TRANSPORTATION & GEOTECHNICAL GROUP
DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF SASKATCHEWAN
SASKATOON, SASKATCHEWAN

CHARACTERIZATION OF FREEZE-THAW EFFECTS ON SUBGRADE SOILS

BY

A.T. BERGAN
and
D.G. FREDLUND

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RP-4

INTRODUCTION

The freezing and thawing of an unsaturated soil has an effect on its response to dynamic loading. The soil parameter changes complicate the response analysis of an asphalt pavement to moving wheel loads. This in turn, influences the estimate of fatigue damage caused by repetitive stressing of the asphalt pavement.

In a northern environment such as experienced in central Canada, the deflection response of an asphalt pavement varies considerably throughout the year as a result of changes in the stiffness characteristics of the subgrade soil, base course and asphaltic concrete. Figure 1 illustrates the seasonal variation in Benkelman beam deflections of a section of highway between Regina and Lumsden in Saskatchewan, Canada.

In spite of the complicating effects of freezing and thawing, it is important to order out logic within the context of multiphase, continuum mechanics. This first involves an assessment of the fundamental variables required to describe the "state" of the system. Once the "state variables" are established, suitable constitutive relationships can be written to describe observed processes.

This paper first presents a basic theoretical framework for analyzing the behavior of an unsaturated, cyclically frozen, soil subjected to repetitive loading. The observed effects of freezing and thawing are interpreted with respect to the basic "state variables". Then a procedure is recommended for the repeated loading characterization of a subgrade soil subjected to freeze-thaw cycles. A specific section of highway from Regina to Lumsden in Saskatchewan is used as an example.

THEORETICAL CONSIDERATIONS

Generally, an unsaturated soil is considered as a three-phase system of air, water and soil particles. However, there is now evidence that the air-water interface (commonly referred to as the contractile skin) should be considered as an independent phase (Fredlund, 1973). Therefore, an unsaturated soil can be visualized as a mixture with two phases that come to equilibrium under applied stresses (i.e., soil particles and the contractile skin) and two phases that flow under applied pressures (i.e., the air and water.)

The success of the effective stress equation for saturated soils has led research workers in a continual search for a similar equation for unsaturated soils. However, all proposed equations have met with limited success. In 1973, Fredlund theoretically proved and experimentally verified that two independent stress tensors are required to describe the stress state of an unsaturated soil. One possible set of stress tensors, in matrix form, can be written:

$$\begin{bmatrix} \sigma_x - u_a & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_y - u_a & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_z - u_a \end{bmatrix}$$

and

$$\begin{bmatrix} u_a - u_w & 0 & 0 \\ 0 & u_a - u_w & 0 \\ 0 & 0 & u_a - u_w \end{bmatrix}$$

where σ_x, σ_y, σ_z = total stresses in the cartesian coordinate directions

u_a = pore air pressure

u_w = pore water pressure

The above stress tensors are not the only combination of stresses that describe the stress state. Another possible combination is,

$$\begin{bmatrix} \sigma_x - u_w & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_y - u_w & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_z - u_w \end{bmatrix}$$

and

$$\begin{bmatrix} u_a - u_w & 0 & 0 \\ 0 & u_a - u_w & 0 \\ 0 & 0 & u_a - u_w \end{bmatrix}$$

A third possible combination uses the total stress as a datum.

The above stress tensors assume that changes in the physico-chemical properties do not change for the processes we wish to describe. In order to facilitate physico-chemical effects, let (R - A) (i.e., the difference between the Repulsive and Attractive stresses in the adsorbed water hull) describe the state of stress in the adsorbed layer. The stress tensors must now be revised. One possible combination is:

$$\begin{bmatrix} \sigma_x - u_w - (R - A) & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_y - u_w - (R - A) & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_z - u_w - (R - A) \end{bmatrix}$$

and

$$\begin{bmatrix} u_a - u_w & 0 & 0 \\ 0 & u_a - u_w & 0 \\ 0 & 0 & u_a - u_w \end{bmatrix}$$

The first stress tensor is consistent with the equation experimentally verified by Balasubramanian (1972) for saturated soils.

The magnitude of (R - A) is commonly referred to as the solute or osmotic suction while the term $(u_a - u_w)$ is referred to as the matric suction (Aitchison, 1965). The sum of the solute and matric suction is referred to as the total suction and is measurable by the psychrometric technique (Richards, 1969). Krahn and Fredlund (1972) independently measured the solute suction (using a squeezing and electrical conductivity technique), the matric suction (using a null pressure plate technique; Pufahl, 1970) and the total suction (using the psychrometric technique) on essentially identical soil samples. The results experimentally verify the above subdivision of soil suction.

The "state variables" associated with a partly frozen soil have never been theoretically derived and experimentally verified to the authors' knowledge.

However, the "state variables" associated with a partly frozen soil are not imperative to the present study since only the unfrozen conditions are being given consideration.

The study of the freezing and thawing, and the repetitive loading of a soil, both involve cyclic phenomena which are associated with a reversal in the direction of deformation of the soil structure. Most solids exhibit hysteretic effects during a change in the direction of deformation. Commonly observed in a saturated soil is the hysteresis associated with a change in the direction of deformation of the soil structure. For an unsaturated soil there is also hysteresis associated with the reversal in the direction of deformation of the contractile skin (Fredlund, loc cit).

BASIC EFFECTS OF THE FREEZE-THAW CYCLE

There are two extreme boundary conditions under which a soil can be frozen. In the open system the soil has free access to unlimited quantities of air and water. In the closed system, no access of air or water is allowed. Although heaving and ice lensing is a problem in highway design, the more common case of concern in Central Canada and many parts of northern United States is the freezing of an unsaturated subgrade soil in essentially a closed system.

Deformation occurring as a result of freezing and thawing of a soil in a closed system can be examined in terms of changes in the "stress state" variables. Before and after freezing, the total pressure is unchanged and the air pressure is essentially unchanged, however, the water pressure undergoes changes. Changes in the water pressure alters the $(u_a - u_w)$ and the $(\sigma - u_w)$

"stress state" variables. Either one, or both of the "stress state" variables can be used to describe observed behavior (Fredlund, 1973).

Freezing and thawing a compacted soil in a closed system results in volume changes of the type shown in Figure 2. Hamilton (1966) found that samples compacted below a 90 percent degree of saturation shrank upon freezing while those compacted wetter increased in volume. The greatest amount of shrinkage on freezing was observed for samples compacted between 60 and 70 percent saturation. Upon thawing, a net increase in volume was observed. Similar tendencies have been observed by Mickleborough (1969), Rix (1969) and Lidgren (1970) (Figure 3).

If the freezing and thawing of a soil were a non hysteretic process, the matric suction $(u_a - u_w)$ should be the same before and after freezing. The same is true for the swelling pressure (i.e., $\sigma - u_w$) measurements before and after freezing. Lidgren (1970) showed that the swelling pressure underwent a significant reduction after three freeze-thaw cycles (Figure 4).

Matric suctions on undisturbed samples from the Regina to Lumsden highway were measured before and after freeze-thaw, using a null pressure plate technique (Pufahl, 1970). Following the matric suction measurements on the undisturbed samples, the soil from all test samples was combined and remoulded. Matric suctions were then determined on remoulded samples compacted at comparable water contents.

Results of all the suction tests on Regina clay are shown on Figures 5 and 6. Figure 5 compares the matric suction values on undisturbed and remoulded samples prior to freeze-thaw. It is important to note that the undisturbed samples have already been subjected to several freeze-thaw cycles in the field. It is apparent that the matric suctions on the undisturbed samples are considerably lower than on the remoulded samples. It is difficult to detect a difference in suction values between the fall of 1970 and the spring of 1972. In all cases, the undisturbed samples exhibit relatively low suction values. Figure 6 shows matric suction values for remoulded and undisturbed samples before and after freeze-thaw. On the remoulded samples, a very significant drop in suction is evident after the freeze-thaw cycle. On the undisturbed samples a small but significant drop in suction occurred after one freeze-thaw cycle. As noted previously, the undisturbed samples obtained during the fall of 1970 have been subjected to several cycles of freeze-thaw, but since the last cycle, the roadway has been subjected to considerable truck traffic.

A well-defined secondary structure was present in the undisturbed samples as shown in Figure 7 and definite ice segregation was evident in the samples as observed by breaking undisturbed samples in the frozen state. The average matric suction of the undisturbed samples of Regina clay was 15 pounds per square inch (1.1 kg/cm^2). Six of these samples were subjected to one cycle of freeze-thaw and an average suction of 5 pounds per square inch (0.4 kg/cm^2) was measured after thawing (Figure 6). This may represent in some way what happens in the subgrade between fall and spring in a cold region.

Mickleborough (1970) also did suction tests using a pressure plate device on remoulded Regina clay (the same material as tested in this investigation), and found that freeze-thaw cycles reduce the matric suction as shown in Figure 8.

A possible explanation for the drop in suction after freeze-thaw is as follows. The water accumulates in the secondary structure during the winter as previously discussed, and then on thawing the **free water** in the secondary structure controls the matric suction measured in the laboratory. The observations would indicate that the mechanism is similar to three-dimensional ice lensing on a reduced scale (Penner, 1971). During the summer, with repeated stress applications, and an internal suction gradient, the moisture is redistributed and the suction measured in the laboratory increases.

REGINA - LUMSDEN HIGHWAY STUDY AREA

The main object of this study is to develop a means of simulating spring and fall field behavior using an analytical model based on relatively simple laboratory techniques. The Regina to Lumsden highway has been in service for several years and was selected for investigation because the subgrade was relatively uniform and it formed part of a larger fatigue simulation program (Bergan, 1972).

During the fall of 1970, and again during the spring of 1972, twelve sites were selected for detailed study. At these sites, block samples of asphalt concrete, disturbed samples of base and subbase, and undisturbed samples of the lacustrine clay subgrade were obtained. A summary of the test program for the subgrade soils is contained in Table I.

TABLE I

DETAILS OF SUBGRADE SAMPLING AND TESTING ON THE REGINA TO LUMSDEN TEST SECTION

Number and Type of Undisturbed Samples	Two or three 4-1/2 inch (11.4 cm) diameter Shelby tube samples taken at each site.
Location of Samples	Sample #1; 0-2 feet (0-61 cm) below top of subgrade. Sample #2; 2-4 feet (61-122 cm) below top of subgrade. Sample #3; 4-6 feet (122-183 cm) below top of subgrade. All samples taken in outer wheel path, right hand lane.
Testing Program on Samples	Plastic and Liquid Limits Moisture Content and Density Tests. Matric Suction and Resilient Modulus Tests.

Water content and dry density test results for all samples obtained are shown in Figure 9. In this figure, it is interesting to note that forty-five samples exhibited water contents greater than the optimum water content based on the Standard AASHO compaction test while only four samples were below the optimum water content. The average plastic and liquid limits for this soil are 30 and 75 percent, respectively. When the subgrade was constructed in 1961, the soil was placed several percent dry of the Standard AASHO optimum water content, at a dry density ranging from 80 to 90 pounds per cubic foot (1.28 to 1.44 kg/cm^3). The test results indicate that a significant increase in water content has taken place in the subgrade since construction. The test results, however, do not indicate a difference in water content and dry density between the fall of 1970 and the spring of 1972.

The suction test results on undisturbed samples from the highway section between Regina and Lumsden and the section of highway studied by MacLeod (1970) indicate that the matric suctions on the undisturbed field samples varied between 5 and 20 pounds per square inch (0.4 and 1.4 kg/cm^2). It is possible, based on limited freeze-thaw test results, that the maximum suction during the spring is approximately 20 pounds per square inch (1.4 kg/cm^2).

Details of a water content study completed during the fall of 1970 at a typical cross-section on the Regina to Lumsden highway are shown in Figure 10. All water contents are higher than the plastic limit of 29.8 percent and the optimum moisture content of 27.8 percent as determined by the Standard AASHO Compaction Test. A change in water content across the section or with depth is not evident. This data indicates that the suction value in all areas of the roadbed are probably less than 20 pounds per square inch (1.4 kg/cm^2).

An extensive amount of field work has been carried out to determine the suction under covered areas in regions of moderate temperature. DeBruijn (1965) reported a soil suction of 2.8 to 3.8 pF* under covered areas in South Africa. Aitchinson and Richards (1965) reported soil suctions between 3 pF and 4 pF in a number of areas studied in Australia. The suction measurements reported on the Regina-Lumsden highway (Figure 5) are much lower than those reported by DeBruijn and Aitchison and Richards. Low suction values are difficult to measure in the laboratory and extremely difficult, if not

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* in psi 2 pF = 1.42 pounds per square inch = 0.10 kg/cm^2
3 pF = 14.2 pounds per square inch = 1.0 kg/cm^2
4 pF = 142 pounds per square inch = 10 kg/cm^2

impossible, to measure in the field under extremely adverse climatic conditions.

Sauer (1968) measured matric suctions under thin pavements (i.e., 1 inch (2.5 cm) of asphalt concrete on subgrade) using Gypsum Blocks during the fall of 1966 in the province of Saskatchewan. Suctions measured 2 feet (61 cm) below the pavement, on centerline are summarized in Table II.

TABLE II

SUCTION MEASURED BY GYPSUM BLOCK - FALL, 1966
(After Sauer, 1968)

	Test Site Number	Suction at 2 feet (61 cm) in pounds per square inch (kg/cm^2)	Water Content at 2 feet (61 cm) depth (%)	Plastic Limit (%)
acustrine Clay	GB-1	10 (0.70)	20	25.5
	GB-9	10 (0.70)	22	25.4
lacial Till	GB-2	13 (0.91)	13	16.8
	GB-4	15 (1.05)	17	11.4
	GB-8	17 (1.20)	18	20.7
	GB-3	2 (0.1)	18	15.6
	GB-7	8 (0.6)	8	16.6
	GB-10	2 (0.1)	10	16.5

The water contents were below the plastic limit, however, the suction values were very low. With water contents 5 percent below the plastic limit, the suction could be anticipated to be as high as 100 pounds per square inch (7.0 kg/cm^2). However, Sauer (loc cit) reported suctions in the order of only 10 pounds per square inch (0.70 kg/cm^2). These observations are in agreement with the observed suctions on undisturbed samples from the highway between

Regina and Lumsden as discussed previously. These field observations substantiate the differences found in the laboratory between the matric suction measured on the remoulded and undisturbed samples.

In situ psychrometers designed and calibrated as outlined by Richards (1969), were installed immediately below the outside wheel path on the Regina-Lumsden highway (Bergan and Monismith, 1973). Readings during April, May, and June of 1971, indicated that deviations in the output readings (0 to 3 μV) masked an accurate measurement of the suctions. However, the results do indicate that the suctions were low.

Repeated load triaxial tests were performed on samples from the Regina to Lumsden highway to determine resilient moduli. Specimens 2.8 inches (7.1 cm) in diameter by about 6.0 inches (15.2 cm) in length were used for the first few tests; however, it was soon concluded that more uniform results could be obtained by using specimens 4 inches (10 cm) in diameter and 8 inches (20 cm) long. During the repeated load testing, lateral and axial deflections were measured using LVDT's (i.e., Linear Variable Displacement Transducers).

In a recent study, Dehlen (1969) found that 1,000 loading repetitions were sufficient to condition the specimen for end imperfections. The same procedure was found to be adequate for the Regina clay samples. After a stress level change, it was observed that 50 or 100 stress repetitions were sufficient to eliminate significant changes in modulus on further applications of repeated loads. Similar results were observed for glacial till by MacLeod (1970).

Load was applied for 0.1 seconds at 20 cycles per minute and the samples were tested at a confining pressure of 2 pounds per square inch (0.1 kg/cm^2), and a range in deviator stresses from 1 to 5 pounds per square inch (0.1 to 0.4 kg/cm^2). These stresses were selected on the basis of typical stress conditions in the subgrade as determined by analytical techniques (Bergan, 1972).

Results of the resilient moduli tests at a $\sigma_3 = 2$ pounds per square inch (o.1 kg/cm^2), and $\sigma_d = 5$ pounds per square inch (0.4 kg/cm^2) are shown in Figure 11. While there is considerable scatter in the data, most of the moduli fall in the range from 3,000 to 10,000 pounds per square inch (211 to 703 kg/cm^2) with an average value of 8,200 pounds per square inch (576 kg/cm^2) for the spring of 1972. These results agree reasonably well with observed pavement response in cold regions where a peak deflection is experienced in the spring probably due to a decrease in subgrade modulus.

After the samples had been tested, some were frozen and retested. Prior to freezing the samples were wrapped in a plastic film, placed in a Zonolite insulated container and surcharged with a 5 pound (2.3 kg) weight. The samples were frozen for 8 hours at 0°F (-18°C) and then thawed for 8 hours and retested. A confining pressure was not applied during freezing nor were repeated loads applied during freezing. Typical results shown in Figure 12, indicate that the resilient modulus dropped considerably after one freeze-thaw cycle. The results after freeze-thaw were taken after 1,000 stress repetitions. With continued stress repetitions, the modulus increased to approximately the original modulus prior to freeze-thaw. Approximately 10,000 stress repetitions at $\sigma_d = 5$ pounds per square inch (0.4 kg/cm^2) and a confining pressure of 2 pounds per square inch (0.1 kg/cm^2) were required to increase the modulus to its original value. MacLeod (1970) also reported significant decreases in resilient moduli of undisturbed samples of glacial till after one freeze-thaw cycle and a modulus regain after a number of repeated load applications.

After all the suction and resilient moduli tests were completed on the undisturbed samples, the soil was combined and remoulded samples were prepared at comparable water contents and densities (Figure 13). In order to obtain resilient moduli which are more indicative of the spring value the remoulded samples were put through two cycles of freeze-thaw. Table III compares resilient moduli obtained for undisturbed samples from the spring and fall samplings with results from remoulded samples with and without freeze-thaw. Two cycles of freeze-thaw appear sufficient to condition the samples in order to obtain stiffness values comparable to those observed in situ.

TABLE III

	Undisturbed Samples		Remoulded Samples	
	Spring (1972)	Fall (1970)	No Freeze-Thaw	Two Cycles Freeze-Thaw
Pounds per square inch	6300	8200	14,800*	6,500*
kg/cm^2	443	576	1,040	457

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* Water content of samples ≈ 33 percent

SUMMARY AND CONCLUSIONS

(1) In cold regions the resilient modulus of the subgrade exhibits a significant seasonal change.

(2) The effects of freezing and thawing should be considered with respect to the "state variables" controlling the soils behavior.

(3) Matric suctions measured on undisturbed Regina clay were considerably lower than those for remoulded Regina clay. It was suggested that this difference is caused by the development of secondary structure.

(4) Field suction values appear to be between 5 and 25 pounds per square inch (0.4 and 1.8 kg/cm^2) for the roads investigated in Saskatchewan. This indicates the need for a precise measuring technique to determine in situ suction values. The psychrometer is not sufficiently accurate for the measurement of such low suctions.

(5) After one freeze-thaw the resilient modulus of the undisturbed samples decreased significantly and after 10,000 applications of load the unfrozen modulus was regained. It was suggested that the behavior reflects what happens in the roadway during spring and summer with repeated truck loading.

(6) Testing remoulded samples does not duplicate field conditions in cold regions. For Regina clay, approximately two cycles of freeze-thaw are required to obtain a moduli indicative of the spring condition.

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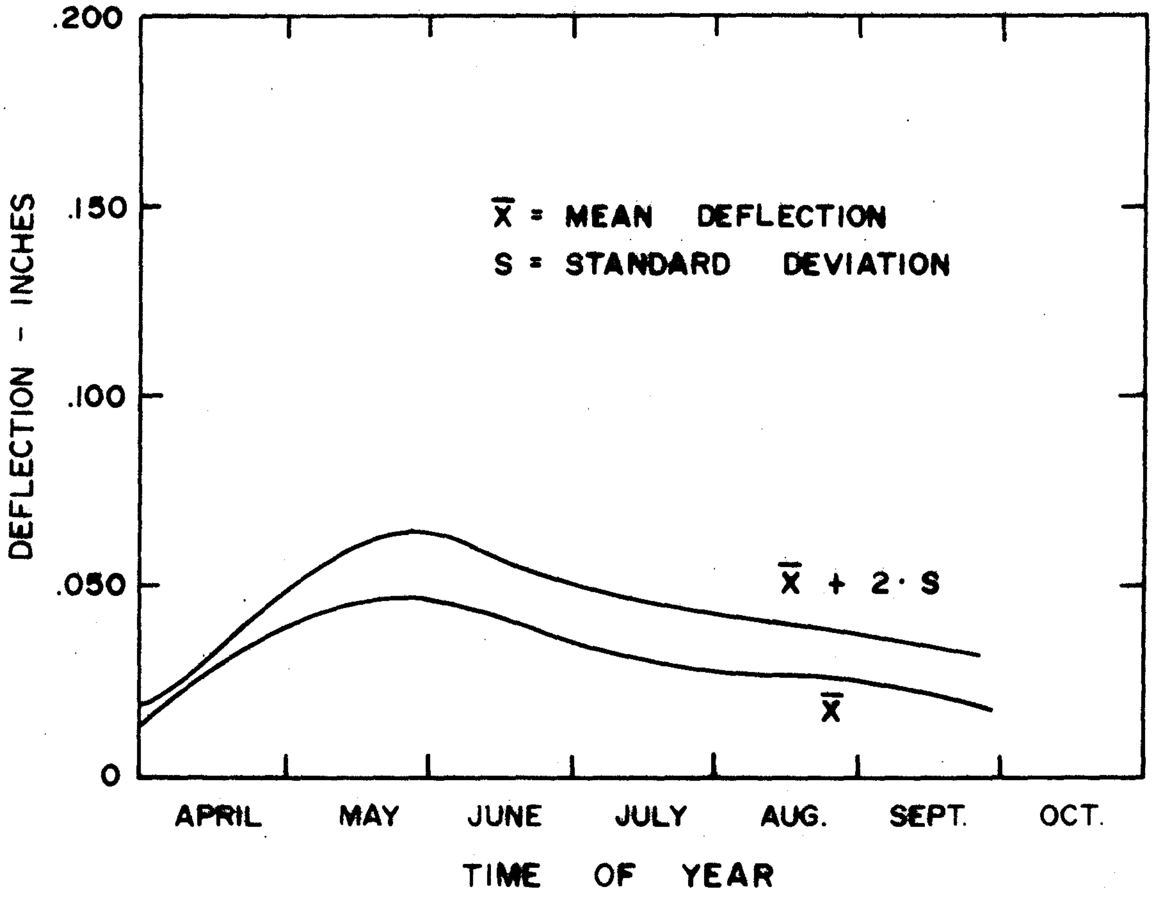
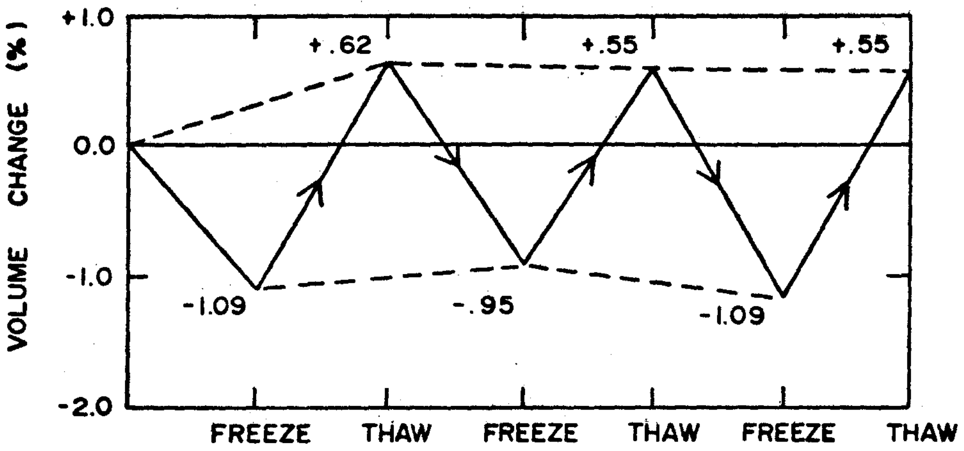


FIGURE I TYPICAL BENKELMAN BEAM DEFLECTIONS VERSUS TIME OF YEAR (REGINA - TO LUMSDEN HIGHWAY)



SAMPLE # 122 - 95 - F
(GLACIAL TILL)

INITIAL CONDITIONS

WATER CONTENT 8.5 %
DRY DENSITY 120.2 PCF
DEGREE OF SATURATION 53.8 %

CLASSIFICATION DATA

LIQUID LIMIT 33.9 %
PLASTIC LIMIT 17.0 %
% CLAY 29.7 %
SPECIFIC GRAVITY 2.74

FIGURE 2 VOLUME CHANGES DURING FREEZE-THAW CYCLES (AFTER LIDGREN, 1970)

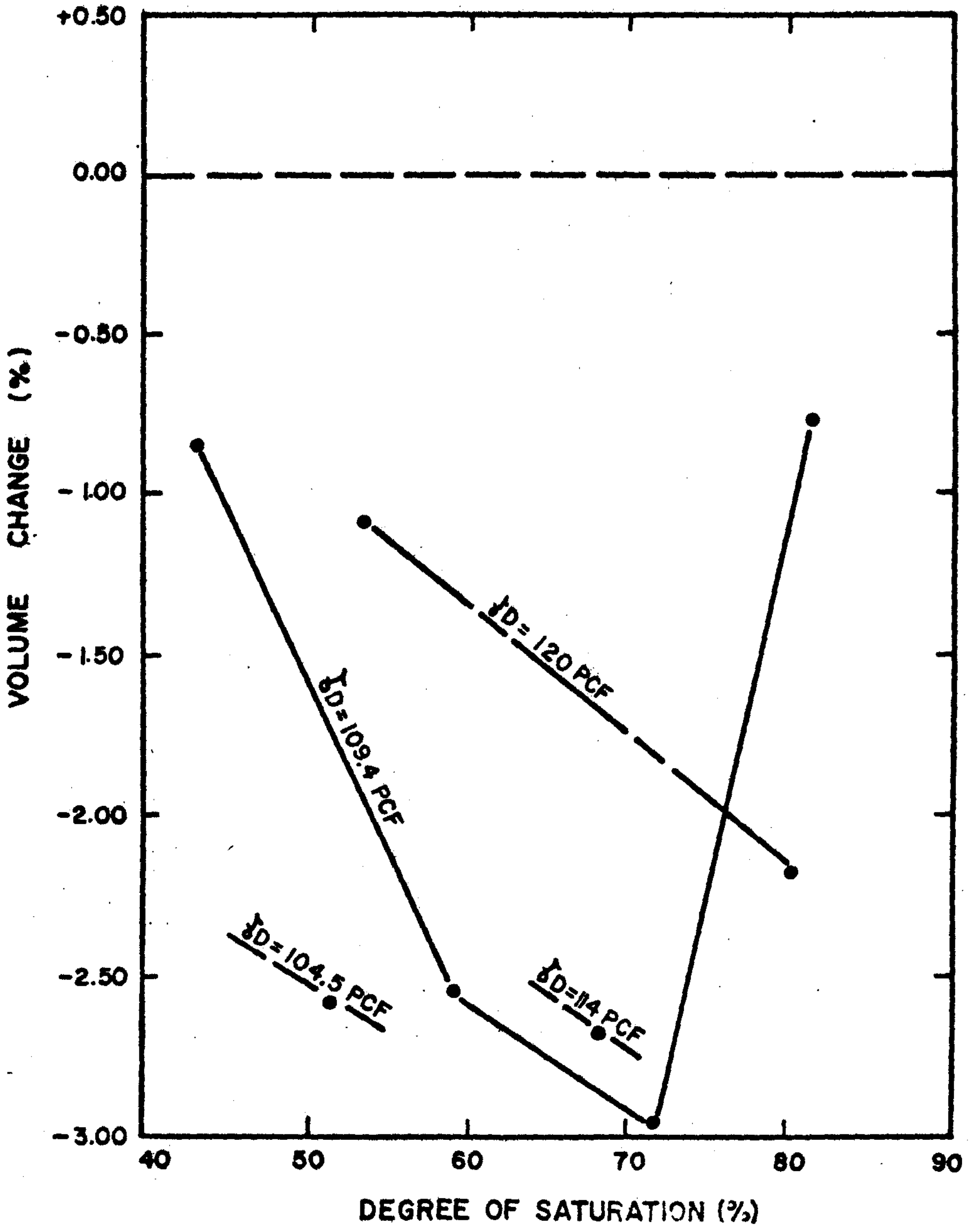


FIGURE 3 VOLUME CHANGE UPON FREEZING VERSUS DEGREE OF SATURATION FOR GLACIAL TILL (AFTER LIDGREN, 1970)

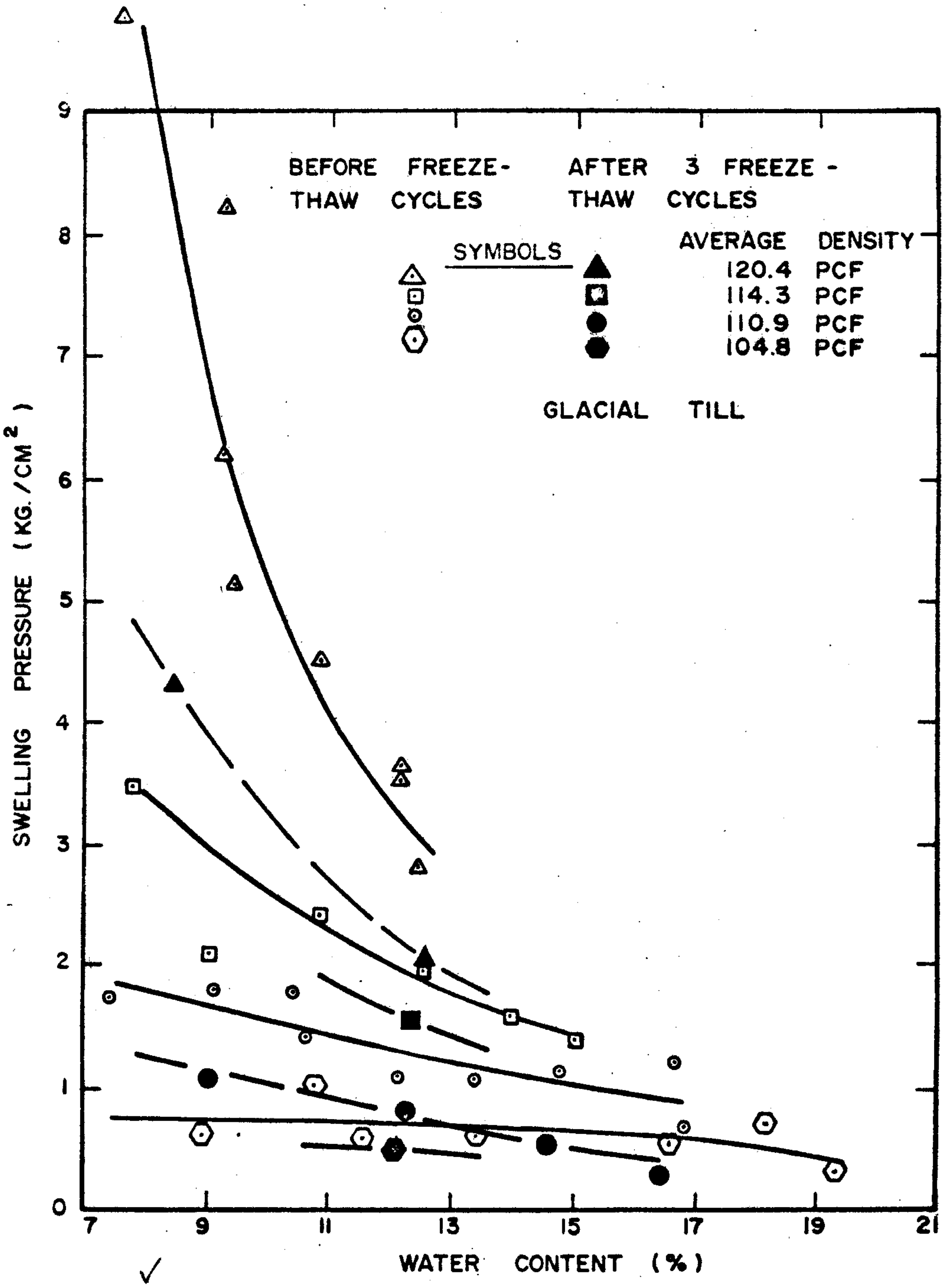


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FIGURE 4 SWELLING PRESSURE VERSUS WATER CONTENT BEFORE AND AFTER THREE FREEZE-THAW CYCLES (AFTER LIDGREN, 1970)

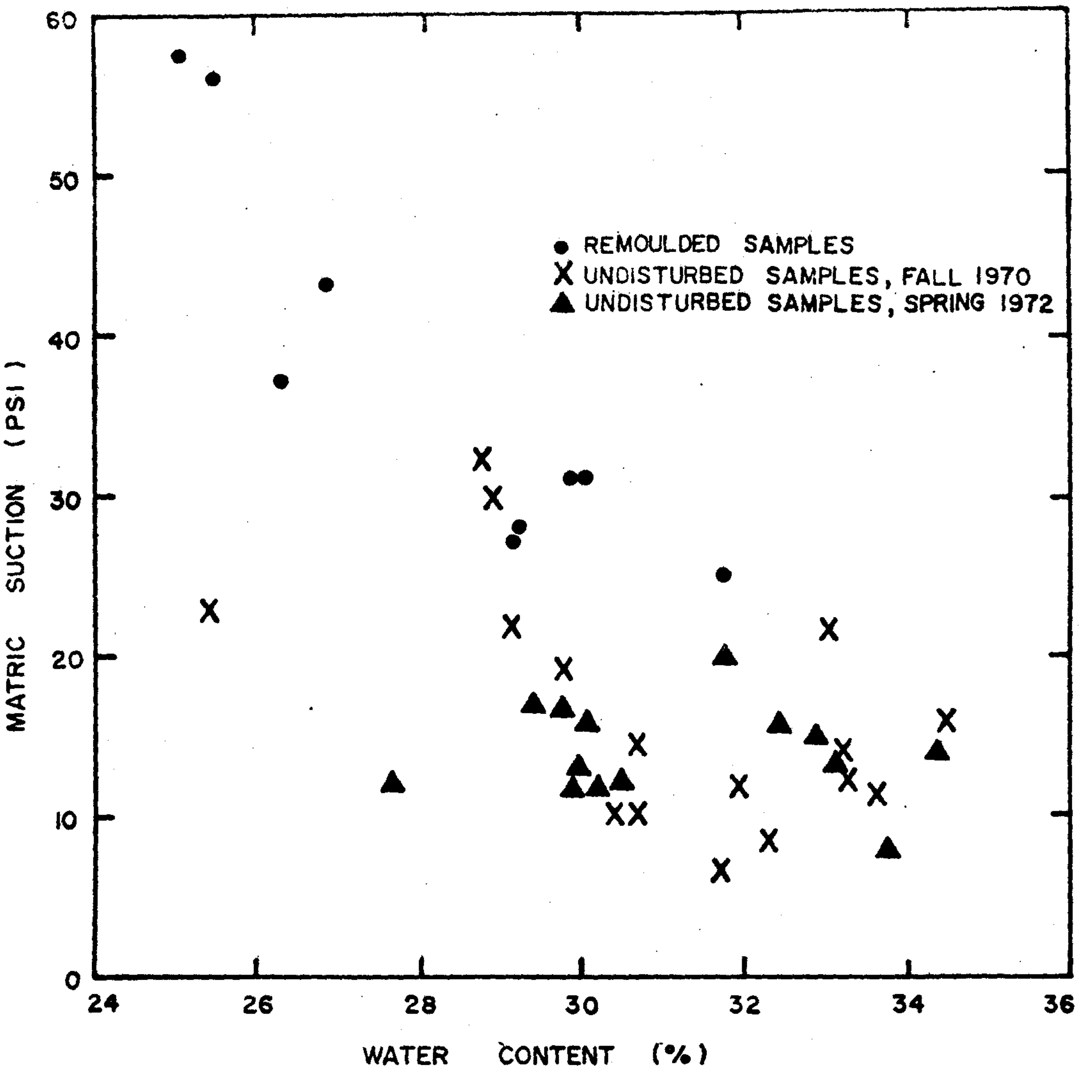


FIGURE 5 REGINA CLAY MATRIC SUCTION VERSUS WATER CONTENT. UNDISTURBED AND REMOULDED SAMPLES WITH NO FREEZE-THAW CYCLES.

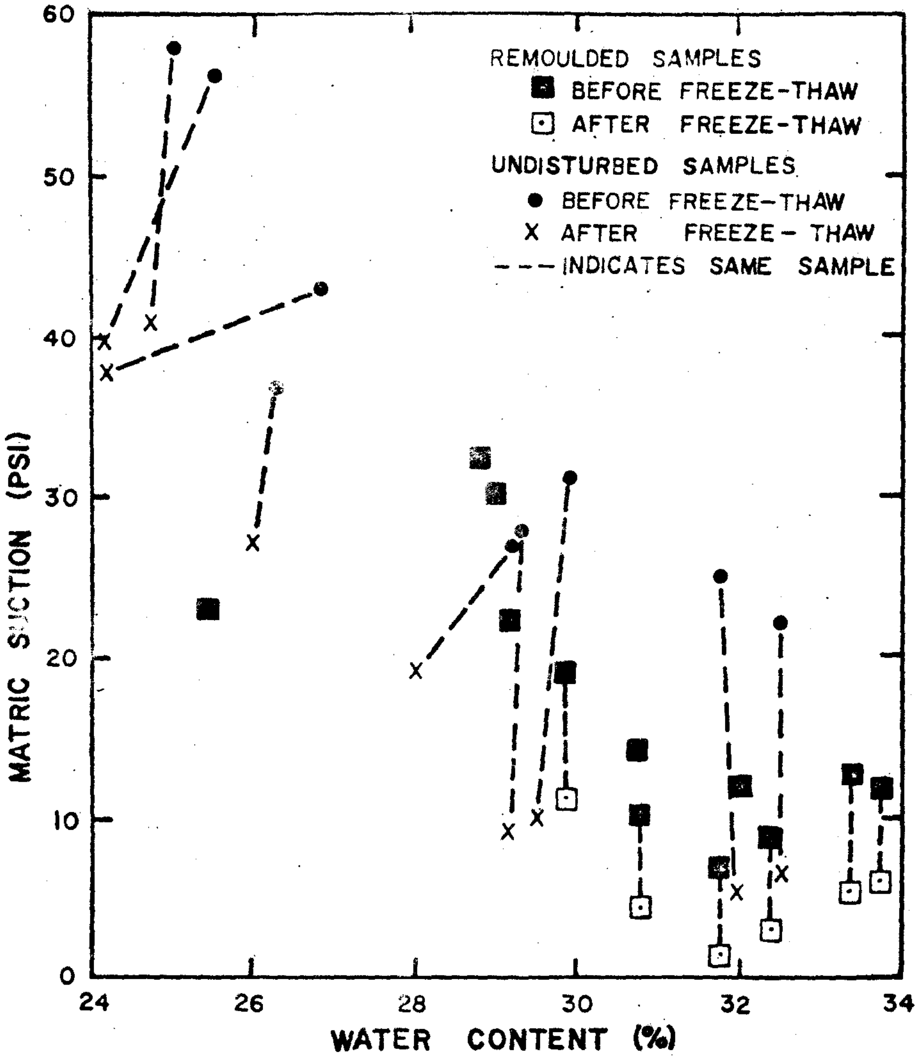


FIGURE 6 MATRIC SUCTION VERSUS WATER CONTENT FOR REMOULDED AND UNDISTURBED SAMPLES (FALL OF 1970)

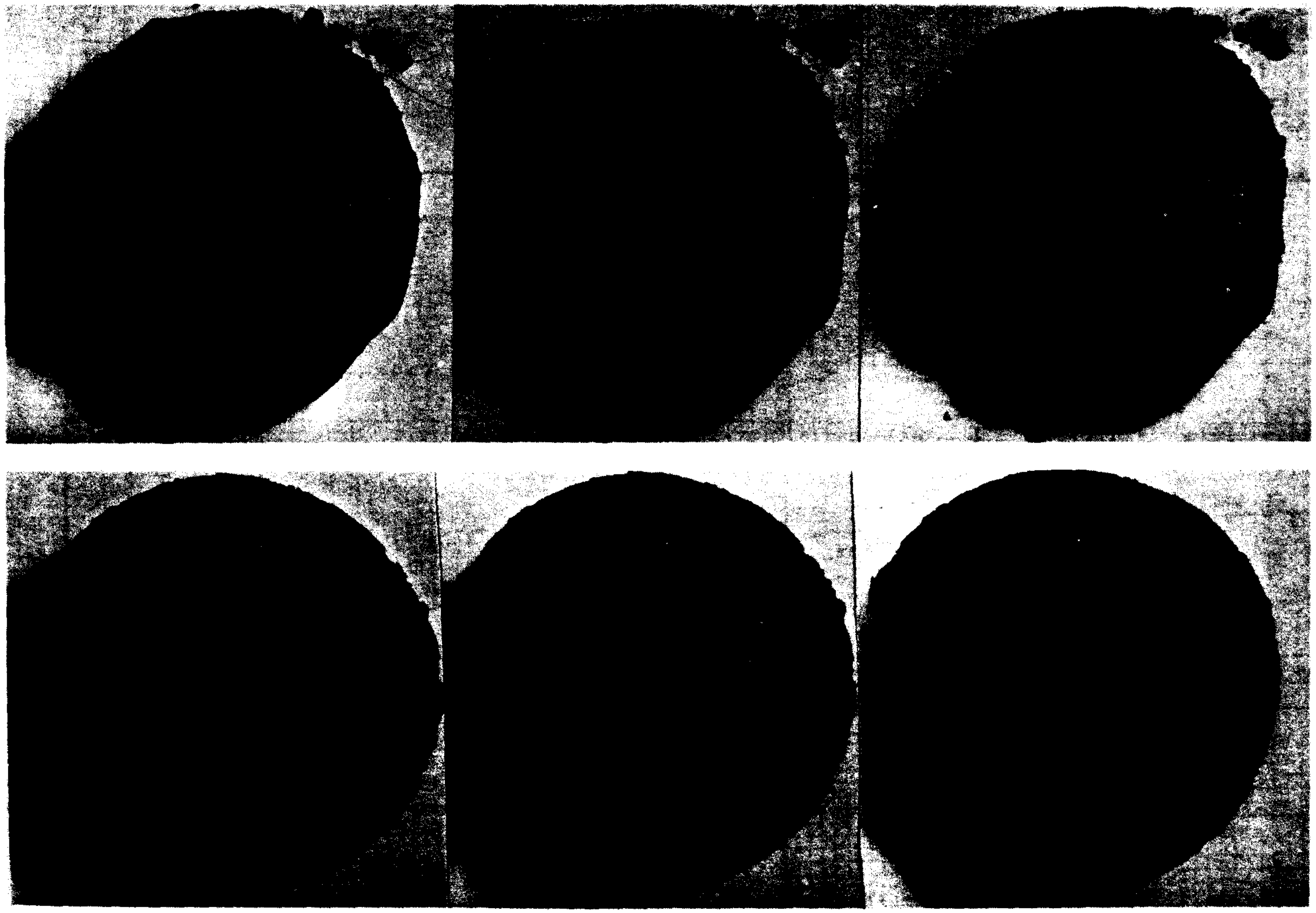


FIGURE 7 SECONDARY STRUCTURE (STEREO VIEW) PRODUCED IN REGINA CLAY BY FREEZE - THAW

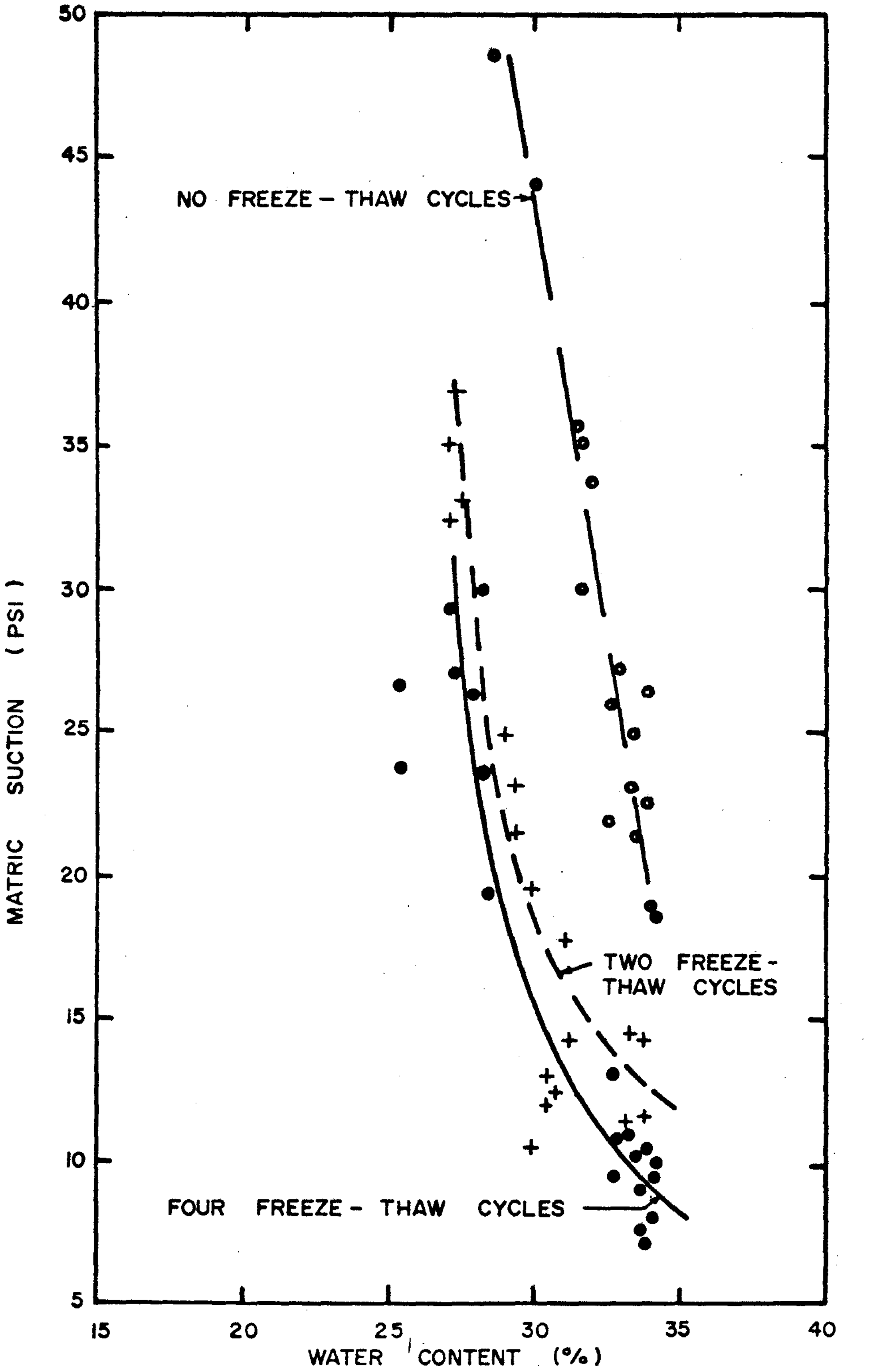


FIGURE $\overset{\vee}{8}$ MATRIC SUCTION VERSUS WATER CONTENT FOR REGINA CLAY (AFTER MICKLEBOROUGH, 1970)

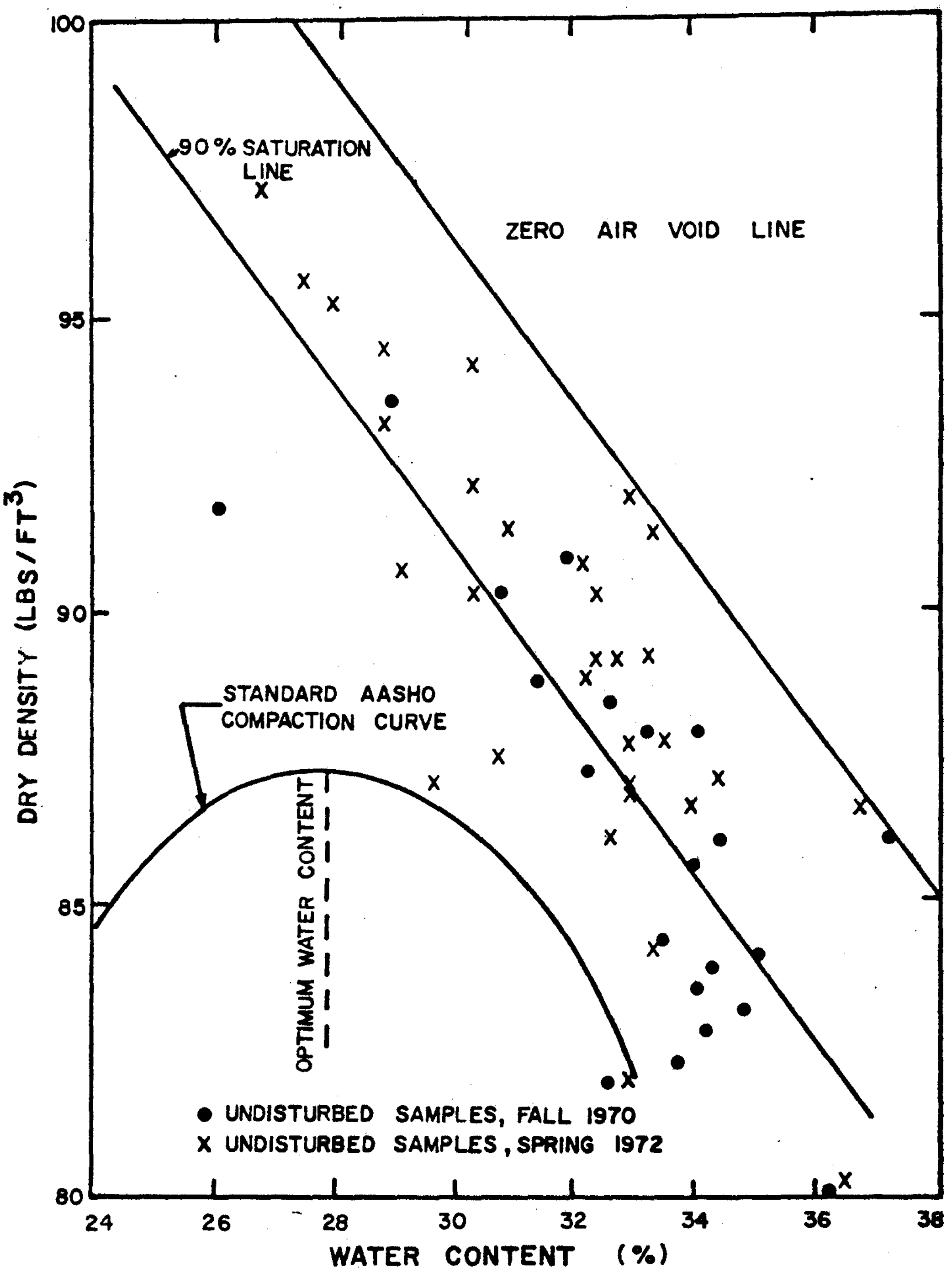
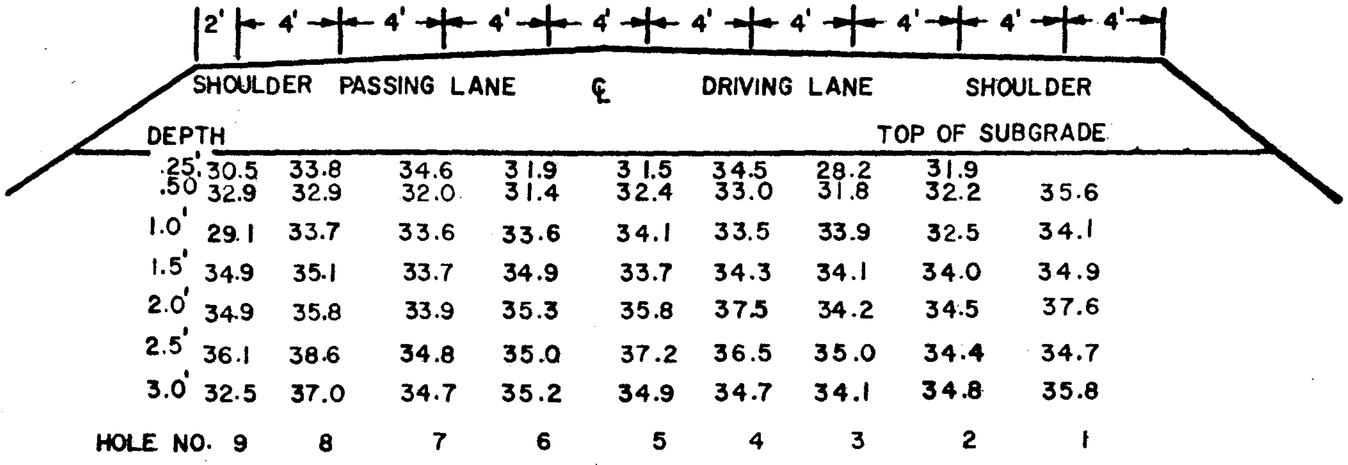


FIGURE 9 STANDARD AASHO COMPACTION CURVE (REGINA CLAY) SHOWING WATER CONTENT-DENSITY CONDITIONS OF TEST SECTION SAMPLES



DEPTH									
.25'	30.5	33.8	34.6	31.9	31.5	34.5	28.2	31.9	
.50	32.9	32.9	32.0	31.4	32.4	33.0	31.8	32.2	35.6
1.0'	29.1	33.7	33.6	33.6	34.1	33.5	33.9	32.5	34.1
1.5'	34.9	35.1	33.7	34.9	33.7	34.3	34.1	34.0	34.9
2.0'	34.9	35.8	33.9	35.3	35.8	37.5	34.2	34.5	37.6
2.5'	36.1	38.6	34.8	35.0	37.2	36.5	35.0	34.4	34.7
3.0'	32.5	37.0	34.7	35.2	34.9	34.7	34.1	34.8	35.8
HOLE NO.	9	8	7	6	5	4	3	2	1

NUMBERS INDICATE PERCENT WATER CONTENT
PLASTIC LIMIT = 29.8 %
OPTIMUM WATER CONTENT (STANDARD AASHO) = 27.8%

FIGURE 10 MOISTURE DISTRIBUTION IN THE REGINA TO LUMSDEN HIGHWAY SUBGRADE.

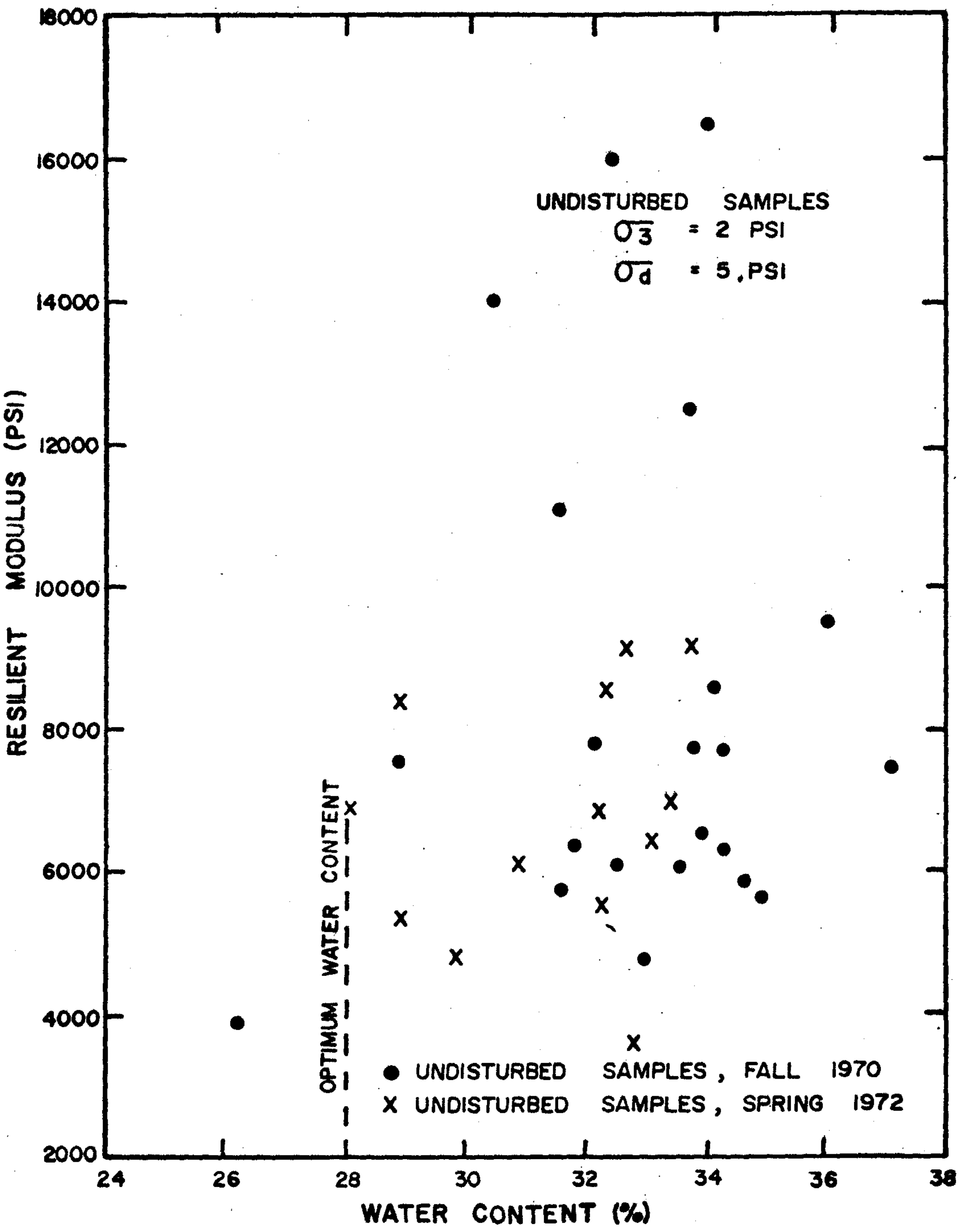


FIGURE 11 RESILIENT MODULUS VERSUS WATER CONTENT FOR REGINA CLAY (REGINA-LUMSDEN HIGHWAY)

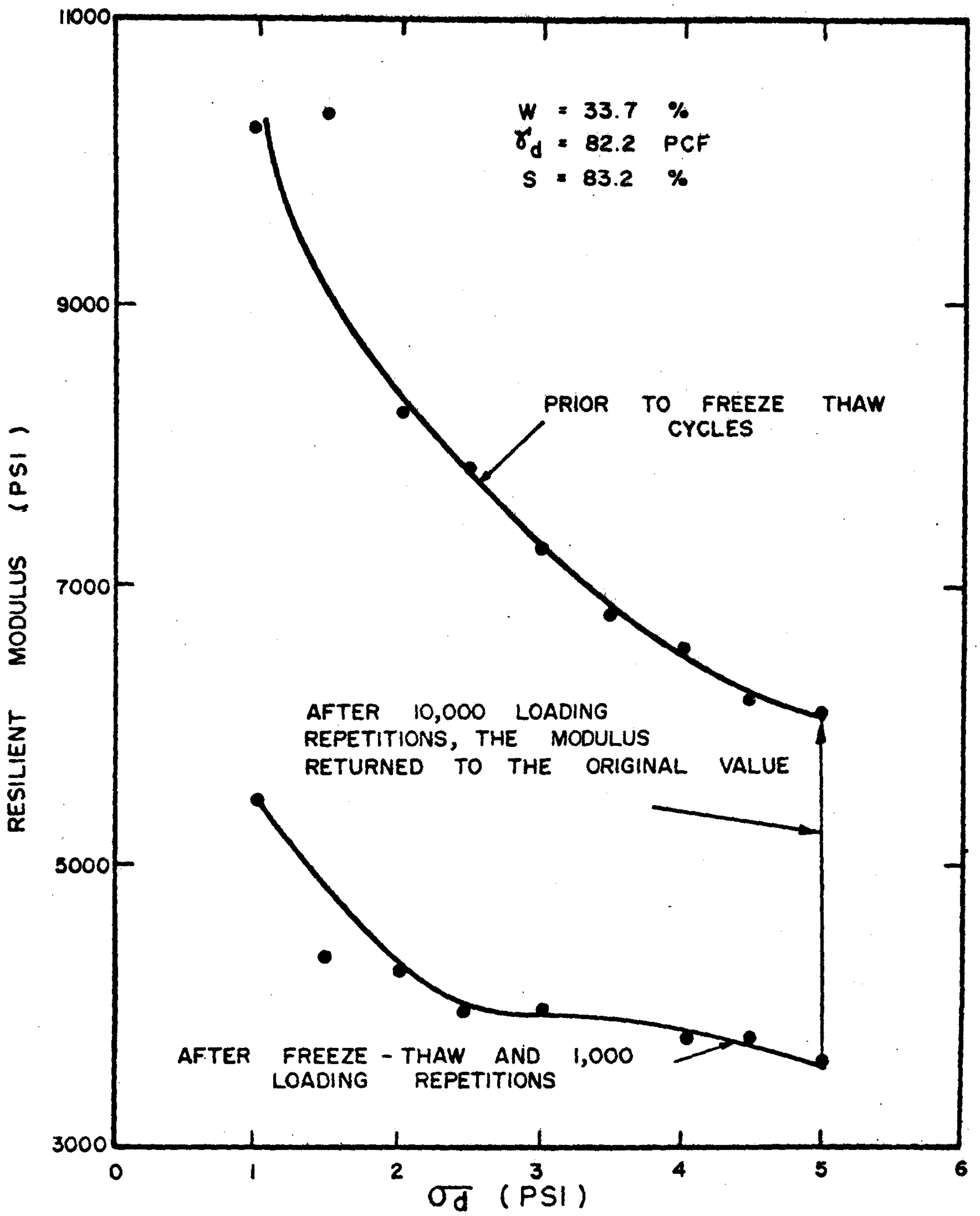


FIGURE 12 RESILIENT MODULUS TESTS BEFORE AND AFTER FREEZE - THAW FOR UNDISTURBED REGINA CLAY (FALL, 1970)

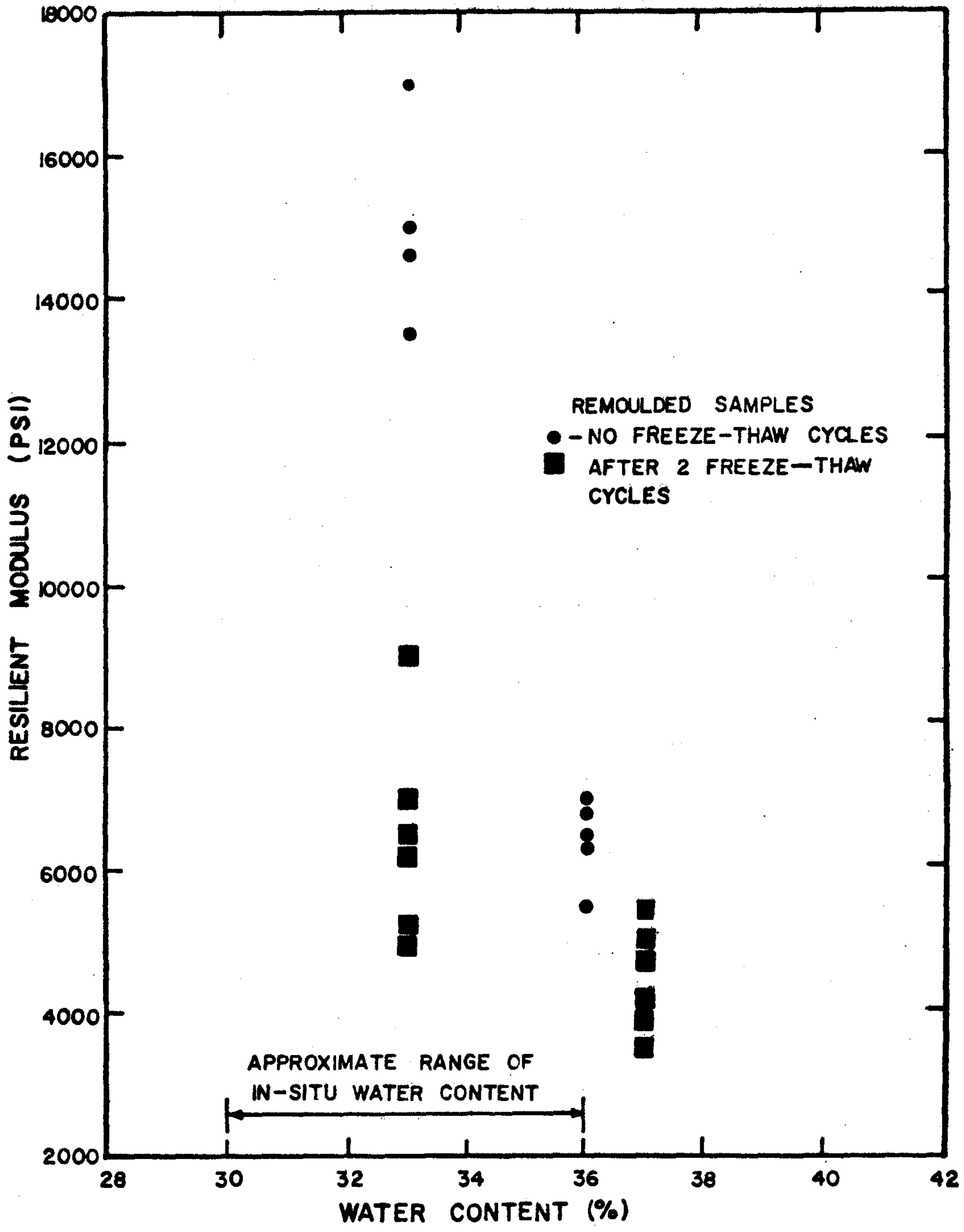


FIGURE 13 RESILIENT MODULUS VERSUS WATER CONTENT FOR REGINA CLAY SUBJECTED TO ZERO AND TWO FREEZE - THAW CYCLES (σ_3 = 2 PSI , σ_d = 5 PSI)