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THE INFLUENCE OF SEVERAL FACTORS ON THE RATE
OF SECONDARY COMPRESSION OF SOIL

BY 641

WILLIAM JOEL GREEN, 1945 -

A

THESIS

submitted to the faculty of

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Approved by

Herbert Schmidt (advisor) M. B. Aughenbaugh
Thomas S. Fry

ABSTRACT

This research program has been undertaken to study the influence of load increment ratio, temperature, and sample thickness on C_{α} (rate of secondary consolidation) for a high organic content and low organic content soil. Consolidation equipment was designed to produce constant temperatures both above and below ambient, and to accommodate both $3/4$ and $1\frac{1}{2}$ inch thick samples. Samples were molded into oedometer rings at the liquid limit.

It was found that C_{α} was independent of the sample thickness and load increment ratio for both the high organic and low organic soils. The influence of temperature on C_{α} was found to be dependent upon the effective stress level. Temperature had a major effect on the magnitude of C_{α} at low effective loads but had little influence at higher effective stress levels.

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CHAPTER I

INTRODUCTION

A subject that arouses much controversy in soil mechanics is secondary consolidation. While for some soils oedometer tests have shown that there exists a secondary compression strain that follows approximately a linear relationship when plotted against the logarithm of time, some writers have found that it continually decreases and others have found almost no secondary compression at all.

This variation is primarily due to the type of soil. It has been found that the secondary compression of sand is small while that for organo-mineral soils is very great. But there are other factors which may affect secondary consolidation. Lo (1961) stated that secondary consolidation is extremely susceptible to environmental changes, particularly temperature. But Plum and Esrig (1969) noted that temperature changes had very little effect on secondary consolidation. Mitchell (1969) stated "evidence on the influence of temperature variations on secondary compression rates is conflicting, with some investigators indicating secondary compression rates increase significantly with increasing temperature". He further stated that because of its great importance and controversial nature it should be given further study. Barden (1968) commented that there is much dispute as to the effect (on secondary compression) of total load, load increment ratio and the thickness of sample used in oedometer tests.

Research in the past has generally been of such a nature that two or three of the variables mentioned have been studied while holding the other variables constant. In order to eliminate the confusion that now exists concerning the effect of various factors that have been

reported to influence secondary consolidation, a study is necessary which will include as many of the variables as possible.

It was realized that this could be a monumental task and that certain simplifications would be necessary. Because of the great effect organic matter in soil has on the soil's secondary consolidation behavior it was necessary to use in the study an organic soil, and the same soil with a substantial quantity of the organics removed. Other variables included in the study were sample thicknesses, load increment ratios and the testing temperature.

Secondary compression was measured in terms of C_{α} , the change in void ratio per logarithm of time on a plot of void ratio versus the logarithm of time.

It was hoped that in the limited time available using this system of variables, valuable insight into the related nature of their influence on secondary consolidation could be obtained.

CHAPTER II

PROCEDURES

A. Soil Description

The soil chosen for the investigation was Bryce clay loam to clay (Wascher, Smith and Odell 1951). It is third in predominance in Iroquois County, Illinois, occupying an area of 125 square miles or approximately 10% of the county area. The sample used in the analysis was taken from the NW 1/4 of SW 1/4 of Sec. 19, T.24, R.13 W of Iroquois County, Illinois (Wascher, Alexander, Ray, Beavers, and Odell 1960).

Bryce clay is a dark humic-gley soil that is found on nearly level to gently sloping areas (Wascher et al 1951). The parent material to a depth of at least 18 inches is mostly water deposited lakebed sediments of the Wisconsin glacial period. The "A" horizon ranges from a black clay loam to a very dark brown silty clay loam. It is 8 to 12 inches thick. The "A" horizon gradually grades into the "B" horizon. The "B" horizon is not distinctly defined until a depth of 12 to 16 inches is reached. The "B" horizon is a plastic clay mottled with pale yellow and dull rusty brown, and grades into glacial till at 25 to 30 inches. Bryce clay was chosen for the investigation because it was a high clay content soil and because it has a relatively high organic carbon content. From laboratory tests the soil in the "A" horizon just below the sodded layer from 0 to 2 inches in depth had an average carbon content of 5.0%. From 2 to 4 inches the carbon content dropped to 4.8%, from 4 to 6 inches to 4.6%. The entire testing program was conducted using soil from the 2 to 6 inch depth. In its natural state the average organic carbon content was found to be 4.7%.

A listing of other pertinent physical properties of Bryce clay used in this investigation is summarized in Table 1.

B. Soil Preparation

The soil was stripped from the natural ground in 2 inch lifts. It was bagged and marked according to the depth from which it was taken. The soil was initially air dried and the clods were broken down in a Lancaster PC Mixer until nearly all would pass a #40 sieve. Of the 150 lbs. of natural soil, approximately 98% passed the #40 sieve with limited grinding. The remaining 2% was discarded. The soil passing the #40 sieve was then split into two equal portions. One portion was ready for testing. (From this point it shall be referred to as the carbon soil.) The remaining portion was treated to remove most of the organic matter.

In order to test the same soil with and without the organic matter, it was necessary to use a technique whereby substantial organics could be removed without significantly affecting the mineral fraction of the soil. To do this a standard method of isolating organic matter using hydrogen peroxide was utilized (Baver 1930). Hydrogen peroxide is an ideal oxidant for organic matter since it decomposes into water and free oxygen. Schmidt, in his work with organic soils (Schmidt 1965), experimented with various treatments utilizing different concentrations of hydrogen peroxide and time of reaction. He also varied the rate of the reaction through the use of a water bath at different temperatures. Schmidt suggested that a 50°C water bath using a relatively short reaction time would be most efficient.

After some experimentation the procedure finally adapted was as follows: 100 grams of soil was added to 100 ml of hydrogen peroxide

TABLE 1
 Physical Properties of Bryce Clay Loam
 and H₂O₂ Treated Bryce Clay

	Particle Size Distribution (%)			Atterburg Limits			Organic Carbon (%)	Specific Gravity
	Sand >.05mm	Silt 50-2μ	Clay <2μ	LL	PL	PI		
Bryce Clay	17	47	36	60.3	40.0	20.3	4.7	2.57
Treated Bryce Clay	14	38	48	45.1	25.0	20.1	1.1	2.66

over a 1 hour period utilizing a 2000 ml flat bottom flask in a 50°C water bath. The 1 hour period was needed to assure that the reaction would be slow enough that the soil-hydrogen peroxide mixture would not froth over into the water bath. After 2 to 4 hours another 50 ml of hydrogen peroxide was mixed with the thick suspension to insure sufficient organic removal had been accomplished. If little reaction occurred, an additional 100 ml of hydrogen peroxide and 100 grams of soil was added over a 1 hour period. After the reaction had slowed to an insignificant rate 150 ml of hydrogen peroxide was added and the flask allowed to remain for 8 hours in the 50°C bath. The thick mixture was then poured into evaporating dishes and allowed to dry. The soil, air dried, was reground to pass a #40 sieve and the complete treatment process was repeated. The first treatment accomplished an average removal of 3.4% organic carbon, the second treatment an additional 0.2%.

This method of treatment was found to be the most efficient in terms of time and equipment because it was possible using this method to process 200 grams of carbon soil per 2000 ml flask every two days. Through the use of this treatment, organic soil was reduced from a carbon content of 4.7% to a carbon content of 1.1%. Hereafter the treated soil will be referred to as the noncarbon soil although strictly speaking, it contained 1.1% organic carbon. A listing of other pertinent physical properties is given in Table 1.

C. Equipment Design and Utilization

While developing a treatment procedure for the removal of organic matter from the natural soil, it was first necessary to determine the effectiveness of one treatment versus another and secondly to know the carbon contents of the treated and untreated soils used in the investigation.

Organic carbon content was determined using Allison's Method (1960). This method is a gravimetric determination of carbon dioxide generated when organic matter is treated with strong oxidants. The apparatus, as constructed, is shown in Fig. 1.

The procedure for the determination of organic carbon using Allison's Method is as follows. A known weight of an oven dried carbon soil is placed in a flask. To this flask is added potassium dichromate and a mixture of sulfuric and phosphoric acid. These reagents combine to form chromic acid, a very strong oxidant. The carbon in the soil is oxidized and in a gaseous phase carried by a carbon dioxide free air stream through a system of vials and "U" tubes (see Fig. 1). Carbon dioxide and water vapor are removed from the air stream by passing free air through a tower containing mica and soda-lime, on which the gasses are sorbed. Any gases other than carbon dioxide that might be sorbed in the Nesbitt bulb are removed by the reagents in the system of vials and "U" tubes. The only reactions in the Nesbitt bulb are those of carbon dioxide with potassium hydroxide on mica and water sorbed by magnesium perchlorate. The remaining gasses of the air stream pass through the Nesbitt bulb freely.

Quantitatively the weight gain in the Nesbitt bulb is due solely to the complete reaction of carbon dioxide with materials in the Nesbitt bulb. Therefore, knowing the weight of the original sample and the weight gain of the Nesbitt bulb due to the sorption of carbon dioxide, a direct measure can be made of the organic carbon content of the soil.

In order to control the temperature of the soil in the consolidometer ring it was necessary to add certain equipment. For one frame to make possible a temperature range both above and below ambient temperature

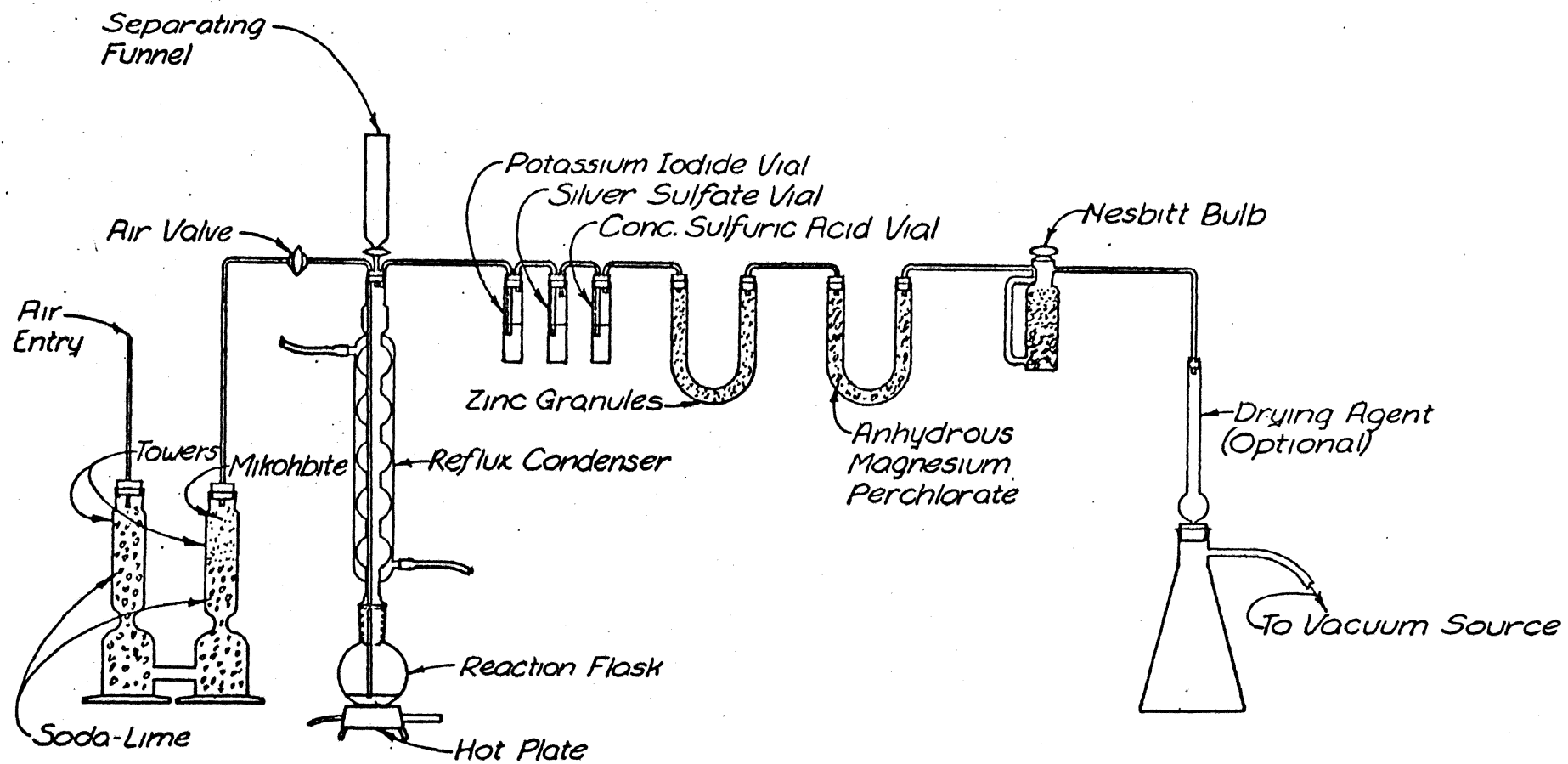


Fig. 1. Apparatus for Allison's carbon determination.

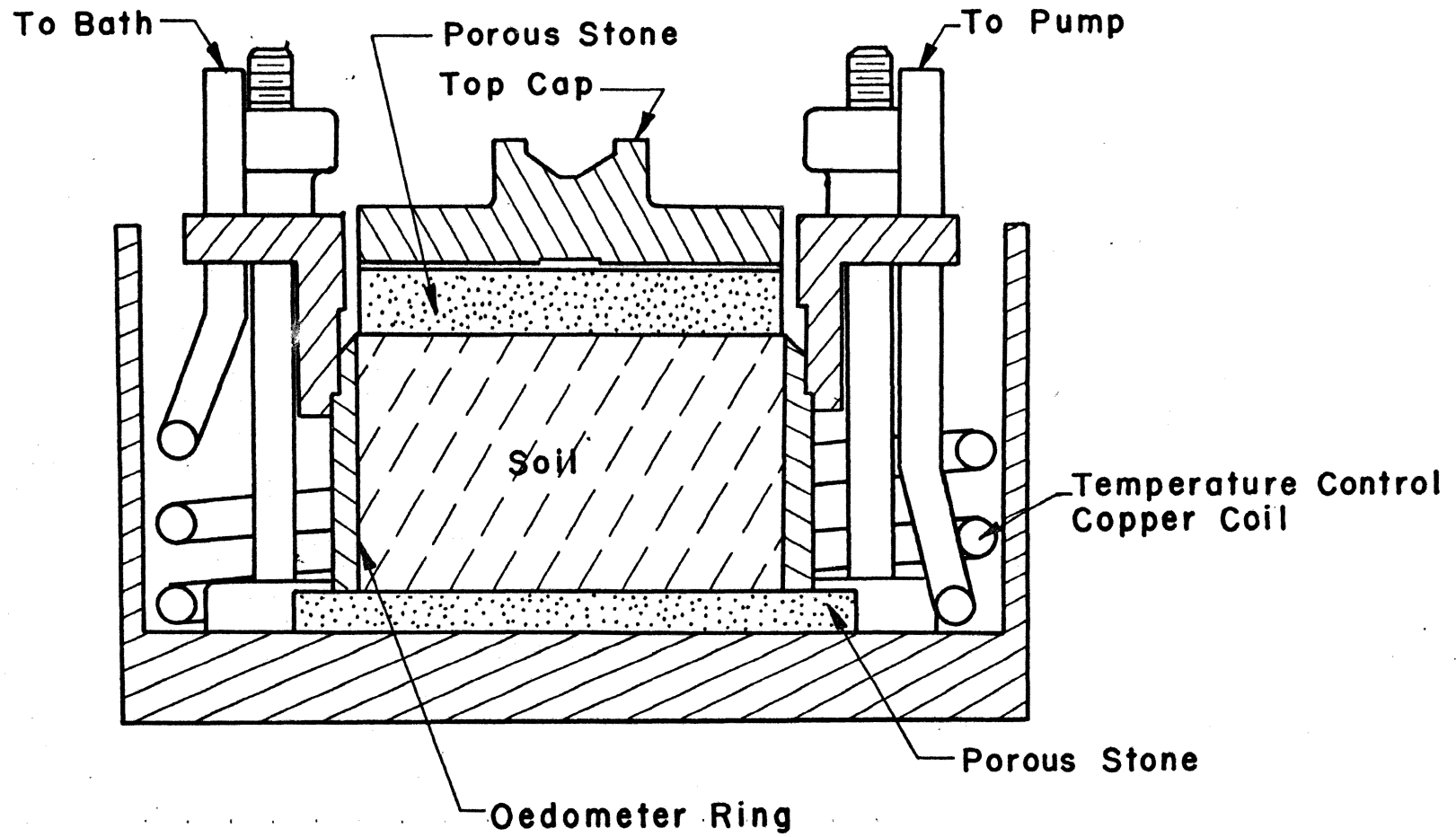


Fig. 2. Bishop Consolidation Cell with temperature control.

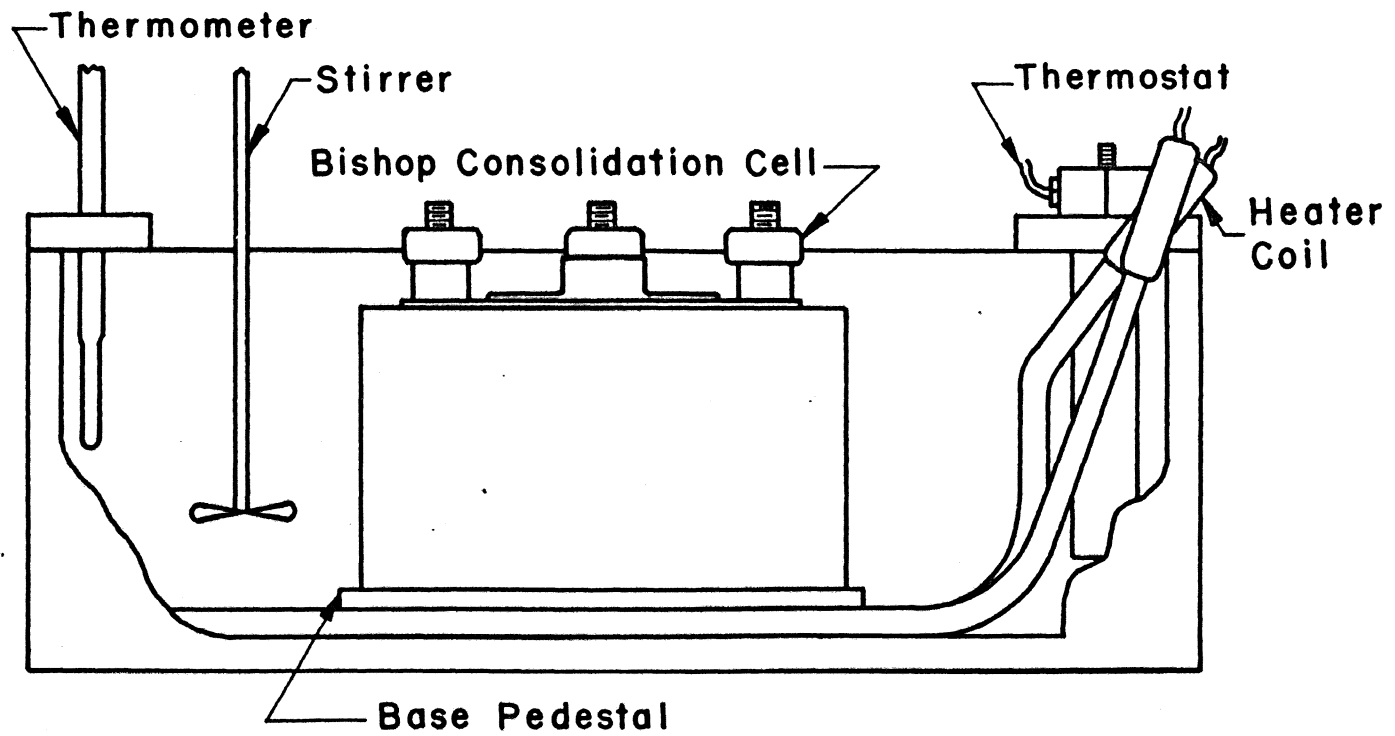


Fig. 3. Consolidation cell and temperature bath for above ambient.

copper coils lined the inside circumference of the Bishop type consolidometer cells. These coils were connected to a circulating water pump in a controlled temperature water bath (see Fig. 2). A continuous flow of water from the temperature bath to the cells and back to the bath maintained the desired temperature of the soil sample.

Small individual baths for above ambient temperature were made for the two positions of the second frame. A small heater coil connected to a thermostat regulated the bath temperature. A cell rested in this bath and an electrical stirrer helped maintain a constant temperature (see Fig. 3).

The Bishop type cells with extended base posts and both $3/4$ and $1\frac{1}{2}$ inch thick rings to fit these cells were made in the school machine shop. For both the $3/4$ and $1\frac{1}{2}$ inch thick samples the soil preparation for consolidation testing was the same. Distilled water was added to the soil until a water content approximately equal to the liquid limit was reached. The mixture was allowed to age for 24 hours at a constant moisture content. The soil was then brought to the liquid limit and molded into the oedometer rings. The ends were trimmed both top and bottom and oedometer ring and soil were weighed immediately and placed in the cells.

D. Testing Program

A controlled schedule of consolidation tests with several variables was planned. These variables included soil type, test temperature, ring thickness, and load increment ratio (Table 2). Basically two sets of identical tests were performed, one on high carbon soil, the other on the same soil with substantial quantities of the carbon removed. The test temperatures used were 5° , 25° , 35° , and 50°C . The samples were

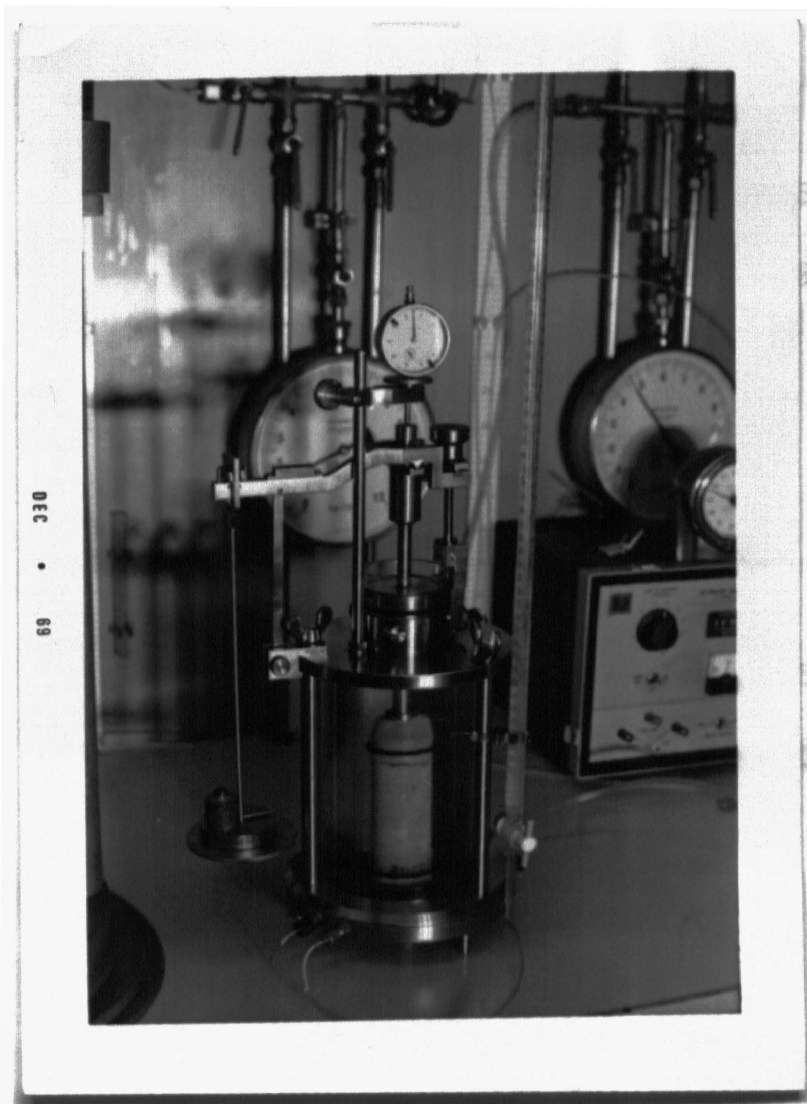
TABLE 2

Testing Program

H - 4.7% Organic Carbon Soil
 L - 1.1% Organic Carbon Soil

<u>Sample Thickness</u>	<u>Load Inc. Ratio</u>	<u>Temperature</u>			
		<u>5°C</u>	<u>25°C</u>	<u>35°C</u>	<u>50°C</u>
3/4	1.00	H, L	4H, L	H, L	H, L
3/4	1.83	H, L		H, L	
3/4	0.415	H, L		H, L	
1 1/2	1.00	H, L	H, L	H, L	

either $3/4$ inch or $1\frac{1}{2}$ inches thick and all samples were 2.5 inches in diameter. The loading ratios utilized were $\Delta P/P$ equal .415, 1.0, and 1.83. The $\Delta P/P$ ratio was not constant throughout the test but varied between 0.125 to 1.0 tsf and from 2.0 to 16.0 tsf (Fig. 4).



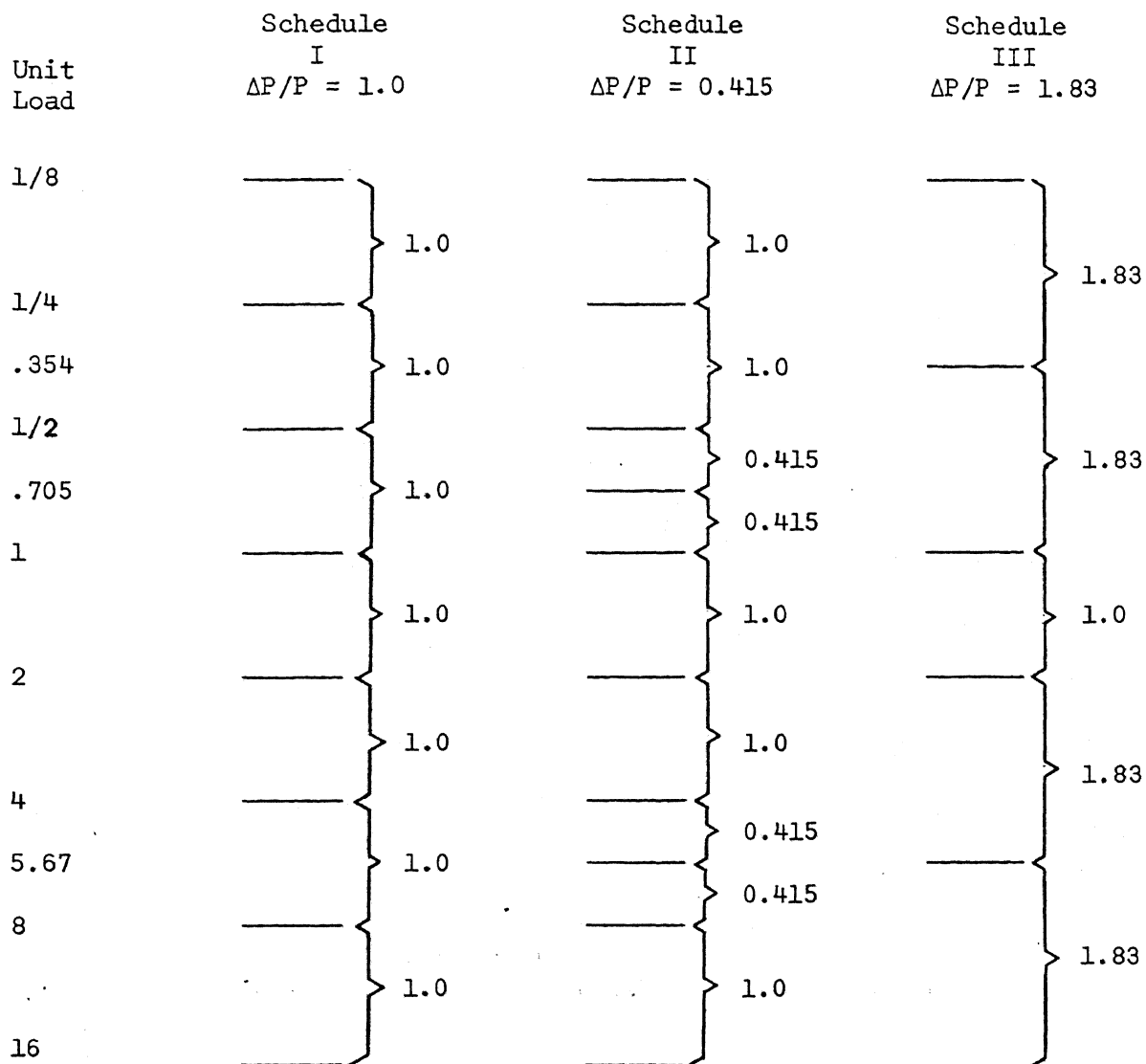


Fig. 4. Loading methods.

CHAPTER III
LITERATURE REVIEW

A. Introduction

Consolidation is the gradual reduction in volume of a soil mass resulting from an increase in compressive stress (ASTM). Skempton and Bjerrum (1957) suggest that consolidation can be divided into three phases. Initial consolidation is a comparatively sudden reduction in volume due principally to the expulsion and compression of gas in the soil voids. Primary consolidation is the reduction in volume due to the squeezing out of water from the void spaces of the soil mass and is accompanied by a transfer of the load from the soil water to the soil solids. Secondary consolidation is the reduction in volume due to the adjustment of the internal structure of the soil mass after most of the load has been transferred from the soil water to the soil solids (ASTM D 653-67).

Although the mechanisms of initial and primary consolidation are generally understood and accepted (Yong and Warkentin 1966), secondary consolidation has been explained in several ways and the American Society for Testing and Materials definition given above does not explain why an adjustment of the internal structure occurs. Barden (1969) suggested that the mechanism responsible for secondary consolidation could be explained in three different ways. It could be a viscous structural reorientation of interparticle contacts through the layers of absorbed water (Terzaghi 1941). It could also be explained as the jumping of electrostatic bonds of a card-house structure (Tan 1957). Finally, secondary consolidation could be explained as a two level structure with primary consolidation being the drainage of a macropore structure

and the secondary consolidation the drainage of a micropore structure (DeJong 1965).

Because of the importance of secondary consolidation and because there are contradicting theories as to its true mechanism, much research has been done in an attempt to gain insight into the true nature of its behavior.

B. The Shape of Secondary Consolidation on the Void Ratio Logarithm of Time Plot

Buisman (1936) was perhaps the first to document secondary consolidation. He reported that secondary consolidation was approximately linear on a void ratio versus logarithm of time plot. Since that time many others have reported the linearity of secondary consolidation on a logarithm of time plot [Leonards and Altschaeffl (1964), Barden (1969), Mitchell (1968)]. Others have reported that the plot may not be linear [Lo (1961), Wahls (1962)]. Lo (1961) stated that secondary consolidation could not plot linearly indefinitely, because a time would be reached at which there would be zero voids. Lo in fact found for all soils tested both organic and inorganic that ultimate settlement was reached within 3 weeks.

Lo stated that secondary compression curves could be characterized by one of three shapes. These shapes were classified as type I, II, and III curves. Type I curves showed a gradual decrease of the rate of secondary consolidation until the soil finally reaches ultimate settlement. Type II curves were characterized by the proportionality of secondary compression with the logarithm of time for an appreciable range of time before the final settlement was reached. The change in void ratio of the straight line portion of secondary consolidation is known as C_{α} .

Type III curves show an acceleration of the rate of secondary to a sharp equilibrium void ratio. Leonards and Giraults' (1961) curves agree basically with Lo's work. Wahls (1962) preferred a separation into two basic types. The first type were those in which primary consolidation dominated, the second type were those in which secondary consolidation dominated.

C. Factors Affecting Secondary Consolidation

It would appear that because there have been several characteristic shapes cited that there must be factors which affect secondary consolidation or the shape of the void ratio logarithm of time plot. Within the literature there are several factors which have been reported to influence secondary consolidation.

There are conflicting views as to how secondary consolidation is related to the effective unit load. Newland and Allely (1960) found that C_{α} was almost independent of the effective stress except near the preconsolidation pressure where values of C_{α} were slightly higher. Wahls (1962) found for both undisturbed and remolded organic silt that as the effective stress increased C_{α} increased rapidly to a maximum and then decreased slowly with further increase in stress. Jonas (1964) agreed that C_{α} increased with increasing effective unit load up to the preconsolidation pressure but was constant thereafter. Goldberg (1965) suggested that after the preconsolidation pressure was reached C_{α} increased almost linearly with increasing effective pressure. Olson (1965), for a sensitive soil, found a sharp increase to the preconsolidation pressure and thereafter a sharp decrease in C_{α} . Barden (1969) found C_{α} almost independent of the effective stress.

There is also controversy as to whether C_{α} is a function of the load

increment ratio, often referred to as the $\Delta P/P$ ratio (ratio of the effective load applied during the latest increment to the total previous effective load applied). Several authors have reported that C_α is independent of the $\Delta P/P$ ratio Newland and Allely (1960), Leonards and Girault (1961), Wahls (1965) . But Leonards and Altshaeffl (1964) found that C_α decreases for extremely small load increment ratios. Barden attempted to explain this behavior using a viscosity parameter, b . He suggests b is responsible for different amounts of secondary consolidation, because of b 's thixotropic nature. b is dependent upon the viscosity of the pore fluid which may increase because with time diapolar water will orientate itself with the clay platelets. If the load increment is small, secondary effects may be extremely sensitive to the load increment ratio because viscous effects rather than pore pressures dominate.

Temperature is another factor which may affect secondary consolidation. Gray (1936) found that secondary consolidation was greater at higher temperatures. Hanrahan (1954) reached the same conclusion with the peat he studied. Lo (1961) found that a decrease of 3°C completely altered C_α . Schiffman, Ladd, and Chan (1966) reinforced earlier works by finding a large change in C_α due to a small change in temperature.

Unlike earlier work Paaswell (1968) studied the temperature affects from a different viewpoint. He induced a temperature gradient across the sample and found there was an increase in strain. His argument was that this increase in strain was due to the movement of bulk water, not a rearrangement of the internal structure; thus the movement was primary, not secondary consolidation. Campanella and Mitchell (1968) found that an increase in temperature increased the pore water pressures and upset the balance between structure and temperature at a particular stress

level. The change, they stated, was due to additional primary consolidation and did not significantly affect C_{α} . Plum and Esrig (1969) found C_{α} changed only slightly due to a change in temperature.

C_{α} may also be dependent upon the thickness of the consolidation sample. Newland and Allely (1960) found that the secondary consolidation was independent of the sample thickness. Barden (1969) concurred with result of Newland and Allely but stated that further research was needed to confirm their result.

The quantity of organic matter within the soil has a definite effect on secondary consolidation as pointed out by Gray (1936). He found that secondary consolidation was greater for organic soils. These findings have been substantiated by many writers [Hanrahan (1954), Barden (1968), Schmidt (1964)] in a comparison study of the physical properties of an organic soil versus the same soil treated with hydrogen peroxide to remove a majority of the organics, found C_{α} varied approximately linearly with the organic content.

Lo (1961) found that a sudden vibration of the soil displaced the consolidation curve downward but C_{α} remained essentially constant. Recently work has begun on the effects of dynamic vibratory loads on consolidation behavior. Hardin and Black (1968) and Humphries and Wahls (1968) found that a small amplitude and repeated loading and unloading of cohesive soil increased secondary consolidation.

The amount of disturbance also has an effect on the secondary compression. Both Gray (1936) and Taylor (1942) observed that remolded soils exhibit less secondary compression effects than undisturbed soils. Other writers have substantiated their conclusion [Lo (1961), Barden (1965)].

D. Effects of the Hydrogen Peroxide Treatment

Schmidt (1965) found that the removal of organic matter using hydrogen peroxide had little effect on the clay minerals but there was a great influence on the physical properties of an organic soil due to the decrease in organic matter. He found that although there was a decrease in the liquid and plastic limit due to the treatment, there was no significant change in the plasticity index. The clay mineralogy of both the treated and untreated soils were essentially the same. The moisture density relations varied somewhat. He found that the higher the carbon content the lower the maximum dry density and the higher the optimum moisture content. In consolidation tests, the higher the carbon content the higher the void ratio at a given stress level. Neither the coefficient of permeability nor coefficient of consolidation were significantly different.

CHAPTER IV
STATISTICAL EVALUATION OF REPRODUCIBILITY

Four tests were performed at each oedometer position, in which the temperature, load increment ratio (the ratio hereafter referred to as $\Delta P/P$ ratio), sample thickness, and organic carbon content of soil were kept constant in an attempt to obtain duplicate results from each oedometer position. This was done to assure that a test could be performed at any oedometer position without a significant variation in test results. The tabulated values of C_{α} obtained for the four tests are given in table 3.

An analysis of variance was used to split the variation into variance between samples (due to the load increment) and variance within samples (which represents the inherent variation, or the experimental error). Each variance was calculated as the sum of the squares of deviation divided by the number of degrees of freedom and the variances were compared by the F test. From a standard table of F values (Neville & Kennedy 1966) at the 5 percent level of significance $F = 2.57$. If the computed F value is less than 2.57, the variation between effective stress levels is insignificant with respect to the variation between loading positions. If the computed F value is greater than 2.57, the variation between positions or for this analysis the inherent experimental error is comparatively insignificant. From the calculations, $F = 32.17$. Therefore the variation from one loading position to the next or the inherent experimental error is insignificant, at the 5 percent level of significance. Fig. 5 shows the variation of C_{α} versus the logarithm of the total effective stress for the four tests.

A load cell was used to assure that calculated applied loads were

TABLE 3
Analysis of Variance

Effective Stress (tsf)	16	8.0	4.0	2.0	1.0	.50	.250	All Systems
Position 1	47	48	54	60	65	61	57	392
2	45	46	50	58	65	61	57	382
3	49	53	56	64	74	66	57	419
4	45	49	56	60	69	65	56	400
Σx	186	196	216	242	273	253	227	1593
\bar{x}	46.5	49.0	54.0	60.5	68.25	63.25	56.75	56.89
Σx^2	8660	9630	11688	14660	18687	16023	12883	92231
Sum of Squares of Deviation = $\Sigma x^2 - \frac{(\Sigma x)^2}{n}$	11	26	24	19	55	21	1	1601

Source of Variation	Sum of Squares	Degree of Freedom	Mean Square
Within Samples (Systems)	157	21	7.48
Between Samples (Systems)	1444	6	240.67
Total	1601	27	59.29

$$F = \frac{\text{Mean Square Between Samples}}{\text{Mean Square Within Samples}} = \frac{240.67}{7.48} = 32.17 > 2.57$$

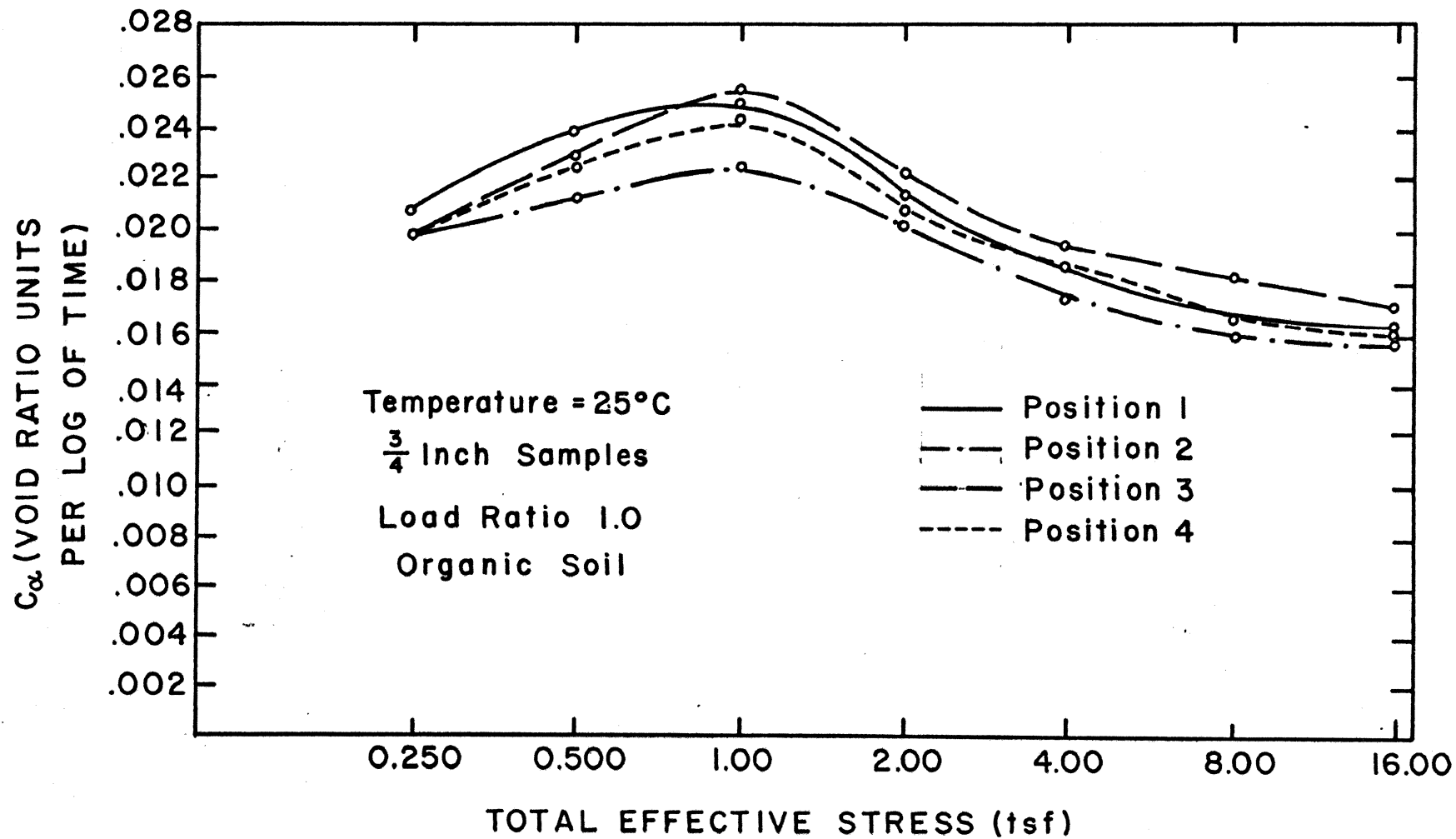


Fig. 5. Position comparison.

the actual loads taken by the ring samples. The loading weights used to apply pressure to the ring samples were applied to the load cell and the weights recorded on the load cell were noted. It was found for one frame, the applied loads were within 2 percent of the theoretical values. For the other frame, the applied loads were within 0.1 percent of the values calculated. The conclusion of this analysis was that a test could be performed at any load position without a significant degree of variance as long as all samples were molded into the oedometer rings at the liquid limit. The initial moisture contents were within 1 percent of the value determined as the liquid limit.

CHAPTER V

DISCUSSION OF THE RESULTS

A. Test Results and Analysis

To study secondary consolidation in terms of C_{α} implies that the slope of the void ratio versus logarithm of time plot, in the secondary region, is a straight line. Lo (1961) found that for all soils he tested the secondary consolidation slope for a single load approached a constant void ratio within three weeks.

For both the carbon and noncarbon soils, C_{α} (change in void ratio per logarithm of time) was found to be nearly constant for 10,000 minutes or approximately 7 days. One sample was allowed to consolidate under a single load for 10 days and no change in the slope from the straight line portion of secondary consolidation was noted. In the program all samples were allowed to consolidate to a point where the straight line portion of secondary consolidation had developed sufficiently to define C_{α} .

In the study of the influence of the load increment ratio on C_{α} a constant $\Delta P/P$ ratio throughout a loading cycle for a single test was not used as has been done in previous investigations, [Lo (1961), Wahls (1962), Leonards and Girault (1961)]. $\Delta P/P$ ratios of 0.415, 1.0, and 1.83 were used between 0.125 and 1.0 tsf and between 2.0 and 16.0 tsf (see fig. 4). All samples were consolidated under load increments of 0.125, 1.0, 2.0, and 16.0 tsf.

In the past C_{α} has been found to be independent of the load increment ratio, [Wahls (1965)]. If this is the case then regardless of what loading sequence is adopted, at any given total effective unit load and equilibrium void ratio, C_{α} should be a constant. The plot of C_{α} versus logarithm of

time should be the same for a variable $\Delta P/P$ from 0.125 to 1.0 tsf and from 2.0 to 16.0 tsf, as that for a constant $\Delta P/P = 1.0$ throughout the test.

In fig. 6 for 5°C is shown a plot of C_{α} versus the logarithm of pressure for tests utilizing $\Delta P/P$ ratios of 0.415, 1.0 and 1.83, on both carbon and noncarbon soils. Although there is some scatter of the data, it can be seen that in general, varying the $\Delta P/P$ ratio within the test does not significantly influence C_{α} . In fig. 7 is shown the same plot for 35°C . Again there is no significant departure of the test curves where $\Delta P/P = 0.415$ and 1.83 from that where $\Delta P/P = 1.0$. These data tend to substantiate the findings of Wahls and other writers, and with the added dimension, temperature, has verified their conclusions both above and below ambient temperatures.

From fig. 6, 7, 8, can be seen the influence of the effective unit load on C_{α} . It is apparent that C_{α} for these tests is not independent of the effective unit load as reported by Newland and Allely (1960) and Barden (1968). C_{α} consistently increased to a maximum at 1.0 or 2.0 tsf and again decreased, regardless of the sample thickness. The change in C_{α} was the most markedly defined for the double thickness carbon samples, (fig. 9). There is only a slight increase in C_{α} with increasing effective stress for the double thickness noncarbon soils. Wahls (1962) found the same increase in C_{α} to a maximum value but he stated the decrease in C_{α} above the maximum value was more gradual with increasing load. Fig. 8 illustrates that C_{α} decreased at approximately the same time rate that it increased and approached a constant value at the highest unit loads of 8.0 to 16.0 tsf.

Fig. 8 and 9 show the influence of temperature on C_{α} versus the

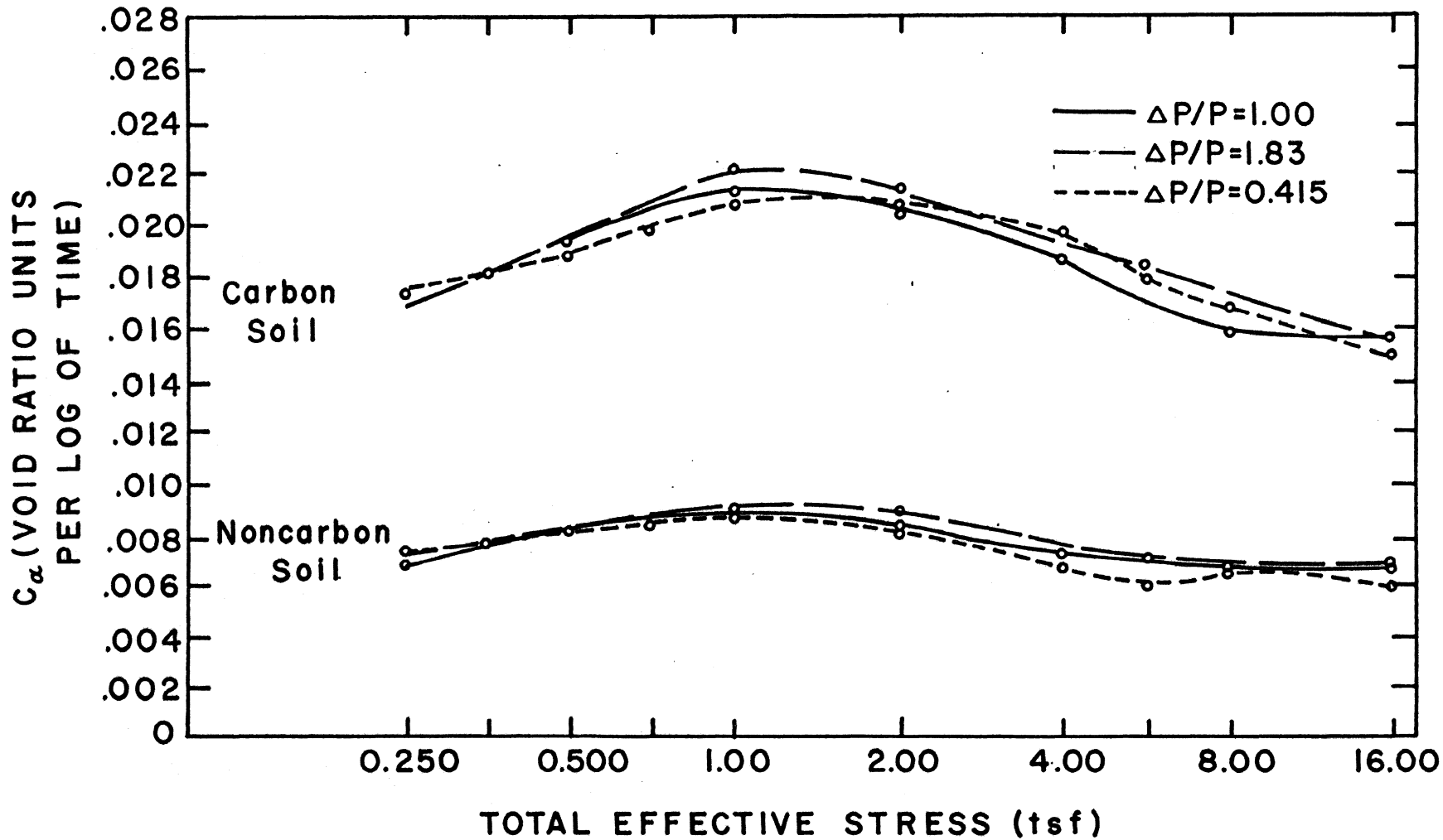


Fig. 6. Load increment ratio comparison, temperature 5°C.

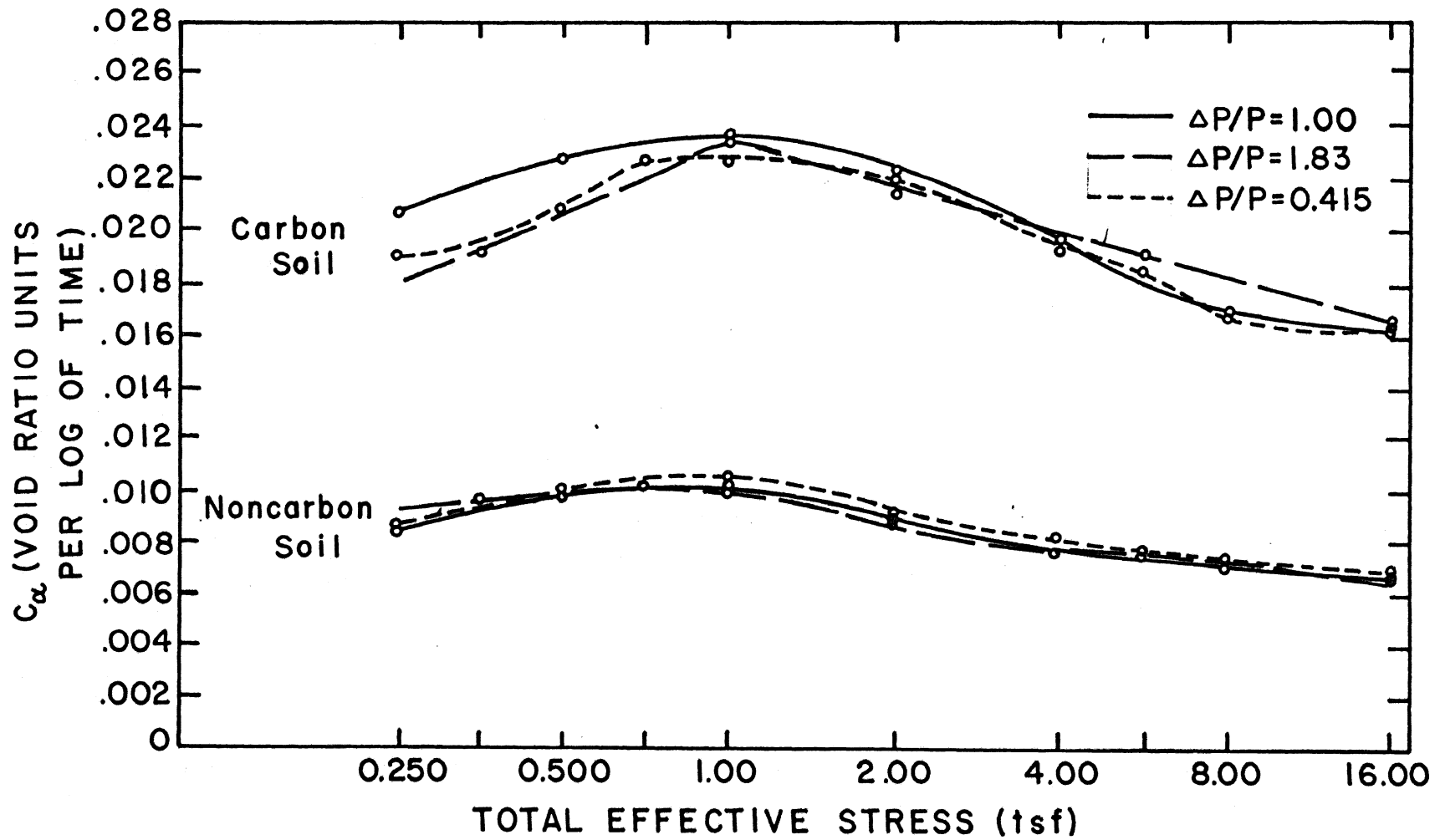


Fig. 7. Load increment ratio comparison, temperature 35°C.

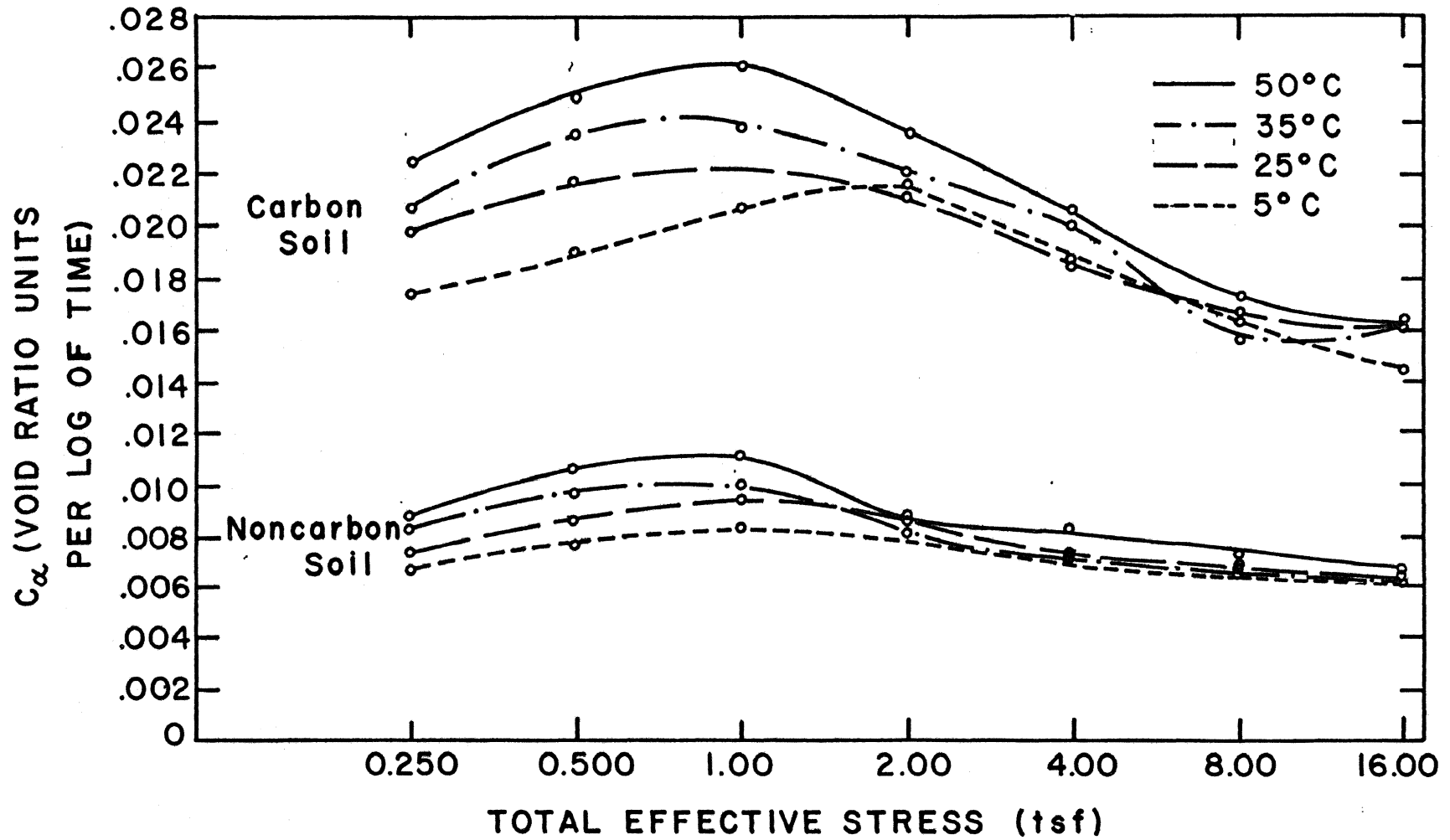


Fig. 8. Temperature comparison, 3/4 inch samples.

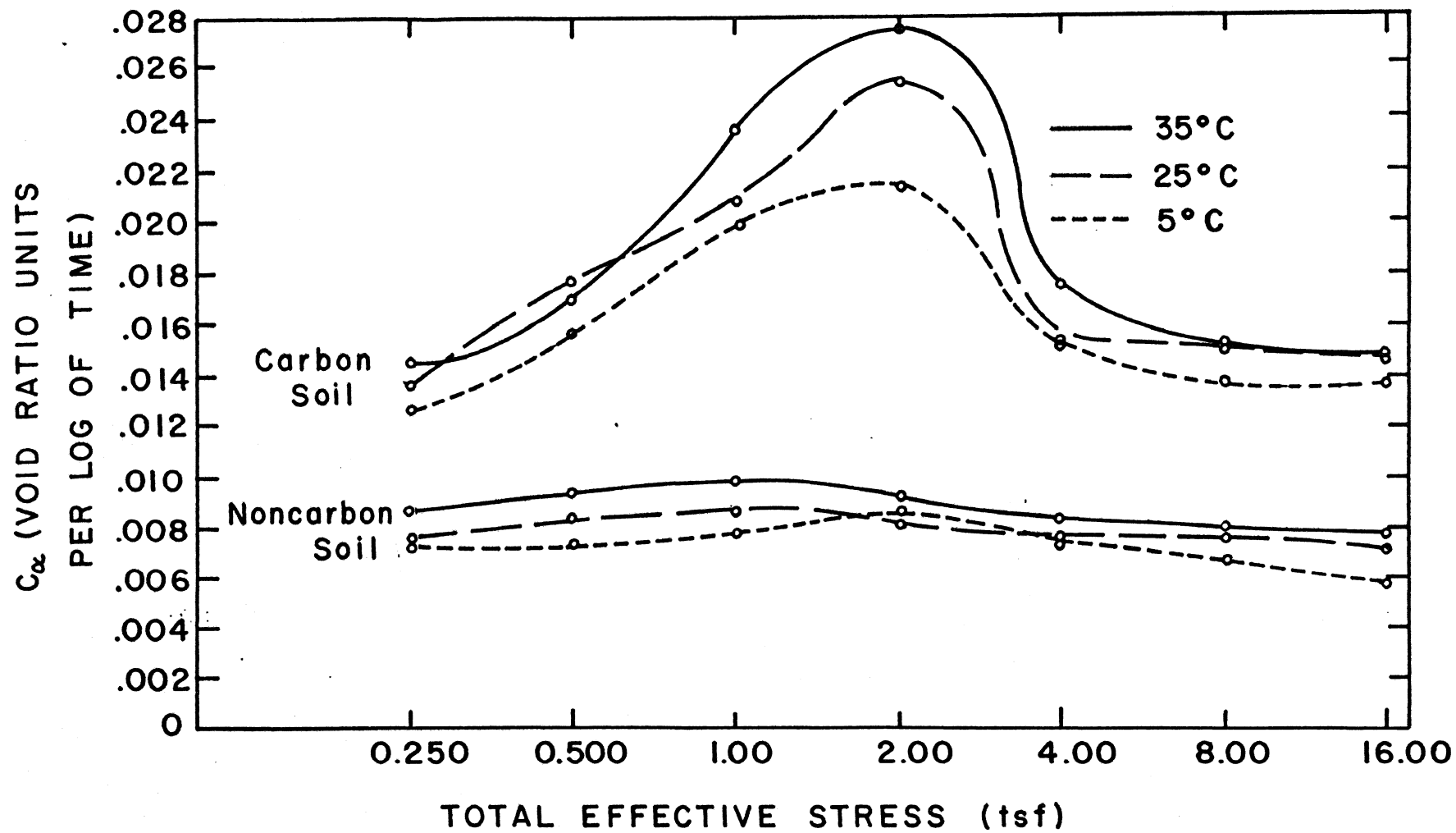


Fig. 9. Temperature comparison, 1 1/2 inch samples.

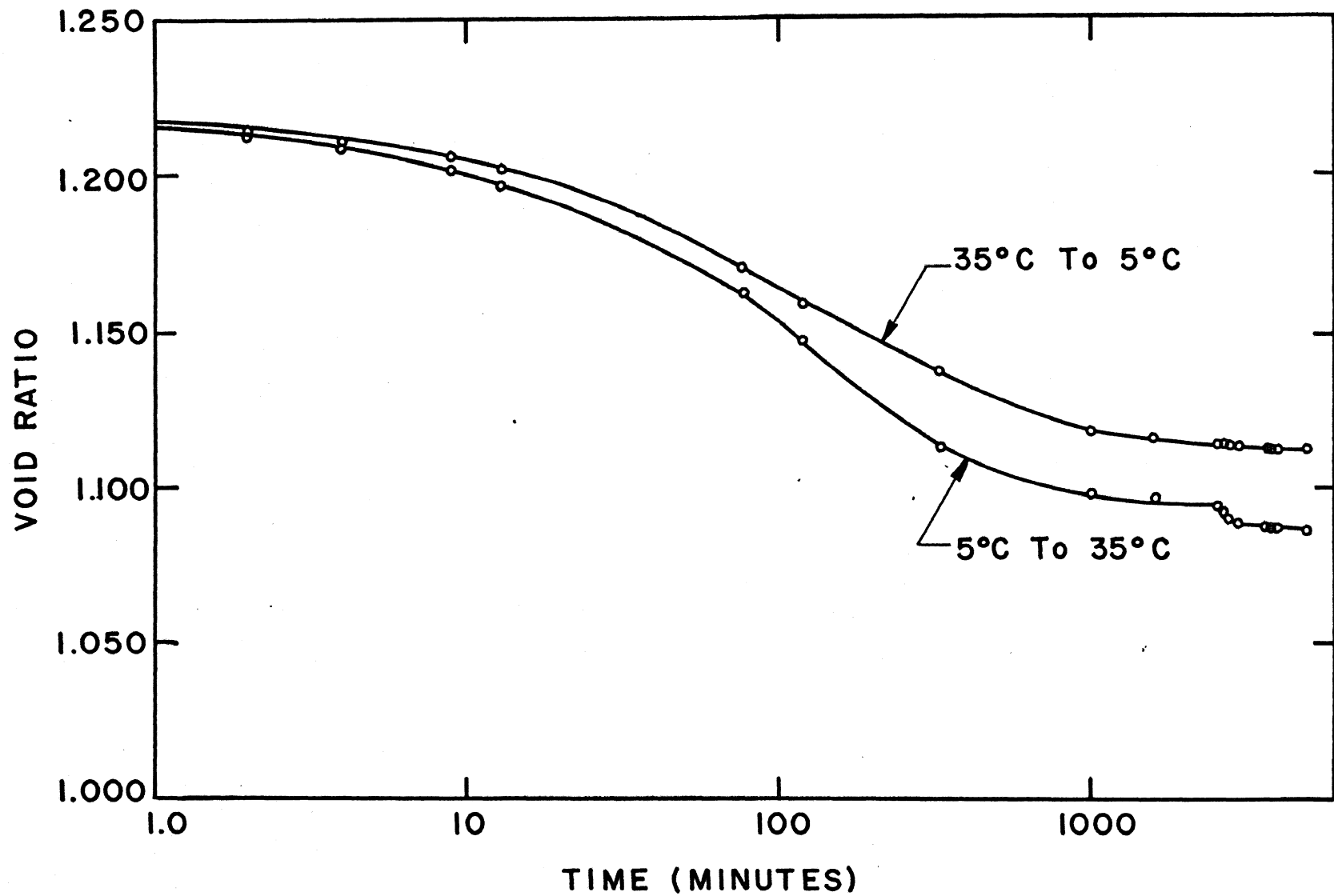


Fig. 10. Void ratio versus the logarithm of time for the organic soil at 0.25 tsf effective unit load.

logarithm of pressure, for both carbon and noncarbon soils. In general the higher the temperature the greater the magnitude of secondary consolidation. For the samples (fig. 8) in the lower load range, the influence of temperature on secondary consolidation appears to be substantially greater than it is for the higher loads. In fig. 9, for the double thickness carbon soils this was not as noticeable and, in fact, it is apparent that the temperature has the greatest influence on secondary consolidation at the maximum value of C_{α} . After the peak C_{α} for both carbon and noncarbon soils at 1.0 or 2.0 tsf the curves tend to converge indicating decreasing influence of temperature on secondary consolidation at higher loads. These findings support the earlier works of Schiffman, Ladd, and Chan (1966) and Hanrahan (1954).

The temperature control was discontinued on two cells during secondary consolidation. One sample test was performed at 35°C and was permitted to decrease to room temperature or 24°C in about two hours. Very little change was noted in C_{α} . (See fig. 10) But the other sample increased in temperature from 5°C to 24°C. For this sample the void ratio versus logarithm of time curve changed drastically showing a vertical displacement of the secondary consolidation portion of the curve. Lo found that a 3°C increase in temperature completely altered the void ratio versus logarithm of time curve. Mitchell (1968) explained this variation as an increase in pore water pressure due to the decrease in viscosity. This increase in pore pressure induced further primary consolidation. The sudden increase in deflection was a renewal of primary consolidation and should not be confused with secondary consolidation.

Murayama and Shibata (1961) suggested a mechanism for secondary consolidation based on structural viscosity. They suggested in equation form that the change in secondary consolidation strain with respect to the logarithm of time was proportional to the absolute temperature. They found experimentally that the plot of the change in strain with respect to the logarithm of time versus temperature was a linear function passing through 0°C at zero strain.

Fig. 11 indicates that for both carbon and noncarbon soils, the change in strain per logarithm of time for low stress levels is approximately a linear function of temperature, but at higher stress levels Fig. 12 is almost independent of the temperature. In short whereas Murayama and Shibata found C_{α} to be a constant function of the temperature, the findings presented herein indicate that the influence of temperature on C_{α} is dependent upon the stress level.

This disagreement in findings could be explained as a difference in testing procedure. Murayama and Shibata eliminated the side friction encountered in oedometer tests by performing their tests using a compression plastometer. This instrument applied a constant effective load to a soil sample in a triaxial cell and measured the resulting deformation. The apparent decrease in influence of temperature on secondary consolidation with higher effective stress levels, found in the results presented, could not be due to the increase in friction of soil against oedometer ring at greater stresses, because C_{α} for the double thickness samples is approximately twice that for the single thickness samples.

Barden (1968) considered a mechanism involving shear failure and jumping of bonds in a highly redundant soil skeleton followed by a gradual relaxation to a new equilibrium, the rate of relaxation being governed by the viscosity of the adsorbed water layers.

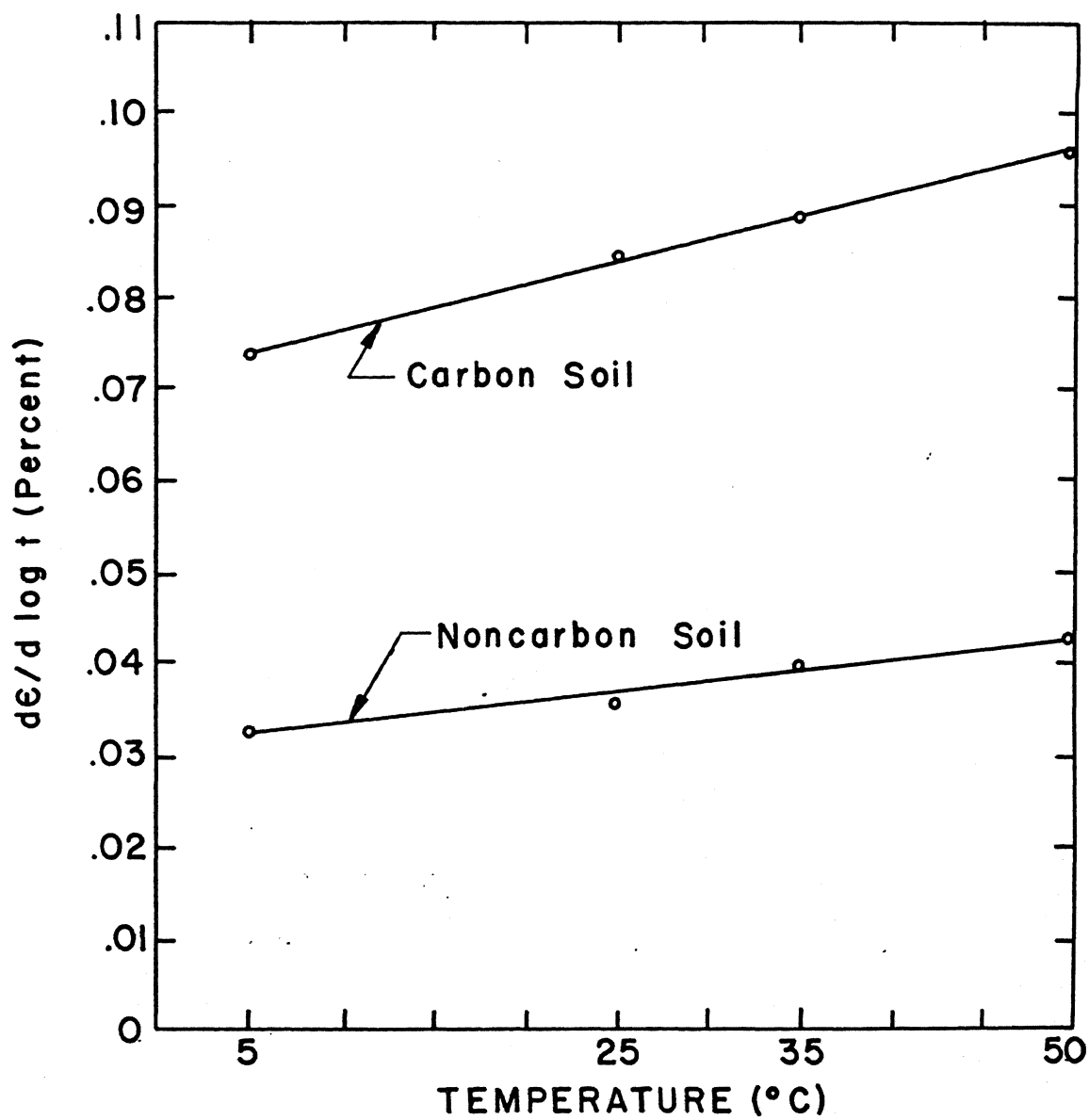


Fig. 11. Rate of flow as a function of temperature 0.250 tsf.

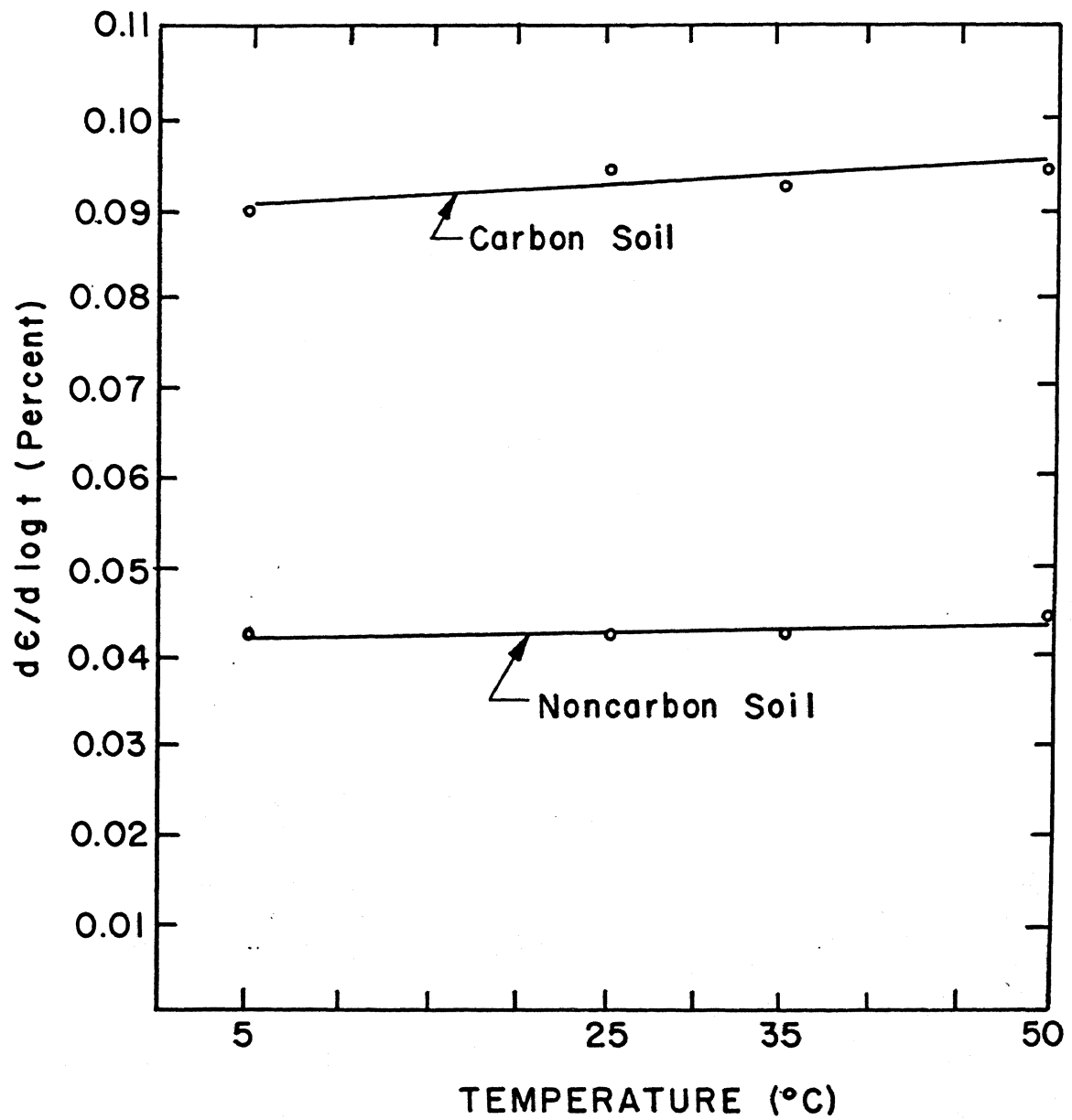


Fig. 12. Rate of flow as a function of temperature 16.00 tsf.

It is suggested that because of the high liquid limit and percent Illite content the remolded organic soil had a more dispersed structural arrangement (Heagler 1969). Barden suggested the dispersed state implied a more parallel orientation of platelets with few contacts and load being transferred by double layer stresses. The charged surface of the clay platelets are surrounded by adsorbed water. The degree of orientation of the molecular structure of this adsorbed water is greatest at the clay surface and gradually decreases with distance from the clay until it merges into free pore water. The effective viscosity of the adsorbed water decreases with distance from the clay surface.

At the lighter loads the movement of pore fluid that occurs during secondary compression could be that of free water, the rate of flow being highly dependent upon the viscosity of the pore fluid. This viscosity would probably be highly dependent upon temperature. At light loads a change in temperature might induce a considerable change in the viscosity of the pore water and a resultant large change in the rate of flow.

But at higher consolidation pressures the clay platelets are much closer together and the predominate pore fluid is probably adsorbed water. This adsorbed water, because it is more highly bound to the clay platelet is less influenced by a change in temperature and the change in the rate of flow is smaller. The change in void ratio that occurs with increase in effective pressure can be seen in fig. 13. The void ratio versus logarithm of pressure curves for the two soils indicate that there is a considerable change in void ratio from 0.125 tsf to 16.0 tsf effective pressure. For the organic soil the change in void ratio is 0.77.

One explanation then, for the greater influence of temperature on

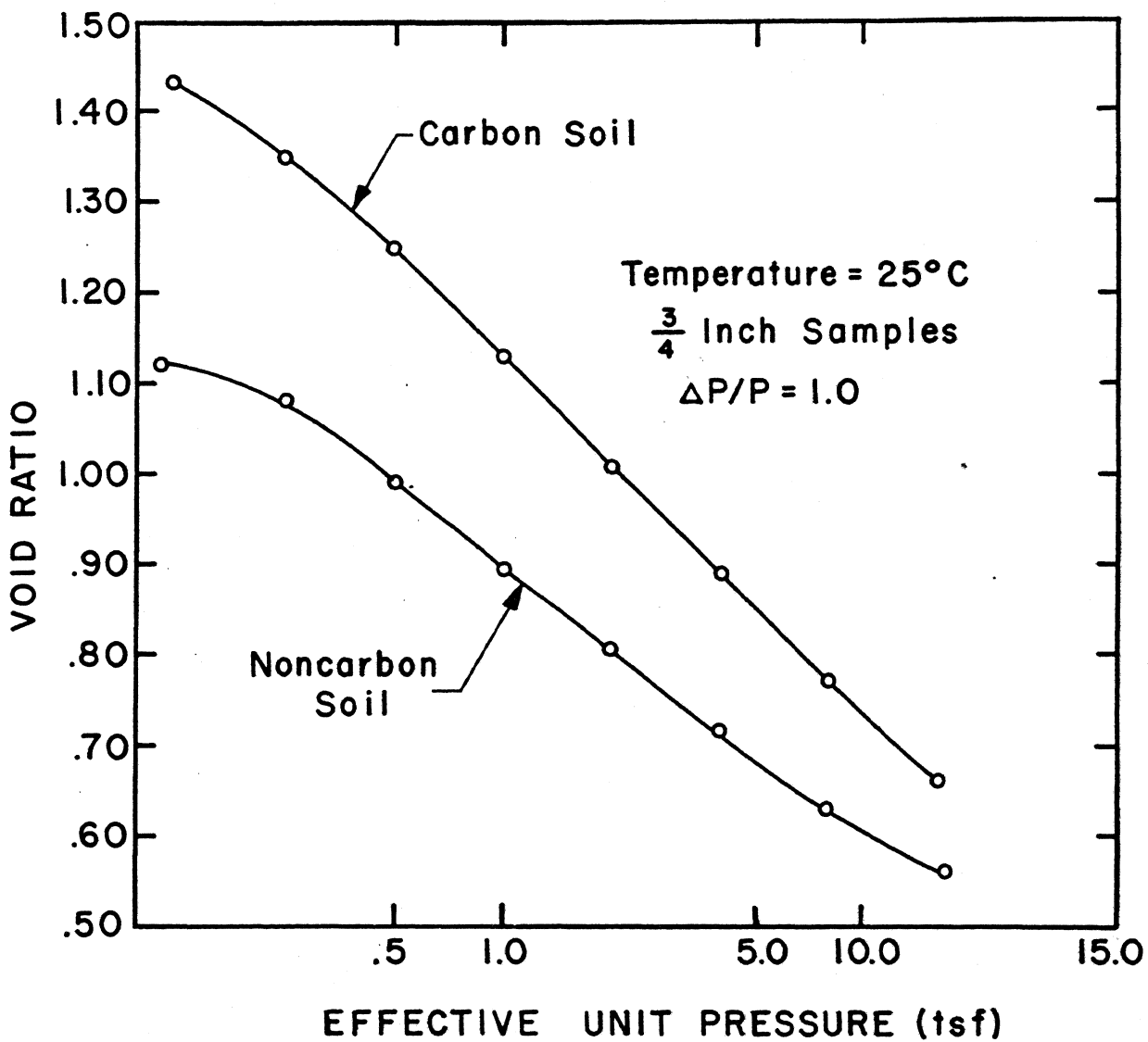


Fig. 13. Typical e-log p Curves.

C_{α} at lighter effective loads than at higher effective loads, is that C_{α} is highly dependent upon the dominating pore fluids. At light loads there is a large change in C_{α} due to a temperature change because free water dominates. At high consolidation pressures adsorbed water dominates and a change in temperature results in a very small change in C_{α} .

This explanation is only of merit if there truly is a large change in viscosity due to a temperature change, and if the variation in C_{α} with temperature for light effective total loads is comparable with the change in viscosity of free water with temperature. The change in viscosity of water at 50°C to 5°C is almost a straight line function. It can be seen from fig. 9 that the increase in C_{α} with temperature was almost linear. So it would appear that C_{α} could be a direct function of the viscosity at low effective total loads.

Mitchell, Campanella and Singh (1968) found a plot of the logarithm of the strain rate versus the logarithm of time was a straight line function with a negative slope for undrained creep of triaxially normally consolidated clays. From these results they further found that a plot of the logarithm of the strain rate divided by the temperature versus the reciprocal of the absolute temperature was linear.

An attempt was made to duplicate the plots of Mitchell et al. but it was found that the oedometer creep rate was a horizontal straight line when plotted versus the logarithm of time. This could be due to friction of the soil against the ring in the consolidation test. Because of this finding no attempt was made to further compare or expand on their work.

Fig. 8 and 9 indicate the influence of sample thickness on secondary consolidation. For both the carbon and noncarbon soils, C_{α} was found to be approximately the same for both single and double thickness samples.

These findings substantiate the findings of both Newland and Allely (1960) and Barden (1969) who agreed that C_{α} was independent of the sample thickness.

The influence of the organic content in soils on secondary consolidation can also be seen from Fig. 8 and 9. It is apparent for both single and double thickness samples that the rate of secondary consolidation is approximately twice as great for the soil with an organic content of 4.7 percent as for the noncarbon soil with an organic content of 1.1 percent. This is in agreement with the findings of Barden (1968) and Schmidt (1965). Schmidt used the same process for the removal of organic matter from an organic soil and concluded that C_{α} varied approximately linearly with the organic content.

B. The Mechanism of Secondary Consolidation

The finding that C_{α} is dependent upon the stress level tends to substantiate the mechanism based on structural viscosity (Terzaghi 1941). Barden (1968) stated that the law governing the nonlinear dashpot, representing the viscosity of the pore fluid, could not be deduced precisely but was certainly dependent upon the predominating pore fluid, be it free water or adsorbed water. The creep rate was related to the temperature of this pore fluid.

Murayama and Shibata (1961) and Mitchell's (1964) mechanism based on jumping of bonds in the form of a rate process theory can neither be substantiated nor disproven because the test data presented herein was limited by the instrument capability and the type of test performed.

It would appear that these findings disprove a mechanism based on micropores (DeJong 1968) because the mechanism suggested that the influence of temperature on C_{α} is independent of the stress level because

all flow of pore fluid in the micropores is free water. It is believed that the viscosity of free water is independent of the stress level.

CHAPTER VI
SUMMARY AND CONCLUSIONS

The purpose of this program of research was to study the influence of sample thickness, temperature, load increment ratio, and organic content, on secondary consolidation and if possible eliminate the confusion that now exists concerning the influence of these factors on secondary compression.

Baths for temperatures above and below ambient were constructed to regulate the sample temperature. Weights were designed for load increment ratios of 0.415, 1.0, and 1.83. Oedometer cells and rings were constructed to accommodate both 3/4 and 1½ inch thick samples. Two soils were used; one, an organic soil with an organic content of 4.7 percent, the other soil was the same soil with a substantial amount of the organic matter removed. The removal was accomplished by treating the organic soils with hydrogen peroxide. The treated soil had an organic content of 1.1 percent. The method and apparatus suggested by Allison (1959) was constructed and utilized to measure the organic content of the soils used in the research program.

A program of consolidation tests was performed on both soils in which the temperature, load increment ratio, and sample thickness were varied in an attempt to determine the relative influence of each on the secondary consolidation characteristics of a soil with a high organic content and a soil with a low organic content. Secondary compression was measured in terms of C_{α} (void ratio change per logarithm cycle on a plot of void ratio versus the logarithm of time). All load increments were allowed to remain until the secondary consolidation parameter C_{α} was clearly defined. Comparisons were presented in the form of plots

of C_{α} versus the logarithm of pressure.

In conclusion it was found C_{α} was dependent upon the effective unit load. It increased to a maximum at a pressure of 1.0 or 2.0 tsf and then decreased at approximately the same rate. Varying the load increment ratio within a single test had no noticeable influence on secondary consolidation. The plot of C_{α} versus the logarithm of the effective total pressure for $\Delta P/P = 0.415$ and 1.83 was approximately the same for the double thickness samples as for the 3/4 inch thick samples. Probably most significant, it was found that the influence of temperature on C_{α} was stress dependent, the greatest effect experienced for lower effective unit loads. Secondary compression for the organic soils was consistently greater than that for the low organic soils.

CHAPTER VII

RECOMMENDATIONS FOR FUTURE RESEARCH

It was the findings of this paper that the effect of temperature on the rate of Secondary Compression was stress dependent. It was suggested that the reason for this dependency was due to the related influence of free and adsorbed water during secondary compression. It was suggested for the soils involved secondary compression was primarily dependent upon a viscous flow phenomenon as compared to a structural reorientation. Although many models have been proposed using various combinations of springs and dashpots to account for the related influence of viscous flow and structural collapse, a more quantitative study is needed to evaluate their relative effect on C_{α} or the rate of secondary compression.

What is proposed is that a more quantitative study be made in which the structure is varied by some mechanical means to form flocculated and dispersed structures. To this study could be incorporated a variation in the distribution of grain sizes studied by using silt-clay mixtures. C_{α} would be analyzed in terms of these variables. Through a research program such as this a better understanding of the effect of temperature on C_{α} in terms of flocculated and dispersed structures for different grain size distributions, could be obtained. Likewise a relationship between free and adsorbed water for increasing effective unit stress might be found.

It has been suggested in the past (ASTM D2216-66) that when determining moisture contents that high organic soils be oven dried at 60°C instead of 110°C . The argument being that organic carbons are lost in a 110°C oven. During the research it was suspected that a majority of the weight

lost between 60°C and 110°C was that of water, not organic carbon. It is proposed that a study of the relative loss of organic carbon and water at different temperatures be studied to check the reasonableness of standard practice.

A better, more accurate method of measuring displacement in consolidation tests is needed for research work than the standard ten thousandths dial gauge which can stick and hang up. With the ever increasing use of transducers in research it is suggested that in the future the more accurate and reliable displacement transducers be utilized for measuring displacements.

BIBLIOGRAPHY

1. Allison, L.E. (1960) Wet-Combustion Apparatus and Procedure for Organic and Inorganic Carbon in Soil. Soil Science Society of America Proceedings 24:36-40.
2. ASTM Standards, Bituminous Materials; Soils; Skid Resistance. Part II, March 1969. American Society for Testing Materials 1916 Race St., Philadelphia, Pa. 19103.
3. Barden, L. (1969). Time Dependent Deformation of Normally Consolidated Clays and Peats. Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers 95:1-31.
4. Barden, L. (1968). Primary and Secondary Consolidation of Clay and Peat. Geotechnique 17:1-24.
5. Barden, L. and Berry, P.L. (1965). Consolidation of Normally Consolidated Clay. Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers 91:15-35.
6. Bauer, L.D. (1930). The Effect of Organic Matter upon Several Physical Properties of Soils. American Society of Agronomy Journal 22:703-708.
7. Buisman, A.S.K. (1936). Results of Long Duration Settlement Tests. Proceedings of the First International Conference on Soil Mechanics and Foundation Engineering 1:103-105.
8. Campanella, R.G. and Mitchell, J.K. (1968). Influence of Temperature Variations on Soil Behavior. Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers 94:709-734.
9. Christensen, R.W. and Wu, T.H. (1964). Analysis of Clay Deformation as a Rate Process. Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers 90:125-157.
10. Cox, J.B. (1936). The Alexander Dam Soil Studies and Settlement Observations. Proceedings of the First International Conference on Soil Mechanics and Foundation Engineering 2:116-117.
11. DeJong, G.D.J. (1965). Primary and Secondary Consolidation of a Spherical Clay Sample. Proc. 6th Int. Conf. Soil Mech., vol. 1, p. 254.
12. Finn, F.N. (1951). The Effect of Temperature on the Consolidation Characteristics of Remolded Clay. American Society for Testing and Materials, Special Technical Publication 126:65-71 as reported by Schmidt, N.O. (1965).

13. Goldberg, D.T. (1965). Discussion of Jonas' Subsurface Stabilization of Organic Silty Clay by Precompression. Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers 91:136-140.
14. Gray, H. (1936). Progress Report on Research on the Consolidation of Fine Grained Soils. Proceedings of the First International Conference of Soil Mechanics and Foundation Engineering 2:138-141.
15. Hanrahan, E.T. (1954). An Investigation of Some Physical Properties of Peat. Geotechnique 4:108-123.
16. Hardin, B.O. and Black, W.L. (1968). Vibration Modulus of Normally Consolidated Clay. Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers 94:353-370.
17. Heagler, J.B. (1969). Personal Communication. University of Missouri - Rolla, Department of Civil Engineering.
18. Humphries, W. Kenneth and Wahls, H.E. (1968). Stress History Effects on Dynamic Modulus of Clay. Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers 94:371-390.
19. Jonas, E. (1964). Subsurface Stabilization of Organic Silty Clay by Precompression. Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers 90:363-376.
20. Leonards, G.A. and Altschaeffl, A.G. (1964). Compressibility of Clay. Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers 90:133-154.
21. Leonards, G.A. and Girault, P. (1961). A Study of the One-Dimensional Consolidation Test. Proceedings of the Fifth International Conference on Soil Mechanics and Foundation Engineering 1:213-218.
22. Leonards, G.A. and Ramiah, B.K. (1959). Time Effects in the Consolidation of Clay. Symposium on Time Rate of Loading in Testing Soils. American Society for Testing and Materials. Special Technical Publication No. 254:116-130.
23. Lo, K.Y. (1961). Secondary Compression of Clays. Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers 87:61-87.
24. Mitchell, J.K. (1964). Shearing Resistance of Soils as a Rate Process. Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers 90:29-61.

25. Mitchell, James K. (1969). Temperature Effects on the Engineering Properties and Behavior of Soils. 48th Annual Meeting of the Highway Research Board.
26. Mitchell, J.K., Campanella, R.G. and Singh, Awtar (1968). Soil Creep as a Rate Process. Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers 94:231-253.
27. Murayama, S. and Shibata, T. (1961). Rheological Properties of Clay. Proceedings of the Fifth International Conference on Soil Mechanics and Foundation Engineering 1:269-273.
28. Newland, P.L. and Allely, B.H. (1960). A Study of the Consolidation Characteristics of a Clay. Geotechnique 10:62-74.
29. Neville, A.M. and Kennedy, J.B. (1964). Basic Statistical Methods for Engineers and Scientists. International Textbook Company, Scranton, Penn.
30. Olson, R.E. (65). Personal Communication with Norbert O. Schmidt as reported in Schmidt, N.O. (1965).
31. Paaswell, R.E. (1967). Temperature Effects on Clay Soil Consolidation. Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers 93:9-21.
32. Paaswell, R.E. (1969). Transient Temperature Influences on Soil Behavior. 48th Annual Meeting of the Highway Research Board.
33. Plum, Robert L. and Esrig, Melvin I. (1969). Some Temperature Effects on Soil Compressibility and Pore Water Pressures. 48th Annual Meeting of the Highway Research Board.
34. Schiffman, R.L., Ladd, C.C. and Chen, A.T. (1966). The Secondary Consolidation of Clay. I.U.T.A.M. Symp. Rheol. Soil Mech., p. 273, Grenoble. as reported in Barden (1968).
35. Schmidt, N.O. (1964). Secondary Consolidation Review of Literature. Personal Notes.
36. Schmidt, N.O. (1965). A Study of the Isolation of Organic Matter as a Variable Affecting Engineering Properties of a Soil. Ph.D. Thesis, University of Illinois, Department of Civil Engineering, Urbana, Illinois.
37. Schmidt, N.O. (1967). Description of Proposed Research. Personal Notes.
38. Singh, Awtar and Mitchell, J.K. (1968). General Stress-Strain-Time Function for Soils. Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers 94:21-46.

39. Skempton, A.W. (1953). The Colloidal "Activity" of Clays. Proceedings of the Third International Conference on Soil Mechanics and Foundation Engineering 1:57-61.
40. Skempton, A.W. and Bjerrum, L. (1957). A Contribution to the Settlement Analysis of Foundations on Clay. Geotechnique 7:168-178.
41. Tan, T.K. (1957). Secondary Time Effect and Consolidation of Clays. Academic Sinica, Institution of Civil Engineers and Architectural Harbin, China, June 1957 as reported in Wahls (1962).
42. Taylor, D.W. (1942). Research on Consolidation of Clays. Department of Civil and Sanitary Engineering. Massachusetts Institute of Technology, Cambridge, Massachusetts.
43. Terzaghi, K. (1941). Undisturbed Clay Samples and Undisturbed Clays. J. Boston Soc. Civ. Engrs. 28, No. 3, 211. as reported in Barden (1968).
44. Terzaghi, K. and Peck, R.B. (1967). Soil Mechanics in Engineering Practice. John Wiley & Sons, Inc., New York.
45. Wahls, H.E. (1962). Analysis of Primary and Secondary Consolidation. Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers 88:207-231.
46. Wascher, H.L., Alexander, J.D., Ray, B.W., Beavers, A.H. and Odell, R.T. (1960). Characteristics of Soils Associated With Glacial Till in Northeastern Illinois. Agricultural Experiment Station University of Illinois Bulletin 665.
47. Wascher, H.L., Smith, R.S. and Odell, R.T. (1951). Iroquois County Soils. University of Illinois Agricultural Experiment Station, Soil Report 74.
48. Yong, R.N. and Warkentin, B.P. (1966). Introduction to Soil Behavior. Macmillan Company, New York.

VITA

William Joel Green, the son of Joel B. Green and Betty J. Green, was born 18 July 1945 at St. Louis, Missouri.

His elementary schooling was at Salem Lutheran School and for his High School education he attended Lutheran High School South, both schools of St. Louis. He entered the University of Missouri - Rolla in 1963, and graduated with a bachelors degree in Civil Engineering in 1968. He received a reserve commission as a Second Lieutenant in the Army Corps of Engineers at that time.

Since January 1968 he has pursued studies toward a Master of Science Degree in Civil Engineering at the University of Missouri - Rolla.

He is a member of Chi Epsilon, National Honor Fraternity. He is a member of the American Society of Civil Engineers, an Engineer in training in the Missouri Society of Professional Engineers, and a member of the International Society of Soil Mechanics and Foundation Engineers.

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