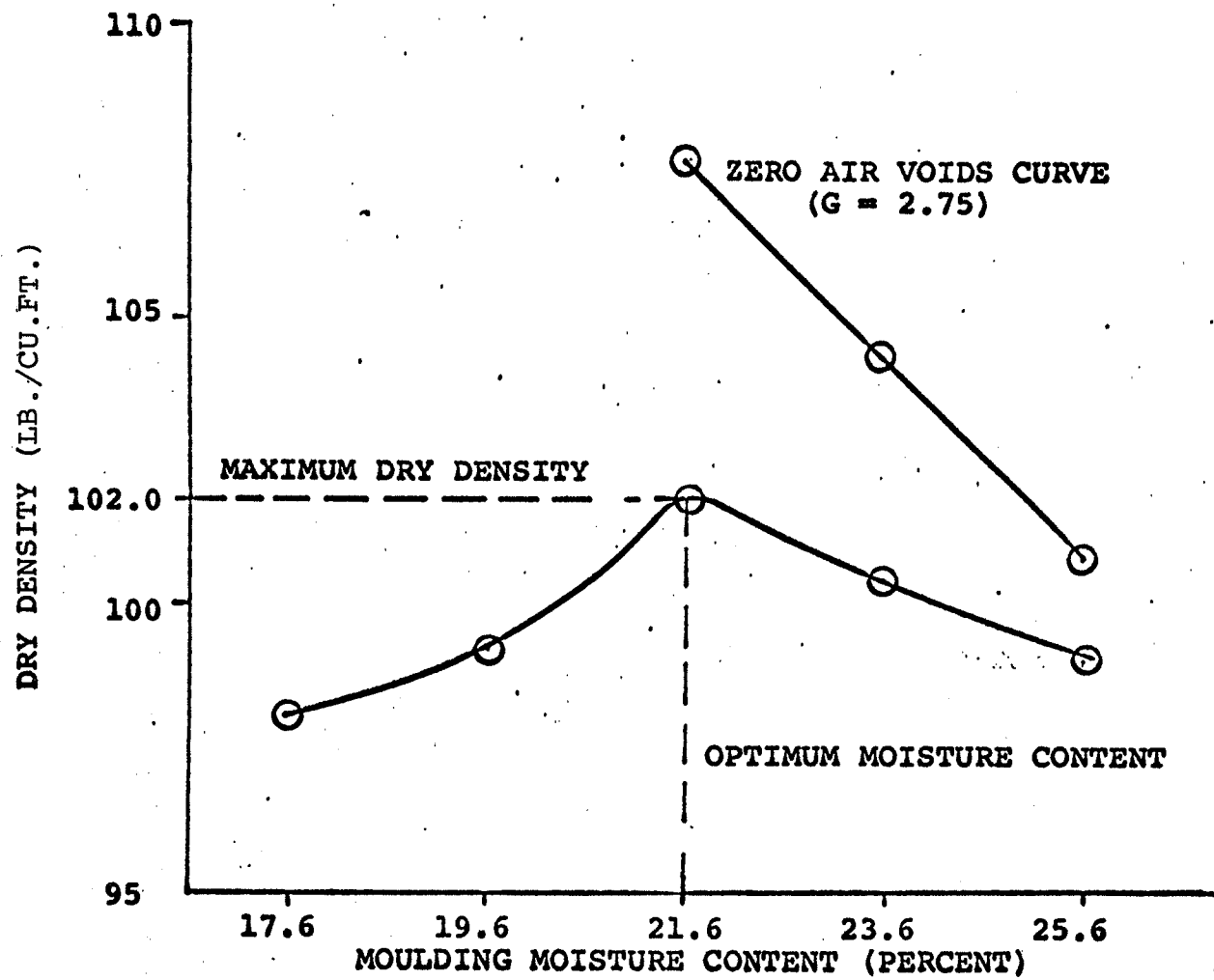


FIGURE 3
DRY DENSITY-MOULDING MOISTURE RELATIONSHIP FOR
SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACT-
IVE EFFORT.

to modified Proctor compactive effort attains a maximum dry density of 102.0 lb/ft³ at an optimum moisture content of 21.6 percent.

B. TRIAXIAL COMPRESSION TESTS

The results of the undrained triaxial compression tests and comments regarding the effect of one freeze-thaw cycle on certain soil properties related to triaxial compression tests are presented in the following discussion.

Mohr-Coulomb envelopes were constructed for each series of frozen and unfrozen, undrained triaxial compression tests for samples at varying moulding moisture contents compacted to standard and modified Proctor compactive efforts. The above noted Mohr-Coulomb envelopes are shown in Figures 4 through 13.

A summary of strength parameters C and ϕ for samples compacted to standard and modified Proctor efforts is presented in Tables I and II.

The symbol ϕ signifies the angle of internal friction. The symbol C denotes the shear stress intercept.

Plots of cohesion versus moulding moisture content for unfrozen samples and samples subjected to one freeze-thaw cycle, compacted to standard Proctor compactive effort at varying moulding moisture contents are shown in Figure 14A. The points plotted in Figure 14A are cohesion values originating from the best-fit tangent lines utilized in the construction of the respective Mohr-Coulomb envelopes, Figures 4 through 13. The decrease in the unfrozen cohesion due to one freeze-thaw cycle was plotted and is presented in Figure 14B.

Figure 14A indicates that the freezing and thawing process induced a decrease in the cohesion of unfrozen samples throughout the range of moulding moisture contents that were examined. It should also be noted that the cohesion for unfrozen and frozen samples decreased with increasing moulding moisture content.

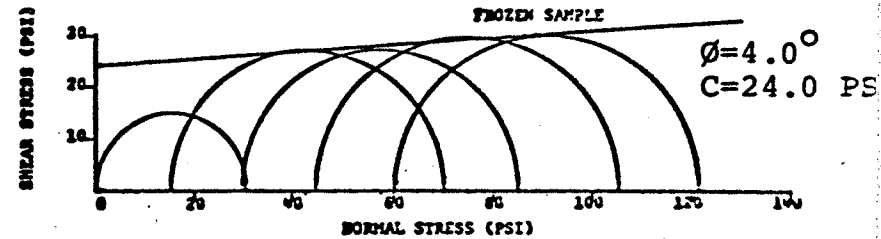
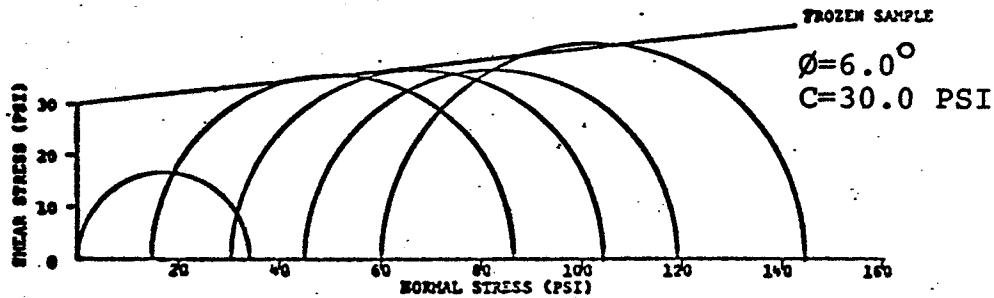
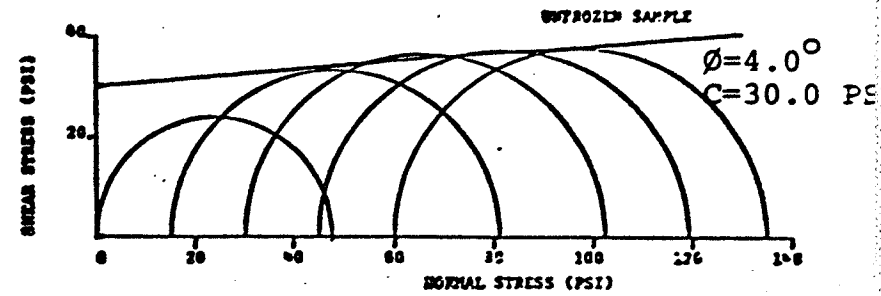
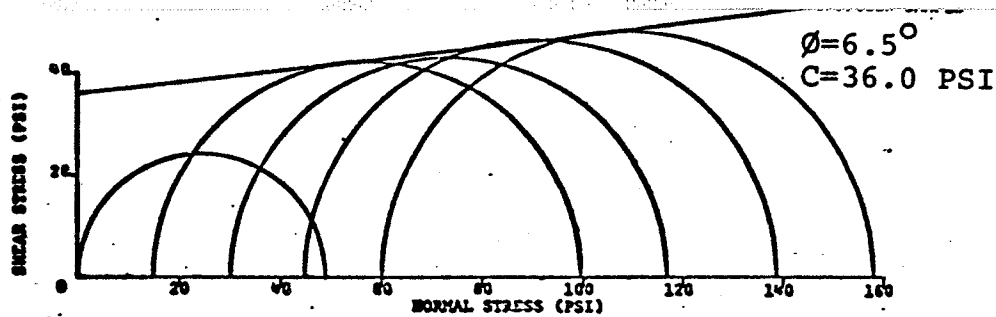


FIGURE 4

MOHR COULOMB ENVELOPES FOR SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT AT 4 PERCENT DRY OF OPTIMUM.

FIGURE 5

MOHR COULOMB ENVELOPES FOR SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT AT 2 PERCENT DRY OF OPTIMUM.

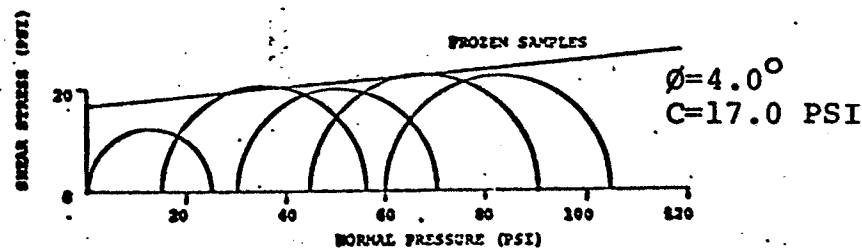
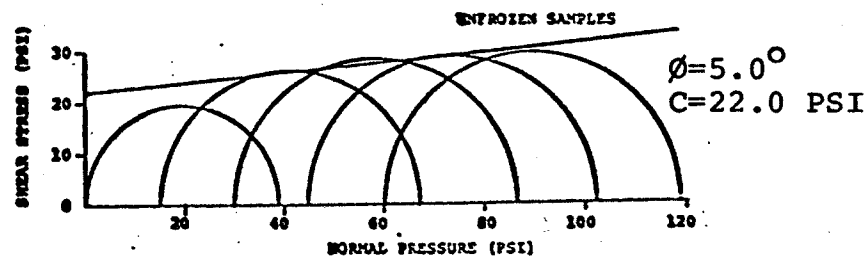


FIGURE 6

MOHR COULOMB ENVELOPES FOR SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT AT OPTIMUM MOISTURE CONTENT.

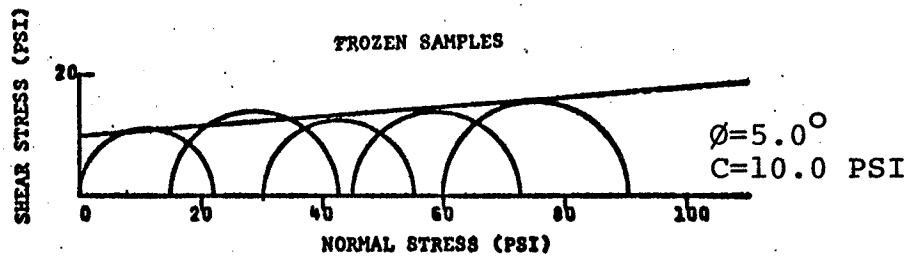
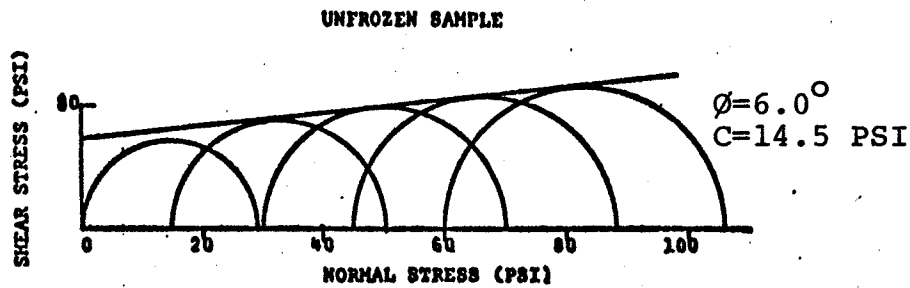


FIGURE 7
MOHR COULOMB ENVELOPES FOR SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT AT 2 PERCENT WET OF OPTIMUM.

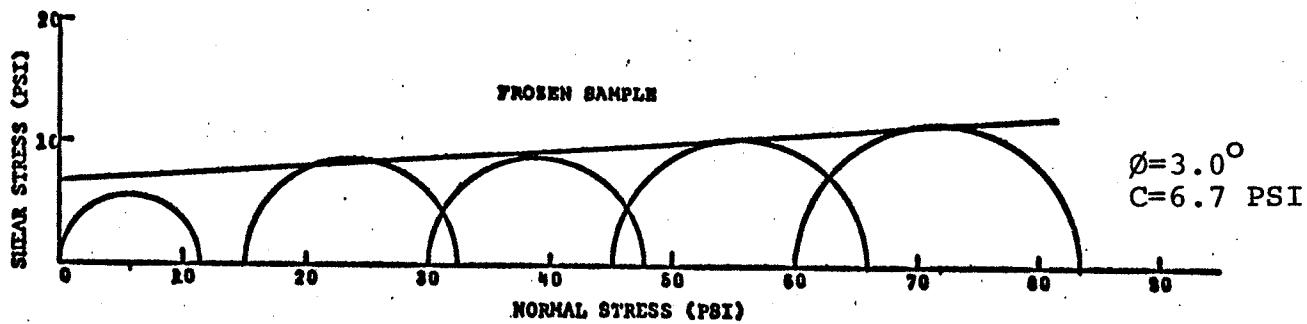
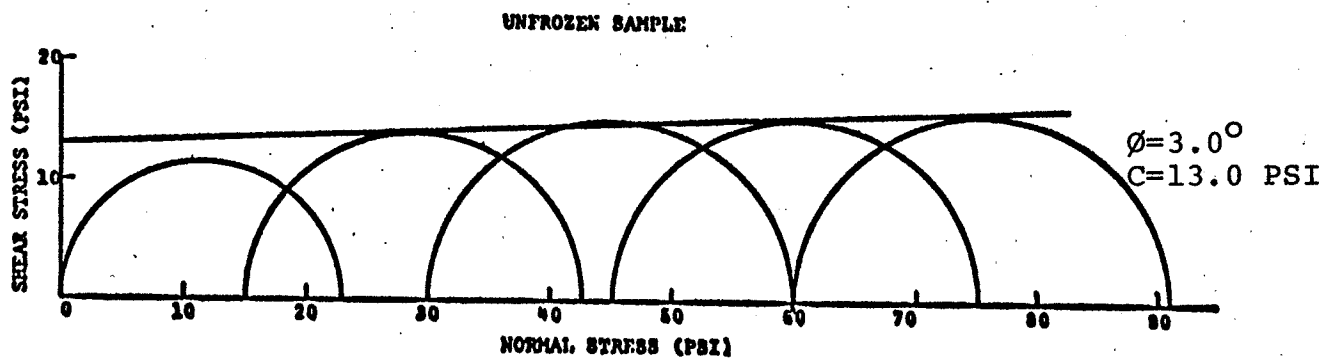


FIGURE 8
MOHR COULOMB ENVELOPES FOR SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT AT 4 PERCENT WET OF OPTIMUM.

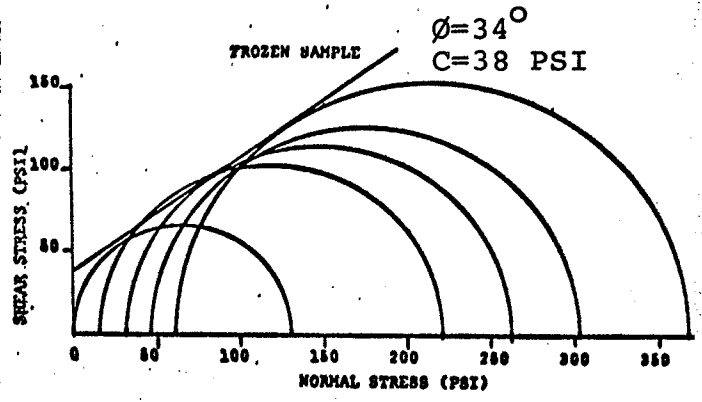
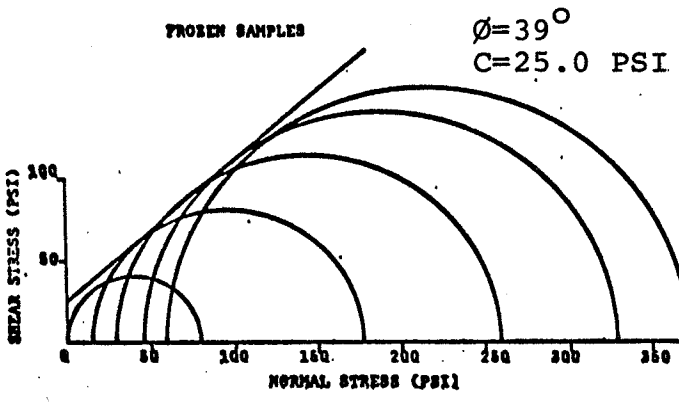
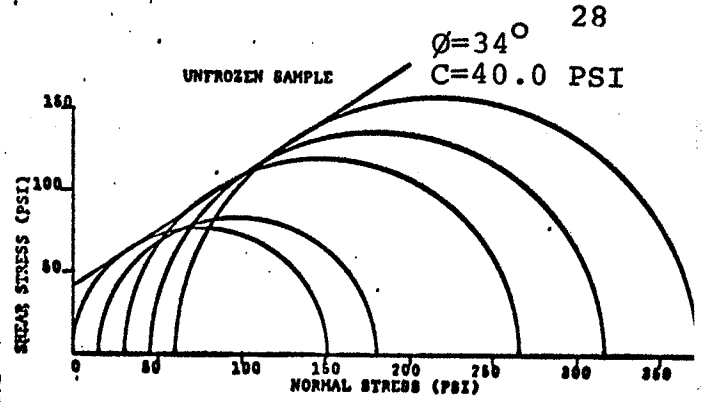
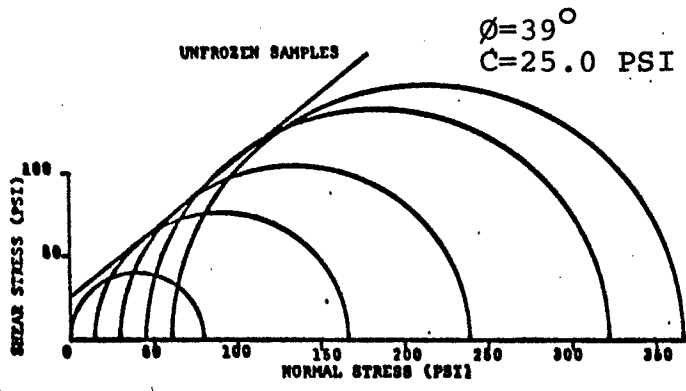


FIGURE 9
 MOHR COULOMB ENVELOPES FOR SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT AT 4 PERCENT DRY OF OPTIMUM

FIGURE 10
 MOHR COULOMB ENVELOPES FOR SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT AT 2 PERCENT DRY OF OPTIMUM.

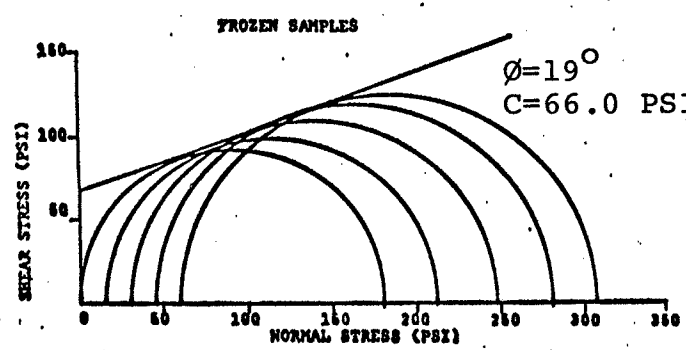
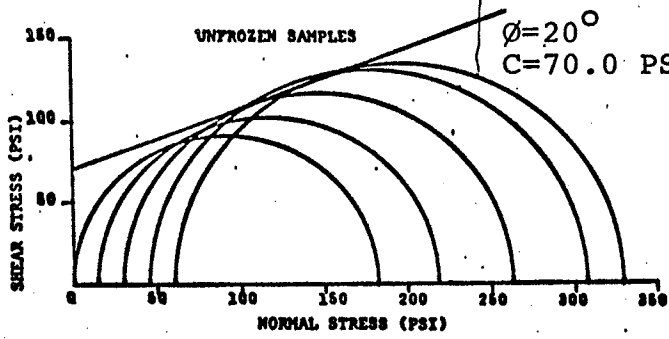


FIGURE 11
 MOHR COULOMB ENVELOPES FOR SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT AT OPTIMUM MOISTURE CONTENT.

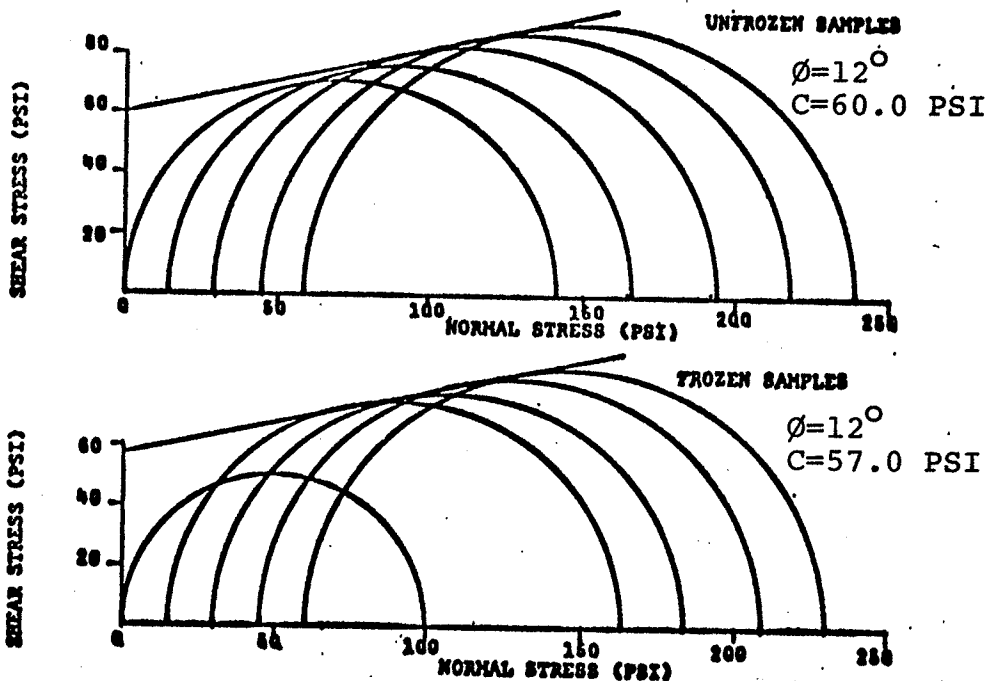


FIGURE 12
 MOHR COULOMB ENVELOPES FOR SAMPLES COM-
 PACTED TO MODIFIED PROCTOR COMPACTIVE
 EFFORT AT 2 PERCENT WET OF OPTIMUM.

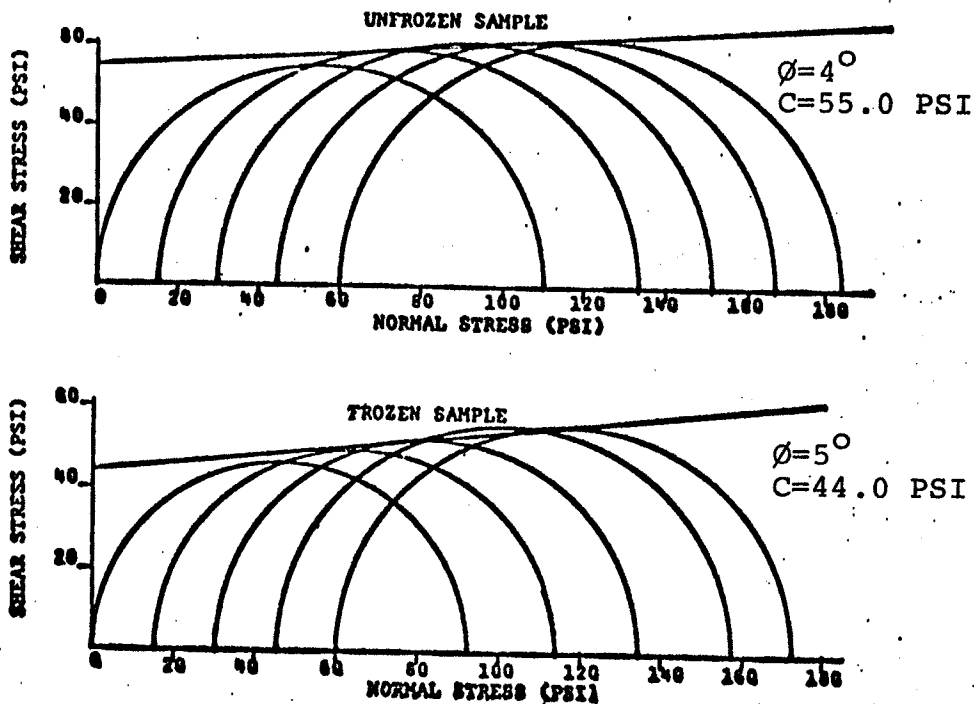


FIGURE 13
 MOHR COULOMB ENVELOPES FOR SAMPLES COM-
 PACTED TO MODIFIED PROCTOR COMPACTIVE
 EFFORT AT 4 PERCENT WET OF OPTIMUM.

TABLE I
SUMMARY OF STRENGTH PARAMETERS C AND ϕ FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

PARAMETER	MOULDING MOISTURE CONTENT (PERCENT DRY OR WET OF OPTIMUM)				
	4% DRY	2% DRY	OPTIMUM	2% WET	4% WET
ϕ° UNFROZEN	6.5	4.0	5.0	6.0	3.0
ϕ° FROZEN	6.0	4.0	4.0	5.0	3.0
C PSI UNFROZEN	36.0	30.0	22.0	14.5	13.0
C PSI FROZEN	30.0	24.0	17.0	10.0	6.7

TABLE II
SUMMARY OF STRENGTH PARAMETERS C AND ϕ FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

PARAMETER	MOULDING MOISTURE CONTENT (PERCENT DRY OR WET OF OPTIMUM)				
	4% DRY	2% DRY	OPTIMUM	2% WET	4% WET
ϕ° UNFROZEN	39.0	34.0	20.0	12.0	4.0
ϕ° FROZEN	39.0	34.0	19.0	12.0	5.0
C PSI UNFROZEN	25.0	40.0	70.0	60.0	55.0
C PSI FROZEN	25.0	38.0	66.0	57.0	44.0

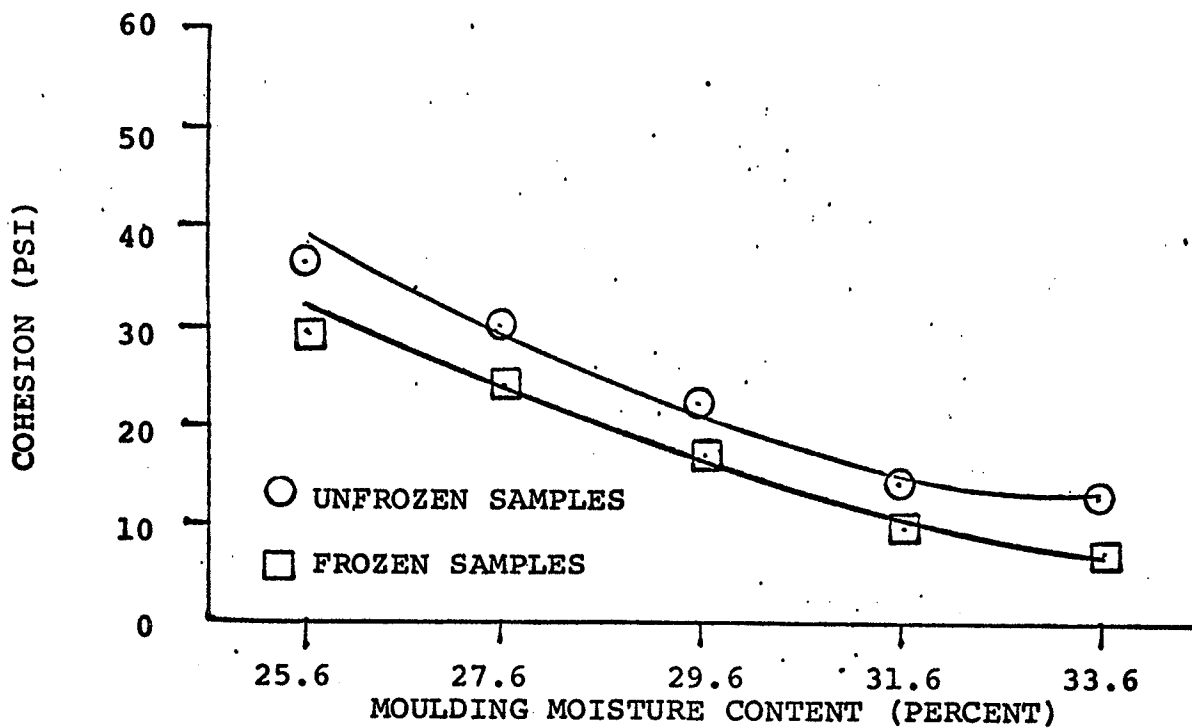


FIGURE 14A

COHESION VERSUS MOULDING MOISTURE CONTENT FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

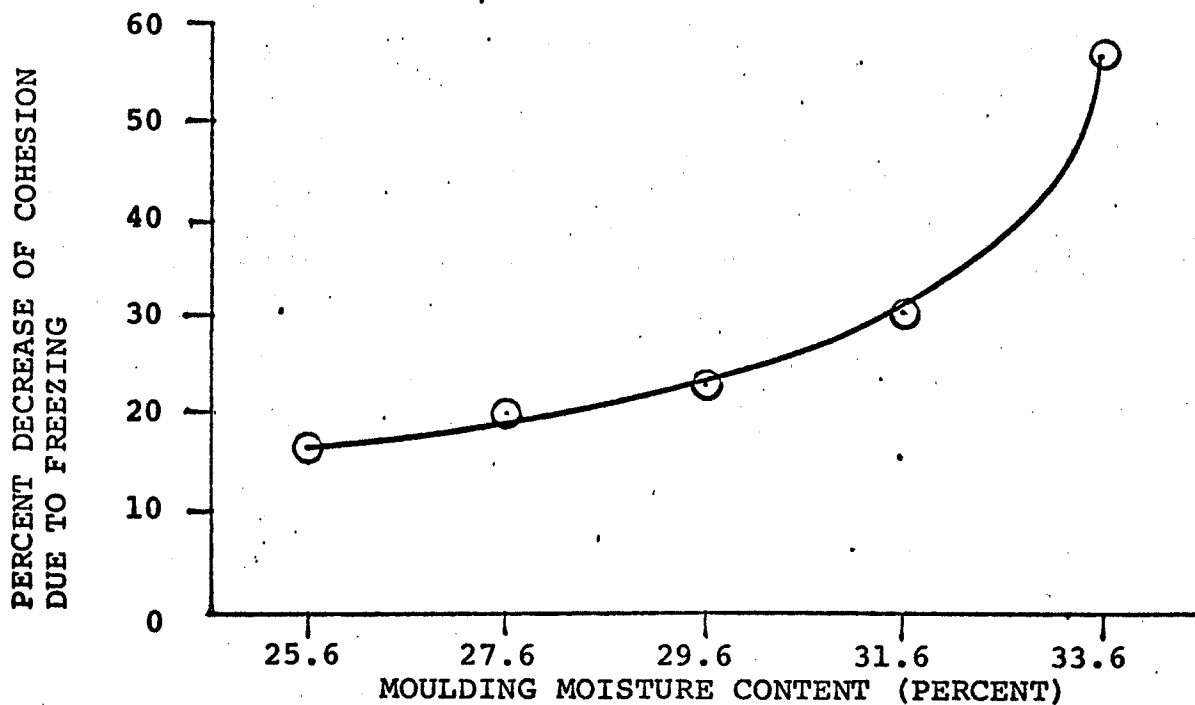


FIGURE 14B

PERCENT DECREASE OF COHESION DUE TO FREEZING VERSUS MOULDING MOISTURE CONTENT FOR SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

Figure 14B shows that the percent decrease in cohesion due to one freeze-thaw cycle increases with increasing moulding moisture content. The percent decrease in cohesion was based on the cohesion decrease divided by the unfrozen value of the cohesion.

Similar plots for unfrozen and frozen samples at varying moulding moisture contents compacted to modified Proctor compactive effort are presented in Figures 15A and 15B.

Figure 15A demonstrates that the cohesion for unfrozen samples and samples exposed to one freeze-thaw cycle reach a maximum value near the optimum moisture content and then decrease on the wet and dry side of optimum. The decrease in cohesion, from the maximum value at the optimum moisture content, is greatest for samples compacted on the dry side of optimum. Figure 15B shows that the percent decrease in the unfrozen cohesion is zero at 4 percent dry of optimum, approximately 5 percent for samples at 2 percent dry of optimum, optimum, 2 percent wet of optimum, and 20 percent for samples at 4 percent wet of optimum. The percent decrease in the unfrozen cohesion was calculated as previously detailed for samples compacted to standard Proctor compactive effort.

A plot of the relationship between the angle of internal friction and the moulding moisture content for unfrozen and frozen samples at varying moulding moisture contents compacted to standard Proctor effort was drawn and is presented as shown in Figure 16. Although there is some scatter apparent in Figure 16 it may be said that the change in the angle of internal friction due to one freeze-thaw cycle is negligible for any given moisture content.

A similar plot was constructed for frozen and unfrozen samples at varying moulding moisture contents compacted to modified Proctor

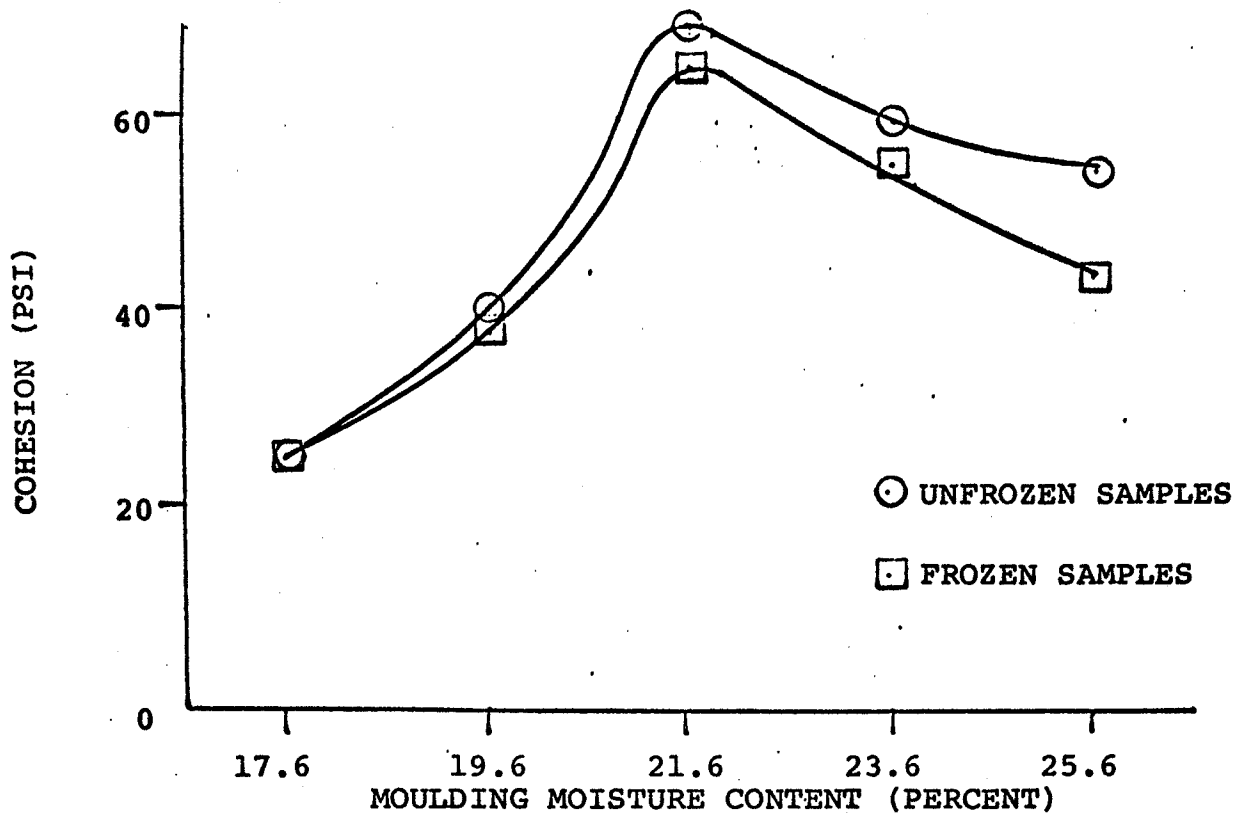


FIGURE 15A
COHESION VERSUS MOULDING MOISTURE CONTENT FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

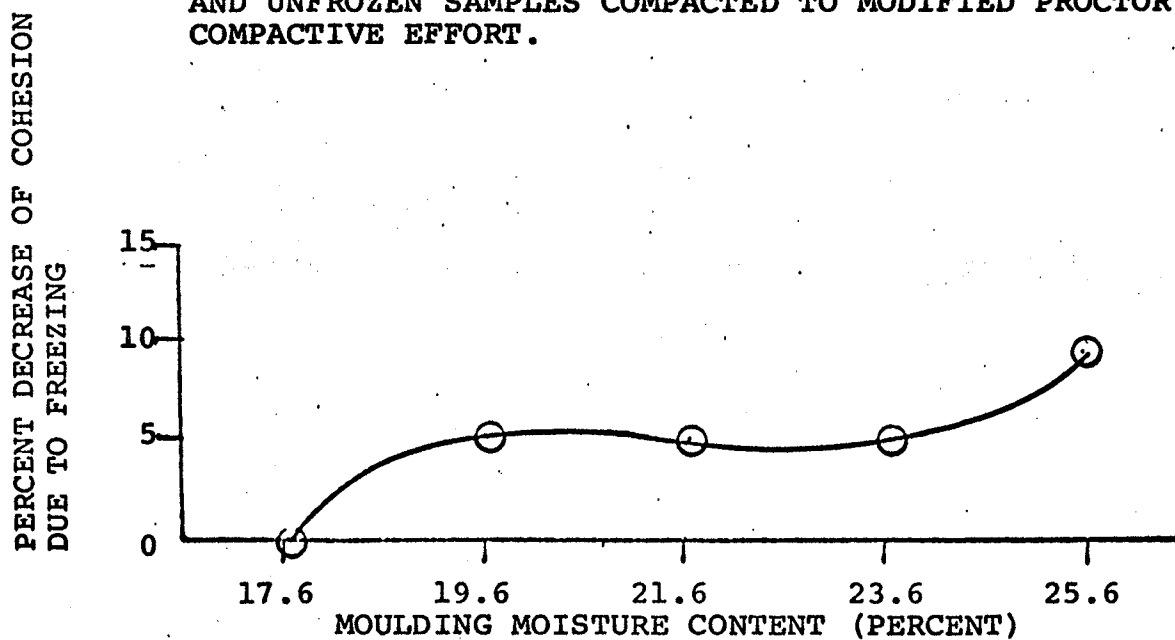


FIGURE 15B
PERCENT DECREASE OF COHESION DUE TO FREEZING VERSUS MOULDING MOISTURE CONTENT FOR SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

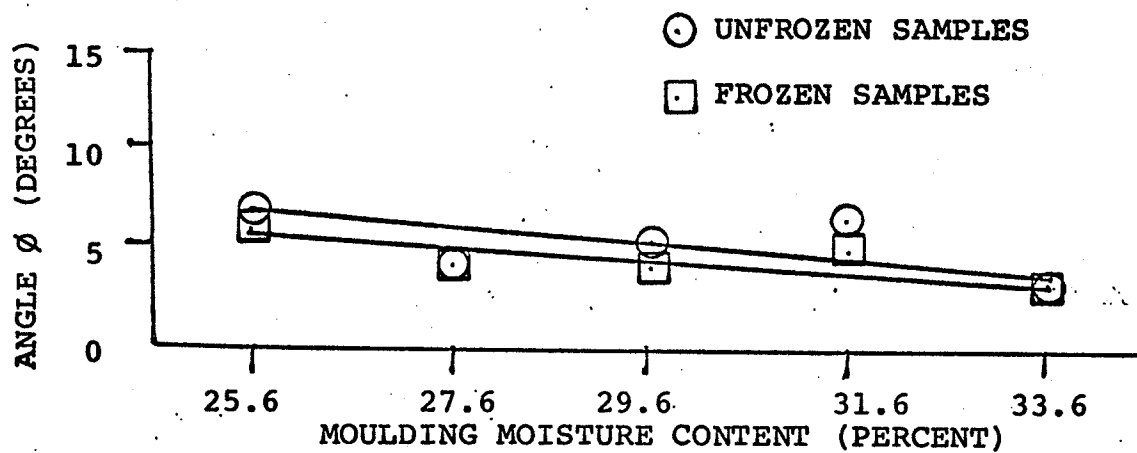


FIGURE 16
ANGLE OF INTERNAL FRICTION ϕ VERSUS MOULDING MOISTURE CONTENT FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

compactive effort and is shown in Figure 17. From Figure 17, we may conclude that the change in the angle of internal friction due to one freeze-thaw cycle is negligible for any given moisture content.

The above discussion indicates that the strength parameters C and ϕ for samples compacted to two different compactive efforts are affected by one freeze-thaw cycle in a closed system. The effect of a freeze-thaw cycle on the strength parameter C was readily detectable, however, the effect of freezing on ϕ appears to be negligible.

The unconfined compressive strength of a soil sample is of particular interest because this figure is often used as a design criteria. For this reason, the relationship between the unconfined compressive strength and the moulding moisture content for samples compacted to both Proctor efforts was examined.

Figure 18A shows the relationship between the unconfined compressive strengths and the corresponding moulding moisture contents for frozen and unfrozen samples compacted to standard Proctor compactive effort. Figure 18A demonstrates that the unconfined compressive strengths for unfrozen samples and samples exposed to one freeze-thaw cycle decrease with increasing moulding moisture content.

Figure 18B demonstrates that the percent decrease in the unconfined compressive strengths due to one freeze-thaw cycle reaches a maximum between the moulding moisture contents of 2 percent dry of optimum, and optimum, for samples compacted to standard Proctor compactive effort. Similar plots were constructed for samples compacted to modified Proctor compactive effort and are presented in Figures 19A and 19B.

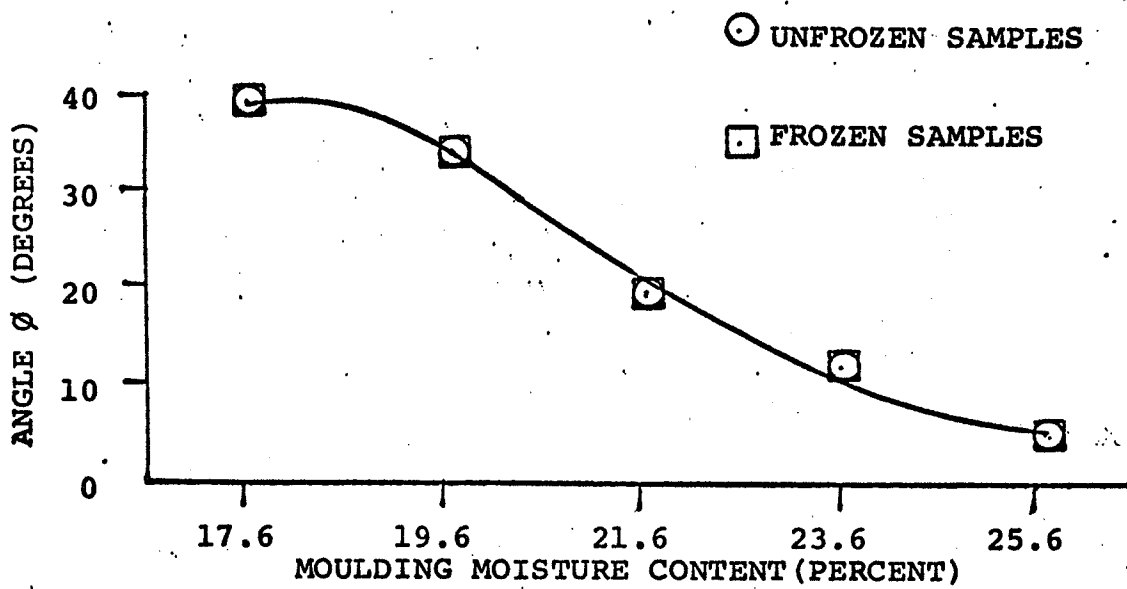


FIGURE 17
ANGLE OF INTERNAL FRICTION ϕ VERSUS MOULDING MOISTURE CONTENT FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

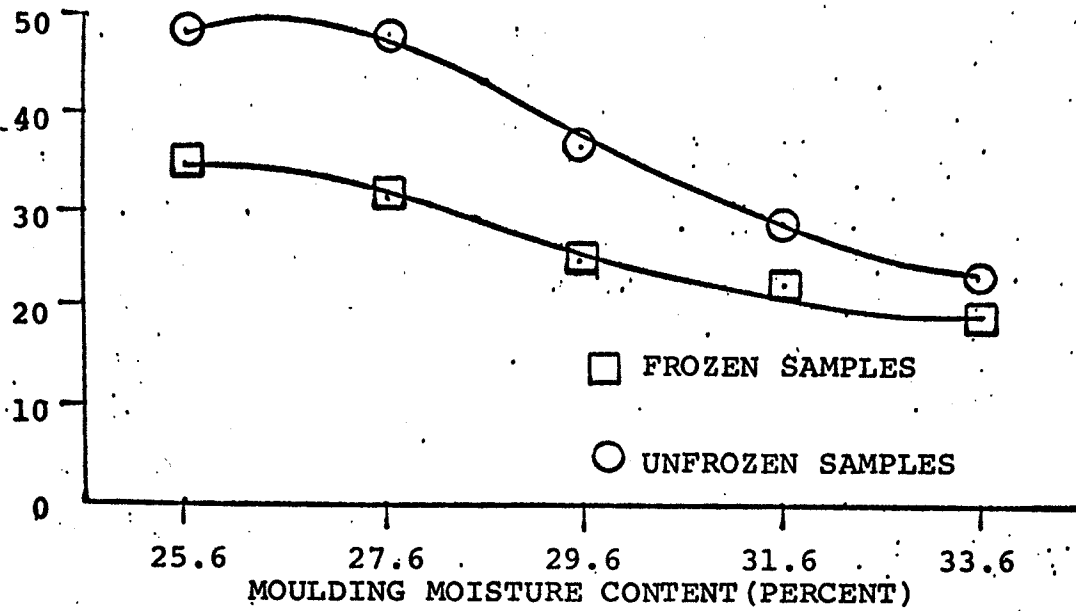
UNCONFINED COMPRESSIVE STRENGTH
(PSI)

FIGURE 18A

UNCONFINED COMPRESSIVE STRENGTH VERSUS MOULDING
MOISTURE CONTENT FOR FROZEN AND UNFROZEN SAMPLES
COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

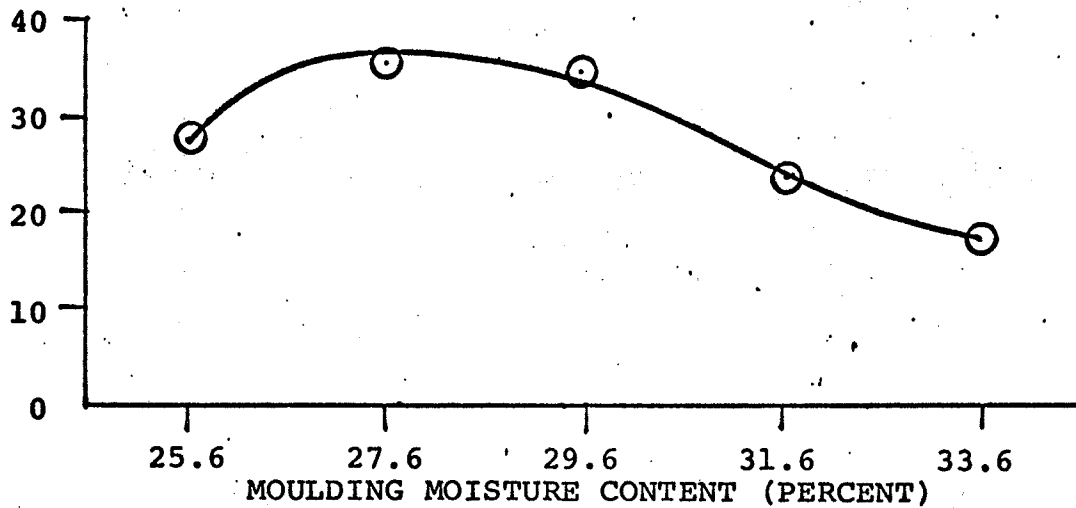
PERCENT DECREASE IN
UNCONFINED COMPRESSIVE STRENGTH

FIGURE 18B

PERCENT DECREASE IN UNCONFINED COMPRESSIVE STRENGTH
DUE TO FREEZING, VERSUS MOULDING MOISTURE CONTENT
FOR SAMPLES COMPACTED TO STANDARD PROCTOR COMPACT-
IVE EFFORT.

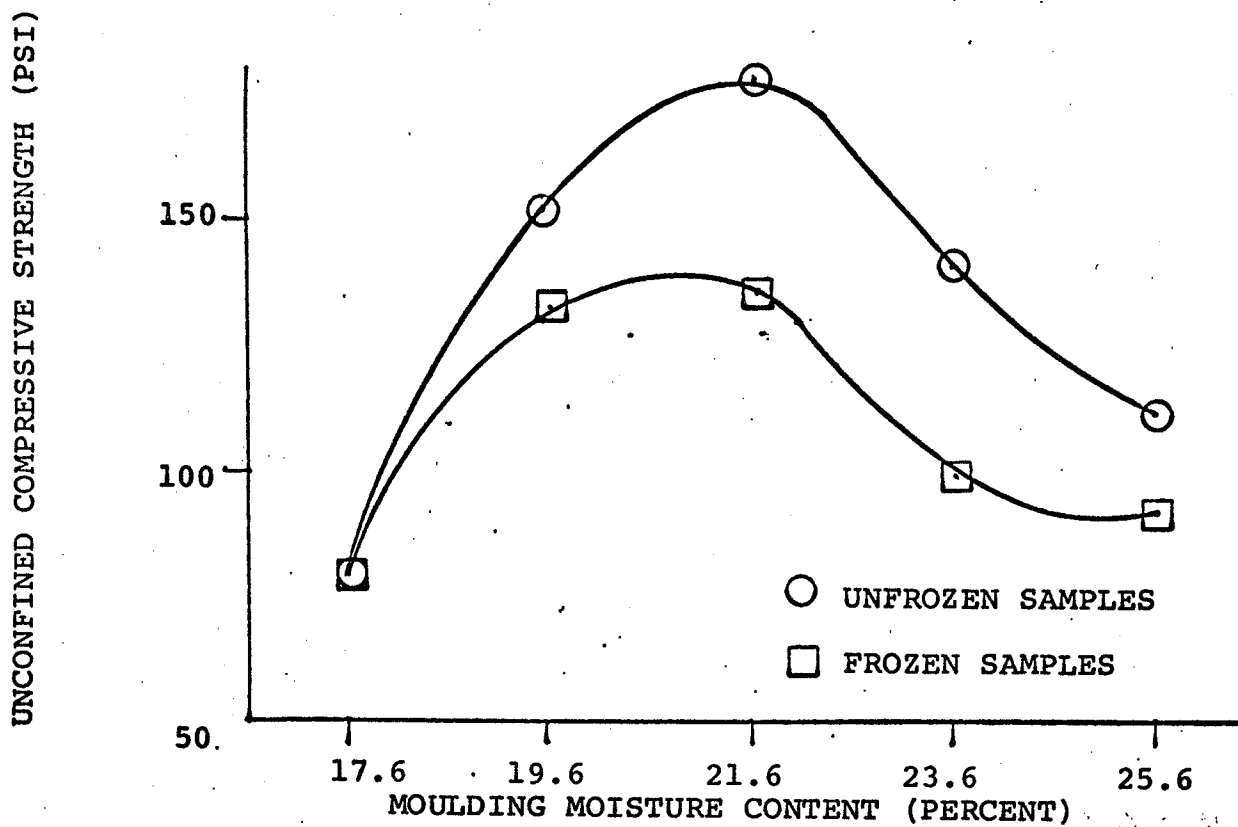


FIGURE 19A
UNCONFINED COMPRESSIVE STRENGTH VERSUS MOULDING
MOISTURE CONTENT FOR FROZEN AND UNFROZEN SAMPLES
COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

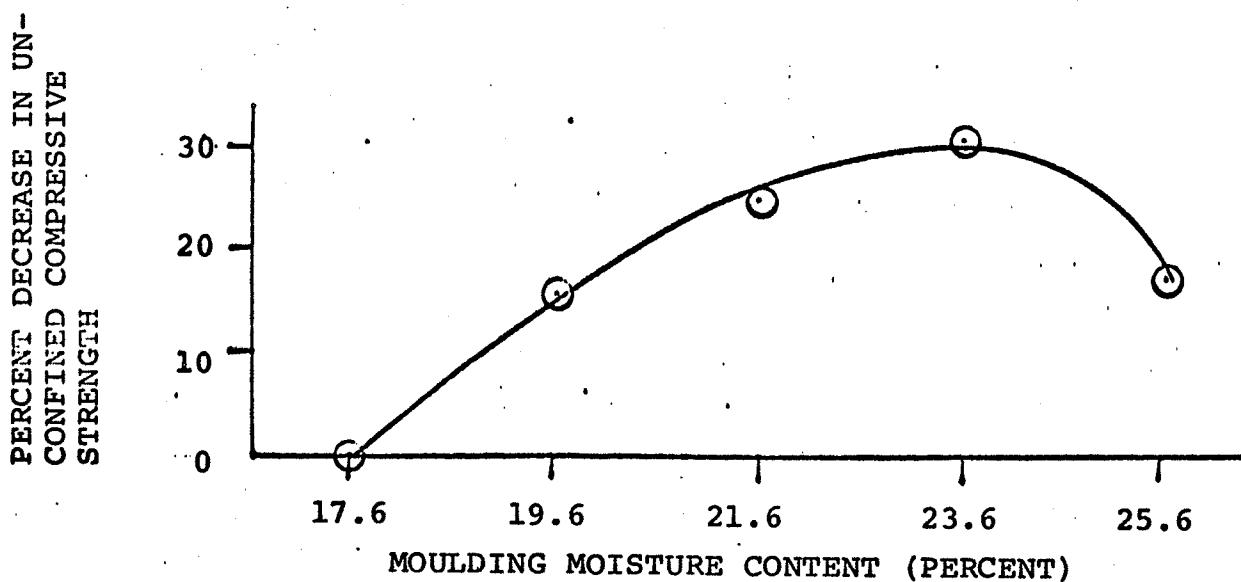


FIGURE 19B
PERCENT DECREASE IN UNCONFINED COMPRESSIVE STRENGTH
DUE TO FREEZING, VERSUS MOULDING MOISTURE CONTENT
FOR SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACT-
IVE EFFORT.

Based on Figure 19A, we may conclude that the unconfined compressive strength moulding moisture content relationship for frozen and unfrozen samples compacted to modified Proctor compactive effort is approximated by the shape of the usual dry density-moulding moisture content curve, with the peak occurring at the optimum moisture content.

Figure 19B sets forth the percent decrease in the unconfined compressive strengths, due to one freeze-thaw cycle, versus moulding moisture content for samples compacted to modified Proctor compactive effort. Figure 19B indicates the unconfined strength loss increases from 0 percent at 4 percent dry of optimum to a maximum value at a moulding moisture content of 2 percent wet of optimum, and thence decreases.

The percent loss in the unfrozen unconfined compressive strengths due to one freeze-thaw cycle for a given moisture content was based on the loss in strength over the unfrozen strength.

A summary of volume change upon freezing, and therefore a change in density (decrease), and percent loss of unconfined compressive strengths at corresponding moulding moisture contents is presented in Table III.

Table III indicates that for samples compacted to modified Proctor compactive effort, the greatest percent decrease in unconfined compressive strength occurred at the same moisture content that displayed the greatest increase in volume due to freezing; namely at a moulding moisture content of 2 percent wet of optimum. This, however, was not the case for samples compacted to standard Proctor compactive effort. For samples compacted to standard Proctor compactive effort, the greatest

TABLE III

SUMMARY OF PERCENT CHANGE IN VOLUME AND PERCENT LOSS IN UNCONFINED COMPRESSIVE STRENGTH DUE TO ONE FREEZE-THAW CYCLE FOR SAMPLES AT VARYING MOULDING MOISTURE CONTENTS COMPACTED TO STANDARD AND MODIFIED PROCTOR COMPACTIVE EFFORTS .

MOULDING MOISTURE CONTENT % DRY OR WET OF OPTIMUM	COMPACTIVE EFFORT			
	STANDARD PROCTOR		MODIFIED PROCTOR	
	% VOLUME CHANGE (INCREASE)	% STRENGTH CHANGE (DECREASE)	% VOLUME CHANGE (INCREASE)	% STRENGTH CHANGE (DECREASE)
4 % DRY	2.295	27.5	0.0	0.0
2% DRY	0.824	35.2	0.008	15.6
OPTIMUM	0.775	34.9	0.839	25.0
2% WET	0.135	23.9	1.613	31.0
4% WET	0.422	17.0	0.96	20.0

loss in unconfined compressive strength occurred at a moulding moisture content which did not render the largest volume change upon freezing. This apparent difference in behaviour may reflect possible differences in soil structure generated by different compactive efforts.

Figures 20, 21 and 22 show the relationship between the deviator stress and percent strain, the σ_1/σ_3 ratio and the percent strain and the major total principal stress and percent strain respectively for frozen and unfrozen samples compacted to standard Proctor and modified Proctor compactive efforts.

The data presented in Figures 20, 21 and 22 were provided by samples compacted at optimum moisture content and tested at a confining pressure of 30 pounds per square inch. Although somewhat different curves are obtained for samples compacted at different moulding moisture contents and tested at different cell pressures, the graphs are, in the author's opinion, typical of the relationship that each of the individual curves represent. There is, however, one set of triaxial test results that do not conform to the relationships presented in Figures 20 to 22. This set was compacted at 4 percent dry of optimum using the modified Proctor compactive effort. It was found that the samples at 4 percent dry of optimum compacted to modified Proctor compactive effort displayed relationships which are opposite to those presented in Figures 20 to 22. For example, at a given percent strain the deviator stress for the frozen sample exceeds the deviator stress for the unfrozen samples. This is exactly the opposite to what Figures 20 to 22 present. A more detailed discussion of the previously mentioned graphs is presented below.

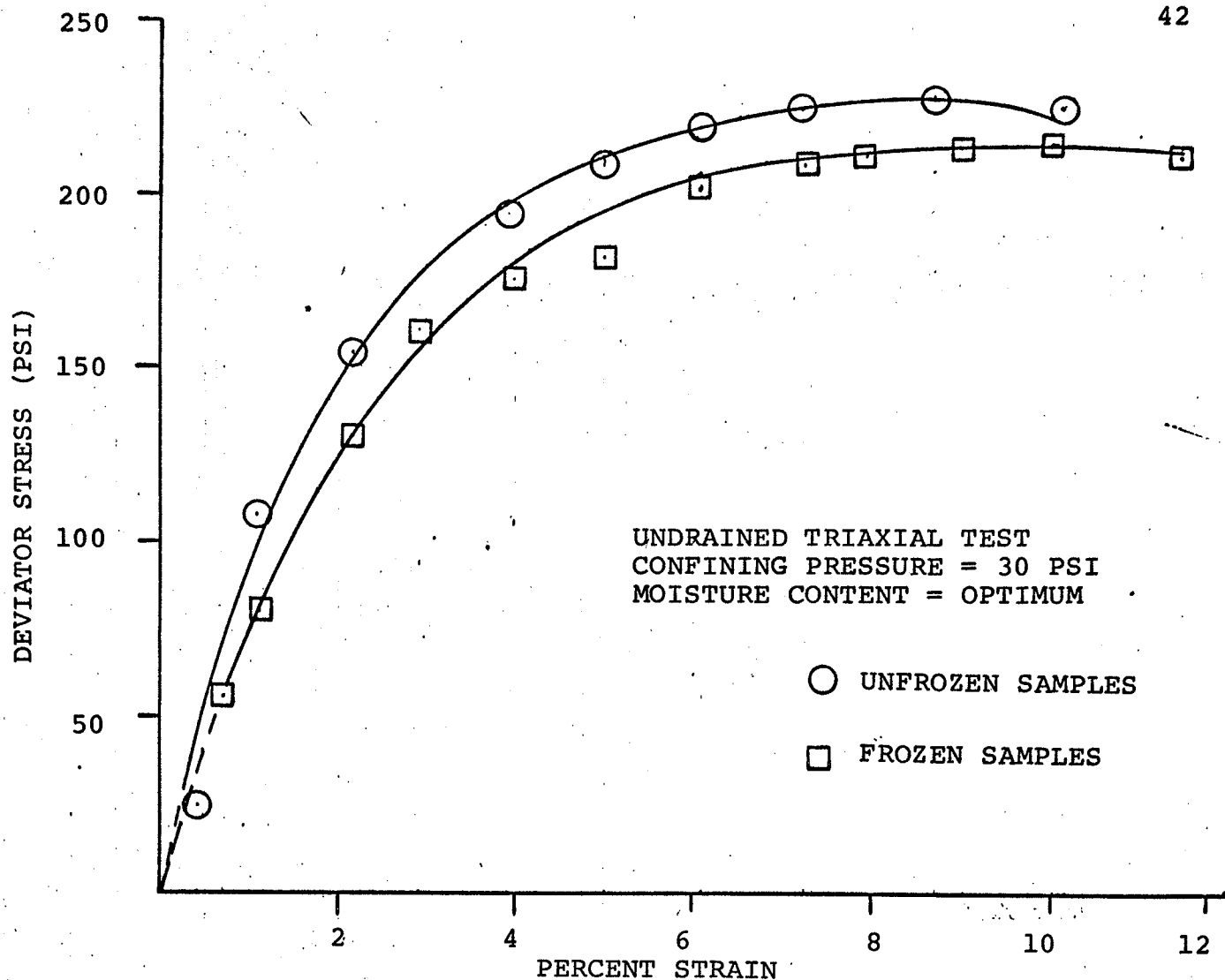


FIGURE 20A

TYPICAL DEVIATOR STRESS VERSUS PERCENT STRAIN CURVES FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

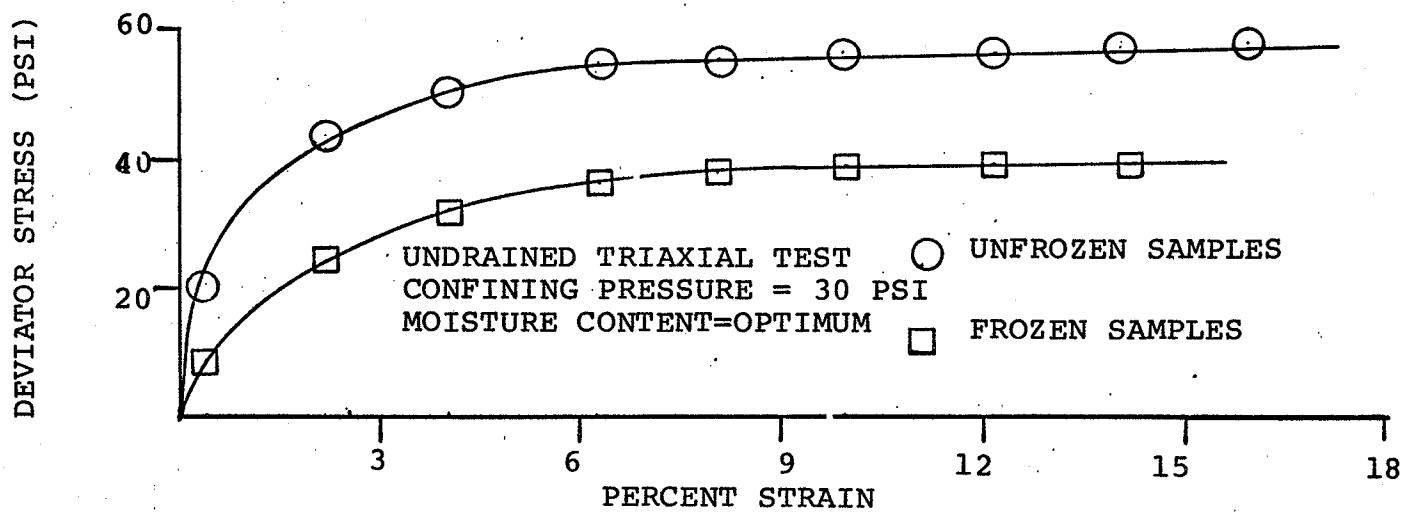


FIGURE 20B

TYPICAL DEVIATOR STRESS VERSUS PERCENT STRAIN CURVES FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

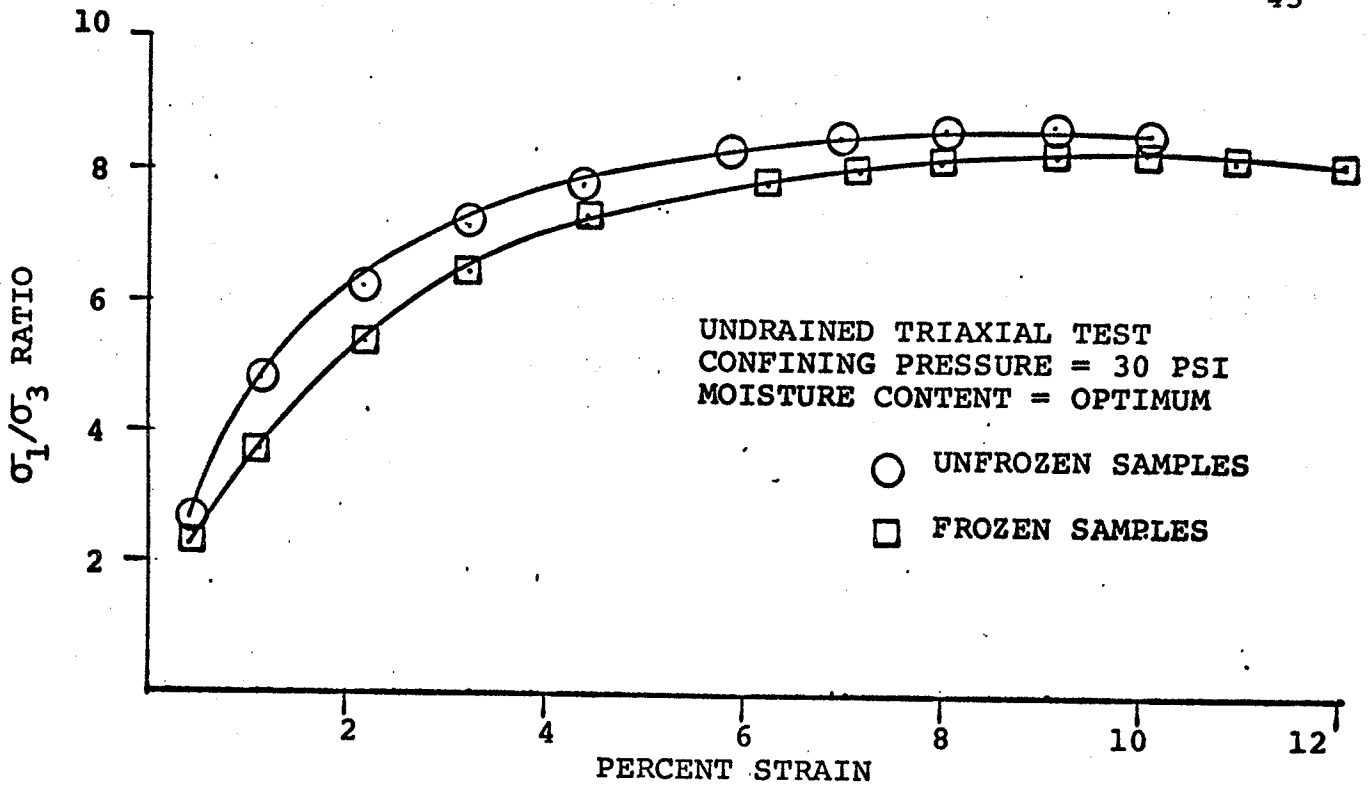


FIGURE 21A
 TYPICAL CURVES SHOWING THE RELATIONSHIP BETWEEN THE RATIO OF σ_1/σ_3 AND PERCENT STRAIN FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

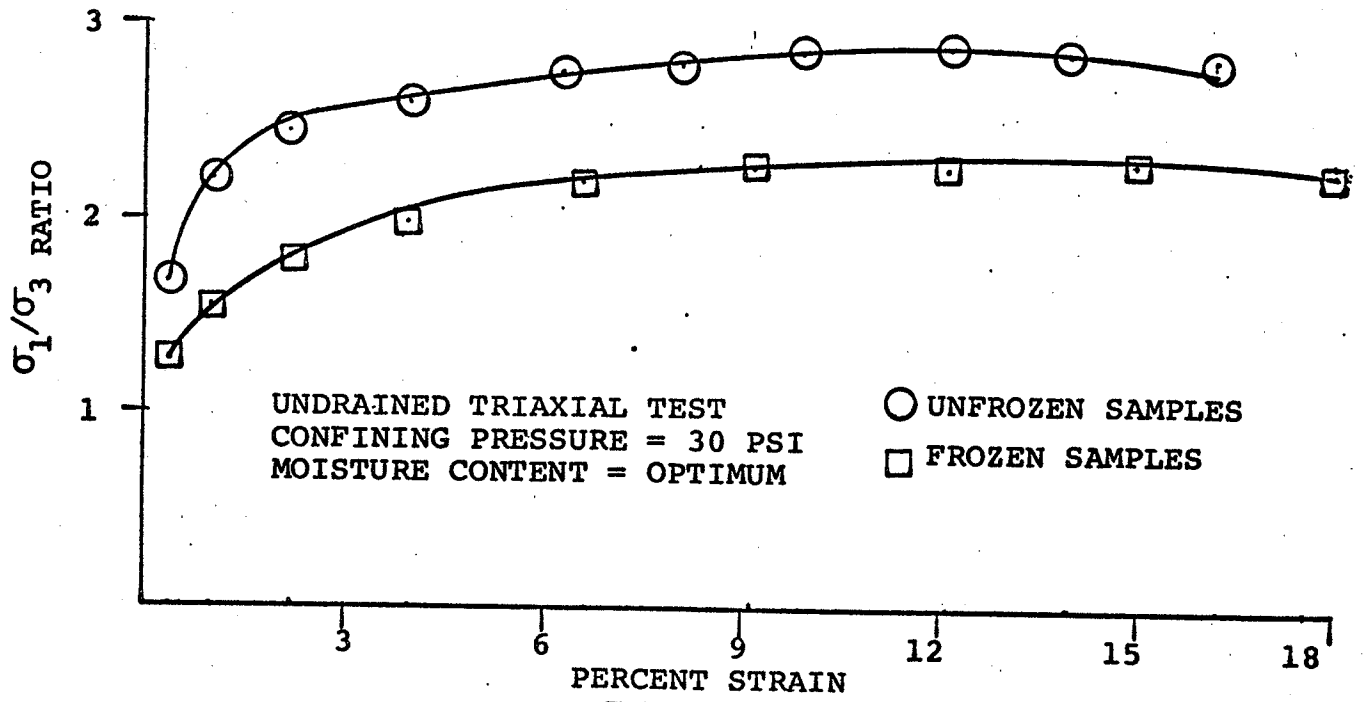


FIGURE 21B
 TYPICAL CURVES SHOWING THE RELATIONSHIP BETWEEN THE RATIO OF σ_1/σ_3 AND PERCENT STRAIN FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

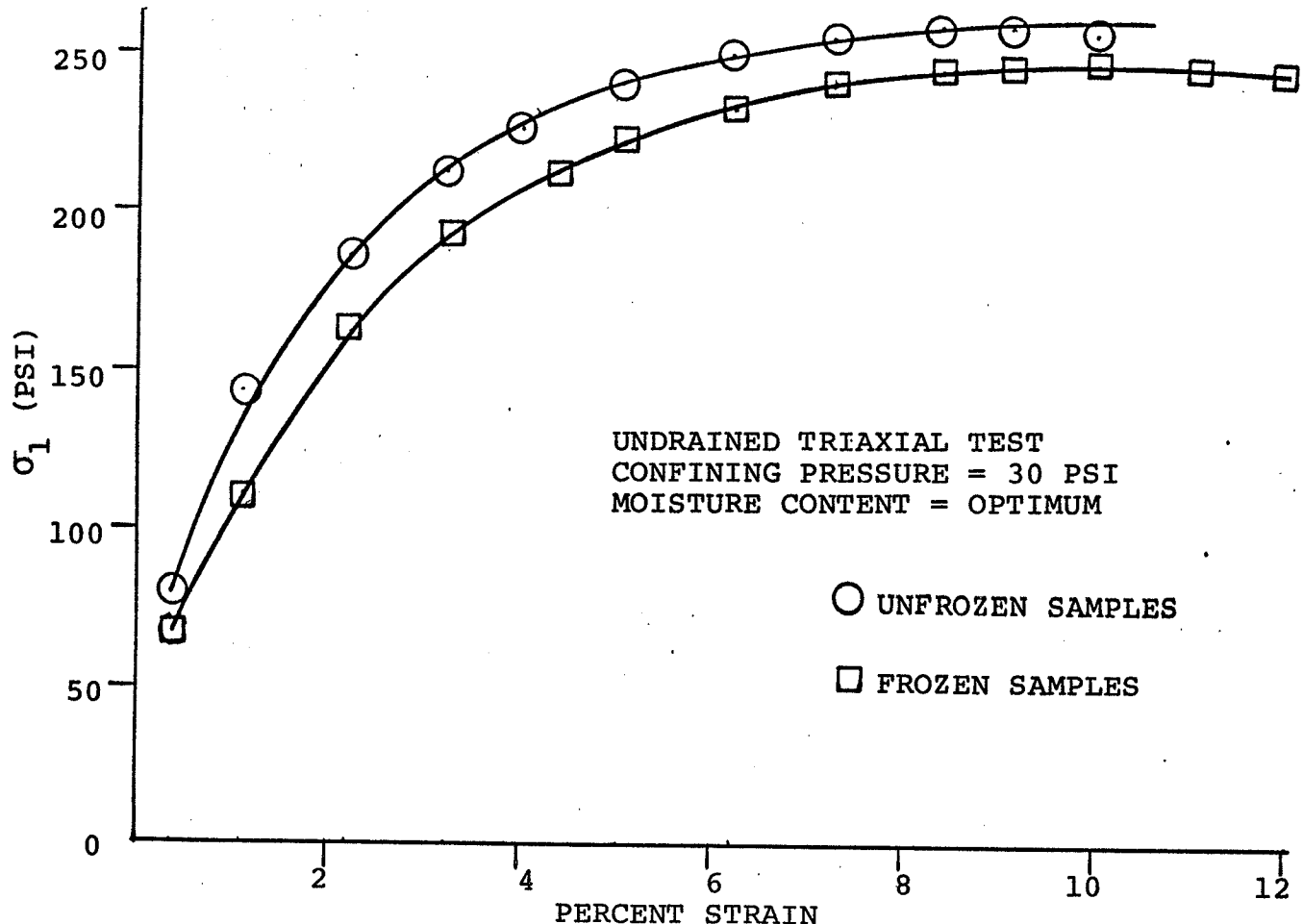


FIGURE 22A

TYPICAL CURVES SHOWING THE RELATIONSHIP BETWEEN THE MAJOR TOTAL PRINCIPAL STRESS AND PERCENT STRAIN FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

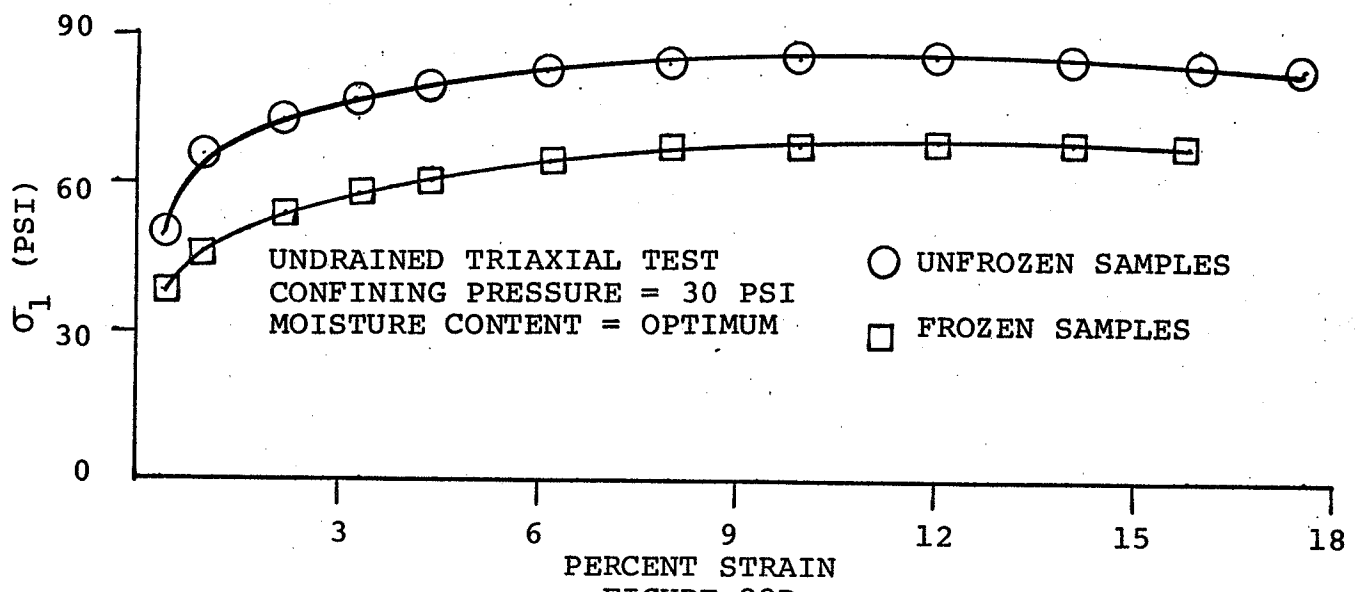


FIGURE 22B

TYPICAL CURVES SHOWING THE RELATIONSHIP BETWEEN THE MAJOR TOTAL PRINCIPAL STRESS AND PERCENT STRAIN FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

Graphs 20A and 20B show how the deviator stress changes with applied percent strain. The deviator stress, as used in this paper, is defined as the difference between the major total principal stress and the minor total principal stress. Both graphs 20A and 20B show that at a given percent strain, the deviator stress for samples exposed to one freeze-thaw cycle is less than the deviator stress displayed for unfrozen samples. It appears from graphs 20A and 20B that the decrease in the deviator stress due to one freeze-thaw cycle is approximately uniform after 3 percent strain and that the curves for frozen and unfrozen samples have the same general shape for both standard and modified Proctor compaction that was examined.

Figures 21A and 21B are curves showing the typical relationship between the stress ratio σ_1/σ_3 and the percent strain. The quantity σ_1 is the major total principal stress and σ_3 is the minor total principal stress. From the graphs we see that one freeze-thaw cycle generally decreases the σ_1/σ_3 ratio at any given applied strain for both the standard and modified Proctor compactive efforts. It also appears that the general shape of the σ_1/σ_3 curves is not appreciably altered by one freeze-thaw cycle.

The relationship between the major total principal stress, σ_1 , and the percent strain for both standard and modified compactive efforts is presented in Figures 22A and 22B. Similar to the above noted relationships, the σ_1 versus percent strain curves are affected by one freeze-thaw cycle. For a given percent strain, the unfrozen major total principal stress decreases after freezing and subsequent thawing. The general shapes of the curves appear to be unaltered after one freeze-thaw cycle.

The maximum major total principal stress, the maximum ratio of the major total principal stress to the minor total principal stress, and the maximum deviator (total stresses) stress are of particular interest for the following reasons. The maximum major total principal stress is used as an indication of the ultimate strength of a soil at a given confining pressure. The maximum σ_1/σ_3 ratio and the maximum deviator stress are used as failure criteria. The above mentioned quantities (for the standard and modified Proctor efforts) were therefore plotted against cell pressure and the results are presented in Figures 23 through 28. It should be noted that an element of distortion is introduced in Figures 23B to 28B. The distortion originates in the percent change concept. For example, Figure 23A shows the difference between frozen and unfrozen results seem to be independent of cell pressure. The difference expressed as a percent will show an increase because the divisor of the percentage is getting smaller. The results of the zero-cell pressure triaxial tests (unconfined) significantly differ from confined tests and for this reason have been separately discussed.

Figure 23A shows a family of curves for unfrozen and frozen samples at varying moulding moisture contents compacted to modified Proctor compactive effort representing the relationship between the maximum σ_1/σ_3 ratio and the various cell pressures. This plot implies that for a given cell pressure, the maximum σ_1/σ_3 ratio at a particular moulding moisture content is less for frozen samples than for unfrozen samples. Furthermore, Figure 23A also indicates that for a given cell pressure, the maximum σ_1/σ_3 ratio increases with decreasing moulding moisture contents. It was observed that the maximum σ_1/σ_3 ratio for a given moulding moisture content increases with decreasing confining pressure.

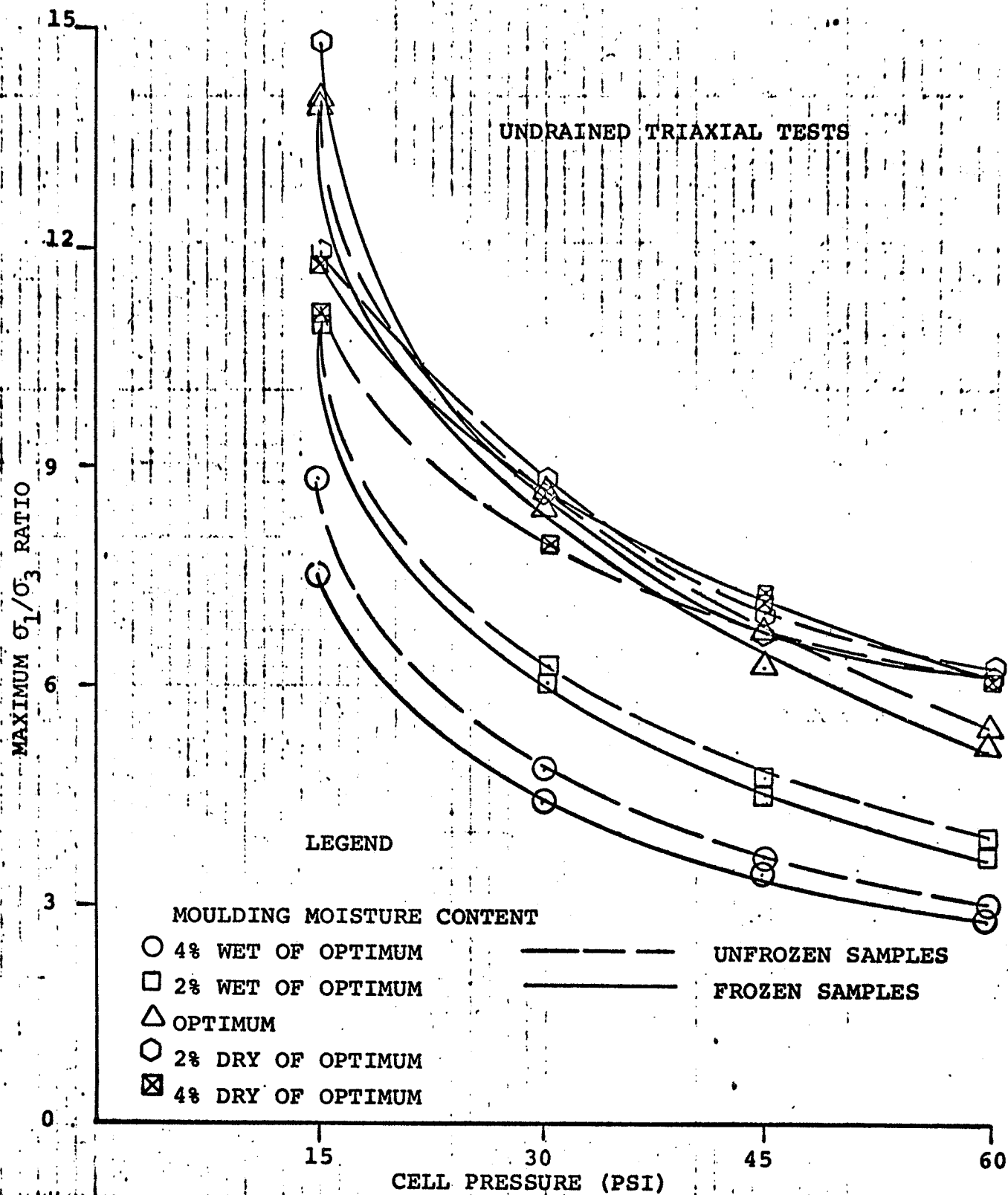


FIGURE 23A

CURVES SHOWING THE MAXIMUM RATIO OF THE MAJOR TOTAL PRINCIPAL STRESS TO THE MINOR TOTAL PRINCIPAL STRESS VERSUS CELL PRESSURE FOR FROZEN AND UNFROZEN SAMPLES AT VARYING MOULDING MOISTURE CONTENTS FOR SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

Figure 23B is a plot of the percent change (positive or negative) due to one freeze-thaw cycle of the maximum σ_1/σ_3 ratio versus cell pressure for samples at varying moulding moisture contents compacted to modified Proctor compactive effort. Although a definite trend is not established in Figure 23B, it may be said that generally, samples at the various moulding moisture contents and cell pressures show a decrease in the maximum σ_1/σ_3 ratio. The exception to the previously noted relationship are those samples compacted at 4 percent dry of optimum. It should be noted that for cell pressures of 30, 45 and 60 pounds per square inch, the decrease in the maximum σ_1/σ_3 ratio remains relatively constant at between 5 and 10 percent.

Figure 24A represents frozen and unfrozen samples compacted to standard Proctor compactive effort. Figure 24A shows the same trend as does Figure 23A, namely the maximum σ_1/σ_3 ratio for frozen samples is generally less than for unfrozen samples. Also the maximum σ_1/σ_3 ratio increases with decreasing moulding moisture content at a given cell pressure and increases with decreasing cell pressure at a particular moulding moisture content. Furthermore, the maximum σ_1/σ_3 ratio appears to be affected little by changes in the moulding moisture content and cell pressure for cell pressures exceeding 45 pounds per square inch.

Figure 24B shows that the percent change in the maximum σ_1/σ_3 ratio is usually a 10 to 20 percent decrease. It is of interest to note that generally, regardless of moulding moisture content, the greatest decrease in the maximum σ_1/σ_3 ratio occurs at a cell pressure of 30 pounds per square inch.

If Figures 23B and 24B are jointly examined, it appears that the maximum σ_1/σ_3 ratio for unfrozen samples is affected to a greater extent, due to one freeze-thaw cycle, in specimens compacted to standard

LEGEND

MOULDING MOISTURE CONTENT

- 4% WET OF OPTIMUM
- 2% WET OF OPTIMUM
- △ OPTIMUM
- ◇ 2% DRY OF OPTIMUM
- ⊠ 4% DRY OF OPTIMUM

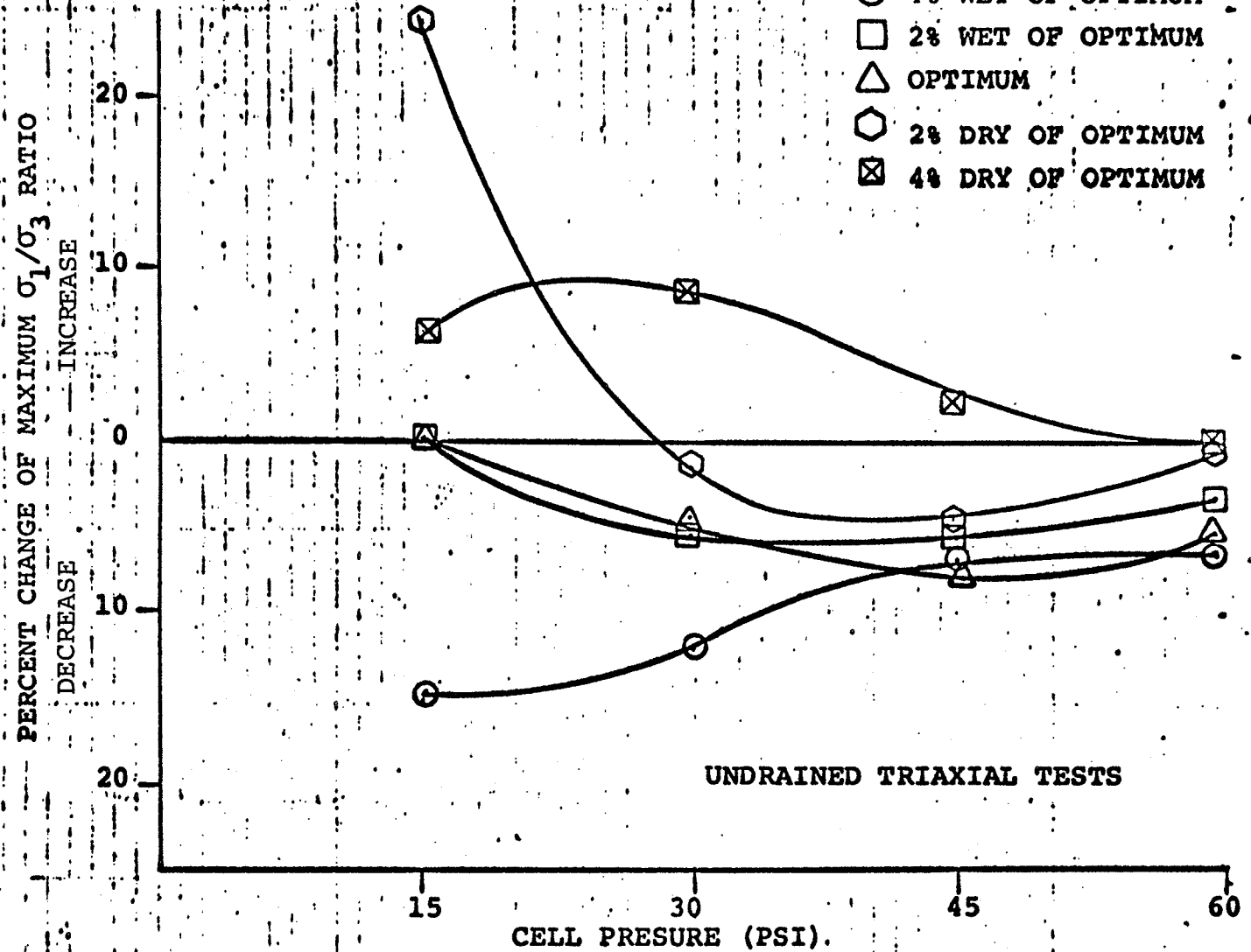
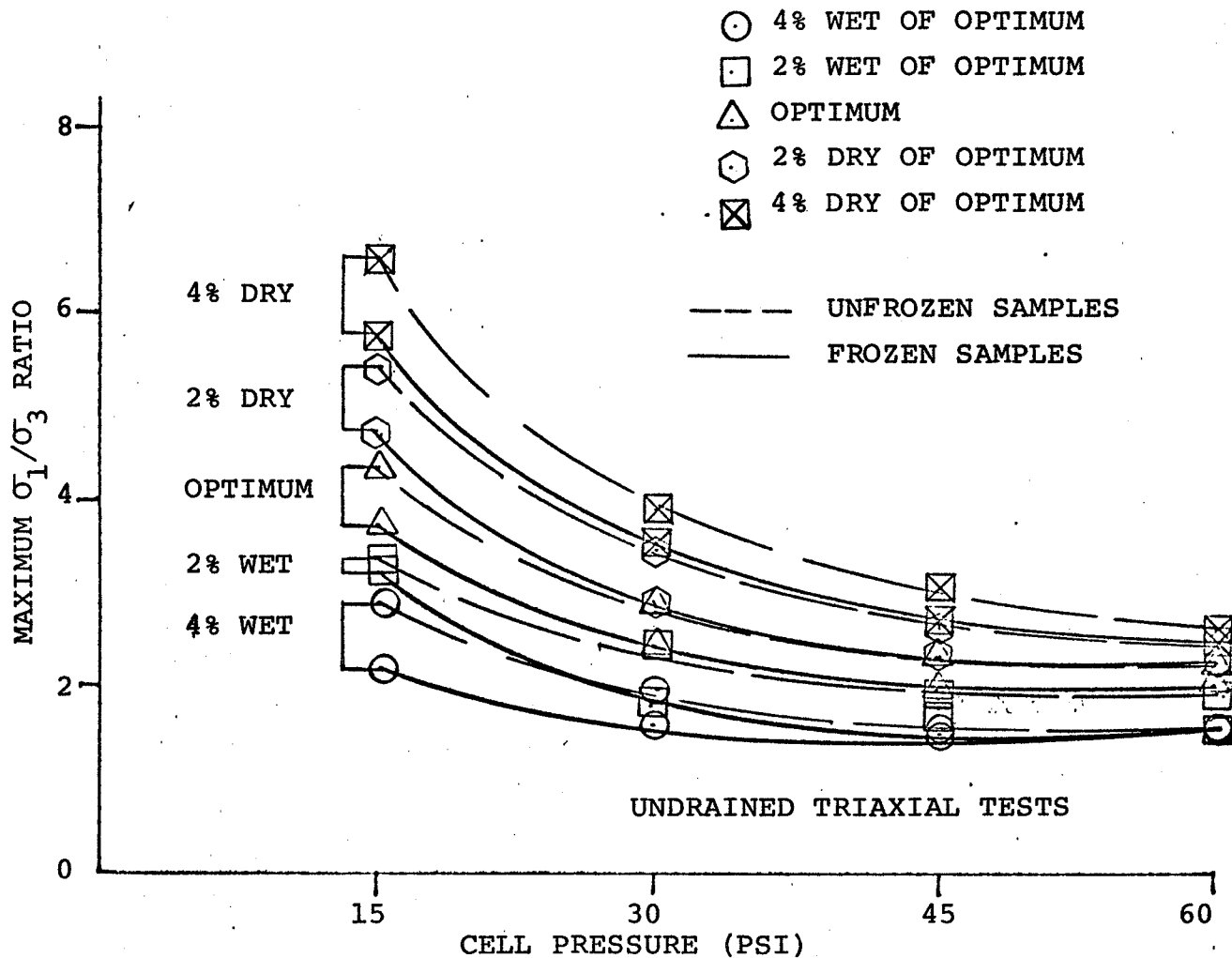


FIGURE 23B

PERCENT CHANGE DUE TO ONE FREEZE-THAW CYCLE, IN THE MAXIMUM RATIO OF THE MAJOR TOTAL PRINCIPAL STRESS TO THE MINOR TOTAL PRINCIPAL STRESS VERSUS CELL PRESSURE FOR SAMPLES AT VARYING MOULDING MOISTURE CONTENTS COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

LEGEND

MOULDING MOISTURE CONTENT



UNDRAINED TRIAXIAL TESTS

FIGURE 24A

MAXIMUM RATIO OF THE MAJOR TOTAL PRINCIPAL STRESS TO THE MINOR TOTAL PRINCIPAL STRESS VERSUS CELL PRESSURE FOR FROZEN AND UNFROZEN SAMPLES AT VARYING MOULDING MOISTURE CONTENTS COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

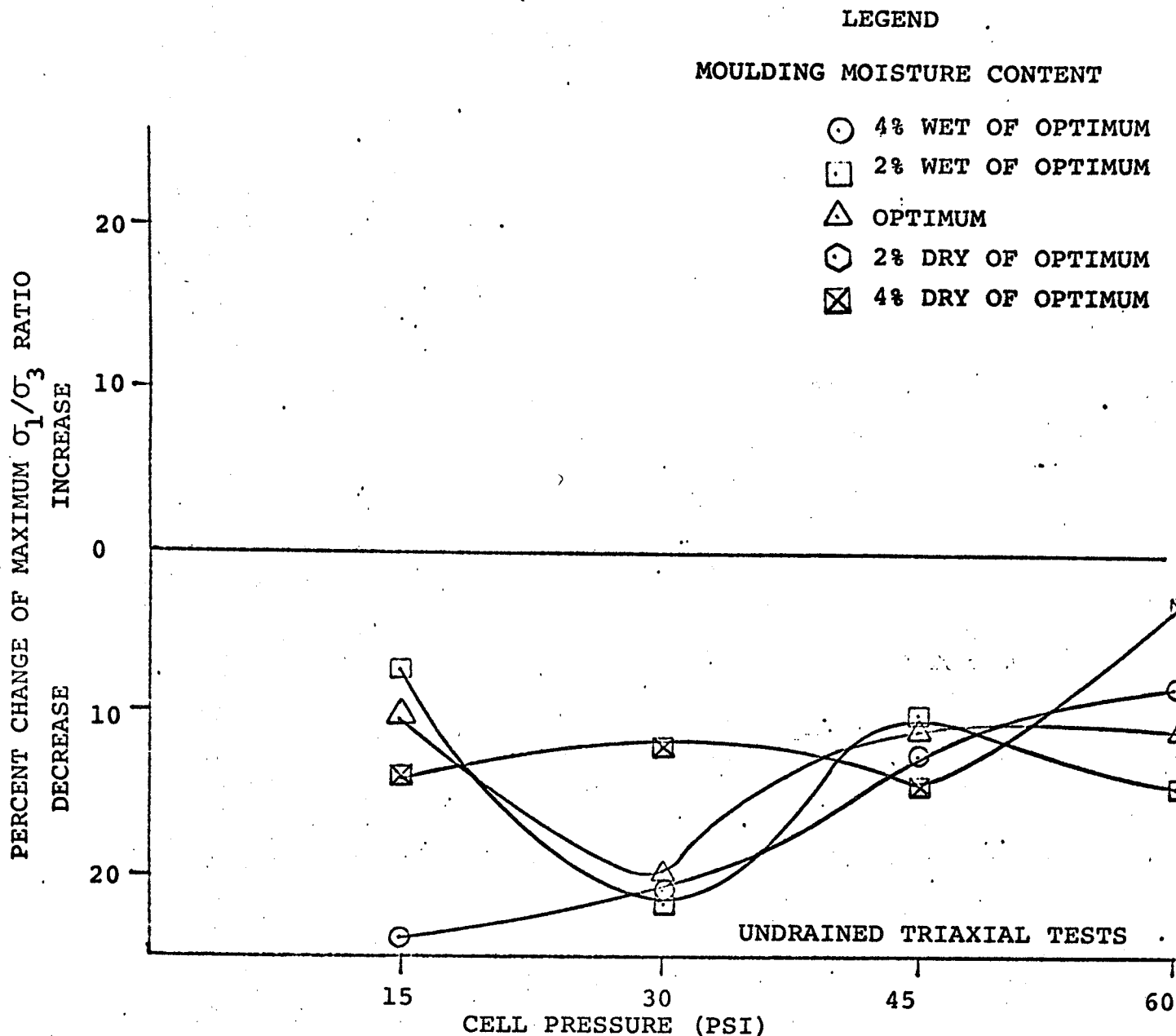


FIGURE 24B

PERCENT CHANGE DUE TO ONE FREEZE-THAW CYCLE IN THE MAXIMUM RATIO OF THE MAJOR TOTAL PRINCIPAL STRESS TO THE MINOR TOTAL PRINCIPAL STRESS, VERSUS CELL PRESSURE FOR SAMPLES AT VARYING MOULDING MOISTURE CONTENTS COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

Proctor compactive effort than for specimens compacted to modified Proctor compactive effort.

The percent decrease, due to freezing of the maximum σ_1/σ_3 ratio was based on the unfrozen maximum σ_1/σ_3 ratio.

Figure 25A shows a family of curves representing the relationship between the maximum deviator stress and the cell pressure for frozen and unfrozen samples at different moulding moisture contents compacted to modified Proctor compactive effort. This figure generally indicates that the maximum deviator stress is less for frozen samples than for unfrozen samples. The exception, again, is the set of points provided by samples compacted at 4 percent dry of optimum. For a moisture content of 4 percent wet of optimum, the maximum deviator stress for frozen and unfrozen samples appears to be relatively independent of cell pressure. For the remaining moulding moisture contents, the maximum deviator stress appears to increase with increasing cell pressure. Furthermore Figure 25A indicates that for a given cell pressure, the maximum deviator stress increases with decreasing moulding moisture content.

Figure 25B shows the percent change due to one freeze-thaw cycle in the maximum deviator stress versus cell pressure for samples at varying moulding moisture contents compacted to modified Proctor compactive effort. The percent decrease is between 5 and 18 percent for the cell pressures and corresponding moulding moisture contents that were examined.

Figure 26A shows the same relationship as 25A except the data in Figure 26A was provided from samples compacted to standard Proctor compactive effort. Figure 26A implies that the maximum deviator stress is less for frozen samples than for unfrozen samples at corresponding moulding moisture contents and cell pressures. The maximum deviator stress

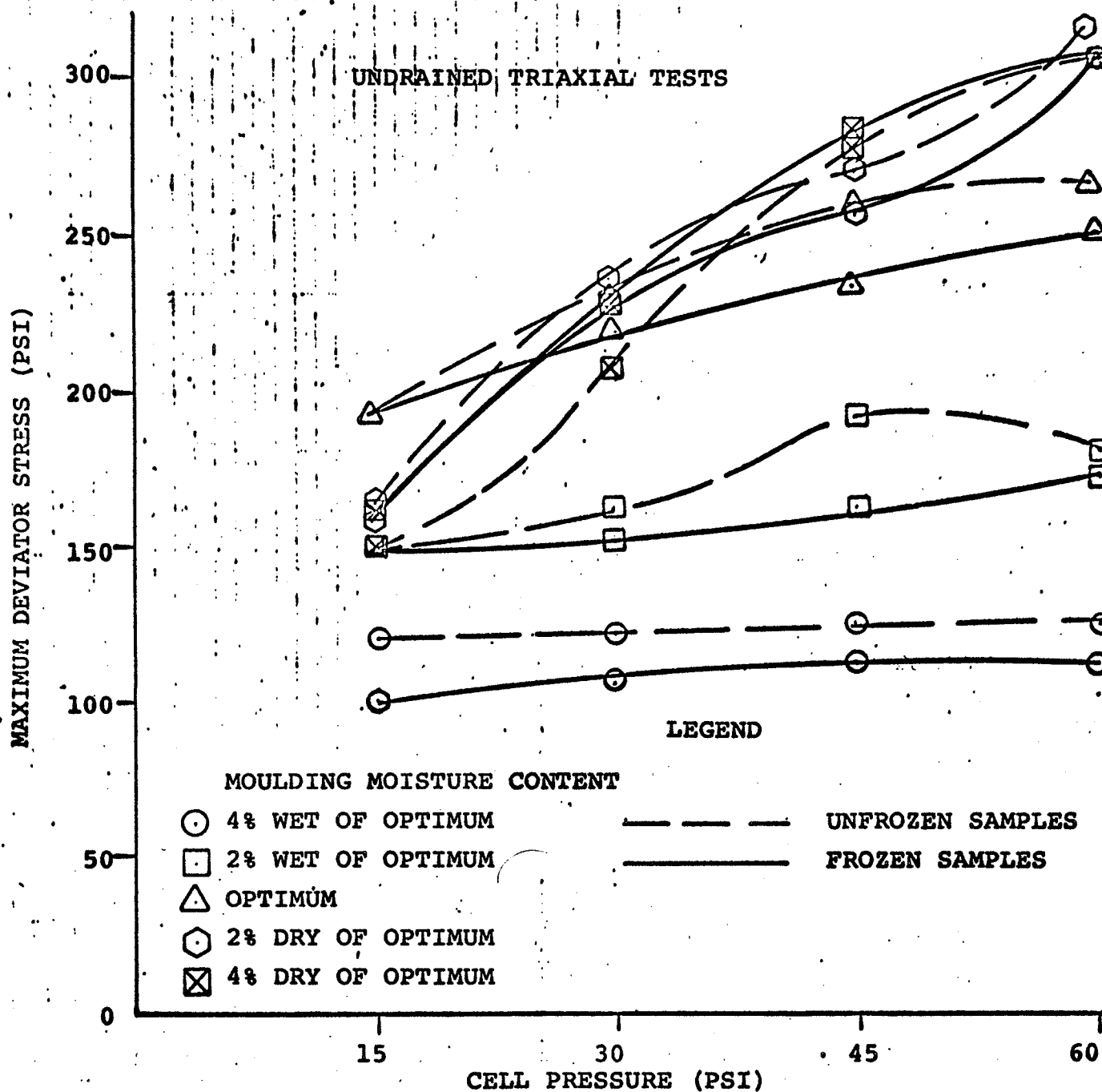


FIGURE 25A

MAXIMUM DEVIATOR STRESS VERSUS CELL PRESSURE FOR UNFROZEN AND FROZEN SAMPLES AT VARYING MOULDING MOISTURE CONTENTS COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

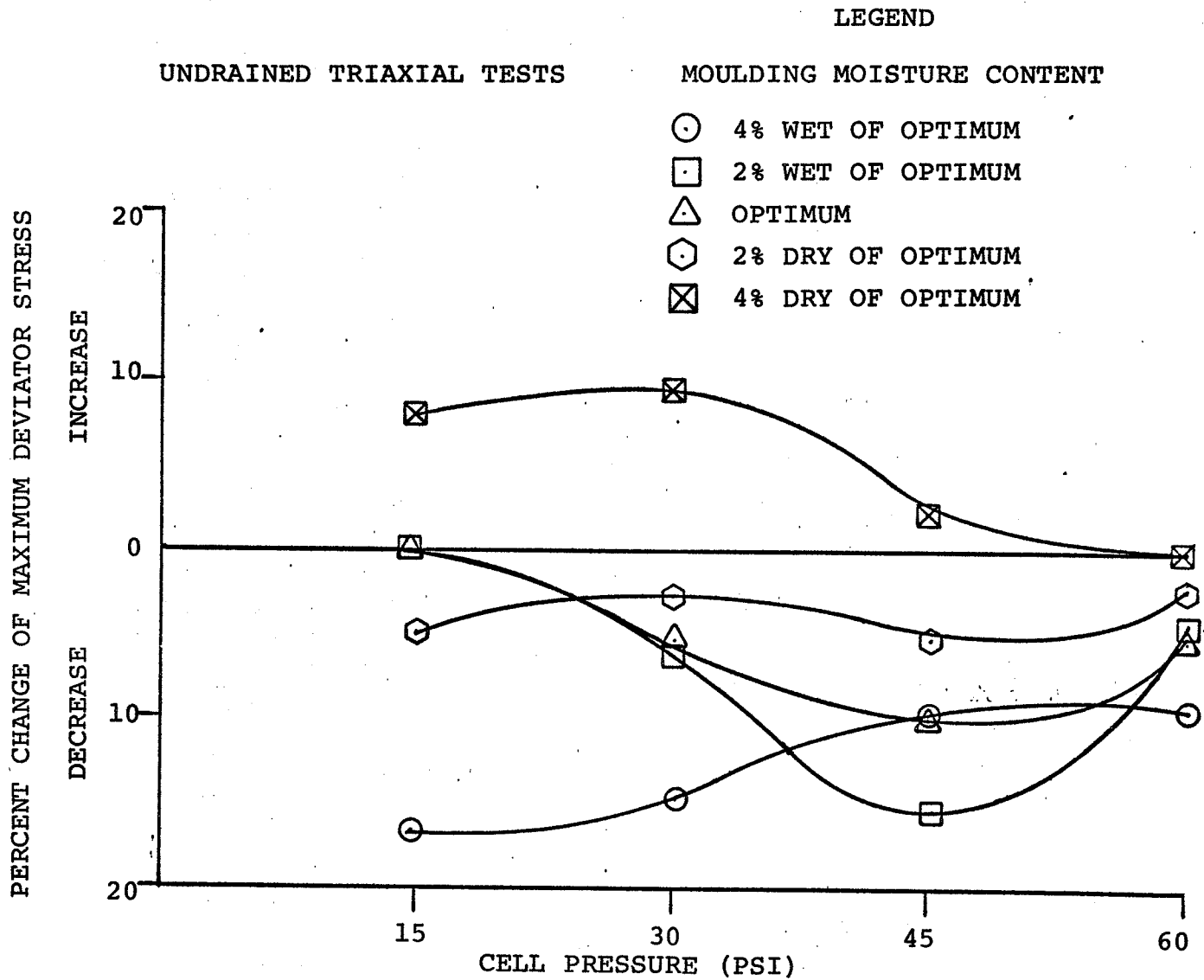


FIGURE 25B
 PERCENT CHANGE DUE TO ONE FREEZE-THAW CYCLE IN THE MAXIMUM
 DEVIATOR STRESS VERSUS CELL PRESSURE FOR SAMPLES AT VARYING
 MOULDING MOISTURE CONTENTS COMPACTED TO MODIFIED PROCTOR
 COMPACTIVE EFFORT.

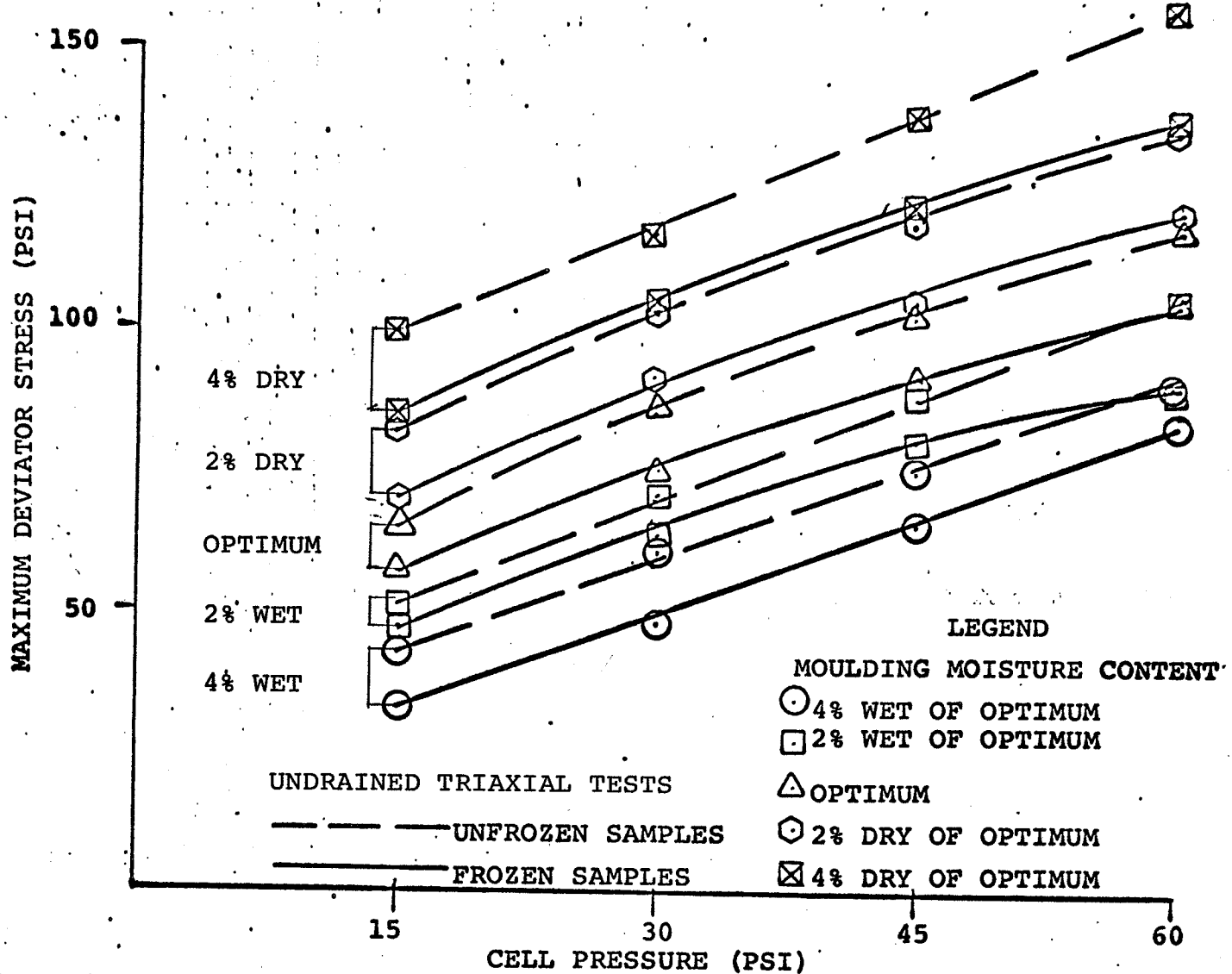


FIGURE 26A
 MAXIMUM DEVIATOR STRESS VERSUS CELL PRESSURE FOR UNFROZEN AND FROZEN SAMPLES AT VARYING MOULDING MOISTURE CONTENTS COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

increases with increasing cell pressure at a given moulding moisture content, and increases with decreasing moulding moisture content at a particular cell pressure.

Figure 26B implies that the percent decrease in the maximum deviator stress, due to one freeze-thaw cycle for samples compacted to standard Proctor compactive effort at varying moulding moisture contents is between 10 and 20 percent.

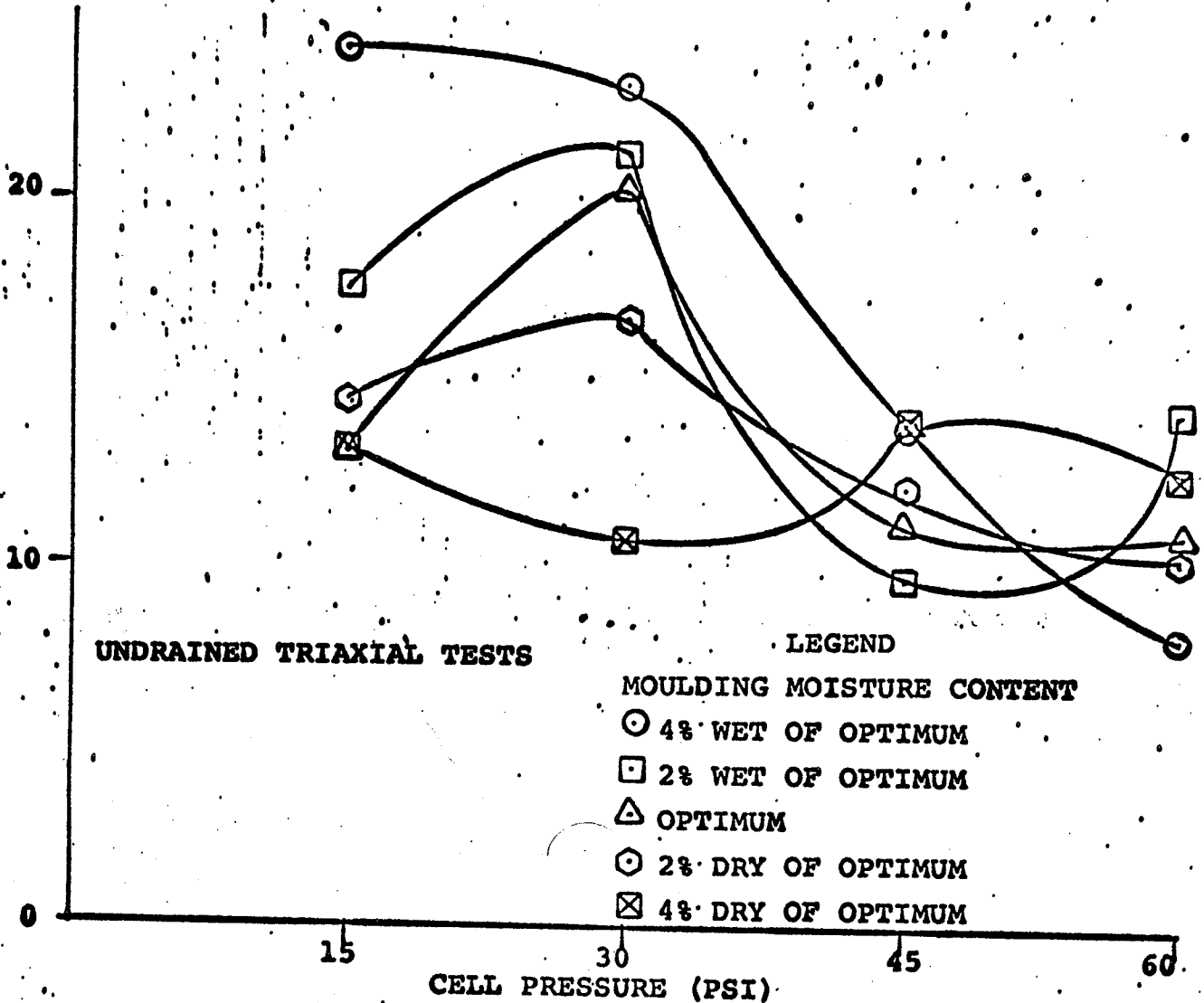
It would appear that after studying Figures 25B and 26B, that the percent decrease in the maximum deviator stress due to one freeze-thaw cycle is slightly higher for samples compacted to standard Proctor compactive effort than for the modified Proctor effort.

The percent decrease in the maximum deviator stress due to one freeze-thaw cycle as shown in Figures 25B and 26B was based on the maximum deviator stress for the unfrozen samples.

Figure 27A presents a family of curves representing correlation between the major total principal stress and the cell pressure for frozen and unfrozen samples at varying moulding moisture contents compacted to modified Proctor compactive effort. The graph indicates that the major total principal stress is less for frozen samples than for unfrozen samples. It is noted that generally, with decreasing moulding moisture content, at a particular cell pressure, the value of the major total principal stress increases, and also increases with increasing confining pressure at a constant moulding moisture content. As noted on several previous occasions, the samples compacted at 4 percent dry of optimum do not conform to the above noted pattern.

Figure 27B graphs the percent change in the major total stress due to one freeze-thaw cycle versus cell pressure for samples at varying moulding moisture contents compacted to modified Proctor com-

PERCENT DECREASE OF MAXIMUM DEVIATOR STRESS



CELL PRESSURE (PSI)
FIGURE 26B

PERCENT DECREASE DUE TO ONE FREEZE-THAW CYCLE IN THE MAXIMUM DEVIATOR STRESS VERSUS CELL PRESSURE FOR SAMPLES AT VARYING MOULDING MOISTURE CONTENTS COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

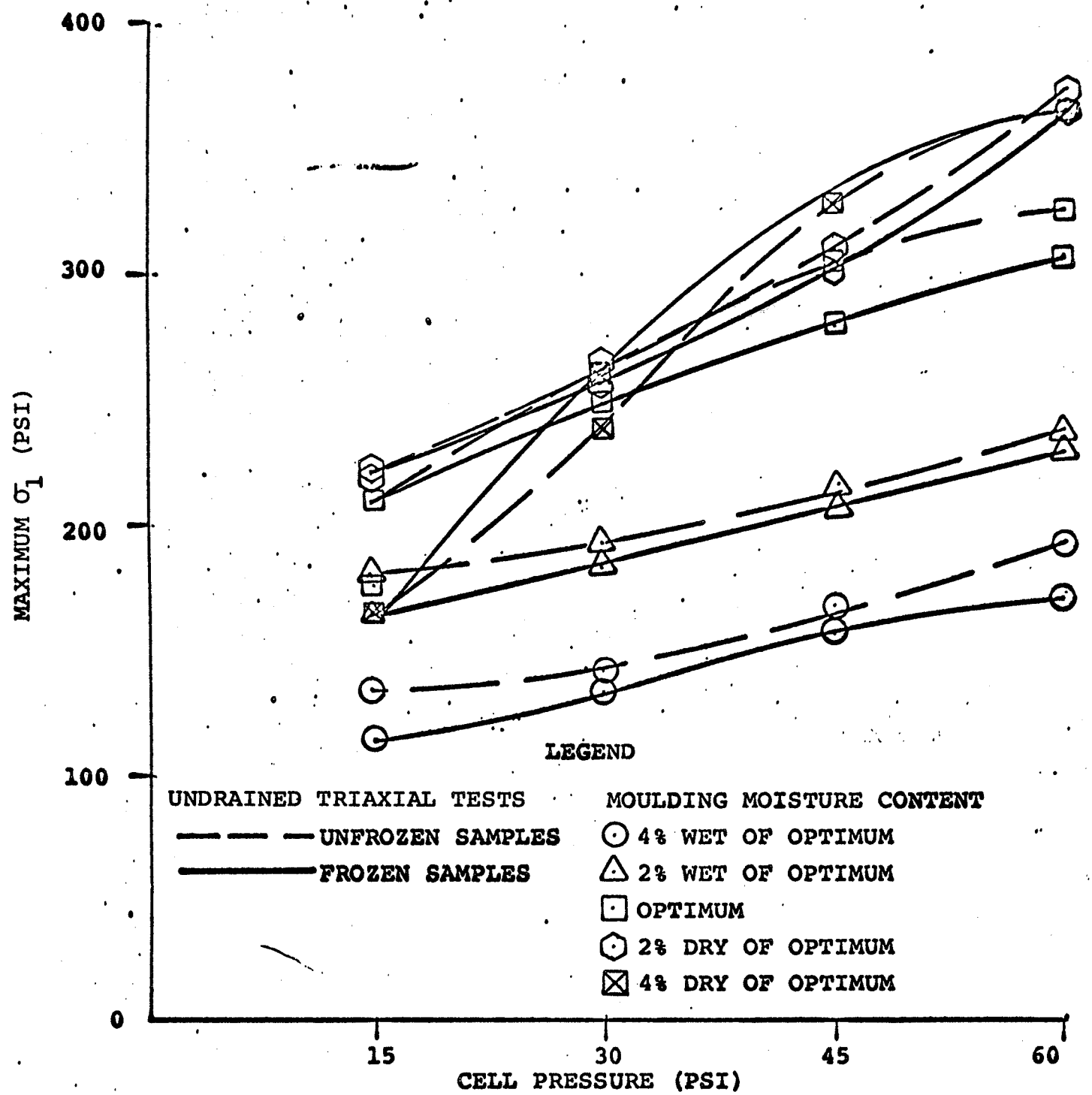


FIGURE 27A
MAJOR TOTAL PRINCIPAL STRESS VERSUS CELL PRESSURE FOR FROZEN AND UNFROZEN SAMPLES AT VARYING MOULDING MOISTURE CONTENTS COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

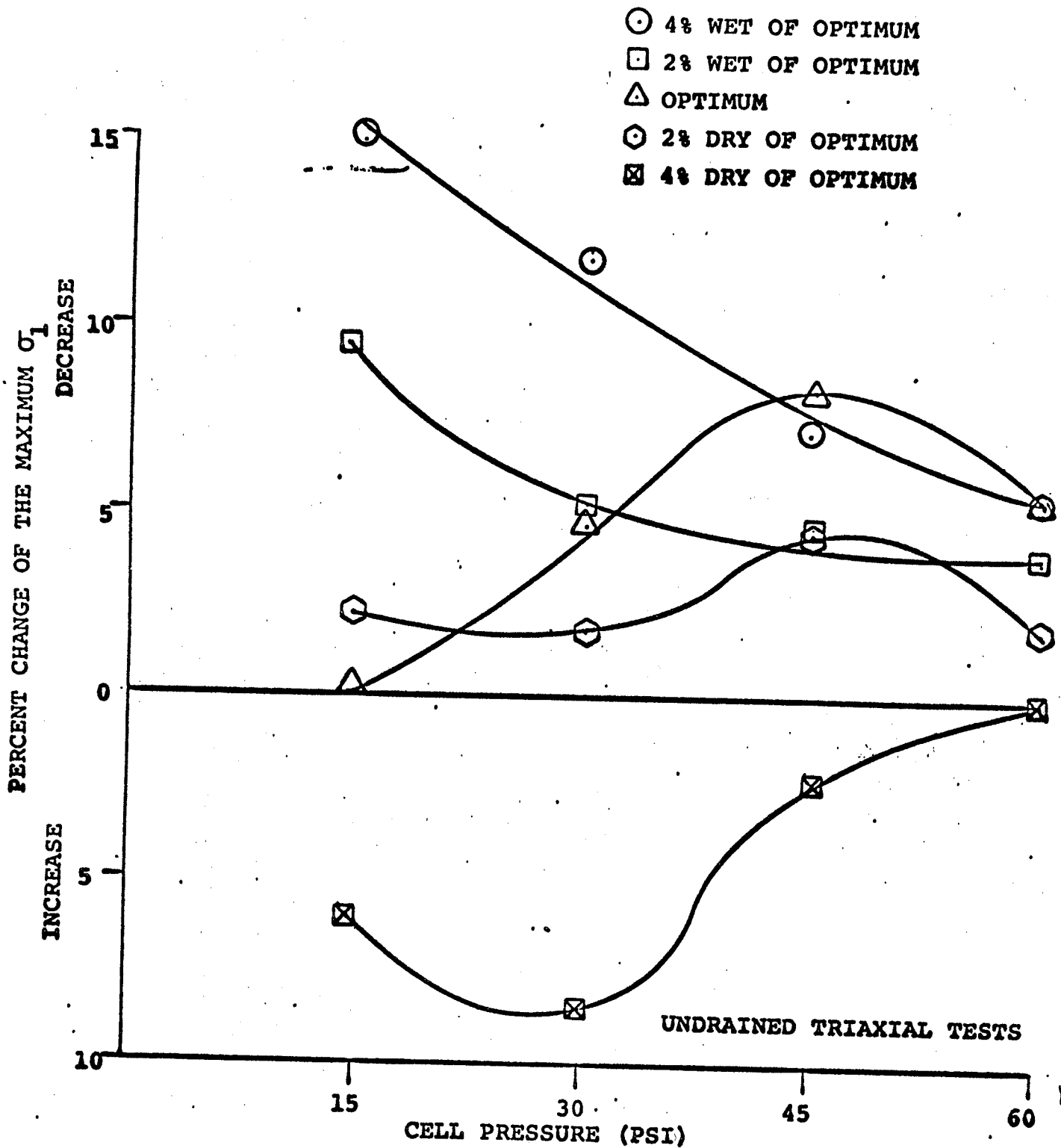


FIGURE 27B
 PERCENT CHANGE DUE TO ONE FREEZE-THAW CYCLE IN THE MAJOR
 TOTAL PRINCIPAL STRESS VERSUS CELL PRESSURE FOR SAMPLES
 AT VARYING MOULDING MOISTURE CONTENTS COMPACTED TO MOD-
 IFIED PROCTOR COMPACTIVE EFFORT.

active effort. On the basis of Figure 27B it may be stated that the change in the unfrozen major total principal stress is generally a decrease ranging from 2 to 10 percent. Samples compacted 4 percent dry of optimum did not adhere to the previously noted trend.

Figure 28A illustrates the same relationship as Figure 27A, except the data presented in Figure 28A was supplied by samples compacted to standard Proctor compactive effort. Similar to Figure 27A, Figure 28A indicates the major total principal stress is less for frozen samples than for unfrozen samples at similar moulding moisture contents and cell pressures. Also the major total principal stress increases with the decreasing moulding moisture content at a particular confining pressure, and increases with increasing cell pressure at a given moulding moisture content.

Figure 28B shows the percent decrease in the major total principal stress due to one freeze-thaw cycle versus cell pressure for samples at varying moulding moisture contents. Figure 28B shows that this change is a decrease generally ranging from 5 to 20 percent. A comparison of Figures 27B and 28B reveals that the change in the major total principal stress, due to one freeze-thaw cycle, is greater for unfrozen samples compacted to standard Proctor compactive effort than for the unfrozen samples compacted to modified Proctor compactive effort. The percent change in the major total principal stress was based on the decrease of the major total principal stress divided by the unfrozen value of the major total principal.

From the foregoing discussions it appears that certain strength properties and other characteristics of a compacted clay are affected by one freeze-thaw cycle for the range of moisture contents and compactive efforts examined. Changing the compactive effort applied to

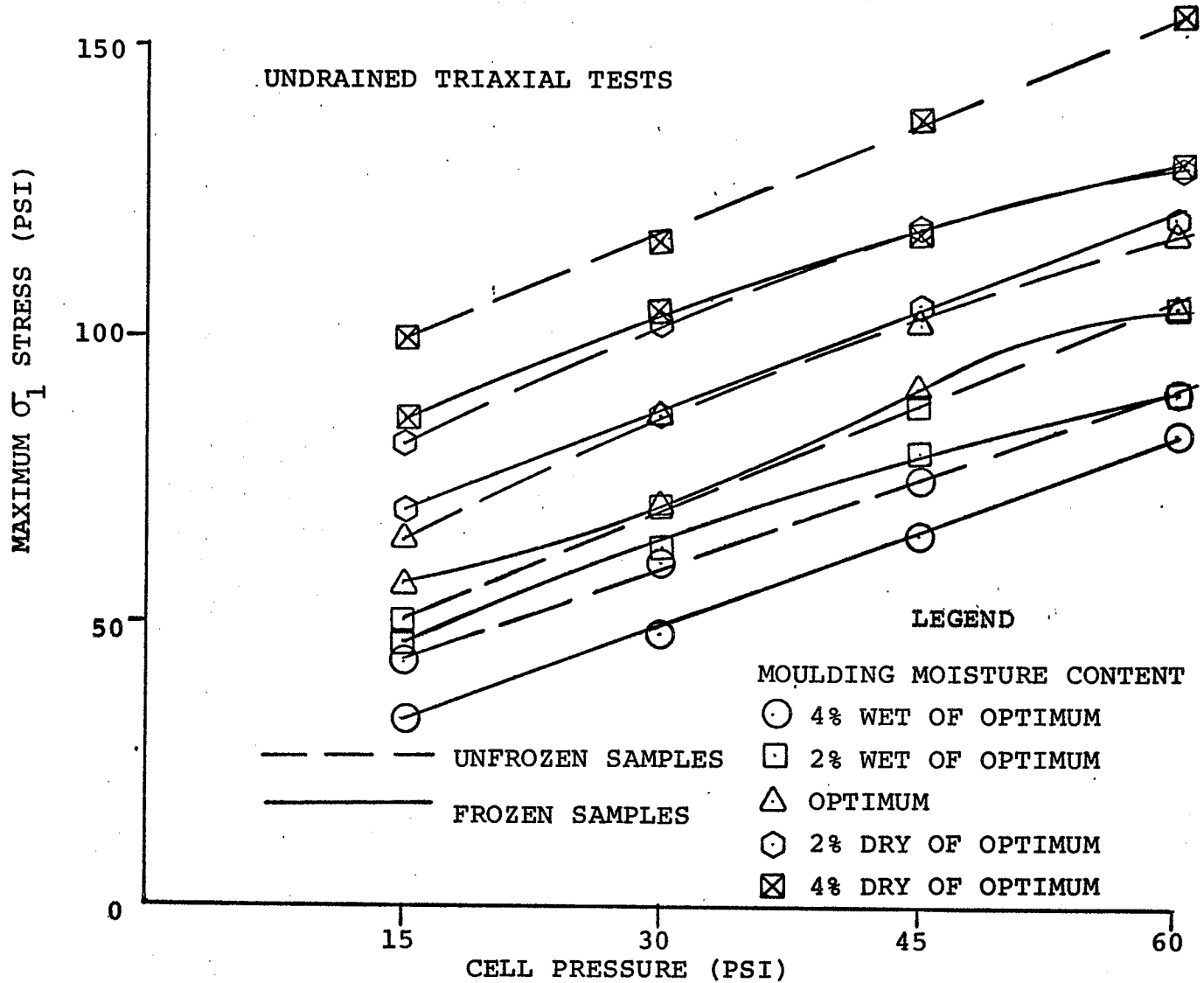


FIGURE 28A
 MAJOR TOTAL PRINCIPAL STRESS VERSUS CELL PRESSURE FOR FROZEN AND UNFROZEN SAMPLES AT VARYING MOULDING MOISTURE CONTENTS COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

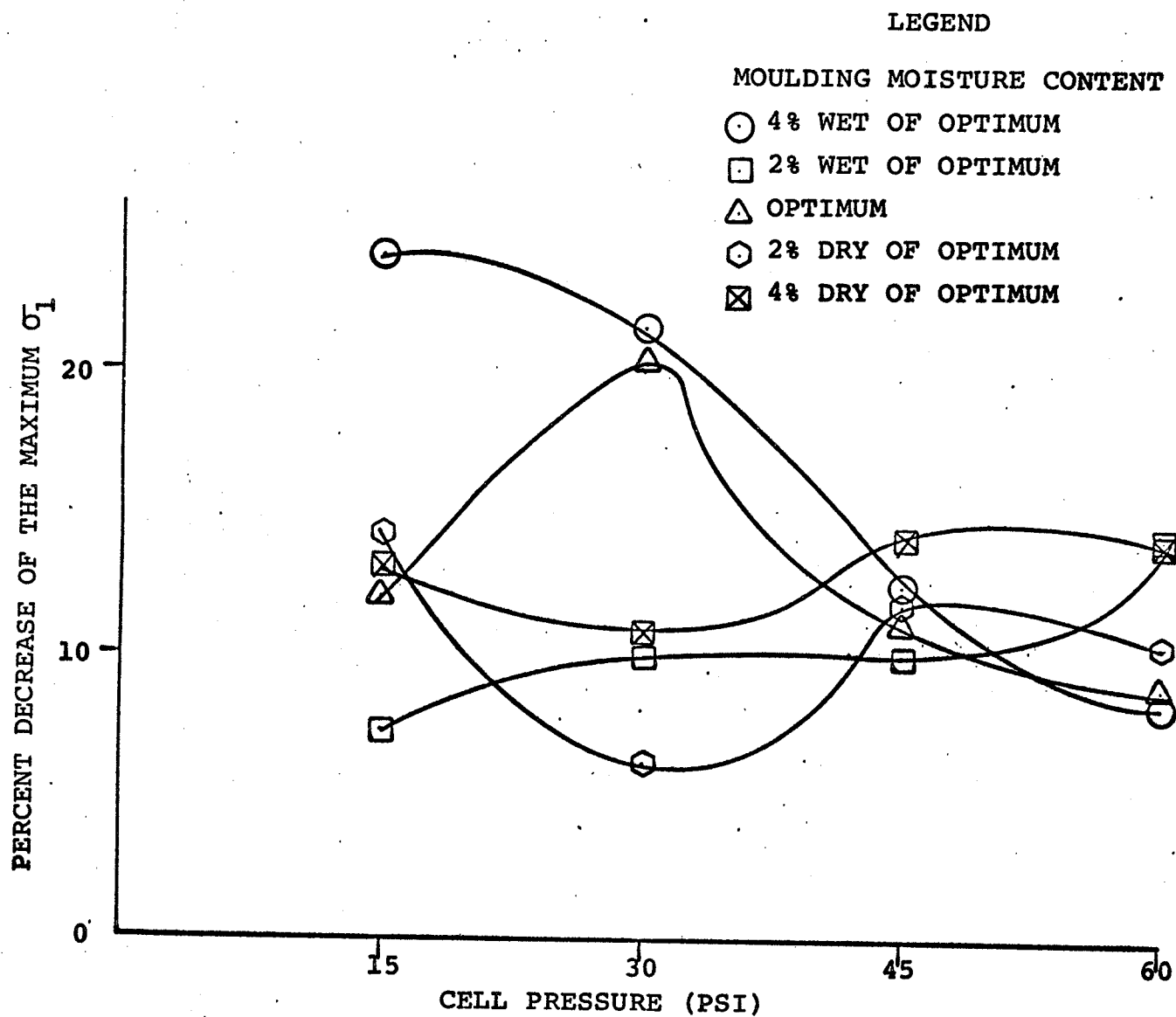


FIGURE 28B
PERCENT DECREASE DUE TO ONE FREEZE-THAW CYCLE IN THE MAJOR TOTAL PRINCIPAL STRESS VERSUS CELL PRESSURE FOR SAMPLES AT VARYING MOULDING MOISTURE CONTENTS COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

the samples does not affect the nature of the above noted quantities, but rather the degree of change induced by one freeze-thaw cycle.

C. ONE DIMENSIONAL CONSOLIDATION TESTS

The results of the one dimensional consolidation tests, and comments regarding the effect of one freeze-thaw cycle on certain soil properties related to one dimensional consolidation tests, are presented in the following discussion.

Plots showing the percent change in the initial sample height due to swelling versus moulding moisture content for frozen and unfrozen samples compacted to standard and modified Proctor efforts are shown in Figures 29A and 30A. Swelling was permitted under the conditions of partial submergence and an applied vertical load of 1.1 kilograms per square centimeter. The percent change in the amount of swell between frozen and unfrozen samples versus moulding moisture content for standard and modified compactive efforts is shown in Figures 29B and 30B.

Figure 29A indicates that the percent swell for frozen and unfrozen samples, compacted to standard Proctor compactive effort, decreases with increasing moulding moisture content. For samples compacted to modified Proctor compactive effort, the percent swell reaches a maximum value at optimum moulding moisture content and then decreases on either side of optimum as shown in Figure 30A. Figure 30A also indicates that the percent swell decreases more rapidly for samples compacted wet of optimum than for samples compacted dry of optimum. Figures 29A and 30A show that frozen and unfrozen samples compacted to modified Proctor compactive effort displayed a greater percent swell than samples compacted to standard Proctor compactive effort.

The percent swell as detailed in Figures 29A and 30A was calculated as shown below.

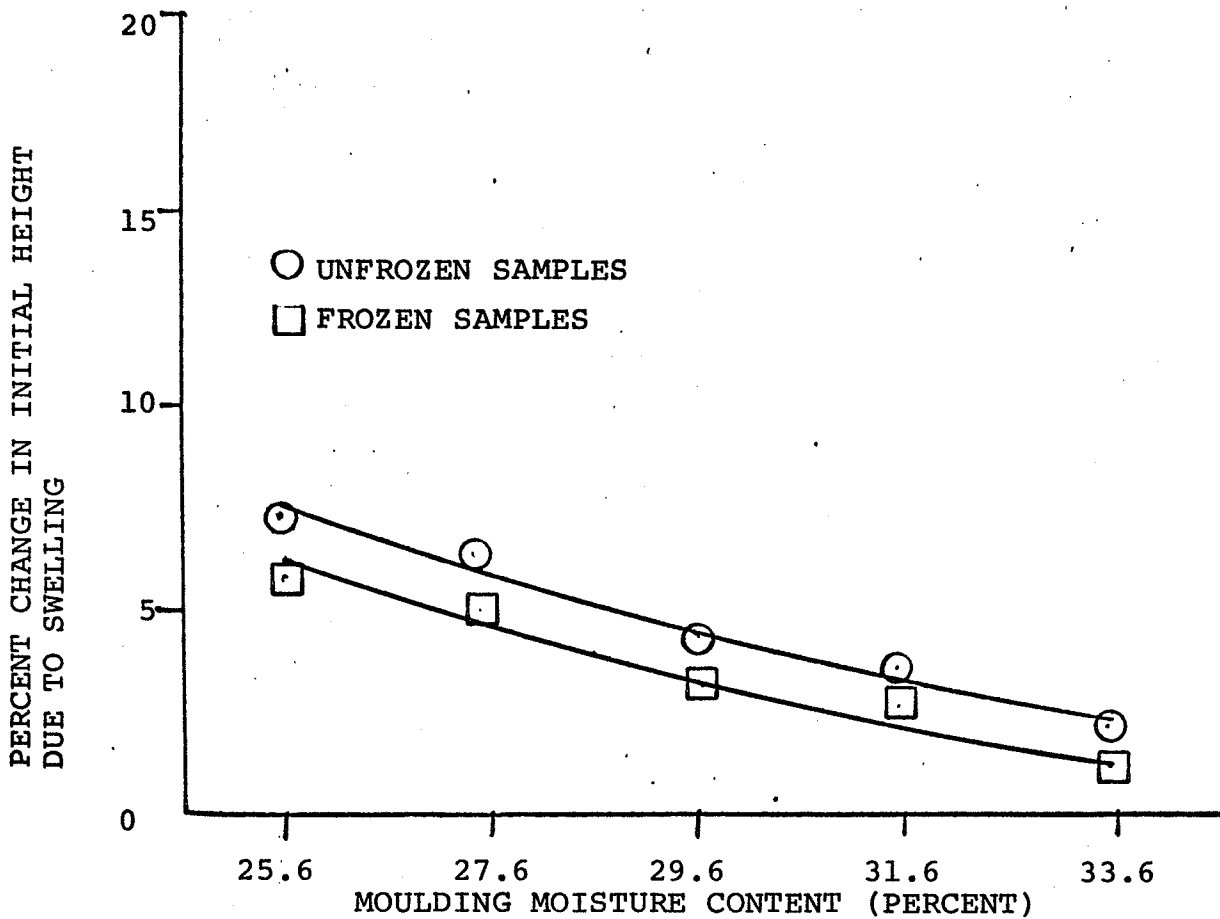


FIGURE 29A
PERCENT CHANGE IN INITIAL HEIGHT DUE TO SWELLING FOR FROZEN AND UNFROZEN SAMPLES AT VARYING MOULDING MOISTURE CONTENTS COMPACTED TO STANDARD PROCTOR OR COMPACTIVE EFFORT.

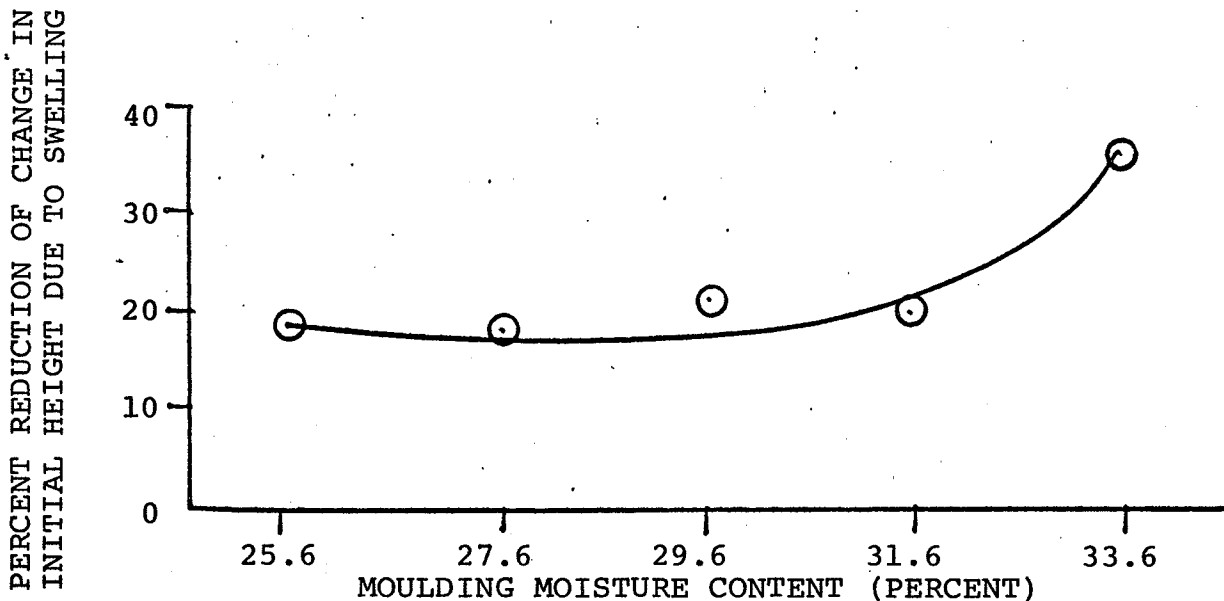


FIGURE 29B
PERCENT REDUCTION IN THE CHANGE OF INITIAL HEIGHT OF UNFROZEN SAMPLES, DUE TO SWELLING, CAUSED BY ONE FREEZE-THAW CYCLE VERSUS MOULDING MOISTURE CONTENT FOR SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

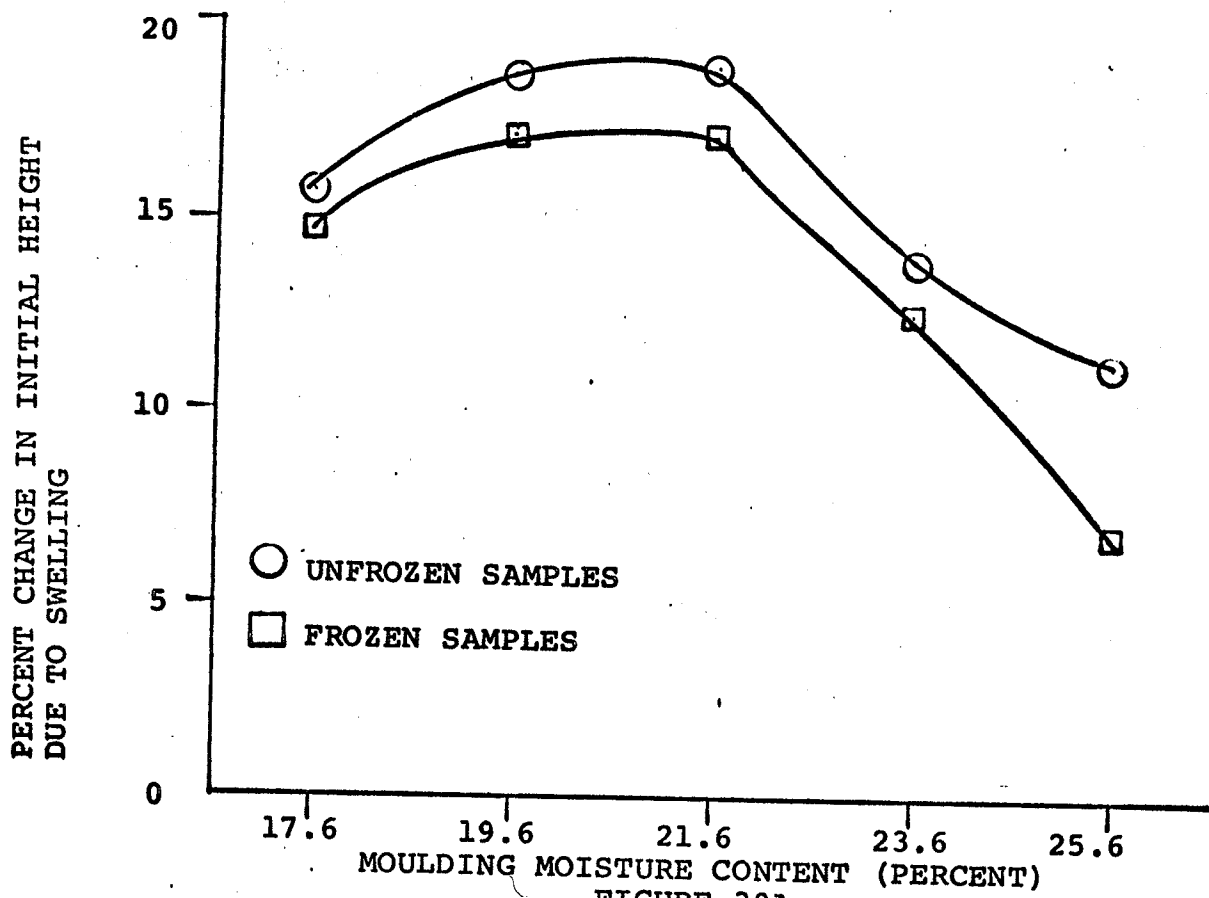


FIGURE 30A.
 PERCENT CHANGE IN INITIAL HEIGHT DUE TO SWELLING FOR FROZEN AND UNFROZEN SAMPLES AT VARYING MOULDING MOISTURE CONTENTS COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

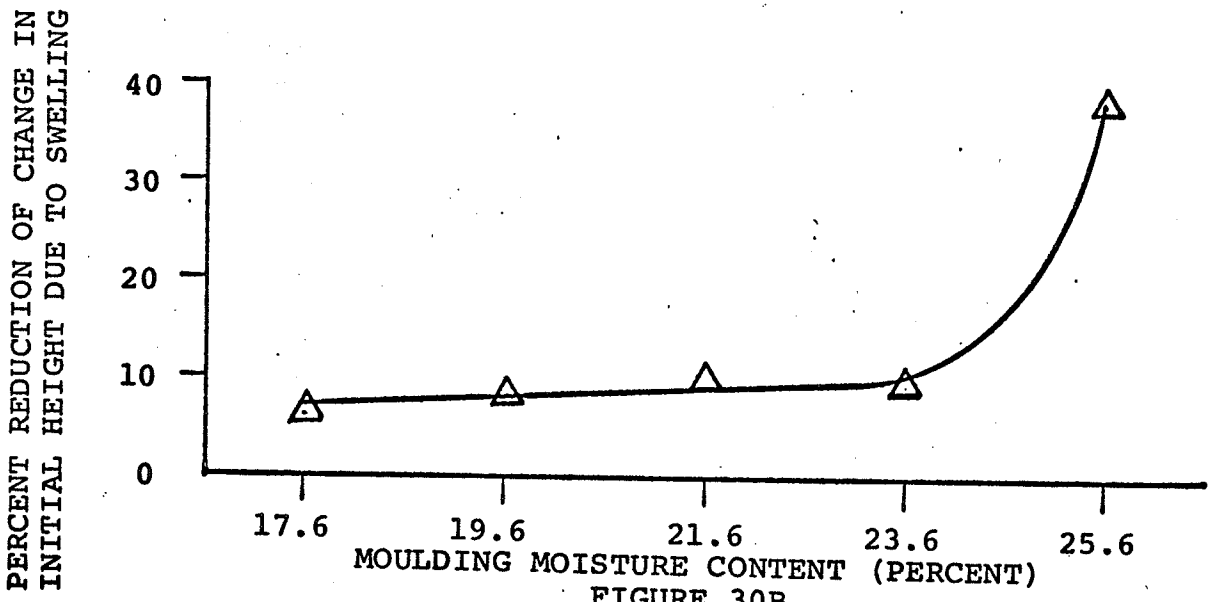


FIGURE 30B
 PERCENT REDUCTION IN THE CHANGE OF INITIAL HEIGHT OF UNFROZEN SAMPLES DUE TO SWELLING, CAUSED BY ONE FREEZE-THAW CYCLE, VERSUS MOULDING MOISTURE CONTENT FOR SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

$$\text{PERCENT SWELL} = \frac{H}{H_0} \times 100\%$$

WHERE: H change in initial height due to swelling.

H_0 initial height of consolidation sample.

The difference in the amount of swell displayed by frozen and unfrozen samples versus moulding moisture content for standard and modified compactive efforts is shown in Figures 29B and 30B. Figure 29B indicates that the samples compacted to standard Proctor compactive effort and subjected to one freeze-thaw cycle displayed approximately 20 percent reduction in swell when compared to similar unfrozen samples. The reduction in the amount of swell is indicated to be relatively constant at 20 percent for all samples except those compacted 4 percent wet of optimum. Samples compacted at 4 percent wet of optimum showed a 40 percent reduction in swell height. Figure 30B shows the reduction in swell between frozen and unfrozen samples compacted to standard Proctor compactive effort. Figure 30A shows that frozen samples swell less than similar unfrozen samples. From Figure 30B it appears that the percent reduction in swell is fairly constant for all samples except those compacted at 4 percent wet of optimum. Samples compacted 4 percent wet of optimum showed that unfrozen samples exhibited 40 percent less swell than did similar frozen samples.

The reduction in swell between frozen and unfrozen samples as used in Figures 29B and 30B was calculated as shown below.

$$\text{PERCENT REDUCTION IN SWELL} = \frac{H_{su} - H_{sf}}{H_{su}} \times 100\%$$

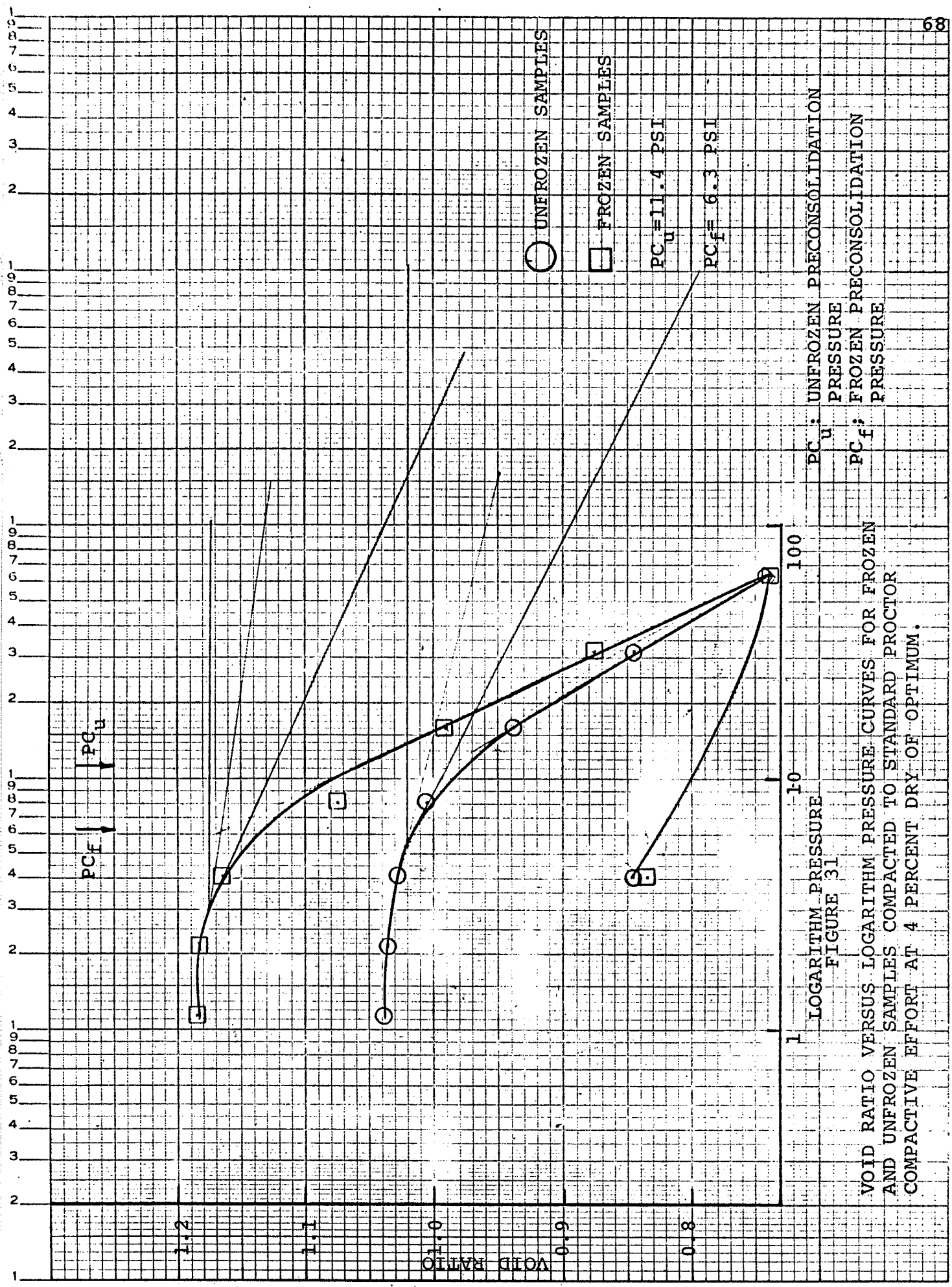
WHERE: H_{su} is the change in initial height due to swell for unfrozen samples.

H_{sf} is the change in height due to swell for frozen samples.

Void ratio versus logarithm pressure curves for all samples investigated were constructed. The preconsolidation pressures for the various frozen and unfrozen samples were calculated using Casagrande's method as outlined in Foundation Engineering by Leonards¹⁵.

The void ratio, logarithm pressure curves and the corresponding preconsolidation pressures for frozen and unfrozen samples compacted to standard and modified Proctor efforts are shown in Figures 31 to 40. Figures 31 to 35 apply to samples that were compacted to standard Proctor compactive effort. Figures 36 to 40 were based on samples compacted to modified Proctor compactive effort.

The preconsolidation pressures for the various frozen and unfrozen samples were plotted against moulding moisture content, and the resulting curves are shown in Figures 41 and 42. Figure 41 shows the relationship between the preconsolidation pressure and the moulding moisture content for frozen and unfrozen samples compacted to standard Proctor compactive effort. Figure 42 details the above noted relationship for frozen and unfrozen samples compacted to modified Proctor compactive effort. Figures 41 and 42 indicate that, for the samples studied, the frozen samples displayed less preconsolidation pressure than did similar unfrozen samples. Although there is some scatter of data, Figure 41 indicates that the preconsolidation pressure for frozen and unfrozen samples compacted to standard Proctor compactive effort increases with increasing moulding moisture content to a maximum value at the optimum moisture content, and thereafter remains relatively constant. The preconsolidation pressure for unfrozen and frozen samples compacted to modified Proctor compactive effort increases with increasing moulding moisture content to a maximum value for samples compacted at 2 percent wet of optimum; it then decreases.



UNFROZEN SAMPLES
 FROZEN SAMPLES
 $PC_u = 11.4$ PSI
 $PC_f = 6.3$ PSI

LOGARITHM PRESSURE
 FIGURE 31
 VOID RATIO VERSUS LOGARITHM PRESSURE CURVES FOR FROZEN
 AND UNFROZEN SAMPLES COMPACTED TO STANDARD PROCTOR
 COMPACTIVE EFFORT AT 4 PERCENT DRY OF OPTIMUM.

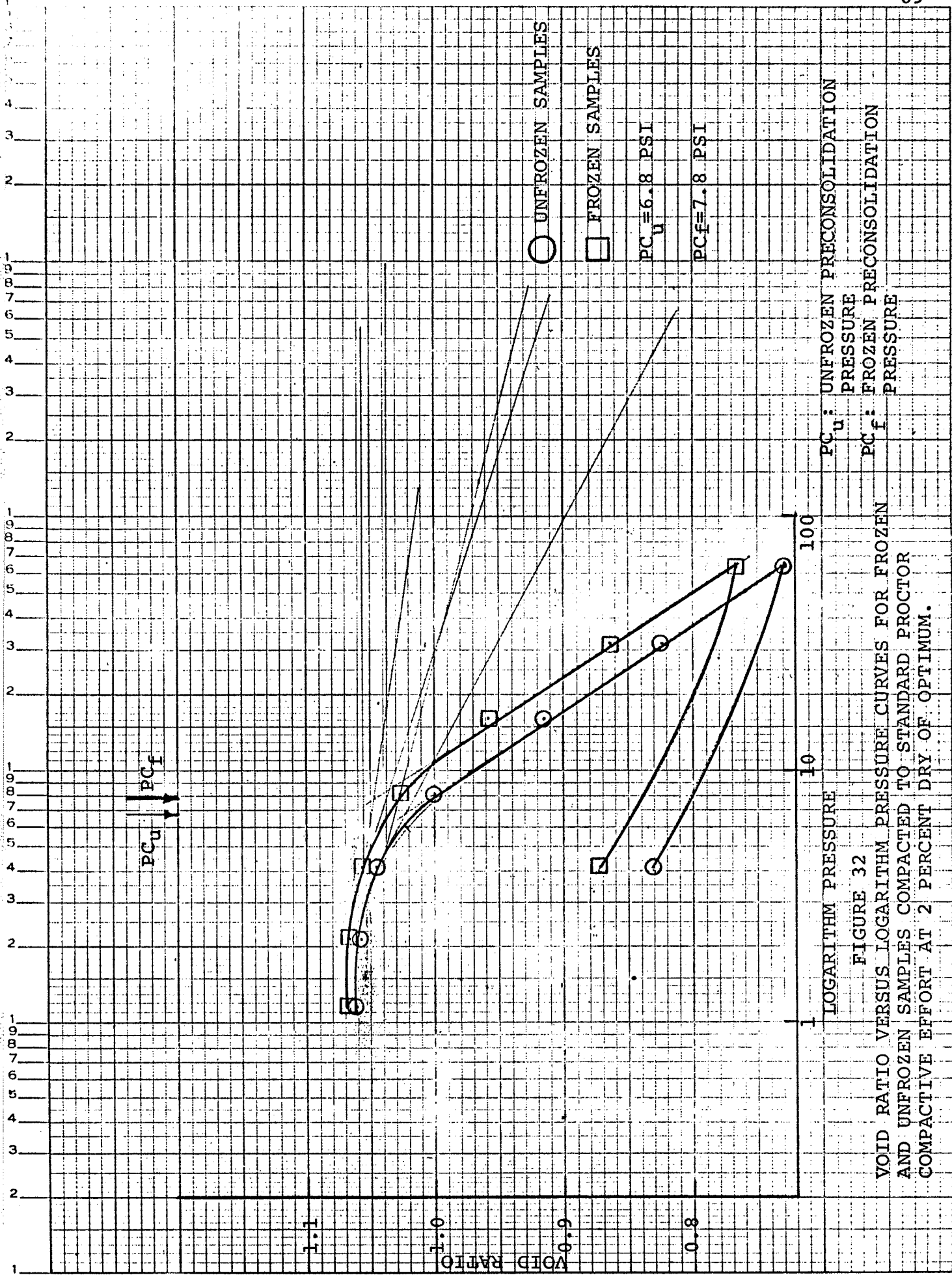


FIGURE 32
 VOID RATIO VERSUS LOGARITHM PRESSURE CURVES FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT AT 2 PERCENT DRY OF OPTIMUM.

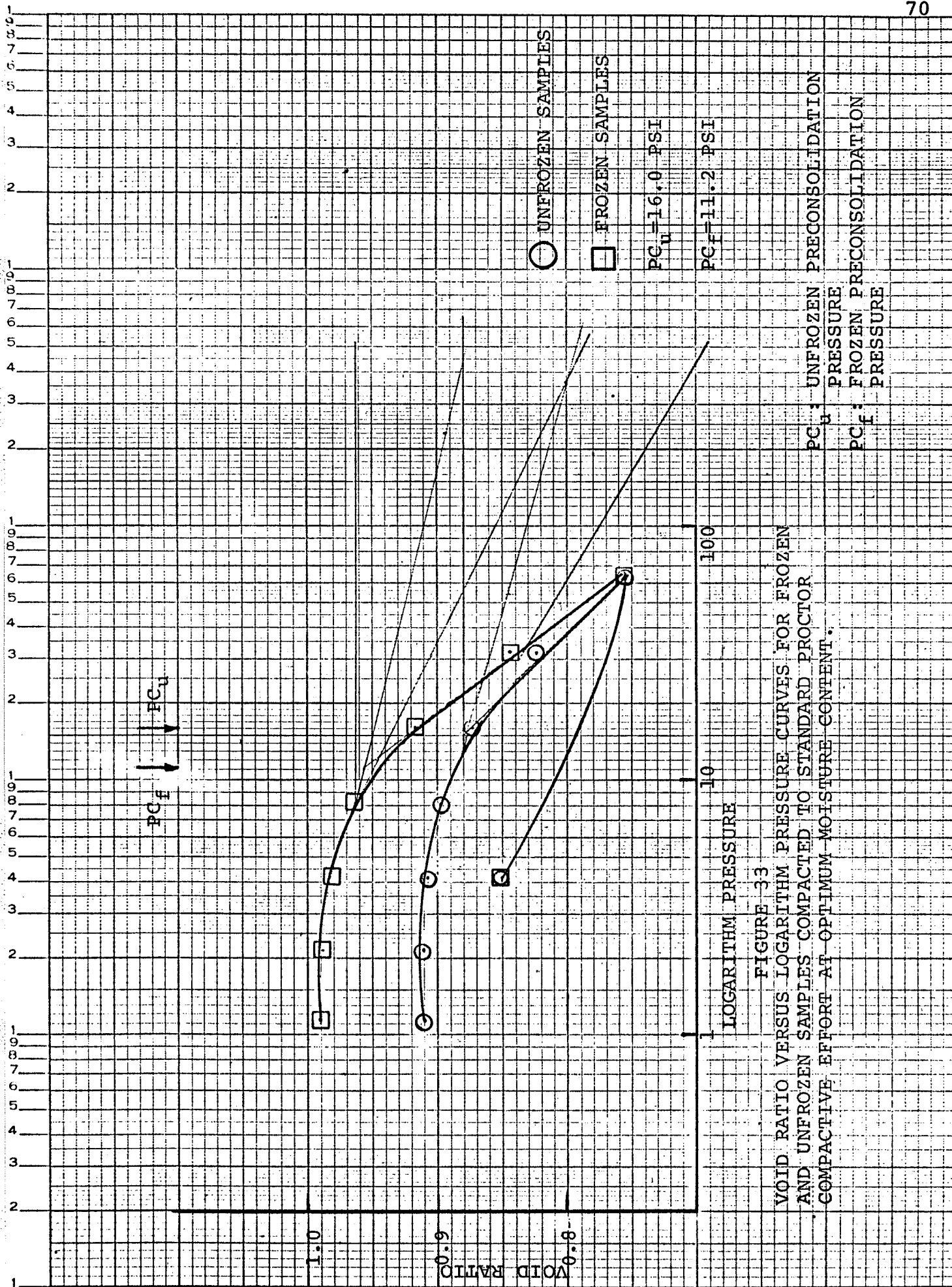
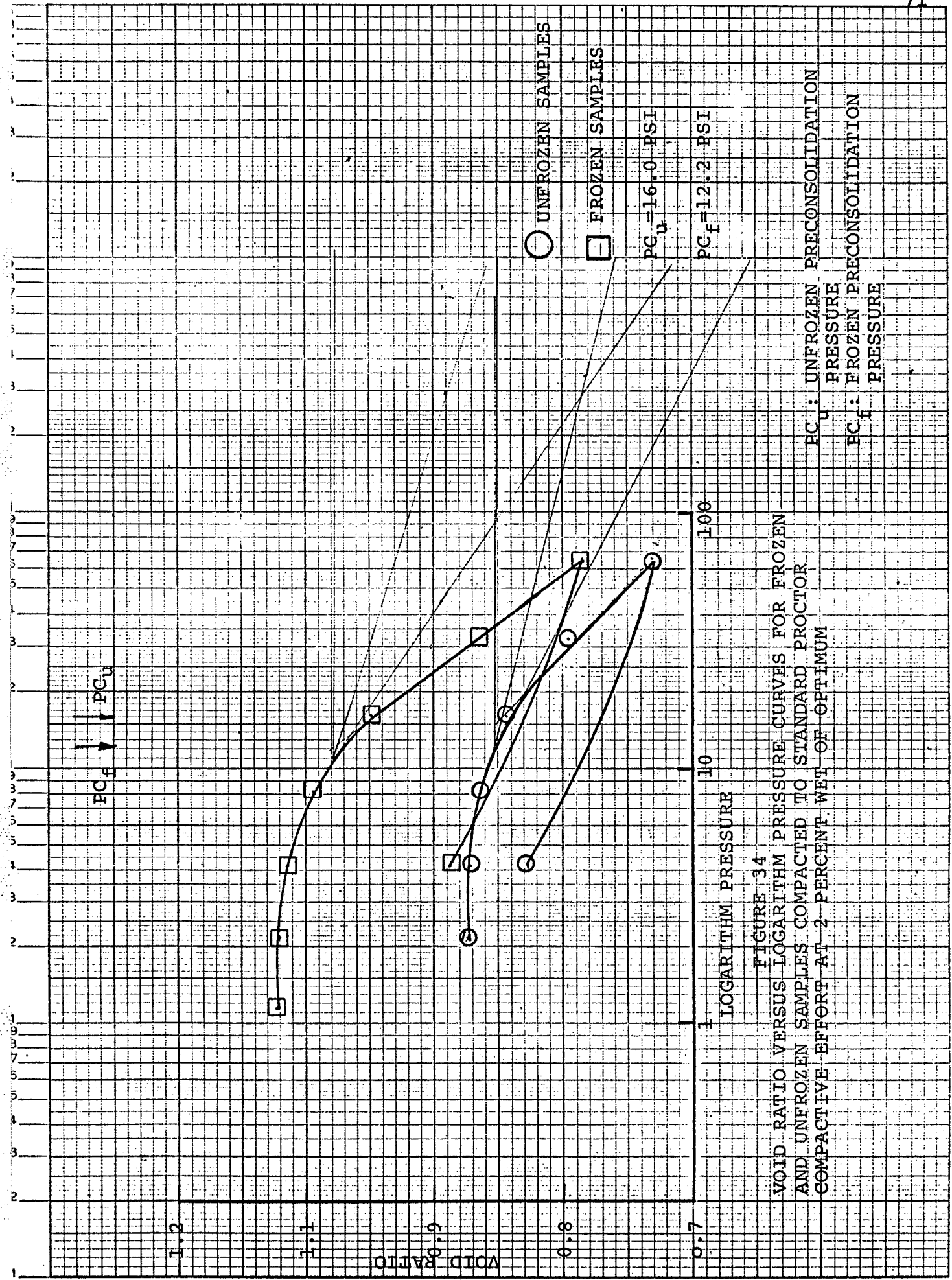
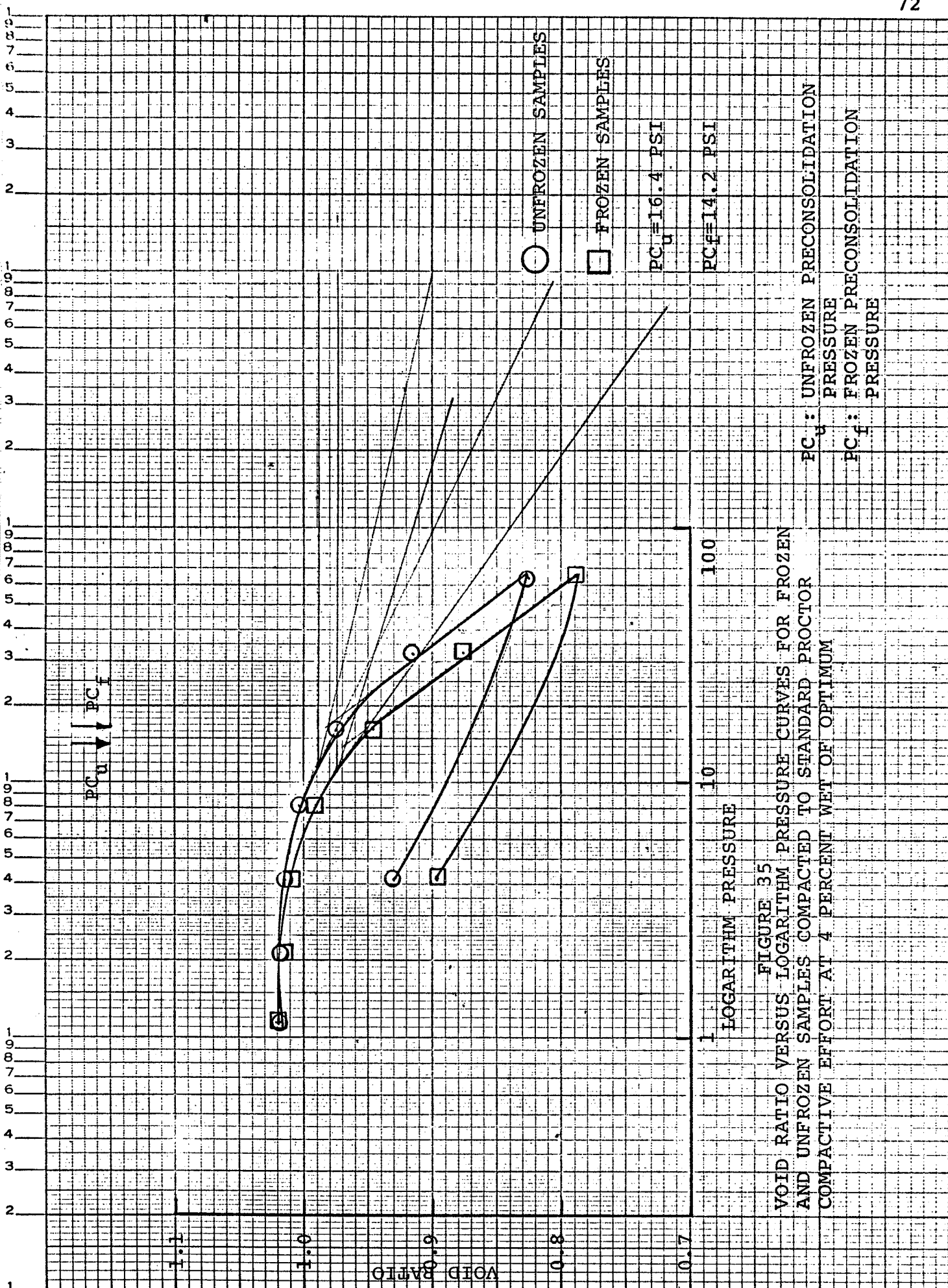


FIGURE 33
VOID RATIO VERSUS LOGARITHM PRESSURE CURVES FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT AT OPTIMUM MOISTURE CONTENT.

UNFROZEN SAMPLES
FROZEN SAMPLES
 $PC_u = 16.0$ PSI
 $PC_f = 11.2$ PSI
UNFROZEN PRECONSOLIDATION PRESSURE
FROZEN PRECONSOLIDATION PRESSURE





ARITHMIC, 5 CYCLES X 10 TO THE INCH
5TH LINES ACCENTED

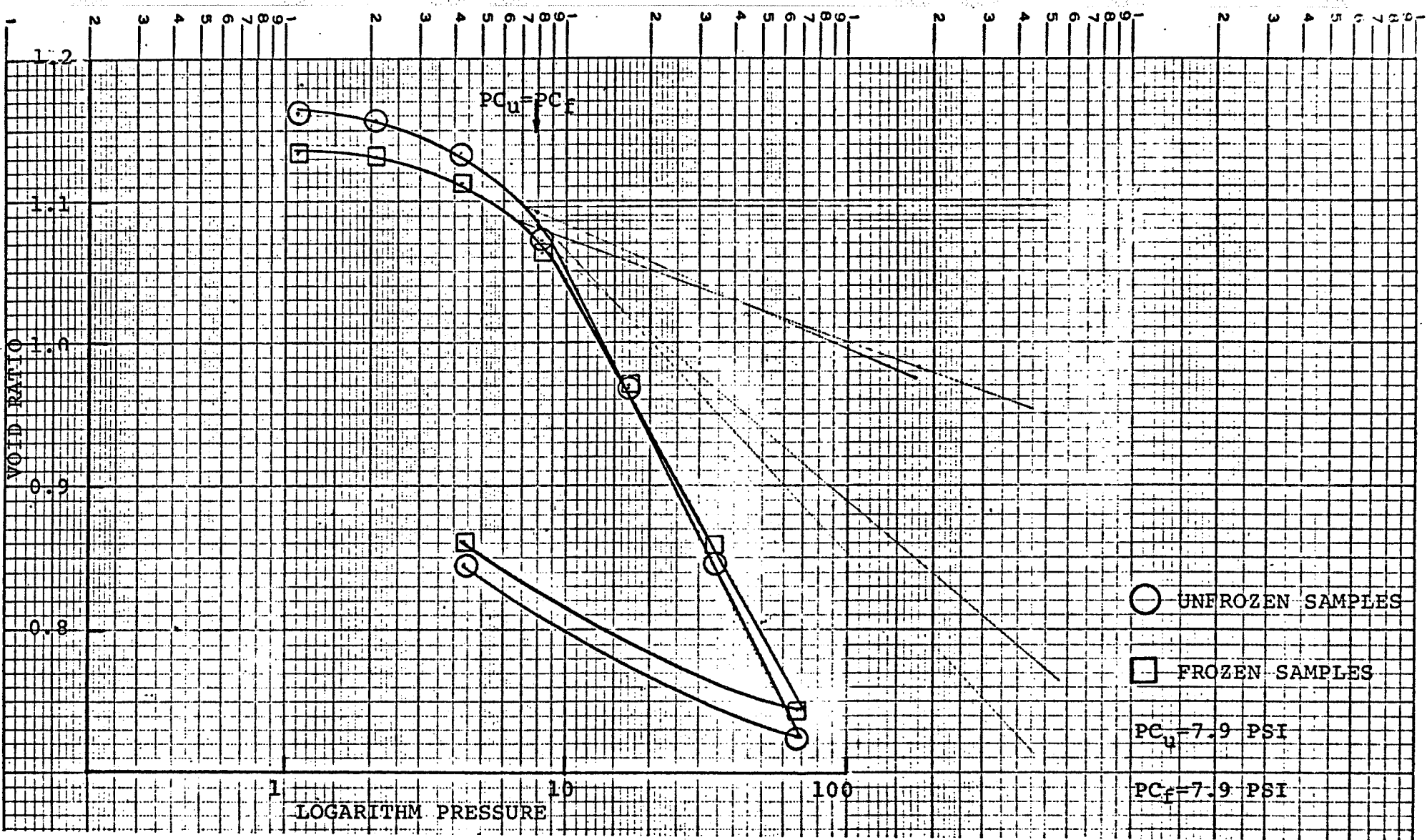


FIGURE 36
VOID RATIO VERSUS LOGARITHM PRESSURE CURVES FOR FROZEN
AND UNFROZEN SAMPLES COMPACTED TO MODIFIED PROCTOR
COMPACTIVE EFFORT AT 4 PERCENT DRY OF OPTIMUM.

PC_u : UNFROZEN PRECONSOLIDATION
PRESSURE
 PC_f : FROZEN PRECONSOLIDATION
PRESSURE

ARITHMIC 5 CYCLES X 10 TO THE INCH
5TH LINES ACCENTED

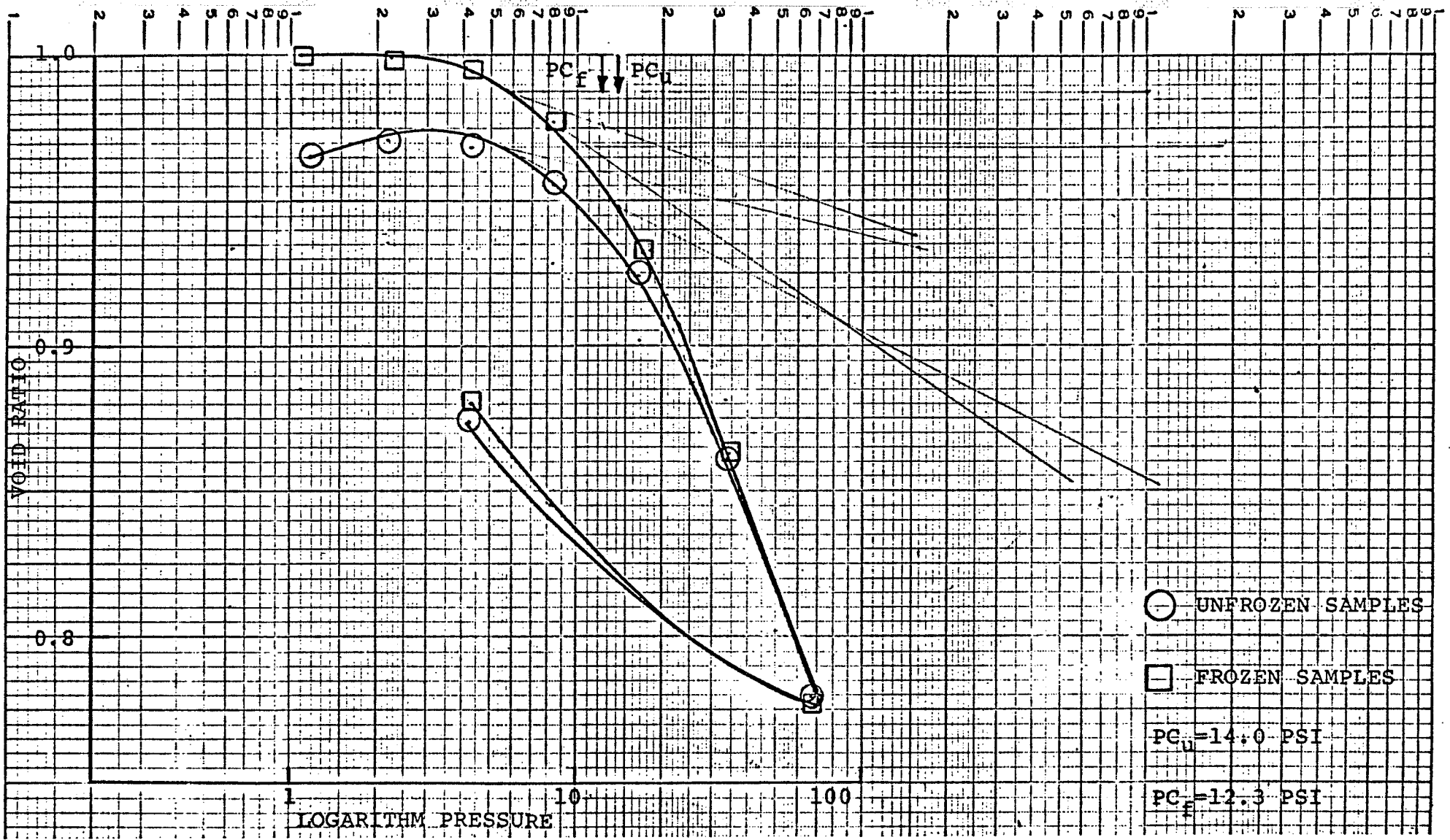


FIGURE 37

VOID RATIO VERSUS LOGARITHM PRESSURE CURVES FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT AT 2 PERCENT DRY OF OPTIMUM.

PC_u : UNFROZEN PRECONSOLIDATION PRESSURE
 PC_f : FROZEN PRECONSOLIDATION PRESSURE

ARITHMIC, 5 CYCLES X 10 TO THE INCH
5TH LINE(S) ACCENTED

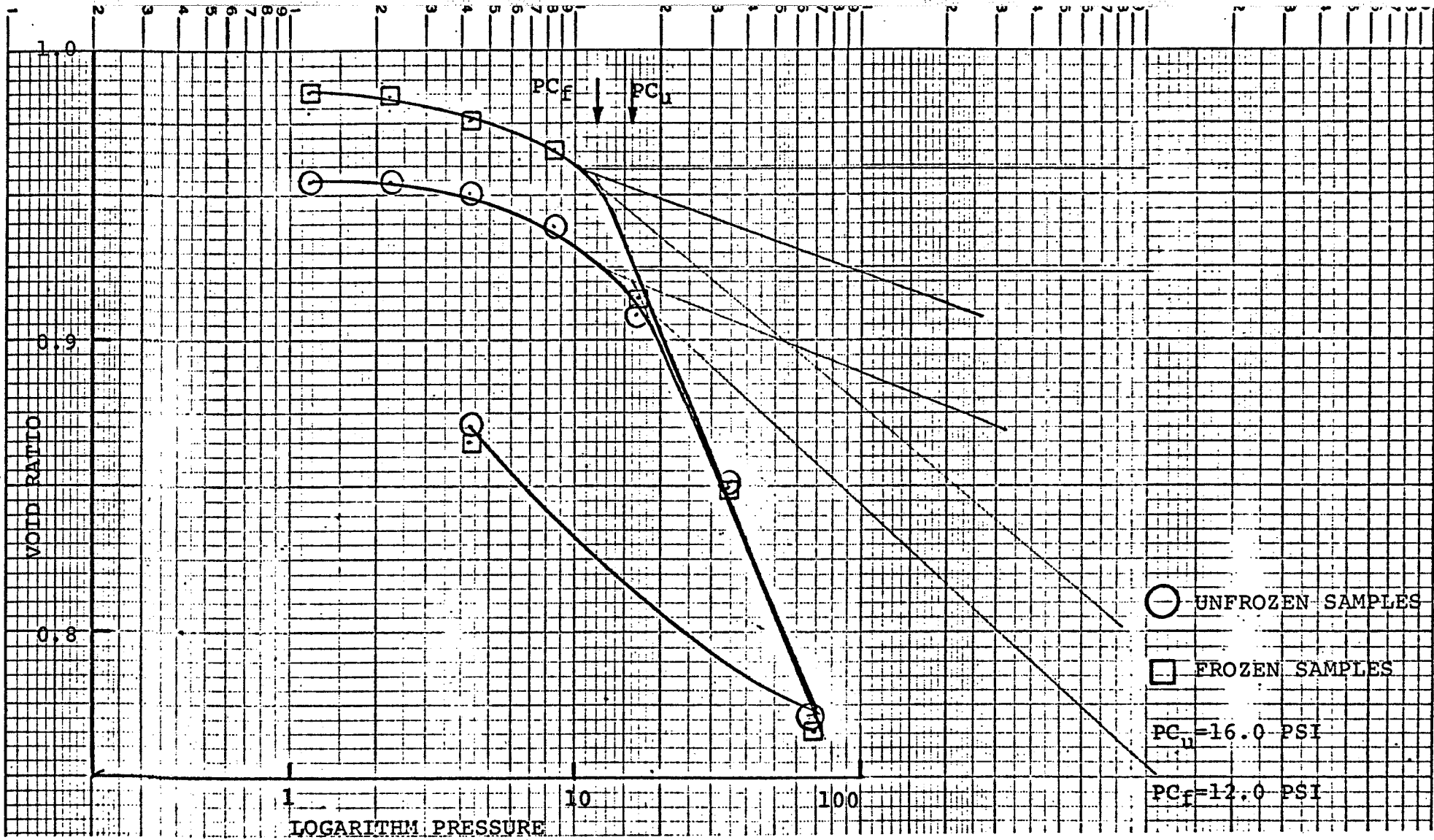


FIGURE 38
VOID RATIO VERSUS LOGARITHM PRESSURE CURVES FOR FROZEN
AND UNFROZEN SAMPLES COMPACTED TO MODIFIED PROCTOR
COMPACTIVE EFFORT AT OPTIMUM MOISTURE CONTENT.

PC_u : UNFROZEN PRECONSOLIDATION
PRESSURE
 PC_f : FROZEN PRECONSOLIDATION
PRESSURE

ARITHMIC: 5 CYCLES X 10 TO THE INCH
5TH LINES ACCENTED

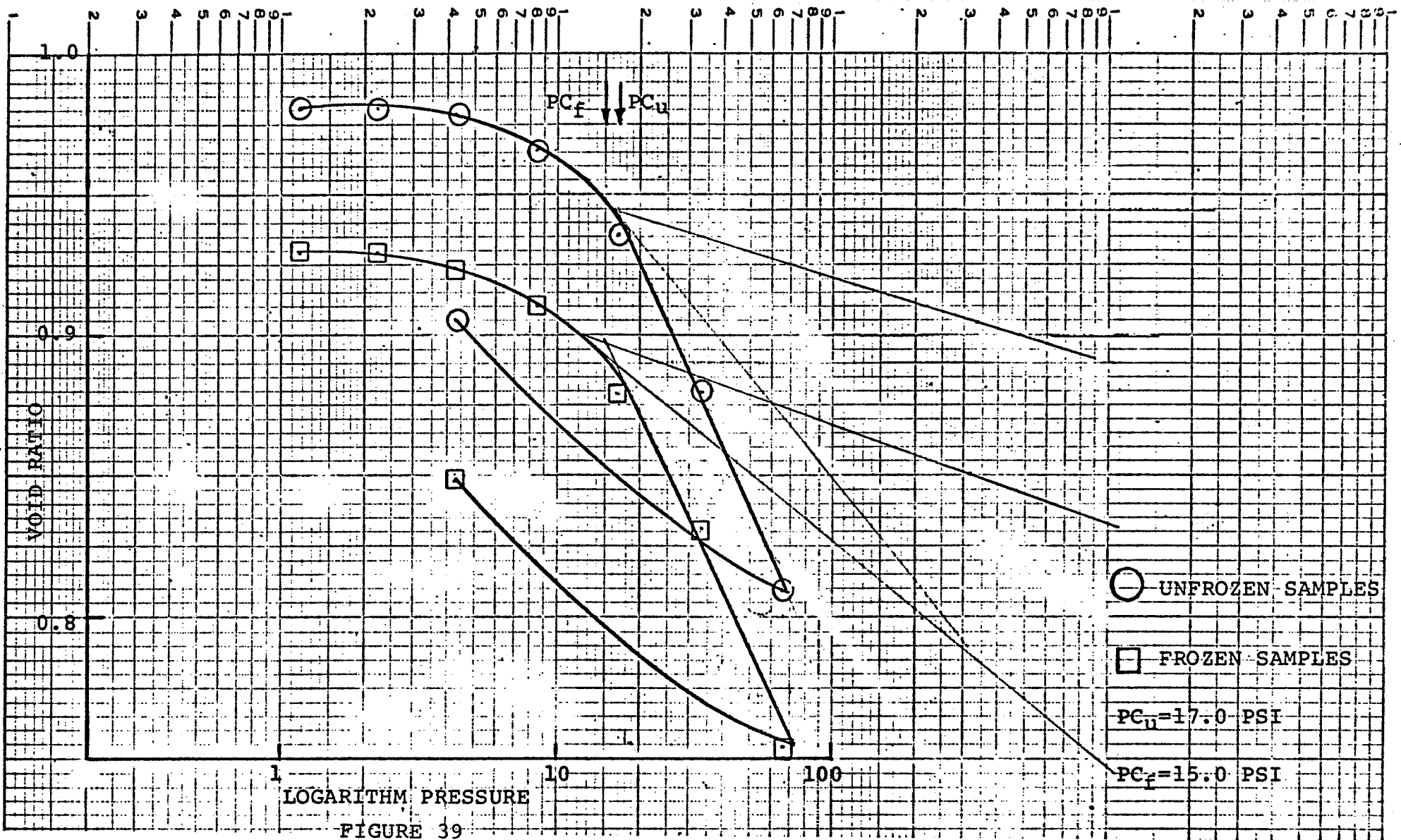


FIGURE 39

VOID RATIO VERSUS LOGARITHM PRESSURE CURVES FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT AT 2 PERCENT WET OF OPTIMUM.

PC_u : UNFROZEN PRECONSOLIDATION PRESSURE
 PC_f : FROZEN PRECONSOLIDATION PRESSURE

ARITHMIC, 5 CYCLES X 10 TO THE INCH
5TH LINES ACCENTED

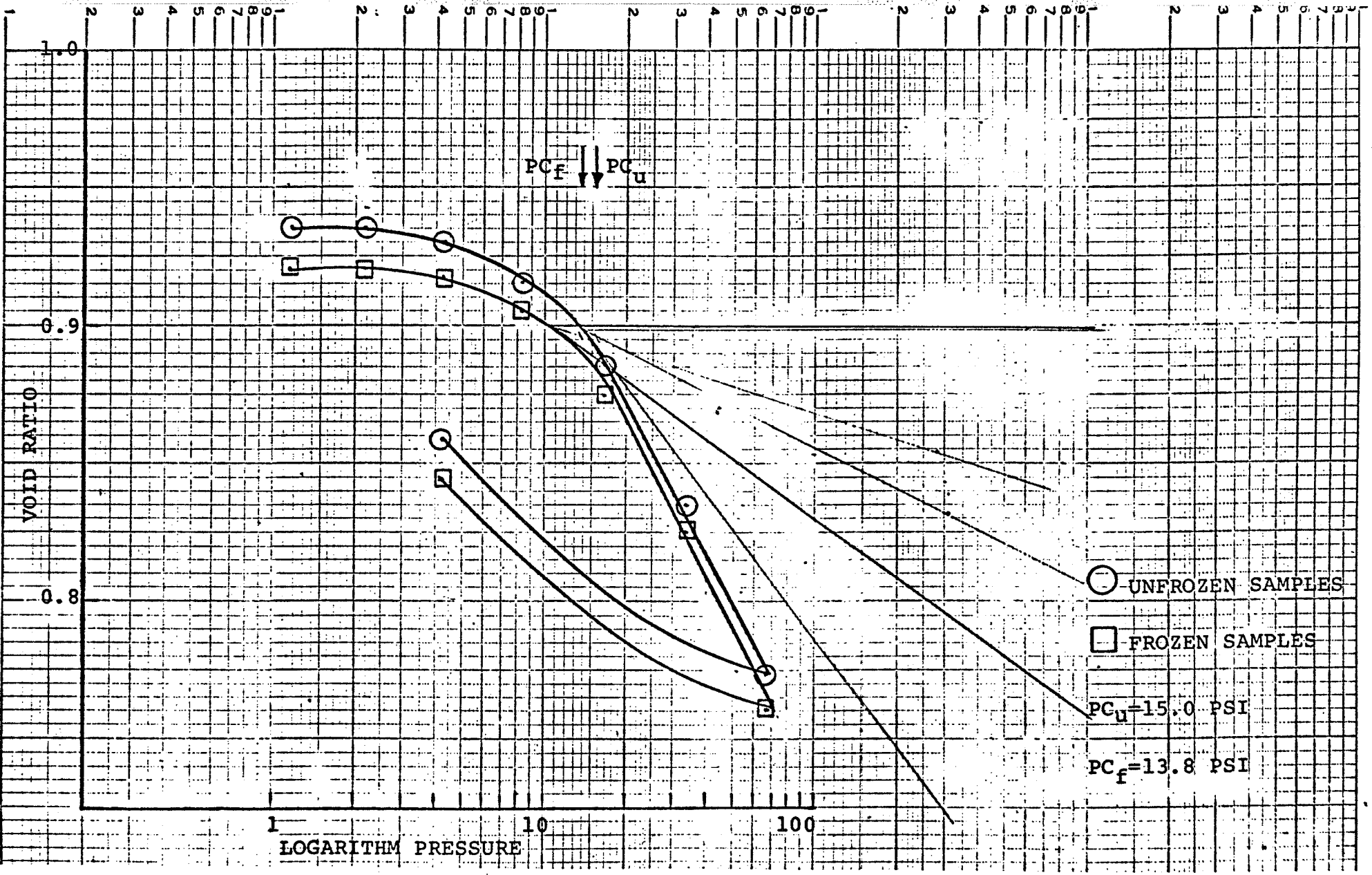


FIGURE 40
VOID RATIO VERSUS LOGARITHM PRESSURE CURVES FOR FROZEN
AND UNFROZEN SAMPLES COMPACTED TO MODIFIED PROCTOR
COMPACTIVE EFFORT AT 4 PERCENT WET OF OPTIMUM

PC_u : UNFROZEN PRECONSOLIDATION
PRESSURE
 PC_f : FROZEN PRECONSOLIDATION
PRESSURE

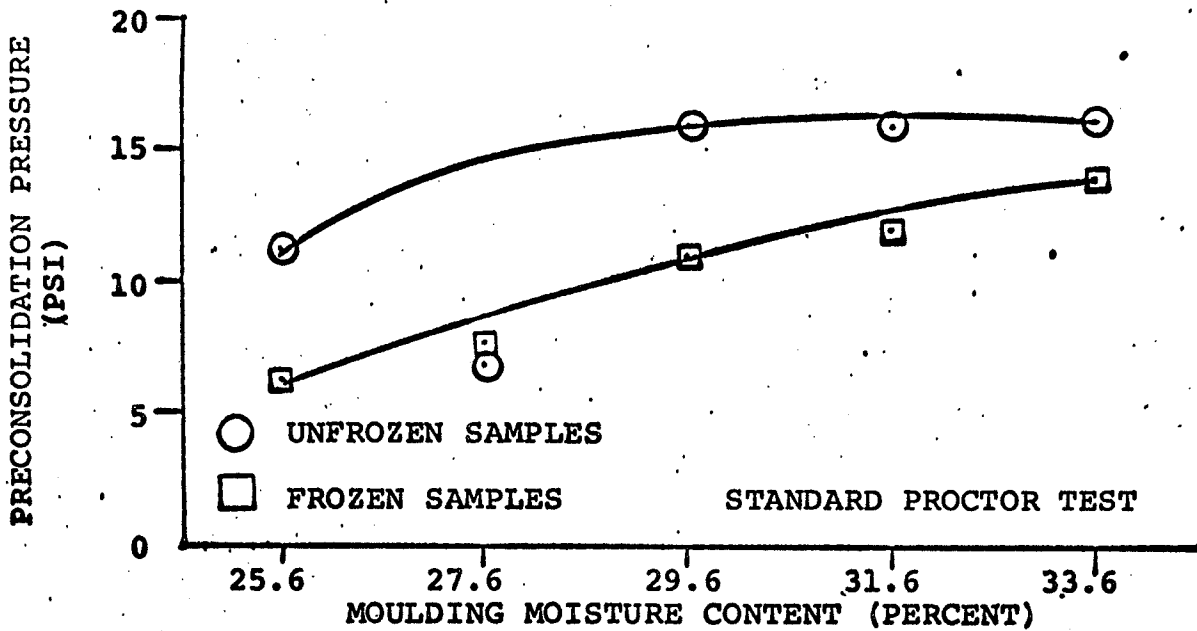


FIGURE 41

PRECONSOLIDATION PRESSURE VERSUS MOULDING MOISTURE CONTENT FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO STANDARD PROCTOR COMPACTIVE EFFORT.

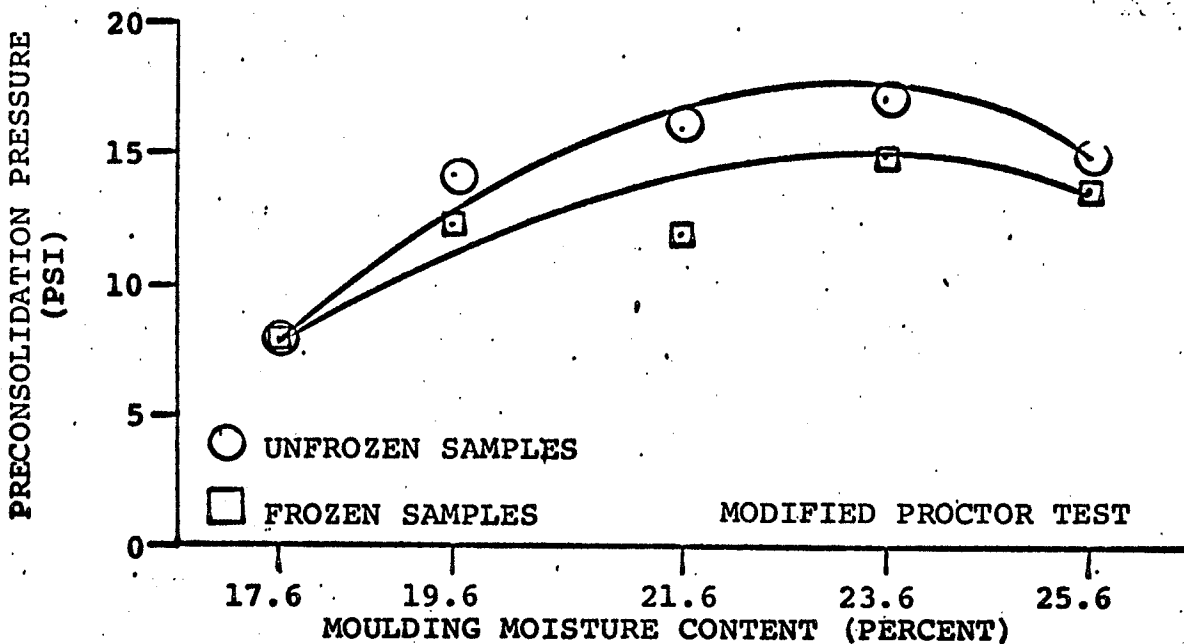


FIGURE 42

PRECONSOLIDATION PRESSURE VERSUS MOULDING MOISTURE CONTENT FOR FROZEN AND UNFROZEN SAMPLES COMPACTED TO MODIFIED PROCTOR COMPACTIVE EFFORT.

The difference in preconsolidation pressure between frozen and unfrozen samples for specimens compacted to standard Proctor compactive effort is greatest dry of optimum and decreases with increasing moulding moisture content. This difference is generally constant for frozen and unfrozen samples compacted to modified Proctor compactive effort.

In the following discussion, three soil characteristics pertaining to one dimensional consolidation tests are examined for standard and modified compactive efforts. The three characteristics are coefficient of consolidation, coefficient of compressibility and coefficient of permeability. These coefficients were studied because they are important practical soil parameters and are easily obtained from the one dimensional consolidation test. It should be noted that the various parameters were plotted against moulding moisture content for only certain load increments. The reason for this is that the amount of scatter of data for those load increments not shown was so great that no general trend could be developed in the plots. The load increments that produced the scatter were the load increments of least magnitude.

The coefficient of consolidation is the first parameter that was examined. The coefficient of consolidation is a value obtained from one dimensional consolidation theory and is a function of the permeability, compressibility, void ratio and unit weight of water.

The coefficient of consolidation versus moulding moisture content for various load increments for frozen and unfrozen samples compacted to standard and modified compactive efforts is shown in Figures 43 and 44. Figure 43 pertains to those samples compacted to standard Proctor compactive effort, and Figure 44 to those samples compacted to modified Proctor compactive effort.

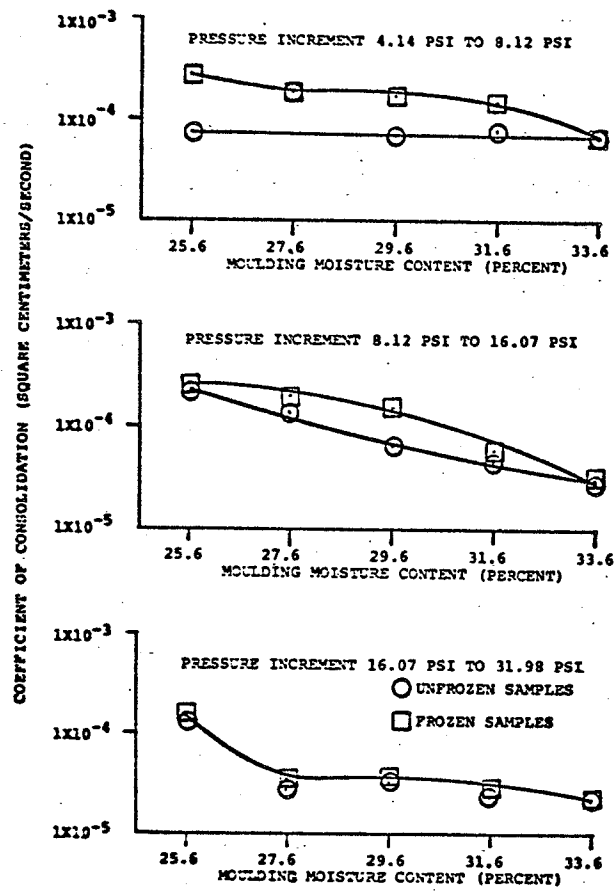


FIGURE 43A
 COEFFICIENT OF CONSOLIDATION VERSUS
 MOULDING MOISTURE CONTENT AT VARY-
 ING PRESSURE INCREMENTS FOR FROZEN
 AND UNFROZEN SAMPLES COMPACTED TO
 STANDARD PROCTOR COMPACTIVE EFFORT.

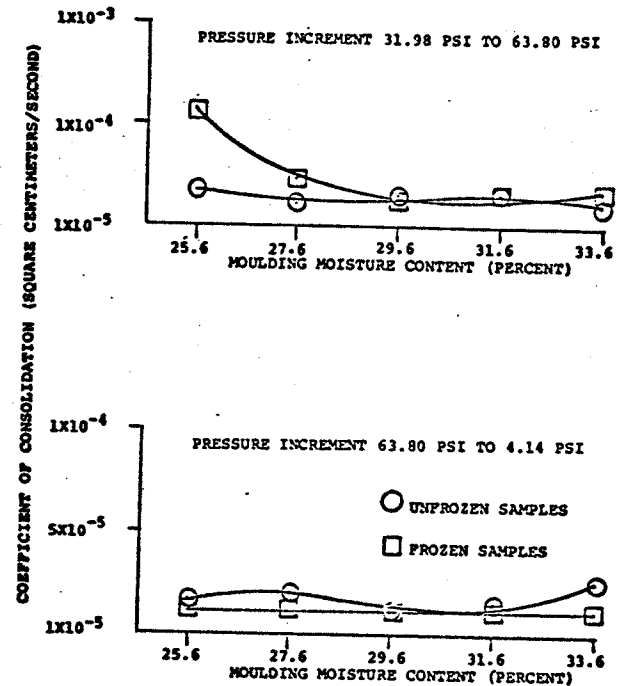


FIGURE 43B
 COEFFICIENT OF CONSOLIDATION VERSUS
 MOULDING MOISTURE CONTENT AT VARY-
 ING PRESSURE INCREMENTS FOR FROZEN
 AND UNFROZEN SAMPLES COMPACTED TO
 STANDARD PROCTOR COMPACTIVE EFFORT.

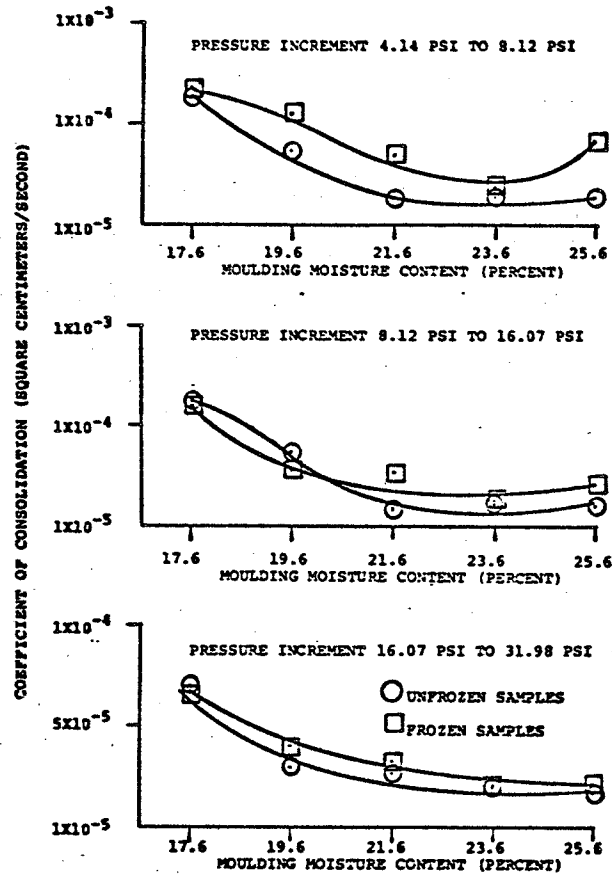


FIGURE 44A
 COEFFICIENT OF CONSOLIDATION VERSUS
 MOULDING MOISTURE CONTENT AT VARY-
 ING PRESSURE INCREMENTS FOR FROZEN
 AND UNFROZEN SAMPLES COMPACTED TO
 MODIFIED PROCTOR COMPACTIVE EFFORT.

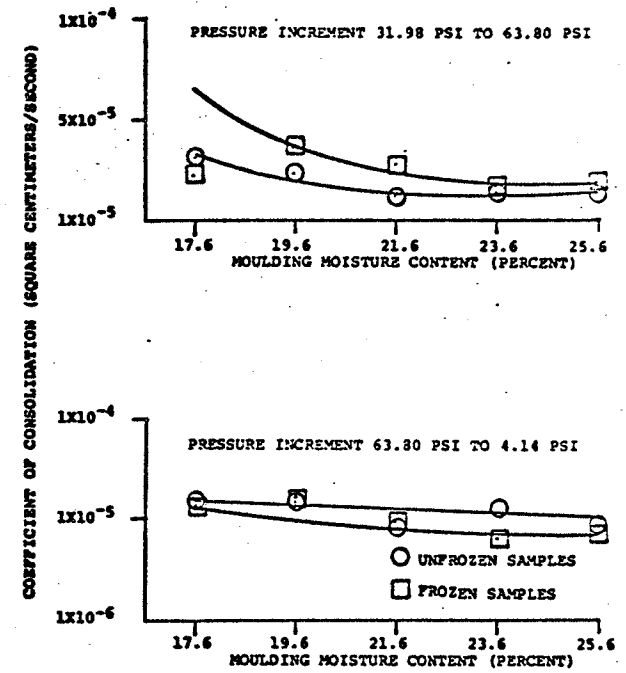


FIGURE 44B
 COEFFICIENT OF CONSOLIDATION VERSUS
 MOULDING MOISTURE CONTENT AT VARY-
 ING PRESSURE INCREMENTS FOR FROZEN
 AND UNFROZEN SAMPLES COMPACTED TO
 MODIFIED PROCTOR COMPACTIVE EFFORT.

Figure 43 and 44 both indicate that after one freeze-thaw cycle the coefficient of consolidation decreased with increasing load increments and decreased with a reduction in the applied load. The coefficient of consolidation generally decreases or remains the same with increasing moulding moisture content for frozen and unfrozen specimens compacted to standard and modified Proctor efforts and subjected to various load increments. At a given moulding moisture content the coefficient of consolidation appears to generally decrease for frozen and unfrozen samples with increasing load increments. The coefficient of consolidation is usually greater for frozen samples than for unfrozen samples. Figures 43 and 44 indicate that for the same load increment and relative moulding moisture content, the coefficient of consolidation is greater for those samples compacted to the lower of the two compactive efforts.

The coefficient of compressibility is defined as the average slope of the pressure-void ratio curve over the range of the load increment being considered. The relationship between the coefficient of compressibility and the moulding moisture content for frozen and unfrozen samples compacted to standard and modified compactive efforts is shown in Figures 45 and 46. The data presented in Figure 45 was provided by samples compacted to standard Proctor compactive effort. Figure 46 was based on data from samples compacted to modified Proctor compactive effort.

Figures 45 and 46 indicate that irrespective of load increment or moulding moisture content, one freeze-thaw cycle generally induces an increase or no change in the coefficient of compressibility. The coefficient of compressibility decreases or remains the same with increasing moulding moisture content at various load increments for frozen

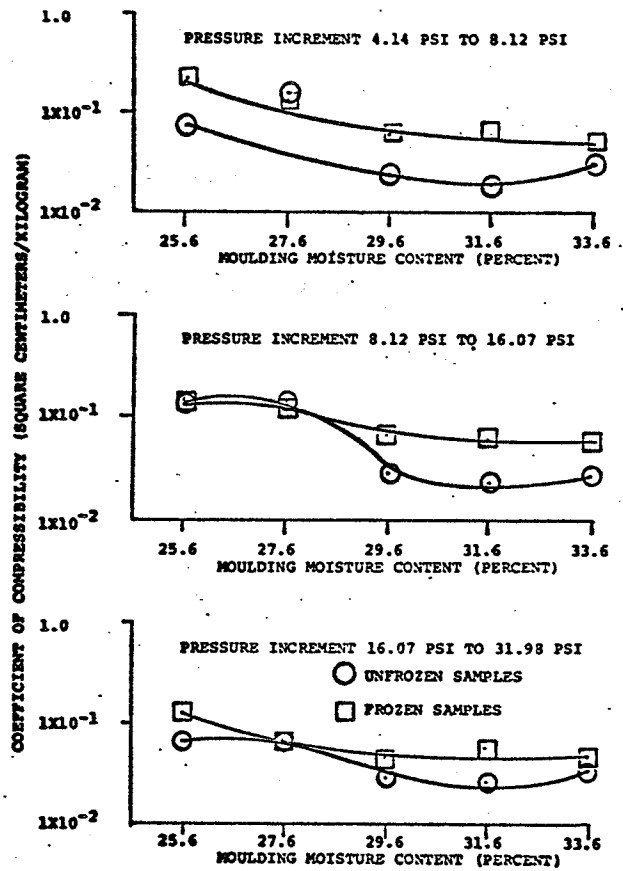


FIGURE 45A
 COEFFICIENT OF COMPRESSIBILITY VER-
 SUS MOULDING MOISTURE CONTENT AT
 VARYING PRESSURE INCREMENTS FOR
 FROZEN AND UNFROZEN SAMPLES COMPACT-
 ED TO STANDARD PROCTOR COMPACTIVE
 EFFORT.

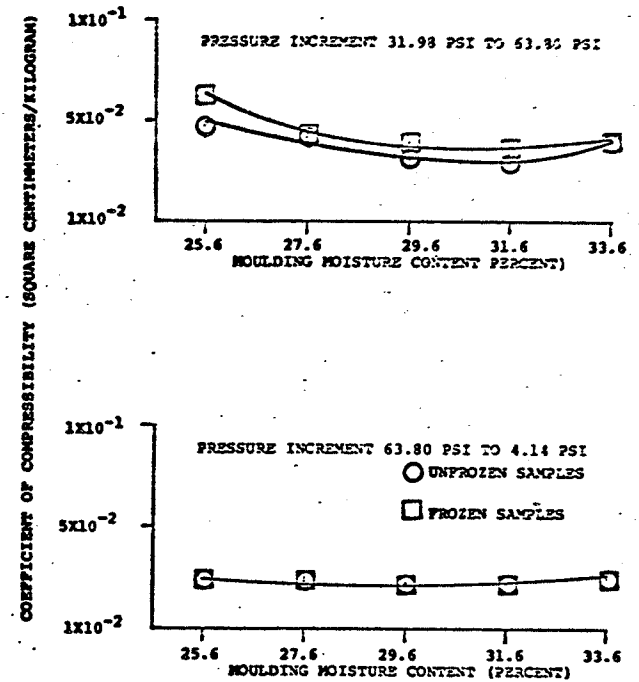


FIGURE 45B
 COEFFICIENT OF COMPRESSIBILITY VER-
 SUS MOULDING MOISTURE CONTENT AT
 VARYING PRESSURE INCREMENTS FOR
 FROZEN AND UNFROZEN SAMPLES COMPACT-
 ED TO STANDARD PROCTOR COMPACTIVE
 EFFORT.

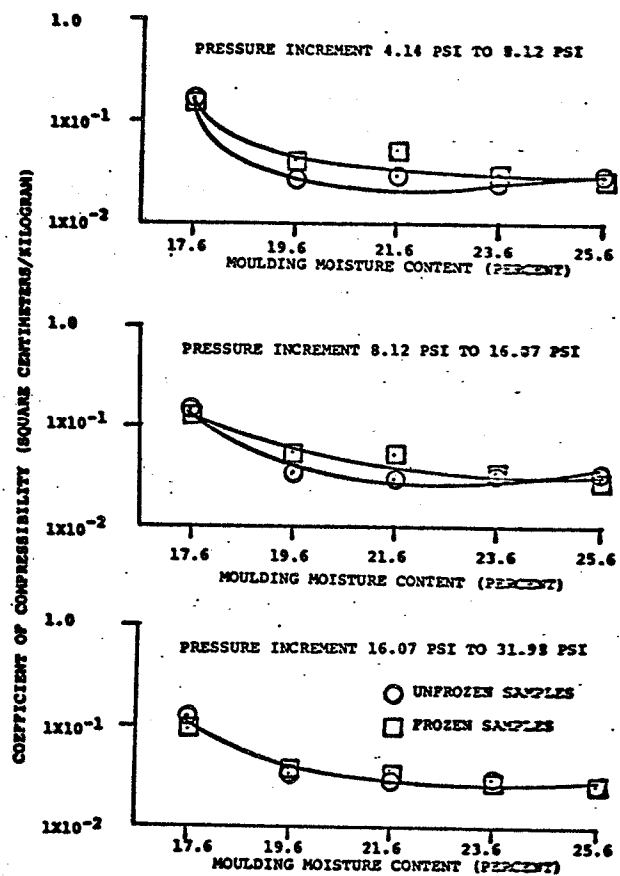


FIGURE 46A
 COEFFICIENT OF COMPRESSIBILITY VER-
 SUS MOULDING MOISTURE CONTENT AT
 VARYING PRESSURE INCREMENTS FOR
 FROZEN AND UNFROZEN SAMPLES COM-
 PACTED TO MODIFIED PROCTOR COMPACTI-
 VE EFFORT.

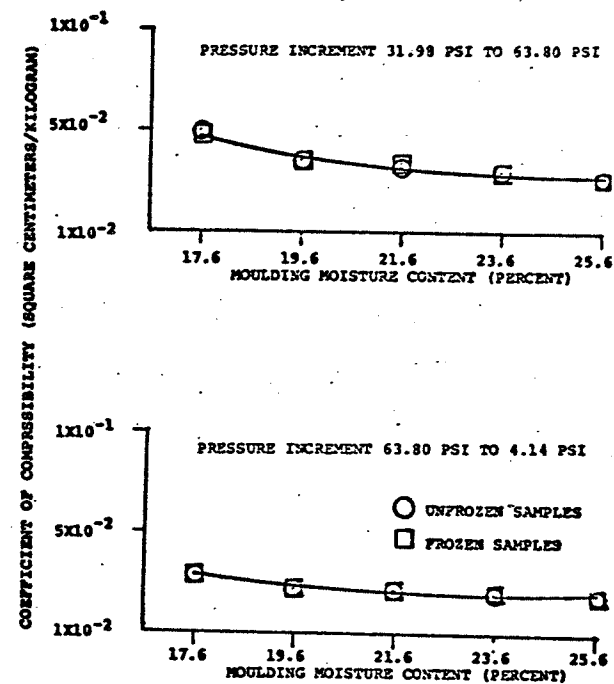


FIGURE 46B
 COEFFICIENT OF COMPRESSIBILITY VER-
 SUS MOULDING MOISTURE CONTENT AT
 VARYING PRESSURE INCREMENTS FOR
 FROZEN AND UNFROZEN SAMPLES COMPACT-
 ED TO MODIFIED PROCTOR COMPACTIVE
 EFFORT.

and unfrozen samples compacted to both modified and standard compactive efforts.

Based on the graphs presented in Figures 45 and 46, and consistent with consolidation theory, it appears that with increasing load increment at a given moulding moisture content, the coefficient of compressibility generally decreases.

The above noted trend appears to be most prominent for those samples compacted to standard Proctor compactive effort. The coefficient of compressibility for frozen and unfrozen samples at a particular load increment and moulding moisture content is generally greater for those samples compacted utilizing the lesser effort.

The coefficient of permeability, like the coefficient of consolidation, is a numerical value yielded by the theory of consolidation. The coefficient of permeability is a function of the coefficient of compressibility, height of the consolidation sample, unit weight of water, time and the void ratio of the sample.

Figures 47 and 48 detail the relationship between the coefficient of permeability and moulding moisture content at varying load increments for frozen and unfrozen samples compacted to both Proctor efforts. Figure 47 pertains to samples compacted to standard Proctor compactive effort and Figure 48 to those samples compacted to modified Proctor compactive effort. The above noted figures indicate that with increasing load increment, one freeze-thaw cycle generally produces an increase in the coefficient of permeability. For decreasing load increments, the coefficient of permeability decreases.

The coefficient of permeability for frozen and unfrozen samples generally decreases with increasing moulding moisture content for standard and modified compactive efforts regardless of load increment. Unfrozen

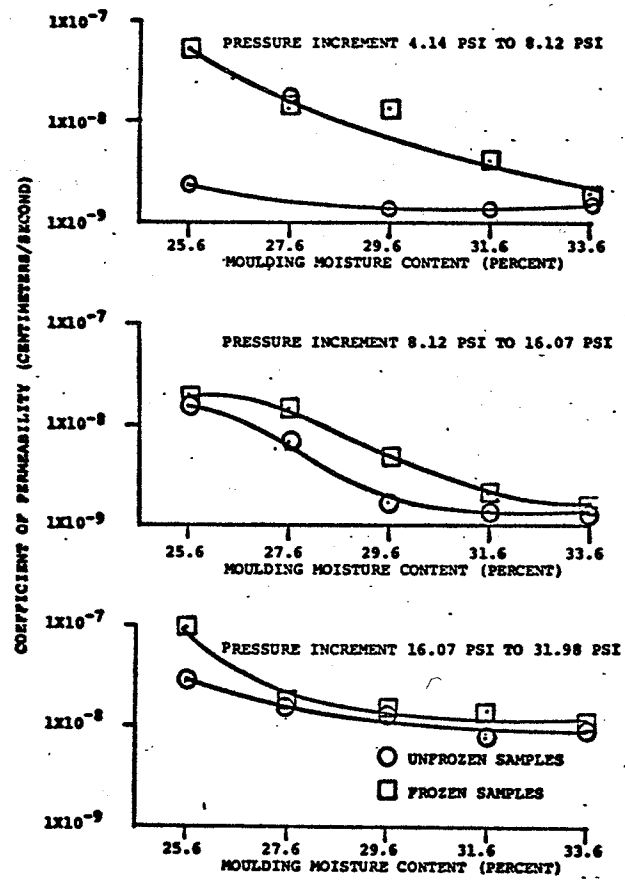


FIGURE 47A
 COEFFICIENT OF PERMEABILITY VER-
 SUS MOULDING MOISTURE CONTENT AT
 VARYING PRESSURE INCREMENTS FOR
 FROZEN AND UNFROZEN SAMPLES COM-
 PACTED TO STANDARD PROCTOR COM-
 PACTIVE EFFORT.

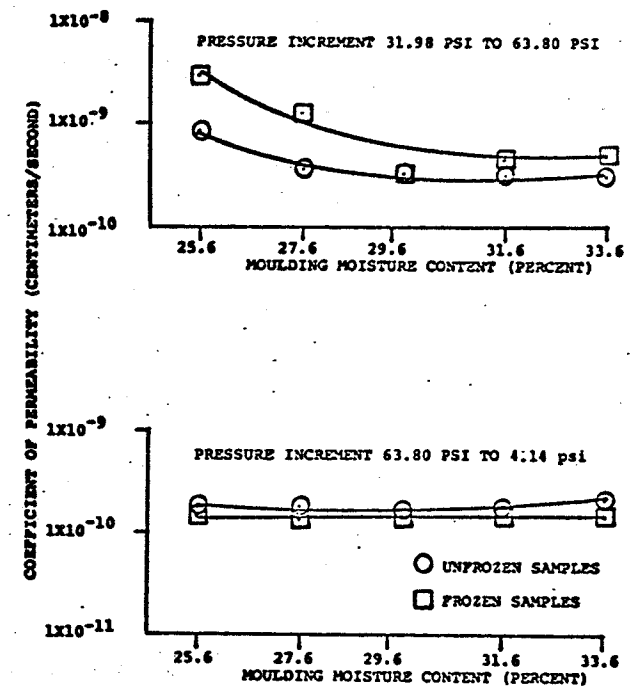


FIGURE 47B
 COEFFICIENT OF PERMEABILITY VER-
 SUS MOULDING MOISTURE CONTENT AT
 VARYING PRESSURE INCREMENTS FOR
 FROZEN AND UNFROZEN SAMPLES COM-
 PACTED TO STANDARD PROCTOR COM-
 PACTIVE EFFORT.

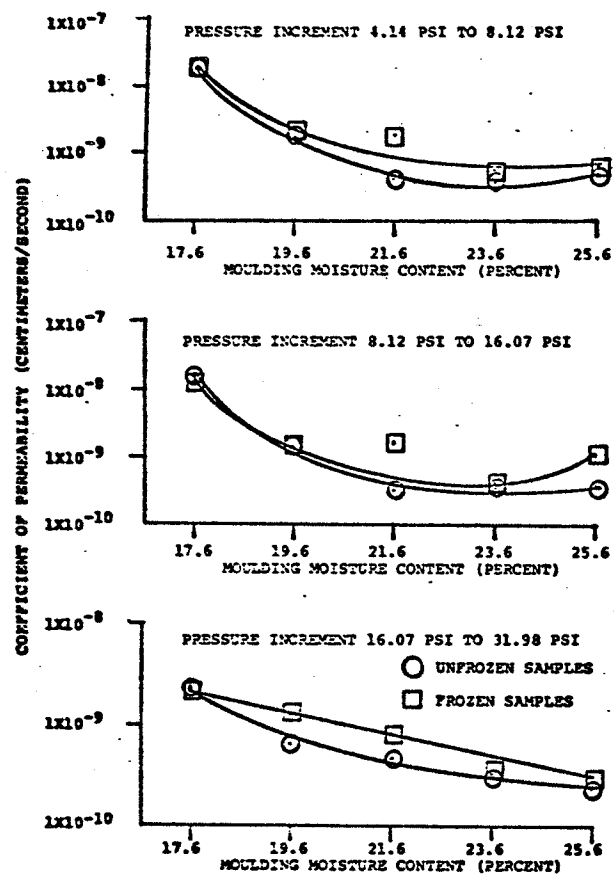


FIGURE 48A
 COEFFICIENT OF PERMEABILITY VER-
 SUS MOULDING MOISTURE CONTENT AT
 VARYING PRESSURE INCREMENTS FOR
 FROZEN AND UNFROZEN SAMPLES COM-
 PACTED TO MODIFIED PROCTOR COM-
 PACTIVE EFFORT.

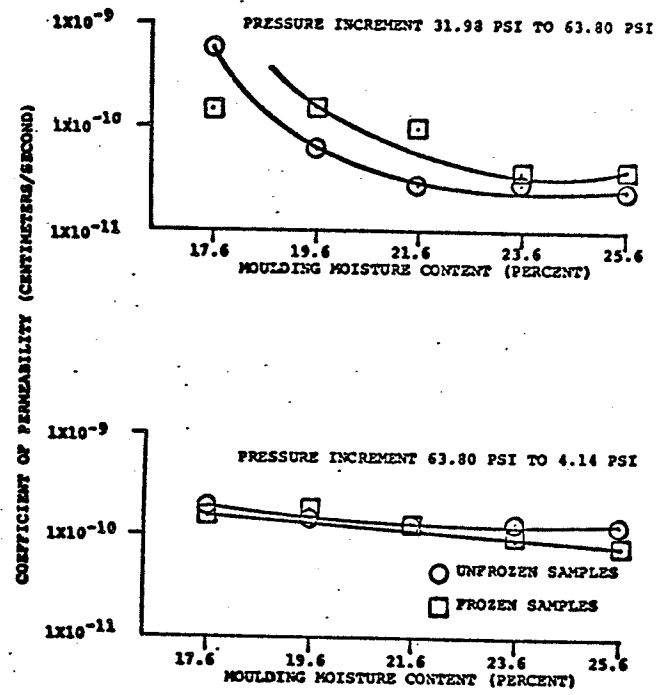


FIGURE 48B
 COEFFICIENT OF PERMEABILITY VER-
 SUS MOULDING MOISTURE CONTENT AT
 VARYING PRESSURE INCREMENTS FOR
 FROZEN AND UNFROZEN SAMPLES COM-
 PACTED TO MODIFIED PROCTOR COM-
 PACTIVE EFFORT.

and frozen samples compacted to standard Proctor compactive effort generally displayed a greater coefficient of permeability than did samples compacted to modified Proctor compactive effort.

Chapter V

CONCLUSIONS AND RECOMMENDATIONSA. CONCLUSIONS

This thesis has shown that the strength and compressibility characteristics of a compacted clay are changed by the effects of a single freeze-thaw cycle in a closed system. As a conclusion, comparisons are made of these characteristics for samples subjected to one freeze-thaw cycle, and samples not frozen before testing.

1. The strength parameter C obtained in undrained triaxial tests is reduced. The loss of such strength is detrimental. In the case of the standard Proctor compactive effort, the reduction in C ranged from approximately 17 percent for samples compacted at 4 percent dry of optimum to approximately 58 percent for samples compacted at 4 percent of wet optimum. In the case of the modified Proctor compactive effort the decrease in the strength parameter C ranged from approximately 5 percent to 10 percent for four of the moulding moisture contents that were examined, that is from 2 percent dry of optimum to 4 percent wet of optimum. Samples compacted at 4 percent dry of optimum showed no change in the strength parameter C .

With the modified compaction less reduction in cohesion was obtained.

2. The change of the parameter ϕ , obtained from undrained triaxial tests, was small, amounting to no more than 1

degree. Samples compacted dry of optimum for both standard and modified Proctor compactive efforts appear to be the least affected. With small observed changes, it is not considered possible to establish what changes are due to the freeze-thaw cycle, and what reflect experimental deviation in sample uniformity.

3. A general decrease in unconfined compression strengths was noted, except for those samples compacted to modified Proctor compactive effort at 4 percent dry of optimum. These samples remained unchanged after one freeze-thaw cycle. The percent decrease in the unconfined compressive strengths for samples compacted to standard Proctor compactive effort varies from approximately 17 percent for samples compacted at 4 percent wet of optimum to about 35 percent for those samples compacted to optimum and 2 percent dry of optimum. The percent reduction in the unconfined compressive strength for samples compacted to modified Proctor compactive effort, excluding those samples compacted at 4 percent dry of optimum, ranged from approximately 16 percent for samples at 2 percent dry of optimum to about 30 percent for samples at 2 percent wet of optimum.
4. The principal stress ratio σ_1/σ_3 , for any given percent strain in the undrained triaxial test is reduced for both the standard and modified compactive efforts. This reduction is less with the higher compactive effort and is generally independent of confining pressure and moulding moisture content.

The principal stress ratio σ_1/σ_3 obtained at failure in the undrained triaxial tests for both standard and modified Proctor compactive efforts is reduced by the freeze-thaw cycle. The effect was more pronounced for the higher moisture contents, lower confining pressures and for the lower compactive effort.

5. The deviator stress obtained in the undrained triaxial test for any given percent strain is reduced for both standard and modified Proctor compactive efforts. This reduction is generally independent of confining pressure and moulding moisture content.

The deviator stress at failure for samples compacted by the standard and the modified compaction efforts generally decreased after exposure to one freeze-thaw cycle. A clear correlation between the percent reduction in the maximum deviator stress and the cell pressure for a given moulding moisture content could not be established for either of the compactive efforts, although the greater compactive effort generally produced less reduction in the deviator stress at failure.

6. Again with reference to the undrained triaxial test, the major total principal stress for any given percent strain is reduced. This reduction is generally independent of confining pressure and moulding moisture content. The above noted reduction generally decreased with the greater compactive effort.

The major total principal stress at failure for a given cell pressure and moulding moisture content generally

shows a readily detectible decrease. This decrease was evident for samples compacted to standard and modified Proctor compactive efforts. However, samples compacted to modified Proctor compactive effort at 4 percent dry of optimum generally showed a marked increase in the major total principal stress at failure after one freeze-thaw cycle.

7. Samples which undergo a single freeze-thaw cycle show lower preconsolidation pressures. This was apparent for both standard and modified Proctor compactive efforts at all moulding moisture contents that were examined. The larger compactive effort does not appreciably affect the decrease of the preconsolidation pressure.
8. The coefficients of consolidation, compressibility and permeability generally showed a detectable change due to one freeze-thaw cycle for both compactive efforts and all moulding moisture contents and pressure increments examined. The changes are apparently related to whether the pressure on the sample in a consolidometer is being increased or decreased. The change in the aforementioned coefficients was usually an increase for those cases where the pressure was being increased. For those cases where the pressure was reduced, the samples subjected to the single freeze-thaw cycle show reduced coefficients. Changes in the coefficients of consolidation, compressibility and permeability due to the single freeze-thaw cycle appear to be independent of compactive effort.

B. RECOMMENDATIONS

This thesis examined the effect of a single freeze-thaw cycle on the strength and the compressibility characteristics of one type of soil. Future research could encompass the effect of a similar testing program on different soil types. The soils to be utilized in future studies would contain varying proportions of silt and clay. Also, the number of freeze-thaw cycles could be increased and the resulting effect on certain soil properties examined.

Another aspect of the freezing process, as it pertains to this study, is the rate of freezing. Further research on the strength and compressibility characteristics of a compacted clay could determine the effect, if any, of varying the freezing rate. Similarly, the effect of the rate of thawing could also be investigated. The length of time that the soil samples are frozen could be varied in order to determine if this has an effect on strength and compressibility characteristics.

Various additives or combinations of additives could be introduced into the soil in order to enhance or initiate desirable effects resulting from the freezing process. Additives could also be utilized in an attempt to reduce or eliminate undesirable effects caused by freezing.

The compaction utilized to facilitate sample preparation could also be investigated. Kneading compaction was utilized to facilitate sample preparation in this thesis. Future research could be undertaken to investigate the effect of freezing on the strength and compressibility characteristics of a clay

compacted utilizing static compaction.

Furthermore, different combinations of the previously noted suggestions could also be examined.

A further extension of this thesis could be into a study of a system which permits a controlled amount of moisture migration in open systems of freezing.

It is hoped that, with increasing research into the effect of freezing on a compacted clay soil, there will come a better appreciation of the use of a compacted soil which will be subjected to cycles of freezing and thawing.

References

- 1 Johnson, A.W., and Sallberg, J.R., 1960. Factors That Influence Field Compaction of Soils. Highway Research Board, Bulletin Number 272, Washington, Forward.
- 2 Proctor, R.R., 1948. Laboratory Soil Compaction Methods, Penetration Resistance, and the Indicated Saturated Penetration Resistance. Proceedings 2nd International Conference on Soil Mechanics and Foundation Engineering. Rotterdam, Volume V, Pages 242 to 247.
- 3 Ray, P.N., and Chapman, T.G., 1954. The British Standard Compaction Test For Soils: A Study of Some Factors Affecting the Test Results. Geotechnique 4, December 1954, Pages 169 to 177.
- 4 Lambe, T.W., 1958. The Structure of a Compacted Clay. Proceedings of the ASCE May 1958, SM2, Volume 84, Page 21.
- 5 Seed, H.B., and Chan, C.K., 1959. Structure and Strength Characteristics of Compacted Clays. Proceedings of the ASCE October 1959, SM5, Volume 85, Page 109.
- 6 Leonards, G.A. 1962. Foundation Engineering. McGraw-Hill, 1st Edition, Page 355.
- 7 Leonards, G.A. 1962. Foundation Engineering. McGraw-Hill, 1st Edition, Page 167.
- 8 Lambe, T.W., 1958. The Structure of a Compacted Clay. Proceedings of the ASCE, May 1958, SM2, Volume 84, Pages 25 and 27.
- 9 Haley, J.R., and Kaplar, C.W., 1952. Cold-Room Studies of Frost Action in Soils. Highway Research Board, Special Report Number 2, Frost Action in Soils, Washington, Pages 246 to 268.
- 10 Takagi, S., 1963. Fundamentals of the Theory of Frost Heaving. Proceedings International Permafrost Conference, November 11-15, 1968, Lafayette, Indiana. Pages 203 - 216.
- 11 Kaplar, C.W., 1963. Laboratory Determination of the Dynamic Moduli of Frozen Soil and Ice. Proceedings International Permafrost Conference, November 11-15, 1963, Lafayette, Indiana. Pages 293 - 300.
- 12 ASTM, 1971. Bituminous Materials, Soil and Rock, Skid Resistance, Part 11. 1916 Race Street, Philadelphia, Pa., U.S.A.
- 13 Bishop, A.W., and Henkel, D.J., 1962. The Measurement of Soil Properties in the Triaxial Test. Arnold, 1st Edition, Page 28.

- 14 Terzaghi, K., 1966. Theoretical Soil Mechanics. John Wiley and Sons, 14th Edition, Page 266.
- 15 Leonards, G.A., 1962. Foundation Engineering. McGraw-Hill, 1st Edition, Page 152.