SAND COMPRESSION AS A FACTOR
IN
OIL FIELD SUBSIDENCE

by

JAMES E. ROBERTS
S. B. Massachusetts Institute of Technology (1951)

Submitted in Partial Fulfillment of the Requirements
for the Degree of Doctor of Science
in Civil Engineering

at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
February, 1964

Signature of Author __________________________________
Department of Civil Engineering, Feb. 6, 1964

Certified by __________________________________
Thesis Supervisor

Accepted by __________________________________
Chairman, Departmental Committee
on Graduate Students

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ABSTRACT

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In certain oil fields the production of oil has been accompanied by measurable surface subsidence. At Long Beach, California, a maximum subsidence of approximately 25 feet has been observed. There has been fairly unanimous agreement among investigators that the primary cause of subsidence is the compression of sediments due to the reduction of fluid pressure caused by oil withdrawal. However, considerable difference of opinion has existed in the past as to whether the compressing soils are the oil bearing sands, the interbedded shales and/or siltstones, or a combination of both.

A comprehensive experimental investigation of the compressibility of clastic sediments at high pressure was conducted. It was discovered that, in the pressure range of 1,000 to 20,000 psi, certain sands may be at least as compressible, if not more so, than typical clays. This high compressibility, which is due to a shattering of individual grains, indicates that a stratum of oil-bearing sand which is subjected to effective stress changes of the same pressure range may contribute significantly to the subsidence.

Previously published work on sand compression which has been reviewed either has not shown the high relative compressibility (in part because the pressures used were not high enough) or has not recognized completely the significance and mechanism of the behavior, particularly as applied to the oil field subsidence problem.

The mechanics of oil field subsidence have been studied and it is suggested that the deformation of any non-producing overburden formation may result in a surface subsidence significantly less than the compression within the producing formation.

The relative importance of clay and sand compression as contributory to subsidence and the conditions under which either or both is important have been evaluated. Even at a depth of 3,000 feet (the depth at which the major amount of oil in the Free World can be expected to be found) compression of the oil bearing sands may contribute significantly to the subsidence.

Thesis Supervisor: Professor T. William Lambe

Title: Professor of Soil Engineering and Head
of the Soil Engineering Division

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I: INTRODUCTION

1.1 BACKGROUND AND PURPOSE

The large surface subsidence which has been observed in certain oil fields has been the object of considerable study in recent years. A maximum subsidence of approximately 25 feet has been observed at the Wilmington Field, Long Beach, California, and a maximum subsidence in excess of 10 feet has been observed at the Bolivar Coastal Field in Venezuela. Although subsidence is undoubtedly occurring at other oil fields, the possible consequences of subsidence associated with the production of oil are particularly well dramatized in these two areas because the oil fields are adjacent to an ocean or large lake. The land areas on the shore have been lowered gradually to such an extent that the construction of dike systems became necessary to protect valuable shore property from flooding. In the Wilmington Field considerable damage of structures has resulted from differential settlements and from horizontal displacements. In addition, sewage and storm drainage systems have been upset.

The various investigators who have studied the problem have agreed, generally, that the subsidence is due to the compression of subsurface soils as a result of the reduction in fluid pressure accompanying the removal of oil from the oil bearing sands. However, there is far from unanimous agreement as to whether the primary cause of the subsidence is the compression of the shales, the compression of the oil-bearing sands and sandstones, or a combination of both. Computations of subsidence by the Creole Petroleum Corporation, using the results of laboratory tests on clay and shale core samples, indicated smaller settlements than those actually observed. In many studies it has been assumed that the compressibility of the sand is negligible compared to the compressibility of the compressibility of the clay or shale. This assumption undoubtedly has been based primarily on a knowledge of soil behavior at low pressures.

Between July 1956 and June 1959 research on the compaction behavior of soils at high pressures at M.I.T. was sponsored by the Creole Petroleum Corporation. Unsponsored research was continued through June 1960. This research was initiated in the hope that a fundamental study of compression behavior at high pressures would help provide an explanation of the subsidence which had occurred in the Bolivar Coastal Field at Lake Maracaibo, Venezuela, and would aid in predicting future consolidation which will take place in the oil producing formations underlying Lake Maracaibo. The ability to evaluate reliably the anticipated subsidence and locate the seat of this subsidence would aid in the prediction of reservoir capacity. The ability to determine whether compression is in the sand or clay also would be of importance in evaluating the total reserves and the amount of water cut to be expected if water were being forced out of shale during consolidation.

1.2 OBJECTIVES OF RESEARCH

Originally the general objective of the research program on which this dissertation is based was to investigate experimentally the fundamental behavior of consolidating soils in order to determine the effects of pressures as high as 20,000 psi on the magnitude of and rate of soil compression. This objective was motivated by the disagreement among investigators as to whether the clays, the sands, or both were undergoing compression, and by the previous general lack of success in predicting subsidence.

Soil characteristics to be studied experimentally in relation to their influence on the behavior of soil were:

(1) soil composition;

(2) pore fluid characteristics;

(3) soil structure, i.e., orientation of the mineral particles and forces between these particles.

Extremes of structure and its effects on soil behavior were to be studied by preparing highly flocculated and highly dispersed sediments of various selected minerals, consolidating the prepared sediments, and determining the changes in orientation due to consolidation. The soils were to be sedimented in various fluids - pure water, sea water, organic fluids, etc., in order to study the influence of pore fluid on behavior. A study of temperature effects up to 200°F was envisioned.

All consolidation data obtained were to be evaluated to determine whether there are any characteristics of the data at the high pressures which would indicate the amount of precompression to which the sample had been subjected. This was to be best determined by inducing precompression of known magnitude, rebounding, and reloading samples.

After a number of compression tests on core samples supplied by Creole had been performed, it became evident that the compressibilities determined from these tests were too small to account for the subsidence which had actually occurred in the oil fields of interest to Creole. An additional objective was then established: to study the possibility of producing in the laboratory a clay which would have a high compressibility in the pressure range encountered in the field, and to determine why the high compressibility, if it exists in the laboratory samples, does not show up in the normal laboratory test using undisturbed or core samples.

Originally, compression tests on sands were not envisioned, but during January 1958, a series of tests performed on sands indicated the possibility that, at pressures above approximately 1,000 psi, certain sands may be more compressible than typical clays. Because of this discovery research then was concentrated on a study of the factors influencing the compressibility of sand.

The principal objectives of this thesis are:

(a) to present and discuss the results of the experimental investigation and to show that, within the pressure range of 1,000 to 20,000 psi, sands can have compressibilities equal to or greater than similarly determined compressibilities of some clays; and

(b) to demonstrate that, at the high pressures encountered in deep sedimentary deposits, the compression of sands can be of equal, if not greater, importance than the compression of clays.

1.3 SCOPE OF WORK

Included in this thesis are:

A brief review of the habitat of oil (Chapter 2);

A review of published reports pertaining to subsidence in oil fields, and a review of the possible causes of subsidence (Chapter 2);

A discussion of the subsidence mechanism and the validity of assuming that the compression is one-dimensional (Chapter 3);

A discussion of the evaluation of the one-dimensional compression characteristics of deep clastic sediments (Chapter 4);

A discussion of the relative importance of clay and sand compression in oil field subsidence (Chapter 5);

An historical review of published results of studies of compressibility at high pressure (Appendix A);

A summary of the experimental studies of compressibility at high pressures conducted in connection with this thesis research (Appendix B);

A summary of experiments on the crushing strength of individual quartz particles (Appendix C).

Because the writer has not had at his disposal the actual field records and detailed information regarding subsurface conditions it has not been possible personally to evaluate subsidence data in detail. Information on observed subsidence has been limited to that obtainable in the technical publications or through personal communications. For this reason Chapter 5 consists primarily of an evaluation of the conditions under which the compression of sand could be an important factor.

Although all the factors having an effect on the compressibility of sand have not been studied in complete detail, it is felt that the important factors have been studied and that additional studies probably are not warranted until a detailed analysis of all existing field evidence has been completed.

1.4 ACKNOWLEDGEMENTS

The author wishes to express his appreciation to the Creole Petroleum Corporation for their support of the research described herein and in particular to Mr. John Martin of that Company. Particular appreciation is due John M. DeSouza and Paul A. Harremoes, Research Assistants to the author during the conduct of the research. Appreciation is due Robert T. Martin who performed the mineralogical analyses on the clay core specimens, R. M. Quigley who provided the mineralogical data on the Hawaiian Beach Sand, and D. R. Parrish and N. W. Kneissler who performed the secondary compression and side friction tests under the direction of the writer.

Finally, the author is indebted to Dr. T. William Lambe, Head, Soil Engineering Division, Department of Civil Engineering, Massachusetts Institute of Technology, for his continuous encouragement (moral and fiscal), guidance, and patience.

2: SUMMARY OF OIL FIELD SUBSIDENCE RECORDS

2.1 INTRODUCTION

In at least three areas of the world the production of oil has been accompanied by measurable surface subsidence. Subsidence data obtained from publications and personal communications relative to Long Beach, California; Goose Creek, Texas; and the Maracaibo Basin, Venezuela are summarized in this Chapter.

However, for background, a brief review of the habitat of oil is presented first.

2.2 HABITAT OF OIL

Three conditions appear to be necessary in order for oil to accumulate in reservoir rocks (Longwell, Knopf and Flint, 1949).

(1) There must be a source rock which contains the necessary carbonaceous matter from which oil can be formed. The most common source rocks apparently are marine bitumous shales.

(2) There must be a favorable structural arrangement of strata which allows the oil to collect.

(3) There must be an impervious layer overlying the reservoir stratum to form the structural trap in which the oil is held. Figure 2.1 shows in simplified form a typical oil reservoir in an anticlinical trap.

Muskat (1946) assumes that petroleum gas and oil are formed in shales some considerable time after burial and then migrate to the reservoir sediments.

According to Meinschein (1959) marine sediments and crude oils contain the same types of hydrocarbons and from this he concludes that petroleum is derived from sedimentary organic matter. However, because of the low concentration of hydrocarbons in sediments, crude oil deposits can be formed only when there is an accumulation or concentration of these hydrocarbons. Meinschein hypothesises that the deposits of oil result when small quantities of oil, which are formed at various times and places, migrate and accumulate at favorable structural locations.

Because of the necessary migration a certain minimum porosity is probably required for movements of oil droplets or emulsion. This migration is not likely in shale and more than likely occurs in the coarse grain sediments.

Knebel and Rodrigues-Eraso (1956) compiled data on the location of oil in the major fields* throughout the so-called "free" world; the Soviet Union was excluded because of the lack of information. Statistics were developed for the location of oil as a function of depth of occurrence,

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*Those fields with an ultimate recovery greater than 100 million barrels.

type of deposit, lithology, geologic age, etc. According to the figures of Knebel and Rodrigues-Eraso, 80 percent of the total oil is found in an anti-clinical trap; although many of the fields also are faulted it is their opinion that the primary geologic feature is structural folding. If the fields of the Middle East are neglected 40 percent of the remaining oil can be considered to be in an anti-clinical trap.

As confirmation of the idea that oils migrate to the reservoir and that this migration is more likely in coarse grain sediments, the statistics of Knebel and Rodrigues-Eraso show that sands* are the most common reservoir deposit. Fifty nine percent of the oil found in major fields is in sand reservoirs.

Their figures further show that 90 percent of the oil is produced from Mezozoic or younger sediments. Approximately 28 percent of the reservoirs are composed of Mio-Oligocene sediments and approximately 52 percent are composed of Mezozoic sediments. If the Middle East reservoirs are excluded, 34 percent of the reservoirs are composed of Mio-Oligocene, 26 percent of Paleozoic, and 21 percent of Mezozoic sediments.

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*The term sand is used by geologists in reference to both uncemented sands and cemented sandstones generally with no further distinction other than the value of porosity.

Approximately 85 percent of the oil in the free world exists in reservoirs between a depth of 2,000 and 8,000 feet; if the oil fields of the Middle East are excluded, approximately 80 percent of the oil lies in reservoirs between depths of 1,000 and 6,000 feet.

A detailed break-down of the percent of the total oil as a function of depth is shown in Table 2.1. To indicate the range of pressures possible at various depths, approximate values of initial fluid pressure, initial effective stress, and maximum final effective stress which would develop if the fluid pressure were reduced to zero have been added.

2.3 WILMINGTON FIELD, LONG BEACH, CALIFORNIA

2.3.1 General

The Wilmington Field was discovered in 1932 but it was not until the last half of 1936 that a drilling boom began in the Los Angeles Harbor Area and spread to Long Beach in 1937.

Subsidence at Long Beach has been the object of considerable study and has been reported extensively in the literature. In addition, a number of investigations have been conducted which have resulted in unpublished reports. Prior to 1936 subsidence of the order of a few tenths of a foot had been noted, presumably caused by groundwater withdrawal. However, observations of benchmarks in the Long Beach Area indicate that the major subsidence started sometime between 1934 and 1936; the maximum subsidence had reached a value of five feet by 1946 and twenty-five feet by 1958. Contours of subsidence as of 1958 are shown in Figure 2.2. In 1952 the rate of subsidence close to the point of maximum subsidence was about 2.4 feet per year but had declined to about 1.0 feet per year in 1958 (Figure 2.3).

An area of about 15 square miles has undergone subsidence of 2 feet or more; this area is roughly elliptical in shape with lengths of about 6 miles and 4 miles along the major and minor axes. According to the report of the Stanford Research Institute (1949) there is an approximate areal coincidence between surface movement and the oil field.

In addition to vertical subsidence, horizontal movements of points on the ground surface as large as 6 feet have been measured. These horizontal movements are roughly perpendicular to the subsidence contours and are directed, generally, toward the region of maximum subsidence.

Through 1958 over 800,000,000 barrels of oil and 758,000,000 MCF of gas had been produced. However, the economic benefits accruing from this production have been somewhat offset by the damage resulting from subsidence. Prior to any subsidence the land surface was only a few feet above extreme high tides of the Pacific Ocean. Because of the highly developed industrial complex and harbor facilities along the waterfront the resulting subsidence has necessitated remedial work including dikes and fill. Berbower (1959) estimates that about 100 million dollars spent by all parties for remedial work can be attributed to subsidence.

The subsidence apparently now has been arrested by continuous, high pressure, salt water injection, but it is anticipated that injected quantities eventually will amount to 48 mgd and will cost approximately $31,000,000 (Roberts 1959).

2.3.2 Geologic Conditions

There are five major oil bearing formations in the Wilmington Field (Figure 2.4). In order of depth they are: Tar, Ranger, Upper Terminal, Lower Terminal and Ford. The formations vary in thickness from 310' (Tar) to 1010' (Ford) and in age from lower Pliestocene (Tar) to Upper Miocene (Terminal and Ford). Entrapment of the oil appears to be the result of a gentle anticlinical structure plus faulting which has divided the field into five major fault blocks and numerous smaller zones (Figure 2.4). The depth of the producing zones varies from about 2200 feet at the top of the Tar zone to about 5300 at the estimated bottom of the Ford zone. According to Grant (1958) the Terminal zone, the top of which is at a depth of from 3200 to 3400 feet, is the greatest oil producing interval and the zone that has compacted the most.

The oil bearing zones have been described generally as consisting of layers of shale interbedded in the oil sands. However, Terzaghi (1958) felt that the shales had been improperly designated. According to Terzaghi the Long Beach sediments can be described as alternating layers of oil bearing sands and silty sandstones. The oil sands have a median grain size of from 0.35 mm to 0.15mm, contain from 2 to 10 percent silt (exceptionally as high as 16 percent), and have the grain size characteristics of a fine dune sand. The silty sandstones contain from 10 to 27 percent silt and have the grain size characteristics of fine dune sands with an admixture of silt. Both sediments have little or no clay.

Above the oil producing layers, the upper eighteen hundred feet of sediments contain generally more or less fresh water and presumably have been a source of fresh water supply in the past which resulted in some minor subsidence prior to that associated with oil production.

2.3.3 Possible Causes of Subsidence

In connection with their studies at Long Beach, Harris and Harlow (1948) considered five factors as possibly contributing to the subsidence:

(1) An increase in pressure due to:

(a) Changes in the land surface from filling and dredging;

(b) Pumping of water for industrial and domestic uses;

(c) Pumping of water during dewatering of the site of drydock No. 1., U. S. Naval Drydocks;

(d) Pumping of oil from five major oil zones in the Wilmington Oil Field;

(2) Tectonic forces.

Gilluly and Grant (1949) also considered items (1) a, b, d, and (2).

The report of the Stanford Research Institute to the Harbor Subsidence Committee (1949) considered as possible causes of subsidence: tectonic movements, collapse of roof of cavities, removal of underlying material by subsurface erosion, consolidation due to decline in fluid (water or oil) pressure, application of surcharges, desiccation, and base (ion) exchange (replacement of fresh water by salt water).

Data which have been available for study of the subsidence include measurements of horizontal and vertical movements of points located at ground surface, measurements of the change in length of oil well casings, fluid pressures, and production records.

Movements of points located at ground surface establish directly the amounts of and rates of subsidence. Changes in the length of well casings have been interpreted as indicating that compression is occurring within the producing formations and that the subsoil between ground surface and the producing formation expands by about 0.3 ft per foot of subsidence at the point of maximum subsidence (Terzaghi 1958). According to Grant (1958) some wells located near the region of maximum subsidence have been damaged by vertical tension.

Until 1951-52 (Harris and Harlow 1948, Grant 1958) the rate of subsidence increased in general agreement time-wise with the pressure reductions; i. e., fluctuations in subsidence rate could be correlated with production fluctuations and movements due to earthquakes. Since 1952 the rate of subsidence has been declining as have the average daily total production and the average daily pumped production* (Figure 2.3).

According to Grant (1958, 1960), who has made a detailed study of the subsidence and has had access to the detailed records, the rate of subsidence appears to lag behind changes in production rate by from several months to up to 2 years and he suggests that siltstone and shale compaction is the chief contributor to surface subsidence at the present time (1960). However, it is not clear whether Grant is referring to total or pumped production.

Figure 2.4 shows reasonably good agreement between rate of subsidence and average daily pumped production

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*Average daily total production includes flowing wells and wells being pumped. Average daily pumped production includes only production from wells that are pumped.

through 1952 and with both average daily total and average daily pumped production subsequent to 1952.

Although there appears to be a lag between rate of subsidence and total production, there seems from the data in Figure 2.4, to be very little lag when rate of subsidence and pumped production are compared. It would seem to the writer that pumped production would probably be more indicative of pressure declines below normal static fluid pressures. Any wells which are flowing must have fluid pressures which are above normal static pressures. It would seem reasonable to expect that the sediments after deposition would have been consolidated under effective pressures commensurate with static fluid pressures. Therefore, until fluid pressures were reduced below the static fluid pressure, the underlying sediments should be expected to behave as precompressed soil. Significant compression should occur only when the fluid pressure is reduced to values below normal static pressures.

Since the production data is for the entire field, whereas the settlement is at a given location, there is no reason why the rate of subsidence at a given point should have a 1 to 1 correlation with production. A more appropriate comparison would be to compare rate of subsidence with rate of fluid pressure decline in the same general area.

Although many possible mechanisms have been considered, there is fairly unanimous agreement among the various investigators who have studied the problem at Long Beach that the one process compatible with the observed subsidence and horizontal movements and the geologic profile is a gradual compression of the oil bearing strata which are located between a depth of about two thousand and sixty-five hundred feet. This compression is caused by an increase in effective stress due to the reduction in fluid pressure in the oil bearing sands (Figure 3.5).

2.3.4 Subsidence Estimates

Even though there has been general agreement as to the primary cause of the subsidence, a lack of success in predicting subsidence is evident from Berbower's (1959) summary of the predictions made by various investigators. These predictions, which were predicated on no repressuring and continued production of oil, are tabulated below:

Investigator	Year of Estimate	Estimated Ultimate Subsidence (ft)
Frederick R. Harris, Inc.	1945	7
Gilluly, Johnson and Grant	1945	9
Technical Committee of Harbor Subsidence Comm.	1948	16 to 18
Frederick R. Harris, Inc.	1949	22
McGann and Welts	1951	24
McGann and Welts	1954	30
Richfield Oil Co.	1955	35
Frank S. Hudson	1956	54
Frank S. Hudson	1957	43 (by 1977)
Grant	1957	34 (by 1980)
Grant	1960	50

In Chapter 3 the writer reviews the mechanism of subsidence and discusses the factors affecting subsidence computations, particularly the validity of computing subsidence on the assumption that compressions are one-dimensional.

2.4 MARACAIBO BASIN, VENEZUELA

According to the report of Miller, Edwards, et. al., the ultimate reserves of the Bolivar Coastal and Mene Grande Fields constitute 2/3 to 3/4 of the proven reserves of about 14,600,000,000 barrels of the entire Maracaibo Basin. The Mene Grande field was discovered in 1914; the Bolivar Coastal Fields were opened to exploration in 1917 and the major companies developed active interest after about 1922. In the various areas of the Bolivar Coastal Field the producing formations and depth of producing interval and daily rate of production in 1953 are shown below:

Field	Formation	Rate of Prod. Bbls/day 12/31/53	Depth of Prod. Interval (ft)
La Rosa (Cabimas)	Younger Tertiery Eocene	90,747	1,000-5,500
Tia Juana	"	244,598	1,000-5,500
Lagunillas	"	461,103	1,000-8,500
Pueblo Viejo	Eocene	3,299	1,600-3,700
Bachaquero	Younger Tertiery Eocene	280,115	1,800-8,000

Three-fourths of the estimated ultimate reserves are found in Olego-Miocene and Eocene sandstones deposited in shallow marine to brackish water and are associated with an unconformity and an Eocene hinge belt. Position of the fields reflects the zone of maximum interstratification of Eocene sandstones and shales. A representative geologic profile is shown in Figure 2.6.

Through 1958 subsidences amounting to 10 to 11 feet at Well LL87 and 2 to 3 feet at Well TJ25 had occurred. According to Martin (1959) investigations by the Creole Petroleum Corporation using radioactive bullets, have indicated fairly conclusively that the subsidence is due to vertical compression within the producing formation which exists between depths of 3200 and 3800 feet.

Additional observational data which were available to Creole for study are shown by typical data in Figure 2.7 where both subsidence and fluid pressure are plotted separately as a function of time. Figure 2.8 shows the same typical data plotted as subsidence versus fluid pressure. In this oil field the area of subsidence coincides generally with the area of fluid pressure reduction.

In connection with studies of the Bolivar Coastal Field, Martin (1955) considered three possible causes of the subsidence:

(1) Clay consolidation;

(2) Sand compression;

(3) Invasion of sand by clay particles.

Martin felt that the evidence available at the time of his study indicated that the consolidation of the shales interbedded between the oil bearing sand layers was the chief cause of the subsidence although he also indicated that the other two mechanisms, mainly sand compression and invasion of clay into the sands may not be as small as once believed. However, according to Martin examination of core samples did not indicate any evidence of squeezing of clay into sand voids. Clay cores supplied by Creole and examined visually by the writer also did not show any evidence of squeezing of clay into sand voids. Although no filter tests were performed, this evidence suggests that the invasion of clay into the sands is probably minor.

Assuming that the primary cause of subsidence is compression of the sediments within the producing formation, there apparently appears to be a variation in compressibility from one point to another throughout the subsiding area. In addition, in certain areas the subsidence does not appear to start immediately upon development of the pressure reduction but the subsidence data suggest that the sediments may be precompressed (Figure 2.8).

2.5 GOOSE CREEK, TEXAS

The Goose Creek oil field, which is located in San Jacinto Bay near Galveston and Houston, Texas, was developed in 1917 and three feet of subsidence were observed in an eight year period. Production is from lenticular sands which occur in the Flemming Clays at depths between 1,000 and 4,000 feet. The sediments, which are of Pliocene and Miocene age, were deposited in a brackish marine environment. Due to oil production the fluid pressure has been reduced from initial values of between 1,000 and 1,200 psi to a final value equal to atmospheric pressure.

Pratt and Johnson (1926) implied that the resulting subsidence is due primarily to consolidation of the clay. They point out, however, that at the time of their study the volume represented by surface subsidence was only about 20 percent of the total subterranean void created by removal of oil, gas, water, and sand. (It is difficult to evaluate what volume they attributed to the gas and whether they considered any lateral inflow from outside the oil producing region.)

Snyder (1927), however, considered the hypothesis that the oil producing sands may be in a loose so-called "quick" state because of high fluid pressures and a reduction of the fluid pressures upon the production of the oil causes the sand to return to their normal dense state. This suggestion was later refuted by Pratt (1927) who pointed out that fluid pressures high enough to support the whole weight of the overburden are never encountered in fields.

However, Thomeer and Bottema (1961) have presented case histories of fields where fluid pressures before the inception of oil production have been interpreted to be as high as 80 to 90 percent of the total overburden.

2.6 MISCELLANEOUS

In addition to the three cases cited where subsidence can be attributed to the production of oil there are other areas where important subsidences have resulted from withdrawal of water from the near surface deposits.

In the Santa Clara Valley of California water from the upper several hundred feet of deposits (confined sand aquifers) is used for agricultural, industrial, and domestic purposes resulting in substantial drawdown of the water table. At San Jose the drawdown has lowered the water table in the aquifer as much as 120 to 150 feet and the resulting subsidence has amounted to more than 9 feet since about 1910. The area being affected by the subsidence amounts to something of the order of two hundred square miles.

In Houston, Texas water pressure reductions corresponding to about 140 feet of water between 1949 and 1953 resulted in a maximum subsidence of from 1 to 1.7 feet during the same period (Dawson 1963).

A classic example of subsidence is Mexico City which underwent a maximum settlement of about 16 feet between 1900 and 1960, and at present is settling at a rate of between 18 inches and 2 feet per year. The settlement has been caused by pumping from sand layers which exist within the major deposit of soft clay of volcanic origin which underlies the city (Jumikis 1962).

TABLE 2.1*

PERCENT OF TOTAL OIL VS DEPTH OF DEPOSIT

	TOTAL WORLD		EXCLUDING MIDDLE EAST		STRESSES**		
DEPTH (ft)	(%)	CUMULATIVE (%)	(%)	CUMULATIVE (%)	$\overline{\sigma}_o$ (psi)	μ_o (psi)	$\overline{\sigma}_f$ (psi)
0-1000	1.5	1.5	3.9	3.9	490	433	923
1-2000	6.2	7.7	13.3	17.2	980	866	1846
2-3000	10.2	17.9	18.0	35.2	1470	1299	2769
3-4000	26.2	44.1	20.9	56.1	1960	1732	3692
4-5000	16.8	60.9	10.6	66.7	2450	2165	4615
5-6000	9.5	70.4	13.6	80.3	2490	2598	5538
6-7000	14.0	84.4	8.0	88.3	3430	3031	6461
7-8000	8.5	92.9	5.4	93.7	3920	3464	7384
8-9000	3.5	96.4	2.5	96.2	4410	3897	8307
9-10,000	1.6	98.0	1.7	97.9	4900	4330	9231
10-11,000	1.5	99.5	1.3	99.2			
11-12,000	0.4	99.9	0.4	99.6			
12-13,000	0.1	100.0	0.4	100			

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*(After Rodrigues-Eraso, 1956)

**Tabulated stresses are the estimated stresses acting at the bottom of the depth interval given in the first column.

$\overline{\sigma}_o$: estimated initial effective overburden pressure. Evaluated assuming static fluid pressures and a water table at ground surface.

μ_o: estimated initial fluid pressure assuming static fluid pressures

$\overline{\sigma}_f$: estimated final effective overburden pressure if the fluid pressures were reduced to atmospheric due to withdrawal of fluids.

Modified from Hewett and Lupton, U. S. Geological Survey.

FIG. 338. Gas, oil, and water as they occur in an anticline. Gas, being the lightest, occupies the crest of the arch; oil, being heavier, lies below the gas; and water, the heaviest of all, is at the bottom.

Fig. 2.1 TYPICAL ANTICLINICAL ENTRAPMENT CONDITION (Longwell, Knopf, and Flint;1948)

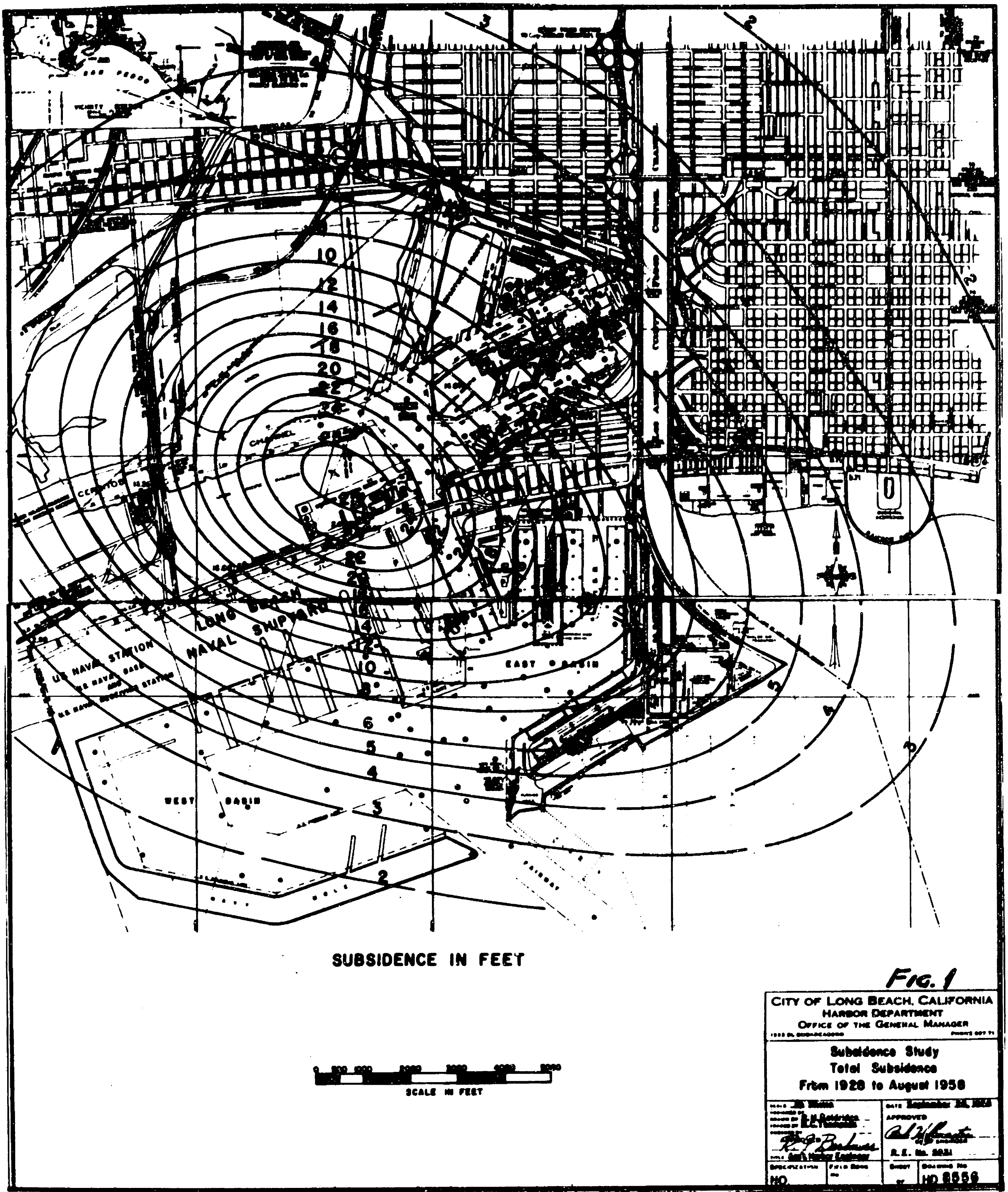


Fig. 2.2 SUBSIDENCE CONTOURS,WILMINGTON FIELD (After Berbower,1959)

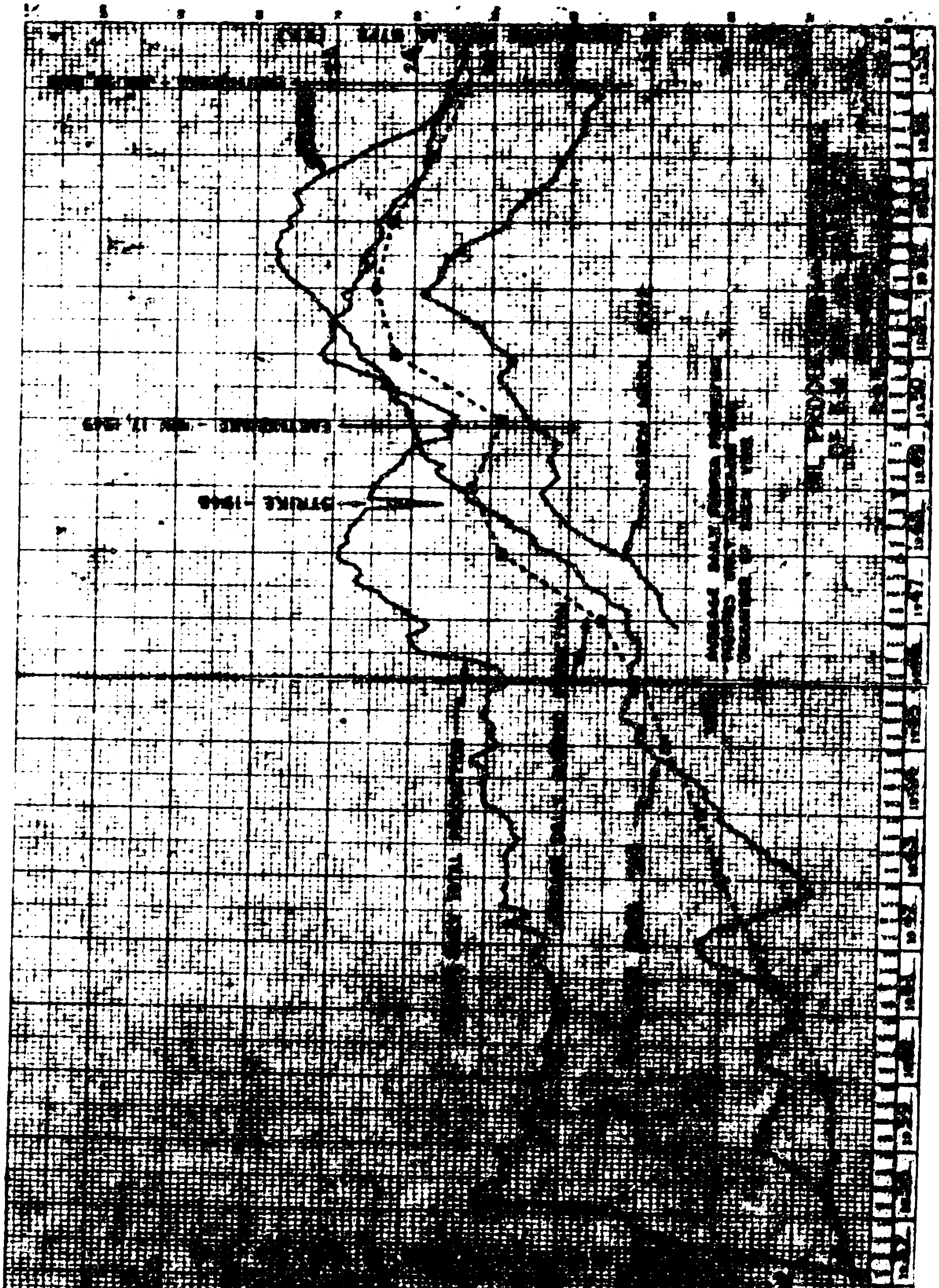


Fig. 2.3 SUBSIDENCE AND OIL PRODUCTION, WILMINGTON FIELD (After Berbower,1959)

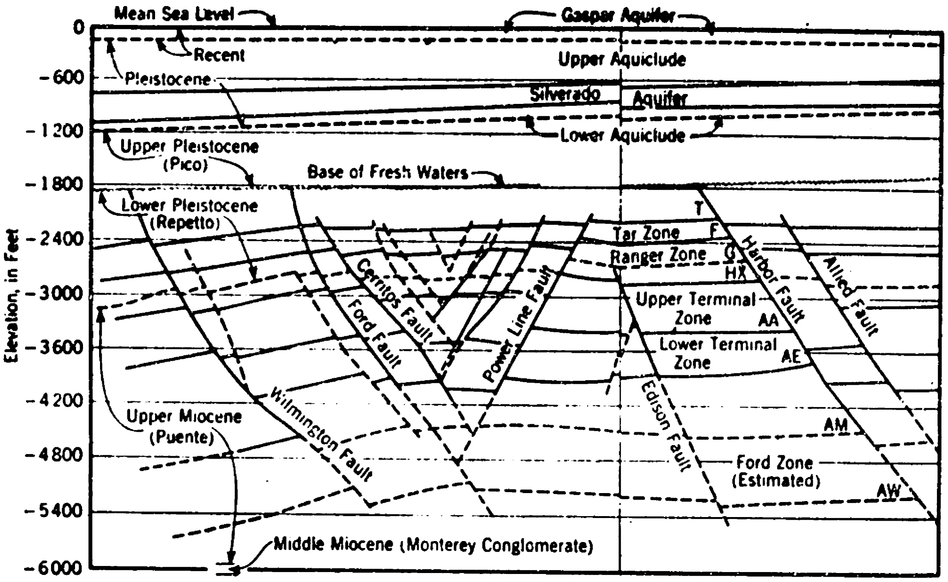


Fig. 5.—Section through Wilmington Oil Field

Fig. 2.4 GEOLOGIC CONDITIONS, WILMINGTON FIELD

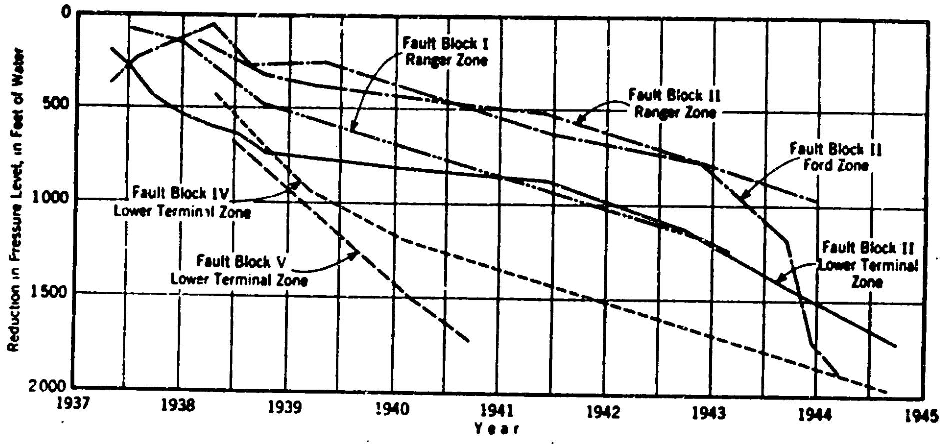


Fig. 6.—Reduction in Oil Zone Pressure Levels for Typical Wells

Fig. 2.5

(After Harris and Harlow, 1948)

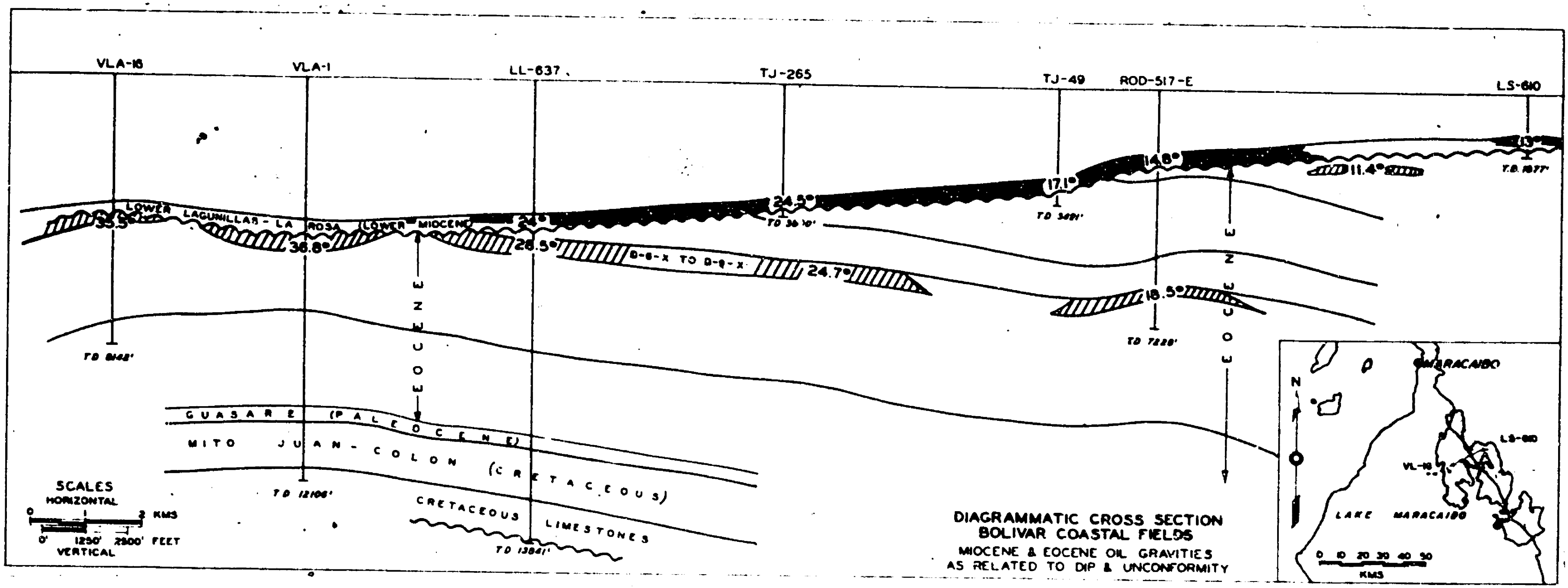


Fig. 2.6

(After Miller, Edwards, Wolcott, Anisgard, Martin, and Anderegg, 1954)

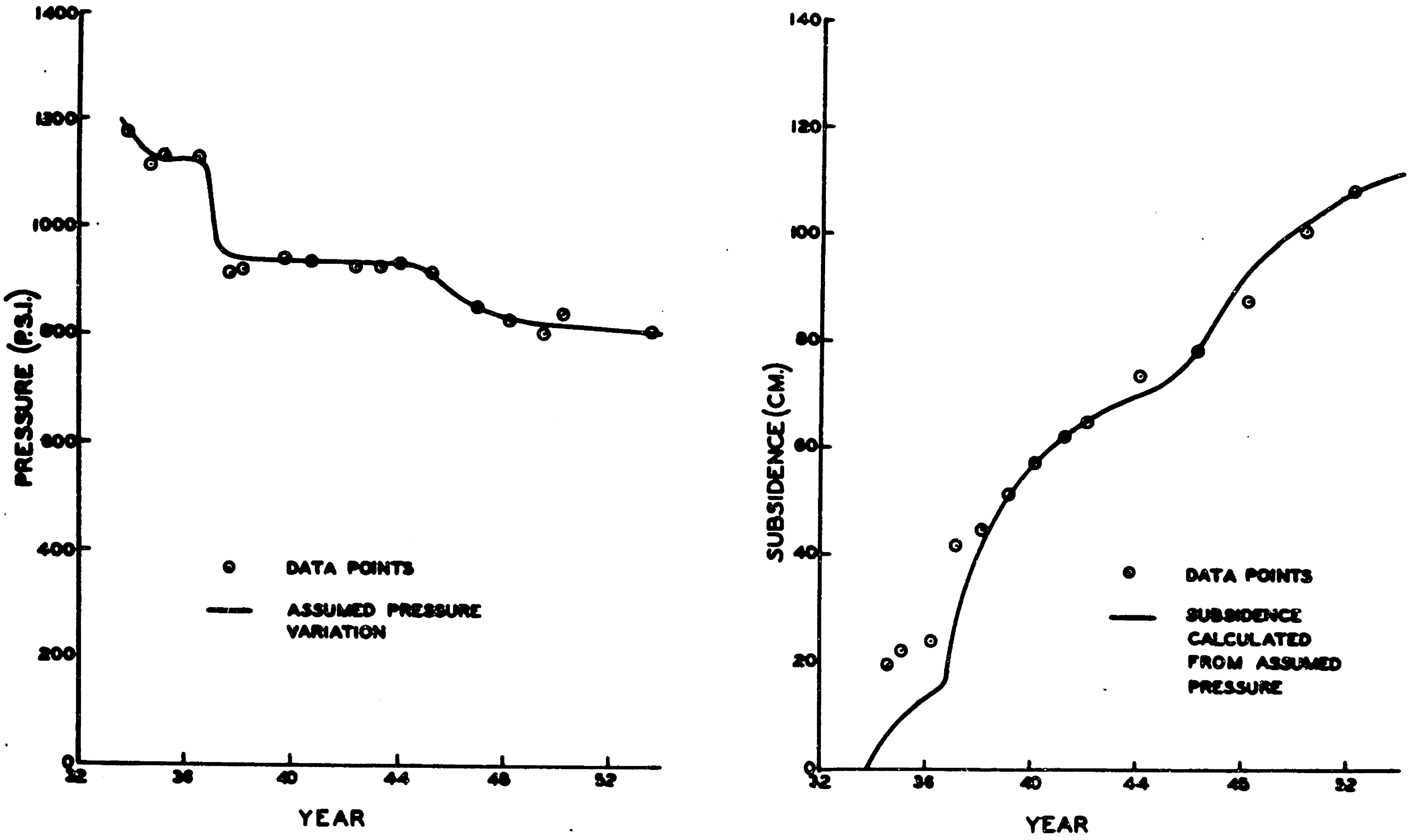


Fig. 2.7 TYPICAL FLUID PRESSURE AND SUBSIDENCE DATA, BOLIVAR COASTAL FIELD (After Martin, 1955)

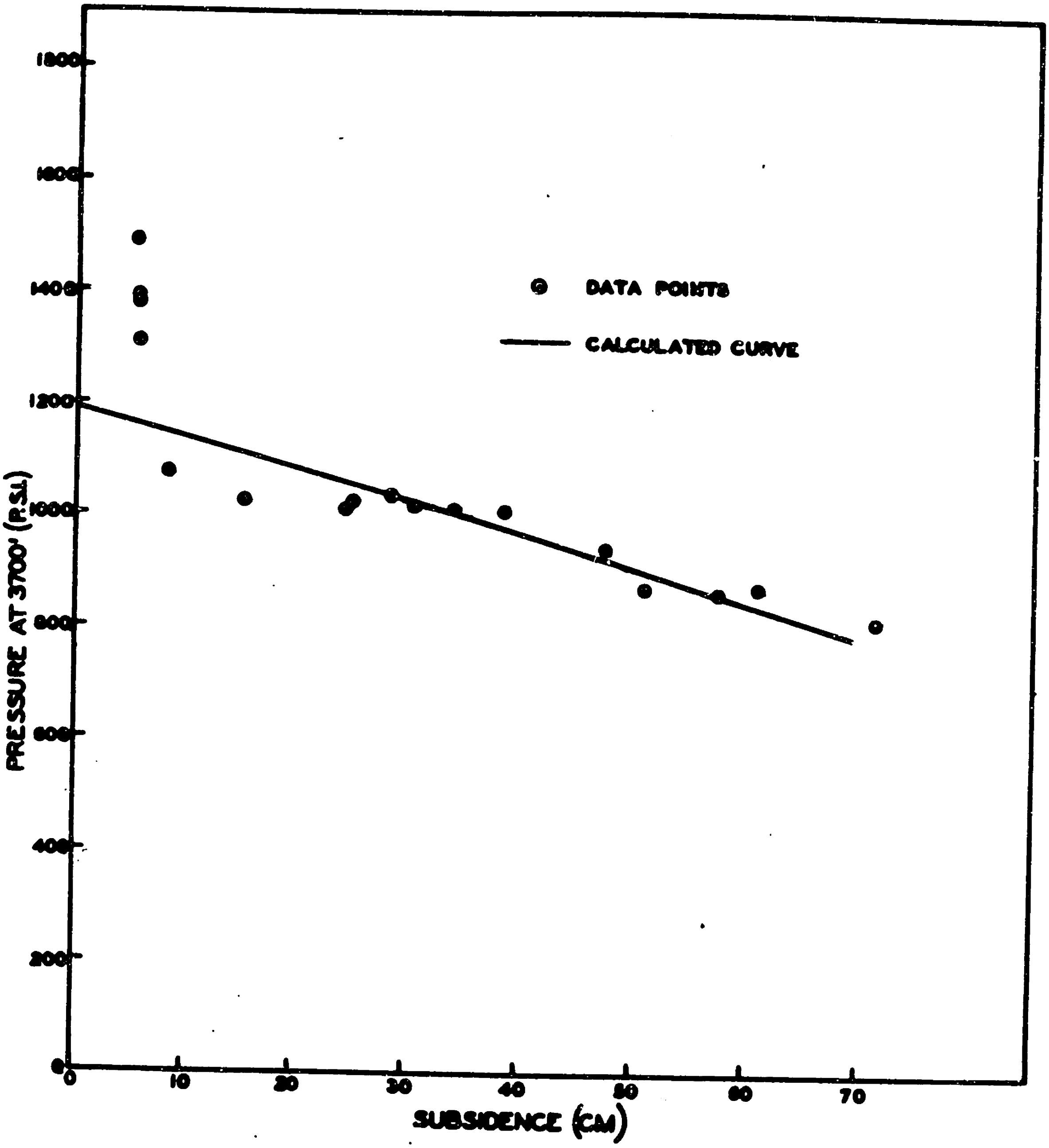


Fig. 2.8 TYPICAL FLUID PRESSURE AND SUBSIDENCE DATA, BOLIVAR COASTAL FIELD (After Martin, 1955)

3: ANALYSIS OF THE MECHANICS OF SUBSIDENCE AND ASSOCIATED DEFORMATIONS

3.1 INTRODUCTION

Because the advent of important subsidence can be correlated with the beginning of oil production, there is agreement among the various investigators that the subsidence is caused by a compression of the underlying sediments due to a reduction in fluid pressure.

Studies of subsidence generally have proceeded on the tacit assumption that the compressions within the producing formation are one-dimensional.

The purposes of this chapter are to review the factors controlling subsidence, to examine the validity of assuming that compressions are one-dimensional, to discuss probable causes for the discrepancies between computed and observed subsidences, and to discuss the possible mechanism causing the horizontal movements which have been observed at Long Beach.

3.2 FACTORS CONTROLLING SURFACE SUBSIDENCE OR AFFECTING SUBSIDENCE ESTIMATES

Estimates of the magnitude of and the rate of subsidence require information or assumptions regarding the following:

(1) The thickness of compressible strata;

(2) The nature of deformations and volume changes within the compressible strata;

(3) The compressibilities of the various strata;

(4) The relationship between pressure decline and effective stress increase applicable to the study of deep sediments;

(5) The influence of overlying non-producing formations;

(6) The relation between time and pressure decline for each stratum;

(7) The seat of any time lag.

3.2.1 Thickness of Compressible Strata

Obviously, knowledge of the soil or geologic profile is essential before any reliable estimates of settlement can be made. The subsequent discussion in this chapter assumes that the soil profile is known.

3.2.2 Nature of Deformations and Volume Changes Within the Compressible Strata

Stress changes occur within the producing formation because of reductions in fluid pressure. The following discussion considers the nature of the resulting deformation of soils within the producing formation.

The cross section in Figure 3.1 is assumed to represents an ideal producing formation. This formation is bounded on the top by a non-producing overburden formation and on the bottom by a rigid basement rock. As a limiting case it is further assumed that the producing formation is bounded laterally by an impervious boundary a-a.

justification

Deformations which will result when the fluid pressure within the oil reservoir is reduced can be evaluated by considering two elements, A and B, on opposite sides of the impervious boundary. Approximate values of total and effective stresses acting on the two elements before any fluid pressure reduction are shown on the left side of the figure.

In the limiting case, the fluid pressure within the producing formation might be reduced to zero, with no change in the fluid pressure outside the impervious boundary. If the fluid pressure were reduced to zero and if there were no lateral strain of either element at the impervious boundary, then the total and effective stresses on the two elements would have to be as shown on the right side of Figure 3.1. These stresses were determined assuming no change in total unit weight of the sediments, and shear stresses on vertical planes were neglected. The resulting vertical subsidence would be due to one-dimensional compression within the producing formation due to the increase in vertical effective stress. The producing formation would be analogous to a sample in a laboratory one-dimensional consolidation test.

For the assumed conditions, the total lateral stress acting on the outside of the impervious boundary would have to be larger than the total lateral stress acting on the inside of the impervious boundary. If we assume that the impervious boundary has no structural rigidity, the total lateral stresses shown are not possible. For equilibrium the total stress would have to be the same on each side of the impervious boundary. Thus, the total lateral stress on element B must be reduced somewhat and that on A increased somewhat. The only way this change can occur is for element B to undergo lateral expansion and for element A to undergo lateral compression

The actual stress acting when equilibrium is achieved will depend on the stress strain characteristics of the sediments. Roughly speaking, however, the total lateral stress A and B will have to be about $1.2\,\overline{\nabla}_{v_1}$. This means that the coefficient of lateral earth pressure on B must reduce from an initial value of 0.5 to a final value of about 0.35. The coefficient of lateral earth pressure on A must increase from an initial value of 0.5 to a final value of about 0.65.

If we consider the impervious boundary to be analogous to a vertical retaining wall, an order of magnitude of the amount of movement necessary to obtain equilibrium can be evaluated by reference to Terzaghi (1954, Figure 3). Data presented by Terzaghi relate the coefficient of earth pressure to relative movement. Relative movement is the ratio of the movement of the top of a vertical wall to the height of the wall. For both loose and dense sands the data indicate that a relative movement away from the soil of less than 0.0002 will reduce the coefficient of earth pressure to values less than 0.35.

For a formation thickness of 3,000 feet, this means that a horizontal movement of the impervious boundary of about 0.6 feet would be sufficient for the horizontal stresses to be in equilibrium.

This horizontal movement will result in horizontal compression of the producing formation and, because of Poisson's effect, some vertical expansion will occur. Any vertical expansion will mean that the actual vertical compression of the producing formation will be less than that computed on the assumption that compressions are one-dimensional.

Assuming that the overburden or the basement rock provide no restraint to lateral compressions, the vertical expansion which a horizontal movement might cause can be evaluated as follows:

Using the data from Terzaghi, the horizontal movement of the impervious boundary, ΔR, can be related to the thickness H by the expression:

$$\Delta R = 0.0002\,H$$

Then:

$$\epsilon_h = 2\,\Delta R/D$$

$$\epsilon_z = 2\,\nu\,\epsilon_h$$

$$\epsilon_z = 2\,\nu\,2\,(0.0002\,H)/D$$

$$\Delta H_1 = H\,\epsilon_z = 4\,\nu\,(0.0002)\,H^2/D$$

$$\Delta H = 2.4 \times 10^{-4}\,H^2/D$$

where: ϵ_h = horizontal strain (compression)
ϵ_z = vertical strain (expansion)
ν = Poisson's ratio ($\approx$ 0.3)
H = Thickness of the producing formation
D = Diameter of the zone within which the pressure decline occurs
ΔH_1 = vertical expansion of the producing formation (negative subsidence) resulting from the lateral compression

At a depth of from 3000 to 5000 feet, the percent compression computed on the assumption that the compression is one-dimensional would vary between about 2 and 6 percent depending on the type of sediment (See Table 6.1). The subsidence based on one-dimensional compression, ΔH_2, can be expressed by the equation:

$$\Delta H_2 = (0.02 \text{ to } 0.06)\ H$$

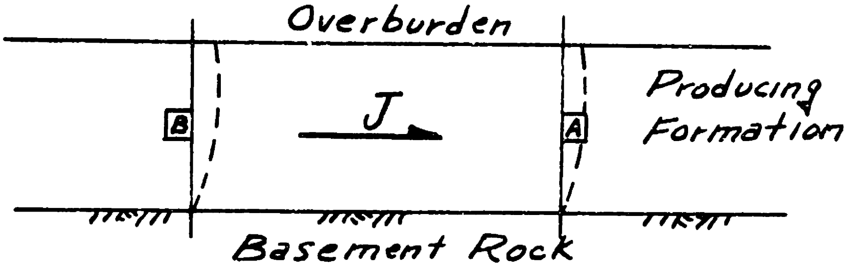
Using the value of 2 percent, the effect of the vertical expansion produced by the horizontal compressions can be evaluated by examining the ratio, $\Delta H_1/\Delta H_2$:

$$\frac{\Delta H_1}{\Delta H_2} = \frac{2.4\times10^{-4}}{2\times10^{-2}}\ \frac{H^2}{D\ H} = 1.2\times10^{-2} H/D$$

For an H/D ratio equal to unity, the vertical strain resulting from horizontal compression would amount to about 1 percent of the strain computed on the assumption that the strain is one-dimensional.

Because of the presence of a rigid basement rock boundary, it is reasonable to assume that this lateral yielding would develop straining primarily in the zone represented by the Rankine passive wedge as shown in Figure 3.1. The effect of the lateral compression on sediments near the center of the producing formation would be even less than computed above.

With no impervious boundary such as assumed above a similar analysis could be made. This time the variation in fluid pressure between two points such as B and A in the accompanying figure would be gradual and could be represented by a typical drawdown curve.



In this case, elements A and B would be separated by a block of soil which would have some rigidity. Because of the pressure gradient between A and B, seepage forces, J, would be developed between B and A. These seepage forces might result in a deformation of the soil block between A and B as exaggerated by the dashed lines. In order to develop static equilibrium of the soil block between A and B when deformed as shown, shear stress would develop on the top and bottom of the block, lateral stresses would reduce at B, and lateral stresses would increase at A. However, because of the shear on the top and bottom of the block the necessary reduction at B and increase at A would be less than required in the previous case, and the resulting horizontal compression at A would be less than in the case with the impervious boundary considered above.

In summary, it is the writer's opinion that the vertical compression occurring in an oil producing formation can be estimated on the assumption that the compression is one-dimensional. Although horizontal compression undoubtedly will occur when the fluid pressures are reduced, the resulting vertical expansions due to this horizontal compression should be minor.

Before leaving this subject, it is appropriate to mention the approach of investigators at the Stanford Research Institute since their approach differs from that of all other investigations.

Their studies were based on substituting a so-called tension center for the oil bearing zone. The seat of pressure decline was replaced by a group of spherical cavities. These cavities were assumed to be hollow and free to contract under the action of a radial tension acting on the walls of the cavity. By assuming the surrounding soil to be homogeneous, elastic and isotropic the resulting surface movements, horizontal and vertical, due to the contraction of the tension center at a given depth and location could be computed.

The effect of a number of tension centers could be determined by direct superposition. By superimposing the effect of a number of tension centers it was possible to develop a subsidence curve matching the actual surface movement. Pressure decline studies were not made because of the feeling that without reliable data relative to the response of soils to stress changes any such study would be relatively inconclusive.

However, the Stanford Research Institute report showed that the observed surface subsidence which had occurred at the time of their study could be reproduced approximately by three tension centers spaced about 2500 feet slong a horizontal line at a depth of about 3500 feet below the surface. Within a distance of about 3500 feet from the center of the subsidence the shape of the theoretical bowl of subsidence agreed remarkably well with that of the real bowl. Beyond this distance the difference between the real and theoretical bowls increased rapidly.

However, as pointed out by Terzaghi (1958) the real seat of contraction consists of a disc shaped body of oil bearing sediments with a very low compressibility which does not contract unless it is compressed under the increase in effective pressure resulting from the lower fluid pressure.

3.2.3 Compressibilities of the Various Strata

The evaluation of the one-dimensional compression behavior of deep clastic sediments is discussed in detail in Chapter 4 where the results of the experimental investigation are summarized and discussed. The relative importance of clay and sand compression in general is discussed in Chapter 5.

3.2.4 Relationship Between Pressure Decline and Effective Stress

Although the primary stress change is a fluid pressure reduction, compressions occur because of increases in effective stress and it is necessary to relate changes in fluid pressure to changes in effective stress. There continues to be considerable difference of opinion regarding the relationship between total, σ , fluid pressure, μ , and effective stress $\bar{\sigma}$ when the void ratio is small.

Hedberg (1936) assumed that the water contained in the void spaces does not contribute any buoyancy; he assumed that it is "...largely held by adsorption and can scarcely be thought of as exerting a buoyant force on the rock particles at any considerable distance below the surface of deposition..."

Skempton (1944) assumed a progressive reduction in pore pressure effectiveness for void ratios less than 0.5 when converting Hedberg's data to void ratio vs pressure data.

Tests by Fatt (1958) on a Boise Sandstone with an initial porosity, n, equal to 26 percent led him to conclude that: "A change in internal pressure, at constant external pressure, is only about three-quarters as effective in changing bulk volume as is a change in external pressure at constant internal pressure." However, in order to arrive at this conclusion he assumed that there is no hysteresis in the stress strain curve but does not conclusively prove it. With hysteresis considered, the effectiveness of change in internal pressure might be larger.

Test data by Van de Knaap (1958) on a Belait sandstone with a porosity of approximately 15 percent indicate that the bulk and pore compressibilities depend only on the difference between external pressure and pore fluid pressure.

Handin, Hager, Friedman and Feather (1963) studied the shear strength of Berea Sandstone (n = 18 percent), Marianna limestone (n = 13 percent), Hasmark dolomite (n = 3.5 percent), Repetto siltstone (n = 5.6 percent) and a Muddy shale (n = 4.7 percent), at confining pressures and internal pore pressures as high as approximately 29,000 psi. Equipment allowed independent control of chamber and pore pressure on a sample 1/2 inch high and 1 inch in diameter. Pore pressure was maintained constant throughout the test. Results of tests on Berea sandstone indicated that the ultimate compressive strength is dependent on an effective confining pressure defined by the simple expression, $\bar{\sigma} = \sigma - \mu$. Although there is some scatter in data (particularly so at an effective confining pressure of 0.5 kilobars) the tests on the Marianna limestone also show the ultimate compressive strength to be dependent on the effective confining pressure. However, for the Hasmark dolomite the simplified effective stress relationship is not efficacious. For the Reppeto siltstone the simplified relationship was found adequate when kerosene was used as pore fluid. When water was used, the strength at equal effective confining pressures was found to increase with increased pore pressure. The authors postulate that the water probably reacted with montmorillonite which comprised about 12 percent of sample and thus the water actually altered the mechanical properties of the aggregate.

According to the authors, the test data suggest that the ultimate compressive strength and ductibility are functions of effective stress provided:

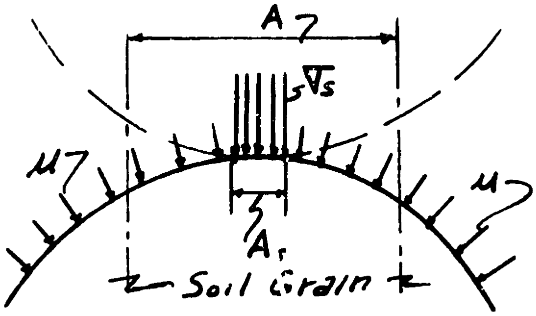
(a) the interstitial fluid is inert relative to the mineral constituents so pore pressure effects are purely mechanical;

(b) the rock is a sandlike aggregate with connected pore space the configuration of which insures that the pore (neutral) pressure is transmitted fully throughout the solid phase.

The effective stress evaluated from the simple expression adequately describes the strength of sandstones and porous limestones, of siltstone when kerosene is used for pore fluid instead of water, of shales if pore pressure equilibrium can be achieved but not of crystalline rocks of low porosity such as the Hasmark dolomite.

For describing the compressibility of natural sediments, Skempton (1960) concludes that Terzaghi's equation should be applicable to depths of several thousand feet of sediment. He cites the results of a consolidation test by Laughton on Globigerina ooze which indicate that the effective stress controlling volume changes can be represented with small error by the expression $\bar{\sigma} = \sigma - \mu$ up to pressures of at least 800 kg per sq cm.

In the case of sands, we can consider the contact pressure, σ_s, at the point of contact between particles to be made up of u and (σ_s - u). (σ_s - u) can be considered an unbalanced or deviator stress acting over the small area of contact.



σ_s = average stress between particles at point of contact

μ = fluid pressure

A_s = area of contact

If σ and u are changed the change in length of an individual particle can then be considered to be the sum of two components:

(a) The change due to change in radius of the particle as a result of the cubical compression of the particle under the change in u.

(b) The deviator stress (σ_s - u) will develop shear stresses within the particle which will result in deformation and volume change.

The deviator stress (σ_s - u) can be related to the total stress, σ, and fluid pressure, u, by the relation:

$$(\sigma_s - u) = \frac{A}{A_s} (\sigma - u)$$

This means then that any compressions within the mass which result from change in geometry of the particle due to shear stress can be described in terms of $\sigma - u$ (provided of course, that the stress strain characteristics of the solid particle are not altered by the hydrostatic confining pressure u). In addition to the bulk compression of the mass due to deformation of individual particles there will be some additional compression of the mass due to the slight shortening of the radius of each particle due to cubical compression resulting from a pore fluid pressure increase.

The relative magnitude of the two contributions to the total compression will depend on what Skempton has defined as the ratio C_c/C. According to Skempton (1960) the effective stress controlling volume change is given with sufficient accuracy by the equation:

$$\Delta p' = \Delta p - \Delta \mu (1 - C_s/C)^*$$

where: C_s = cubical compressibility of solid mineral

C = bulk volume compressibility

Δp = change in applied pressure

$\Delta \mu$ = change in fluid pressure

In the case of clastic sediments it appears that the ratio of C_s/C is sufficiently small that it can be neglected. This means that the contribution to overall compressibility, $\Delta V/V$, of the cubical compression of the grains is negligible, and the compression can be described by the simple effective stress relationship.

Similarly, the pressure at which fracturing of particles occurs also can be evaluated by the simple relationship $\overline{\sigma} = \sigma - \mu$ if one assumes the fracturing of individual

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*The percent change in bulk volume due to $\Delta \mu$ could be less than $C_s \times \Delta u$ if the geometry of packing of the grains changed. This situation is more likely in the one-dimensional compression than in the triaxial compression.

grains is due primarily to shear failure. Examination of grains after shattering suggest this to be reasonable. If so, then the unbalanced stress at points of contact should control the shear stresses developed within a particle. The simple effective stress relationship thus should be applicable even when fracturing occurs, as long as the compressive strength of the individual particle does not vary with confining pressure*.

3.2.5 Influence of Overlying Non-Producing Formations

(a) Stress Transmission

In subsidence studies it is usually assumed that the entire weight of any overburden is carried directly by the underlying sediments and that there is no change in total stress when the fluid pressure is reduced. However, when the oil bearing formation is located beneath an unproductive overburden stratum any compression of the oil bearing sediments will be accompanied by a deflection of the overburden. Because of its structural rigidity the overburden, acting as a plate, may carry part of its own weight and only the balance would be available for compressing the underlying sediments within which the fluid pressure decline is occurr-

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*According to data from Birch (1942), the compressive strength of single quartz crystals compressed parallel to the C axis increases only from 344,000 psi to 390,000 psi when the confining pressure is increased from 15 psi to 132,000 psi (lead the confining medium).

ing. Thus, because of a possible reduction in total stress all of the fluid pressure decline may not manifest itself as an effective stress increase within the producing formation. Any such reduction in total stress due to deformation of the overburden could be important when studying existing subsidence and when estimating future subsidence.

If one is attempting to evaluate the relative compressibility of a sediment from measured surface settlements and measured pore pressure declines, any compressibility computed on the assumption that there is no reduction in total stress would be lower than the actual compressibility of the underlying sediment.

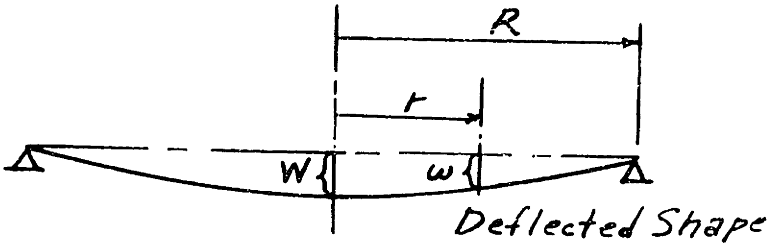
If one is attempting to predict anticipated settlements on the basis of experimentally determined compressibilities, and changes in total pressure are neglected predicted maximum settlements would be larger than what should actually be expected.

Some indication of the order of magnitude of the reduction in total stress due to "structural rigidity" of the overburden at Long Beach can be obtained from available solutions for the deformation of symmetrically loaded circular elastic plates.

The curve of surface subsidence at Long Beach along the minor axis of the elliptically shaped subsidence contours has been plotted in Figure 3.2. Points of inflection are indicated at Points A and B.

For purposes of analysis consider a symmetrically loaded circular plate simply supported at a radius corresponding to point A. The basic differential equation for such a plate is*:

$$\frac{d^3w}{dr^3} + \frac{1}{r}\frac{d^2w}{dr^2} - \frac{1}{r^2}\frac{dw}{dr} = \frac{Q}{D'}$$



where: w and r are as shown;

Q = shearing force per unit of length of cylindrical section of radius r

$D' = \frac{EH^3}{12(1-\nu^2)}$

E = modulus of elasticity

H = thickness of the plate

ν = Poisson's ratio

If the deflected curve between points A and B is assumed to be a sine curve of the form $\omega = W \sin \frac{\pi}{2R}(R-r)$, appropriate differentiation with respect to r yields the

---

*Timoshenko (1940)

following relation for Q/D' at the point of inflection:

$$\frac{Q}{D'} \qquad \frac{2.3W}{R^3}$$

or

$$Q = \frac{2.3WEH^3}{12R^3(1-\nu^2)}$$

For the Wilmington Field substitution of the following values:

$H = 2,000$ ft

$W = 6.5$ ft

$R = 2,000$ ft

$\nu = 0.4$

gives:

$Q = 1.48\ E$

The elastic solution used above is for deflections due to bending stresses only and is applicable only to thin plates and small relative deflections. For the dimensions of the assumed idealized plate used above, only about 1/2 of the observed deflection would be due to bending; about 1/2 would be due to shear. This means that the reduction in total stress due to structural rigidity would be about 1/2 of the value which would be evaluated directly from the above solution.

The results are dependent directly on E. Terzaghi and Peck (1948, Pg.109) present a relation between initial tangent modulus, E_i, and all round pressure, p_c, for dense sand. Above p_c= 5 kg per sq cm the relationship can be represented by the equation:

$$E_i = 3000 + 150\ p_c \text{ (kg per sq cm)}$$

An upper limit for the average value of E of the overburden can be obtained from this expression. At a depth of 1,000 ft p_c might be of the order of 17 to 20 kg per sq cm and the upper limit to E would be about 6000 kg per sq cm.

With E equal to 6000 kg per sq cm, the reduction in total stress due to structural rigidity might be as high as 60 psi. This includes the effect of shear deflection.

Two factors limit the use of the plate analogy in making quantitative evaluations. One is the necessity of assuming elastic behavior of the non-producing overburden formation. This is necessary since the only available theoretical frameworks are those based on the assumption that the material is homogeneous, elastic, and isotropic. A second limitation is due to the shear stresses which develop on the plane of contact between the non-producing overburden formation and the subsiding producing formation. Such shear stresses are not considered in the theoretical solution.

With these limitations, the above analysis probably gives a lower limit of the value of total stress which can be carried through the structural rigidity of the overburden.

An upper limit to the value of shear force on vertical planes at the point of inflection can be obtained by assuming that the shear strain on vertical planes is equal to the slope of the subsidence curve, δ. The evaluation of Q is as follows:

$$\tau = G\delta \quad ; \quad G = \frac{E}{2(1+\nu)}$$

$$\tau = \frac{E\delta}{2(1+\nu)} = \frac{E\delta}{2.6} \quad ; \quad \delta = 0.0055 \text{ (Fig. 3.2)}$$

$$\tau = \frac{E}{2.6} \times 5.5 \times 10^{-3}$$

$$Q = \tau H = \frac{E \times 5.5 \times 10^{-3} \times 2000}{2.6} \approx 4E$$

Assuming a probable upper limit of E equal to 6000 kg per sq cm, the vertical shear force, Q, would be equal to 24,000 tons per ft. This shear force can be interpreted as an average total stress supported by the overburden in shear equal to about 330 psi over the area of the plate.

The two procedures outlined above indicate probable limiting values of 60 and 330 psi. Undoubtedly the actual value lies somewhere between these two limiting values.

Computations above have been for a radius measured along the minor axis of the elliptically shaped contour lines. If the radius to the point of inflection along the major axis of the ellipse had been used, the average stress carried by structural rigidity would be less than above.

Data by Harris and Harlow (Figure 2.5) show fluid pressure reductions equivalent to as much as 2000 feet of water (860 psi) through 1945 when the maximum subsidence was only 4 feet. The computations above are based on a subsidence curve with a maximum subsidence equal to 25 feet; therefore, the fluid pressure reduction corresponding to the limiting values of total stress computed above must have been larger than 860 psi.

A comparison of the reduction in total stress due to structural rigidity of the overburden with the fluid pressure reduction indicates that, at the center of the bowl of subsidence at least, the reduction in total pressure due to vertical shear stresses acting on vertical planes at a radius of 2000 feet might vary between a minimum of less than 10 percent to a maximum of about 25 to 30 percent of the fluid pressure reduction.

(b) Expansion of Overburden

As mentioned in Chapter 2, measurements of the change in length of oil well casings at Long Beach indicate that the overburden was expanding by about 0.3 ft per foot of subsidence at the point of maximum subsidence. This means that the actual compression within the producing formation must be about 20 to 25 percent higher than the surface subsidence.

This expansion can cause considerable difficulty when attempting to convert surface subsidence to formation compression. When evaluating compressibilities from subsidence data, the neglect of this expansion will result in indicated compressibilities less than actual insitu compressibilities. When estimating subsidence, neglect of this expansion will result in an overestimate of the surface subsidence.

3.2.6 Rate of Subsidence

Because the oil, in general, is located in sand layers, any fluid reduction initially occurs in these layers. The fluid pressure decline may develop gradually with time; the actual rate would depend on the rate of oil production. However, if the pressure reduction is measured at the well, such measurements may indicate a larger pressure reduction than the average throughout the subsiding area.

In order to predict subsidence, reliable information about the compressibilities of the oil bearing strata is required.

In order to predict the rate of subsidence additional information about the consolidation characteristics would be required, and it would be necessary not only to predict the rate of fluid pressure decline but also to obtain detailed information regarding the detailed stratification and particularly the thickness of the interbedded impervious layers. According to Terzaghi (1958) this stratification information cannot be obtained by any practicable means. Therefore, even if estimates of the magnitude of subsidence can be made, reliable estimates of the time-rate of subsidence probably are impossible to make in advance.

If the subsidence is due to compression of the interbedded clay and shale layers only, the rate of such sompression would be controlled by the consolidation process (dissipation of excess pore pressure) within the shale layer. If the fluid pressure in the sand layers is being reduced gradually with time, the resulting subsidence versus time curve due to consolidation of shale layers should be similar in shape to a settlement curve one would predict for a clay deposit during the loading period (Taylor, 1948, pg. 291).

However, this must be tempered with a consideration of time effects. Even if the rate of fluid pressure reduction and thickness of the shale layers could be predicted, the resulting compression vs time curve due to consolidation of even normally consolidated clay, would depend on when the stress increase was applied relative to the time that the overburden stress had been acting on the sediment. If the previous load under which the sample had come to equilibrium had been applied for a relatively short period of time, it is likely that the shape of the compression vs time curve for the stress increase would be similar to the classical shape predicted by Terzaghi's theory of consolidation (with the exception that secondary compression might develop). If, however, the previous load had been applied for a long period prior to the application of the stress increase, the resulting compression curve due to a small increase, might have an appearance similar to the laboratory time curves for precompressed soils. As the stress increase became larger, the resulting time curve should again resemble that suggested by the classical Terzaghi theory.

If, on the other hand, the settlement is due to compression of the oil bearing sands, hydrodynamic time lags should be minor and any time effects should be solely those due to the rearrangement of particles. Although time lags may be important once significant crushing of individual particles has been initiated, the time effect would be similar to that indicated by the experimental data (Appendix B).

Since the time effects are relatively independent of the drainage paths, the time effects in the case of the sand should be independent of the thicknesses of individual layers of the oil bearing sand. In any event, the major percentage of the compression occurring within the sand should occur within a relatively short period after the reduction in fluid pressure.

The subsidence vs rate of oil production data for the Wilmington Field which has been previously mentioned suggests that either the sand layers in this particular instance are a significant contributing factor to the total compression or that the compression is occurring in relatively thin shale layers. Terzaghi (1958) indicated that the time lag at the Wilmington Field due to consolidation of the siltstone layer would be negligible and that the average time lag for 50 percent consolidation associated with consolidation of the siltstones could hardly exceed one year.

Subsidence and fluid pressure data for the Bolivar Coastal Field presented by Martin (Figures 2.7 and 2.8) illustrate the reduction in fluid pressure which occurs at some locations within this field before any appreciable subsidence is observed. Once subsidence begins a rough relationship appears to exist between additional pressure decrease and subsidence. However, there is quite a scatter of data. As can be seen from the data, there are times when compression continues even though there is an apparent increase in fluid pressure (i.e., an apparent decrease in effective stress). This is quite probably due to the continued consolidation of the shale under the lower pressures.

In order to significantly compare fluid pressure decline and observed subsidence, it would then be necessary to consider not only the fluid pressure decline but the required drainage of the underlying shale. To do this, detailed information would be necessary regarding the stratification and particularly the thickness of the interbedded shale layers.

3.2.7 Summary

Even if the thickness and compressibilities of the various sediments with a producing oil formation are known and the pressure decline can be estimated reliably there are several factors which can influence any estimates of subsidence:

(a) Because the area of fluid pressure decline is limited, horizontal compression and resulting vertical expansion of the producing formation may occur. This expansion, which is probably minor, will result in an actual subsidence slightly less than that estimated on the assumption of one-dimensional compression.

(b) If there is an overlying non-producing formation, part of the weight of the overburden may be carried by structural rigidity of the overburden formation as it sags. For the Wilmington Field the resulting reduction in total stress transmitted to the lower sediments might be between about 10 and 25 percent of the fluid pressure reduction. If this reduction in total pressure is neglected in computations, the observed surface subsidence will be less than the estimated subsidence.

(c) If there is an overlying non-producing formation vertical expansion of this formation may occur near the region of maximum subsidence. At the Wilmington Field this expansion has been about 30 percent of the surface subsidence. If this factor is neglected, the observed subsidence may be about 20 to 25 percent less than the estimated subsidence.

It appears that, unless the above factors are considered in subsidence estimates, the observed surface subsidence could be as little as 50 percent of the estimated vertical compression of the producing formation.

With respect to the rate of subsidence, it is doubtful that reliable estimates can be made in advance. The prediction of the future course of subsidence probably will have to be based on extrapolating observed data. Any indication of substantial time lags between fluid pressure decline and subsidence would suggest consolidation occurring within the shale layers. Any fairly rapid response between fluid pressure decline and subsidence would represent either compression occurring within the sands or compression occurring within relatively thin shale layers.

3.3 SUBSIDENCE COMPUTATIONS

3.3.1 Wilmington Field

Harris and Harlow (1948) attributed the subsidence primarily to compression and consolidation of the interbedded shales. The compression curve for a typical one-dimensional consolidation test on a shale core is shown in Figure 3.3. This curve indicates a maximum past pressure of the order of 120 tons per sq ft and a virgin compression index of approximately 0.4. The results of additional tests which are summarized in Figure 3.4 indicate a fairly uniform decrease in compression index from a value of approximately 0.4 at a depth of 2,500 feet to a value of approximately 0.05 at a depth of 5,000 feet.

It is of interest to note that Harris and Harlow tested only shale cores because of the following three reasons:

(1) They were expected to be more compressible than the sands;

(2) Previous tests had demonstrated fairly conclusively that sands and particularly sandstones are relatively incompressible at high pressures;

(3) Relatively undisturbed shale cores suitable for testing could be obtained with less difficulty than sand cores.

Although Harris and Harlow assumed that the sands were incompressible, the total thickness of the producing formation was used in computing the maximum ultimate subsidence and the subsidence through 1945. It was assumed that the entire producing formation had a virgin compression index, C_c, equal to that of the shale cores and a correction factor was applied to the computed subsidence. This correction factor, which was equal to 8 percent,was the ratio of the measured to computed subsidence for the pressure decline as of 1945. The computations indicated an ultimate subsidence equal to about 100 feet; applying the correction factor Harris and Harlow concluded that the maximum ultimate subsidence should be about 8 feet. Not only was it assumed that only the shales were consolidating but it also was assumed that time lags were relatively small.

Two factors were mentioned as possible sources of the discrepancy between computed and observed values: (1) the presence of many water bearing strata which may not be affected greatly by pumping and which thus would reduce the pressure decline in the shales, and (2) the samples which were tested were chosen because of their suitability for machining, and, therefore, probably were more compressible than the majority of samples.

There is an additional possible factor which was not considered by Harris and Harlow. Although the depth of the sample for which Figure 3.3 applies was not given, the data in Figure 3.4 suggest it was from a depth no greater than about 2500 feet. At a depth of 2500 feet the effective overburden stress before any fluid pressure decline would not be greater than about 85 to 80 tons per sq ft, compared with the indicated maximum past pressure of about 120 tons per sq ft. No mention was made of when the samples which were tested were obtained. If the samples had been obtained prior to any fluid pressure decline, a real precompression is indicated. Since their computations assumed virgin compression this precompression could account for part of the apparent discrepancy. If the samples had been obtained after the fluid pressures were reduced then the apparent precompression could be due to consolidation under the fluid pressure decline and should not influence the computations.

The apparent precompression also might be due to drying if the sample was not stored properly prior to testing.

Gilluly and Grant (1949) based their estimates of subsidence on the results of laboratory tests on sand cores. It was argued that, since the fluid pressure decline, and thus the effective stress increase, was occurring only in the sands, only the sands would be compressed. It was assumed that the thickness of sand undergoing pressure decline was equal to the length of perforated casing. Their argument was that the casing was gun-perforated only in the sand zones.

Although a maximum ultimate subsidence equal to about 16 feet was originally computed, Gilluly and Grant concluded that the maximum ultimate subsidence would be about 10 feet. However, if a pressure decline developed in the shale additional subsidence was to be expected. A correction was made because a maximum subsidence of 9 feet was computed using the pressure decline through 1945 whereas the observed maximum at that time was only 3.5 to 4 feet.

Factors which were mentioned as possible explanations for the apparent discrepancy between observed and computed subsidence included the following:

(1) A possible error in thickness of stratum undergoing pressure decline;

(2) Pressure declines were measured at the well whereas the average pressure decline throughout the stratum are undoubtedly smaller;

(3) Laboratory tests on core samples indicated modulii which are too low because the test data included plastic or permanent deformations.

However, if plastic deformations occur in a confined compression test, it is reasonable to assume that they also will occur in the ground. The only explanations, therefore, that can be given for the difference between the observed and computed values of subsidence is that the compression tests did not give the true subsurface behavior of the sands, that the estimates of thickness of compressible stratum were in error, or that part of the subsidence was due to shale compression.

Compressibility measured in a laboratory test on core samples could be in error because of disturbance of the samples or by unsuitability of the compression apparatus. Terzaghi (1958) has suggested that the equipment used for the tests on the sand cores was unsuitable, probably because there was no provision for drainage of the sample during the test. However, at pressures above the maximum past pressure both of these factors should result in a measured compressibility less than the insitu.

In his latest paper Grant (1960) has apparently revised his original conception of the seat of compression. His latest feeling is that the available data indicate that the subsidence now is due to compression of the shales or so-called siltstones interbedded between the oil bearing sand layers.

The problem of locating the seat of subsidence at Long Beach is best appreciated by quoting the conclusion of Terzaghi (1958) that the facts which were known at the end of 1953 about the subsidence at Long Beach could be explained on the basis of two sets of different assumptions:

"<u>Case A</u>: Subsidence is entirely due to the gradual compression of the oil bearing sand strata. This assumption is identical with the writer's original assumption of 1950. However, at the present state of our knowledge of the rate of increase of the subsidence, it calls for the supplementary assumption that the compressibility of the sand increases with increasing pressure whereas according to results of standard laboratory tests on sand it decreases with increasing pressure.

"<u>Case B</u>: It is assumed that the oil sands are practically incompressible and that the subsidence is almost exclusively due to the consolidation of the layers of siltstone and shale located between the oil sands.

"At the present time (1954) it is still impossible to decide whether the subsidence will increase in accordance with one of the two forecasts A or B, or whether it will follow an intermediate course."

As mentioned in Chapter 2, more recent estimates of the ultimate maximum subsidence have been as high as 50 feet. This suggests that the compressibility measured in the laboratory tests or the estimates of the thickness of the compressible stratums may not have been as much in error as either Harris and Harlow or Gilluly and Grant originally thought.

With estimates of surface subsidence as high as 50 feet, the actual compression of the producing formation might be as high as 100 feet if the effects of the non-producing overburden discussed in this chapter are considered.

Harris and Harlow used the total thickness of formation to obtain their uncorrected estimate of about 100 feet, and Gilluly and Grant estimated an ultimate subsidence as high as 16 feet assuming that the sand only was compressing. It thus seems reasonable to assume that the subsidence at Long Beach has been due to compression of both the oil bearing sands and the interbedded siltstone or shales.

3.3.2 Bolivar Coastal Field

Martin indicates that the sum of the thicknesses of the shale layers is considerably less than 200 feet in the area of maximum subsidence. He further felt that the formation has been precompressed so that the fluid pressure had to be reduced several hundred psi before subsidence began.

Using the following expression, a simple calculation can be made to indicate the order of magnitude of Compression Index which would be required in order to account for the subsidence by shale compression only:

$$\rho = \frac{\Sigma H}{1+e_1} \times \frac{0.434\, C_c}{P_{av}} \Delta p$$

where: ρ = surface subsidence

ΣH = thickness of shale layers

e_1 = initial void ratio

Δp = fluid pressure reduction

P_{av} = average effective pressure during fluid pressure reduction

C_c = Compression Index

If we assume a shale thickness of 200 feet, a maximum subsidence of 11 feet, a fluid pressure reduction of 1000 psi, and an initial void ratio equal to 0.4, the required Compression Index is approximately 0.41. That is, a unit vertical strain ($\frac{\Delta H}{H_o}$) equal to about 5 percent is required in the shale under the assumed pressure increment to account for the subsidence from shale compression only.

In his 1955 report, Martin indicates that the sand thickness is approximately 120 feet in the area of maximum subsidence. A unit vertical strain of about 10 percent would be required to account for all subsidence from sand compression only.

However, the sum of the thicknesses of the sand and shale indicated by Martin is equal to only 360 feet whereas the producing region apparently extends from a depth of about 3200 to 3800 feet. If we assumed that the entire 600 feet consisted of compressible sediments then a computation as outlined above indicates that the entire producing formation must have an average Compression Index equal to only 0.13.

These simple computations neglect any influence of the non-producing overburden. If the overburden has an effect similar to that suggested for the Wilmington Field, then the compression within the producing formation would have to be larger than the surface subsidence and the computed Compression Indices even larger than the values above.

A maximum compression index of about 0.26 is indicated by the results of the laboratory tests on core samples of shale (see Chapter 4 and Appendix B). At a depth of 3000 feet, the maximum unit compressibility indicated by the tests on oil sands would be less than about 4 percent for a pressure decline of 1000 psi (see Table 5.1).

From this data, it appears that the subsidence probably is due to compression of both the oil bearing sands and the interbedded shales. However, it is difficult to make any more significant analysis or to evaluate the relative contribution of sand and shale compression without access to the complete field data.

3.4 HORIZONTAL MOVEMENTS

In addition to the vertical movements which have been measured in the Wilmington Field horizontal displacements of surface points in excess of 6 ft. also have been observed. These movements have been toward the zone of maximum subsidence.

Two concepts have been developed by investigators to account for these observed horizontal movements at ground surface. Grant (1958) considered the sediments overlying the producing formation to be analogous to a plate resting on an elastic foundation. As the producing formation compresses, the overlying sediments lose part of their support within the subsiding area and sag in a manner analogous to a plate.

This analogy provides at least a qualitative picture of the mechanism responsible for the development of compressive strains and horizontal movements. When the plate deflects, the top surface of the plate in the zone of maximum subsidence will be subject to horizontal compressive stresses and points on the top surface will be deflected horizontally toward the point of maximum subsidence. Similarly, points on the bottom of the plate will be deflected horizontally away from the point of maximum subsidence.

Grant (1958, 1960) has used the plate analogy to explain sudden horizontal shear displacements which have been observed in the Wilmington Field which have produced local earthquakes and have damaged oil wells. In the case of a deflecting plate the maximum shear stresses would be at approximately mid-depth of the plate; at the Wilmington Field this would be at a depth of about 1600 to 1700 feet and according to Grant this is the interval of the greatest shear damage.

However, because of the two factors previously mentioned, it has not been possible to use the plate analogy for making quantitative comparisons between predicted and observed movements. Even so, all the investigators have arrived at the conclusion that the observed horizontal movements at Long Beach cannot be explained rationally except by assuming that the center of the seat of the subsidence is well below the top of the oil bearing formation, the top of which is located at a depth of about 2,000 feet.

In a qualitative sense, at least the horizontal movements which accompany subsidence can be seen as a natural consequence of the deflection of the non-producing overburden formation.

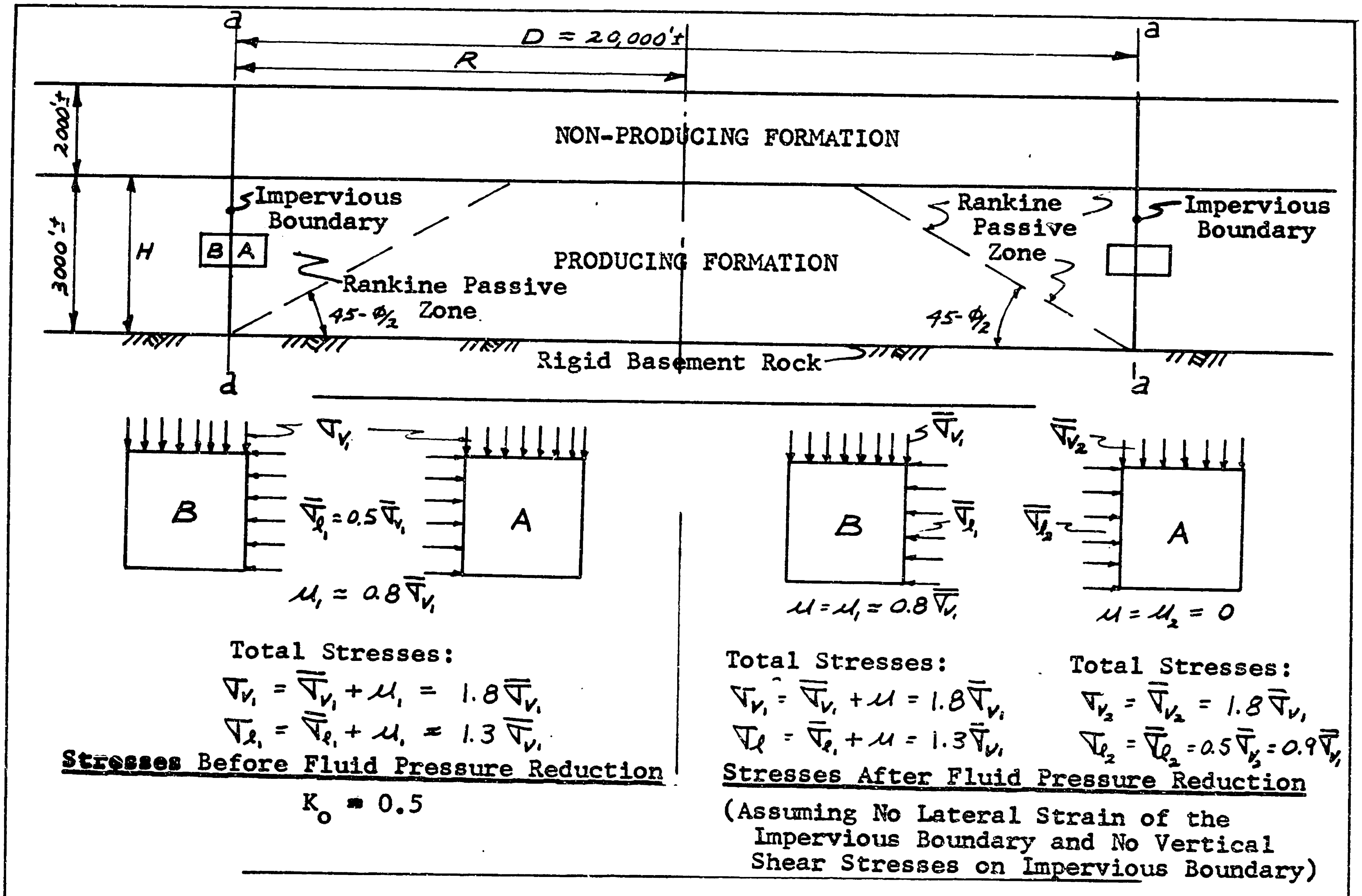


Fig. 3.1 STRESSES IN IDEAL PRODUCING FORMATION

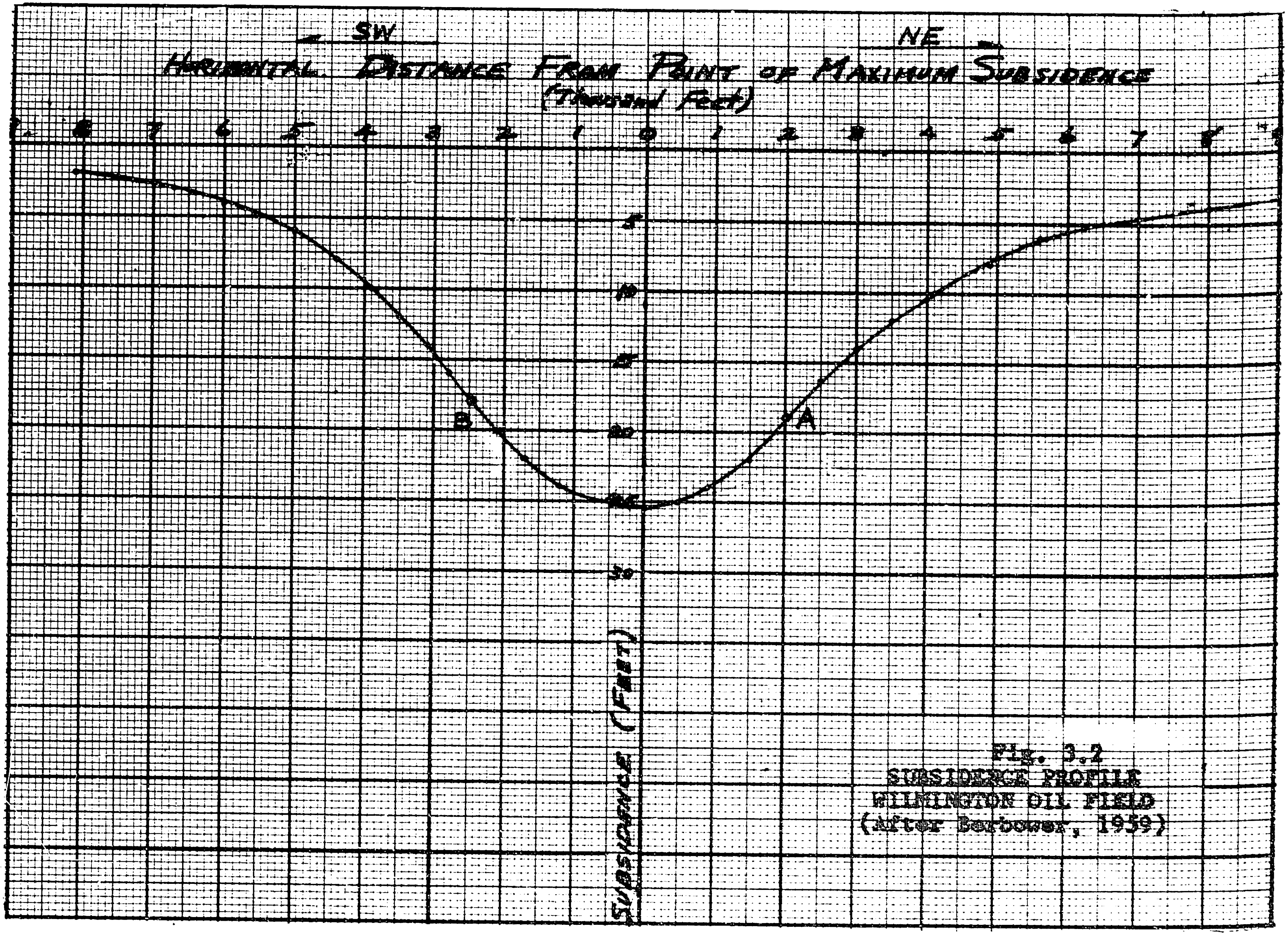


Fig. 3.2
SUBSIDENCE PROFILE
WILMINGTON OIL FIELD
(After Berbower, 1959)

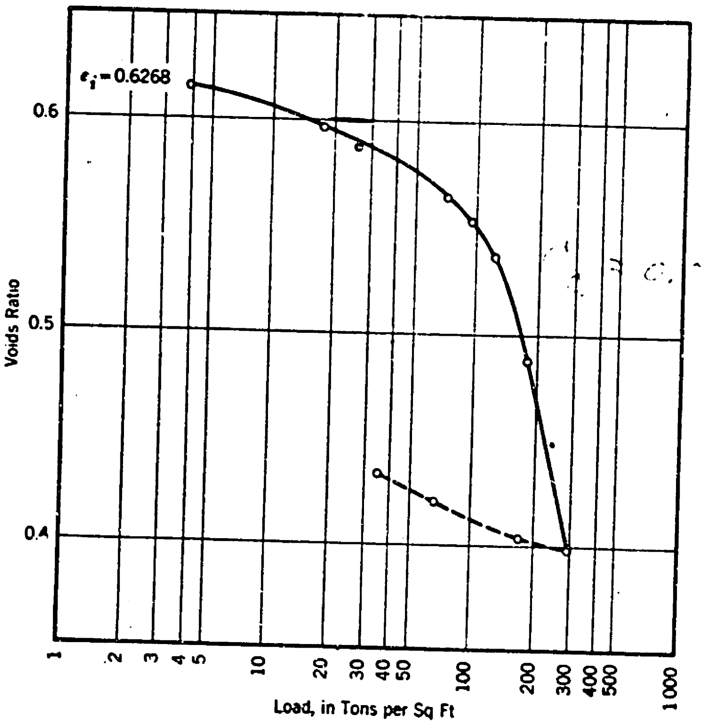


Fig. 8.—Typical Consolidation Test of Shale

Fig. 3.3

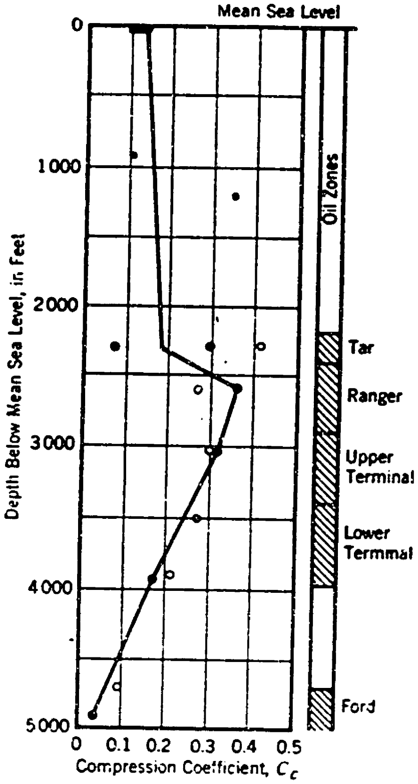


Fig. 10.—Compressibility of Wilmington Oil Shales in Relation to Depth

Fig. 3.4

(After Harris and Harlow, 1948)

4: ONE-DIMENSIONAL COMPRESSION BEHAVIOR OF DEEP CLASTIC SEDIMENTS

4.1 INTRODUCTION

As indicated previously, there has been fairly unanimous agreement among various investigators who have studied the subsidence problem that the primary cause of the subsidence is the compression of sediments due to the reduction of fluid pressures within the producing formation. However, there is still considerable difference of opinion among various investigators as to whether the compressing soils are the oil bearing sands, the interbedded shales and/or siltstones or a combination of both. This disagreement has been due, in part, to a lack of experimental data on the compression behavior of soils at high pressure.

A comprehensive experimental investigation of the compressibility of clastic sediments at high pressure was conducted in connection with the present investigation (Appendix B). The available literature also was reviewed (Appendix A). The significant results of both the experimental investigation and the literature review are discussed in this chapter.

In addition to experimental work the literature contains a limited amount of data correlating the porosity of core sample with depth of burial. This correlation can be used to evaluate the field compressibility of a sediment.

In this chapter the compressibilities evaluated from such a correlation are compared with the compressibilities indicated by the results of the laboratory tests.

4.2 FACTORS INFLUENCING COMPRESSION BEHAVIOR OF SEDIMENTS

Factors which must be considered in evaluating the compressibility of deep sediments and more particularly in evaluating the efficacy with which laboratory data obtained from one-dimensional compression tests can be extrapolated to predict the compressions of deposits of natural sediments include:

(a) Soil composition, particularly its mineralogy, particle size and distribution, and particle shape;

(b) Pore fluid characteristics at the time of deposition;

(c) Changes in pressure, temperature, and pore fluid subsequent to deposition;

(d) Elapsed time subsequent to deposition.

4.3 COMPRESSIBILITY FROM LABORATORY TEST DATA

4.3.1 Fine Grained Soil

The experimental results of laboratory tests at high pressures reported by Westman (1932), Parasnis (1952), Skempton (1944, 1953), Laughton (1957), and Chelingar and Knight (1960) which are summarized in Appendix A, indicate that at least the laboratory one-dimensional compression behavior of clays at high pressure may be reasonably extrapolated from the laboratory compression behavior at low pressure (i.e., pressures less than about 1,000 psi). The published experimental data further indicate no unexpected or unusual behavior at high pressure.

Experimental work on the behavior of fine grained soils at high pressure completed in connection with the present study included 30 one-dimensional compression tests on shale core samples from the Bolivar Coastal Field. In addition, a number of tests of a preliminary nature were performed on clays to study:

(1) The possibility of evaluating at high pressure the maximum past pressure from the shape of the compression curve;

(2) The influence of sedimentation environment and pore fluid changes on the compression characteristics;

(3) The influence of load increment ratio and load duration on the compression characteristics;

(4) The effect of pressure on the rate of secondary compression of an organic silt;

(5) The effect of temperature on the compression behavior.

The tests are described and the results summarized in Appendix B; the significant results are discussed below.

(a) Core Samples and Slurries

The results of the tests on the clay core samples at high pressure are summarized in Figure 4.1. To obtain each curve identified as "Undisturbed Core Samples" the portion of the compression curve above the precompression pressure was approximated by a straight line; this straight line was then extrapolated over the pressure range 1,000 psi to 10,000 psi even though the experimentally determined curve may have been straight over only a portion of this pressure range. Many of the samples showed a precompression of 1,000 psi to 2,000 psi.

The values of virgin compression index thus obtained vary from 0.11 to 0.26.

At a pressure of 100 kg per sq cm (1421 psi) Skempton (1953) obtained compression indices varying from about 0.35 for highly plastic clay with a liquid limit equal to 80 percent to 0.15 to 0.2 for silty clays with a liquid limit equal to 30 percent. The compression curves for these two soils also are shown in Figure 4.1.

One of the objectives of the laboratory investigation was to study the possibility of producing in the laboratory a clay with a very high compressibility in the pressure range encountered in the field; and, if such a high compressibility could be obtained to determine whether or not it would be destroyed by sampling operations.

All sampling operations result in a release of confining pressures and cause some soil disturbance; this release in lateral pressure and disturbance generally results in compressibilities as determined in the laboratory which, at pressures below the maximum past pressure, are higher than the field compressibility and which, at pressures above the maximum past pressure, are smaller than the field compressibility. The degree to which disturbance reduces the compressibility above the maximum past pressure depends on a great many factors, including the amount and type of leaching which has occurred and the pressures which have been imposed since the soil was deposited.

Clays initially deposited in sea water and then leached may show significant differences between the compressibility of undisturbed and remolded samples. Determination of the soluble salt concentration of the core samples tested suggested that the soil deposited in the Shallow Neretic environment had been leached to a salt concentration approximately half that of sea water.

To evaluate whether or not disturbance of the core samples was destroying any "structure" built up by leaching, a number of clays from core samples were resedimented in water with different salt concentrations, loaded, unloaded, leached, and reloaded without removing the sample from the consolidometer. This procedure should have indicated the development of any so-called "structure". The results of these tests also are shown by compression curves in Figure 4.1.

Several tests were run on clay from core samples which were water wet and then mixed with oil; the resulting compression curves also are shown in Figure 4.1.

There are several conclusions which are suggested by the data in Figure 4.1.

(1) Initial depositional environment and subsequent changes in the concentration of soluble salts have a minor effect on the compression characteristics of the particular soil used to form the slurries;

(2) The compression curves for the slurry samples merge with the compression curves of the core samples. Because of this it appears unlikely that the slurry samples could suffer any appreciable structural breakdown and drastically change their compression characteristics and develop compressibilities appreciably higher than indicated by the core sample data.

(3) The compression curves of the slurry samples should be indicative of the virgin compression of the shales. Because the compression curves for the slurry samples merge with the compression curves of the core samples, to the writer it seems unlikely that a clay similar to the Venezuelan clays tested could have a virgin compressibility within the range of 1,000 to 10,000 psi much greater than the maximum determined from the compression tests. Even the sample of undisturbed Boston Blue Clay which has comparable Atterberg limits has a compression index of only

0.3 in this pressure range. However, this conclusion must be tempered with a consideration of the possible effects of long time loadings and temperature differences which are discussed later.

(4) The approximated straight line virgin portions of the compression curves of the core samples are probably reasonably indicative of the insitu virgin compression curve for the pressure range shown. However, the use of the actual laboratory compression curve is likely to lead to serious error if the soil is precompressed. Below the maximum past pressure the insitu compressibility may be only a fraction of the compressibility based on the core sample tests. At pressures well above the maximum past pressure, the insitu compressibility undoubtedly is somewhat larger than that indicated by the tests on core samples.

The effects due to release of lateral pressure and the minor disturbance during trimming are illustrated later in connection with a discussion of the study of disturbance of sand core samples.

(5) The differences in the compression curves of the individual core samples are probably due to differences in mineralogical composition and depositional environment, but even these differences are not great.

Remarks by Skempton (1944) on comparison of the sedimentation compression curve and the compression curve on "undisturbed" samples suggest that laboratory tests on core samples of shales from great depths may give a reliable indication of the insitu compression characteristics. However in discussing the approximate relations between void ratio and pressure as a function of Atterberg Limits which he presented in 1953 he suggests, based on a comparison of laboratory compression curve with porosity vs depth data for Venezuelan Shales reported by Hedberg, that the relations may not be valid for pressures corresponding to depths below 3,000 to 5,000 feet. This anomaly will be discussed further after published porosity vs depth data is presented.

(b) High Pressure Test on Boston Blue Clay

The results of a high pressure test on an "undisturbed" sample of Boston Blue Clay which was performed to evaluate how well precompression could be evaluated at high pressure also have been plotted in Figure 4.1. Examination of the resulting compression curve plotted in Figure B.10 shows that precompression can be detected from the slope of the compression curve, but the evaluation of the maximum past pressure may not be as precise as would be desired.

The curve shown represents the evaluation which could be made from the shape of the compression curve for an ideal "undisturbed" sample; any disturbance and pressure release during sampling would decrease the curvature in the vicinity of the maximum past pressure and make the evaluation even less reliable.

(c) Test on Beauharnois Clay

The results of the test on the Beauharnois clay (Figure B.13) indicate the response to be expected after a sample has been subjected to a given stress for a long period of time. An increase in stress may cause very small compressions until a stress is reached which is somewhat larger than that stress which had been maintained for a long time. Beyond this higher stress, the slope of the compression curve appears to have a reasonably unique value independent of the load increment and time duration; it appears that the increase in time duration merely shifts the curve without greatly altering its slope*.

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*Terzaghi (1941) describes and discusses a bond in natural clays which allows them to carry small load increments with smaller compressions than would be expected from the normal compression curve. Taylor (1948) discusses the same phenomenon and also suggests the uniqueness of the slope of the compression curve for a given time duration of load increment.

This behavior has been observed by Leonards and Ramiah (1959), Hamilton and Crawford (1959).

Madden (1960), working under the direction of the writer, measured pore pressures during the consolidation test.

In some tests the normal loading procedure was used. In others a small stress increment was added to a normally consolidated sample which had previously been allowed to consolidate for an extended period of time. When the plots of pore pressure versus logarithm of time were compared very different shapes were observed.

The practical significance of this behavior is quite important. Consider a normally consolidated soil which is subjected to essentially constant stress for long periods of time and then subsequently loaded with small stress increments. The settlements which occur in a period of time which is small compared to the time the sample previously had been loaded may be small. The resulting settlements may be a negligible percentage of the settlement which would be estimated from the results of a normal compression test performed in the laboratory. If the load increment in the field is large enough, the shape of the resulting settlement vs pressure curve may lead one to suspect a maximum precompression larger than the actual value. However, even with the behavior described, the settlements, when measured for long enough periods of time, may continue and may eventually become as large as would be predicted from the results of a normal compression test.

(d) Secondary Compression of an Organic Silt

The results of the tests on an organic silt which were made to investigate whether or not the rate of secondary compression (defined as the percent change in sample thickness per log cycle of time*) was dependent on

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*There are cases where the logarithmic time relationship is not satisfactory and where extrapolation on the basis of a logarithmic relationship may underestimate or overestimate the long term compression. See for example Lambe and Whitman (1959) and Lo, (1961).

pressure are shown in Figure B.14. Although there is some scatter in the data there is a definite relationship between rate of secondary compression and pressure. A replot of the data as in Figure B.15 where pressure is plotted to a logarithmic scale reveals that the relation between rate of secondary compression and pressure is rougly logarithmic in nature. For the soil tested this relationship can be represented over the range 1.0 to 16.0 kg per sq cm reasonably well by the expression:

$$R_p = 1.1 + 0.5 \log_{10} p$$

where: R_p = rate of secondary compression at pressure p (percent change of thickness per log cycle of time)

p = effective pressure in kg per sq cm

When defined in this fashion, R_p is analogous to true or instantaneous strain.

If the relationship between void ratio and pressure also is assumed to be represented by a logarithmic expression of the form:

$$e_p = e_1 - C_c \log_{10} \frac{p}{p_1}$$

then the rate of secondary compression at a given void ratio can be related to that void ratio by an expression of the form:

$R_p = a - b\ e_p$

where: a and b are constants for a given soil

R_p = rate of secondary compression at pressure p.

e = void ratio at pressure p.

However, although the rate of secondary compression as defined above does increase with increasing pressure, the e log p curves, for this particular soil at least, will be found to become slightly flatter with increasing time duration of loading. Although the true rate of strain, $\frac{d}{dt}\left(\frac{\Delta e}{1+e_p}\right)$, during secondary compression increases with increasing pressure, the void ratio e_p decreases with increasing pressure and thus the denominator decreases. Because the denominator decreases in a given time interval, Δe then actually could decrease with increasing pressure even though $\frac{\Delta e}{1+e_p}$ was increasing. Consider the soil tested by Parrish, (1959). When the void ratio is equal to 1.0 the change in void ratio per log time cycle is 0.034; when the void ratio is equal to 0.5 the change per log time cycle is 0.031. Thus with increased duration of loading the curve of e vs log p should flatten somewhat, i.e., C_c should decrease slightly.

(e) Effect of Temperature

The results of the test in which the temperature of a consolidated sample of Boston Blue Clay was increased are shown in Figures B.16 and B.17. When the resulting compressions are compared with the estimated compression which would have resulted with no temperature change it is seen that the increase in temperature from 20°C to 40° resulted in an increase in compression of about 30 percent. It also appears that the effects of temperature are not completely reversible. The reduction in temperature was not accompanied by a complete recovery to the compression curve without the temperature change. During the additional compression due to the temperature change, some rearrangement of particles must have taken place. Because of this rearrangement it is not possible to achieve a completely reversible behavior due to temperature changes.

Although quite preliminary in nature, the test results indicate that, if a sample of clay is consolidated to a given pressure and then cooled or heated with free drainage, the sample will compress if heated and swell if cooled*.

This behavior is undoubtedly due to changes in

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*A limited amount of experimental data by Gray (1936 also show the same reduction in equilibrium void ratio with increasing temperature and that further increasing the temperature also increases the rate of secondary compression. Based on his data, Gray felt that the effect only would be significant in material with high organic content.

Data by Parsonson (1959) on a silty fat clay also show this reduction in void ratio upon heating and slight increase in void ratio upon cooling.

double layer thickness and the change in repulsion between particles. An increase in temperature alone, all other factors constant, should result in an increase in double layer thickness and repulsive force. However, Lambe (1959) has shown that, when the effect of temperature on dialectic constant also is considered, an increase in temperature should depress the double layer and reduce the repulsive force and thus result in a compression of the sample.

4.3.2 Sands

(a) General

The experimental investigation of the factors influencing the compression behavior of sands included a study of the effects of particle size distribution and shape, density, time, mineralogical composition, pore fluid composition, disturbance, and side friction.

The most important fact brought to light by the experimental investigation is the relatively high compressibility of sands as measured in the one-dimensional laboratory test at high pressures. The significance of this high compressibility and comparison with the compressibility of clays at high pressures is considered later.

At low pressures sands are relatively incompressible and the Compression Index is generally small. The compression at low pressures is due to particle rearrangement.

Because of elastic shortening of particles they shift by sliding and rolling. There may be some yielding or crushing at the points of contact, although Figure B.30 shows that at pressures as high as 1,000 psi only slight degradation of the uniform quartz sand tested had occurred.

When the pressure on the sample becomes sufficiently high, the load on individual grains becomes large enough to cause shattering or fracturing of the particles. Shattering generally manifests itself as an increased slope of the compression curve* shown, for example, by typical curves in Figure 4.2. The slope increases to a maximum and then gradually decreases as the pressure is increased to very high values. The pressure at which the shattering becomes evident will be referred to as the "critical pressure" or the break-point. In the case of rounded particles, the shattering can easily be heard as a continual "popping" sound as the grains break. This "popping" only becomes readily detectable at pressures in the vicinity of the "critical pressure" and above. At pressures high enough to cause this shattering, quartz sands have maximum compression indices ranging from 0.35 to 0.70.

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*In Chapter 5 it is pointed out that an increase in Compression Index cannot always be interpreted as an increase in compressibility.

That this shattering does indeed occur, is shown conclusively by the several grain size distribution curves in Figures B.30 and B.46 and by the photomicrographs of various samples before and after compression to various stresses in Figures B.31, B.20, and B.50.

The pressures at which shattering begins depends on the initial density of the sample, on the angularity of the grains and on the grain size distribution. This pressure varies from about 100 psi for initially very loose, uniform, highly angular sand to about 9,000 psi for initially very dense, well graded, well rounded sand. The higher the initial relative density, the higher the break-point pressure. The more angular the grains, the lower the break-point pressure for any given method of deposition. The smaller the median grain size, the higher the break-point pressure for any given method of deposition.

The results of a number of representative tests on quartz sand are shown in Figure 4.2. The results of all the laboratory compression tests on uniform quartz sands of different sizes are summarized in Figure 4.3. This plot shows the range of variation of the compression curves for pressures above the break-points. The void ratio of a sand at any pressure below the break-point will be dependent on and will not differ greatly from the void ratio at the time of deposition. Thus a curve representing the one-dimensional compression behavior of 20-40

Ottawa Sand deposited at a void ratio of say 0.55 can be approximated as follows: construct a horizontal or slightly sloping line, starting from the left axis of Figure 4.3 at e = 0.55, until it intersects the band for 20-40 Ottawa Sand. Beyond this point the band shown for 20-40 Ottawa is used.

Terzaghi's (1925) early tests on crushed quartz and also the compression curve for dense sand given by Terzaghi and Peck (1948) suggest that crushing of sand grains does occur, and the important work of Maxwell and Verral (1954), although not directly concerned with determinations of the magnitude of compressibility, considered the influence of many factors on the compression behavior of sands and can be used as a guide to future work.

The studies at high pressure by investigators in the U.S.S.R. which were reviewed by Drashevska (1958) unfortunately appear to have been concerned only with the degradation of soil as a function of pressure; there is no indication that they recognized the effect of degradation of sand on compressibility.

DeBeer (1963) obtained experimental evidence of an increase in compressibility and degradation of sand at high pressures and recognized that this compressibility was due to fracturing of individual sand grains.

However, neither Terzaghi and Peck nor DeBeer compared the compressibility thus measured with the compressiof clays nor did either recognize the significance of this high compressibility on the study of settlement due to compression of deep sediments.

(b) Time Effects

Once the gross stress on the sample reaches or exceeds the critical stress, the time lags during compression become important. At pressures above the critical pressure the compression is not instantaneous as usually assumed for sands at low pressures but is due to a continuing process. Because the stress in not carried uniformly by all particles, there is a gradual build-up of stress on individual grains resulting in shattering; a redistribution of stress occurs followed by a stress build-up and shattering of other grains. This type of behavior can be visualized readily from an examination of the type of inter-particle contact shown in Figure 4.4. In this figure Lucite discs were used to evaluate stress transmission in a particulate medium. The arrangement of discs indicates a possible arrangement of particles in a loose graded particulate medium; initially, some particles may not carry any appreciable stress.

The rate of compression under a given stress appears to decrease exponentially with increasing time as shown by the representative plot in Figure 4.5. For comparison, the same data are plotted to an arithmetic scale in Figure 4.6.

At low pressures the evidence suggests that the importance of the time lag, which is due essentially to a continuous rearrangement of particles, depends on the initial density of the sample. Taylor (1948, p.217) presents a time curve for a typical load increment on a uniform fairly dense sand in which about 95 percent of the total compression occurred during the first minute. Terzaghi and Peck (1948, p.59) present a time curve for a compression test on a loose sand in which the pressure was increased at a fairly rapid rate and then held constant at 6 kg per sq cm; even after one hour, the curve presented indicates that measurable compression was still occurring.

The test results of two long duration tests on quartz further emphasize the importance of time effects in sand when the pressures are high enough to result in shattering of grains. On the basis of the test results shown in Figure B.34, it is hypothesized that there is a unique e-log p curve for a given rate of loading. At any given pressure the lower the rate of loading, the lower the void ratio. If a load acts on the sample for a long period of time, the sample will continue to compress; if at some subsequent time the pressure is increased by a small amount, the resulting compression will be small until the pressure reaches a value corresponding to the loading curve for the new rate of loading.

When the load is increased in smaller increments, as in these tests, the curves are much flatter at the beginning and tend towards a straight line only after about 2 minutes. However, in some of the long-duration load increments the slope of the dial reading vs log t curve was found to increase with increasing time. It is not known whether this is a true characteristic of the material or whether it was caused by slight fluctuations of the applied pressure or of the room temperature.

These observations lead to the belief that the time-compression behavior of sands may be more complex than might appear at first glance.

(c) Effect of Mineralogical Composition

The effect of mineralogical composition was studied using highly angular sands composed of quartz, feldspar, and dolomite. A natural beach sand of volcanic origin from Hawaii also was tested. Adjusted compression curves for the different minerals are shown in Figure 4.7.

The maximum compression index was determined for each test and is plotted in Figure 4.8 as a function of initial void ratio. There is an indication that the maximum compression index increases with increasing initial void ratio but the scatter of data even when the different minerals are considered separately is too large to define a unique relation between compression index and initial void ratio.

The surprising conclusion to be drawn from the data is that the maximum compression index is little affected by the type of mineral constituting the sand.

In Figure 4.8, maximum compression indices from tests on various gradations of Ottawa Sand have been added to the data obtained on ground sands of different mineral composition. The data for the Ottawa Sand show a larger scatter than that of the ground material. As load is increased on the angular sands, crushing is probably a slow steady process starting at relatively small loads. As a load is increased on the relatively rounded grains, crushing does not start until relatively high pressures are reached. At a critical pressure many grains probably fracture simultaneously, resulting in a "collapse". The influence of the "collapse" on the compression index undoubtedly is greatly dependent on the arrangement of the grains, and different grain arrangements at the same initial void ratio might account for the relatively larger scatter.

Within the accuracy of measurements obtainable with the present apparatus, the maximum compression index for all minerals with angular particles has a value:

$$C_c = 0.48 \pm 15\%$$

and this maximum value tends to occur at a void ratio between 0.5 and 0.6. However, as will be pointed out later, compression index alone is not necessarily the most significant measure of compressibility.

In order to compare the position of the compression curves for different minerals, the effect of initial void ratio was eliminated by adjusting each curve to a common initial void ratio by interpolation.

Within the pressure range at which substantial crushing occurs, the position of the compression curve is a function of the shape and hardness of the mineral constituent of the sand. At a given pressure in the crushing range, the curves will be positioned in the following order:

Highest void ratio:	Well rounded material:	Ottawa Sand
Medium void ratio:	Ground material No pronounced cleavage:	Quartz and Feldspar
Lowest void ratio:	Pronounced cleavage:	Dolomite

This is undoubtedly a result of the shape of the individual particles. Dolomite with very clear cleavage planes will have many face-to-face contacts which will give a low void ratio, i.e., it can be compacted to a dense state. Feldspar has a single, but not particularly pronounced, cleavage plane as can be seen on the photomicrographs. Because the surfaces of the crystals are terraced and ideal face-to-face contact cannot be made, it is therefore reasonable to expect that the void ratio will be somewhat higher than that of dolomite.

The degradation of material which occurs during compression to high pressures is again demonstrated by the grain size distribution curves of the four minerals before and after compression to 20,000 psi shown in Figures B.46 through B.49. Photomicrographs of the four minerals after compression to 20,000 psi are shown in Figure B.50.

Results of tests on oil sands discussed in the next section indicate little or no effect on degradation due to the presence of or lack of oil in pores.

It is somewhat surprising to note that the amount of degradation is roughly the same for all three mineral compositions. The two minerals with cleavage planes (Dolomite and Feldspar) produced only about 5 to 6 percent more fines than did quartz. This is in apparent disagreement with the observations of Sergeev reported by Drashevska who found the degree of crushing depended on the mineralogical composition, the degree of dispersity and the moisture content.

(d) Effect of Pore Fluid

A series of tests on samples prepared from a core sample (LL87-25) with oil as a pore fluid show that the presence of oil has little or no effect on the compression index at high pressures. However, with oil in the pores it was possible to obtain higher stable initial void ratios than for those cases where the oil had been removed. Therefore, the compression curves for those samples with oil generally were displaced slightly above those without oil (Figures B.54 and B.55).

Although the method of removing oil from the sample (burning or extraction with Xylene) had little affect on the compression behavior at high pressures, the surface characteristics of the individual grains were altered sufficiently to result in different valves of maximum and minimum void ratio which could be obtained.

This effect of surface character has been pointed out by Jakobson (1957), as being quite important. He showed that two sands with essentially the same grain size distribution and grain shape but one having polished grains and the other not, had different packing characteristics and friction angles; the sand with polished grains having lower void ratios in the densest and loosest conditions.

Visual examination of the grains from the oil sand did indicate that the particles from which the oil was burned were somewhat more frosted in appearance than those from which the oil was removed with Xylene. The differences in surface character would have little effect on the behavior at high pressure where the compression is a function primarily of the compressive strength of the individual grains.

(e) Undisturbed Core Samples

Tests on core samples from a depth of approximately 3,000 feet in Well LL87 (Figure B.53) indicate compression indices ranging from 0.17 to 0.27. This compares with the range of maximum compression indices for the clay core samples of from 0.11 to 0.26. Although the tests were run in three different size consolidometers, the data indicate no consistent effect of sample size. In most of the tests the maximum compression index can be seen to occur at approximately 10,000 psi; at smaller pressures the value of C_c is smaller.

The one sample tested from a similar depth from Well TJ-25A gave a substantially higher compression index (C_c=0.35) than any of the tests on samples from Well LL87. This difference may be due to an inherent difference in grain size characteristics of the samples from the two wells. This sample originally had been designated a shale, but in reality was a very fine sand.

(f) Evaluation of Effect of Disturbance

Several tests were run in an attempt to evaluate the possible effect due to inevitable disturbance of a sample which occurs during sampling and trimming.

Figure B.59 shows the compression curves for the test (12.1) on an undisturbed core sample, the two tests (12.4 and 12.5) on prepared samples which were unloaded and recompressed with no disturbance, and Test 12.7 which can be considered as a test on an ideally undisturbed sample. This sample was prepared and compressed in a 4.5 inch ring, unloaded, extruded, trimmed and fitted into a 2-inch diameter ring. The sample was then recompressed. A comparison of the various compression curves shows that releasing the lateral pressure, extruding, and preparing the sample have an effect on the compression behavior of the sand similar to that which remolding has on the compression behavior of clay. This unavoidable disturbance resulted in a 17 percent reduction in the value of maximum compression index (from 0.30 to 0.25). During the trimming operation there is undoubtedly disturbance of all faces of the sample (a loosening of sand grains even though the oil tends to impart considerable cohesion to the soil). There also is always some difficulty in fitting the sample into the container perfectly without excessive disturbance. These effects tend to loosen the sample and result in a somewhat steeper compression curve in the recompression region and a slightly flatter curve in the virgin compression region.

Variations in density throughout a sample for a given test (or undisturbed core) also could result in a gradually increasing slope rather than a "sharp" break. Core samples conceivably could develop this variation in density because of loosening at the surface during preparation. Of considerable interest is the fact that the shape of the compression curve for Test 12.1 (undisturbed core sample) and the curve for Test 12.7 (ideal undisturbed laboratory sample) are almost identical. This similarity suggests that the test on the undisturbed core sample has been influenced primarily by sample preparation.

Based on the limited data it appears that the field compression index is more likely to be the value obtained from tests on disturbed samples which are compressed from initial void ratios comparable to those at which the material was originally deposited than from tests on undisturbed samples.

(g) Side Friction Effects

Originally a detailed study of side friction was not made; a series of tests run on samples of different thicknesses in the compression cylinder suggested little effect as long as the height was limited to about one-half inch. The effect of friction was neglected in computations. Subsequent to studies of other factors affecting the compressibility of sands, a series of tests was run on 20-40 Ottawa Sand in which the side friction load was measured directly. Above the so-called "break-point" the total side friction force varied from about seven percent of the applied load for a sample of initial height 0.174 inches to 25 to 30 percent for a sample with an initial height of 0.7 inches. If no correction is made for side friction the resulting compression curve will be displaced horizontally to the right of the "true" curve.

Uncorrected and corrected curves for samples with initial heights of 0.17 and 0.7 inches are shown in

Figures B.39 and B.40. As seen, the slope of the compression curve is essentially unaffected by the side friction.

If laboratory test data are used without correcting for side friction, then quite obviously the indicated compressibility will be somewhat less than the actual compressibility.

4.4 POROSITY VS DEPTH RELATIONSHIPS

4.4.1 Introduction

The best available indication of the insitu compression behavior of sediments should be the published data of porosity vs depth of core samples. However, because of the inelastic behavior of soils, if erosion has occurred, the maximum depth of burial must be estimated in order to properly evaluate the data. In addition, as previously discussed there is still considerable difference of opinion regarding the relationship between total pressure, intergranular pressure, and pore fluid pressure when the void ratio becomes very small (of the order of 0.1 to 0.2). Because of this difference of opinion the conversion of depth of burial to effective pressure may vary between investigators, depending upon the approach to the pressure problem.

In the interpretation of the data presented herein, it has been assumed that the relationship between the various pressures can be represented by the following expression over the entire range of void ratio:

$$\sigma_t = \bar{\sigma} + \mu$$

σ_t = total pressure

$\bar{\sigma}$ = intergranular or effective pressure (compression is a function of change in effective pressure

μ = pressure in the pore fluid

To convert depth in feet to pressure, the following additional assumptions were made:

(1) When the eroded material was present the water level was at ground surface and water pressure was assumed to have increased linearly with depth*.

(2) The samples were fully consolidated before the sediments were eroded.

(3) At the surface the sediments had an average void ratio approximately equal to unity.

(4) The mineral constituents of all sediments have an average specific gravity of 2.70.

4.4.2 Published Porosity Data

The average curve of porosity vs depth which Athy (1930) obtained for shale cores from wells in Oklahoma and

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*According to Muskat (1946) the values of virgin fluid pressures are usually very near the hydrostatic head corresponding to a comparable depth of water (i.e., 0.433 per ft of depth).

Texas has been replotted in terms of void ratio and intergranular pressure (log scale) in Figure 4.9. The data, when replotted as in Figure 4.9, indicate compression indices equal to about 0.53 in the range of 400 to 2,000 psi, about 0.33 in the range of 2,000 to 3,000 psi, and 0.15 in the range of 4,500 psi.

The data from Hedberg (1936) also have been replotted in Figure 4.9. The relationship can be approximated by a straight line between pressures of 1,000 and 3,500 psi; the slope of the resulting line indicates a compression index equal to approximately 0.55. Hedberg also indicates that the temperature increased from 144°F at a depth of 2,850 feet to 186°F at a depth of 5,050 feet. These samples are from Tertiary shales from wells drilled in the large geosynclinal basin of Venezuela. Samples are described as grey or greenish grey shale and Hedberg indicates that the strata are approximately horizontal.

Data from Terzaghi (1958) on the porosity and depth of cores from Long Beach also have been plotted in Figure 4.9.

The data on Long Beach cores are for materials with a median grain size of from 035 mm to 0.15 mm and according to Terzaghi the grain size distribution curves representing the oil sands resemble those of a fine dune sand and the sediments encountered in the oil bearing formation contain no clay. The silty sandstone strata which separate the oil bearing sand layers have curves which are similar to the grain size curves of a fine dune sand with an admixture of loess. The silt content of the oil sands varies between 2 and 10 percent (exceptionally as high as 16 percent). The silt content of the silty sandstones range between 10 and 27 percent.

Porosity determinations were made on 700 samples of oil bearing sands from every part of the oil bearing formation. The void ratio varied from a value of about 0.65 at a depth of 2,000 feet to about 0.3 at a depth of 6,000 feet. No significant difference was noted between the void ratio of oil bearing sands and that of the siltstones.

4.5 COMPARISON OF LABORATORY TEST RESULTS WITH POROSITY DATA

4.5.1 Shales

The range of results obtained from laboratory tests on core samples are indicated by the three lines A, B, and C in Figure 4.9. Line A represents the test (C11) resulting in the largest compression index and also the highest values of void ratio. Line B represents the test (C17) resulting in the smallest compression index. Line C represents the test (C16) having the smallest void ratio throughout the test. To obtain each line, the portion of the compression curve above the precompression was approximated by a straight line; this straight line was then extrapolated over the pressure range 1,000 psi to 10,000 psi even though the experimentally determined curve may have been straight over only a portion of the pressure range.

When replotted in terms of void ratio and effective stress, the porosity data presented by the various authors indicate a possible insitu compression index for shales as high as about 0.5. The laboratory test data on core samples indicate much smaller compression indices (a maximum of 0.26). For soils of comparable plasticity*, Skempton's data (1953) does not indicate insitu compression indices as high as those indicated by the void ratio vs overburden pressure data.

The void ratios indicated by the data of Athy and Hedberg at pressures above 2,000 psi are lower than these obtained from the laboratory tests and thus, the indicated insitu compressibility would be even larger than indicated by a comparison of the compression indices.

Skempton (1953) explains the apparent higher compressibility thus:

"The explanation is, presumably, that in nature recrystallization takes place under these great pressures, and over the immense time during which the shale is subject to these pressures." Unfortunately, no elaboration of the mechanism is given. He states further: "Below depths of

---

*Classification tests on core samples from Venezuela indicated liquid limits varying from 27 to 67 percent and plasticity limits from 15 to 26 percent.

3,000 feet or perhaps 5,000 feet, it is, therefore, impossible at the present time to predict with any confidence the pressure void ratio relationship..."

However, in 1960 Skempton developed the more general effective stress relationship presented in the previous chapters; he suggests that Terzaghi's simple relationship can be used for clastic sediments to depths of several thousand feet.

Possible reasons for the differences in void ratio and compression data are:

(1) A basic difference in soils;

Classification data were not presented by Athy or Hedberg, and therefore direct comparisons between field and laboratory data cannot be made. However, the reasonably good agreement between Athy's and Hedberg's data, even though from widely separated locations, suggest that this cannot account for the difference.

(2) Secondary Compression

The data presented in Figure 4.9 show a tendency for the curves of insitu void ratio and laboratory data to diverge at high pressures. One possible cause of this divergence could be secondary compression. The divergence could be explained if the rate of secondary compression is proportional to the pressure acting on the sample. The general belief, to date, has been that the rate of secondary compression is essentially independent of the stress. However, the data obtained from the tests on the organic silt suggest that the rate of secondary compression (at least at low pressures) is a function of pressure. However, when the effect that secondary compression would have on the void ratio log pressure is considered, it is probable that with increasing duration of loading, the slope of the void ratio log pressure curve will decrease.

The void ratio data presented by Athy and Hedberg include the effects of very long periods of loading on the soil, whereas the laboratory results represent the effect of relatively short periods of loading. Some indication of whether or not secondary compression could indeed be a factor can be obtained by extrapolating the compression obtained in the laboratory tests on the core samples. The dashed lines below Curves A, and C in Figure 4.9 indicate the position of the void ratio log pressure curves if compression continued for 10 million years along the secondary compression curves obtained during the relatively shorttime interval used in the laboratory test. The difference cannot be accounted for in this manner.

(3) Temperature

The data presented by Athy and Hedberg include any temperature effects, whereas the laboratory tests were performed at approximately 70°F. Principles of Soil Technology indicate that increased temperatures should result in lower equilibrium void ratios for a given pressure.

In addition to the test previously mentioned, a limited amount of experimental data by Gray (1936) also show that temperature does indeed influence the equilibrium void ratio in the manner mentioned and that increased temperatures also increase the rate at which "secondary compression" occurs. Gray's data does not show temperatures to have a marked influence on the slope of the compression curve. Changes in temperature appear to merely shift the compression curve up or down, depending on whether the temperature is decreased or increased. He indicates that all soils are affected in some degree but that the phenomenon is particularly pronounced in those soils containing organic material.

If temperature influences the equilibrium void ratio at any pressure, then the gradually increasing temperature which occurs with depth in the ground could account for the divergence of the field and laboratory curves. The field data would be influenced by the gradually increasing temperature with depth whereas the laboratory test data represent the results of tests at approximately 70°F.

(4) Conclusions

It is unlikely that a single factor can account for the difference which has been noted between insitu void ratio data and void ratio - pressure data obtained on core samples in the laboratory. However, secondary compression characteristics and temperature effects obtained for the soils tested in this study point toward explaining part of the difference.

The rate of secondary compression appears to be at least somewhat dependent on temperature; the rate of secondary compression is higher the higher the temperature. If a soil is consolidated to a given pressure and then the temperature increased, it will compress and decrease in volume.

The divergence also may be due to the effect of time on the development of a so-called shaly structure of fine grained sediments. According to Weller (1959) this shaly structure invariably occurs in fine grained Paleozoic rocks and is generally absent in the younger Tertiary strata. One would expect then an increase in the stage of development of this type of structure with increasing depth because the deeper deposits are older.

Considerable additional study of these factors is needed, especially at high pressures before a completely satisfactory explanation can be offered.

4.5.2 Sands

It also is interesting to compare the slopes of the data from the Long Beach sand cores with the average slope of the quartz sand data (Figure 4.2) obtained in this investigation. The reasonable agreement of the slopes suggests that these natural sands have undergone a type of compression similar to that of the test samples above the critical pressure. Unfortunately, samples of the cores were not available for microscopic study in order to determine whether fracturing had occurred. However, Terzaghi (1958) noted that the median grain-size of the sands persistently decreased from about 0.35 mm at the top of the column to about 0.15 mm at the bottom. However, no statement was made regarding the angularity of grains. Still to be explained is the fact that the core samples are considerably more dense than would be predicted on the basis of laboratory compression of pure quartz sand. Possible explanations are:

(1) the natural samples have been subjected to the loads for a very great period of time;

(2) solution and redeposition at points of contact might have occurred resulting in volume decrease.

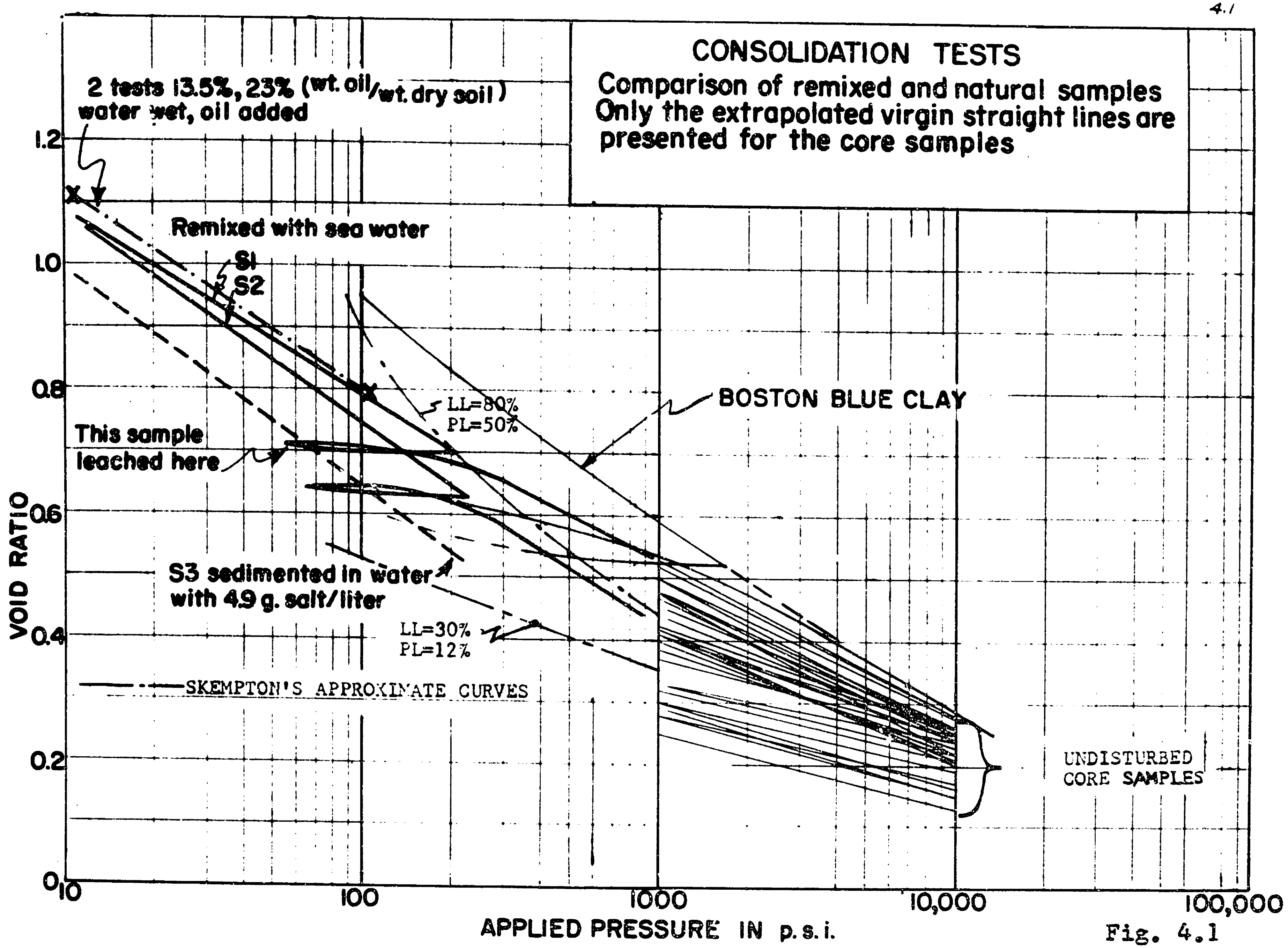

4.1
CONSOLIDATION TESTS
Comparison of remixed and natural samples
Only the extrapolated virgin straight lines are presented for the core samples
2 tests 13.5%, 23% (wt. oil/wt. dry soil)
water wet, oil added
Remixed with sea water
S1
S2
This sample leached here
LL=80%
PL=50%
BOSTON BLUE CLAY
S3 sedimented in water with 4.9 g. salt/liter
LL=30%
PL=12%
SKEMPTON'S APPROXIMATE CURVES
UNDISTURBED CORE SAMPLES
VOID RATIO
1.2
1.0
0.8
0.6
0.4
0.2
0
10
100
1000
10,000
100,000
APPLIED PRESSURE IN p.s.i.

Fig. 4.1

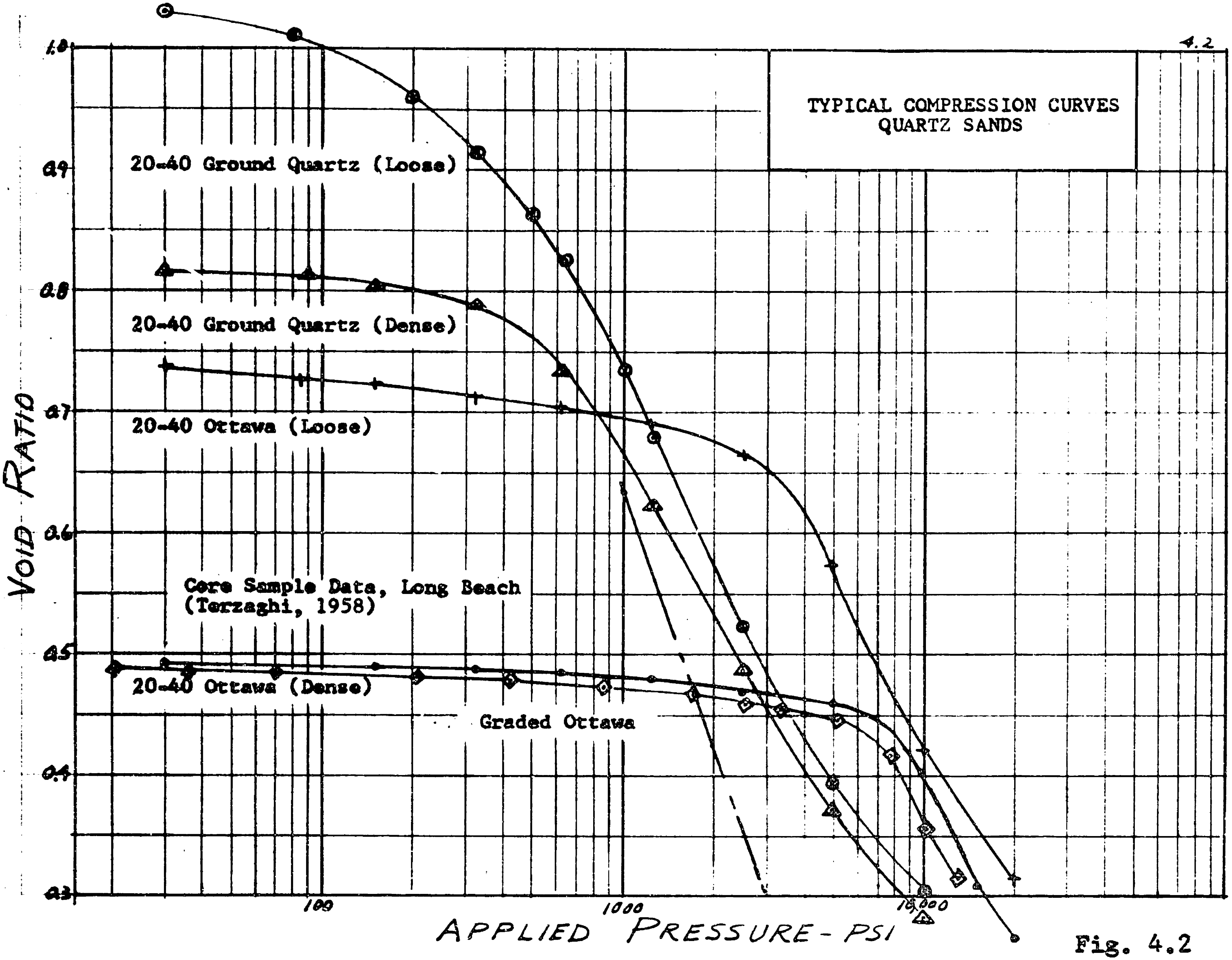

4.2
TYPICAL COMPRESSION CURVES
QUARTZ SANDS
20-40 Ground Quartz (Loose)
20-40 Ground Quartz (Dense)
20-40 Ottawa (Loose)
Core Sample Data, Long Beach
(Terzaghi, 1958)
20-40 Ottawa (Dense)
Graded Ottawa
VOID RATIO
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
100
1000
10,000
APPLIED PRESSURE - PSI

Fig. 4.2

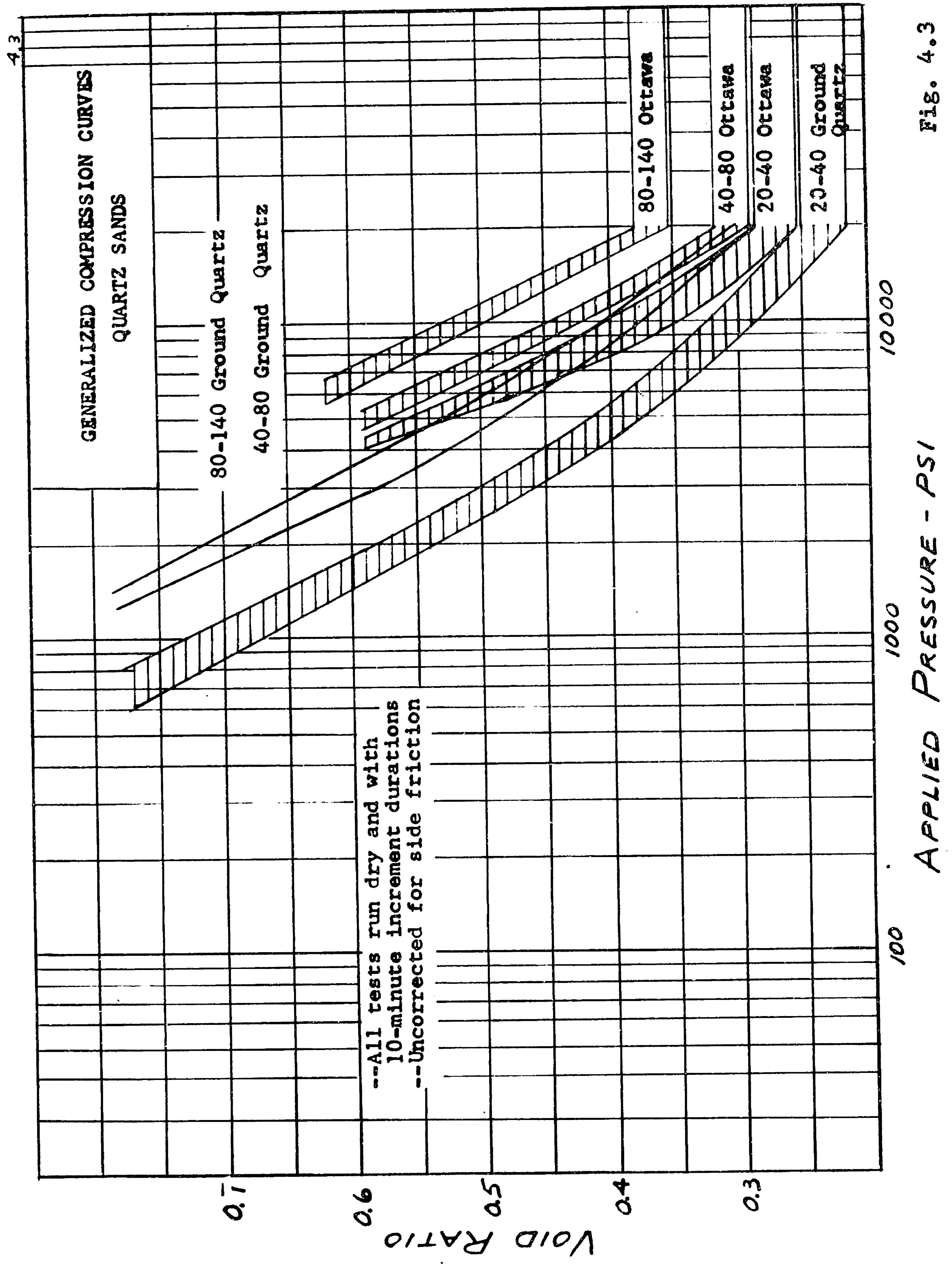

4.3
GENERALIZED COMPRESSION CURVES
QUARTZ SANDS
80-140 Ground Quartz
40-80 Ground Quartz
80-140 Ottawa
40-80 Ottawa
20-40 Ottawa
20-40 Ground Quartz
--All tests run dry and with 10-minute increment durations
--Uncorrected for side friction
0.7
0.6
0.5
0.4
0.3
VOID RATIO
100
1000
10000
APPLIED PRESSURE - PSI

Fig. 4.3

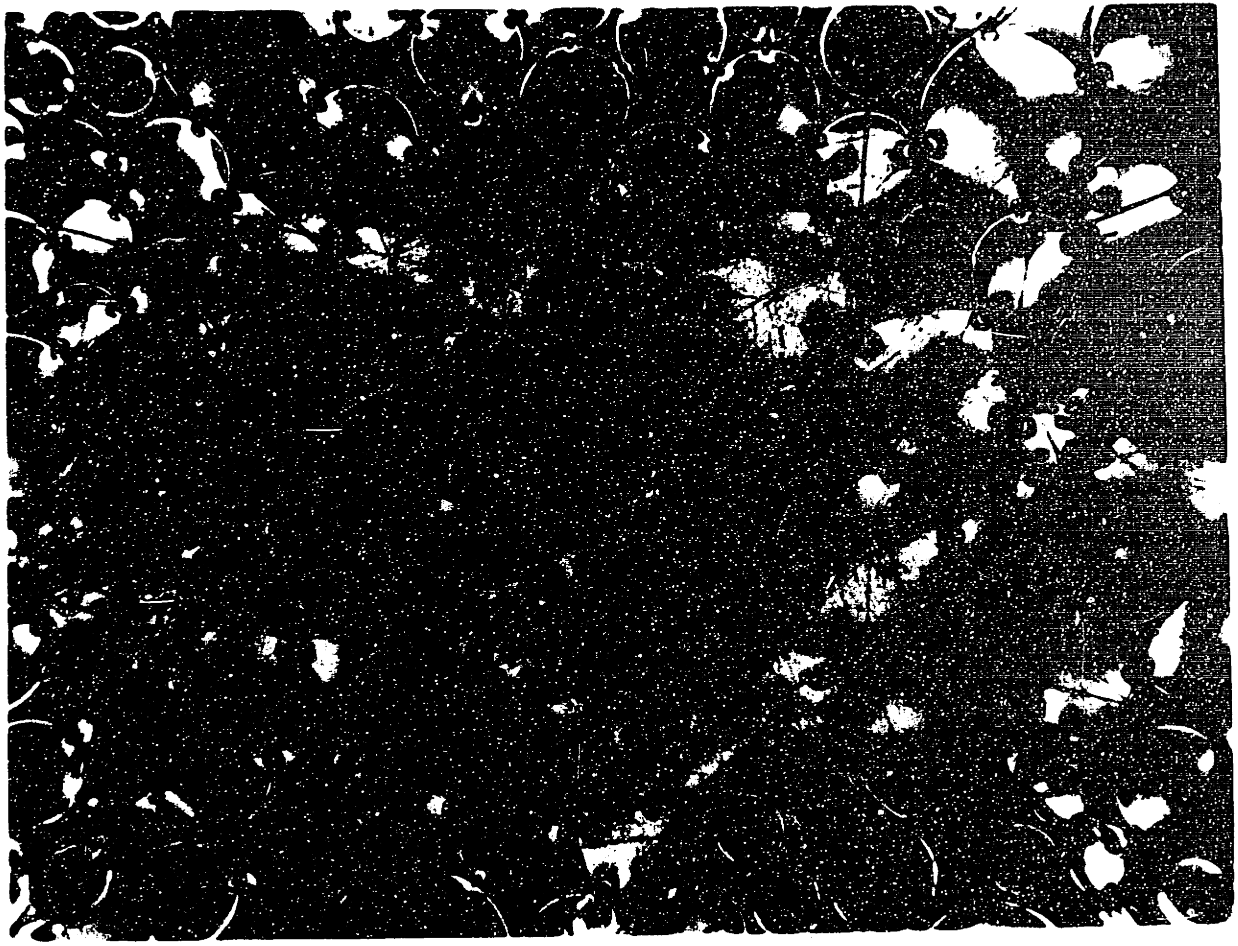


Fig. 4.4 PHOTO ELASTIC STUDY OF STRESS TRANSMISSION BETWEEN PARTICLES (after Taylor, Unpublished)

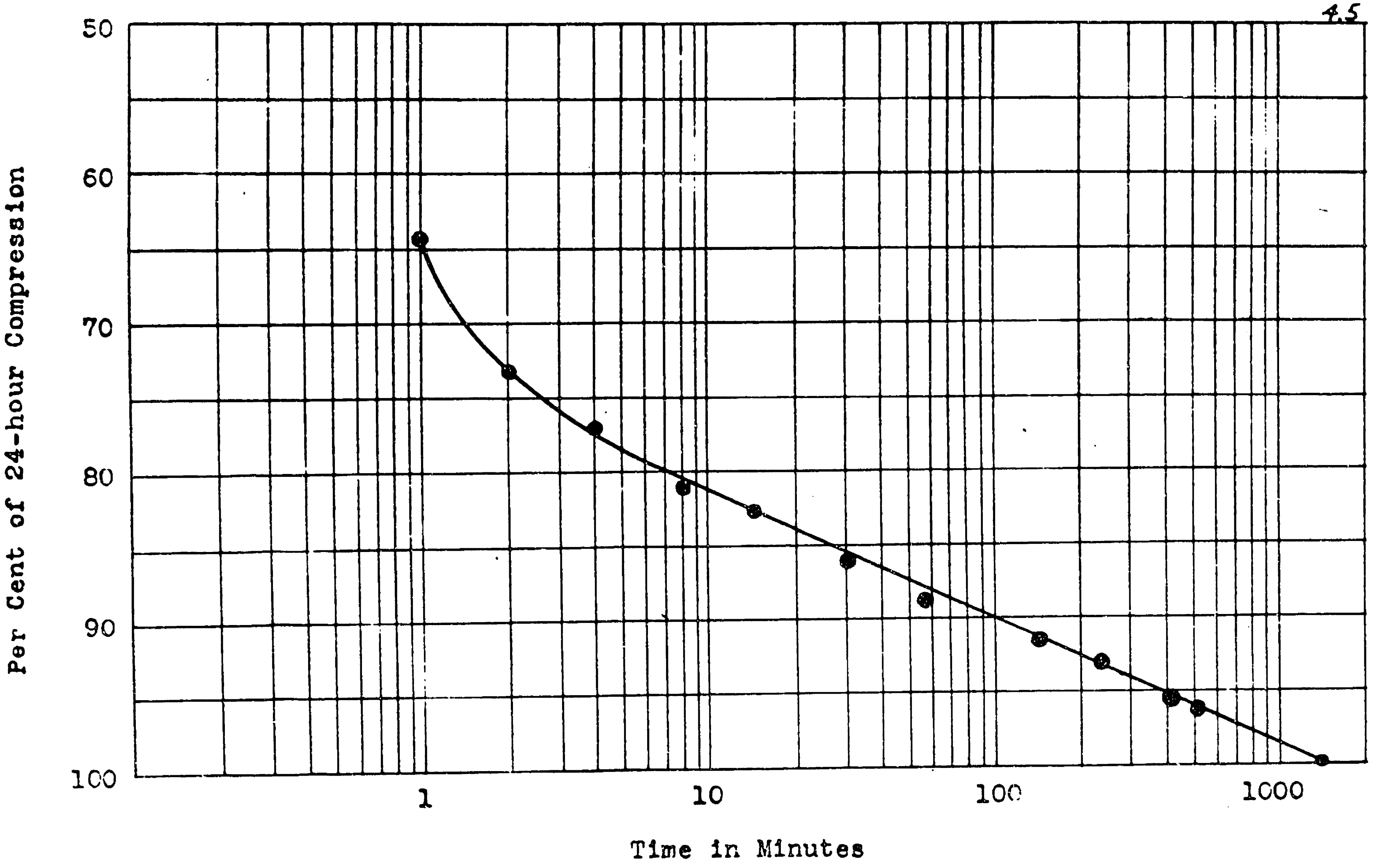
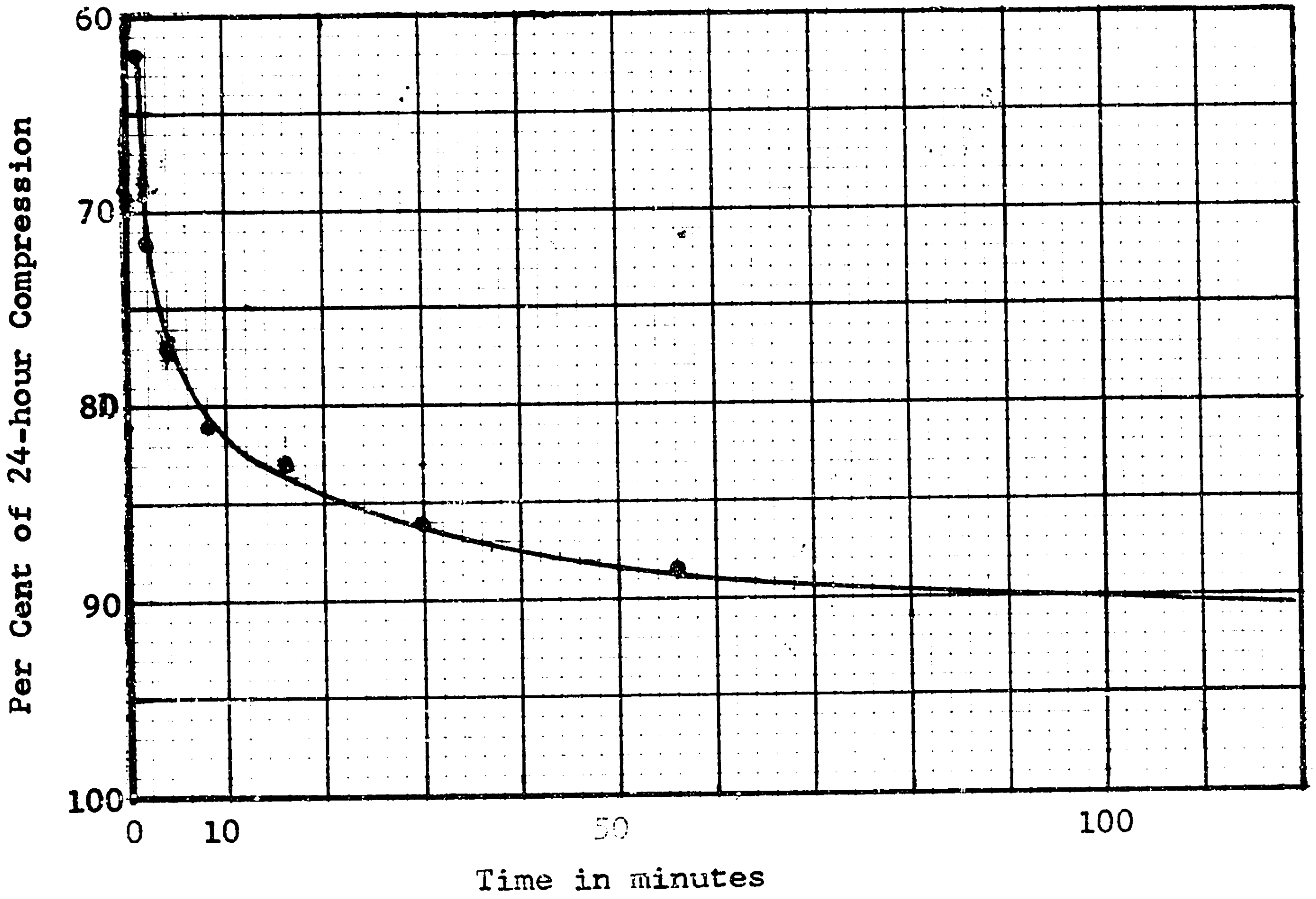


Fig. 4.5 TYPICAL TIME CURVE--HIGH PRESSURE INCREMENT ON SAND



Fig,4.6 TYPICAL TIME CURVE FOR PRESSURE INCREMENT ON SAND

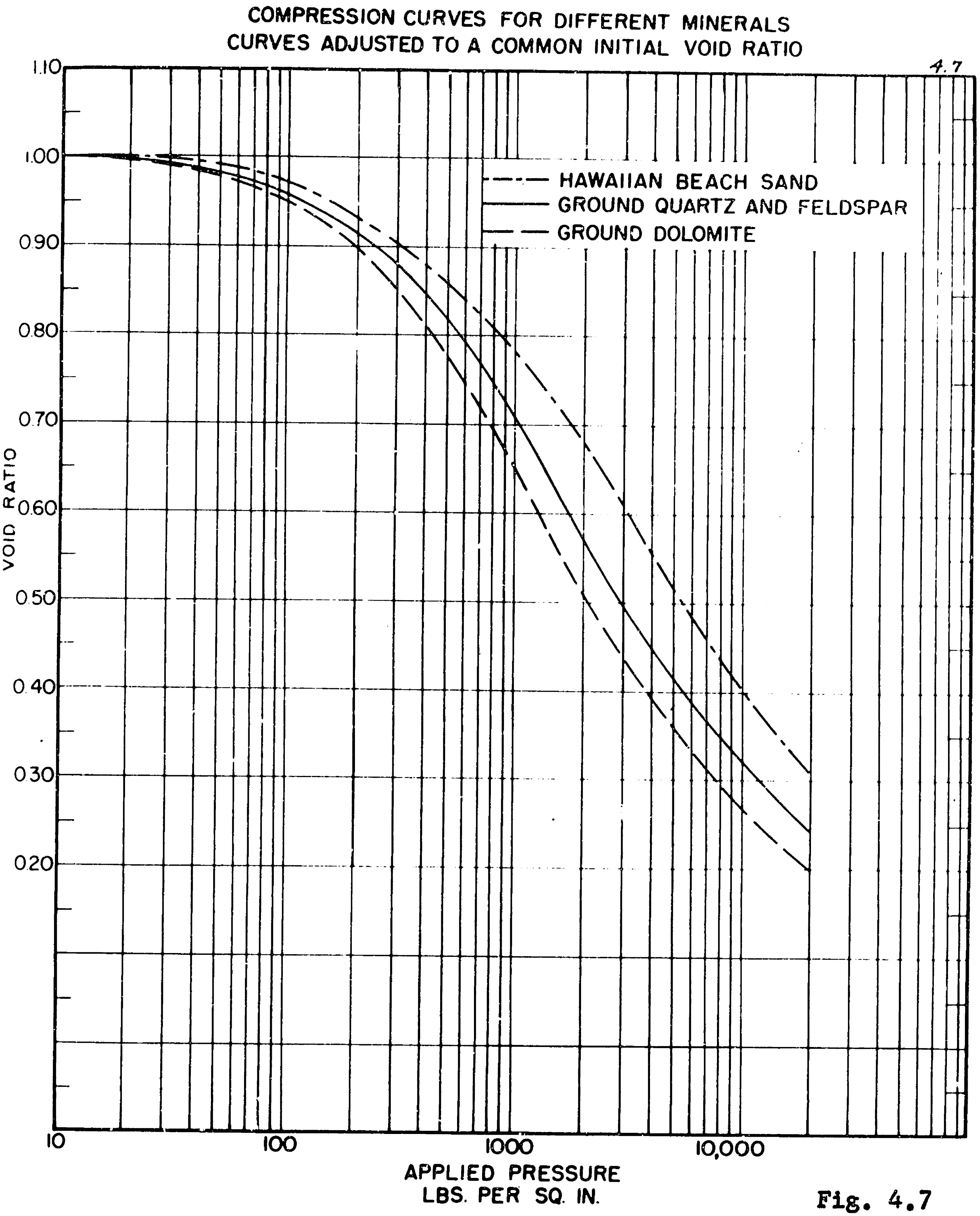
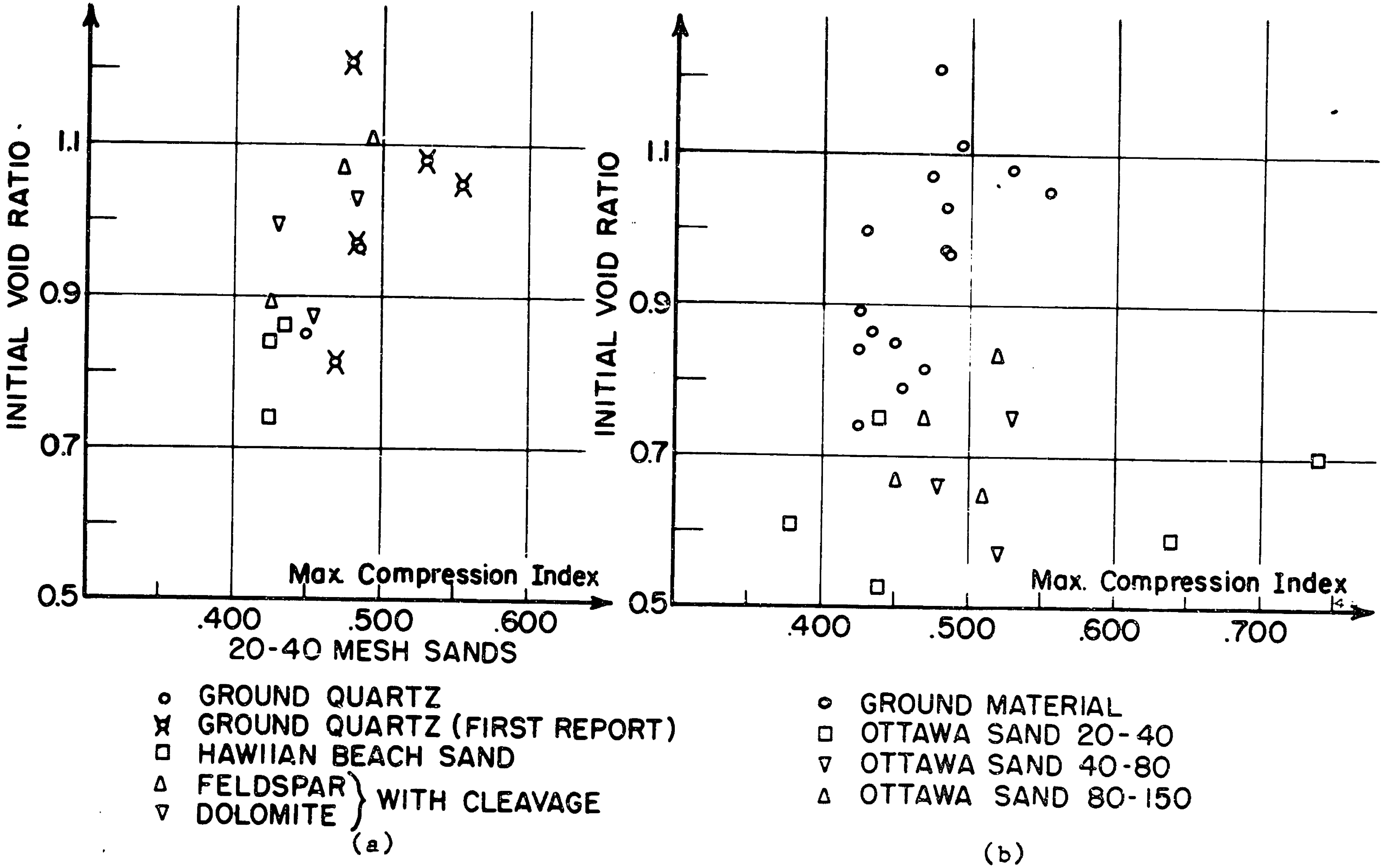

COMPRESSION CURVES FOR DIFFERENT MINERALS
CURVES ADJUSTED TO A COMMON INITIAL VOID RATIO
4.7
HAWAIIAN BEACH SAND
GROUND QUARTZ AND FELDSPAR
GROUND DOLOMITE
VOID RATIO
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
10
100
1000
10,000
APPLIED PRESSURE
LBS. PER SQ. IN.

Fig. 4.7

MAXIMUM COMPRESSION INDEX (C_c)
VS
INITIAL VOID RATIO



(a)

(b)

Fig. 4.8

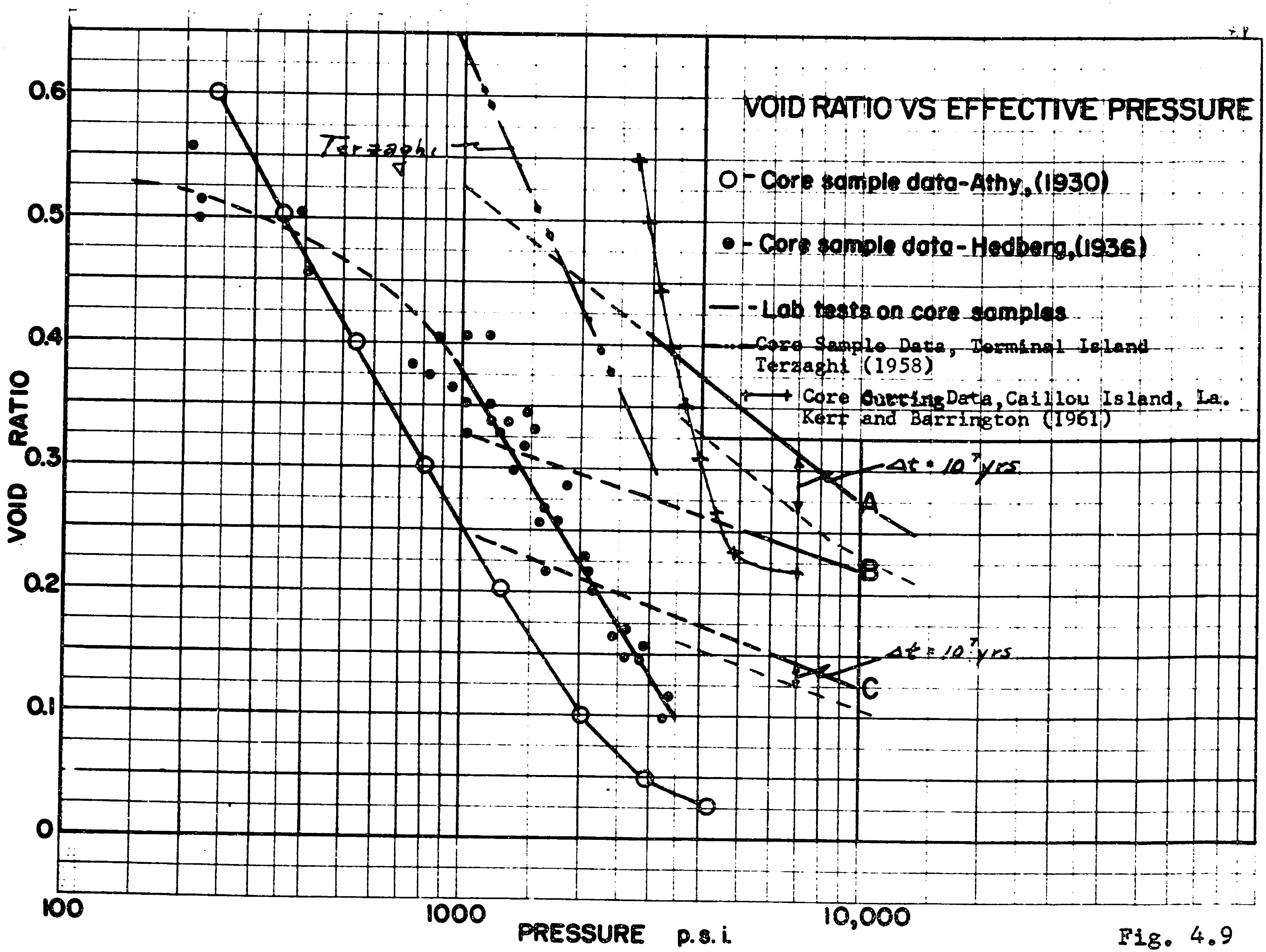

VOID RATIO VS EFFECTIVE PRESSURE
○ - Core sample data-Athy,(1930)
● - Core sample data - Hedberg,(1936)
— - Lab tests on core samples
Core Sample Data, Terminal Island Terzaghi (1958)
Core Cutting Data, Caillou Island, La. Kerr and Barrington (1961)
Terzaghi
Δt = 10⁷ yrs
Δt = 10⁷ yrs
A
B
C
VOID RATIO
0.6
0.5
0.4
0.3
0.2
0.1
0
100
1000
10,000
PRESSURE p.s.i.

Fig. 4.9

5: RELATIVE IMPORTANCE OF CLAY AND SAND COMPRESSION

5.1 INTRODUCTION

In studies of the subsidence associated with the development of oil fields, it is not the total compression which a sediment has undergone since its deposition which is of interest but only the incremental compression which is likely to occur due to a pressure change. Therefore, any comparison or evaluation of the compressibility of sand and clay must be based on a comparison of this incremental compression due to a pressure change after each sediment has been consolidated to a relatively high pressure corresponding to the overburden pressure.

5.2 CHARACTER OF NATURAL SANDS

Because the experimental results indicate that the compressibility of sand is quite dependent on initial density and angularity, it is appropriate to consider first the character of natural sands in order to evaluate how indicative the experimental results obtained in the present program might be of the field compressibility of natural sands.

5.2.1 Angularity

Russell (1939) referred to experiments by Ziegler which indicated that grains less than about 0.75 mm in diameter cannot be rounded by abrasion in water; it was

Twenhofel's opinion (1950) that rounding of sand grains, particularly of the dimensions 0.5 mm or less, involves extremely long tractional transportation. Twenhofel (1950) cited Galloway's conclusion that a non-calcareous sand with more than 50 percent of the particles well rounded is more likely to be of wind than water production and that few quartz particles below about 0.1 mm are much rounded in aquaeous transportation. However, the study by Ries and Conant (1931) showed that even many wind blown deposits have comparatively few truly well rounded grains.

The Corps of Engineers accumulated petrographic data on 51 beach, dune, and river sands from throughout the world. Forty-two were classified as quartz sands, 37 were from beaches, 2 from sand dunes, and three from the Mississippi River near Vicksburg. The sands usually contained 75 to 100 percent quartz with minor amounts of feldspars and acid igneous rocks and trace amounts of assorted heavy minerals.

Most of the sands consisted principally of blocky particles with lesser amounts of pyramidal and irregular particles, generally with rounded to sub-rounded corners and edges. Very few of the river or marine deposits studied by Ries and Conant showed a large percentage of well rounded grains.

Examination of the microphotographs of the oil sands from Venezuela before compression also indicate a high degree of angularity of individual grains. As previously noted, even the so-called well rounded Ottawa Sand shows a decreasing roundness with decreasing grain size.

5.2.2 Initial Density

Surface deposits of sand have void ratios ranging from approximately 0.5 to 0.9 (see, for example, Tschebotarioff, 1951, and Terzaghi and Peck, 1948) and a void ratio of 0.5 is considered dense.

Density data of the California Division of Water Resources have been summarized by Koelzer and Lara (1957). For sediments deposited in water initial densities are dependent primarily on particle size; for sediments with a D_{10} size between 0.125 mm and 2 mm initial void ratios between about 0.7 and 0.8 would be expected. For smaller D_{10} sizes even higher initial void ratios would be expected.

5.2.3 Grain Size Distribution

Grain size distribution curves of natural beach, dune, and river sands vary appreciably. The distribution curves for the coarsest and finest samples examined by the Corps of Engineers are shown in Figure 5.1. In addition, two curves for samples obtained at Cape Cod, Massachusetts are shown to indicate the inherent variation to be expected in a natural sand deposit at a given location. In general, the grain size distribution curves of all the natural sands examined indicate relatively uniform sands. The grain size distribution curve for the most well graded sand which was

(There is no page 124.)

examined also is shown in Figure 5.1; however, this sample was composed of 75 percent shell fragments and 25 percent quartz particles, and all particles above No. 40 sieve were shell fragments.

Grain size distribution curves for representative oil sands (Muskat 1946, Table 2) are shown in Figure 5.2 and a representative curve for a Venezuela oil sand is shown in Figure B.56.

5.2.4 Summary

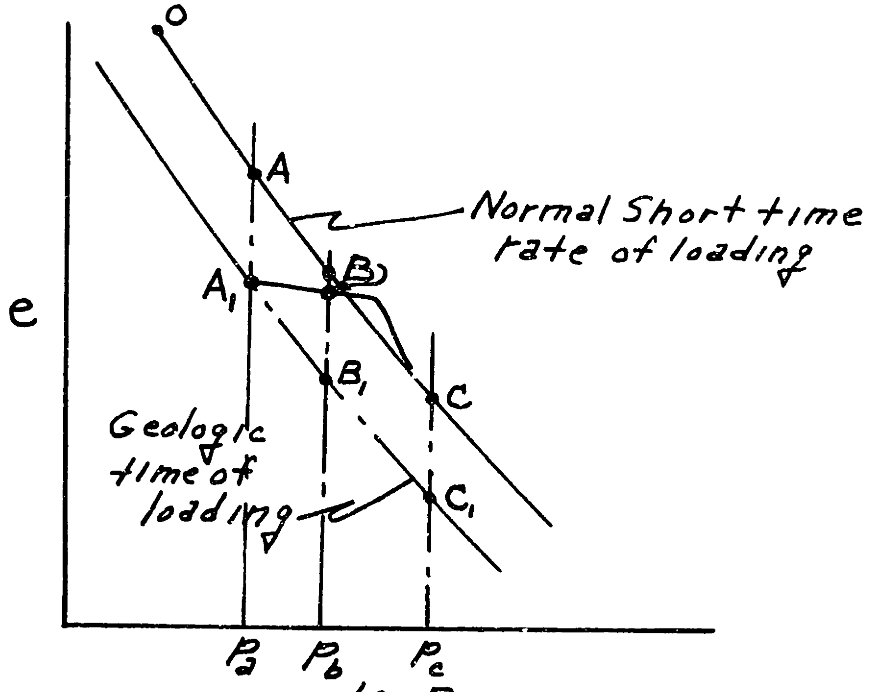
The data on the character of natural sands indicate that, in general, one can expect natural sands to be primarily quartz sands. The sands are likely to be fairly uniform and individual particles are likely to be blocky with rounded to sub-rounded edges; particles finer than about 0.5 mm are not likely to be appreciably rounded if water transported. The initial void ratio of sands sedimented in water is likely to be of the order of 0.7 to 0.8.

Thus, the compression characteristics of natural sands deposited in water probably will be intermediate between the compressibilities of the well rounded and highly angular quartz sands studied in the present investigation.

5.3 APPLICABILITY OF LABORATORY TEST DATA

Previous discussion in Chapter 4 has suggested that the compressibility of a sediment at great depth is quite likely to be influenced by a nunber of factors such as pressure temperature, duration of loading, secondary compression, and the development of any so-called "sensitive" structure due to long time loading.

Various investigators have suggested that the development of a sensitive structure could result in a clay which would have an insitu compressibility higher than that which would be indicated by laboratory test results. Structure, such as obtained in the test on the Beauharnois Clay and in the long term test on quartz sand, can be developed during long term loading at constant pressure. However, for a normally consolidated clay it is doubtful that this structure could indicate a higher total compressibility for a pressure change from p_a to p_c than a laboratory sedimentation compression curve without any structure. However, the time curves for the samples with and without structure will be entirely different in this pressure range.



Based on the limited availble experimental data the following is hypothesized:

In the above figure, the curve from 0 to A is assumed to represent the so-called sedimentation compression curve and could be considered to represent the compression during sediment formation for a clay or sand strata in the oil producing formation. Continued long time loading under the overburden pressure, p_a, could result in compression to a void ratio corresponding to point A_1.

A small stress increment above p_a, corresponding to an initial pressure change due to oil production, might compress the sample to point B. The resulting compression would be very small in a small interval of time compared to the time p_a had been acting. However, if the stress is maintained constant at p_b for a long time, the sample would probably continue to compress to a void ratio corresponding to point B. If the stress increase was large enough, the sample, in a relatively short time interval, would be compressed to point C. With increasing time at pressure p_c, compression would increase to C_1.

A normally consolidated clay, if it developed structure might have an insitu compression curve indicated by A_1 B C. If it is assumed that the laboratory virgin compression curve is given by 0 A C, the estimated compression using this curve would be equal to or larger than the actual compression given by A_1 B B_1 or A_1 C C_1.

Martin (1955) indicates that in parts of the Bolivar Coastal Field the subsidence does not occur as soon as the fluid pressure is reduced, but a definite reduction is necessary before any measureable subsidence is detected. This would suggest a behavior comparable to that shown by A_1 B C for a gradual loading from pressure p_a to p_c.

There may be some objection to evaluating the relative compressibility of the sands and the clays on the basis of short term laboratory tests because of the factors tending to influence the compressibilities of both sands and clays. However, a comparison using compressibility measured under comparable rates of loadings and temperatures should at least indicate whether or not sands, under any condition, could have compressibilities comparable to the clays at similar initial pressures. If, after all, sands can be shown to be as compressible as clays under certain conditions then it will no longer be possible to assume, apriori, that the sand compression is a minor contributor to the resulting surface subsidence.

5.4 POROSITY REDUCTION IN SAND

Most of the early studies of the compression of sands were based on the idea that the sand grains, or at least quartz grains, are essentially unbreakable and behave elastically under the pressures encountered in sedimentary deposits. This idea has persisted among many geologists to the present day with the result that most geology texts dismiss the compaction of sands as of minor significance.

There are two main reasons for this: (1) At low pressures, sands are relatively incompressible; (2) The lack of reliable porosity data of natural sands as a function of depth which is due undoubtedly to the difficulty of obtaining good samples of uncemented sands. Most of the available data on porosity pertain to consolidated or lithified sands, samples of which are much easier to obtain. In many cases these sands are of great age and have been subjected to depths of burial far greater than the depth at which they esist at the present. Therefore, it is difficult to separate the effects of compaction from those of solution recrystallization, and/or infiltration of material from outside sources. The fact remains, however, that surface deposits of sands have void ratios ranging from approximately 0.5 to 0.9, whereas, at great depths, values of 0.2 to 0.4 are more common. A suitable explanation of this reduction in void space has to be found. Also, since subsidence in some instances apparently has occurred, but cannot be accounted for by considering only the compression of clay layers, it is probable that porosity reduction of sands results, at least in part, from volumetric compression.

Hedberg (1936), Athy (1930), Fraser (1935), and others all agree that compression of sands by increasing overburden pressures is very small and accept the explanation that porosity reduction in sands is mainly caused by infiltration of material from outside sources. However, this explanation presents the problem of further explaining where so much material could originate. If it is derived from other nearby sediments, these of necessity would have to be undergoing a very considerable process of disintegration. Much of the interstitial material found in sandstones and especially in quartz sandstones is composed of silica. In a sedimentary deposit composed of sands and clays, the only sources of large quantities of silica are the sands themselves, if it is assumed that the clay minerals remain relatively stable compared to the sand because of their relatively low permeability. Thus, in order that the porosity of some of the sands be reduced, it would be necessary that others either become more porous, or that there be a commensurate decreases in gross volume (thickness) of the sand strata.

The reduction in porosity because of solution at points of contact and recrystallization is given great importance by many geologists. Although there seems to be no doubt that such a process does occur, the magnitude of its contribution in the present investigation would appear to be rather small because very little evidence of secondary crystallization is found in recent sands, even when their porosity is well below that of normal surface deposits. If for the sake of argument it is assumed that this process is of major importance, one has to conclude that the decrease in porosity caused by solution and recrystallization is accompanied by an equivalent decrease in total volume. Since no material is introduced into the system, this volume decrease should manifest itself as a corresponding subsidence. This point does not seem to have been fully realized by some of those who explained the reduction in the porosity of sands in terms of solution and recrystallization and yet imply that subsidence due to gross volume changes within sands is minor.

5.5 RELATIVE COMPRESSIBILITY OF SANDS AND CLAY AT HIGH PRESSURE

When the compressibilities of two soils at different void ratios are being compared, the compression index is not necessarily the best measure of the relative compressibility. For a given change in pressure it is the resulting unit vertical strain, $\frac{\Delta H}{H_o}$, which is of interest. Thus, the volumetric compressibility, m_v*, represents a better parameter for comparing the compressibilities of different soils at a given initial pressure. The Figure 5.3 shows the relationship between void ratio and $m_v x\ p$ for various compression indices. The curves show that two soils at the same pressure which have the same compression index

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$*m_v = \frac{a_v}{1+e_o}$

will have different compressibilities if they are at different void ratios. The soil with the lower void ratio will have a somewhat higher compressibility.

In order to compare the relative compressibility of representative sands and representative clays, four groups of soils were selected. Group 1 included tests on Ottawa sands: Four tests on standard Ottawa sand, one test on a 20-140 Ottawa (an artificially graded Ottawa), and one test of a natural graded Ottawa. Group 2 included tests on ground quartz, ground feldspar, ground dolomite, and tests on natural beach sands from Sandy Point, Rhode Island, and Plum Island, Massachusetts. Group 3 included the test at high pressure on a sample of Boston Blue Clay, two of Skempton's approximate curves, two tests on undisturbed oil shales including the most compressible shale core which was tested (TJ355-2816). Group 4 included six tests on oil sands: three tests on undisturbed sand cores including the least compressible and the most compressible sand cores which were obtainable, and tests on reformed samples of oil sand placed in the loosest and densest initial densities possible.

For purposes of comparing the compressibilities of the different soils the results of the compression tests on each soil are presented in three different forms:

(1) In Figures 5.4 through 5.7 void ratio is plotted against pressure (logarithmic scale);

(2) In Figures 5.8 through 5.11 void ratio is plotted against pressure (arithmetic scale); and,

(3) In Figures 5.12 through 5.13 percent strain, $\Delta H/H_o$, (for a stress increase equal to 500 psi) is plotted against initial pressure.

These latter two types of curves were used to better evaluate changes in compressibility with pressure, and to better compare the compressibility of the various soils. As previously mentioned, soils with the same compression index but with different void ratios will have different compressibilities. For this reason plotting the data in terms of percent strain vs initial pressure was felt to be the most significant way of comparing the various soils.

In preparing Figures 5.12 through 5.13 an arbitrary stress increase equal to 500 psi was chosen for convenience. The slope of the compression curves in Figures 5.8 through 5.8 could have been used to evaluate the unit strain at a given pressure. Then the resulting curves relating unit compressibility to initial pressure would have been similar in shape to those in Figures 5.12 through 5.13 but would have been smooth.

It is important to note advantages of plotting void ratio against logarithmic and arithmetic scales of pressure. The results of the tests on ground quartz point up the advantage. When the results of compression tests are plotted in terms of void ratio and log pressure (Figure 5.5) the curves indicates a gradually increasing compression index up to some limiting value; this suggests offhand a corresponding increase in compressibility of the material. However, when the data are plotted in terms of void ratio vs applied pressure (Figure 5.9) or in terms of percent strain vs initial pressure (Figure 5.13), it can be seen that, above approximately 500 psi, the soils in general have a gradually decreasing compressibility. Thus, some care must be exercised in evaluating compressibility solely on the basis of the shape of a compression curve when it is plotted either as void ratio vs log pressure or as percent strain vs log pressure.

It is of particular interest to compare the curves of percent compression vs initial pressure for the two most compressible shale core samples which were received with the curves for the range of tests on the sand core samples. At an initial effective stress of 500 psi the two sand cores have a compressibility between two and three times the compressibility of the shale core. But, at pressures above 4000 psi the compressibilities of the sands and shales are essentially the same (Figures 5.14 and 5.15).

At a pressure of 1000 psi, the curve for Boston Blue Clay (Figure 5.14), which would be representative of the virgin compression of a medium to highly plastic clay, indicates a compressibility approximately 2 to 2-1/2 times the compressibility of the various oil sands which were tested in the reformed and the undisturbed state (Figure 5.15). At pressures above 3500 psi, however, the compressibilities of the sands are, on the average, about the same as the compressibility of the Boston Blue Clay.

Between pressures of 500 psi and 6000 psi the samples of ground quartz, ground feldspar, and ground dolomite, (Figure 5.13) even when placed in an initially dense condition, are always slightly more compressible than the sample of Boston Blue Clay.

The 100-325 ground quartz, on the other hand, (Figure 5.13) has a compressibility over the entire pressure range not too different from that of the undisturbed sand core samples.

The results of the tests on the various samples of Ottawa sand (Figure 5.12) and the results of the two tests on the natural beach sands (Figure 5.13) show the manifestation of the actual breaking of individual grains quite markedly. The compressibility of all the Ottawa sands decreases until a pressure of approximately 1500 to 2000 psi is reached. At this pressure it increases quite markedly, due undoubtedly to the beginning of important breaking of grains. At pressures of 4000 to 5000 psi the resulting compressibilities in certain instances are approximately twice those of the samples of Boston Blue Clay and undisturbed shale. The compressibilities appear to reach a peak and then gradually decrease with increasing pressure, due undoubtedly to the increased density and increased number of inter-grain contacts. The two natural beach sands, however, show this peaking of compressibility at much lower pressures.

The importance of correcting for side friction is illustrated by the curves in Figures 5.8 and 5.12 where the compression curves for both the uncorrected and corrected tests on the Ottawa sand are shown. It can be seen directly from a comparison of the curves that the correction tends to give somewhat higher compressibilities at a given initial pressure and also tends to indicate a development of the maximum compressibility at lower pressures. This is intuitively obvious if we consider that the effect of correcting for side friction is to displace the compression curve to the left.

Because of the influence of side friction on compressibility, a more detailed comparison of the individual compression curves is probably not warranted until data are available on all soils with side friction measurements so that the effect of side friction can be eliminated. However, Taylor (1942) found that, within the usual low pressure range, the side friction force in some tests on clay was of the order of 10-20 percent of the total applied force. This side friction force is of the same order of magnitude as the side friction force determined in the present investigational program; thus, data for the sands and the clays, even if uncorrected for side friction, should allow at least broad general comparisons.

5.6 MAGNITUDE OF ANTICIPATED SUBSIDENCE

In order to evaluate the relative compressibility of the representative sands and clays somewhat more significantly computations were made to determine the percent compression, $\Delta H/H_o$, to be expected at various depths for strata composed of various soils if the fluid pressures were reduced from an initial static pressure to atmospheric pressure. This would be the normal maximum pressure change which could be developed due to oil or water production. The results of these computations for depths of 3,000, 5,000 and 8,000 feet are shown in Table 5.1.

At a depth of 3,000 feet the computations show that a stratum of soil comparable to the Boston Blue Clay would undergo about 6 percent compression. That is, for an initial stratum thickness of 100 feet a total settlement of approximately 6 feet would be expected. The various sands in general show much lower compressibilities; however, even at this depth, sands similar to the ground quartz or Plum Island sand would result in greater settlements than the Boston Blue Clay. The oil sand which was disturbed and repacked into a loose condition would result in a settlement only 15 percent less than that of the blue clay.

At a depth of 5,000 feet, the Blue Clay would undergo about 5-1/2 to 6 percent compression. At this depth the various sands would undergo from about 1 to 7-1/2 percent compression.

At a depth of 8,000 feet, the Blue Clay would undergo about 5 percent compression whereas the various sands would undergo compressions varying from about 2 to 10 percent. At this depth a sand similar to 20-40 Ottawa would be about twice as compressible as the Blue Clay.

It is interesting to note that the data suggest that, at pressures corresponding to a depth of 3,000 feet, the undisturbed clay core sample is still undergoing recompression. At pressures corresponding to a depth of 8,000 feet, the compressions of the Blue Clay and the clay core are essentially the same. This suggests that at these pressures the core sample is undergoing virgin compression.

From these comparisons there can be no doubt that even at a depth of 3,000 feet (the depth at which the major amount of oil in the Free World can be expected to be found) compression of the oil bearing sands may contribute quite significantly to the subsidence to be expected when the oil field is developed.

6.7 INTERPRETATION OF DATA TO DETERMINE THE SEAT OF SUBSIDENCE

In connection with the Wilmington Field, investigators have attempted to determine whether the subsidence is due to shale or sand compression by analyzing the shape of the subsidence curve.

As previously mentioned it was pointed out by Terzaghi (1958) that the shape of the observed subsidence curve for the Wilmington Field could be explained in either of two ways:

"Case A: Subsidence is entirely due to the gradual compression of the oil bearing sand strata. This assumption is identical to the writers' original assumption of 1950, however, at the present state of our knowledge of the rate of increase of the subsidence it calls for the supplementary assumption that the compressibility of the sand increases with increasing pressure, whereas according to results of standard laboratory tests on sand it decreases with increasing pressure.

"Case B: It is assumed that the oil sands are practically incompressible and the subsidence is almost exclusively due to the consolidation of siltstone and shale located between the oil sands. At the present time (1954) it is still impossible to decide whether the subsidence will increase in accordance with one of the two forecasts A or B or whether it will follow an intermediate course."

The results of the present experimental investigation indicate that under certain conditions sands, indeed, can show an increasing compressibility with increasing pressure. The increasing compressibility could come about by either or both of the following processes:

(1) Increasing compressibility could develop because of a breakdown of individual particles. However, based on the experimental evidence presented in Appendix B, this seems to occur as a well defined phenomenon only in those cases where the sands have a fairly uniform grain-size and are fairly well rounded. In the well graded or highly angular soils there does not appear to be a well defined increase in percent strain, H/H_o, for a pressure increment equal to 500 psi (see for example Figures 5.12, 5.13, and 5.14).

(2) The results of the long term tests on 20-40 Ottawa sand and on 20-40 ground quartz show significant time effects. The results of the test on the 20-40 Ottawa sand, in particular, show the influence of time on the compression characteristics. After a load has been applied to a sample of sand for an extended period of time compression continues at a decreasing rate. When the stress is then increased by a small amount there appears to be an effect comparable to that observed in clay type soils; i.e.,

there appears to be a structure formed during the long term loading under the constant applied stress. In the case of sand this conceivably could be due to plastic flow at the points of contact, or, if the applied pressure is above the pressure at which significant rupture of individual grains occurs, it could be due to the resulting secondary compression and progressive rupture of soil particles with increasing time. When the stress is increased after the sample has been compressed for an extended period of time under a constant stress, the resulting compression is very small for small increases in stress. With increasing stress increase, however, the compressibility gradually increases to a maximum and then decreases again. This behavior can be seen directly from the compression curves for the long term tests shown in Figures B.24 and B.38.

Generalized compression vs time curves for sands at various depths are shown in Figures 5.16 and 5.17. The lower curve in each figure is a plot of percent strain vs time; the upper curve in each figure is a plot of the variation in fluid pressure with time. These figures have been prepared on the assumption that at each depth the fluid pressure was lowered gradually, from an initial value equal to the static fluid pressure corresponding to that depth to a final value equal to atmospheric pressure, over a period of 10,000 days (approximately 25 to 30 years). The compression curves for Ottawa sand were used and it was assumed that there were no time lags in the sand compression. This is admittedly somewhat biased because the Ottawa Sands do show an increase in compressibility and thus result in an increase in m_v with increasing pressure over part of the pressure range.

Similar curves were prepared assuming that compression was due to consolidation within the clay or shale layers. For comparative purposes only the shape of the curve is of interest. Therefore, it was assumed that, if the compression was due to the clay or shale layers, the same percent compression, $\Delta H/H_o$, would occur during the 10,000 day period, regardless of the percent consolidation occurring during this period. It is interesting to note that the shape of the resulting compression curve for the clay during the 10,000 day period is essentially independent of what percent consolidation is assumed to have occurred during this period.

To construct the curve for clay it was assumed that m_v is constant, whereas it actually decreases with increasing pressure. The actual shape for the clay would be influenced by the actual percent consolidation which occurs during the drawdown period. If anything, however, the resulting curve would be flatter than those in Figure 5.17. The degree of flattening would depend on the rate of decrease of m_v, the percent consolidation, and the pressure change.

If the curves for the sand and the clay are compared the important conclusion is that, during the period when the pressures are being lowered, it may be difficult, if not impossible, to interpret, from the shape of the subsidence curve alone, whether or not the subsidence is due to compression within the oil bearing sands; due to consolidation of the interbedded shale, clays or siltstones, or due to compression of both soils.

TABLE 5.1

PERCENT COMPRESSION

REPRESENTATIVE SOILS

Soil	Initial Void Ratio	Percent Compression* at Various Depths		
		3,000 ft.	5,000 ft.	8,000 ft.
Boston Blue Clay		6.0	5.6	4.9
Undisturbed Clay Core (TJ355)		1.75	4.1	4.8
Undisturbed Sand Core TJ25A-1	0.803	4.3	5.7	5.9
Undisturbed Sand Core LL87-14	0.54	2.5	2.8	3.3
Undisturbed Sand Core LL87-25		2.2	2.9	3.0
Reformed Oil Sand LL87-25				
(25.10) Loose	1.09	5.1	5.6	6.1
(25.13) Dense	0.60	2.3	3.9	4.8
Ottawa Sand (20-40) (Corrected for S.F)				
Loose (C3)	0.62	1.35	5.0	10.0
Dense (C6)	0.55	0.73	1.7	6.4
Ottawa Sand (40-80)				
Loose	0.75	1.5	2.7	6.9
Dense	0.57	0.7	1.1	1.8
Ottawa Sand (80-140)				
Loose	0.83	1.9	2.9	5.3
Dense	0.65	1.5	2.8	4.8
Ottawa Sand (20-140)	0.66	1.5	2.7	6.9
Ground Quartz (20-40)				
Loose	1.04	8.7	7.6	5.9
Dense	0.83	8.0	7.4	7.0
Ground Quartz (100-325)	0.85	6.6	7.0	6.9
Plum Island Sand	0.77	6.6	7.0	6.9
Sandy Point, R.I., Sand	0.65	2.1	7.0	7.4

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*For fluid pressure reduction from initial hydrostatic to atmospheric.

GRAIN SIZE DISTRIBUTION

TYPICAL NATURAL SANDS

(After Waterways Experiment Station, 1960)

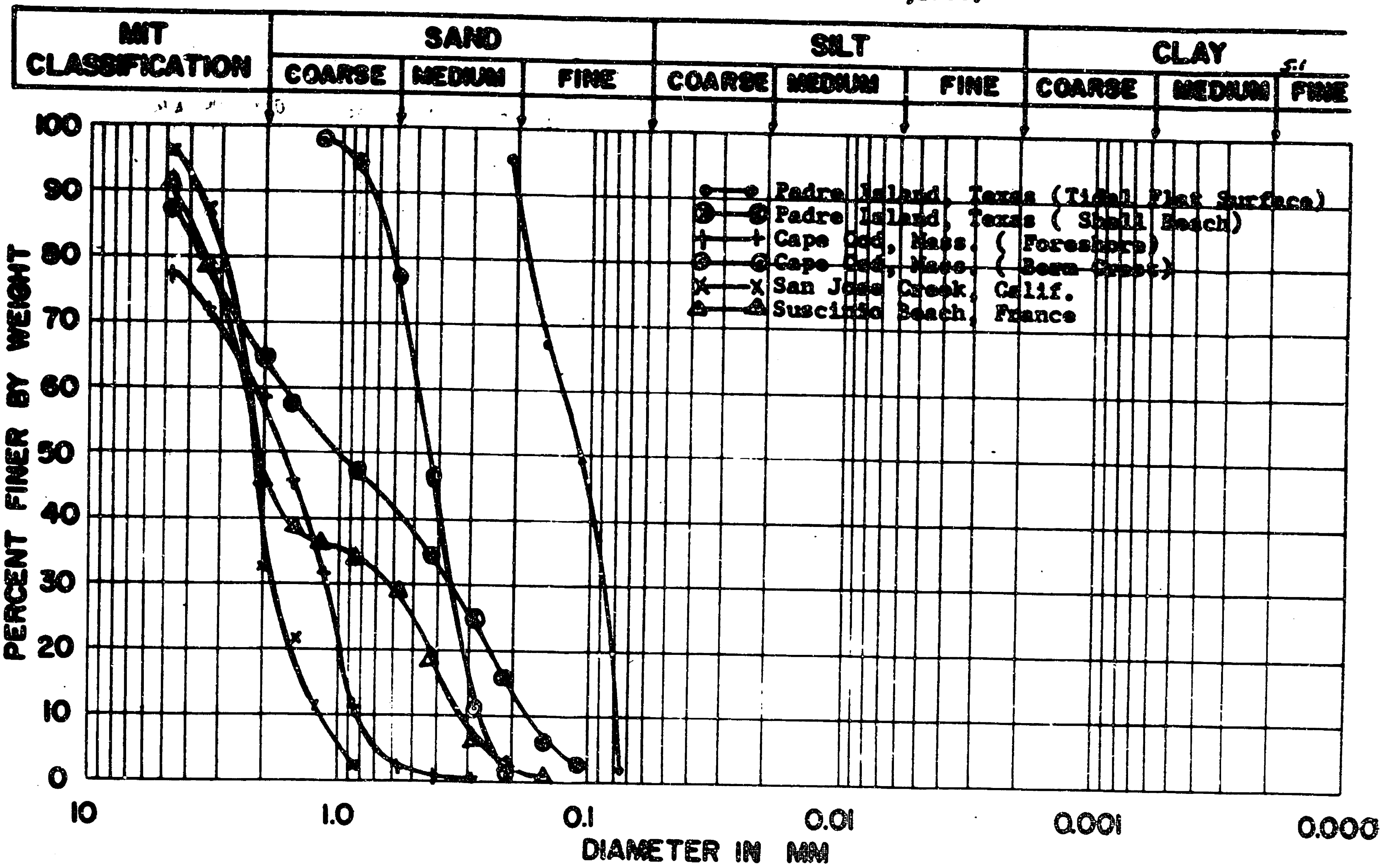


Fig. 5.1

GRAIN SIZE DISTRIBUTION

TYPICAL OIL SANDS
(After Muskat, 1946)

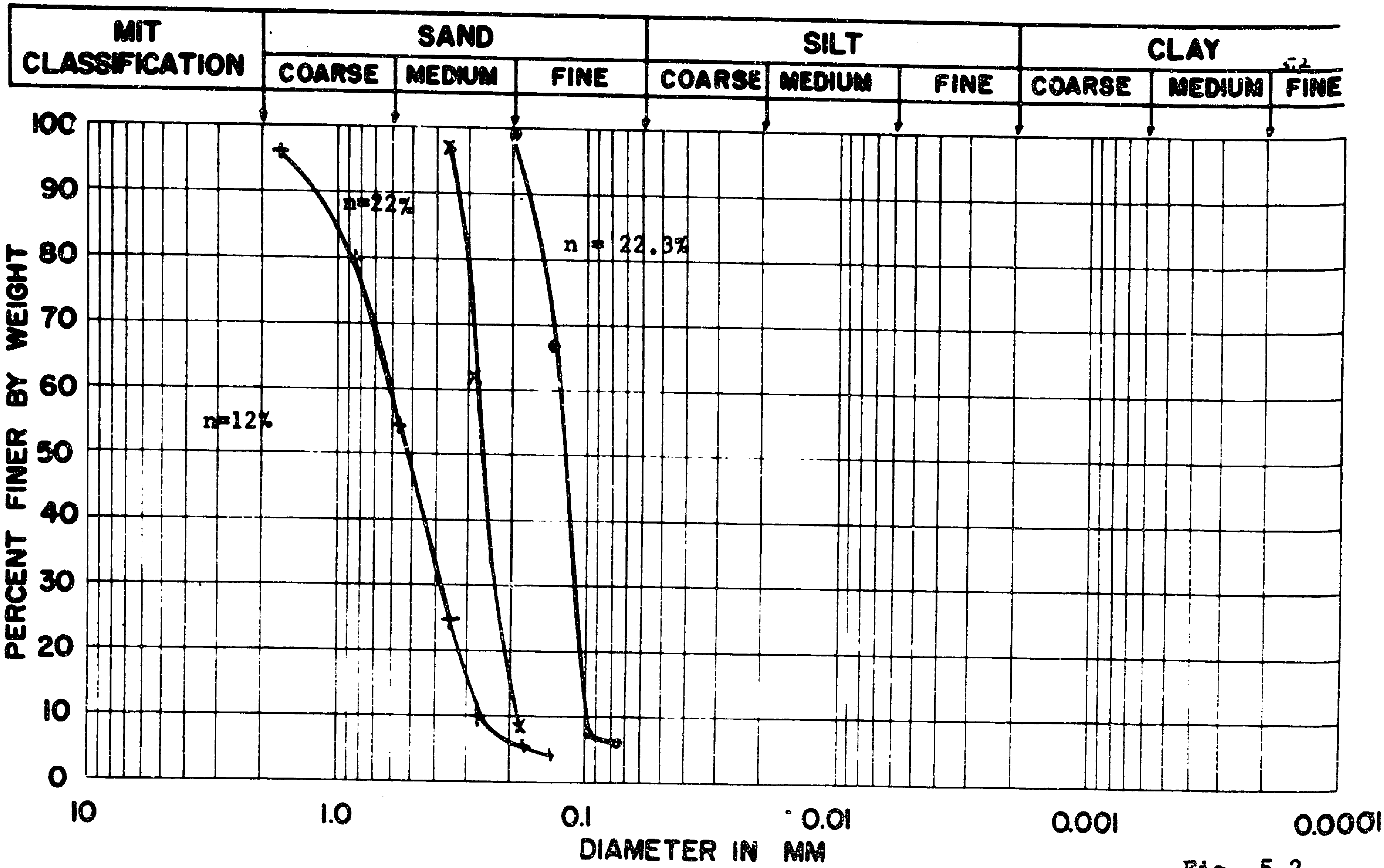
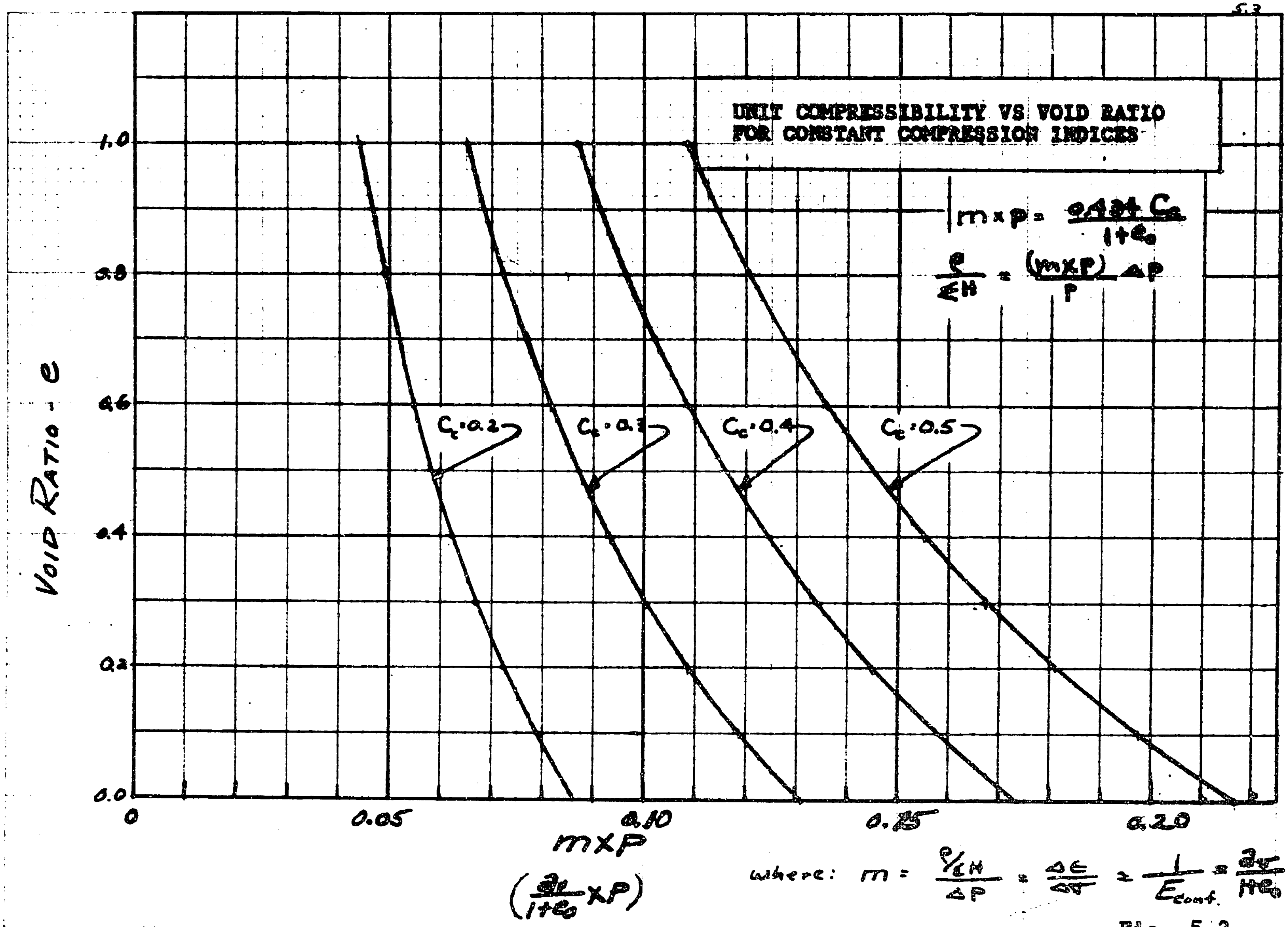


Fig. 5.2



where: $m = \frac{e/\varepsilon_H}{\Delta P} = \frac{\Delta\varepsilon}{\Delta\sigma} = \frac{1}{E_{const.}} = \frac{a_v}{1+e_0}$

Fig. 5.3

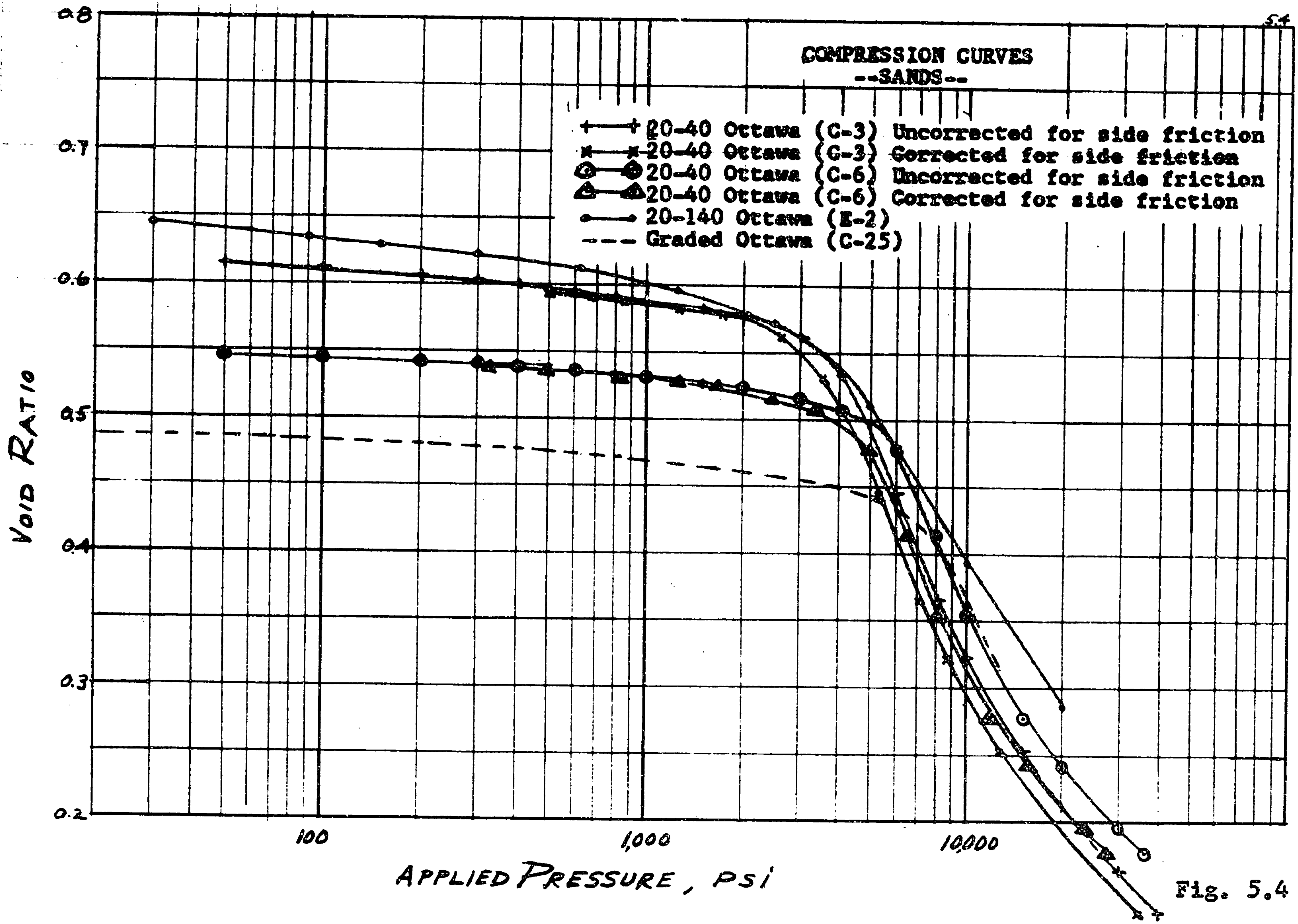

5.4
COMPRESSION CURVES
--SANDS--
20-40 Ottawa (C-3) Uncorrected for side friction
20-40 Ottawa (C-3) Corrected for side friction
20-40 Ottawa (C-6) Uncorrected for side friction
20-40 Ottawa (C-6) Corrected for side friction
20-140 Ottawa (E-2)
Graded Ottawa (C-25)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
VOID RATIO
100
1,000
10,000
APPLIED PRESSURE, PSI

Fig. 5.4

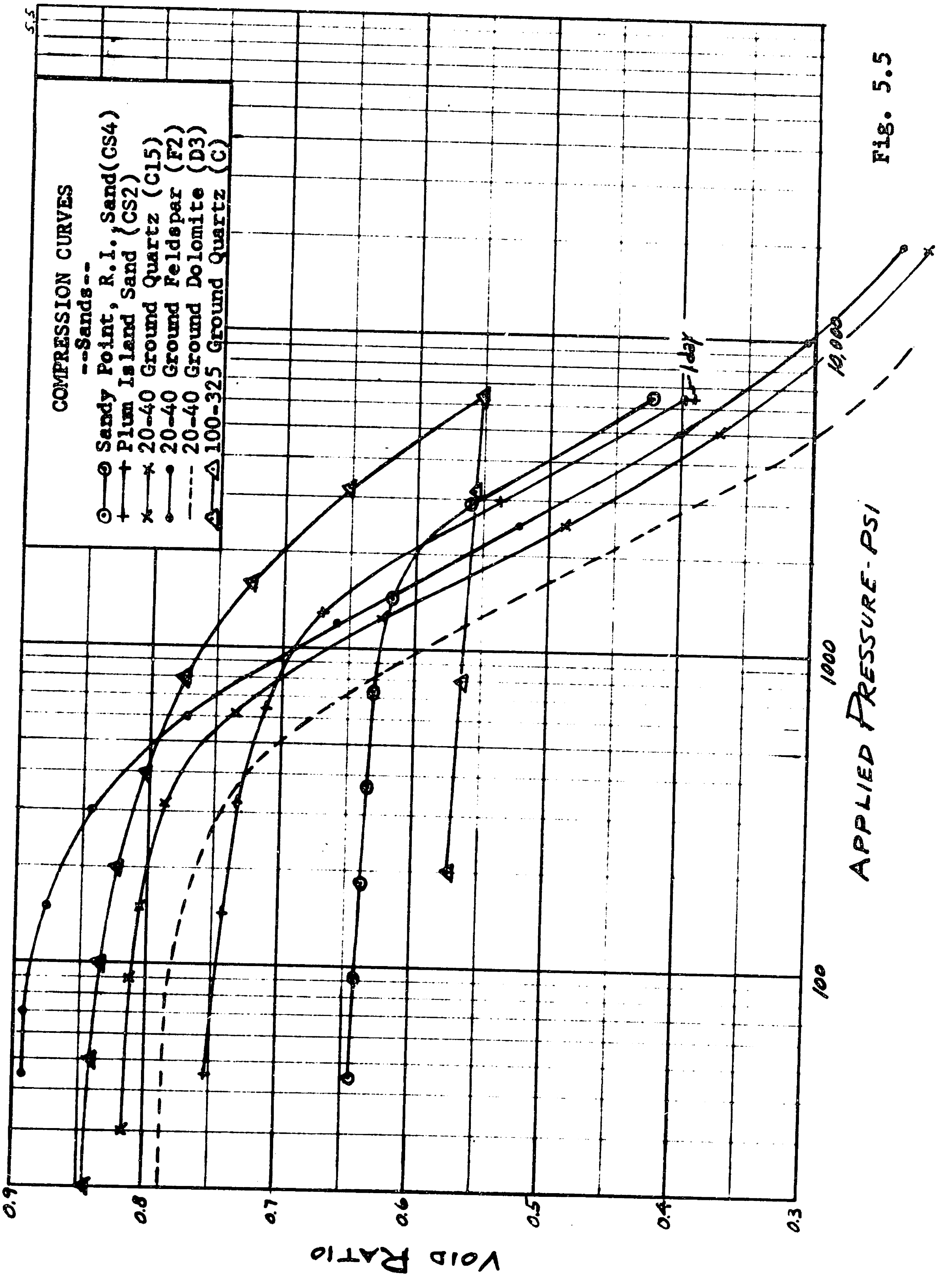

COMPRESSION CURVES
--Sands--
Sandy Point, R.I., Sand (CS4)
Plum Island Sand (CS2)
20-40 Ground Quartz (C15)
20-40 Ground Feldspar (F2)
20-40 Ground Dolomite (D3)
100-325 Ground Quartz (C)
1 day
Void Ratio
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Applied Pressure - PSI
100
1000
10,000
5.5

Fig. 5.5

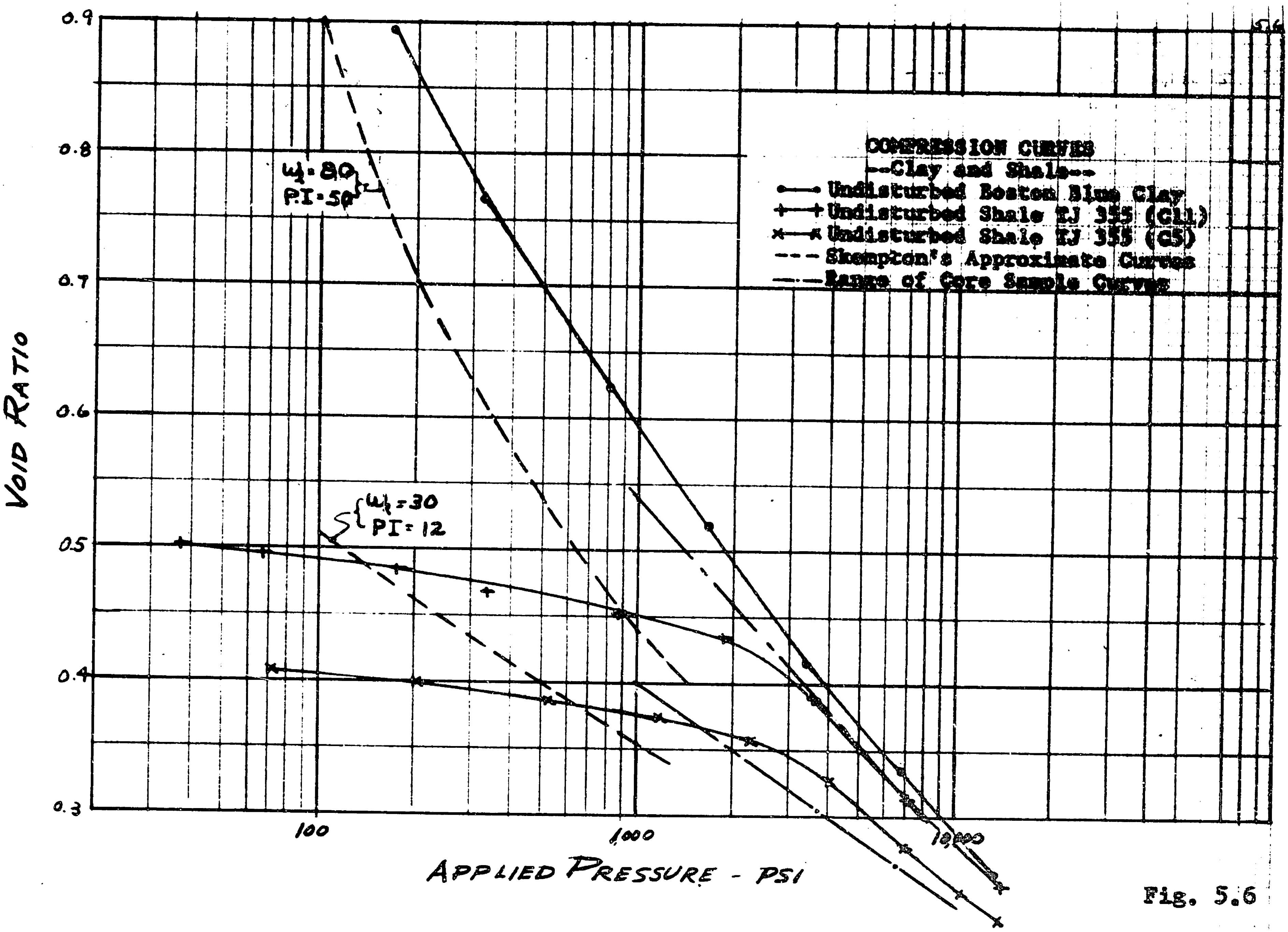

COMPRESSION CURVES
--Clay and Shale--
Undisturbed Boston Blue Clay
Undisturbed Shale EJ 355 (C11)
Undisturbed Shale EJ 355 (C5)
Skempton's Approximate Curves
Range of Core Sample Curves
w_L = 80
PI = 50
w_L = 30
PI = 12
0.9
0.8
0.7
0.6
0.5
0.4
0.3
VOID RATIO
100
1,000
10,000
APPLIED PRESSURE - PSI

Fig. 5.6

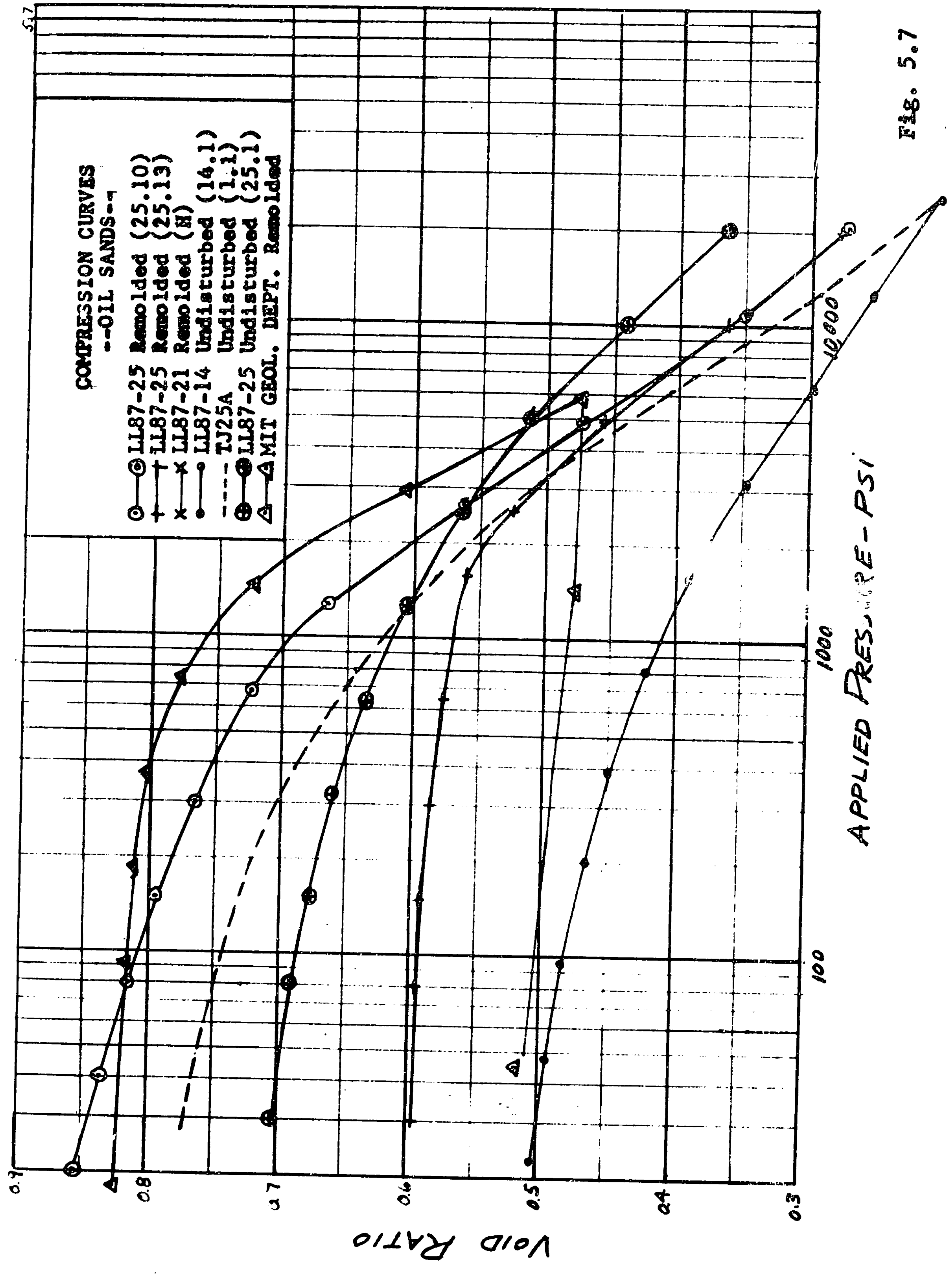

COMPRESSION CURVES
--OIL SANDS--
⊙ LL87-25 Remolded (25.10)
+ LL87-25 Remolded (25.13)
× LL87-21 Remolded (H)
● LL87-14 Undisturbed (14.1)
- - - TJ25A Undisturbed (1.1)
⊕ LL87-25 Undisturbed (25.1)
△ MIT GEOL. DEPT. Remolded
VOID RATIO
0.9
0.8
0.7
0.6
0.5
0.4
0.3
APPLIED PRESSURE - PSI
100
1000
10,000

Fig. 5.7

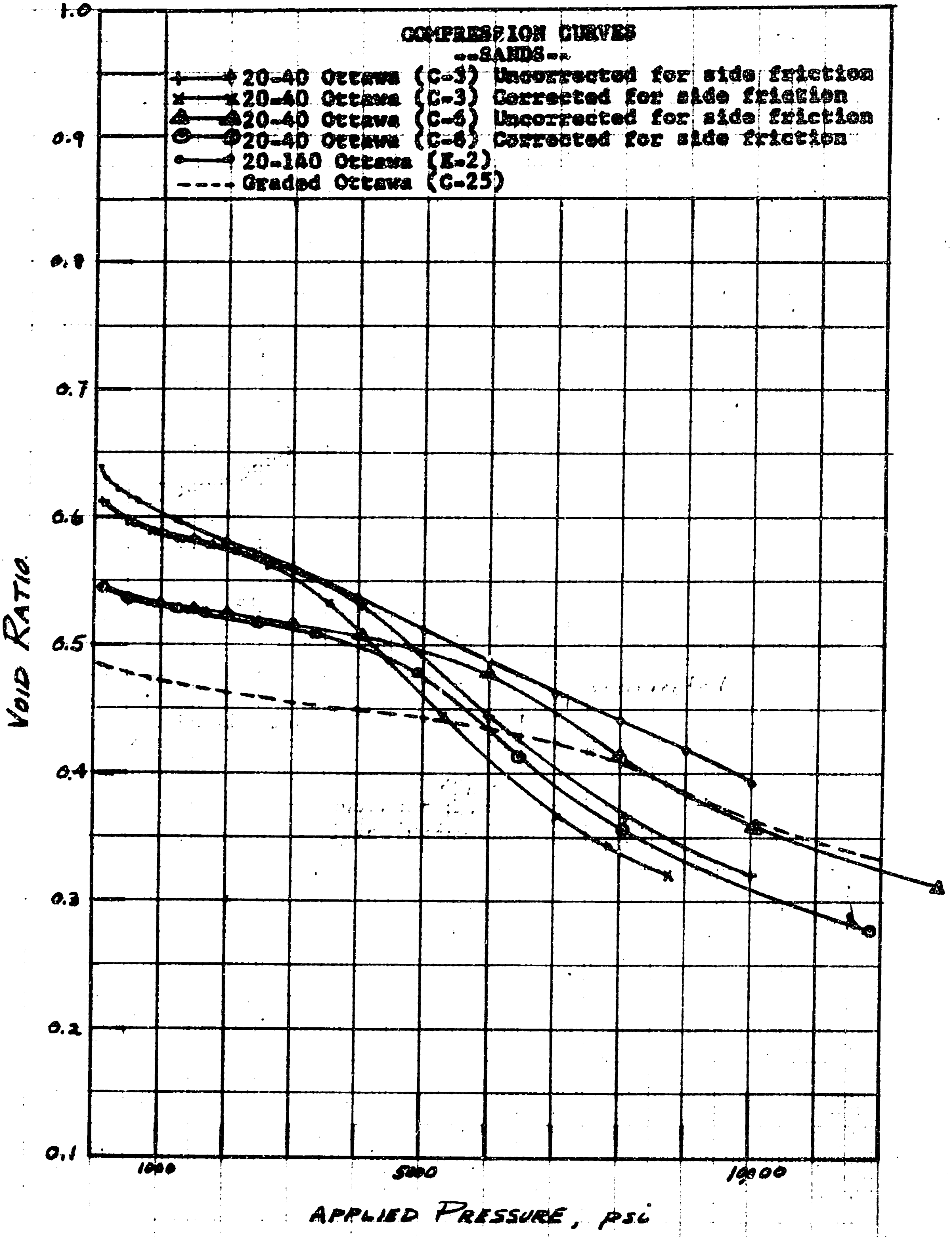

COMPRESSION CURVES
--SANDS--
20-40 Ottawa (C-3) Uncorrected for side friction
20-40 Ottawa (C-3) Corrected for side friction
20-40 Ottawa (C-6) Uncorrected for side friction
20-40 Ottawa (C-6) Corrected for side friction
20-140 Ottawa (E-2)
Graded Ottawa (C-25)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
VOID RATIO
1000
5000
10000
APPLIED PRESSURE, psi

Fig. 5.8

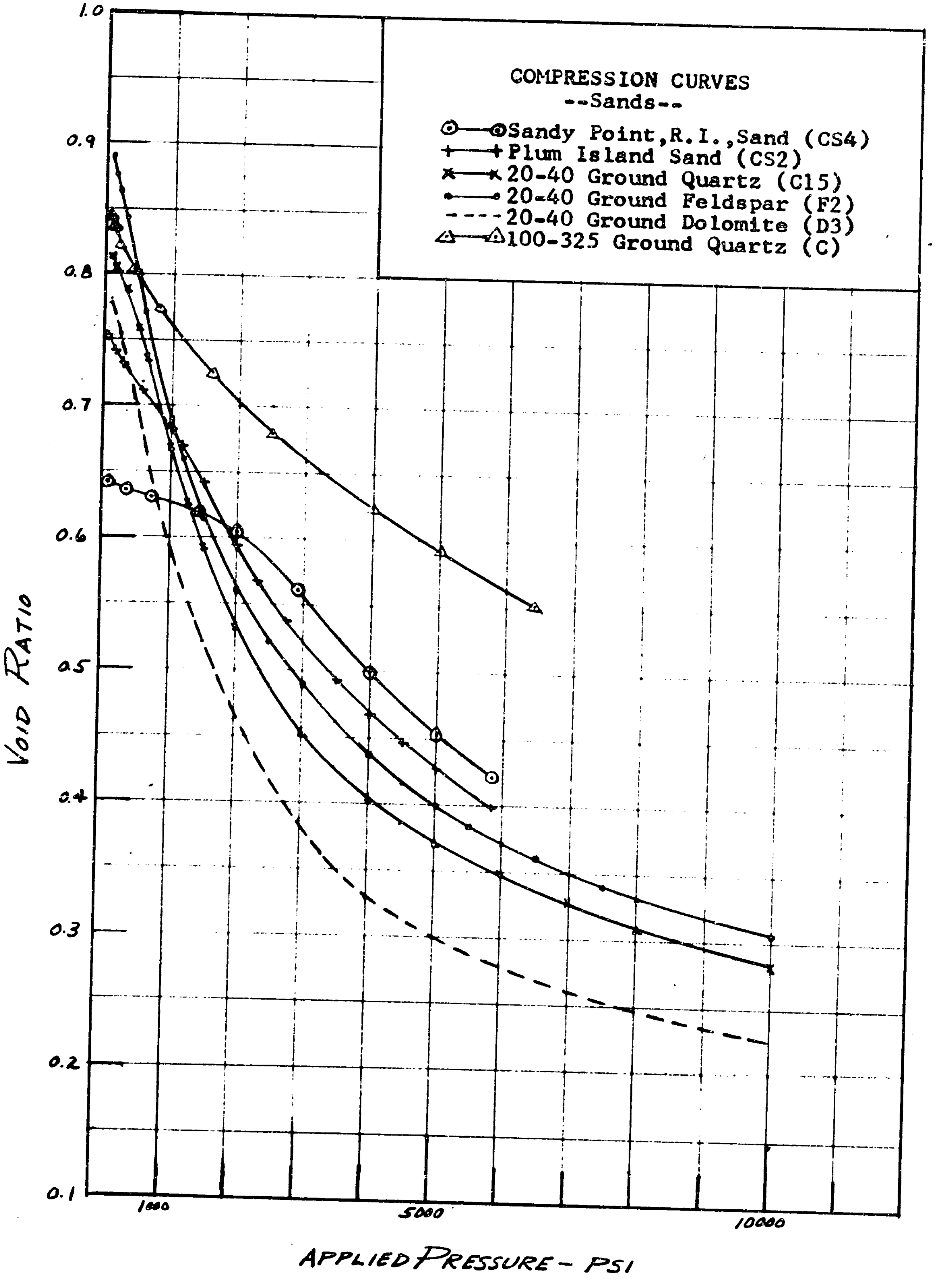

COMPRESSION CURVES
--Sands--
Sandy Point, R.I., Sand (CS4)
Plum Island Sand (CS2)
20-40 Ground Quartz (C15)
20-40 Ground Feldspar (F2)
20-40 Ground Dolomite (D3)
100-325 Ground Quartz (C)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
VOID RATIO
1000
5000
10000
APPLIED PRESSURE - PSI

Fig. 5.9

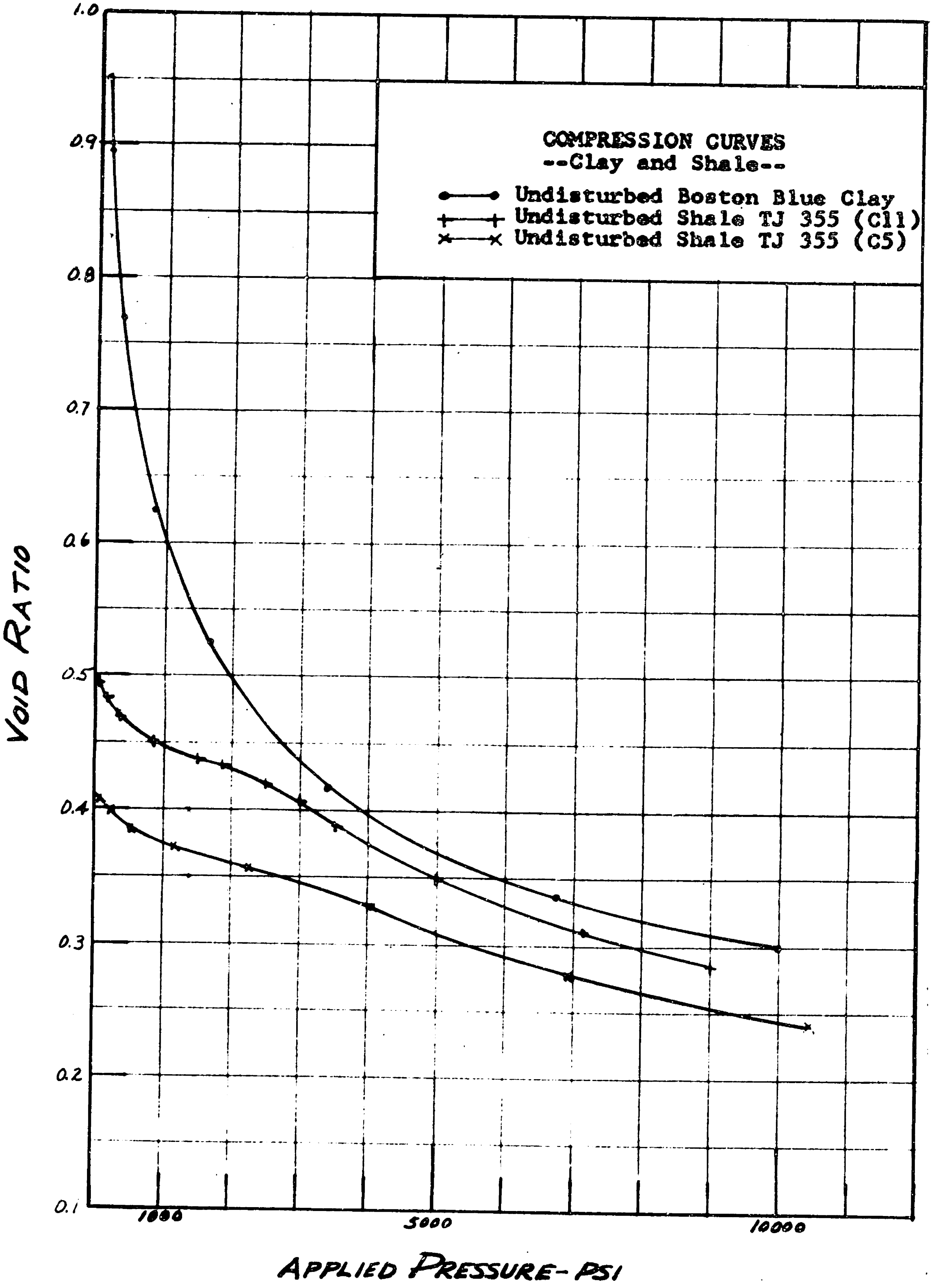

COMPRESSION CURVES
--Clay and Shale--
Undisturbed Boston Blue Clay
Undisturbed Shale TJ 355 (C11)
Undisturbed Shale TJ 355 (C5)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1000
5000
10000
VOID RATIO
APPLIED PRESSURE- PSI

Fig. 5.10

5.11

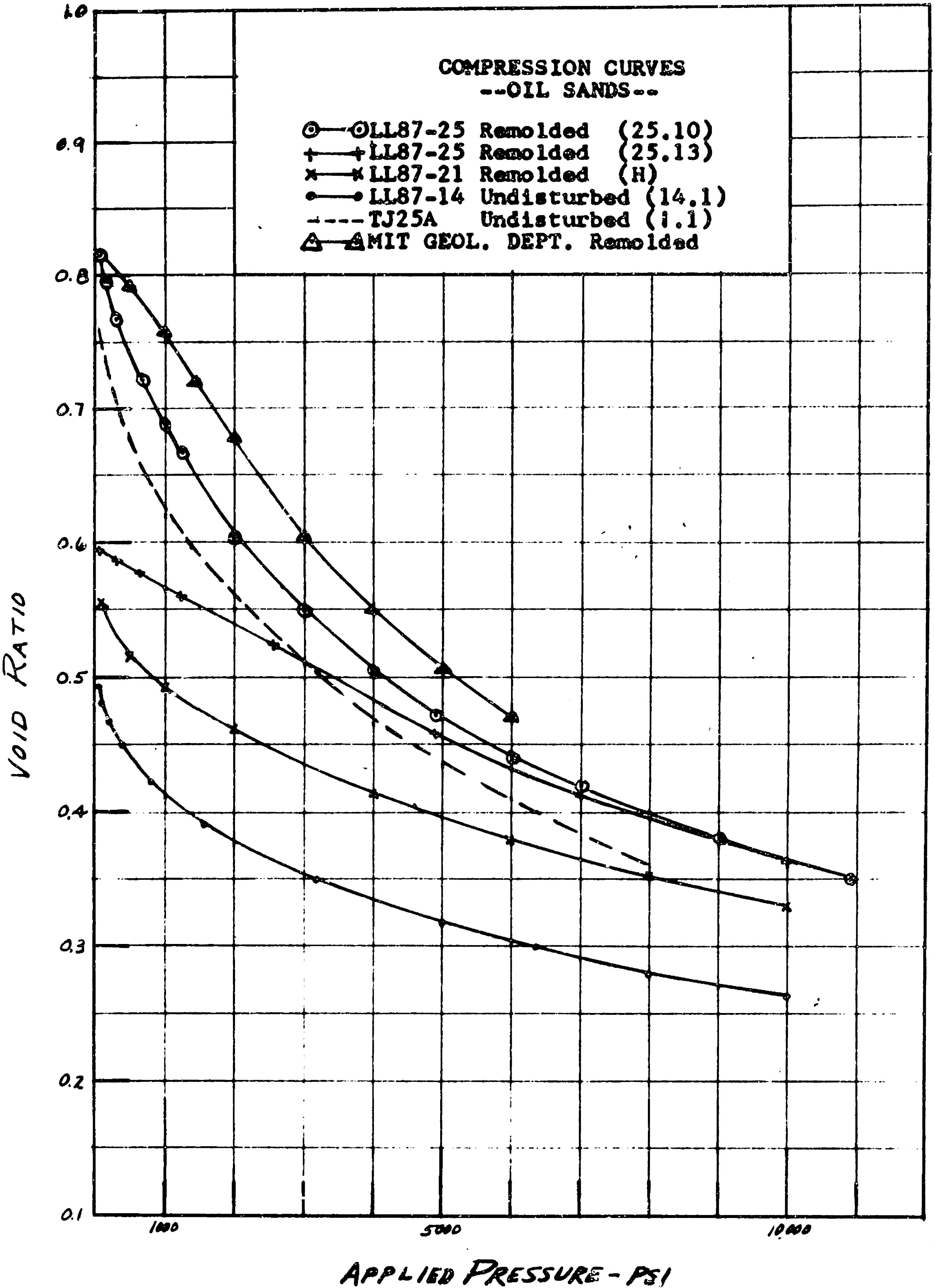

COMPRESSION CURVES
--OIL SANDS--
LL87-25 Remolded (25.10)
LL87-25 Remolded (25.13)
LL87-21 Remolded (H)
LL87-14 Undisturbed (14.1)
TJ25A Undisturbed (1.1)
MIT GEOL. DEPT. Remolded
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1000
5000
10,000
VOID RATIO
APPLIED PRESSURE - PSI

Fig. 5.11

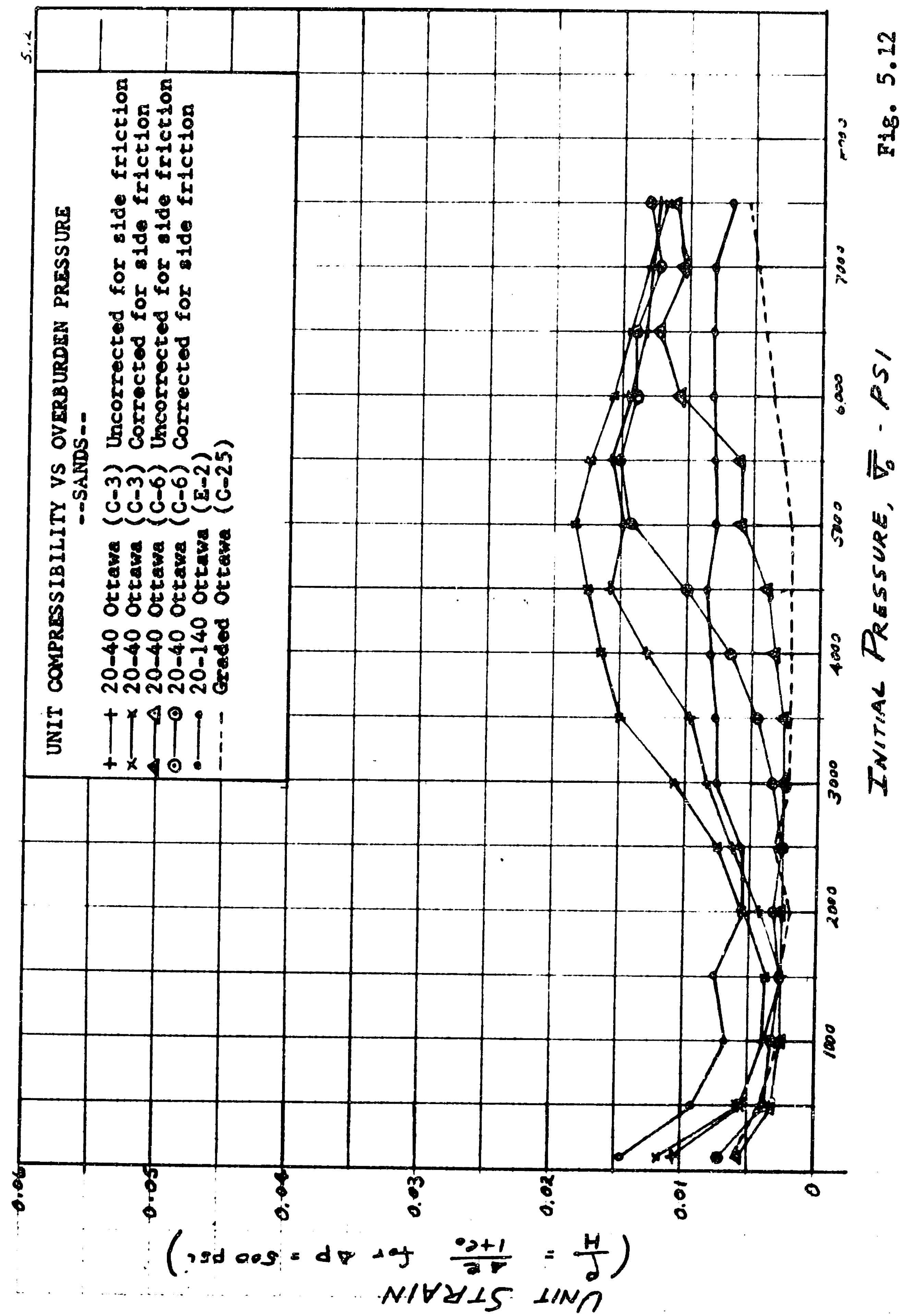

UNIT COMPRESSIBILITY VS OVERBURDEN PRESSURE
--SANDS--
+——+ 20-40 Ottawa (C-3) Uncorrected for side friction
×——× 20-40 Ottawa (C-3) Corrected for side friction
△——△ 20-40 Ottawa (C-6) Uncorrected for side friction
⊙——⊙ 20-40 Ottawa (C-6) Corrected for side friction
•——• 20-140 Ottawa (E-2)
- - - Graded Ottawa (C-25)
0.06
0.05
0.04
0.03
0.02
0.01
0
1000
2000
3000
4000
5000
6000
7000
8000
INITIAL PRESSURE, $\overline{\sigma}_o$ - PSI
UNIT STRAIN
$\left(\frac{\rho}{H} = \frac{\Delta e}{1+e_o}\right.$ for Δp = 500 psi)
5.12

Fig. 5.12

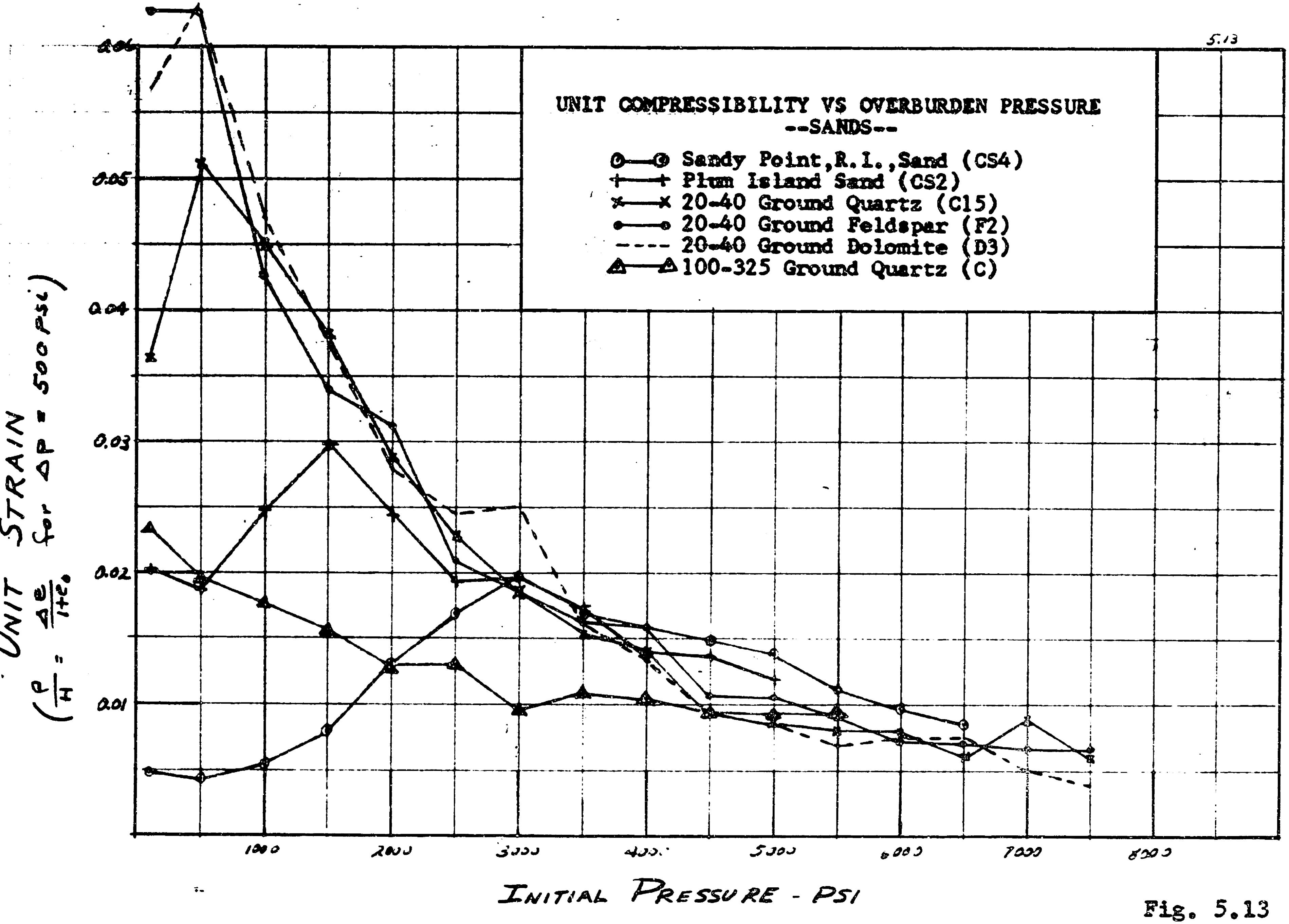

5.13
UNIT COMPRESSIBILITY VS OVERBURDEN PRESSURE
--SANDS--
Sandy Point, R.I., Sand (CS4)
Plum Island Sand (CS2)
20-40 Ground Quartz (C15)
20-40 Ground Feldspar (F2)
20-40 Ground Dolomite (D3)
100-325 Ground Quartz (C)
UNIT STRAIN
$(\frac{P}{H} = \frac{\Delta e}{1+e_0}$ for $\Delta P = 500$ psi)
0.06
0.05
0.04
0.03
0.02
0.01
1000
2000
3000
4000
5000
6000
7000
8000
INITIAL PRESSURE - PSI

Fig. 5.13

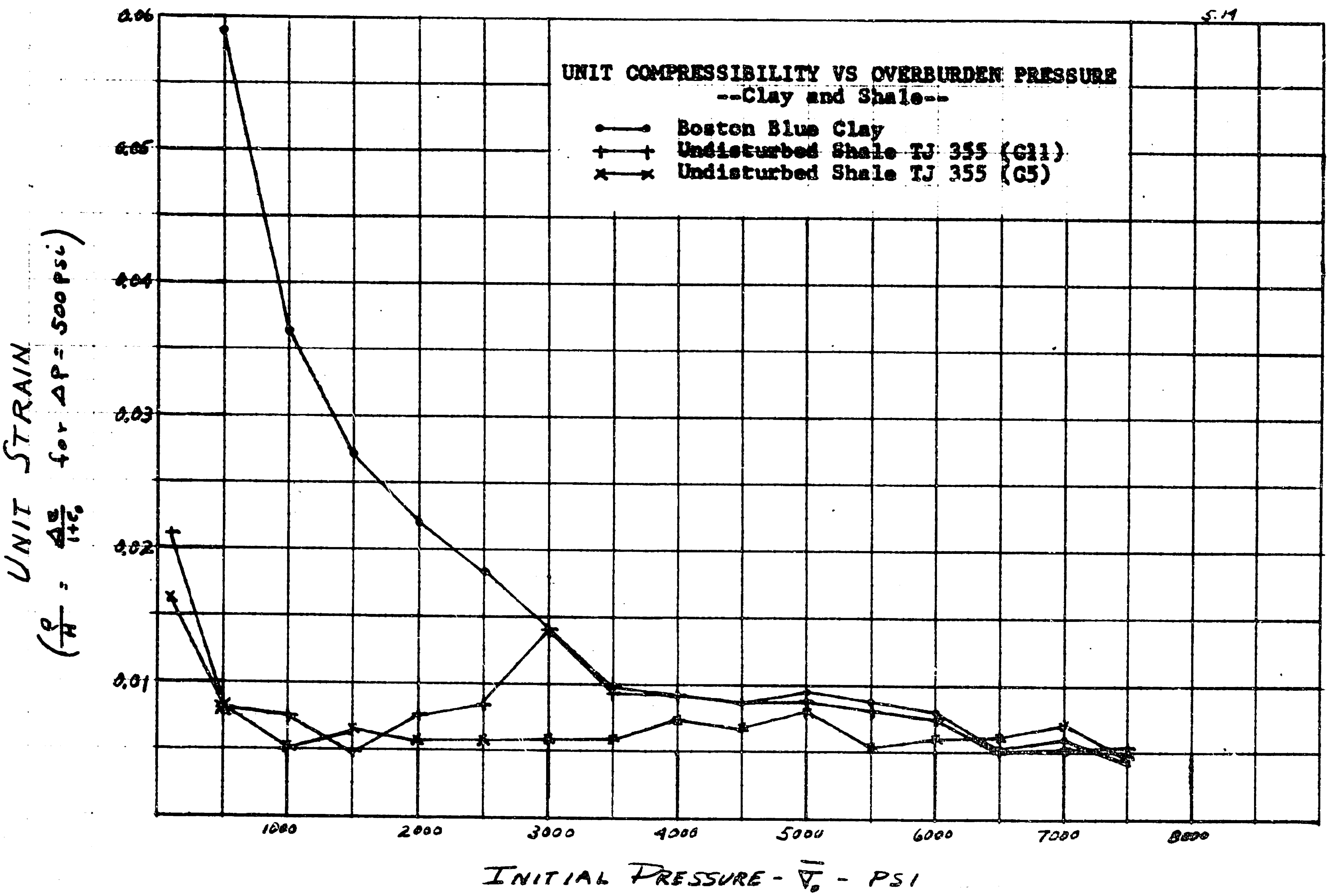

5.14
UNIT COMPRESSIBILITY VS OVERBURDEN PRESSURE
--Clay and Shale--
Boston Blue Clay
Undisturbed Shale TJ 355 (G11)
Undisturbed Shale TJ 355 (G5)
0.06
0.05
0.04
0.03
0.02
0.01
UNIT STRAIN
$\left(\frac{\rho}{H} = \frac{\Delta e}{1+e_0} \text{ for } \Delta P = 500 \text{ psi}\right)$
1000
2000
3000
4000
5000
6000
7000
8000
INITIAL PRESSURE - $\overline{\sigma}_0$ - PSI

Fig. 5.14

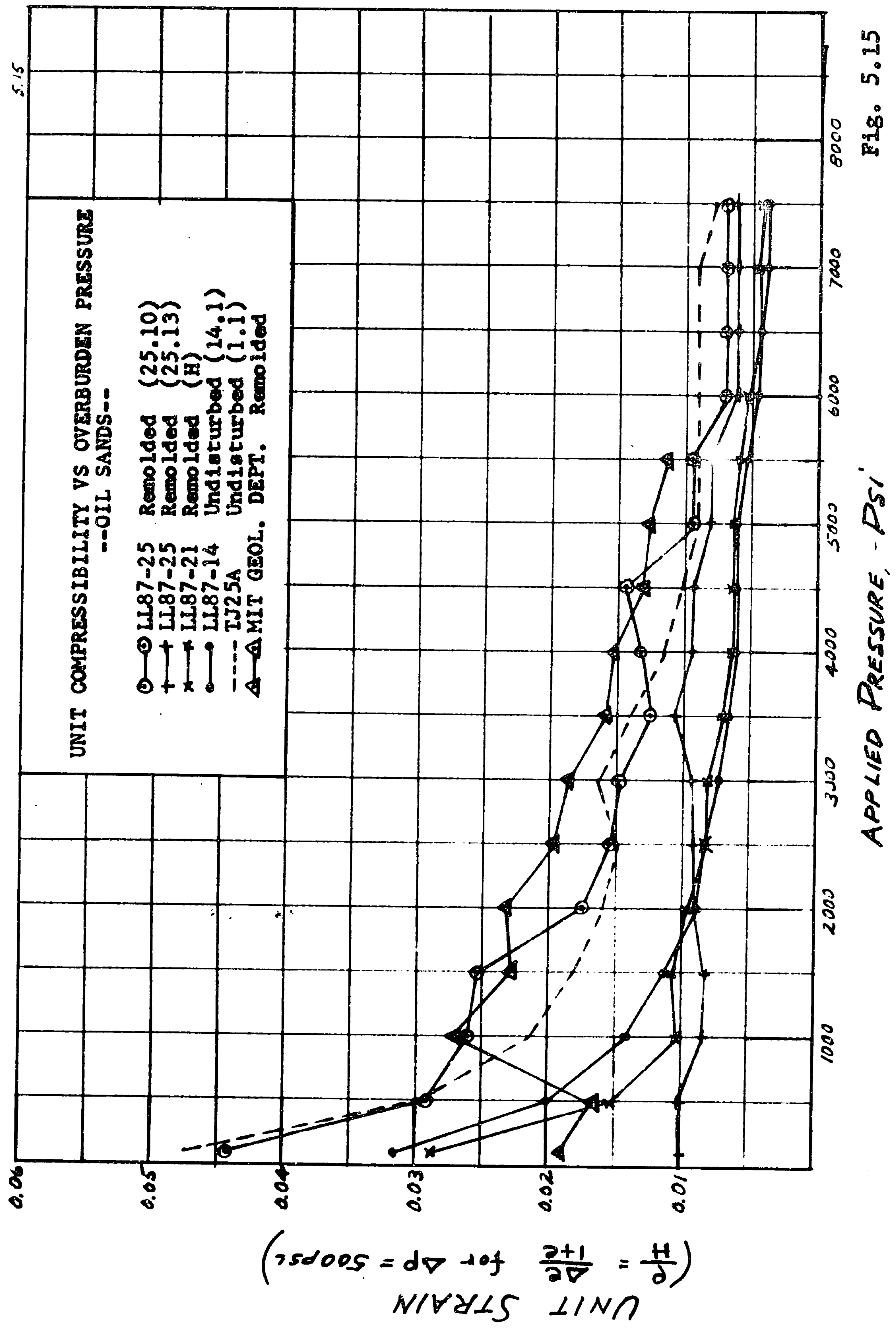
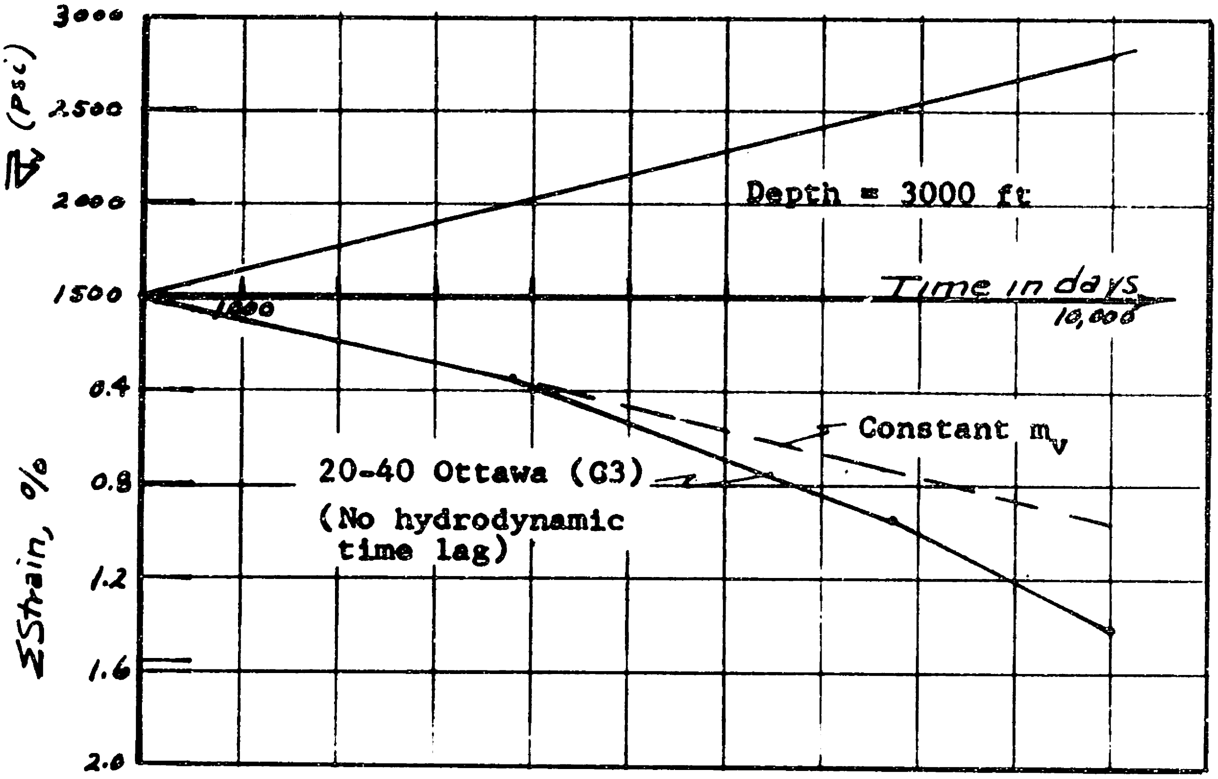
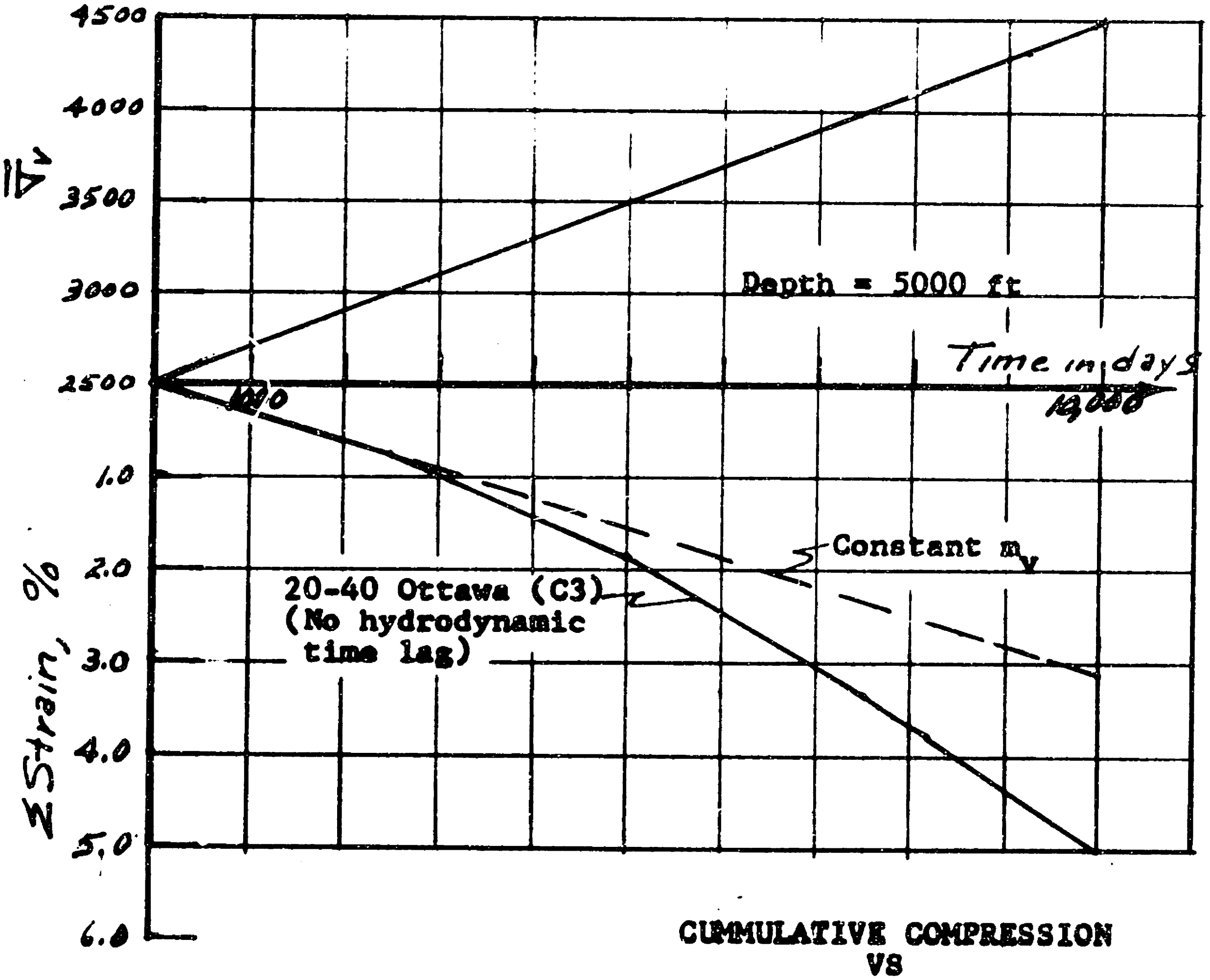
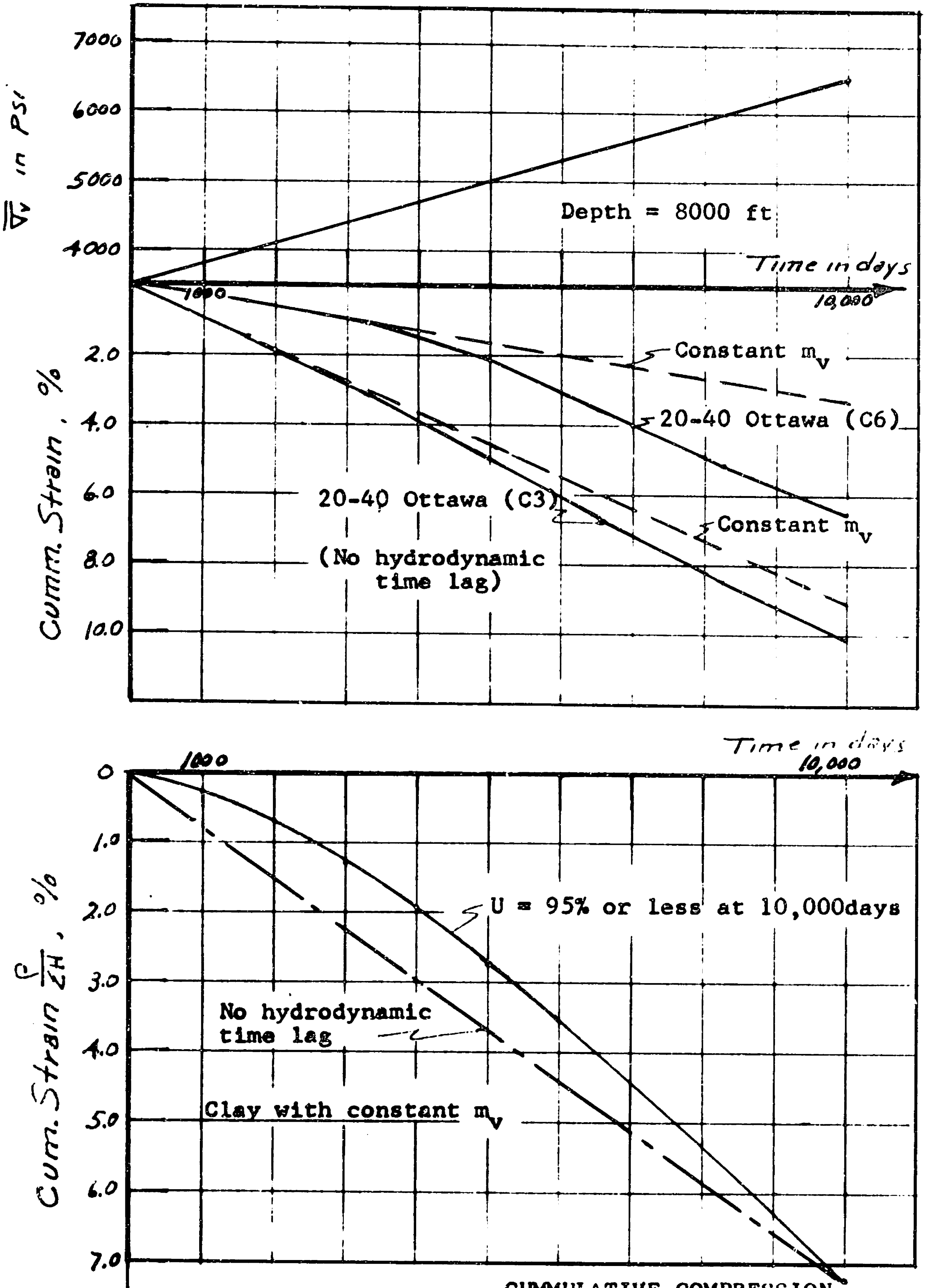

5.15
UNIT COMPRESSIBILITY VS OVERBURDEN PRESSURE
--OIL SANDS--
LL87-25 Remolded (25.10)
LL87-25 Remolded (25.13)
LL87-21 Remolded (H)
LL87-14 Undisturbed (14.1)
TJ25A Undisturbed (1.1)
MIT GEOL. DEPT. Remolded
0.06
0.05
0.04
0.03
0.02
0.01
1000
2000
3000
4000
5000
6000
7000
8000
APPLIED PRESSURE, - PSI
UNIT STRAIN
$\left(\frac{\rho}{H} = \frac{\Delta e}{1+e}\right.$ for $\Delta p = 500psi\Big)$

Fig. 5.15





CUMMULATIVE COMPRESSION
VS
EFFECTIVE PRESSURE INCREASE
Fig. 5.16



CUMMULATIVE COMPRESSION
VS
EFFECTIVE PRESSURE INCREASE
Fig. 5.17

6: CONCLUSIONS AND PRACTICAL SIGNIFICANCE OF INVESTIGATION

The study of the mechanics of oil field subsidence suggests that the compression within the producing formation can be assumed to be one-dimensional with little error. However, the presence of a non-producing overburden formation can have an important influence on subsidence computations:

(1) The overburden may undergo horizontal compression and vertical expansion in the region of masimum subsidence, this can cause difficulty in relating surface subsidence to formation compression;

(2) The overburden, as it sags, may behave in a manner analogous to an elastic plate and may support part of its own weight. This will result in a decrease in total stress within the underlying sediments as subsidence occurs.

From the test data and comparisons of the relative compressibility of sand and clay, the following conclusions can be drawn:

(1) At sufficiently high pressures, sand may be more compressible than clay;

(2) The high compressibility is due primarily to crushing and fracturing of individual sand grains;

(3) Tests run on ground quartz shows that breakdown pressures as low as several hundred pounds per square inch can be obtained under certain conditions. Although natural sands in general are angular it is doubtful that any natural quartz sand as originally deposited contains grains quite as angular as those used in this particular test program.

The practical significance of these conclusions is that the compression of sands by the weight of overlying sediments is a phenomenon which cannot be neglected by geologists and petroleum engineers. At the high pressures encountered in deep sedimentary deposits, the compression of the sands can be of equal, if not greater, importance than the compression of clays. This is particularly so when the compressions of deep layers which are initially under high pressures is to be evaluated for pressure increases due to a reduction in fluid pressure.

The increase in intergranular pressure brought about by the production of oil from deep sand layers may cause large amounts of compression in these layers resulting in, not only land subsidence, but also augmented recovery of oil.

The fact that most void ratio reduction in sands takes place by a process of fracturing of the grains implies that deeply buried sands with low void ratios almost certainly do not have the same grain-size characteristics that they possessed when first deposited: the median grain-size will tend to be smaller, the angularity more pronounced and the gradation wider. This should be of considerable importance in the interpretation of the origin and depositional environment of sands, and as far as is known this type of post-depositional change has been given little consideration by sedimentologists.

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APPENDICES

APPENDIX A: LITERATURE REVIEW - STUDIES OF COMPRESSIBILITY AND POROSITY REDUCTION OF CLASTIC SEDIMENTS AT HIGH PRESSURE

A.1 INTRODUCTION

Published results of research on the compression behavior of clastic sediments at high pressures before the early 1950's are limited. Prior to that time experimental work on compression behavior had been conducted, in general, at pressures lower than those used in the present research program (normal consolidation testing for Civil Engineering purposes seldom exceeds pressures of 16 tons per sq ft). Most previous estimates of sediment compressibility at high pressures were made by extrapolating the compression characteristics obtained at low pressures. Since the early 1950's there has been an apparent increase in interest in compression behavior at high pressures.

In addition to direct experimental work, a limited amount of data correlating porosities of core samples with overburden pressure has been published. This correlation can be used to obtain indications of the compression which a sediment must have undergone during the development of the sediment.

A.2 REVIEW OF PREVIOUS WORK

Interest in consolidation* of deep sediments appears

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*In this report "consolidation" is synonymous with the term "compaction" and refers to the compression of sediments under applied load.

to have developed as early as 1908. The earlies published reference reviewed is that of Sorby (1908), who presented the results of a series of experiments on various sediments. In relation to the magnitude of the compressibility undergone in extreme cases he states: "...shales and slates may occupy only a ninth of the volume which they possessed when originally deposited." Although he attempted to determine the effect of pressure in compressing a clay material, no directly applicable quantitative data were obtained. He did, however, suggest that the compressibility was related to the volume of voids in a way inversely as the pressure, and he also expressed the opinion that the deformation of the solid particles was important.

Blackwelder (1920) explained the origin of the central Kansas oil domes as due to the differential compaction of shales. Although no quantitative data were available, his assumptions relative to the percentage compression that different materials would undergo (shales, 15 to 35 percent; limestone, 5 percent; and sand, 2 percent) indicate the general feeling at that time that the seat of compression was in the shales and that the compression of sands was negligible.

Teas (1923) explained the existence of certain dips in a similar fashion and is in agreement with Blackwelder as to the relative unimportance of sand compression.

The publication by Terzaghi in 1925 of his theory of consolidation of clays reaffirmed the importance of the compaction of sediments and the time lags associated with the compression of fine grained soils. The same author (1925) describes a series of confined compression tests run on crushed quartz with pressures up to about 1,200 psi. Considerable compression was observed, and about 5 percent of the quartz was found to be crushed to powder after loading to 50 TSF. However, compression tests on natural sands showed very little compression (the pressures undoubtedly were not high enough).

Hedberg (1926) presented porosity data of noncalcareous, nonarenaceous shales from the Ransom, Phillips, and Lynn wells in Kansas. Although the data show a general tendency toward decreasing porosity with increasing depth, a reinterpretation of the data in terms of void ratio and pressure is difficult because, according to Hedberg, approximately 2,500 feet of Cretaceous sediment once existed above the Graneros shale which now exists as outcrop in Hamilton County. Because of this difficulty and the limited data, no reinterpretation has been attempted. However, with respect to the porosity reduction of sands, Hedberg suggests that the major cause of pore space reduction is infiltration of material from an outside source, and he states: "...from an initial porosity of more than 40 percent or less by infiltration."

In the same year van Tuyl and Beckstrom (1927) described experiments in which layers of sand and oil-saturated clay were compressed in a cylinder to pressures as high as 3,750 psi. No observations were made of the volume changes which occurred; therefore, if the sand layers were compressed, the fact was not observed.

The first mention of the possibility that sand compression could be a major factor in the subsidence of an oil field was by Snider (1927) who considered, among others, the hypothesis that the oil-producing sands may be in a loose, "quick" state because of high fluid pressures, and that a reduction of the fluid pressures due to the production of the oil causes the sand to return to its normal dense state.

Snider's suggestion that the sands may be in a quick state because of high fluid pressures was later refuted by Pratt (1927), who pointed out that fluid pressures high enough to support the whole of the overburden are never encountered in oil fields.

Athy (1930) published the results of a study of the variation in porosity and depth of approximately two hundred core samples from various depths in oil wells in Oklahoma and Texas. Using the measured porosities and depths, he extrapolated the data to meet the assumed porosity of average surface clays and thus obtained a hypothetical porosity-depth relation for the younger beds which had been eroded. In Figure 4.9 the average curve of porosity vs depth which he obtained has been replotted in terms of void ratio and intergranular pressure to obtain an indication of the compressibility of natural sediments.

In commenting on the relative compressibility of different sediments, Athy stated: "Among all the different sediments, in shale alone is compaction resulting from pressure of large magnitude", and with specific reference to sand: "...changes caused by pressure in sands are small in comparison with changes caused by other agencies", although he does state that there will be some granulation at the points of contact. He concludes that sand compaction is small, especially when compared to depositional variations in density. This same opinion was supported by Trask (1935).

Westman (1932) studied a number of clays which were molded into plastic briquets and then compressed between water permeable pistons under pressures of from 200 to 20,000 psi until equilibrium was reached. Although Westman was concerned primarily with the subsequent shrinkage (or expansion) of clays when dried, he presents sufficient data to allow determinations of void ratios at pressures of 207 psi, 8,280 psi, and 16,560 psi. The data for Delaware Kaolin, Georgia Kaolin, and a Kentucky Fire Clay are presented in Figure A.1. Data at 16,560 psi were obtained only for the Delaware Kaolin. Connecting the three data points for the Delaware Kaolin with a single straight line indicates a compression index (C_c) equal to 0.27. Comparable values of compression indices would be obtained if a straight line relationship were assumed between the data points of the other two materials.

Botset and Reed (1935) described an experiment in which a sample of coarse sand mixed with kerosene was thoroughly compacted into a cylinder and loaded to a maximum pressure of 3,425 psi. The total porosity reduction was only 4.5 percent, but after unloading and reloading several times some fine powder was found to have been produced from crushing of grains.

Fraser (1935), in a paper discussing porosities and permeabilities of clastic sediments in general made the following statement regarding porosity reduction in the coarser sediments: "Pebbles and sands are laid down in a more nearly stable state than are smaller particles because they are buoyed up much less by the water. Accordingly, their porosity is sufficient to crush the grains and cause more or less complete collapse of the arching across the voids. Athy found that the sand derived from St. Peter sandstone, when artificially deposited under water, could be made to settle about 11 percent by continued jarring under atmospheric pressure. When it was placed under 4,000 pounds pressure, the compaction was only 2 percent more or 12 percent in all."

Later he continues: "It seems clear, then, that in the deposits of coarser material such as sand and gravel, compaction after deposition is relatively unimportant except in cases where the pressure applied has been really great. As a matter of fact, in the average sandstone or conglomerate, there is only rarely to be seen evidence of pressure that exceeded the crushing strength of the component units. In the great majority of cases, therefore, post-depositional reductions of porosity are due to cementation by introduced mineral material." This opinion apparently is held by many geologists and petroleum engineers to the present day.

Hedberg (1936) presented data from core samples of Tertiary shales from wells drilled in the large geosynclinal basin of Venezuela (Greater Oficina Area). The samples, which were described only as being gray or greenish-gray, came from depths of from 300 to 6,000 feet. This data also have been replotted using void ratio and pressure (logarithmic scale in Figure 4.9 to obtain an indication of the compressibility of natural sediments.

The U. S. Bureau of Mines (1940) published the results of a series of compression tests on cores of consolidated (i.e., cemented) sands. These tests were run in connection with a study of the subsidence in the Goose Creek Oil Field. The samples were placed in metal jackets and submitted to all around pressures up to 8,000 psi. The cores were found to behave almost elastically. However, in the writer's opinion, the experimental procedure prevented their measuring any permanent nonelastic deformation. In order to test for leaks in the system, all samples were subjected to a pressure of 8,000 psi before measurements of volume change were begun; thus the sands were artificially precompressed before the start of each test. Upon reapplication of the pressure, the amounts of compression recorded were very small, as would be expected on precompressed samples.

The samples tested by the Bureau of Mines were consolidated sands, and even if the sands had not been inadvertently precompressed before any measurements were made it is possible that a pressure of 8,000 psi would not have been sufficient to cause significant amounts of compression. Furthermore, subjecting the samples to an equal pressure in all directions does not necessarily duplicate the conditions of loading to which an element of soil in a subsiding sedimentary basin is subjected.

During the war years research on compressibility was curtailed. Bell (1943) presented some considerations concerning the depth at which sands might lose their porosity by collapse of the arches formed over the voids; and Howard (1943) suggested that for strata in which fluids are sealed off by impervious boundaries, the overburden pressure would be carried partly by the fluids, and very great depths would be necessary to collapse the voids.

Skempton (1944) compared sedimentation compression curves with normal laboratory compression curves obtained from tests on undisturbed samples. He found that although the laboratory curve invariably lies below the sedimentation curve, the two curves tend to converge. Skempton also pointed out that the difference between the sedimentation curve and the laboratory undisturbed curve is greatest for the soft clays, but suggested that the difference at high pressures would be considerably less. He also showed that the more colloidal clays are the more compressible and possess higher void ratios at any given pressure than sandy clays or silts.

Weller (1959) described tests performed by Ural at the University of Illinois (1945). Ural consolidated sands to pressures of 2,000 kg per sq cm. The sand used was a yellowish quartz sand (No. 40 Sieve to No. 100 Sieve). After compression 40.3 percent passed the No. 100 Sieve. He noticed a change in slope of the void ratio vs logarithm of pressure curve and suggested that the change occurred at the load at which grains begin to crush. Once crushing occurred he obtained compression indices between 0.2 and 0.5.

Terzaghi and Peck (1948) presented the results of compression tests on a dense sand (presumably Ural's tests) and a sample of remolded Detroit Clay which were tested to pressures as high as 2,000 kg per sq cm. Within the pressure range of 100 to 1,000 kg per sq cm the compression index of the clay is approximately 0.2 and that of the sand, a maximum of approximately the same value. Relative to the compression of the sand it is stated: "For sands the middle part is straight from a pressure of about 10 to about 100 kg per sq cm. At this pressure the grains begin to crush and the slope increases. The slope then remains fairly constant up to about 1,000 kg per sq cm whereupon it begins to decrease."

Terzaghi and Peck (1948), using the data of Skempton and others, showed that the compression index for the material in a remolded state could be related to the liquid limit by the following expression:

$$C_c' = 0.007\ (LL - 10\%)$$

This relationship was for a series of samples selected at random from all parts of the world, and including both sensitive and insensitive clays.

Jaky (1948) compressed a sample of fine sand to 200 kg per sq cm in order to estimate the behavior of sediments at great depth. He was of the opinion that the compression curve obtained was extrapolatable to the case of clays and showed that the compression curve can be approximated by an exponential equation of the type, $e = e_o\ C_p^{\ m}$, between pressures of 4 and 200 kg per sq cm.

Harris and Harlow (1948) attributed all large scale subsidence at Long Beach, California, which occurred through 1945 to shale consolidation and assumed that the oil bearing sands are incompressible. It is of interest to note that they tested only shale cores because of the following reasons:

(a) The shales were expected to be more compressible than the sands;

(b) Previous tests had demonstrated fairly conclusively that sands and particularly sandstones are relatively incompressible at high pressures;

(c) Relatively undisturbed shale cores suitable for testing could be obtained with less difficulty than sand cores.

Gilluly and Grant (1949), on the other hand, attributed all large scale subsidence at Long Beach to compression of the oil sands. Compressibility was evaluated from the results of one dimensional compression tests performed on core samples from various depths. The oil sands are described generally as sandstones consisting primarily of quartz with feldspar and other minerals and an admixture of clay and silt all bonded together with a calcite cement. The sands had initial porosities varying from 24 to 36 percent; no water content data are given. The core samples were fitted into steel cylinders and an axial load was applied to the sample through steel loading blocks. Apparently there was no provision for allowing any fluid to drain from a sample during the test. The resulting compression curves are reproduced in Figure A.2 and pertinent data are summarized in the following table:

WELL	ZONE	DEPTH (ft)	COMPRESSION MODULUS (psi)
UP 164	Ford	5030	458,300
Z3595	Terminal	3568	290,000
UP214	Tar-Ranger	2578-2603	146,000
W33	Terminal	3205-3213	162,000
W15	Terminal	3600	139,000
UP215	Terminal	3840-3865	72,700
UP223	Tar	2334-2354	27,500
217	Upper Terminal	3359-3379	290,000

According to Taylor (1950) pore space reduction in sandstone is caused by (1) solution at intergranular contacts (2) distortion of weaker grains and minerals, and (3) crushing of sand grains. In her thin section studies of sandstones from two deep wells in Wyoming she noted crushing and yielding of rock fragments and grains of mica and feldspar, but reported no crushing and yielding of quartz grains. She observed that tangential contacts between sand grains decrease exponentially with increasing depth but that sutured contacts (those types of contacts attributed to flow of material under pressure) first develop at a present depth of 4500 to 6800 feet and increase progressively with increasing depth.

In an attempt to produce synthetic quartzite, Fairbairn (1950) compressed sands containing alkaline solutions to pressures as high as 100,000 psi while controlling fluid pressures and temperatures (all temperatures were in excess of 200°C). Photomicrographs of thin sections of the resulting material showed some of the original grains embedded in a matrix of crushed quartz. The sands were deposited in a loose condition in the compression apparatus without any apparent control of procedure. No volume changes were evaluated.

Parasnis (1952) presented a limited amount of experimental data on slurries consolidated to pressures as high as   kg per sq cm. On a plot of void ratio vs pressure (log scale) all compression curves could be represented by a straight line above 40 kg per sq cm. Representative compression indices are shown in the following table:

SOIL	PERCENT FINER THAN 2 (%)	LIQUID LIMIT (%)	COMPRESSION INDEX C_c
Gault Clay	16.7	85.0	0.26
Athleta Clay	20.0	72.7	0.33
Keuper Marl	26.8	23.6	0.12
Globigerine Ooze	Negligible	Not Determined	0.36(e_1=1.44) 0.73(e_1=2.59)
Terrigenous Mud	0.3	Not Determined	0.40

To study the effect of precompression, Parasnis consolidated slurries of Gault and Globigerine soils, unloaded them, dried them, and then rewet the samples (no reasons are given of why this was done), and then recompressed them. In addition, he obtained an undisturbed sample of Athleta Clay and consolidated this beyond the maximum past pressure. The pertinent compression characteristics are summarized as follows:

SOIL	MAX. PAST PRESSURE (kg/cm^2)	RECOMPRESSION C_c	VIRGIN C_c (above mpp)
Gault Clay	500	0.17	0.5
Globigerine Ooze	650	0.18	0.5
Athleta Clay	280	0.20	0.54

It is quite startling that for both the Gault and Athleta Clay the virgin compression index obtained after precompression is about twice the compression index obtained from tests on slurry samples. Unfortunately, Parasnis takes no note of this behavior and it is difficult to offer an explanation without complete details of the sample preparation and test procedures. Nothing unusual is apparent from the shape of the compression curves; they are similar in shape to those generally obtained for precompressed relatively insensitive soils.

Parasnis also made measurements of the side friction force in separate experiments. For a sample with a length of approximately 1 to 1-1/2 cm and a diameter equal to 1-3/8 inches the side friction varied from approximately 8 to 12 percent of the applied load up to pressures of 80 kg per sq cm.

Skempton (1953) presented empirical curves of void ratio versus overburden pressure for clay sediments having different Atterberg Limits (Figure A.3b). At a pressure of 100 kg per sq cm the curves are slightly concave upward in shape, and at this pressure the highly colloidal clays (LL 120) have a compression index of approximately 0.5 whereas silty clays (LL 30) have a compression index of approximately 0.15 to 0.20. The curves, which are meant to be only approximate, are based on laboratory tests and field data; however, the comparison between laboratory data and field data is reasonably good only up to pressures of the order of 100 kg per sq cm (Figure A.3a). At pressures above 100 kg per sq cm the field data for Venezuelan shales (based on data by Hedberg, 1936) indicate a compression index, C_c, of 0.5; this value is much higher than would be expected from the results of one dimensional laboratory compression tests.

Hall (1953) presented a plot of what he calls Formation Compaction (the change in pore volume per unit pore volume per psi.) This plot indicates a constant value of Formation Compaction of approximately 3 percent for porosities varying from 15 to 30 percent.

Studies of the effects of pressure and temperature on the fabric of sands were carried out by Maxwell and Verral (1954) who attempted to reproduce the environmental conditions existing at great depths. Samples of uncemented sand were compressed in "slotted metal capsules 1 inch in diameter and 3/8 inches deep" which were "contained in a cylindrical stainless steel reaction chamber between a piston and anvil of hardened steel". The apparatus was so designed that total axial load, fluid pressure, and temperature could be controlled at any desired level, and provision was made for circulating fluids through the samples during the test. In most of the tests the fluid pressures and temperatures were made equal to the average value expected at the particular depth of burial being reproduced. In this way conditions comparable to those at depths of up to 40,000 feet were achieved. A sample of well-rounded beach sand and a sample of well-rounded sand from a pit were used. Both sands contained mostly quartz grains and when shaken to a dense state in water, a porosity of 37 percent was obtained. Salt water, distilled water, and alkaline solutions were used to saturate the sands before compression. Constant pressures and temperatures were applied for varying periods of time, after which the samples were removed from the apparatus, washed, dried, and immersed in mercury for density determination. Thin sections of the compressed samples were then prepared and examined under the microscope. The more important of the authors' conclusions are:

(a) Intergranular pressure is more effective in producing cementation than fluid pressure;

(b) Most of the reduction in porosity occurs only after a pressure of about 5,000 psi has been reached;

(c) Longer periods of compression give smaller final porosities;

(d) Higher temperatures tend to give smaller final porosities;

(e) Alkaline solutions (sodium carbonate, sodium silicate) reduce the strength of quartz at moderate temperatures;

(f) Seawater forced through compressed samples contains large quantities of dissolved silica (about 0.1 percent);

(g) The mechanism largely responsible for consolidating the quartz sand used is fracturing of grains with resulting interpenetration of grains and rotation of fragments;

(h) Admixtures of clay (25 percent illite) gave much higher densities but reduced the amount of fraturing of quartz grains by a cushioning effect.

However, from the point of view of the present study the data are somewhat limited in value for the following reasons:

(a) The apparatus was not capable of measuring volume changes during compression;

(b) Porosities were obtained only after the loads had been removed and the samples extruded from the apparatus. (It is the writers' experience that considerable expansion occurs upon removal of the load applied to a sample of sand.);

(c) All of the samples apparently were placed in the apparatus in an initial dense state which is not necessarily representative of the state in which natural sands are deposited;

(d) Most of the tests were run at pressures well above those at which crushing begins to occur.

In spite of these limitations, the authors' conclusions outlined above can be used as a guide to future experimental work.

Lowry (1956) discussed factors contributing to the loss in porosity of Quartzose sandstone in Virginia which ranges in age from early Cambrian to early Pennsylvania. He argues that the work of Maxwell and Verral is not applicable in discussing porosity reductions of this particular sandstone. He attributes the reduction in porosity to the solution of silica at points of contact and a redeposition of this silica in the void space as outgrowths of the original grains. According to Lowry, little or no silica is introduced from the outside. Although he feels that this solution only occurs when the stress is sufficiently high, he considers fracturing an insignificant factor in accounting for the loss of porosity.

Laughton (1957) measured wave velocities in sediments consolidated to pressures as high as 1360 kg per sq cm. However, he was interested primarily in sound propagation phenomenon and data sufficient to evaluate compressibility is presented only for a Terrigenous mud. The resulting e-log p curve is shown in Figure A.4.

Drashevska (1958) in a review of U.S.S.R. publications has referred to work in the U.S.S.R. on the behavior of soils at high pressure:

> "E.M.Sergeev gives a summary of works performed up to 1952[5]. In 1936 M. Filatov studied changes in granular composition of clay soils under pressures of 2,000 kg/cm^2[6]. The tables presented show that the granular composition of clay soils show negligible changes only, thus the plastic deformations of clay soils are not connected with the crushing of particles. This conclusion was confirmed by E.M.Sergeev, who studied clay soils which underwent static loading up to 20,000 kg/cm^2[7]. In his experiments the clay soils did not show any change in granular composition, although they were transformed into a monolithic mass with schistosity observed. M. Filatov's studies of sand sub-

jected to pressure showed that the sand grains were mostly split, many of them being reduced to silt sizes. The fraction 1-0.5 mm was the most damaged. E. M. Sergeev presents photomicrographs showing sands before and after the loading[8]. He found that the degree of crushing depended on the mineralogical composition of the sands. This is to be seen from the study of photomicrographs and also from the data of granular analysis. The degree of crushing also depends on the degree of dispersity of the sands and the moisture content."

Although it was not possible to review the original publications, it appears from the above review that only the effect on grain-size distribution was of interest and that the significance of crushing as it affects compressibility was overlooked.

Fatt (1958) performed tests on a Boise sandstone having an initial porosity of 26 percent. Internal and external pressures could be controlled independently during the tests. Fatt has concluded that: "A change in internal pressure, at constant external pressure, is only about three-quarters as effective in changing bulk volume as is a change in external pressure at constant internal pressure." However, there is some question regarding the validity of his interpretation; to arrive at his stated conclusion he assumes that there is no hysteresis in the stress strain curve but does not conclusively prove it. Test data also is presented for Sespe sandstone which undergoes irreversible crushing at 3,500 psi.

Test data by Van der Knaap (1958) show that the bulk and pore compressibilities depend only on the difference between pore fluid and external pressure. The results of tests on a Belait sandstone with a porosity of approximately 15 percent show that the same compression is obtained whether the pressure change is due to a pore pressure decline at constant external pressure or due to an external pressure increase at constant pore pressure. The results of Van der Knaap's tests suggest that Fatt's assumption of no hysteresis may be incorrect.

Weller (1959) summarized the available published porosity data in an attempt to relate porosity to pressure and depth of burial. Although he has made no quantitative evaluation of compressibility, he has concluded that sands and sandstones will undergo much less compaction than mud and shale because the initial porosity is much lower. He stated that most compaction of sands appeared to result from solution at grain boundaries. However, from a study of 13 core samples ranging in age from Cambrian to Cretaceous with porosities ranging from 0 to 10.4 percent he noted that 8 samples contain more quartz cement than could be produced by intergranular solution and thus reasoned that in many sandstones the cementing material undoubtedly must be introduced from an outside source.

Chilinger and Knight (1960) conducted high pressure studies (up to 200,000 psi) on kaolinite, illite and montmorillonite clays. Compression occurring during loading was not measured. They determined the moisture content after each test and apparently care was taken to remove excess moisture before removal of the load. Samples tested were 1.25 centimeters in diameter and although no dimension was given, the sketch presented in their article indicates a sample height of about 1-3/4 times the diameter. Test data were not corrected for any side friction effects. Prior to testing, all clays were hydrated in an excess of distilled water for a period of one week but no further details are given. The plots of moisture content vs pressure (log scale) for both the kaolinite and illite were straight lines between 40 psi and 200,000 psi and the plot for montmorillonite was a straight line between 1,000 and 200,000 psi. Reinterpretation of the curves in terms of void ratio and pressure indicates compression indices as follows (Figure A.4):

CLAY	Cc
Montmorillonite	0.48
Illite	0.24
Kaolinite	0.16

The authors mention, in passing, that they attempted to use layers of sand instead of micro-metallic filtering discs but that the sand crushed above a pressure of about 3600 psi. In addition they noted that the clay tended to squeeze into the sand (unfortunately, no information is presented on the gradation or type of sand used).

DeBeer (1963) in his paper dealing with the scale effect in deep sounding tests presented the results of high pressure compression tests on a Mol sand. This sand is described as a white fine sand consisting almost entirely of quartz with the gradation shown in Figure A.5b. The sand was placed at an initial porosity of 39 percent. Above a pressure of about 350 kg per sq cm the settlements increased linearly with the logarithm of applied pressure; from the data given a maximum compression index equal approximately to 0.37 is indicated (Figure A.5a). The compressibility is due to crushing of grains and the amount of degradation was evaluated by determining the change in grain-size distribution after compression to various pressures (as high as 3310 kg per sq cm) (Figure A.5b). According to DeBeer, Ladanyi observed some degradation of the Mol sand in triaxial tests under a cell pressure of 25 kg per sq cm and a mean pressure at failure of 50 kg per sq cm.

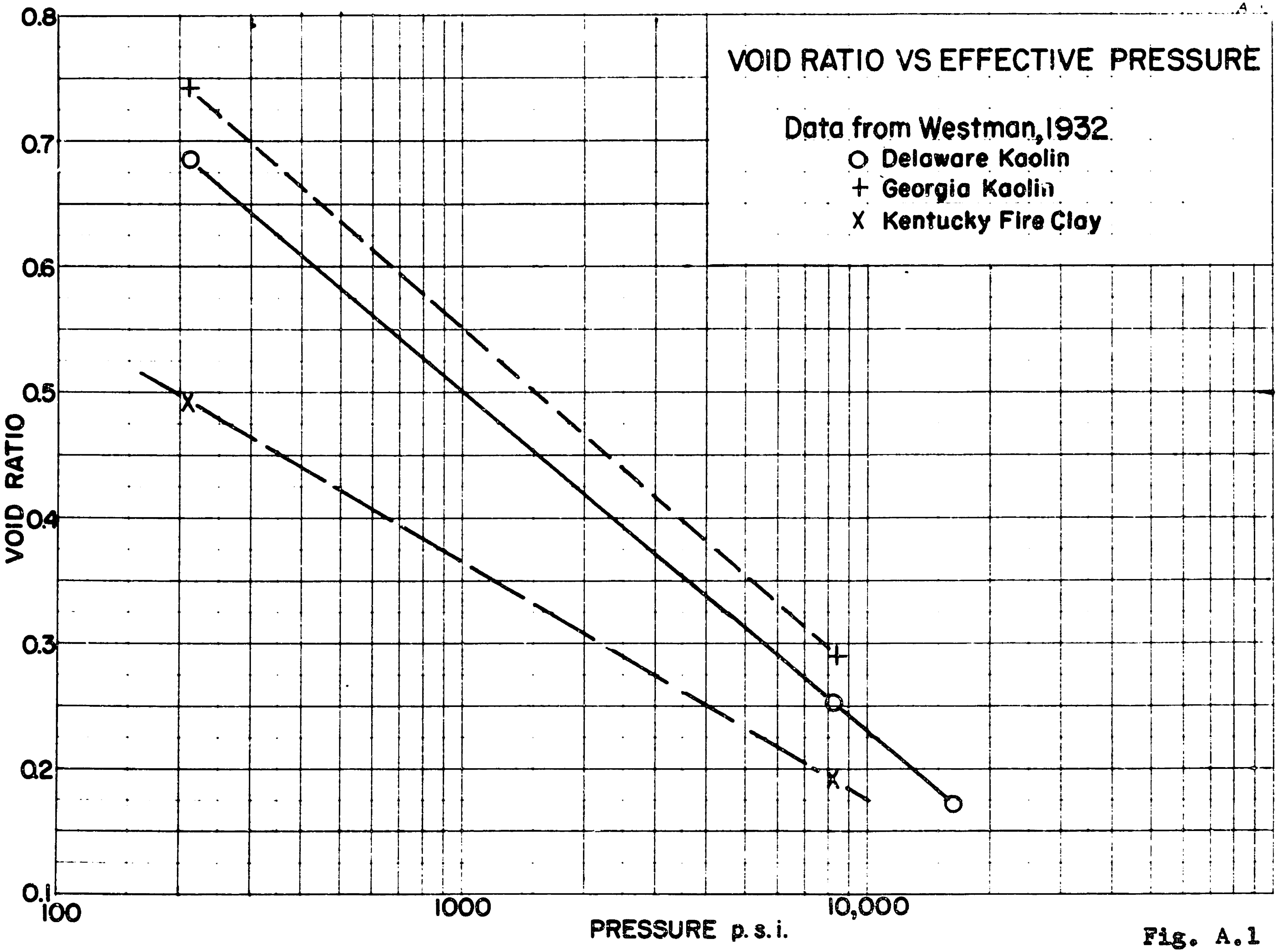

VOID RATIO VS EFFECTIVE PRESSURE
Data from Westman, 1932
○ Delaware Kaolin
+ Georgia Kaolin
X Kentucky Fire Clay
VOID RATIO
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
100
1000
10,000
PRESSURE p.s.i.

Fig. A.1

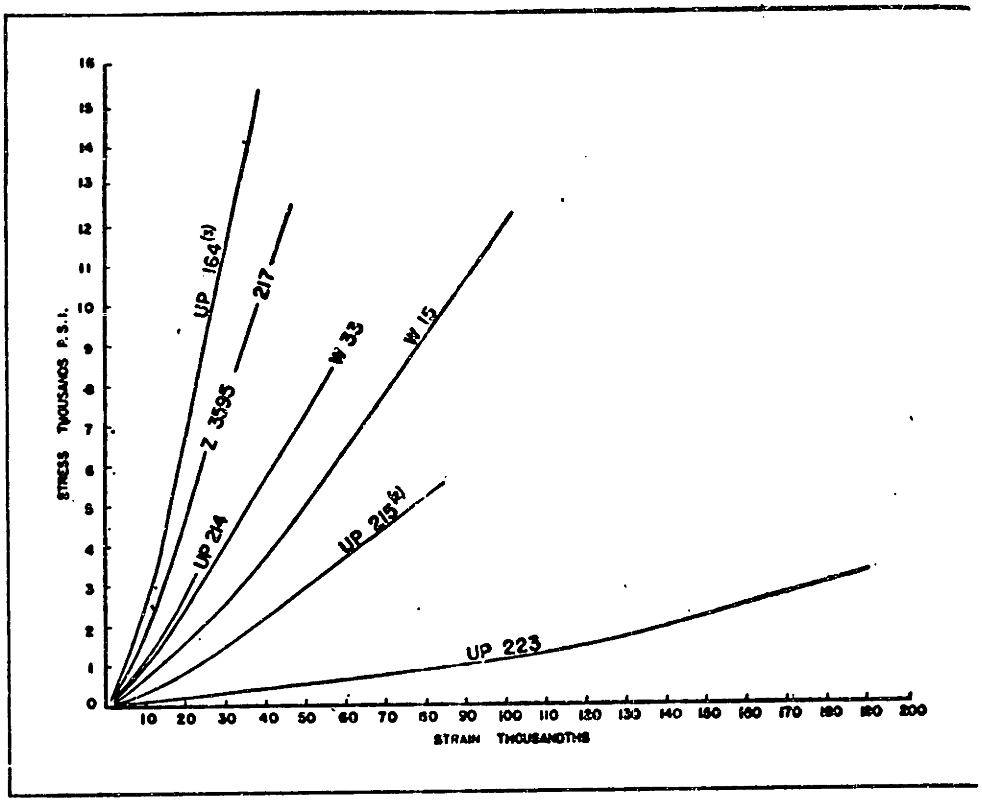


FIGURE 23.—*Stress-strain relations under compression of sandstones from the several oil zones, Wilmington oil field*

The zones from which the specimens were taken are as follows: Ford zone; UP 164; Terminal zone: Z3595, W33, W; UP 215, 217; Tar-Ranger zone: UP 214, UP 223.

Fig. A.2 STRESS-STRAIN CURVES, WILMINGTON OIL SANDS (After Gilluly and Grant, 1949)

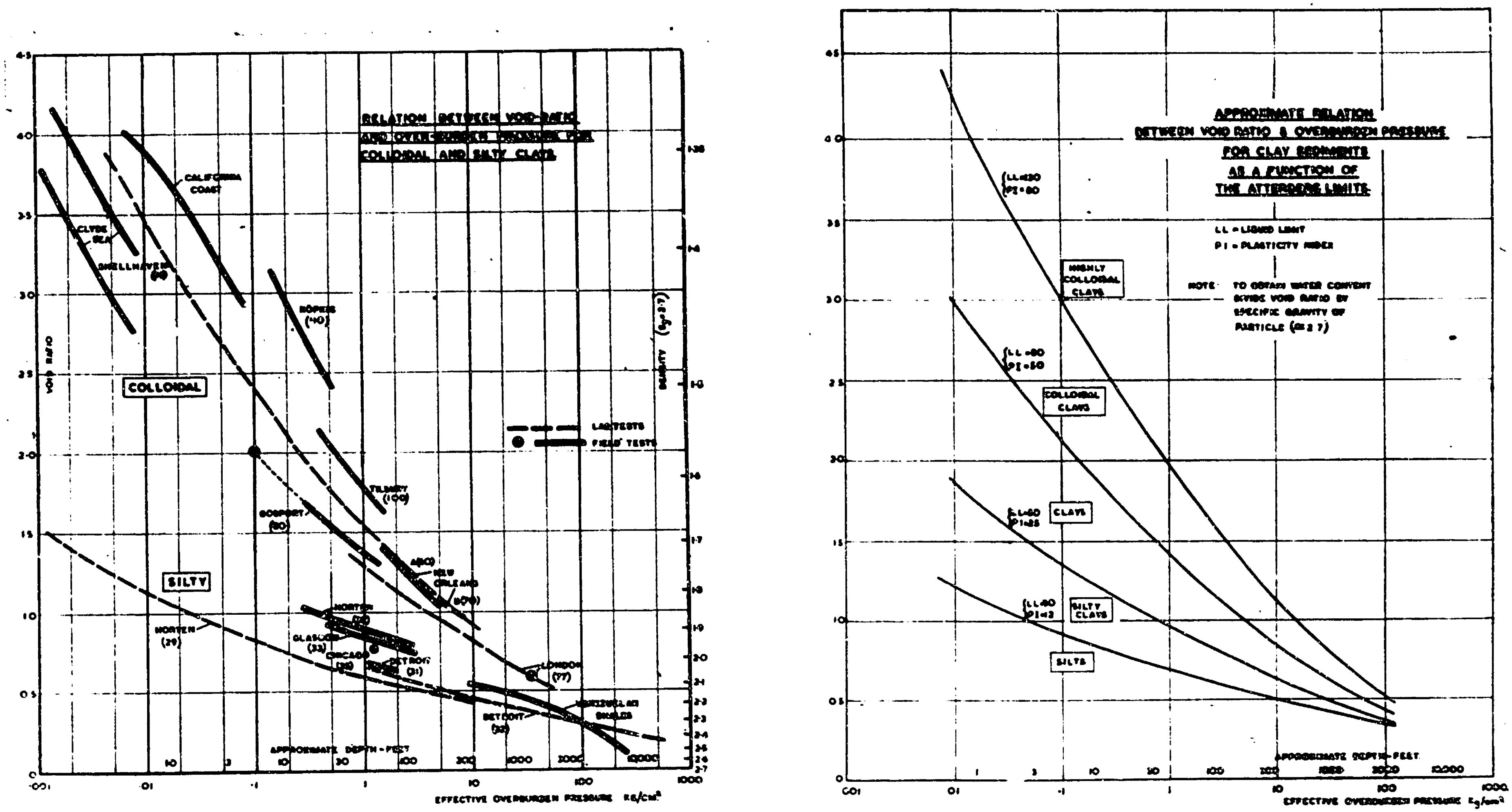


Fig. 11.—Graphs of the relation between void-ratio and overburden pressure for colloidal and silty clays.

(a)

Fig. 12.—Graphs of the approximate relation between void-ratio and overburden pressure for clay sediments, as a function of the Atterberg limits.

(b)

Fig. A.2 COMPRESSION CURVES (After Skempton,1953)

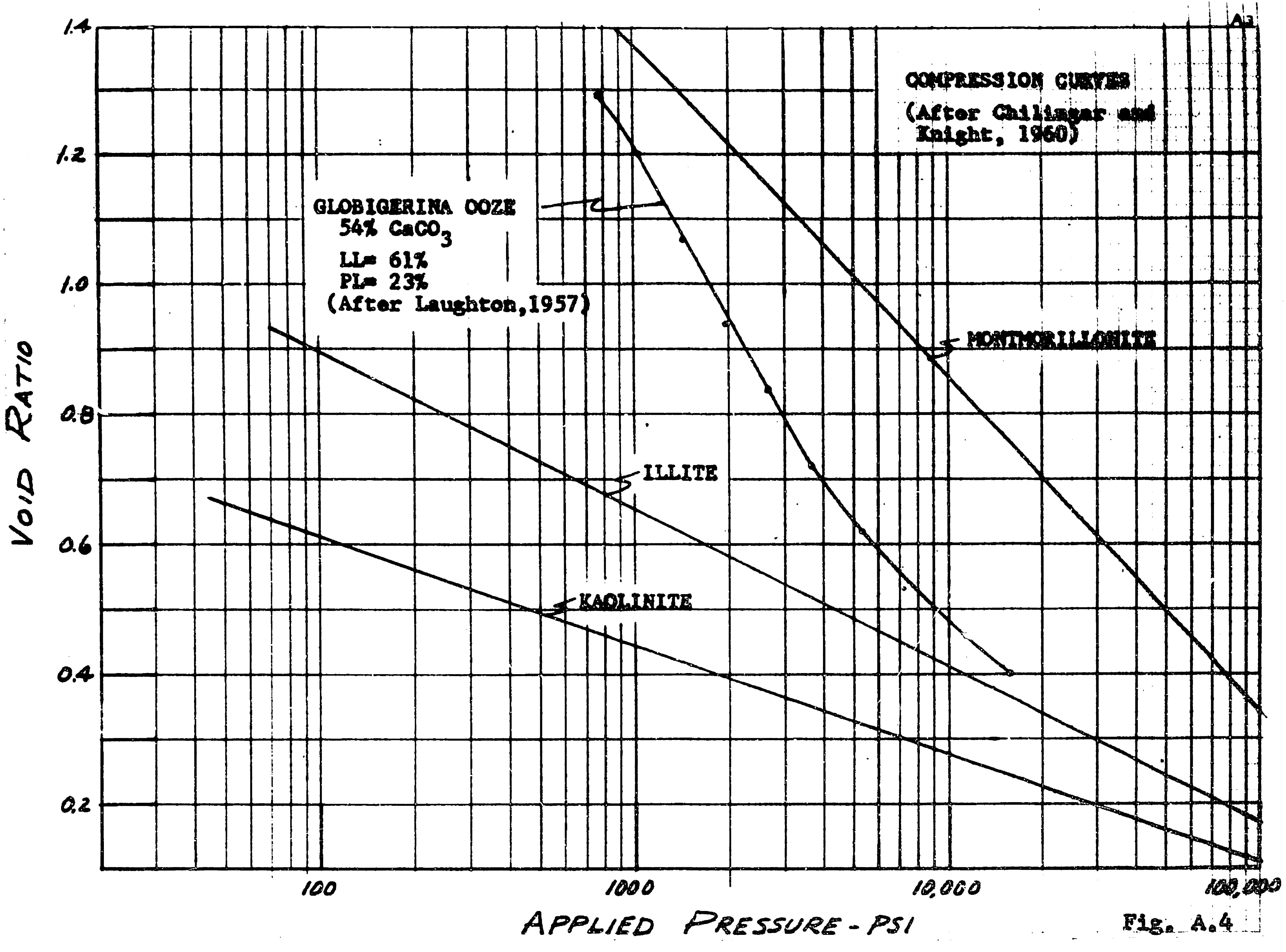
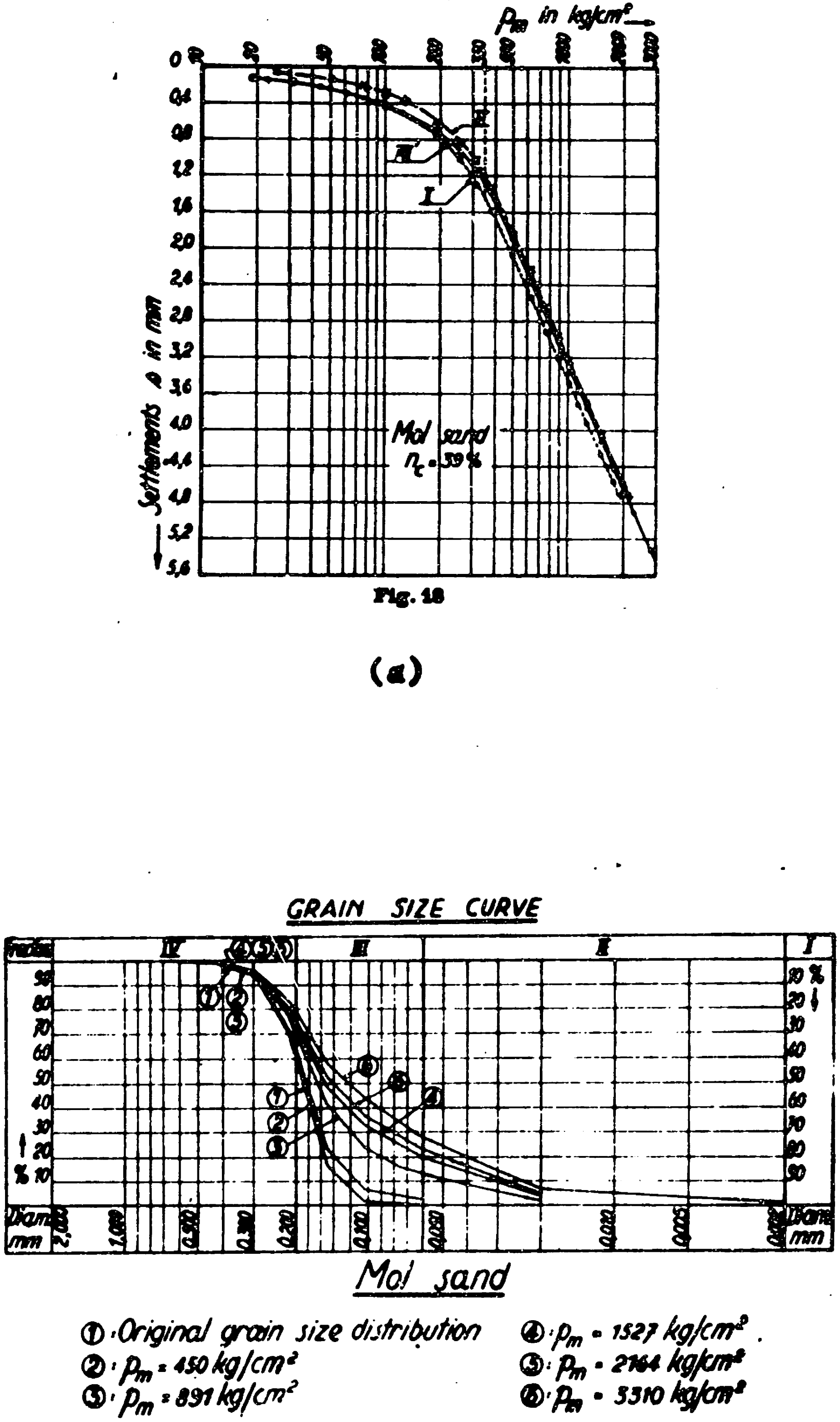

COMPRESSION CURVES
(After Chilingar and Knight, 1960)
GLOBIGERINA OOZE
54% $CaCO_3$
LL= 61%
PL= 23%
(After Laughton,1957)
MONTMORILLONITE
ILLITE
KAOLINITE
VOID RATIO
1.4
1.2
1.0
0.8
0.6
0.4
0.2
100
1000
10,000
100,000
APPLIED PRESSURE - PSI

Fig. A.4



(a)

(b)

Fig. A.5 COMPRESSION CURVES AND GRAIN SIZE CURVES, SAND (After De Beer, 1963)

APPENDIX B: SUMMARY OF EXPERIMENTAL STUDIES OF COMPRESSIBILITY AT HIGH PRESSURES

B.1 INTRODUCTION

The results summarized in this appendix were obtained primarily from one-dimensional, high-pressure compression tests. The research was originally concentrated on clays and shales, but the significant result of the investigation has been the discovery of the relatively high compressibility of sands at high pressures. This high compressibility, which is due to a shattering of individual grains, resulted in compression indices varying from 0.35 to 0.7 for quartz sands in the pressure range of from 1,000 to 20,000 psi.

In addition to high pressure compression tests on both clays and sands, a number of tests of a preliminary nature were run on fine grained soil to study:

(1) Whether or not the maximum past pressure of clay could be evaluated from the shape of the compression curve at high pressures;

(2) The effects of pore fluid changes on compression behavior;

(3) The effect of rate of loading on compression behavior;

(4) The effect of pressure on the rate of secondary compression of an organic silt;

(5) The effect of temperature on the compression behavior of fine grained soils.

A more detailed description and discussion of the performance of the apparatus, test procedures, and results which are summarized in the following sections can be found in two reports prepared by the writer and submitted to the Creole Petroleum Corporation (Refs. B.1 and B.2).

B.2 APPARATUS

Because of the high pressures involved, a special loading frame which was capable of applying constant loads as high as 90,000 pounds for indefinite periods of time was designed and constructed (Figures B.1 and B.2). The loading system consists of a hydraulic ram (a cylinder and hydraulically operated piston) to apply the load and an Emery Load Cell to measure precisely the applied load. The pressure in the ram is maintained constant by a hydraulic accumulator (a cylinder containing a bag which can be filled with nitrogen). The pressure developed in the nitrogen in the bag is transferred to the oil in the accumulator and ram. The gas pressure can be maintained constant by means of a reduction regulating valve attached to a tank of compressed nitrogen. Some difficulty originally had developed in maintaining low loads constant (zero to 5,000 pounds) and the second reduction regulating valve shown in Figure B.1 was added to increase the sensitivity of control at low loads.

With this new valve it became possible to maintain the pressure constant to within ±5 lbs in the range 0 to 5,000 lbs.

A load increment can be applied almost instantaneously. If Valve B (Figure B.1) is closed, pressure in the accumulator can be raised to the desired value without changing the pressure in the ram. After the oil pressure in the accumulator has been raised to the desired value and the reduction valves set to maintain this pressure, Valve B can be opened to increase the pressure in the ram almost instantaneously. As the soil sample compresses under the increased load the piston moves and oil flows from the accumulator to the ram. The reduction valves regulate the flow of gas from the nitrogen tank to maintain a constant pressure in the accumulator and ram.

Existing consolidometers were modified to allow consolidation of clay samples to high pressure (Figure B.3) and a hardened steel compression cylinder was built to allow high pressure compression testing of sands (Figure B.4).

Calibration tests were run with no samples in the consolidometer and compression cylinder to determine the compressibility of each unit.

An estimate of the lateral expansion of the compression cylinder was made. At a vertical pressure of 4,000 psi the corresponding lateral pressure might be of the order of 2,000 psi. For the cross section of cylinder used in the present tests, computations using elastic theory indicate an increase in inside diameter equal to $1.2x10^{-4}$ inches. This computation neglects the restraining effect of that portion of the compression cylinder which has no lateral stress acting on it. The actual change in diameter therefore should be less than the value computed. The computed increase in diameter corresponds to an increase in effective area equal to about 0.02 percent. Because of this small value, the lateral expansion of the steel cylinder was neglected.

To measure the side friction developed between the sample and the compression cylinder during the test, the equipment shown schematically in Figure B.5 was used. The compression cylinder was supported on three struts equispaced around the annulus. Two SR 4 strain gauges were mounted on each strut and the strut calibrated. The side friction load carried by the struts was evaluated from the strain gauge readings.

B.3 PROCEDURES

The principal tests were one dimensional compression tests on samples 1.13 to 2.75 inches in diameter and 0.17 to 0.75 inches in initial height.

Generally, tests on clays were conducted in a manner comparable to the normal consolidation test procedure, i.e., a load increment ratio ($\frac{\Delta p}{p}$) of approximately unity was used and each sample was allowed to consolidate under each load for 24 hours before the next increment was applied.

Tests on sand, in general, followed a similar procedure relative to load increments. However, the loads were applied gradually in order to avoid impact effects. The first reading was usually taken at a load of 10 lbs; the load on each sample was increased in increments, each new load approximately twice the previous load, to a maximum of 20,000 lbs. Below a load of 600 lbs the duration of any load increment depended on the time lag but was usually less than ten minutes; the dense sands showed practically no time lag below 600 lbs. Above 600 lbs each increment duration was generally ten minutes.

The grain-size distribution was determined after each test using standard sieve analysis procedures, and on a number of samples photomicrographs were obtained.

B.4 TESTS ON FINE GRAINED SOILS

B.4.1 Clay Core Samples

High pressure consolidation tests were run on thirty samples of Venezuelan Clays which were obtained from core samples taken from depths of from 2,486 to 4,769 feet below ground surface. These clay samples had liquid limits ranging from 27 percent to 67 percent and plastic limits ranging from 15 percent to 26 percent (Table B.1); when plotted on a plasticity chart (liquid limit versus plasticity index) the data fall in the same range as that of the glacial clays of Boston, Chicago and Canada and for the most part would be classified as inorganic clays of medium or high plasticity. Mineral analyses were determined on three samples representing different depositional environments, and the results are presented in Table B.2. The clay has been identified as containing kaolinite, illite, and montmorillonite.

The individual compression curves and further discussion of test procedures can be found in References B.1 and B.2. The compression curves for the two most compressible core samples (C5 and C11), the least compressible core Sample (C17) and the sample having the smallest void ratio throughout the test (C16) are shown in Figures B.6, B.7, B.8 and B.9 where compression data is plotted as void ratio vs pressure (log scale). Many of the samples tested appeared to have been precompressed to approximately 2,000 psi.

The values of virgin compression index for all tests on core samples vary between 0.11 and 0.26. There seemed to be a tendency for the more oily samples to have higher compressibilities, but there is insufficient evidence available to warrant any generalizations. However, the samples with a Compression Index greater than 0.2 were from depths of about 2,500 to 2,800 feet in Well TJ355, whereas the core samples from a depth of between 4,000 and 4,300 feet in Well LL918, with only one exception, had compression indices between 0.11 and 0.16.

B.4.2 Boston Blue Clay

One high pressure consolidation test was performed on a sample of undisturbed blue gray clay (Boston Blue Clay) which is representative of the glacial clay found in the Boston Basin. The sample tested had a liquid limit of approximately 23 percent. Based on the construction suggested by Casagrande (1936) this soil had a natural maximum past pressure equal to about four tons per square foot. The high pressure test was performed to determine the possibility of evaluating the maximum past pressure at high pressures from the slope of the compression curve.

The sample was consolidated to 122 tons per sq ft, unloaded, and reconsolidated in stages to 974 tons per sq ft. Figure B.10 shows the compression data for the test. During the first unloading the load dropped from 30.5 tons per sq ft to zero overnight; a load of 15.2 tons per sq ft was applied and the sample reconsolidated. During this first unloading the sample had swelled to a void ratio of unity. During the second unloading the sample was allowed to swell to equilibrium under stresses of 490, 122, and 31.5 tons per ft; the load was then dropped to zero and the sample removed.

The dashed portions of the curve in Figure B.10, therefore, represent estimated rebound and loading curves.

Examination of the recompression curve shows that the existence of precompression can be detected from the slope of the recompression curve but the evaluation of the maximum past pressure may not be as precise as would be desired. The curve shown represents the comparison which could be obtained for a perfectly "undisturbed" sample; any disturbance during sampling and preparation would decrease the curvature in the vicinity of the maximum past pressure and make evaluation of the maximum past pressure even less precise.

B.4.3 Tests on Remolded and Resedimented Clay

Three tests were performed to investigate the effect of sedimentation environment on the compression behavior of clay. Soil from Samples B365-11 and B365-17 was ground up and mixed with salt water to prepare a slurry. One sample was tested as prepared. The sample was consolidated to approximately 16 kg per sq cm, unloaded to 4.3 kg per sq cm, and then reconsolidated in increments to 66 kg per sq cm. The resulting compression curve is presented in Figure B.11.

A second sample also was mixed with salt water to prepare a slurry, compressed to about 16 kg per sq cm, rebounded to 4.3 kg per sq cm and then leached with fresh water at this pressure. Owing to the low permeability of the sample, a volume equal to only about half of the void volume was permeated through the sample, even though more than two weeks of leaching was permitted. However, this procedure had reduced the concentration of soluble salt to approximately 6 grams per liter. After leaching, the sample was recompressed in increments to 66 kg per sq cm. The resulting compression curve also is presented in Figure B.11. The compression curve for the leached sample shows no appreciable change in slope above the maximum past pressure and the behavior is essentially the same as that of the unleached sample. There is, however, some slight flattening of each curve above the maximum past pressure.

A sample also was prepared by sedimenting the soil in water having a soluble sale concentration of approximately 4.6 grams per liter. The resulting compression curve, obtained by consolidating the sample in increments to 16 kg per sq cm is presented in Figure B.11. The sample starts at a much higher void ratio than the two previous samples but above a pressure of 1.0 kg per sq cm attains a lower equilibrium void ratio at any given pressure. However, the compression index of this sample, above 1.0 kg per sq cm is essentially the same as the other slurry samples.

B.4.4 Clay Slurry Tests With Oil

To investigate the effect of the presence of oil on the consolidation characteristics of clays, two tests were performed at the lower range of pressures on remolded samples from Core Samples B343-5821. Both samples were prepared in a similar manner but with different percentages of Bachaquero crude oil making up the pore fluid. Two percentages of oil (percent of dry weight of the soil) were used; 13.5 and 23 percent. The samples were initially water wet, the oil was added, and the samples were mixed into a slurry. The resulting compression curves which are essentially the same are shown in Figure B.12. A comparison of the two curves with each other and with the results of the previous compression tests on slurries indicates that the compression characteristics of the slurries are not greatly influenced by the pore fluid.

B.4.5 Test on Beauharnois Clay

A compression test was run on a sample of undisturbed Beauharnois Clay (a very sensitive Canadian clay) having an average initial water content of 76 percent. The purpose of this test was to initiate a study of the effect of load increment ratio and load duration on the compression characteristics of a clay. The compression curve referred to in the following discussion is presented in Figure B.13 where change in thickness is plotted against pressure (log scale).

The test consisted of nine stages:

(1) The sample was consolidated in the normal procedure of doubling pressure increments to 4 tons per sq

ft using one to two-day time durations per increment. The compression produced by this procedure is represented by that portion of the curve between points A and B;

(2) The load on the sample was unloaded to 2 tons per sq ft for 13 days (the resulting rebound amounted to only about 3 percent of the total previous compression);

(3) The sample was allowed to rebound at 2 tons per sq ft for 2 days;

(4) The load on the sample was increased to 8.0 tons per sq ft in increments of from 1/2 to 1.2 tons per sq ft and time durations of 2 days. The resulting compression curve is represented by that portion of the curve from C to D;

(5) The load was held constant at 8.0 tons per sq ft for 24 days. The resulting compression is represented by the vertical line between D and D_1;

(6) The load on the sample was increased to 11.6 tons per sq ft using time increments of 5, 2, 1, 11, 6, and 2 days to obtain the compression curve from D_1 to E;

(7) The load was maintained constant at 11.6 tons per sq ft for 28 days, and the resulting compression carried the curve to E_1;

(8) The load on the sample was increased to 17.9 tons per sq ft in increments of 0.7 to 1.0 tons per sq ft using time intervals of from two to five days to obtain that

portion of the compression curve between E_1 and F;

(9) The load was maintained constant at 17.9 tons per sq ft. The compression occurring between two and thirty-eight days is represented by the portion of the curve between F and F_1.

A number of points are worth noting. The first pertains to the effect of small increments of load on the compression curve. After the sample had been consolidated to 4 tons per sq ft, unloaded to 2 tons per sq ft, and then reloaded in small increments beyond the maximum past pressure, the resulting compression was small until the effective stress exceeded the maximum past pressure by over 1 ton per sq ft. If only that portion of the curve from C to D were available for study, the maximum past pressure of the sample would be estimated at approximately 5.5 tons per sq ft yet it has a known maximum past pressure of 4 tons per sq ft. Beyond 6 tons per sq ft, however, the slope of the curve is comparable to the slope that might be expected had the original compression curve been carried beyond B in the normal fashion.

To determine whether or not the above behavior was due entirely to the effect of precompression, the compression curve was carried to D and with the stress maintained constant, compression continued to D_1. The sample was thus known to be normally consolidated at 8.0 tons per sq ft.

Small increases in stress resulted in very small compressions until the applied stress exceeded approximately 8.8 tons per sq ft; beyond this point the slope of the resulting compression curve again is comparable to what might be expected if the original compression test had been extended beyond Point B.

A similar procedure was repeated at 11.6 tons per sq ft and again small increments of stress produced very small compressions until the maximum past pressure was exceeded by about 1 ton per sq ft. Beyond 12.5 tons per sq ft the slope of the curve is again not too different from what might be expected if the original test had been extended beyond Point B in the normal fashion.

B.4.6 Secondary Compression Study

Samples of an organic silty clay with a liquid limit of 99 percent were prepared by consolidating specimens from a slurry having an initial water content of 139 percent. The initial thickness of individual test specimens ranged from approximately 0.3 inches to approximately 1.7 inches; all samples had a diameter of 2.75 inches. The samples were consolidated in increments to 16 kg per sq cm; the duration of each increment being 24 hours.

The average compression curve obtained from four tests is shown in Figure B.14.

In all the tests a plot of percent change in thickness vs log time could be represented by a straight line in the latter part of each increment. Secondary compression behavior was studied by comparing the slopes of these straight line portions of the plots for the various tests. The secondary compression data are summarized in Figures B.15 and B.16 where percent change in thickness per log time cycle is plotted against applied pressure. The circles represent the average for four tests and the range of values also is indicated.

B.4.7 Temperature Effect on Boston Blue Clay

Sample of Boston Blue Clay was consolidated in two increments to a pressure of approximately 2-1/2 tons per sq ft. The entire consolidation unit was submerged in a water bath and after the sample had consolidated under the pressure of 2-1/2 tons per sq ft for 48 hours, the temperature of the water in the bath was increased to approximately 41°C. The resulting variation of temperature in the bath as a function of time and the resulting compression as a function of time are shown in Figure B.17. The compressions occurring during consolidation under the stress of 2-1/2 tons per sq ft plus the compression during the temperature variations also are shown on a plot of compression vs time (log scale) in Figure B.18. Also drawn in both figures are curves to indicate the probable compression which would have occurred in the sample without a temperature change.

B.5 TESTS ON SAND

B.5.1 Introduction

A number of preliminary compression tests on quartz sand indicated the possibility that at high pressures, sands could have compressibilities equal to or greater than the compressibilities of some clays. Because of this discovery, a rather detailed investigation of the factors influencing the compression of sand at high pressure was initiated. The results of the experimental studies are summarized in the following sections of this appendix. A more detailed discussion of individual test procedures and individual test results can be found in References B.1 and B.2.

B.5.2 Factors Studied in this Investigation

(a) Type of Mineral: Sands containing either a single mineral type (quartz, feldspar, dolomite) or sands containing known percentages of these minerals were prepared and tested. In addition, a number of natural beach and oil sands were tested.

(b) Grain Geometry: (i.e., size, smoothness, sphericity): The size of grains in a test sample was controlled by sieving and tests were performed on samples with grain sizes varying from 1.0 mm in diameter to approximately 0.05 mm. Extremes of sphericity were studied; angular material was produced by crushing a large block of the various minerals; well-rounded soil was available in the form of quartz sand from Ottawa, Illinois. The natural beach sands and oil sands represented intermediate sphericities which could be expected in naturally occurring sands. No detailed study of particle shape was made; the different shapes were compared qualitatively by microscopic inspection. Difficulty was encountered in separating the effect of shape from the effect of size, there being a general tendency in natural sands for the smaller grains to be more angular.

(c) Gradation of Grain Sizes: Grain size distribution was controlled by sieving and the study included gradations varying from uniform to well graded.

(d) The arrangement of grains in any sample was considered to be unquestionably important but a most difficult factor to measure and control. In general, relative density was assumed to be a measure of arrangement and tests were run at the minimum and maximum void ratios obtainable in the laboratory and at an intermediate void ratio to define the effect of density (arrangement).

(e) The influence of pore fluid was studied using air, water, and oil at atmospheric pressure only.

(f) The influence of stress level was studied directly by running all tests over the pressure range of 10 to at least 10,000 psi. The maximum stress in many tests was 20,000 psi and a few tests were run to 40,000 psi.

In one series of tests the side friction was measured and the effect of side friction could therefore be evaluated for this one series.

(g) The influence of time was evaluated by performing two long time tests, one on a uniform well-rounded quartz sand and one on a uniform angular quartz sand.

(h) Miscellaneous

(1) The influence of sample size was studied by testing samples with diameters varying from 1 inch to 2.75 inches and heights up to 1+ inches.

(2) No control of temperature was made, all tests were run at room temperature (70°F).

(3) Tests on "undisturbed" core samples of natural oil bearing sands from Venezuela were conducted and consideration also was given to the effects of precompression, direction of loading and sample disturbance as they might influence the interpretation of tests on core samples.

B.5.3 Description of Sands

(a) Quartz Sand

Sands composed entirely of quartz grains probably do not exist in nature; the purest quartz sands usually contain some other minerals such as ferro-magnesians and heavy minerals. The only relatively pure quartz sands that could be found were the so-called Ottawa sands which are mined by the Ottawa Silica Company and washed and sieved into various size gradations. The fraction of this sand which passes a No.20 sieve and is retained on a No.40 sieve consists almost entirely of well-rounded almost spherical grains, and will be referred to as "20-40 Ottawa Sand". In a similar fashion, "40-80 Ottawa Sand" and "80-140 Ottawa Sand" were obtained. With decreasing grain size, however, sphericity decreases and the finer grains consist mainly of angular particles.

An "80-140 rounded fine sand" was obtained which appeared to have been subjected to considerable abrasion and was therefore much more rounded than the "80-140 Ottawa Sand".

Grains of extreme angularity were obtained by shattering a large block of quartz* with a hammer and then sieving the resulting quartz crystals; 20-40, 40-80 and 80-140 fractions were sieved out and will be referred to as "20-40 ground quartz", etc. The grains were extremely angular and occasionally elongated and spike-like.

Photomicrographs of the various gradations of quartz sands are shown in Figure B.19. Data on the short time compressive strength of quartz is presented in Table B.3.

(b) Feldspar Sand

Since no natural sands consisting entirely of feld-

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*The large blocks of quartz, feldspar and dolomite were made available by Professor Brace of the M.I.T. Geology Department.

spar were known to exist or be available, a highly angular feldspar sand was obtained by shattering a large block of feldspar with a hammer. The 20-40 mesh fraction shown in Figure B.20 is not quite as angular as the quartz because one cleavage plane of feldspar is not very pronounced and does not show up in the photos because the surface is terraced. (Professor Brace of M.I.T. estimated the compressive strength of feldspar to be about two-thirds that of quartz.)

(c) Dolomitic Sand

A dolomitic sand was also obtained by shattering a large block. Figure B.20 shows very well the three cleavage planes typical of dolomite. This type of cleavage results in very angular crystals with plane faces. (Professor Brace estimated the compressive strength of dolomite to be about one-half that of quartz.)

(d) Natural Beach Sands

Sand from Plum Island, Massachusetts, is a medium to coarse dark brown sand composed of subrounded grains primarily of quartz with some feldspar.

The fraction of the sand from Sandy Point, Rhode Island, passing a No. 20 sieve composed primarily of fairly angular (some rounded) quartz particles.

A natural sand from Hawaii was obtained by Professor Whitman of M.I.T. Unfortunately it was slightly contaminated by rust, due to corrosion of the container in which it was shipped. The sand contains irregular subangular grains which contain some air bubbles. The sand is predominantly (70 to 80 percent) a brownish to black volcanic glass-crammed with tiny crystals of pyroxene and calcum feldspar, with up to 20 percent pyroxene fragments and 2 to 5 percent each of olivene, lemonite and brownish black opague. A photomicrograph of this sand is shown in Figure B.20(d).

(e) Oil Sands

Compression tests were run on "undisturbed" and resedimented samples prepared from cores from Wells LL-87 and TJ-25A. The samples from LL-87 were generally a medium sand containing crude oil. A typical grain size distribution curve for the sample from LL-87 is shown in Figure B.56, and as shown by the photomicrograph in Figure B.57(a) it is comprised of a high percentage of quite angular grains. However, horizontal stratification was very pronounced with marked variation in grain size in the vertical direction. Because of this stratification, the average grain size distribution is not necessarily indicative of the type of soil being tested, and it was not possible to make a study of the effect of this stratification.

The sample from TJ-25A was a very fine sand which had been designated a shale on the transmittal list.

B.5.4 Preparation of Test Specimens

Preliminary tests showed that not only was the density of the sample at the beginning of the test a very important factor in the compression behavior, but also the manner in which the density was obtained. It was found that two samples of the same sand prepared by different techniques but having the same initial density behaved quite differently. It is felt that this was due to variations in density within the sample rather than to differences in arrangement of grains at constant density. Although there is no definite proof of this, the effect was most pronounced in the case of the 20-40 Ottawa Sand, the grains of which are almost spherical. For this material it is hard to imagine much variation in arrangement of particles at a constant density, and the only cause of behavior differences would seem to be density variations throughout the sample.

Because uniformly dense samples are necessary in order that comparisons can be made between one test and another, the method of preparation was subjected to careful scrutiny.

Originally the method described by Kolbuszewski (1948) was used.

A known weight of sand was placed in the cylinder and the plunger inserted and held about an inch above the top of the sand; the whole apparatus was then inverted and returned to its upright position. The plunger was allowed to drop gently into contact with the sand, and a small weight was placed upon it to smooth the uneven surface of the sand. A reproducibility to ±0.0005 inch for a sample of about 1/2-inch height could be achieved. This extraordinary reproducibility made it ideal for tests in which the effects of variables other than density were being studied.

Later this procedure was modified slightly. To obtain loose sand samples a test tube with ten grains of sand was quickly tilted to a vertical position so that the sand fell vertically into the compression cylinder through a distance of about five inches. When medium dense sand was desired, the sand was poured into the cylinder as above, the piston put in place, and the cylinder struck repeatedly until the desired void ratio was obtained. Very dense sand was obtained by holding the cylinder against an operating air compressor.

The loosest and densest state of each soil could be reproduced fairly well, but it was not possible to satisfactorily reproduce intermediate values. Because the loosest and densest conditions were not the same for all the minerals, each mineral was tested at at least three different initial void ratios--the maximum, the minimum, and an intermediate value. Interpolation was then used to evaluate the compression curve for any other initial void ratio.

One sample of 20-40 Ottawa sand was prepared by spooning the wet grains into the cylinder and then vibrating the apparatus gently until the sand settled into an approximately homogeneous state. In this way a looser density than that obtained by tipping was produced.

B.5.5 Computation and Plotting of Test Data

A sample computation sheet which contains the complete data and calculations for one test is presented in Figure B.21. The data sheet was originally designed for clay consolidation tests and therefore contains spaces for some data not used in the compression of sands. Also, the term "ring" should be interpreted as "compression cylinder", and the column marked "disc correction" should be interpreted as "correction for compression of apparatus", this value being taken from a calibration curve which had been prepared.

For computation of the solids height, $2H_O$, a value of specific gravity equal to 2.67 was assumed in all of the tests on sand.

Choice of the semilogarithmic plot for presenting the results of the compression tests is somewhat arbitrary, but trial plots on linear paper and double-logarithmic paper showed no particular advantages. The semi-logarithmic plot has the advantage of being familiar to soil engineers because of its use in clay consolidation tests, and the large range of pressures is more conveniently represented on a logarithmic scale.

To facilitate comparisons, percent strain has been used instead of void ratio for some tests. In this way curves of different tests all start at approximately the same point even though the initial void ratios vary considerably.

The results of some sieve tests also are presented. Because of the small quantities of sand involved, 3-inch sieves were used and weights were all determined to the nearest hundredth of a gram.

B.5.6 Results of Tests on Quartz Sands

(a) The Effect of Initial Void Ratio

The pressure at which appreciable crushing of grains begins to occur was found to be dependent to a large extent on the initial density of the sample. Because this pressure also corresponds to the point at which the compressibility increases, a study of the effect of initial void ratio on the compression behavior of several types of sand was initiated. The major difficulty encountered in this study was the separation of extraneous variables, principally the method of obtaining any given density. A comparison of Tests C2 and C3 in Figure B.22 illustrates the fact that two identical samples with the same overall initial density behave quite differently when prepared by different methods.

(1) 20-40 Ottawa Sand

The results of six tests on 20-40 Ottawa Sand are plotted in Figure B.22. Test No. C1 differs from the others in that it was prepared by placing wet sand into the cylinder and then applying vibration until the sand had settled into a homogeneous mass. The higher initial void ratio may be due to the presence of the water. The Sample in test No. C2 was deposited in the cylinder by slowly pouring the sand through a 3-foot high tube; the poorly defined break-point of the compression curve is thought to be due to density variations within the sample. The sample in test No. C3 represents another attempt to obtain a uniform medium density by first using the tilting procedure and then vibrating the sample with the plunger locked. Samples for Tests C4 and C5 were prepared by pouring the sand slowly into the cylinder through a funnel while the apparatus was being vibrated and then vibrating the apparatus with a load applied to the plunger. The sample for Test B2 was prepared by tilting.

Apart from C1 there is a general trend for the pressure corresponding to the break-point to increase with increasing initial densities. After the break-point has been reached, all of the curves fall within a rather narrow, slightly curved band, with the initially looser samples occupying the lower portion of the band. No explanation for this tendency for the curves to cross has yet been found.

(2) 40-80 Ottawa Sand

The results of three tests on 40-80 Ottawa Sand are shown in Figure B.23. Sample C6 was prepared by tilting, Sample C7 by tilting and then vibrating with the plunger locked, and C8 by tilting and vibrating with a weight on the plunger. The curves show the same tendency as those of the 20-40 Ottawa Sand except that the break-point pressure is increased, and the final band is located at void ratios about 0.05 higher. There is less tendency for the curves to cross than with the 20-40 Ottawa Sand.

(3) 80-140 Ottawa Sand

The four samples whose compression curves are presented in Figure B.24 were prepared in the following manners:

No. C9, tilted; No. C10, tilted and vibrated with the plunger locked; No. C11, poured through a funnel and vibrated with the plunger locked; No. C12, poured and vibrated with a weight on the plunger.

The same observations as for the 40-80 Ottawa Sand apply, the break-point pressure has increased and the final band has shifted upward.

(4) 20-40 Ground Quartz

The three tests presented in Figure B.25 were prepared as follows: C13, tilted; C14, poured through a funnel; C15, poured and vibrated with a weight on the plunger. In these tests the break-point is less well defined, apparently because the very angular grains start to crush even at very low pressures. All of the curves merge into a fairly narrow band which has a flatter slope and is considerably lower than that of the 20-40 Ottawa Sand.

(5) Conclusions

The following conclusions can be drawn regarding the effect of the initial void ratio: (a) the pressure at which the compression curves break increases with increasing initial density; (b) after the break-point has been reached, the compression curve is relatively independent of the initial density for a given gradation and angularity. The "break-pressures" varied from about 3,500 psi to about 9,000 psi for the 20-40 Ottawa sand with the initial densities used. For the 40-80 Ottawa sand the range was from approximately 4,500 to 8,000 psi, and for the 80-140, from 4,000 to 7,000 psi. The smaller range of break-pressures for the finer gradations may be a reflection of the smaller range of initial void ratios obtained for these samples. In the case of the ground quartz, the results are less conclusive but seem to indicate the same behavior pattern as for the Ottawa Sand.

(b) Effect of Grain Size

By making use of the data presented in the previous section, the effect of grain size variations on the compression behavior of Ottawa Sand can be studied. Additional tests were performed on 40-80 and 80-140 loose ground quartz to allow a similar comparison for ground quartz. In this type of study the problem of separating out the variable angularity is practically insoluble. As previously mentioned, the Ottawa Sand becomes increasingly angular as the grain size decreases; the same is true to some extent even for the ground quartz. Thus it is difficult to determine how much of the difference between the behavior of different grain size fractions is due to angularity variations and how much is due to grain size variations.

(1) Ottawa Sand

Tests B2, C6, and C9 are replotted in Figure B.26. All of the samples were prepared by the tilting method and therefore start at different void ratios. However, because the final portion of each curve for a given gradation is relatively independent of the initial void ratio. a comparison can be made. The most striking feature is the higher void ratios obtained for the finer material for any pressure above the break-point. That this tendency is not caused by the greater angularity of the finer grains is demonstrated by the fact that a test on the sample of 80-140 "rounded" Ottawa sand (F1) shows somewhat higher void ratios. Furthermore, at high pressures tests on 20-40 ground quartz indicate smaller void ratios than tests on 20-40 Ottawa Sand. It thus seems certain that the smaller the average grain size for a given angularity, the higher will be the void ratio at any pressure above the break-point. It also appears that although the break-point is less clearly defined for the smaller grain sizes, the pressure at which it occurs increases slightly as the average grain size decreases. Further, the final portions of the curves are less concave for the finer grain sizes, that of C9 being almost a straight line, whereas the B2 curve is highly concave.

(2) Conclusions

Two conclusions can be drawn as to the effect of grain size: (a) as the grain size decreases, higher void ratios can be expected for any given pressure above the break-point, and the upward concavity of the final portion of the curve becomes less accentuated; (b) the pressure at which the break-point occurs seems to be almost independent of the grain size when the same method of sample preparation is used, the finer fraction possibly giving slightly higher values. However, if samples of equal initial void ratio are compared, the break-point pressure increases as the average grain size decreases. It appears that the break-point pressure is dependent chiefly on the relative density but because no convenient method of defining the maximum and minimum densities seems to exist, no attempt has been made to define the relationship numerically. It seems likely that the tilting method gives a good approximation of the minimum density attainable in the laboratory without resorting to bulking, but the suggested methods of obtaining the maximum density all utilize hammering or pounding of some sort which almost certainly crushes many types of sand and therefore are not desirable.

(c) Effect of Gradation

The results of four tests which were run in an attempt to evaluate the effect of different gradations are shown in Figure B.27; Test B2 a test on 20-40 Ottawa also is plotted on the same sheet to serve as a reference for comparisons. All of the samples were prepared by the tilting method, and as was to be expected, all had initial void ratios smaller than the 20-40 sample. It is interesting to note that the gap-graded sample of Test E3 had an initial void ratio well below that of the well-graded sample of Test E2, probably because the fine material fills the voids of the coarse grains more efficiently. As would be expected the densest packing was obtained with the well graded "Ottawa".

The break-points all occur at approximately the same pressure except for a slight tendency toward higher break-point pressures with decreases in median grain size and decreasing initial void ratio. Because the final portion of the curve of Test E1 agrees more closely with that of B2 than to a similar curve for 40-80 Ottawa sand (Test C6, Figure B.26), it suggests that the larger grains control the compression behavior more than the smaller ones. This same tendency can be observed in Tests E2 and E3 where the median grain size is about equal to that of the 40-80 Ottawa Sand, yet the curves fall well below that for the 40-80 curve.

However, since such comparisons can be made only for pressures that are above about 8,000 psi, they probably are not of great practical interest. At pressures slightly above the break-point pressure, the curves are less steep and less concave than those of the uniform samples tested previously.

The same tests are plotted again in Figure B.28 in terms of percent strain (percent of initial thickness). Samples with wider grain size ranges (B2 and E3) are more compressible at low pressures but considerably less compressible than the 20-40 sand at pressures above the break-point; Test No. E1 falls into an intermediate position.

In summary, the data suggest that the compression behavior of well-graded samples is influenced by the finer fraction at low pressure and by the coarser fraction at pressures above the break-point. However, the number of tests performed is not sufficient to make definite conclusions.

(d) Effect of Angularity

By comparing tests of similar grain size but varying angularity, some measure of the effect of angularity can be obtained.

(1) 20-40 Sieve Fraction

In Figure B.29 the results of Tests B2 and C13 are plotted; these represent the extremes of angularity available in the 20-40 sieve fraction. The angular material has a much higher overall compressibility than the rounded material, but for pressures above 4,000 psi, the rounded material has a higher compression index. At about 20,000 psi the two compression curves appear to merge.

(2) Conclusions

For any given process of deposition increasing angularity will generally result in higher initial void ratio, higher overall compressibility, and lower break-point pressures. Above the break-point pressure the more rounded sands will be more compressible, but for any given pressure will have a higher void ratio than the angular sands.

(e) Degradation During Compression

Grain size distribution curves of samples of 20-40 Ottawa sand before and after compression to various pressures are presented in Figure B.30(b) and curves for the initially well graded Ottawa are presented in Figure B.30(a).

Photomicrographs of the 20-40 Ottawa Sand before and after compression are shown in Figure B.31.

(f) Time Effects

In early tests it was noticed that after the application of a load increment, the sample continued to compress at a decreasing rate for a considerable time. When the compression dial readings were plotted against the logarithm of time, a straight line was obtained. This straight line relationship was found to hold for any time interval from a quarter of a minute up to several days - several days being the maximum time in the initial test series.

In order to define the compressibility, it became necessary to use a convenient duration of the load increment. Because there is no such phenomenon as "primary" compression in the case of sands a series of tests was run to study the effect of load increment duration.

One series of tests was run on loose 20-40 Ottawa Sand with 2-, 10-, and 50-minute load durations and a second series of tests was run on 20-40 ground quartz, since it had been learned that this material shows appreciable time lags even at small pressures. From these tests, it appeared that a duration of 2 minutes would give considerably less compression than 10 minutes but that the advantage of increasing the time to 50 minutes would not compensate for the reduction in the number of tests that could be run. Using 10-minute time intervals, two and sometimes three tests could be prepared and run in one day, whereas with 50-minute intervals only one test could be prepared and run per day. Time interval was therefore standardized at 10 minutes for all tests in which the time variable per se was not being studied. Unless otherwise mentioned, all tests have 10-minute load increment intervals.

Linear and semilogarithmic plots of compression dial readings vs time for a load increment maintained constant for 205 minutes are shown in Figures B.32 and B.33 and represent the type of compression versus time behavior to be expected once crushing begins.

Natural sands are generally subjected to a very slow increase in load due to the deposition of sediments above them. Thus several million years might be required for a column of sediments 5,000 feet thick to build up over a stratum of sand. If the sand layer is then opened up for production of oil, the resulting decrease in fluid pressure will cause a relatively rapid increase of effective stress within the stratum. In order to simulate this general sequence of loading in the laboratory one long duration test was performed on a sample of well-rounded 20-40 Ottawa sand in which the load was held as nearly constant as possible over a three month period. The sample was loaded to 5,000 psi using time intervals of 10 minutes between successive increments. Originally it was intended to maintain this pressure constant, but because of infrequent attendance and temperature changes, the pressure gradually increased to 6,000 psi between June and October. Because of this increase it became difficult to properly interpret the resulting time lag curve. In October the pressure was increased in increments of varying magnitude and duration to a maximum of

20,000 psi.

The resulting compression curve (void ratio vs log pressure) is shown in Figure B.34. The time duration of each increment of load is indicated directly on the figure. The compression vs log time curves for the first three load increments applied after the long duration loading are shown in Figures B.35, B.36, and B.37.

A long duration test also was run on a sample of 20-40 ground quartz and the resulting compression curve also is shown in Figure B.38.

Natural increases of load and insitu increases brought about by man are gradual continuous processes compared to the intermittent increases used in the normal method of consolidation testing. However, it is possible to draw some conclusions regarding the probable field behavior from the results of tests loaded in increments. The data suggest that for continuous rates of loading a series of parallel compression curves will be obtained - the slower the rate of loading, the lower the curve. If at any pressure the rate of loading is decreased, the compression curve will increase in slope until the curve approaches a new line corresponding to the curve for the decreased rate of loading. If, on the other hand, the rate of loading is increased, the slope will decrease almost to zero until the increased rate curve is reached and surpassed slightly, whereupon a sudden collapse may occur, bringing the curve down to a position below the increased-rate curve. Continuation of the loading at the new rate will eventually result in the curve merging with the curve corresponding to the higher rate of loading.

(g) Side Friction

Originally a detailed study of side friction was not made; a series of tests run on samples of different thicknesses in the compression cylinder suggested little effect as long as the height was limited to about one half inch. The effect of friction was neglected in computations. Subsequent to the other studies, a series of tests was performed on 20-40 Ottawa Sand placed at various initial densities and sample thicknesses to investigate side friction and to obtain "corrected compression" curves.

Uncorrected and corrected curves are shown in Figures B.39 and B.40 for the tests on samples with initial heights of 0.17 and 0.7 inches. The slope of the compression curve is essentially unaffected by the correction for side friction.

The corrected curves for the series of tests on 20-40 Ottawa Sand in which side friction was measured are shown in Figure B.41.

This series of tests in which the side friction load was measured directly shows that above the break-point the total side friction force varies from about seven percent of the applied load for a sample with an initial height of

0.174 inches to from 25 to 30 percent for a sample with an initial height of 0.7 inches. If no correction is made the indicated compression curve will be shifted horizontally to the right by the amount of the side friction relative to the true compression curve.

The tests in which side friction was measured also were used to evaluate lateral pressures developed during the tests but are not considered here.

B.5.7 Results of Tests on Various Minerals

The general compression behavior of quartz sand at high pressure had been reasonably well established by the results presented in the previous sections. To investigate the influence of mineral composition high pressure tests were run on 20-40 mesh samples of: (a) ground quartz; (b) ground feldspar; (c) ground dolomite, and (d) a beach sand of volcanic origin from Hawaii. The compression curves for the four different samples are shown in Figures B.42 through B.45. The grain size distribution curves of the four samples before and after compression to 20,000 psi are shown in Figures B.46 through B.49. Photomicrographs of the four samples before compression are shown in Figure B.20 and after compression to 20,000 psi in Figure B.50.

B.5.8 Results of Tests on Natural Beach Sands

Two additional natural beach sands one from Plum Island, Massachusetts and one from Sandy Point, Rhode Island, were tested to high pressures. The compression curves are shown in Figure B.51.

The grain size distribution curves for the Plum Island Sand before and after compression to 6,000 psi are shown in Figure B.52. Inadvertently, grain size distribution was not determined for the Sandy Point sample.

B.5.9 Results of Tests on Oil Sands

(a) Undisturbed Sand Core Samples

The compression curves obtained from the various tests on sand core samples are shown in Figure B.53. The maximum compression index for each test is indicated directly on the figure.

During compression it was observed that oil was generally squeezed out of a sample at about 500 psi. Computations based on measured oil contents indicated that the samples were still unsaturated when oil was being extruded. By determining the final oil content, computations indicate that the samples tested were essentially saturated at about 20,000 psi.

(b) Effect of Oil in Pore Space

A series of tests with and without oil in the pore space were run on samples prepared from Sample LL87-25. The compression curves at various initial densities with oil present in the pore are shown in Figure B.54, and the compression curves for samples in which the oil was removed with Xylene before compression curves are shown in Figure B.55. The grain size distribution curves for the oil sand before and after compression to 20,000 psi are shown in Figure B.56 and photomicrographs of the sand before and after compression to 20,000 psi are shown in Figure B.57.

(c) Effect of Disturbance

A comparison of the results of the tests which were performed to study the effect of the presence of oil with the results of tests on the undisturbed samples suggests that disturbance of the sample during preparation may have an effect on the compression results. The test results shown in Figures B.54 and B.55, indicate maximum compression indices varying from 0.30 to 0.41 on completely disturbed samples compared to the maximum value of 0.27 for the "undisturbed" sample. In addition, the maximum compression index occurred at lower pressures for the completely disturbed samples than it did for the undisturbed sample. To study the possible effect of disturbance during sample preparation, and to aid in evaluating how reliable the results of tests on undisturbed sand cores are likely to be, the following series of tests was run on soil from Sample LL87-12:

Test No. 12.4 was run on a sample which had been completely disturbed and placed in the 2-inch diameter ring at a void ratio of approximately 1.4. The sample was compressed to 1540 psi, rebounded to zero, and then re-compressed to 25,000 psi.

Test No. 12.5 was run on a disturbed sample placed at an initial void ratio of approximately 1.1. The sample was compressed to 2860 psi, rebounded to zero, and then recompressed to 25,000 psi.

The resulting compression curves of these two tests are shown in Figure B.58. These compression curves show the compression curve during unloading and recompression with no sample disturbance and represent the compression behavior of an ideally undisturbed sand core sample. A completely disturbed sample of the same soil was placed in the 4.5 inch consolidation ring. The sample was compressed to 2850 psi. The sample was then rebounded to zero pressure, removed from the consolidation ring and a 2-inch diameter sample was then cut from this large sample. The 2-inch diameter sample was then compressed to 25,800 psi (Test 12.7).

The resulting compression curve is shown in Figure B.59 and a comparison with the curves of the two previous tests shows the influence of sample preparation on the resulting compression curve for a sample trimmed from an ideal undisturbed sample.

REFERENCES

B.1 M.I.T., Soil Engineering Division, "Research on The Study of Fine Grained Soils Consolidated Under High Pressure", submitted to The Creole Petroleum Corporation, Maracaibo, Venezuela, September, 1958. Unpublished

B.2 M.I.T., Soil Engineering Division, "Research on The Study of Fine Grained Soils Consolidated Under High Pressure - FINAL REPORT", Submitted to The Creole Petroleum Corporation, Maracaibo, Venezuela, October, 1959.

TABLE B.1

VENEZUELA SHALE CORES

TEST	WELL NO.	DEPTH	LIQUID LIMIT (%)	PLASTIC LIMIT (%)	ORIG. SAMPLE HEIGHT (INCHES)	MAX. COMP. INDEX C_c
C1	B347	4769	39.8	17.9	.847	.10
C3	TJ355	2764	57.7	21.8	.591	.20
C4	TJ355	2737	63.1	26.1	.666	.173
C5	TJ355	2724	36.0	19.4	.845	.220
C6	LL918	4143-4170	38.6	20.3	.748	.200
C7	TJ355	2726	39.5	20.2	.733	.24
C8	TJ355	2778	53.0	18.5	.750	.184
C9	TJ355	2814	36.1	18.2	.751	.227
C10	TJ355	2822	47.8	23.9	.750	.221
C11	TJ355	2816	39.3	20.2	.751	.256
C12	TJ355	2814	35.3	18.8	.750	.241
C13	TJ355	2763	48.7	21.2	.751	.234
C14	TJ355	2741	63.1	26.1	564	.190
C15	TJ355	2544.5	40.4	16.9	.751	.138
C16	B347	4768	42.1	19.9	.750	.125
C17	LL918	4143 -70	39.2	21.3	.685	.108
C18	TJ355	2486.5	35.4	17.6	.750	.145
C19	TJ355	2748	54.8	20.6	.701	.182
C20	LL918	4001	57.9	20.9	.749	.111
C21	LL918	4276.5	28.1	16.3	.734	.122
C22	LL918	4296	27.7	14.7	.749	.16
C23	LL918	4275.5	26.6	14.8	.751	.14
C24	LL918	4277.0	31.2	15.2	.580	.11
C25	LL918	4294.0	27.3	14.9	.751	.15
C26	B57	4549.5	-	-	.726	.21
C27	TJ355	2485.5	39.9	13.6	.751	.114
C28	-	2777.2	67.3	17.5	.750	.216
C29	-	2544.5	40.4	16.9	.751	.13
C30	TJ355	2573	48.7	19.0	-	.195
C31	TJ355	2759	39	18.8	-	.21

TABLE B.2

MINERAL ANALYSIS OF CORE SAMPLES

							COMPOSITION (wt.%)			
Sample	Environment	pH	Soluble Salts (m.eq/100g)	Cation Exch. Capacity (m.eq/100g)	Fe_2O_3 Percent	Organic Matter	Kaolinite	Hydrous Mica	(I:M)	Quartz
TJ355-2670'	Brackish	8.1	3.6	28	2.3	2.2	15	35	1:1	20
TJ355-2485.5'	Non-Marine	8.8	1.4	14	1.0	0.1	15	65	4:5	20
LL918-4277'	Shallow Neretic	7.9	2.5	32	0.9	1.3	20	65	2:1	15

NOTE: The hydrous mica is an interstratified illite-montmorillonoid. The ratio of illite to Montmorillonoid (I:M) is indicated in the Table.

TABLE B.3

THE COMPRESSIVE STRENGTH OF QUARTZ

Short-time compressive strength of unjacketed materials:

Quartz, single crystals com. parallel to a c axis:

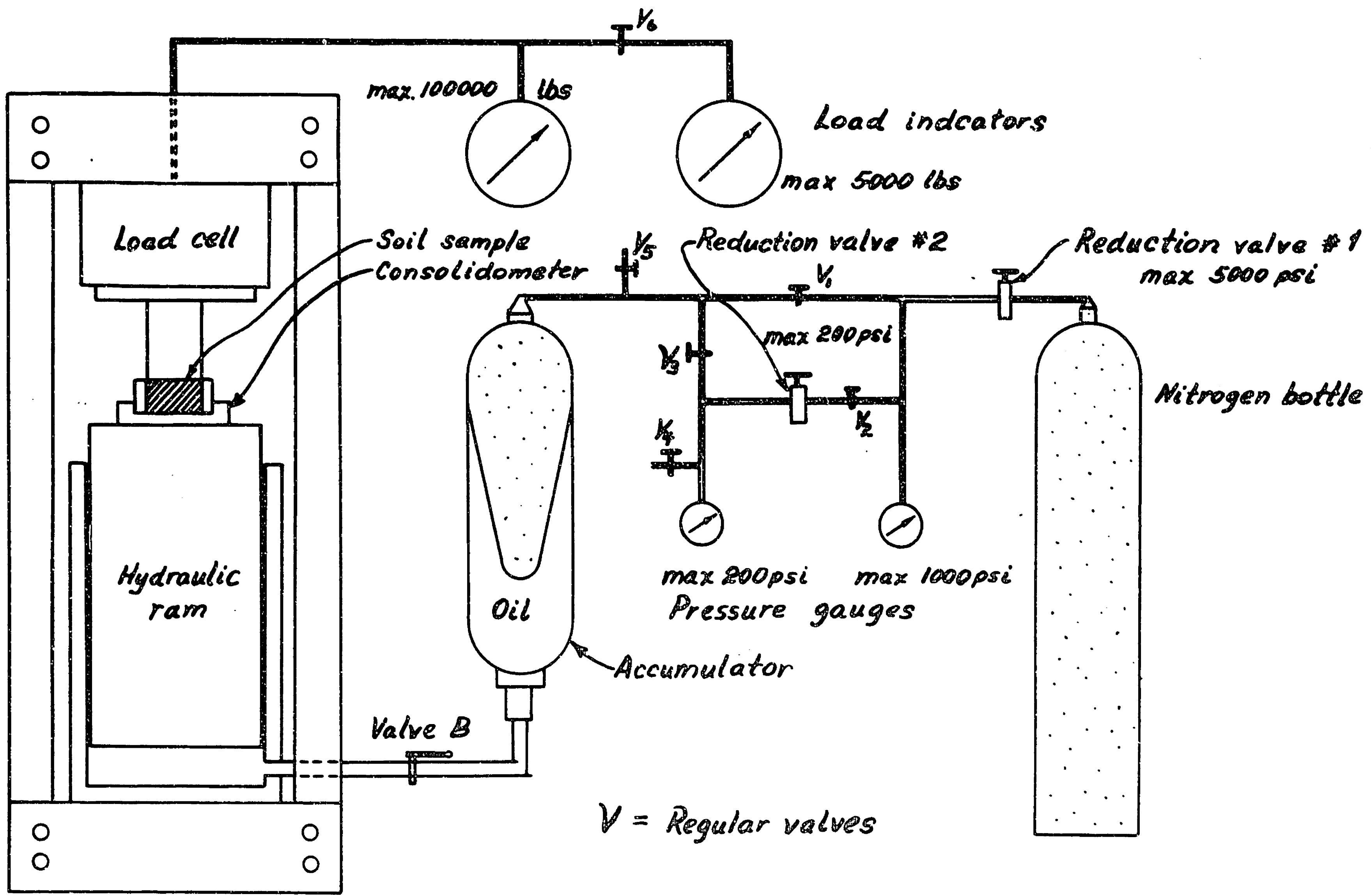
Confining pressure atm.	Compressive strength atm.	psi.
Lead as confining medium		
1	24,200	344,000
9,000	27,500	390,000
12,000	34,200	485,000
13,000	38,700	550,000
16,500	51,000	724,000
19,500	118,500	1680,000
Liquid as confining medium		
16,000	33,000	468,000
23,000	39,000	554,000
25,000	40,000	568,000

Tensile strength	7,000 psi
Compressive strength	190,000 psi

References: (a) Birch, F., Schairer, J. F., and Spicer, H. C., "Handbook of Physical Constants"

(b) Bridgeman, "Applied Physics", V12, P.461, 1941

(c) Smithsonian Physical Tables, Eighth Revised Edition, 1933



Schematic Diagram
of
High Pressure Compression Apparatus

Fig. B.1

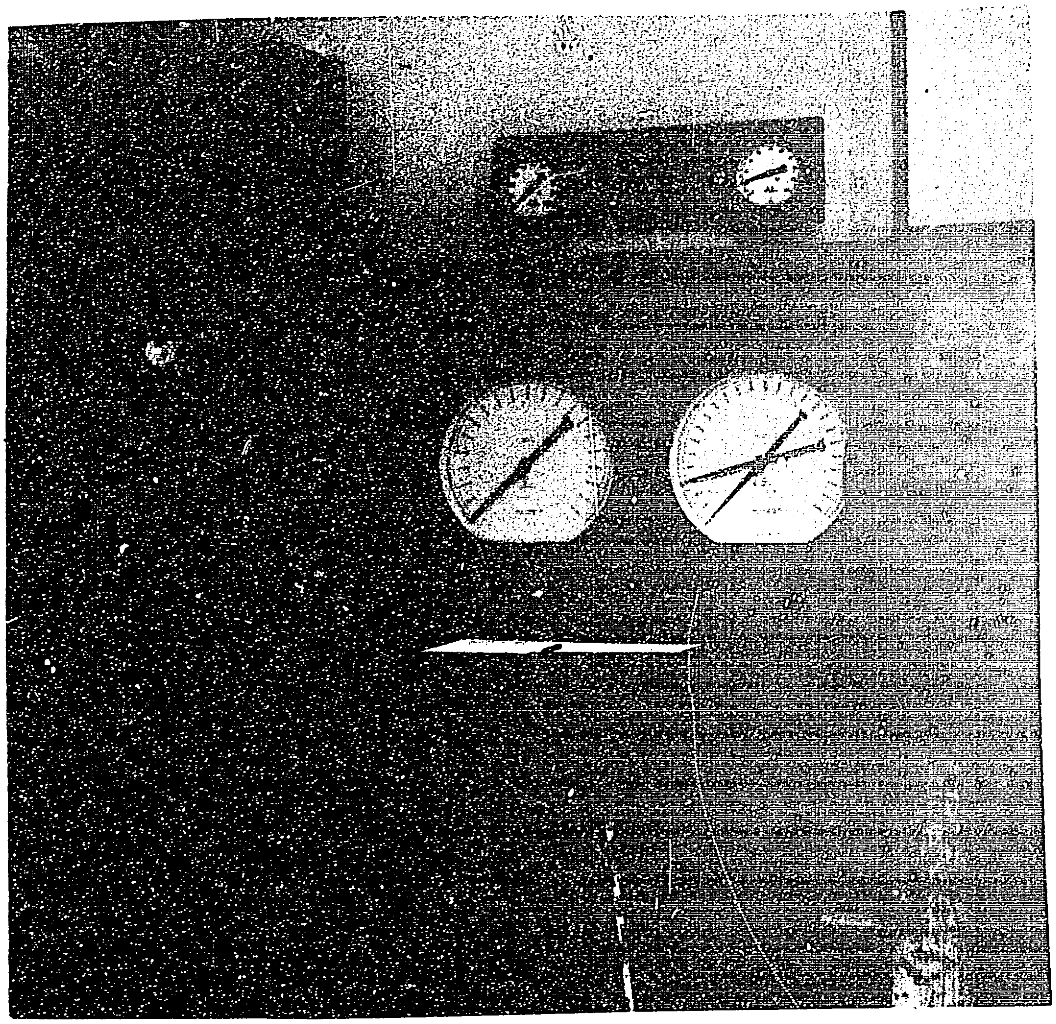


Fig. B.2 HIGH PRESSURE LOADING FRAME

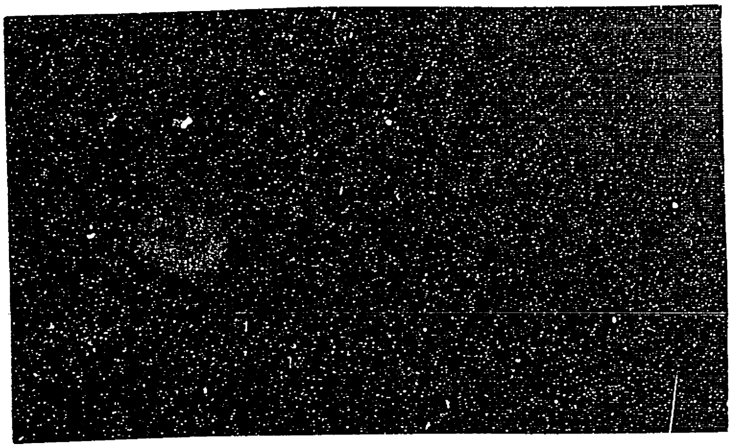
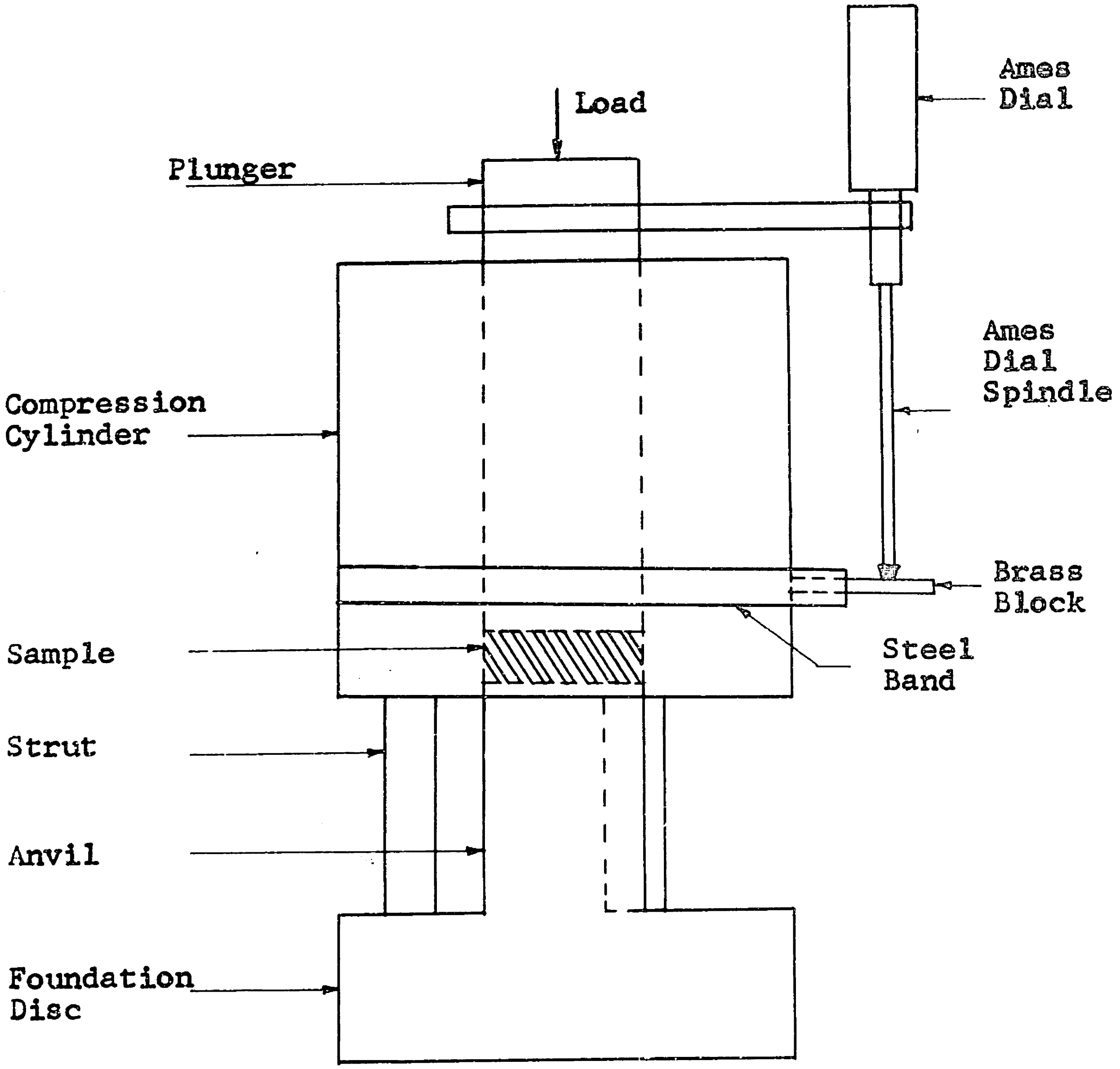


Fig. B.3 CONSOLIDOMETER FOR CLAY AND SHALE

(a) Dismantled

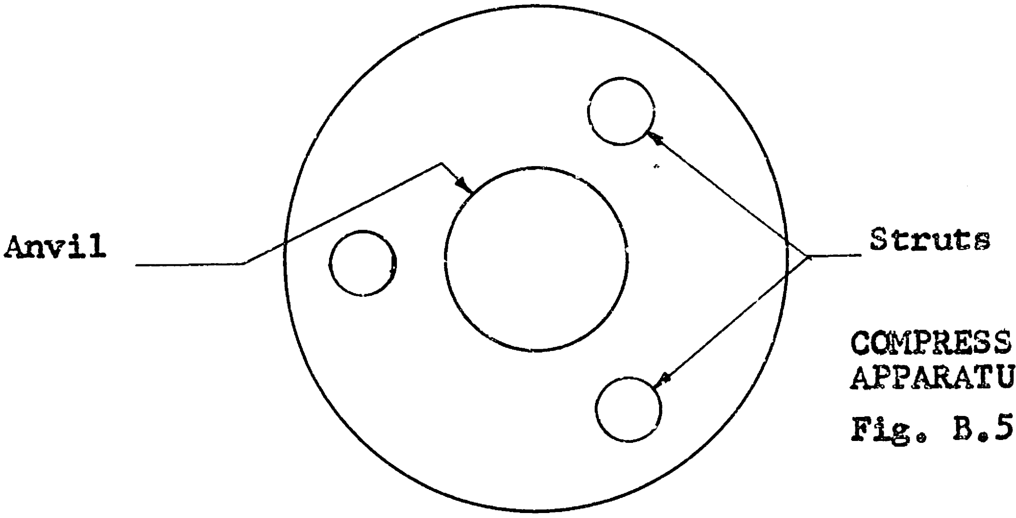
(b) Assembled

Fig. B.4 COMPRESSION CYLINDER



ASSEMBLED COMPRESSION APPARATUS

Scale: 3/4:1



COMPRESSION APPARATUS

Fig. B.5

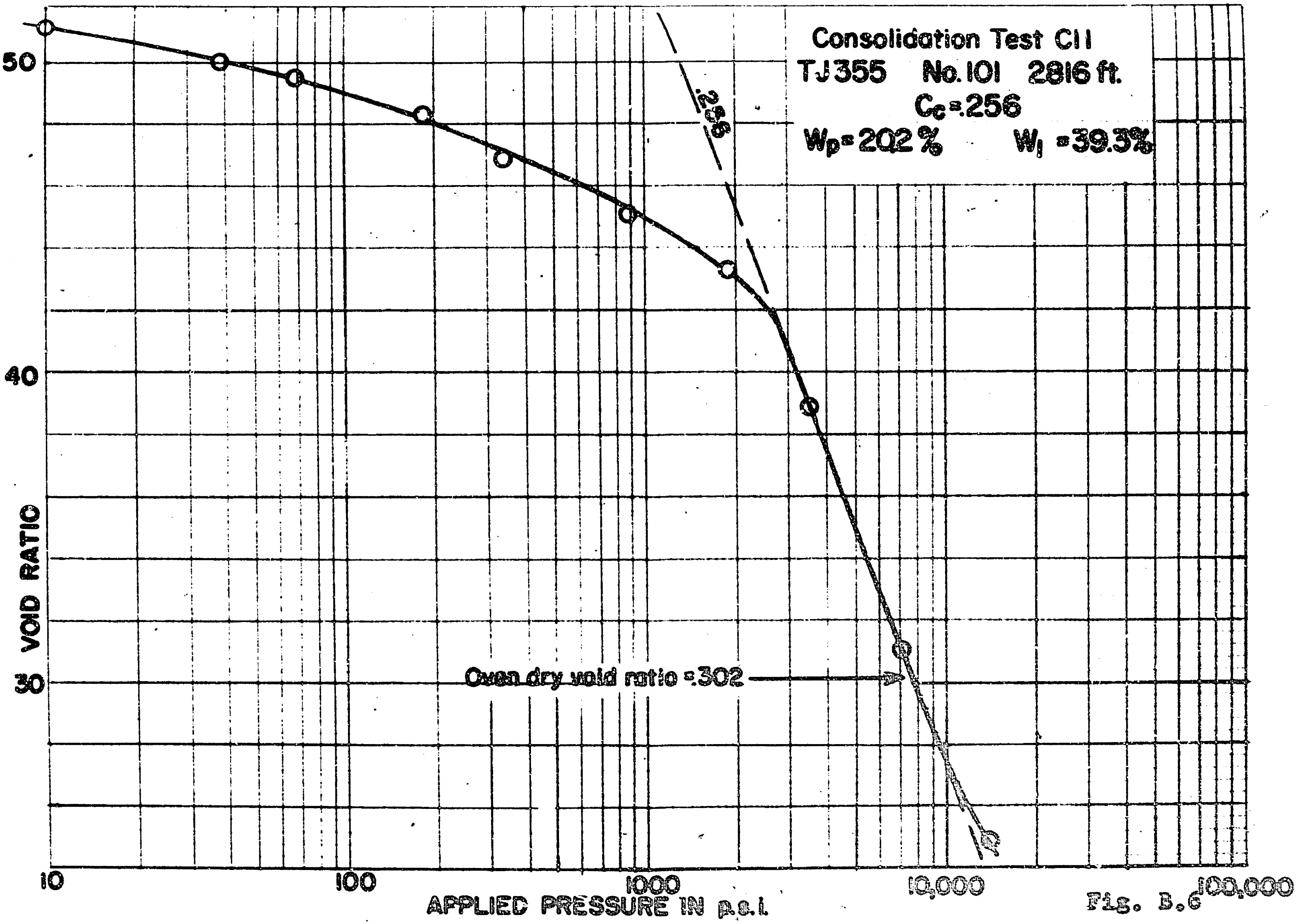

Consolidation Test C11
TJ355 No.101 2816 ft.
C_c=.256
W_p=20.2 %
W_l =39.3%
.256
Oven dry void ratio =.302
50
40
30
VOID RATIO
10
100
1000
10,000
100,000
APPLIED PRESSURE IN p.s.i.

Fig. B.6

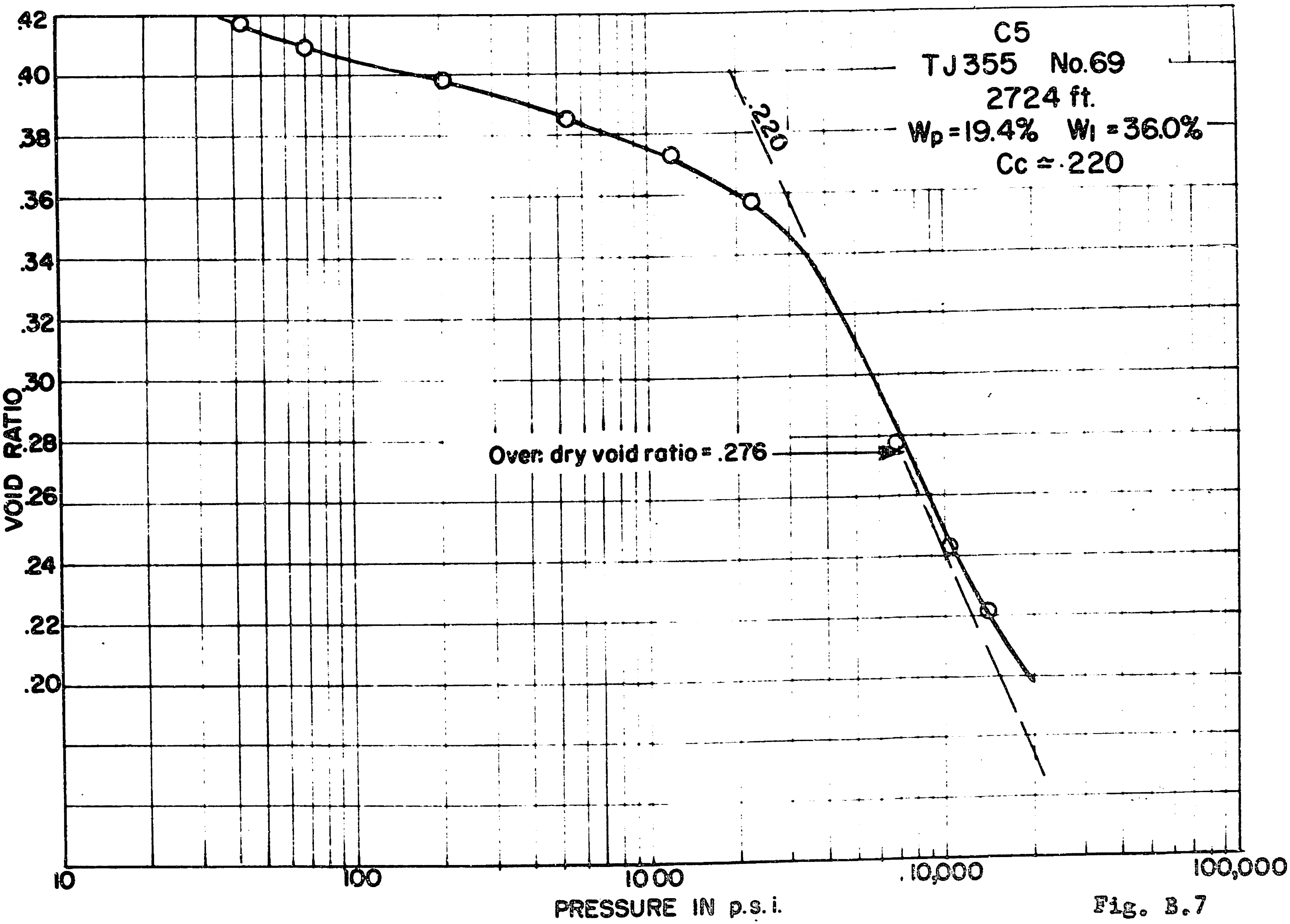
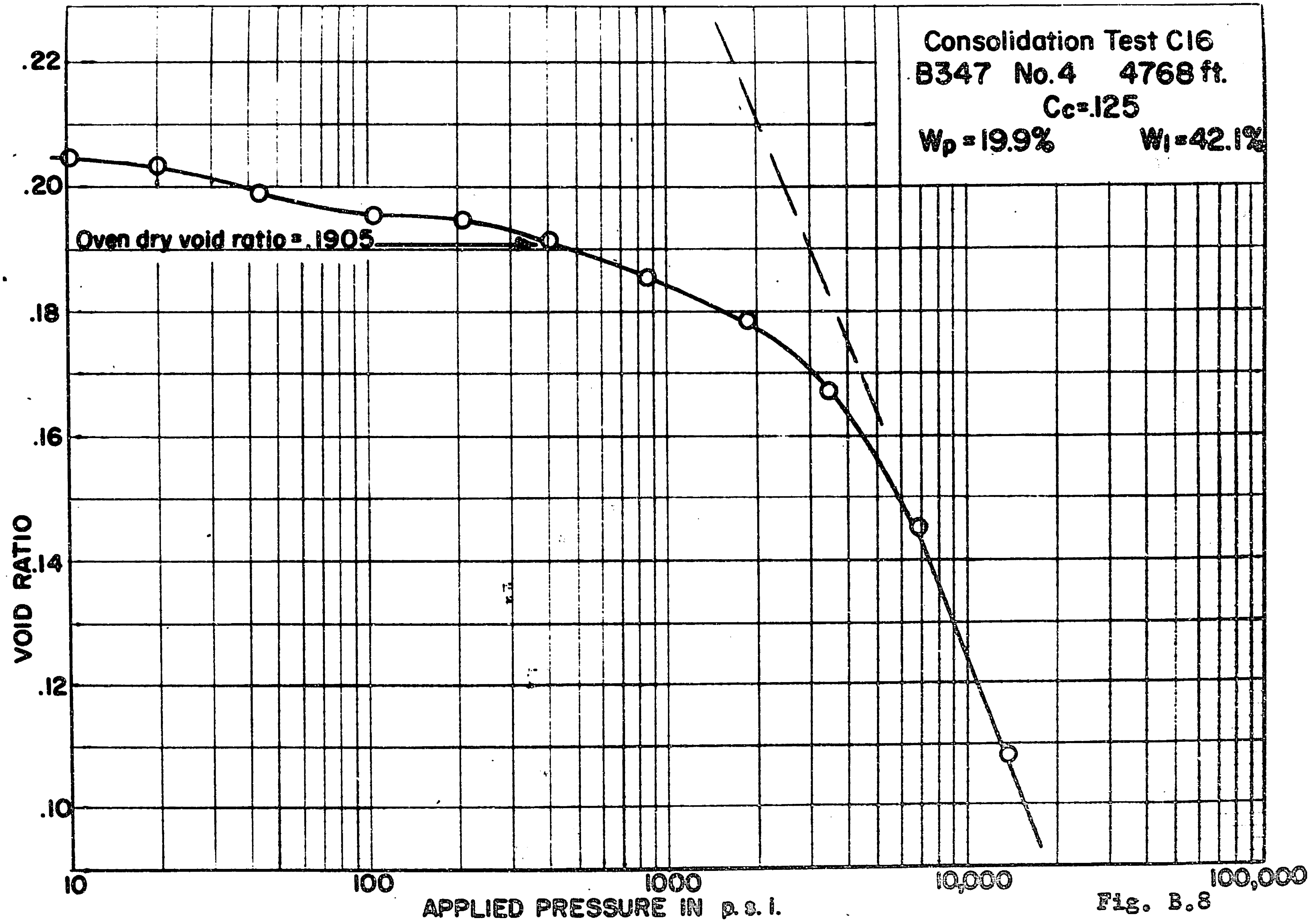

C5
TJ 355 No.69
2724 ft.
Wp = 19.4% Wl = 36.0%
Cc ≃ .220
.220
Oven dry void ratio = .276
VOID RATIO
.42
.40
.38
.36
.34
.32
.30
.28
.26
.24
.22
.20
10
100
1000
10,000
100,000
PRESSURE IN p.s.i.

Fig. B.7



Consolidation Test C16
B347 No.4 4768 ft.
Cc=.125
Wp = 19.9% Wl = 42.1%
Oven dry void ratio = .1905
.22
.20
.18
.16
.14
.12
.10
VOID RATIO
10
100
1000
10,000
100,000
APPLIED PRESSURE IN p.s.i.

Fig. B.8

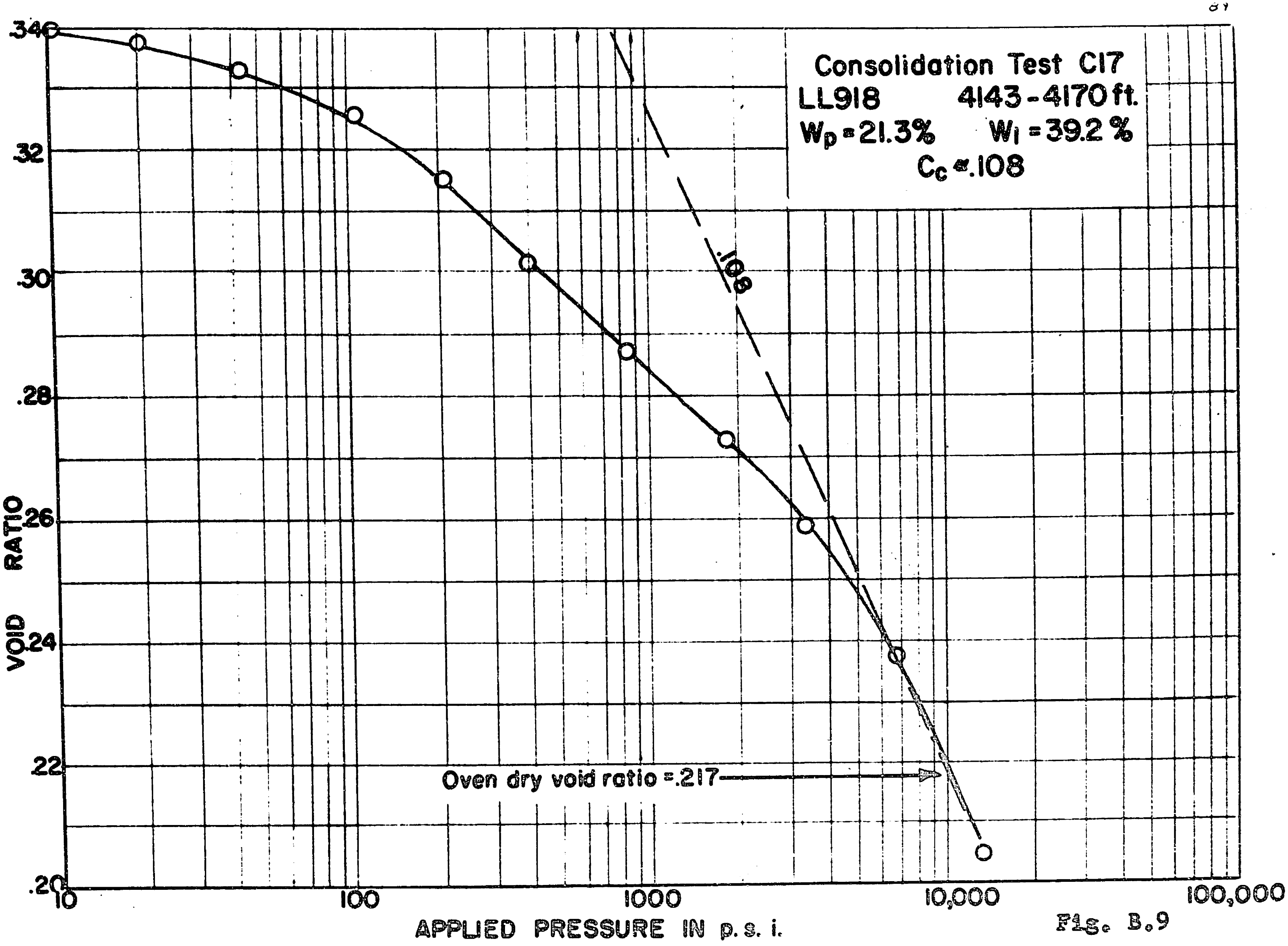

Consolidation Test C17
LL918 4143-4170 ft.
W_p = 21.3% W_l = 39.2 %
C_c = .108
.108
Oven dry void ratio = .217
VOID RATIO
.340
.32
.30
.28
.26
.24
.22
.20
10
100
1000
10,000
100,000
APPLIED PRESSURE IN p. s. i.

Fig. B.9

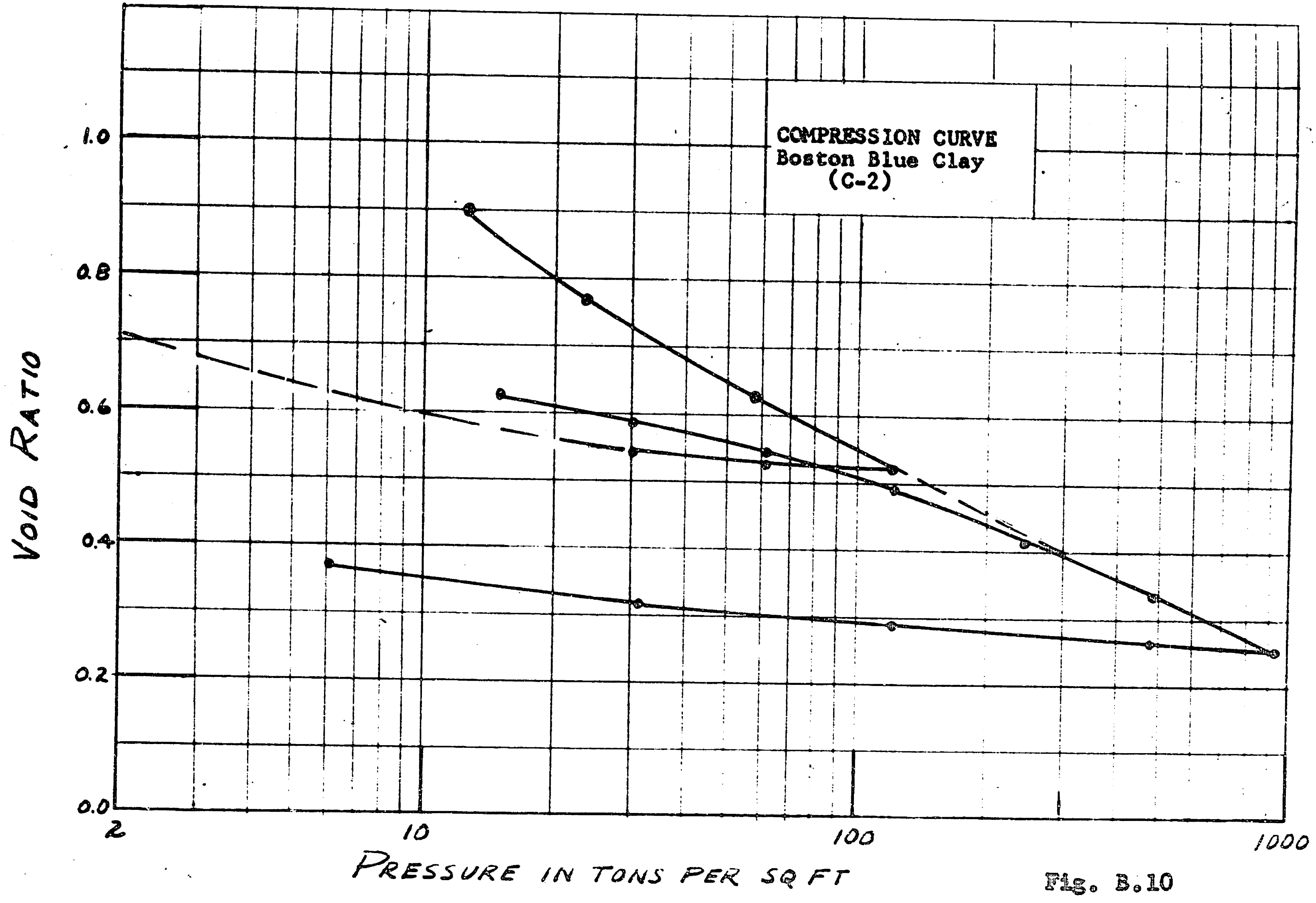

COMPRESSION CURVE
Boston Blue Clay
(C-2)
VOID RATIO
1.0
0.8
0.6
0.4
0.2
0.0
2
10
100
1000
PRESSURE IN TONS PER SQ FT

Fig. B.10

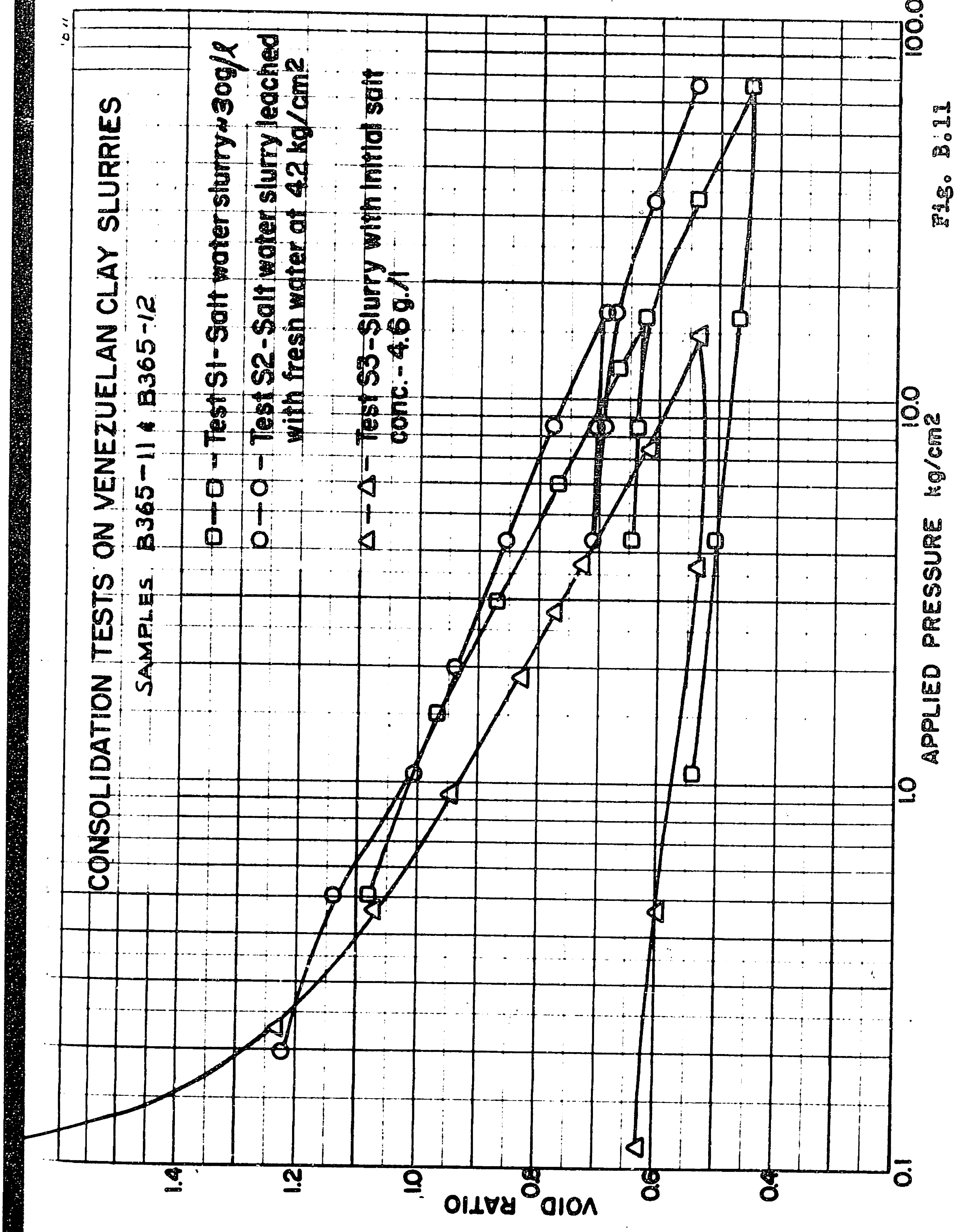

CONSOLIDATION TESTS ON VENEZUELAN CLAY SLURRIES
SAMPLES B365-11 & B365-12
□—□ - Test S1 - Salt water slurry ≈ 30g/ℓ
○—○ - Test S2 - Salt water slurry leached with fresh water at 4.2 kg/cm2
Δ - Δ - Test S3 - Slurry with initial salt conc. - 4.6 g./l
VOID RATIO
1.4
1.2
1.0
0.8
0.6
0.4
APPLIED PRESSURE kg/cm2
0.1
1.0
10.0
100.0

Fig. B.11

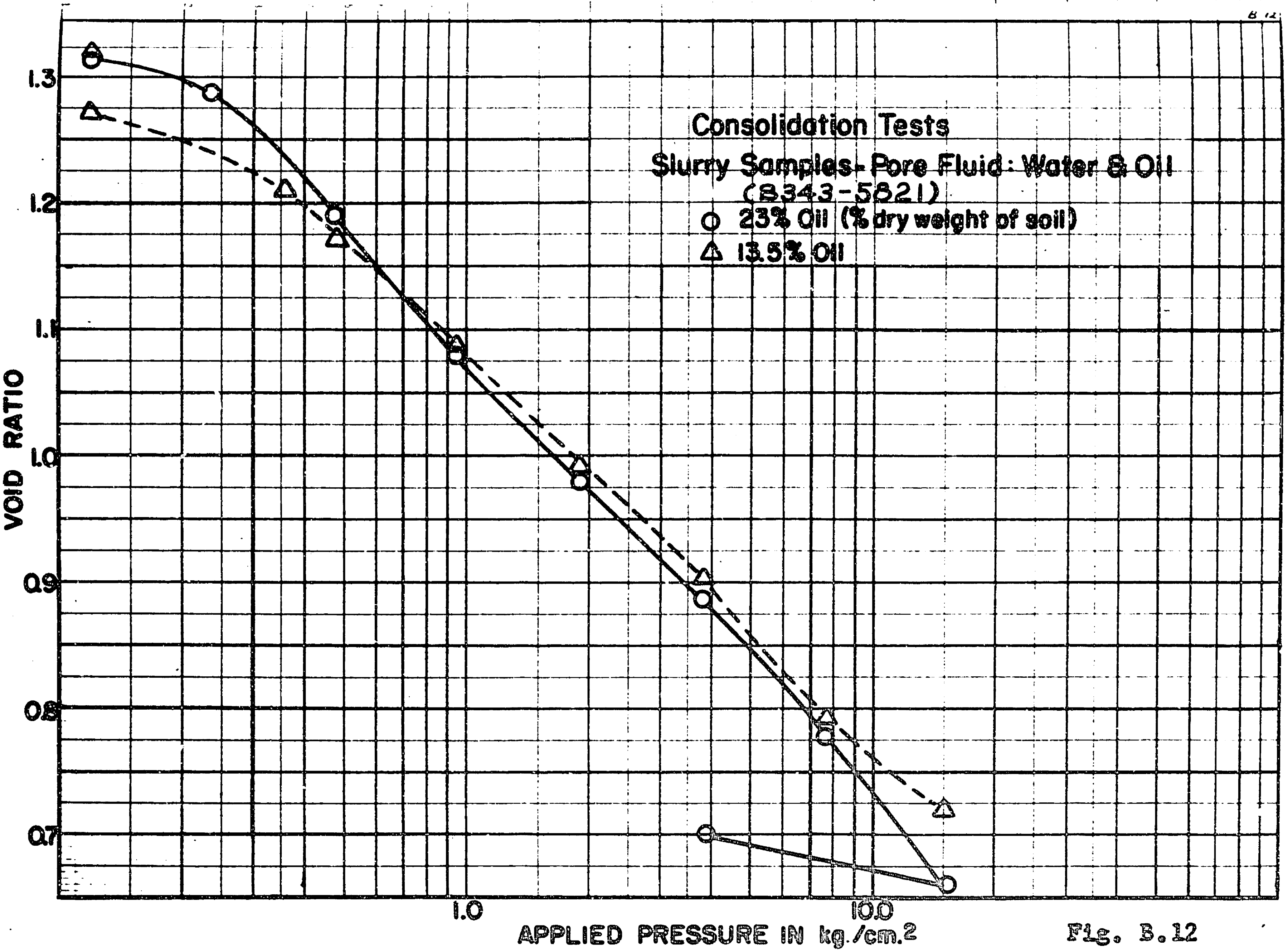

B 12
Consolidation Tests
Slurry Samples - Pore Fluid: Water & Oil
(B343-5821)
○ 23% Oil (% dry weight of soil)
△ 13.5% Oil
VOID RATIO
1.3
1.2
1.1
1.0
0.9
0.8
0.7
APPLIED PRESSURE IN kg./cm.2
1.0
10.0

Fig. B.12

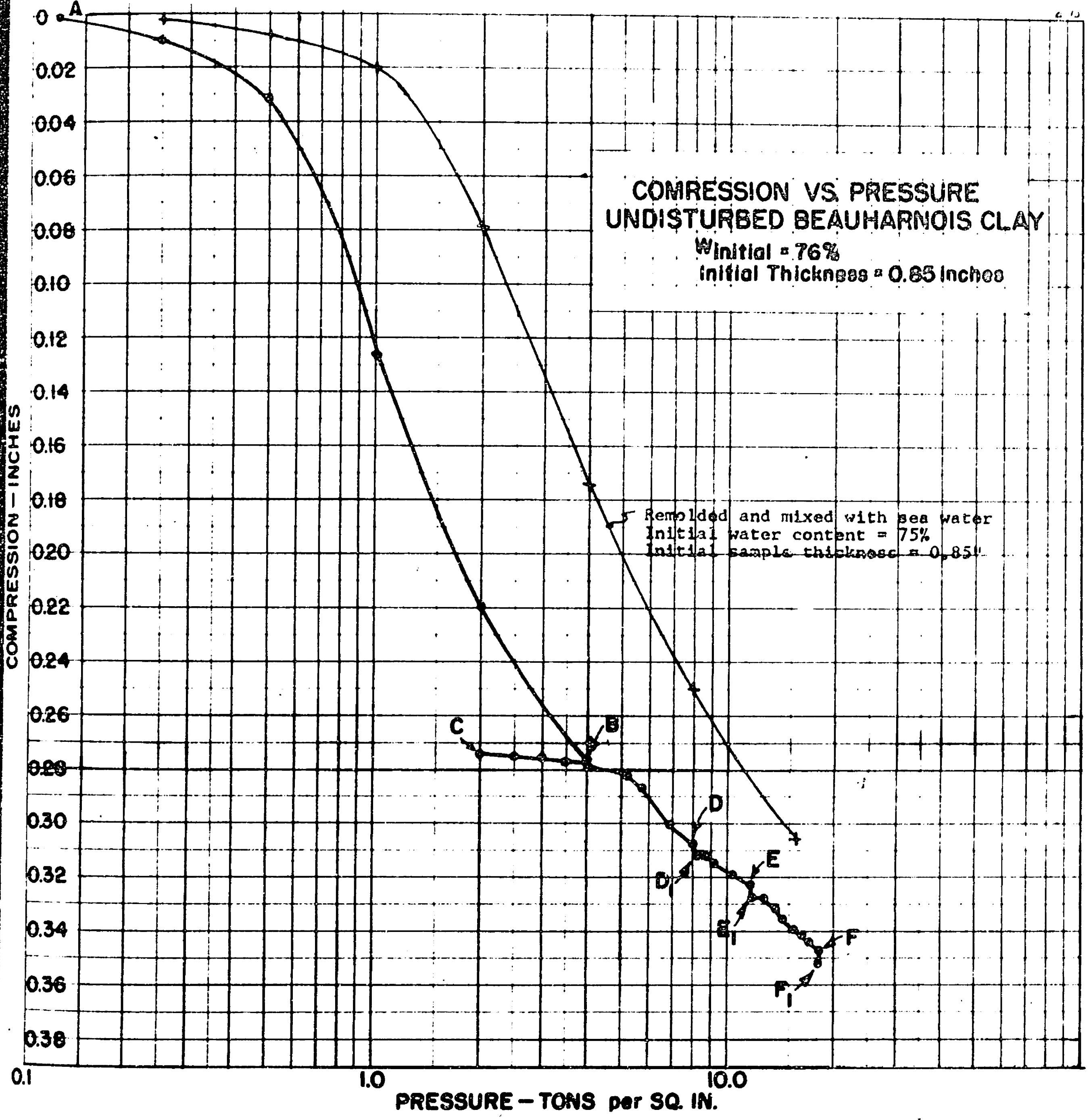

COMRESSION VS. PRESSURE
UNDISTURBED BEAUHARNOIS CLAY
Winitial = 76%
Initial Thickness = 0.85 inches
Remolded and mixed with sea water
Initial water content = 75%
Initial sample thickness = 0.85"
A
B
C
D
D1
E
E1
F
F1
COMPRESSION – INCHES
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
0.26
0.28
0.30
0.32
0.34
0.36
0.38
0.1
1.0
10.0
PRESSURE – TONS per SQ. IN.

Fig. B.13

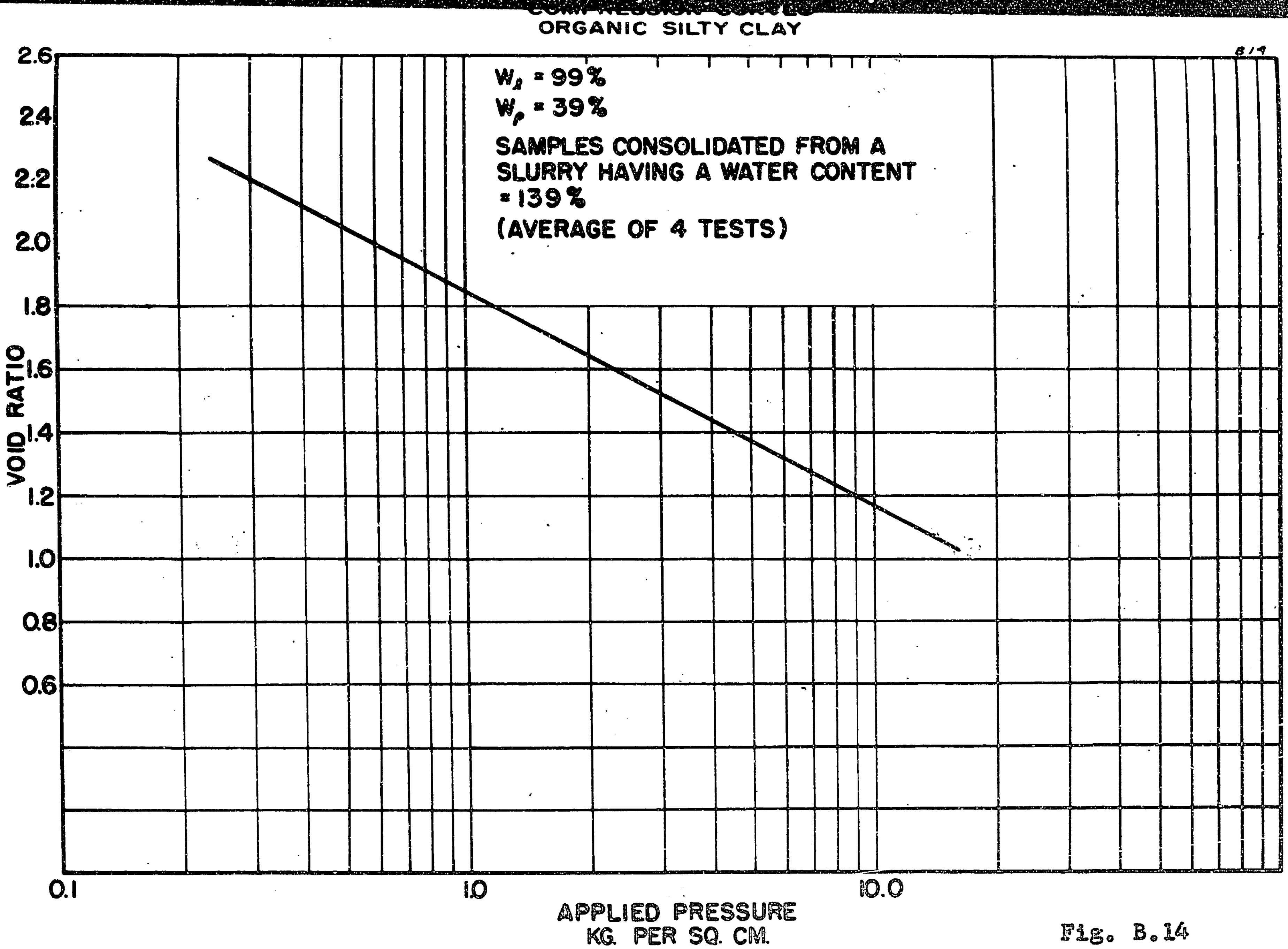
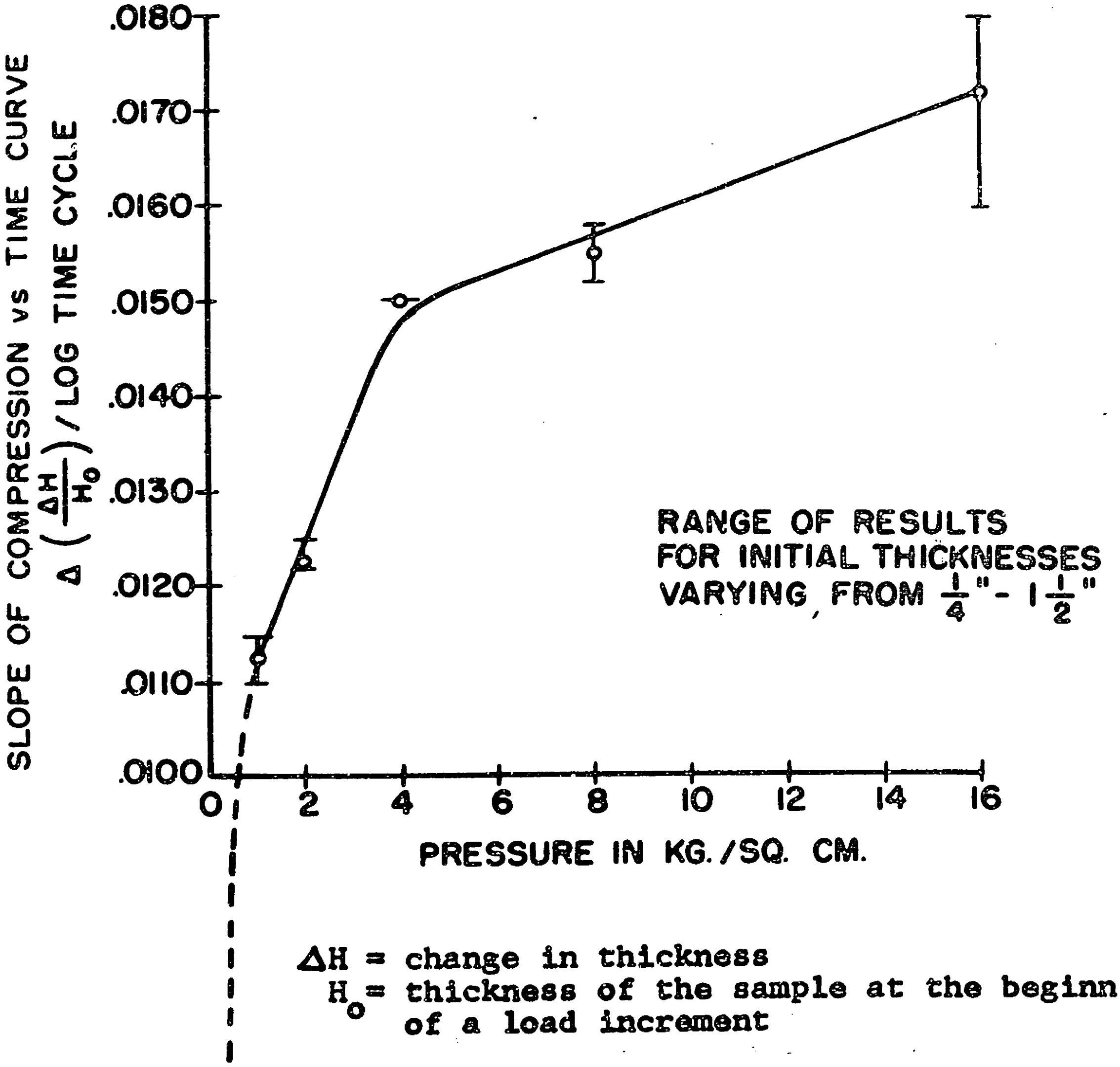

COMPRESSION CURVES
ORGANIC SILTY CLAY
B/4
W_l = 99%
W_p = 39%
SAMPLES CONSOLIDATED FROM A SLURRY HAVING A WATER CONTENT = 139%
(AVERAGE OF 4 TESTS)
VOID RATIO
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.1
1.0
10.0
APPLIED PRESSURE
KG. PER SQ. CM.

Fig. B.14

SLOPE OF COMPRESSION vs TIME CURVE
vs
APPLIED PRESSURE



ΔH = change in thickness
H_o = thickness of the sample at the beginning of a load increment

Fig. B.15

SLOPE OF COMPRESSION VS TIME CURVE
VS
APPLIED PRESSURE

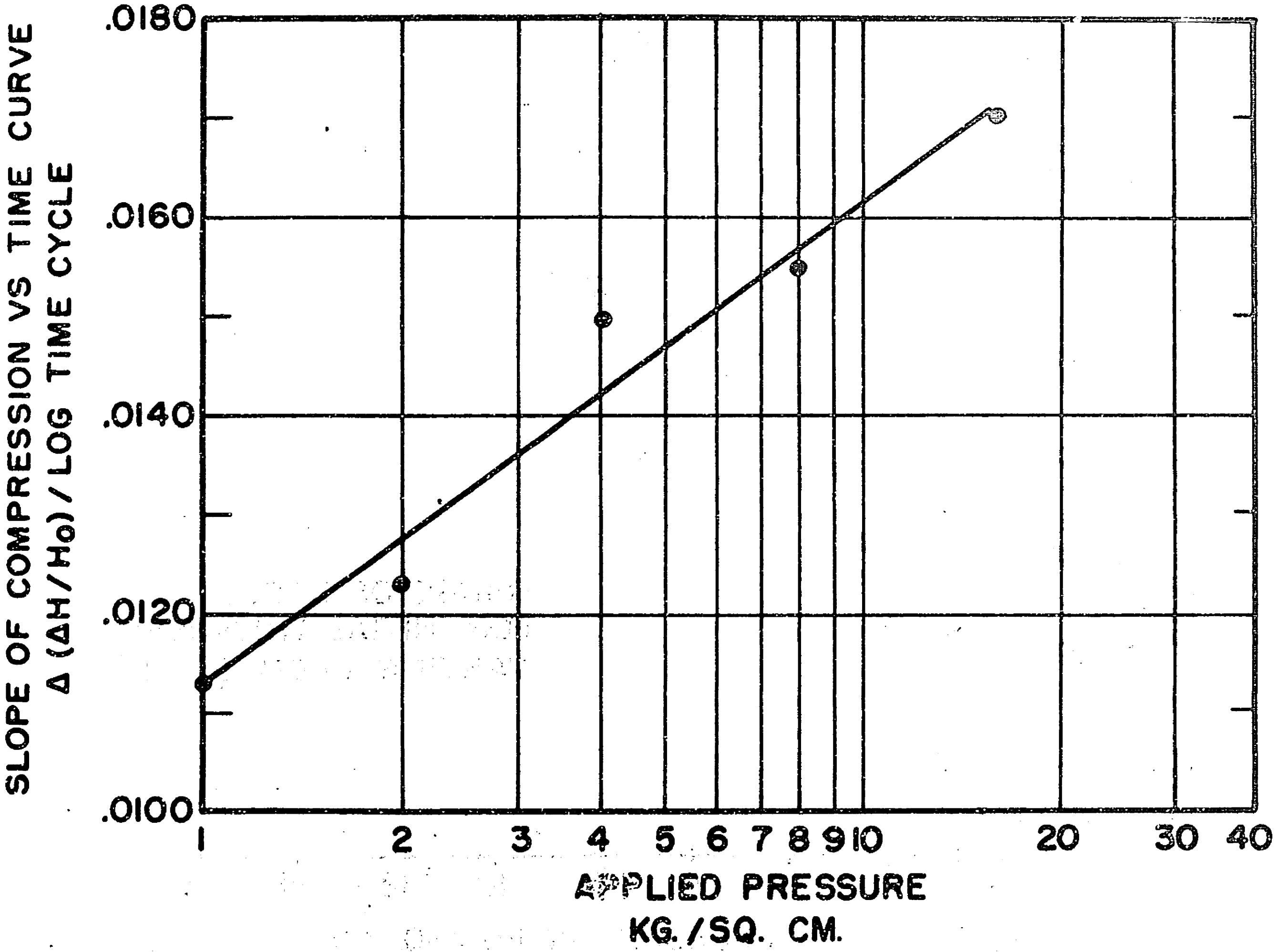
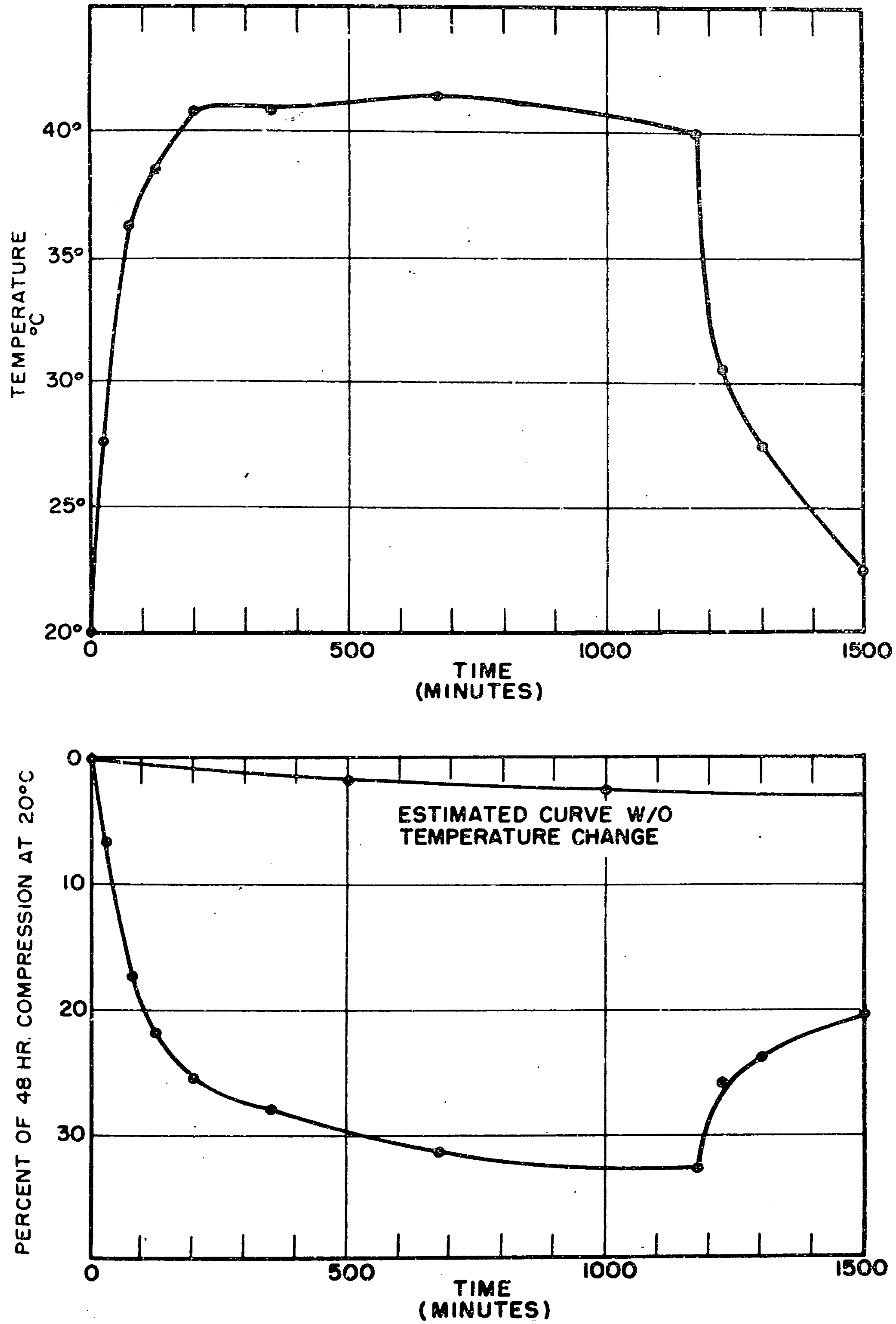


Fig. B.16

COMPRESSION vs TEMPERATURE CHANGE
BOSTON BLUE CLAY

(a) SAMPLE CONSOLIDATED 48 HRS. AT $2\frac{1}{2}$ TSF. (TEMPERATURE = 20°C

(b) APPLIED PRESSURE $2\frac{1}{2}$ TSF DURING TEMPERATURE CHANGE



COMPRESSION vs TIME
BOSTON BLUE CLAY

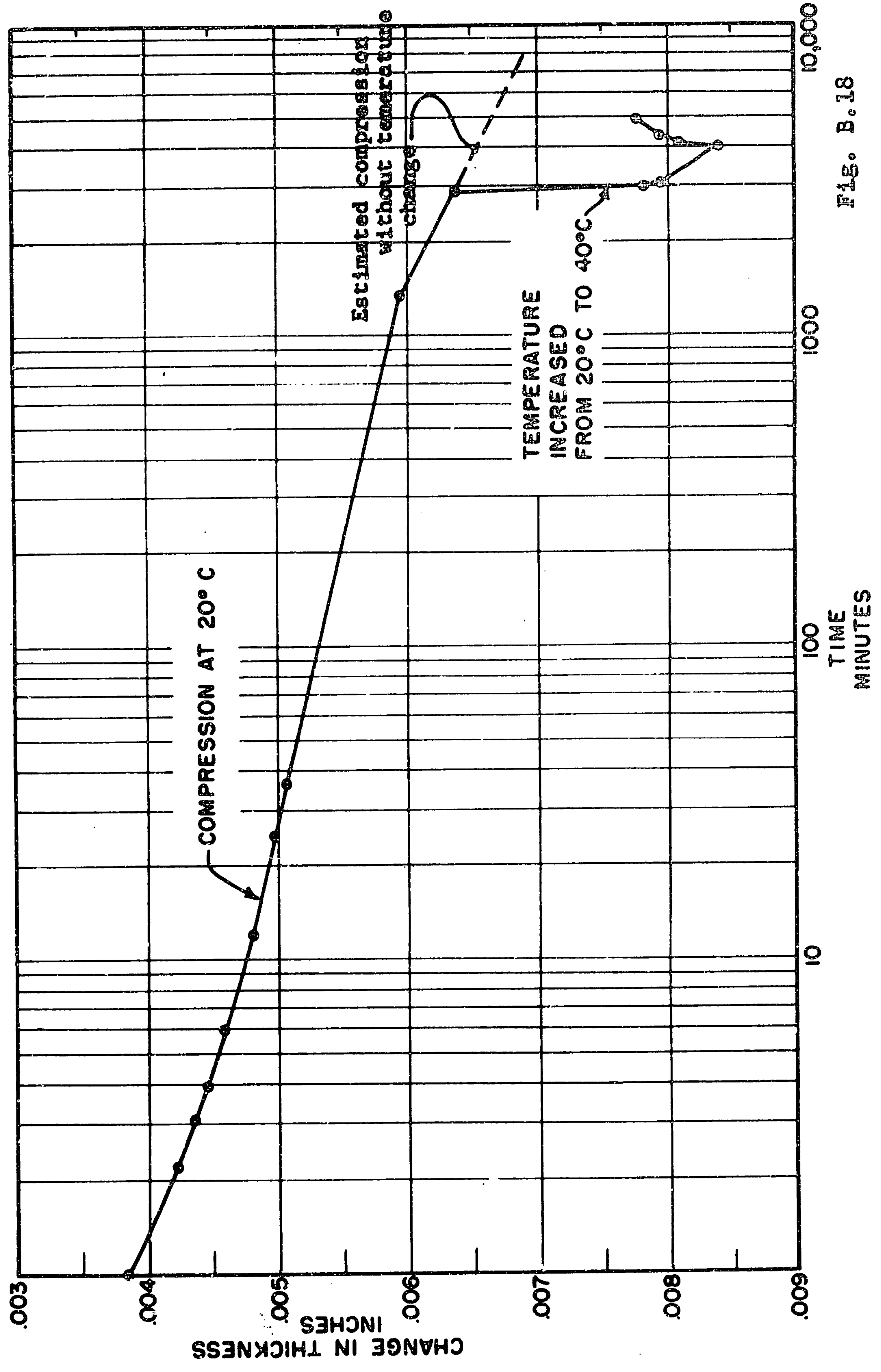
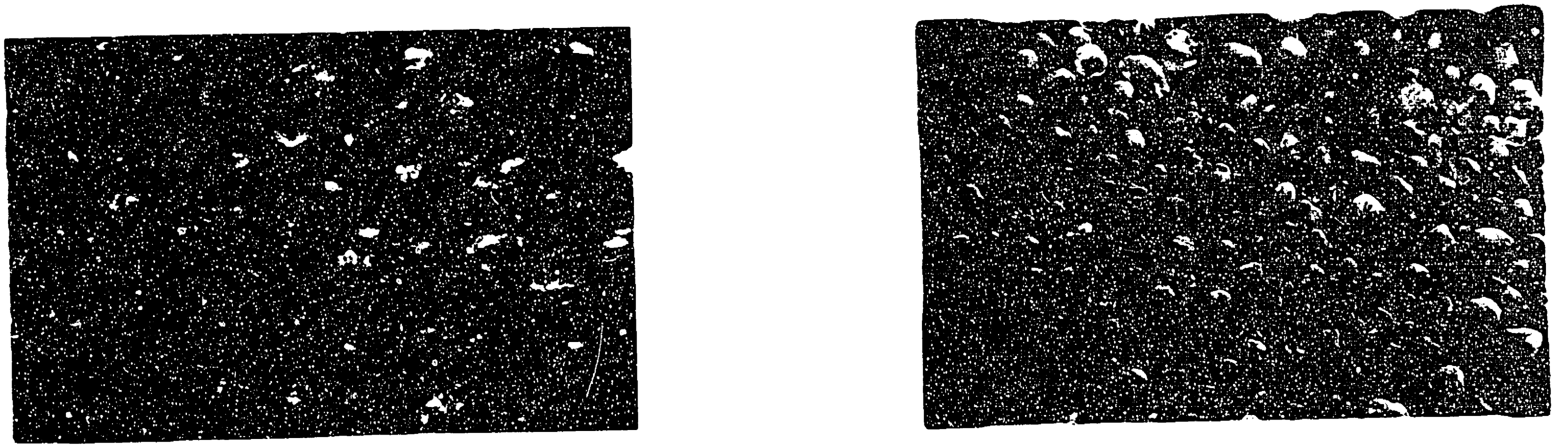
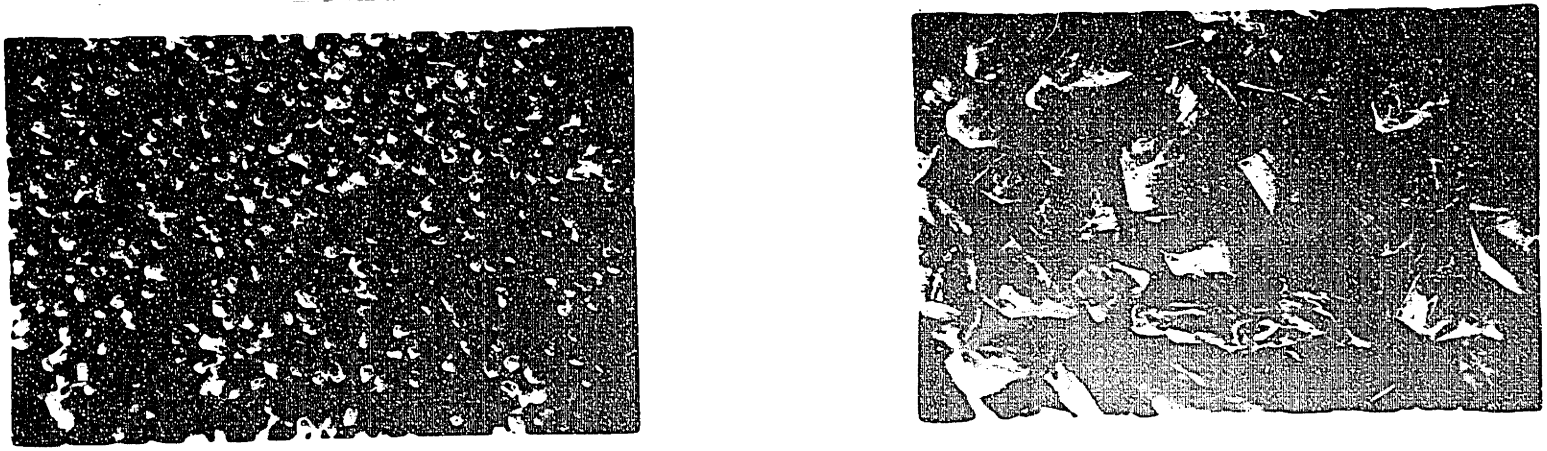


Fig. B.18



(a) 20-40 Ottawa

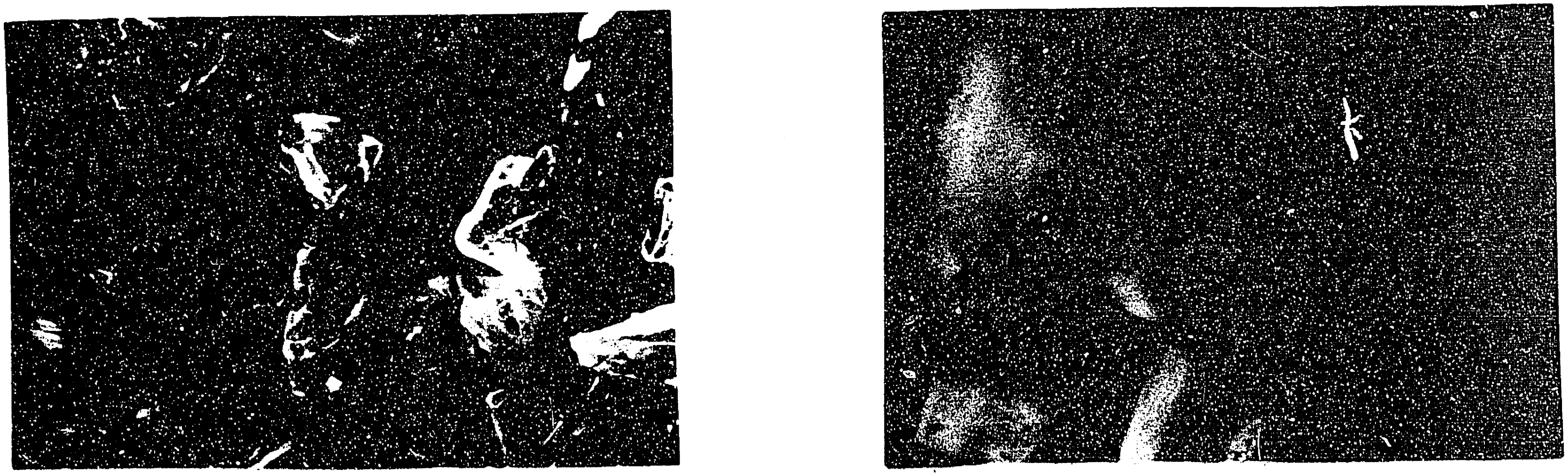
(b) 40-80 Ottawa



(c) 80-140 Ottawa

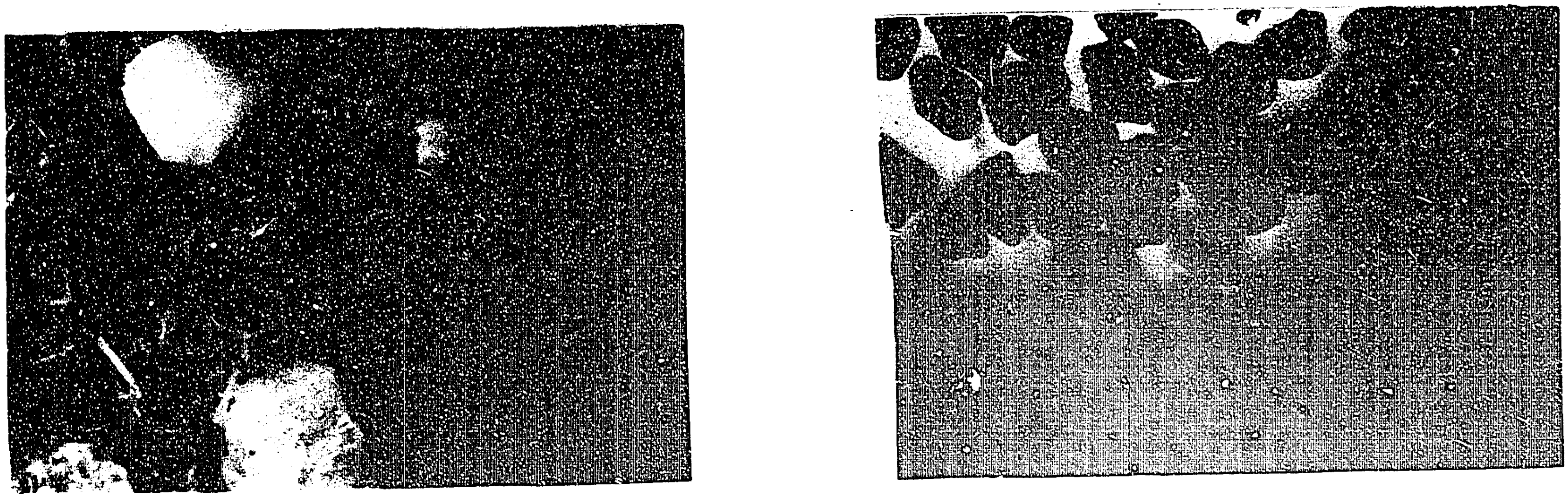
(d) 20-40 Ground Quartz

Fig. B.19 PHOTOMICROGRAPHS OF QUARTZ SANDS



(a) Quartz

(b) Feldspar



(c) Dolomite

(d) Hawaiian Beach Sand

Fig. B.20 PHOTOMICROGRAPHS OF GROUND MINERALS BEFORE COMPRESSION

TYPICAL DATA SHEET

M.I.T. SOIL MECHANICS LABORATORY

CONSOLIDATION TEST NO. C8

WELL NO. —

SAMPLE NO. —

DEPTH — ft.

DESCRIPTION OF SOIL 40-80 Ottawa Sand.

Tipped and vibrated w/ weight.

HEIGHT OF RING — in.

DIAMETER OF RING 1.1285 in.

AREA, A, OF RING 1.00 in.^{2}

6.452 cm^2

SOLIDS HEIGHT, $2H_0 = \frac{10}{2.67 \times 6.452} = \frac{W_s}{G_s \gamma_w A} = $ .5806 cm. = .2286 in.

Height of sample = .4545 - .0954 = = .3591

10-minute increments

NATURAL WATER CONTENT %

PLASTIC LIMIT, W_p %

LIQUID LIMIT, W_l %

WATER CONTENT

SPECIMEN LOCATION	—	
CONTAINER NO.	1	
WT. CONTAINER + WET SOIL IN g.	—	
WT. CONTAINER + DRY SOIL IN g.	93.903	
WT. WATER, W_w, IN g.	—	
WT. CONTAINER IN g.	83.803	
WT. DRY SOIL, W_s, IN g.	10.000	
WATER CONTENT w, IN %	—	

LOAD IN lbs.	APPLIED PRESSURE IN p.s.i.	FINAL DIAL IN in.	CUM DIAL CHANGE IN in.	DISC CORRECTION IN in.	CORRECTED DIAL CHANGE IN in.	SAMPLE HEIGHT 2H IN in.	VOID HEIGHT 2H−2H$_0$ IN in.	VOID RATIO $e = \frac{2H-2H_0}{2H_0}$
0	0	.09540				.3591	.1305	.5709
			.00041	0	.00041			
30	30	.09581				.3581	.1301	.5692
			.00060	.00005	.00061			
80	80	.09600				.3586	.1300	.5687
			.00110	.00010	.00100			
150	150	.09650				.3581	.1295	.5666
			.00177	.00022	.00155			
325	325	.09717				.3576	.1290	.5644
			.00271	.00044	.00227			
620	620	.09811				.3568	.1282	.5609
			.00428	.00066	.00362			
1250	1250	.09968				.3555	.1269	.5552
			.00669	.00089	.00580			
2500	2500	.10209				.3533	.1247	.5456
			.01131	.00100	.01031			
5000	5000	.10671				.3488	.1202	.5259
			.03042	.00150	.02912			
10000	10000	.12582				.3300	.1014	.4436
			.06380	.00200	.06180			
20000	20000	.15920				.2973	.0687	.3006

Fig. B.21

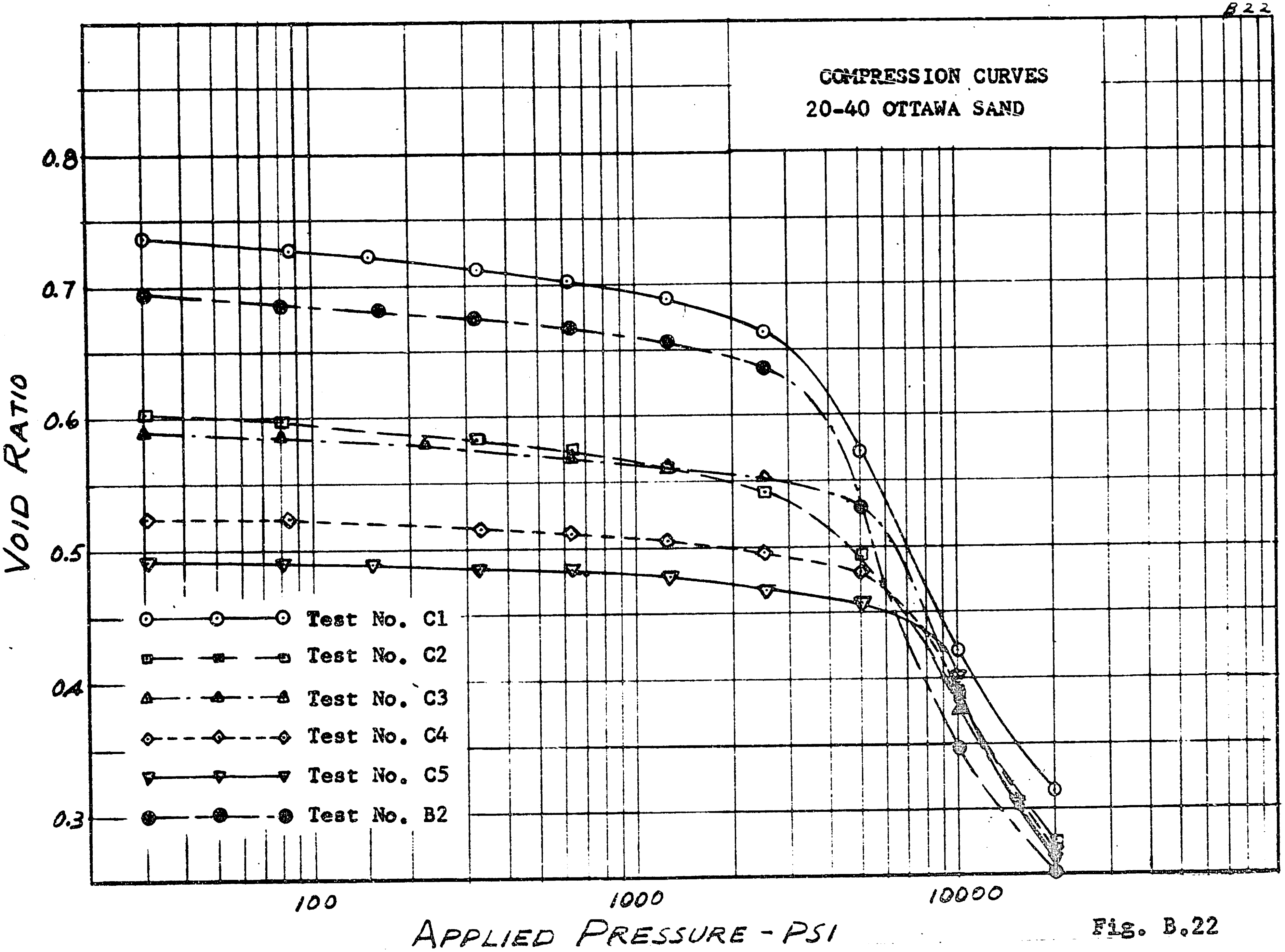

B22
COMPRESSION CURVES
20-40 OTTAWA SAND
VOID RATIO
0.8
0.7
0.6
0.5
0.4
0.3
APPLIED PRESSURE - PSI
100
1000
10000
Test No. C1
Test No. C2
Test No. C3
Test No. C4
Test No. C5
Test No. B2

Fig. B.22

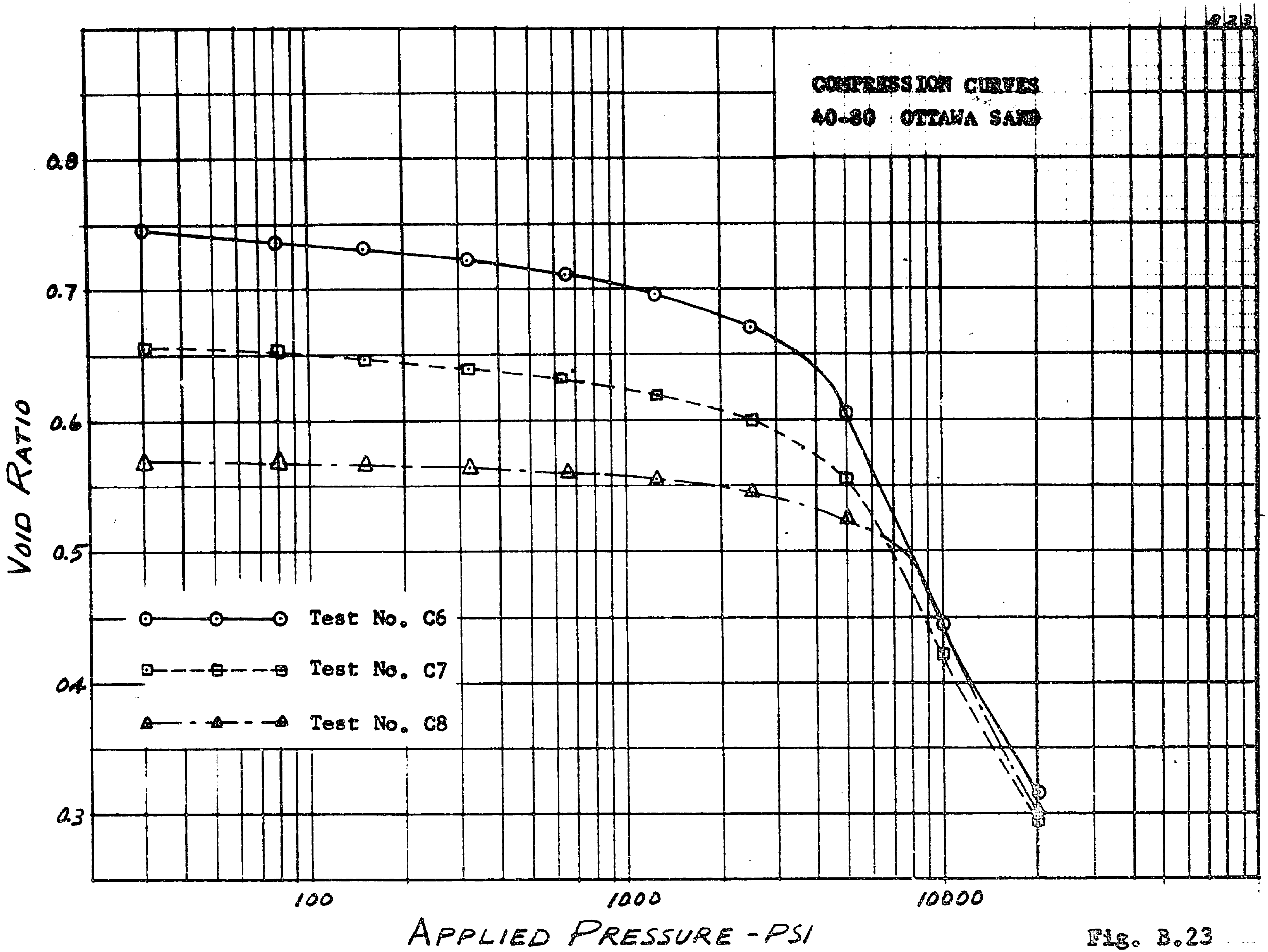

B.23
COMPRESSION CURVES
40-30 OTTAWA SAND
0.8
0.7
0.6
0.5
0.4
0.3
VOID RATIO
Test No. C6
Test No. C7
Test No. C8
100
1000
10000
APPLIED PRESSURE - PSI

Fig. B.23

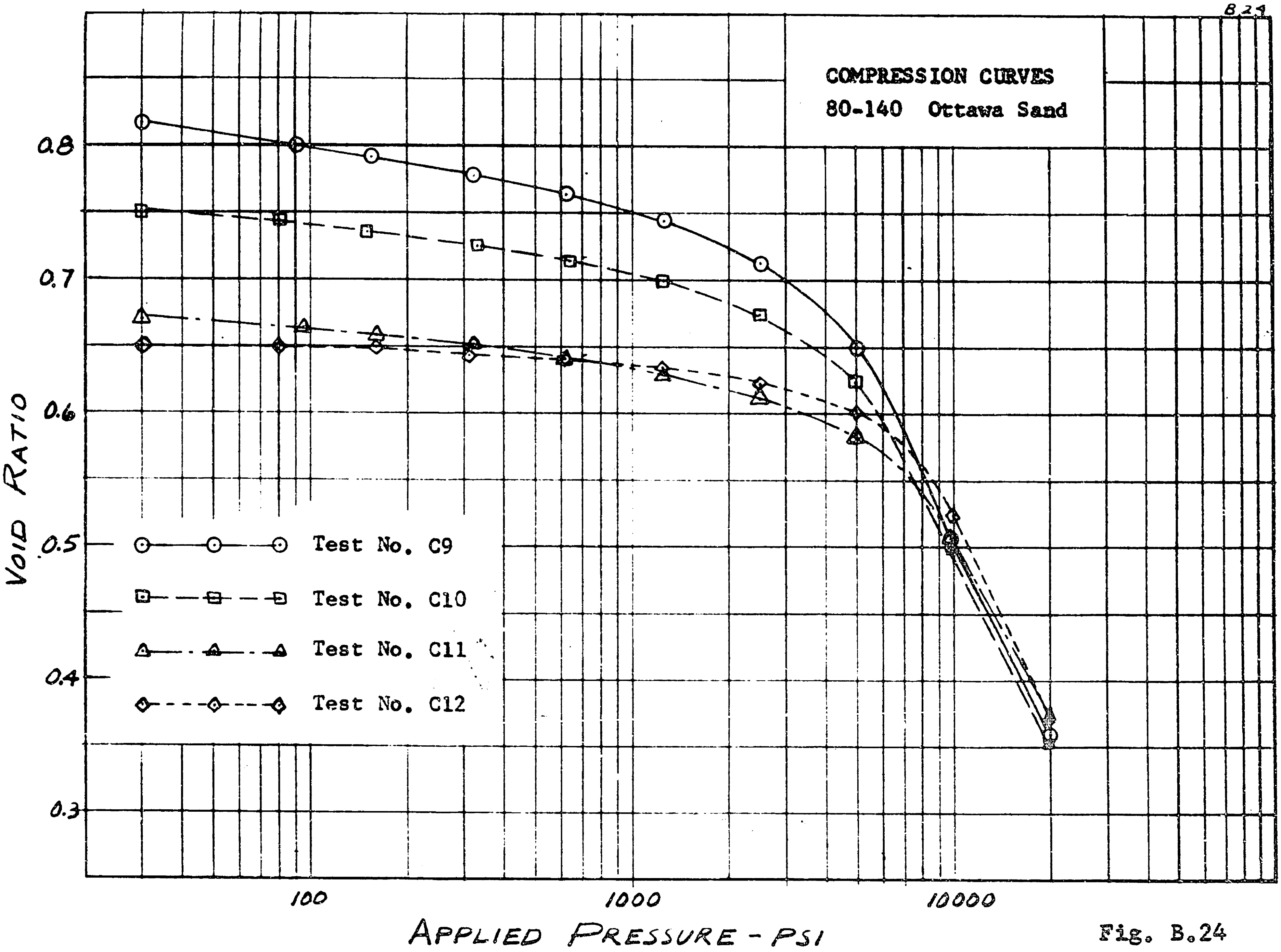

B.24
COMPRESSION CURVES
80-140 Ottawa Sand
Void Ratio
0.8
0.7
0.6
0.5
0.4
0.3
Test No. C9
Test No. C10
Test No. C11
Test No. C12
100
1000
10000
Applied Pressure - PSI

Fig. B.24

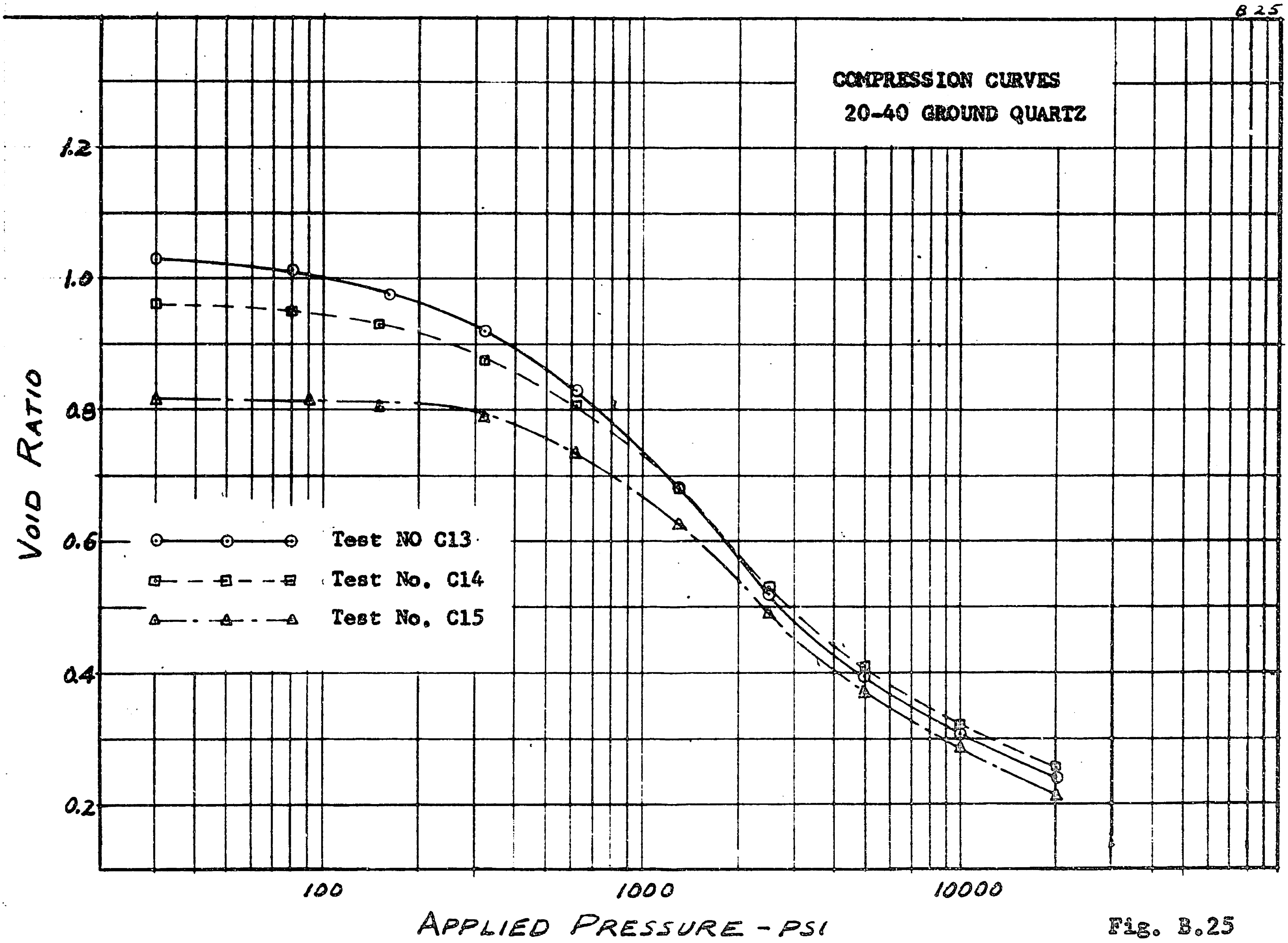

B 25
COMPRESSION CURVES
20-40 GROUND QUARTZ
VOID RATIO
1.2
1.0
0.8
0.6
0.4
0.2
Test NO C13
Test No. C14
Test No. C15
100
1000
10000
APPLIED PRESSURE - PSI

Fig. B.25

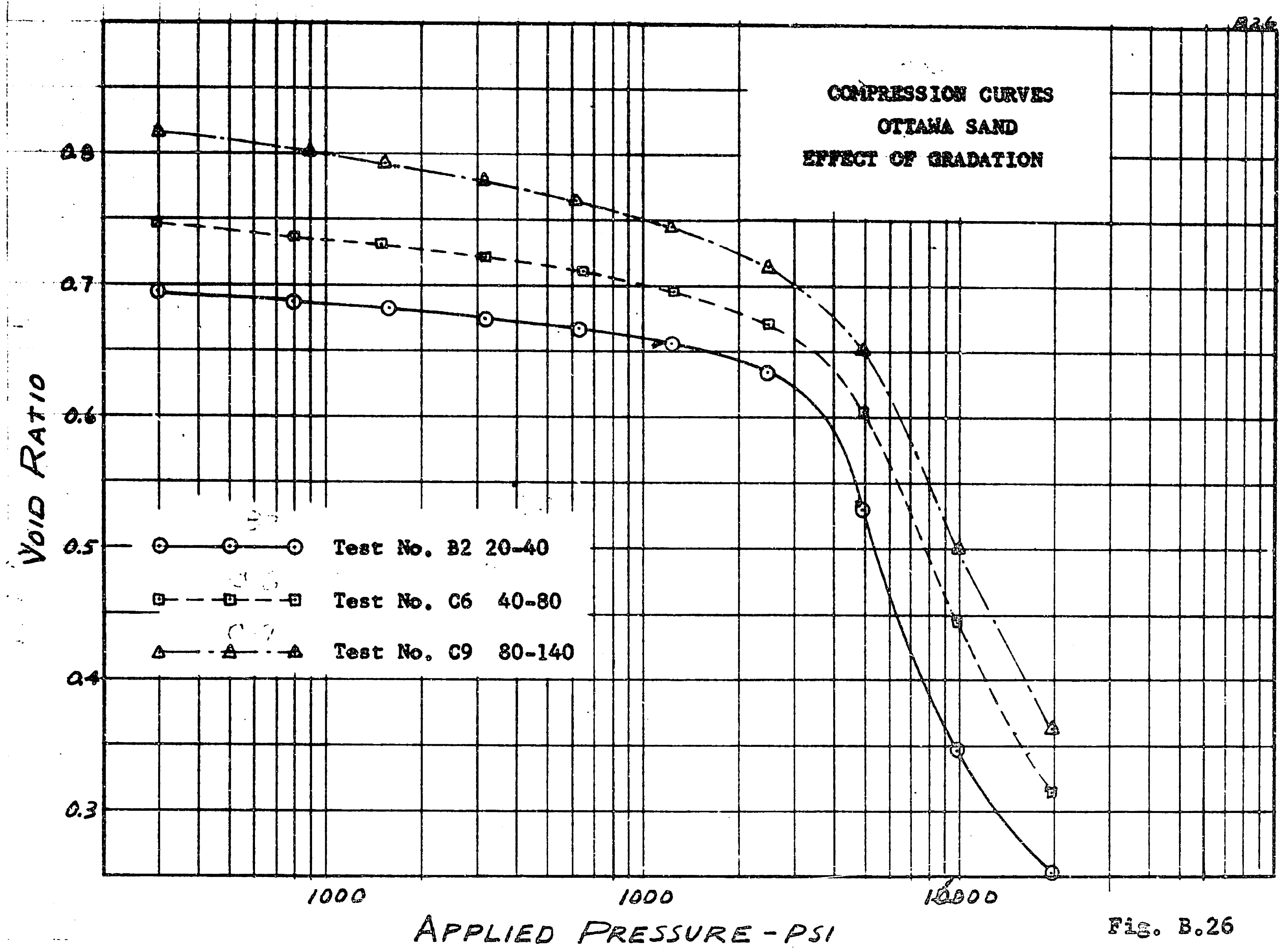

COMPRESSION CURVES
OTTAWA SAND
EFFECT OF GRADATION
Test No. B2 20-40
Test No. C6 40-80
Test No. C9 80-140
VOID RATIO
0.8
0.7
0.6
0.5
0.4
0.3
1000
1000
10000
APPLIED PRESSURE - PSI
B.26

Fig. B.26

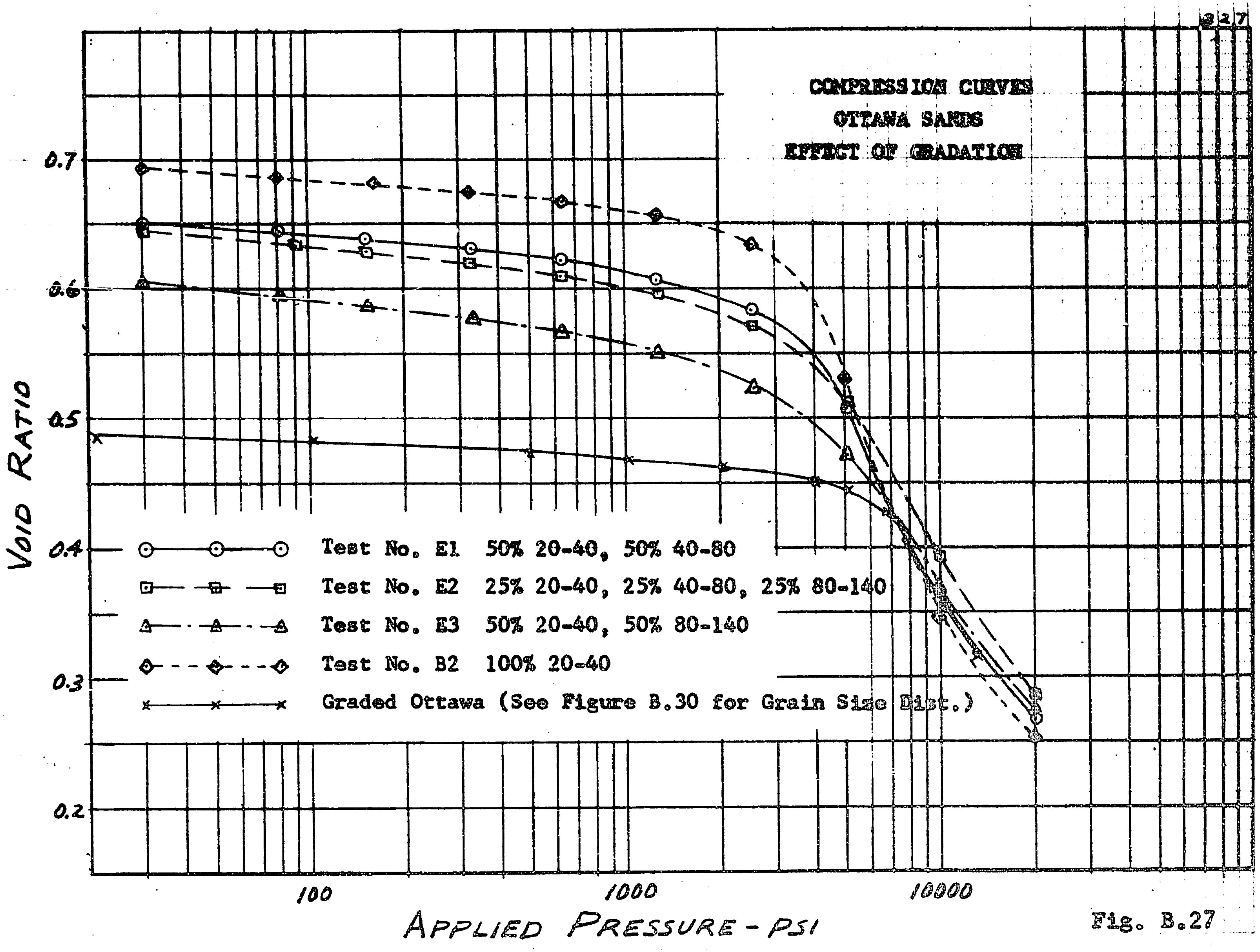

COMPRESSION CURVES
OTTAWA SANDS
EFFECT OF GRADATION
Test No. E1 50% 20-40, 50% 40-80
Test No. E2 25% 20-40, 25% 40-80, 25% 80-140
Test No. E3 50% 20-40, 50% 80-140
Test No. B2 100% 20-40
Graded Ottawa (See Figure B.30 for Grain Size Dist.)
0.7
0.6
0.5
0.4
0.3
0.2
VOID RATIO
100
1000
10000
APPLIED PRESSURE - PSI
B27

Fig. B.27

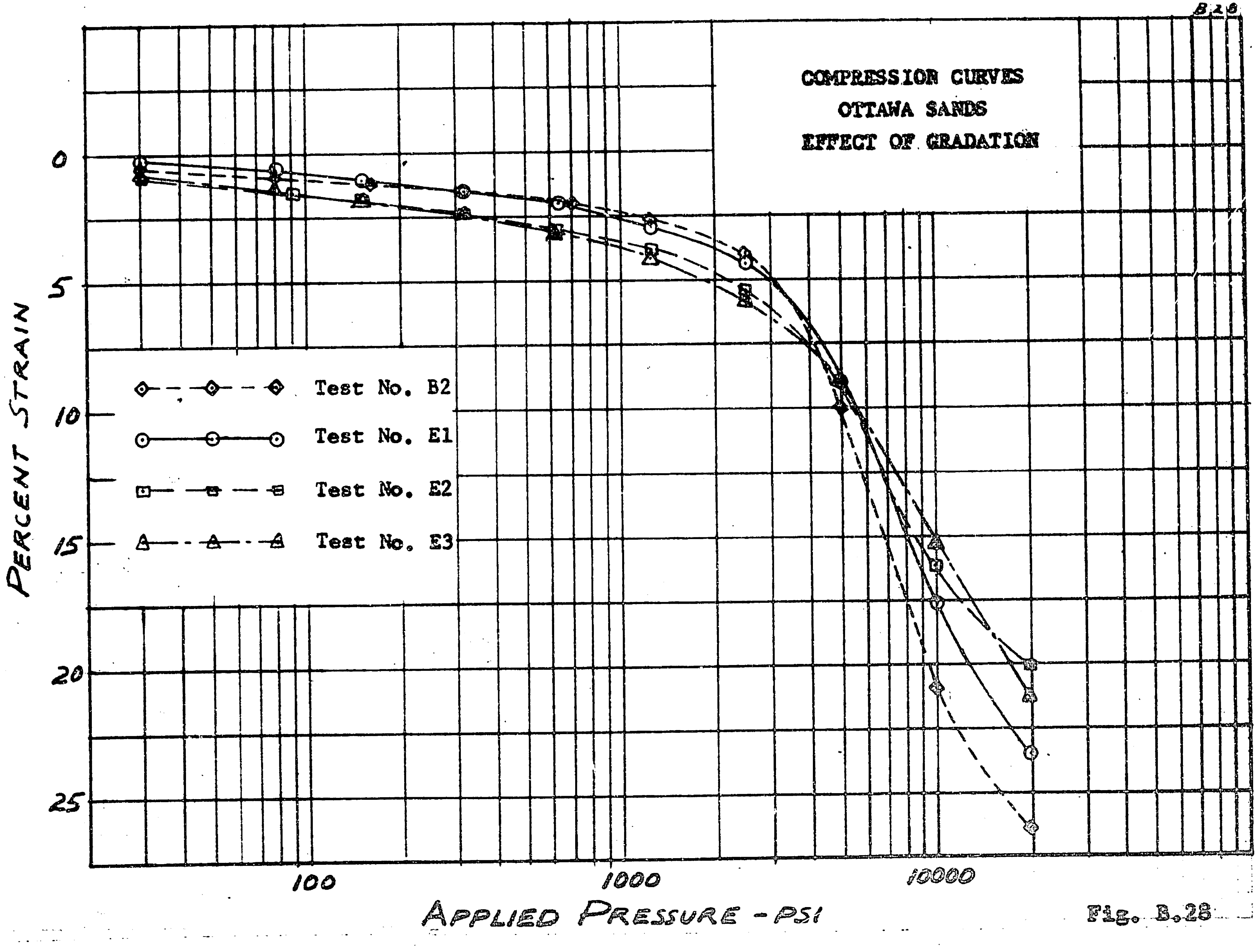
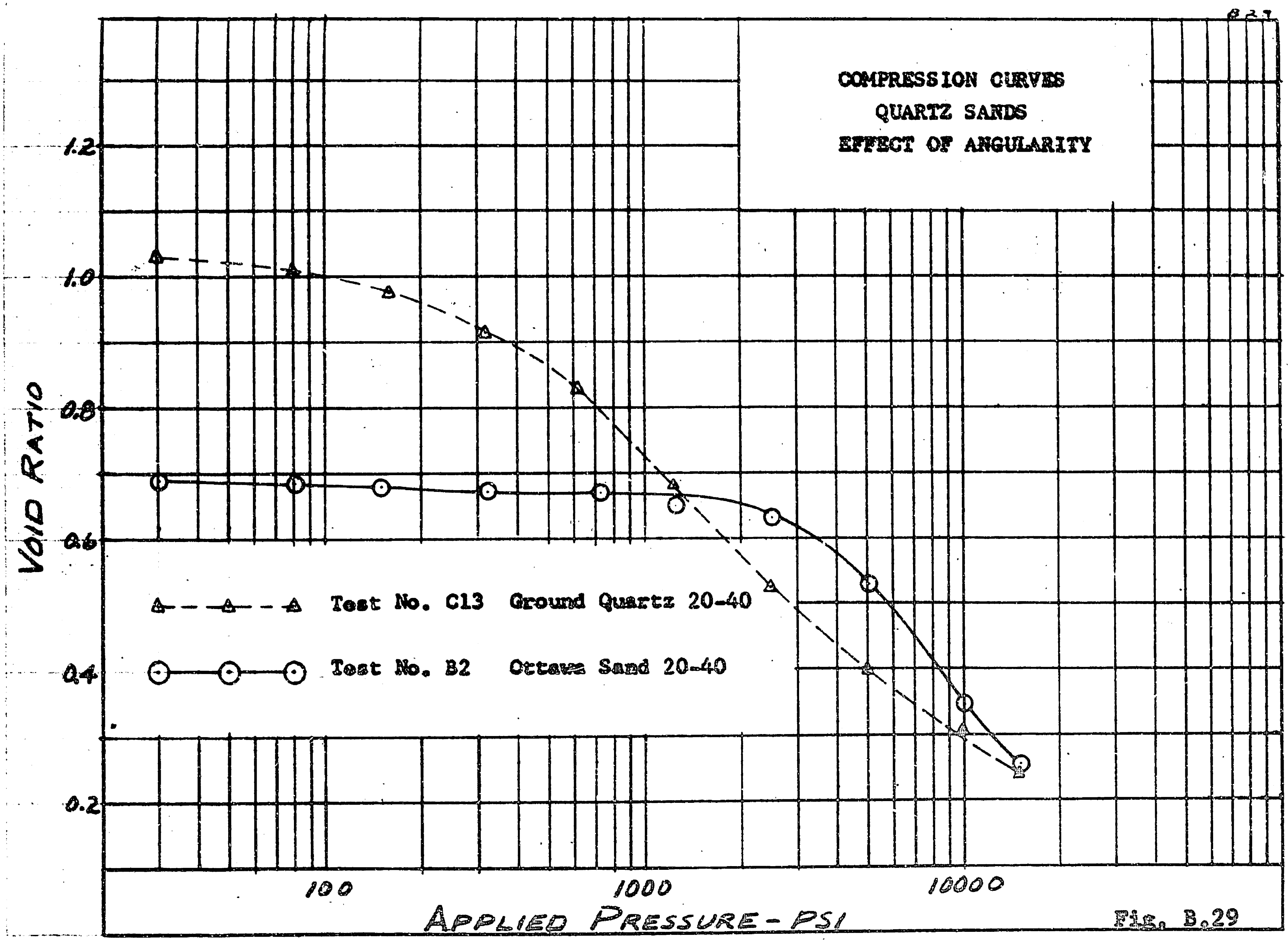
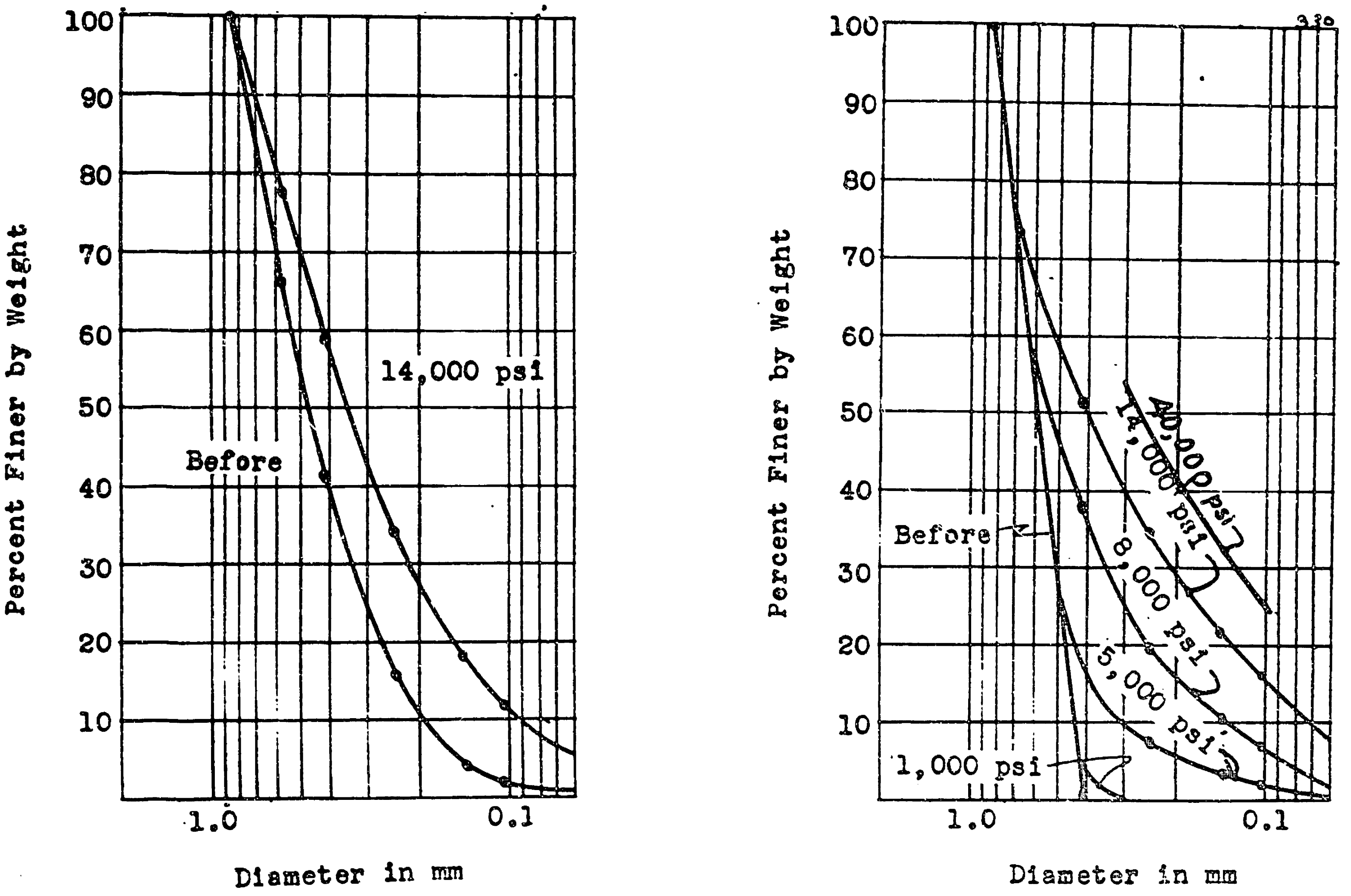

B 28
COMPRESSION CURVES
OTTAWA SANDS
EFFECT OF GRADATION
Test No. B2
Test No. E1
Test No. E2
Test No. E3
PERCENT STRAIN
0
5
10
15
20
25
100
1000
10000
APPLIED PRESSURE - PSI

Fig. B.28



COMPRESSION CURVES
QUARTZ SANDS
EFFECT OF ANGULARITY

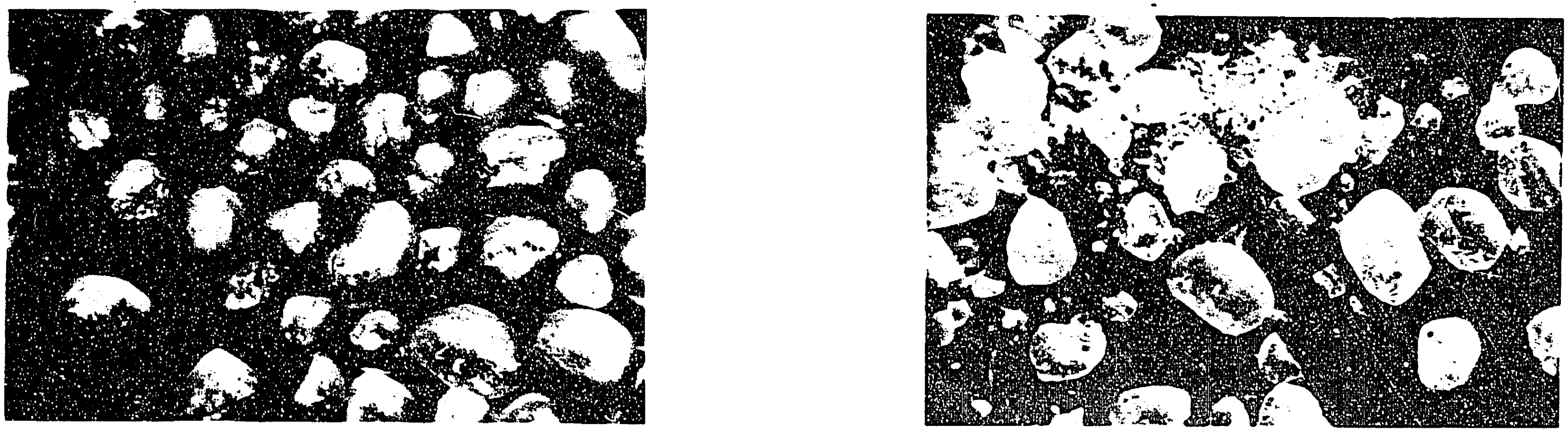
Fig. B.29



(a) Graded Ottawa sand before and after compression

(b) Uniform Ottawa sand before and after compression

Fig. B.30 GRADATION DATA FOR SANDS



(a) 20-40 Ottawa Sand Before Compression

(b) 20-40 Ottawa Sand After Compression

Fig. B.31 PHOTOMICROGRAPHS OF SAND GRAINS

CONSOLIDATION TEST NO. C8

SHEET NO. a

DATE 4/16/58

LOAD INCREMENT FROM 10000 lb. TO 20000 lb.

TIME	ELAPSED TIME Δt	DIAL READING IN in.
0959	0	.12582
	1/2	.15740
	1	.15805
	2	.15840
	4	.15870
	10	.15920
	30	.15975
	67	.16012
	205	.16063

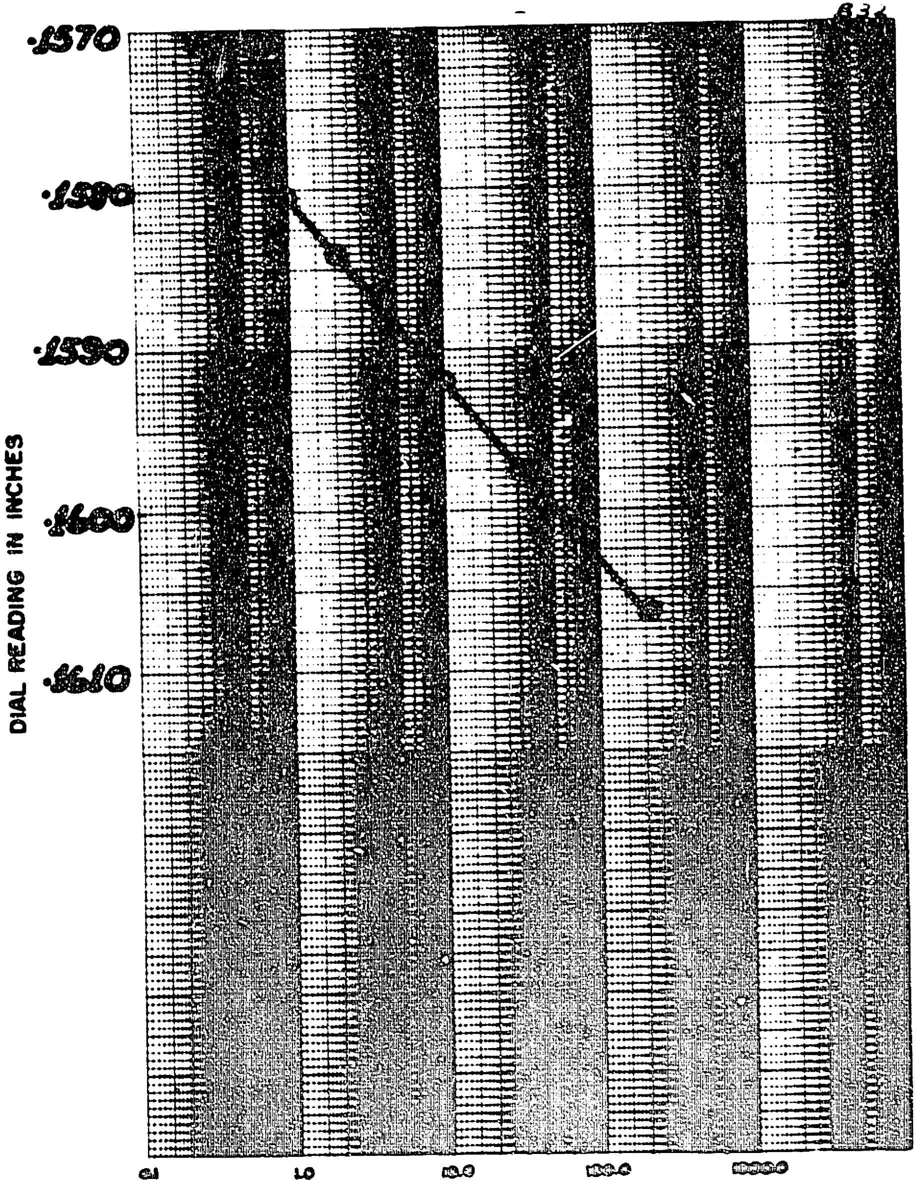


Fig. B.32

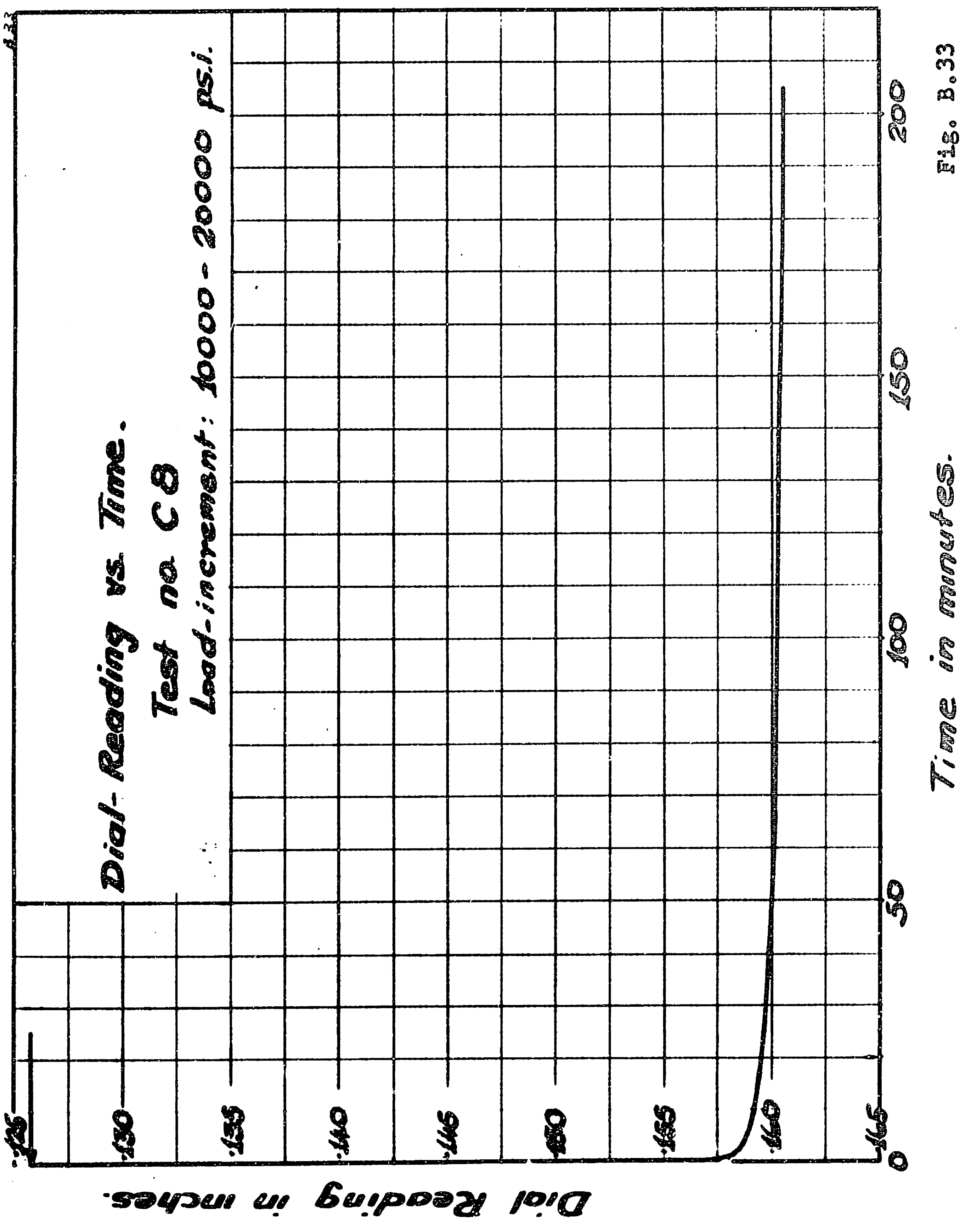

B.33
Dial-Reading vs. Time.
Test no. C8
Load-increment: 10000 - 20000 psi.
.125
.130
.135
.140
.145
.150
.155
.160
.165
Dial Reading in inches.
0
50
100
150
200
Time in minutes.

Fig. B.33

LONG DURATION TEST
20-40 MESH
OTTAWA SAND

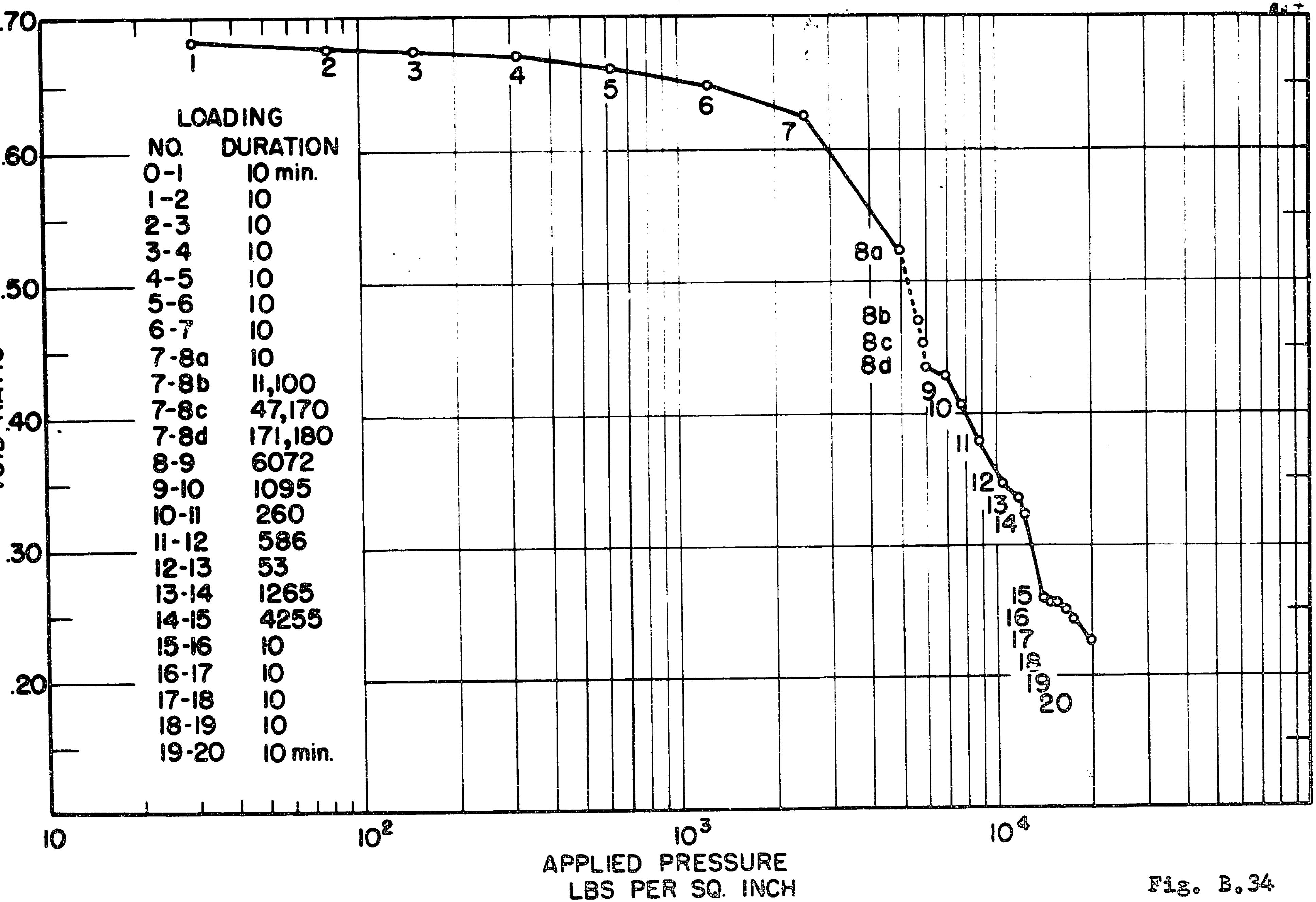


Fig. B.34

LONG DURATION TEST
COMPRESSION vs TIME

	TIME	ELAPSED TIME Δt	DIAL READING IN in.
	10^{04}	0	$.1611^{3}$
		1/4	14^{2}
		1/2	14^{3}
		1	14^{3}
		2	14^{6}
		4	14^{7}
		8	14^{8}
		15	14^{9}
	10^{34}	30	15^{0}
	10^{54}	50	15^{2}
6750	12^{24}	140	16^{1}
not controlled pressure increased to	14^{04}	240	17^{8}
6900	15^{04}	300	18^{3}
6900	15^{51}	347	18^{7}
6850	17^{00}	436	19^{0}
6200	10/14 9''	5707	24^{0}
incr. to 6900	13^{35}	5972	25^{0}
	15^{15}	6072	$.1625^{1}$

P.A.

LOAD INCREMENT FROM 6000 lb. TO 6750 lb.

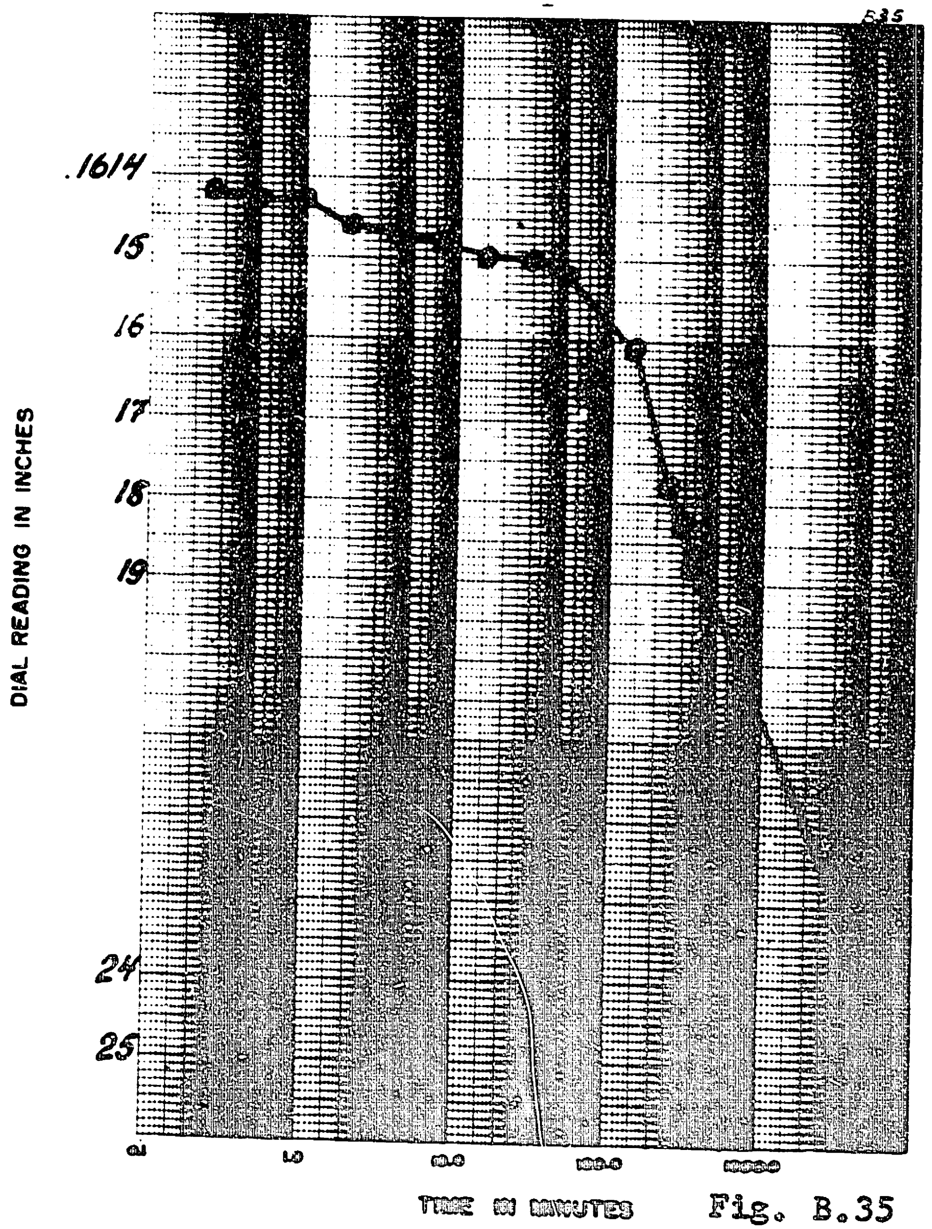


Fig. B.35

LONG DURATION TEST
COMPRESSION vs TIME

	TIME	ELAPSED TIME Δt	DIAL READING IN in.
	15^{20}	0	$.1630^{0}$
		1/4	31^{2}
		1/2	32^{3}
		1	33^{8}
		2	36^{1}
		3	39^{2}
		8	45^{1}
		16	49^{2}
	15^{50}	30	54^{9}
	16^{50}	60	59^{0}
7700	17^{20}	120	62^{9}
7300	10/15 9^{15}	1075	70^{9}
7750	9^{25}	1085	72^{8}
	9^{35}	1095	$.1673^{7}$

LOAD INCREMENT FROM 6900 lb. TO 7700 lb.

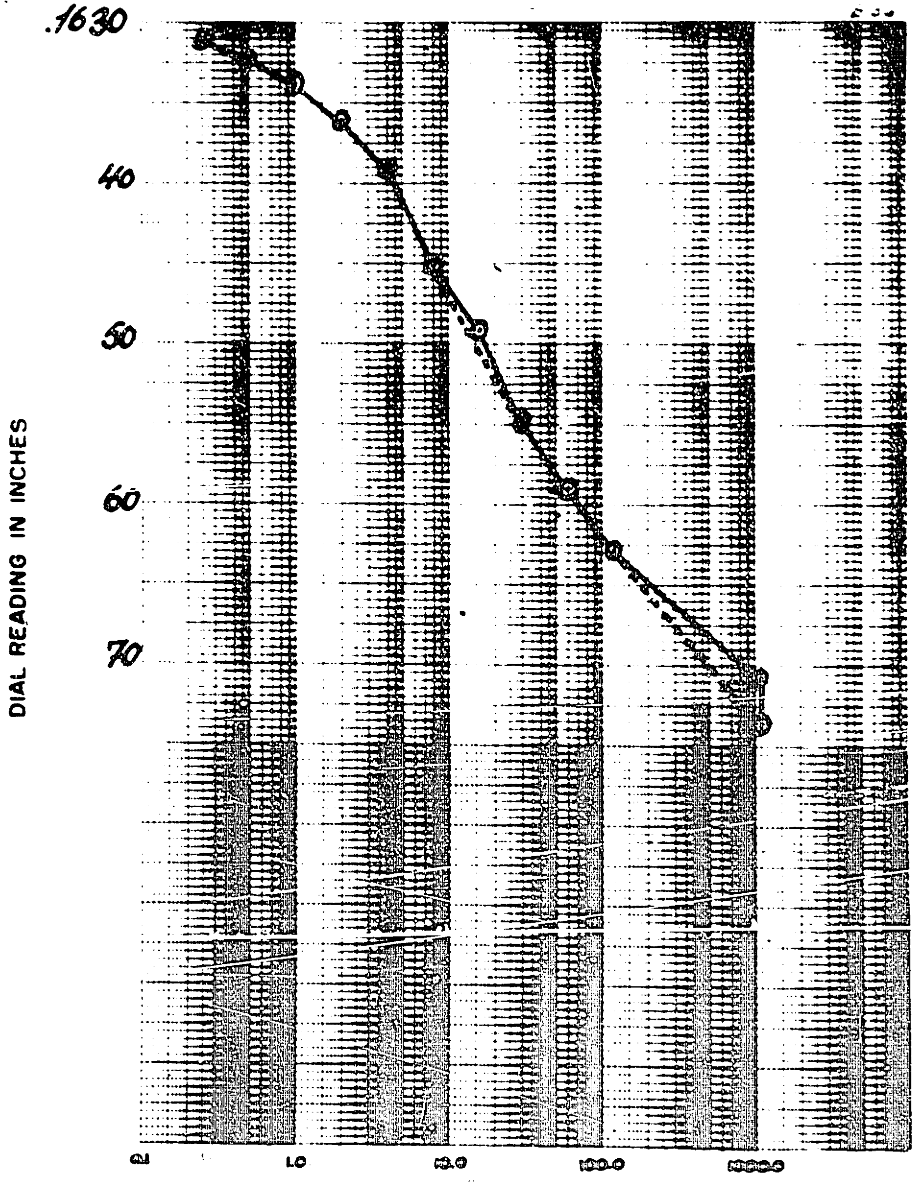


Fig. B.36

LONG DURATION TEST
COMPRESSION vs TIME

LOAD INCREMENT FROM 7750 lb. TO 8800 lb.

TIME	ELAPSED TIME Δt	DIAL READING IN in.
9^{38}	0	$.1673^{7}$
	1/4	97^{0}
	1/2	$.1705^{0}$
	1	11^{0}
	2	16^{5}
	4	19^{9}
	8	23^{3}
	15	26^{1}
10^{08}	30	29^{0}
10^{38}	60	33^{3}
12^{52}	194	40^{7}
13^{58}	260	$.1741^{8}$

8700
8800

P.Ab.

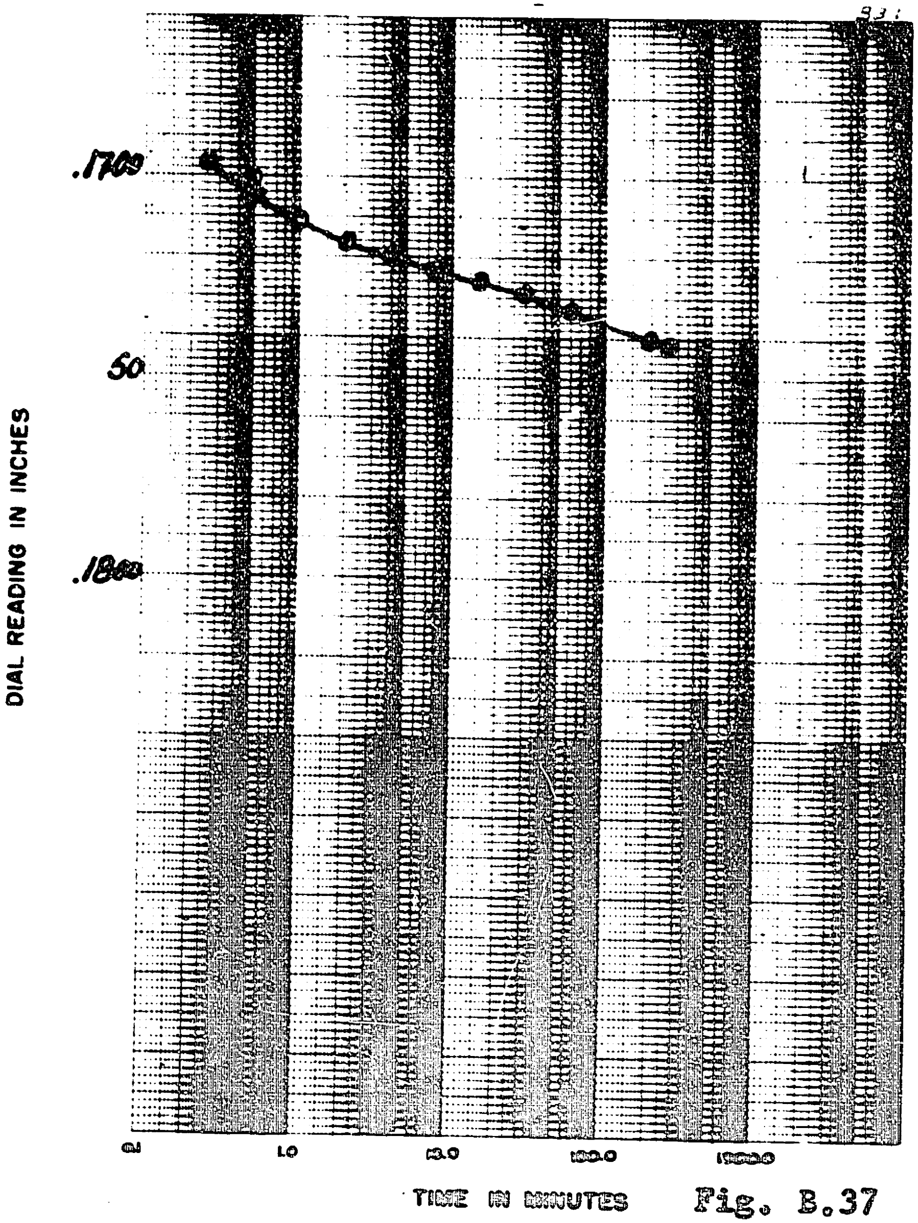


Fig. B.37

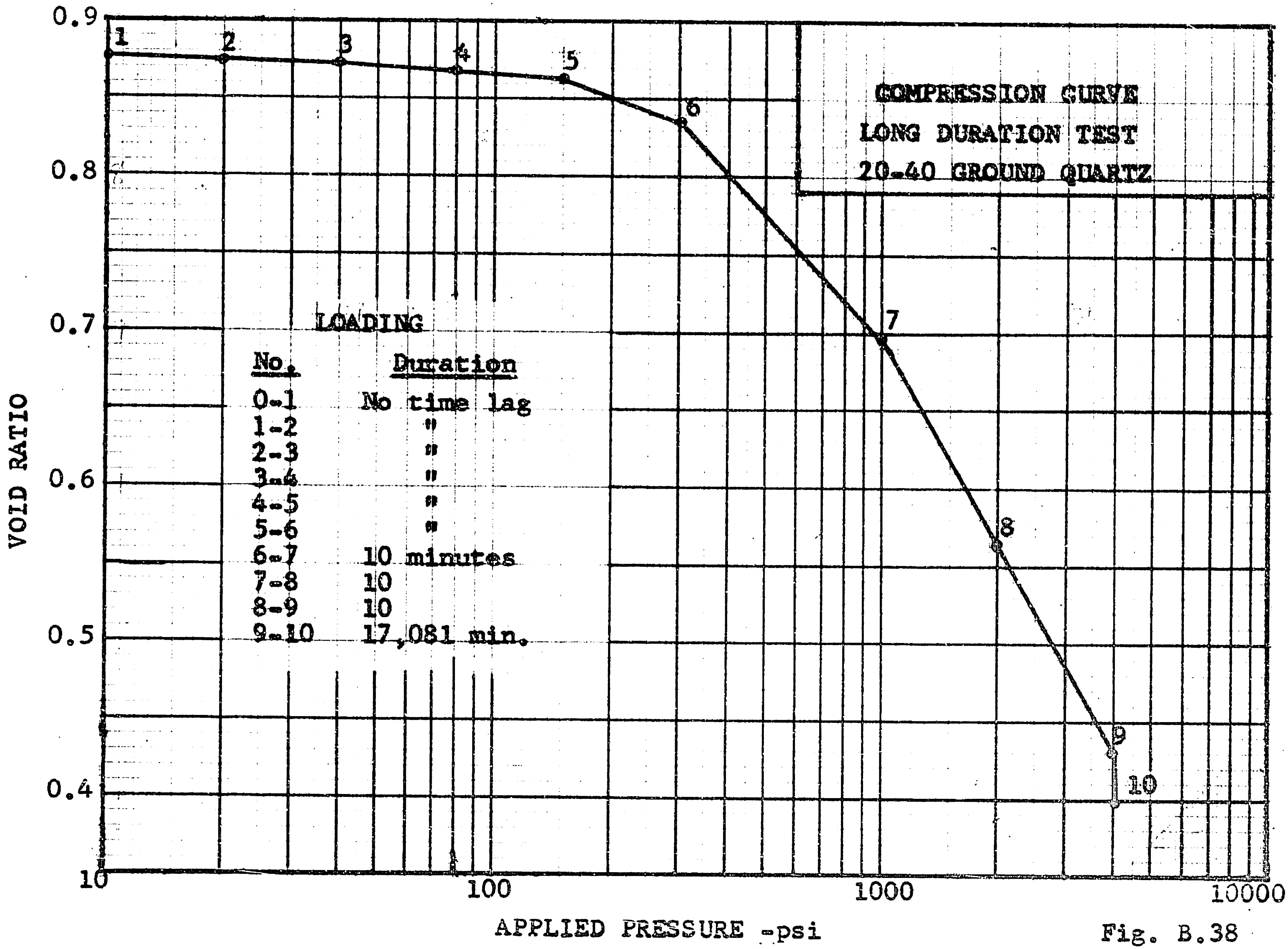

COMPRESSION CURVE
LONG DURATION TEST
20-40 GROUND QUARTZ
LOADING
No.
Duration
0-1 No time lag
1-2 "
2-3 "
3-4 "
4-5 "
5-6 "
6-7 10 minutes
7-8 10
8-9 10
9-10 17,081 min.
1
2
3
4
5
6
7
8
9
10
VOID RATIO
0.9
0.8
0.7
0.6
0.5
0.4
10
100
1000
10000
APPLIED PRESSURE -psi

Fig. B.38

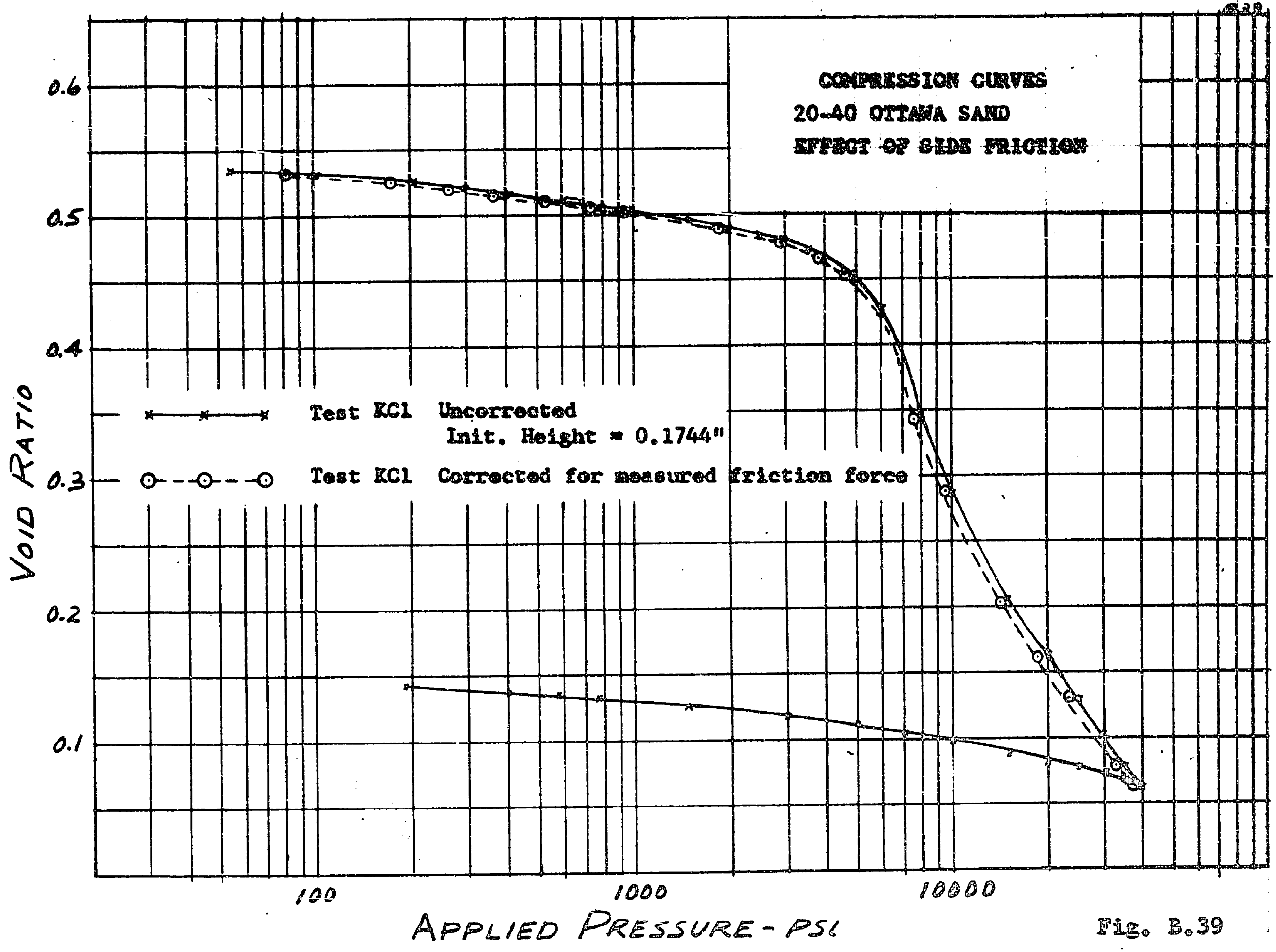

COMPRESSION CURVES
20-40 OTTAWA SAND
EFFECT OF SIDE FRICTION
Test KC1 Uncorrected
Init. Height = 0.1744"
Test KC1 Corrected for measured friction force
VOID RATIO
0.6
0.5
0.4
0.3
0.2
0.1
100
1000
10000
APPLIED PRESSURE - PSI

Fig. B.39

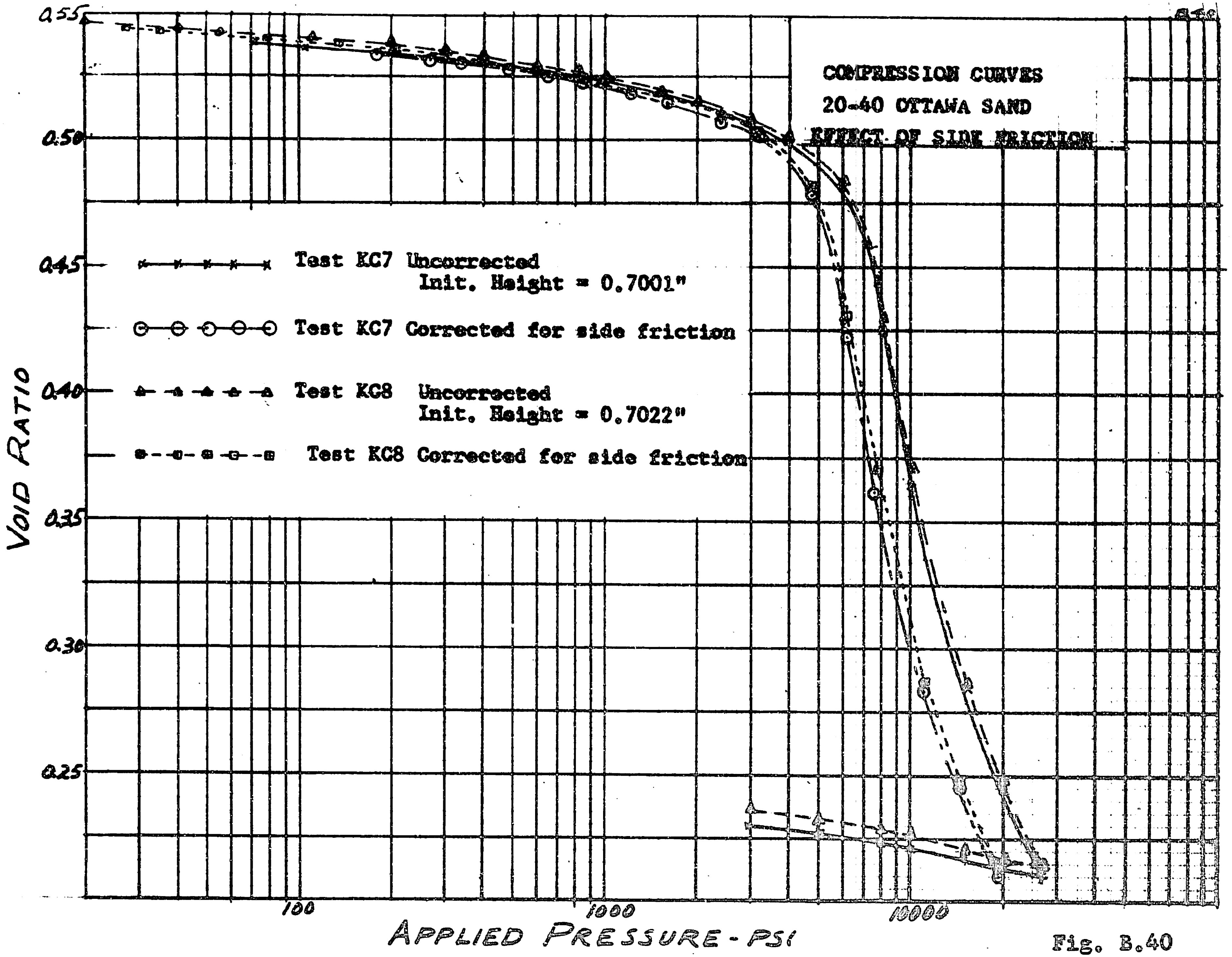

COMPRESSION CURVES
20-40 OTTAWA SAND
EFFECT OF SIDE FRICTION
Test KC7 Uncorrected Init. Height = 0.7001"
Test KC7 Corrected for side friction
Test KC8 Uncorrected Init. Height = 0.7022"
Test KC8 Corrected for side friction
VOID RATIO
0.55
0.50
0.45
0.40
0.35
0.30
0.25
APPLIED PRESSURE - PSI
100
1000
10000

Fig. B.40

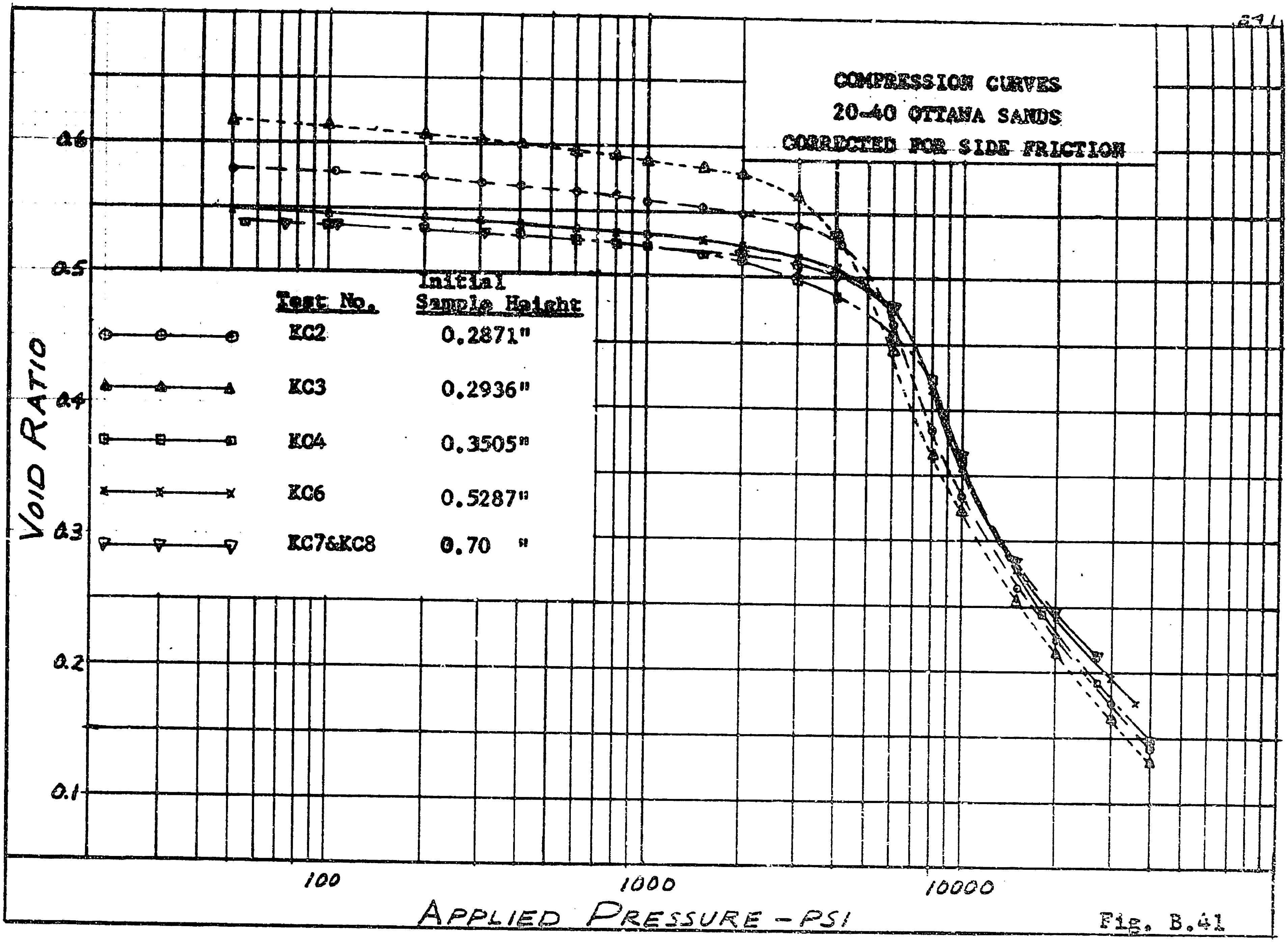

COMPRESSION CURVES
20-40 OTTAWA SANDS
CORRECTED FOR SIDE FRICTION
Test No.
Initial Sample Height
KC2 0.2871"
KC3 0.2936"
KC4 0.3505"
KC6 0.5287"
KC7&KC8 0.70 "
VOID RATIO
0.6
0.5
0.4
0.3
0.2
0.1
100
1000
10000
APPLIED PRESSURE - PSI

Fig. B.41

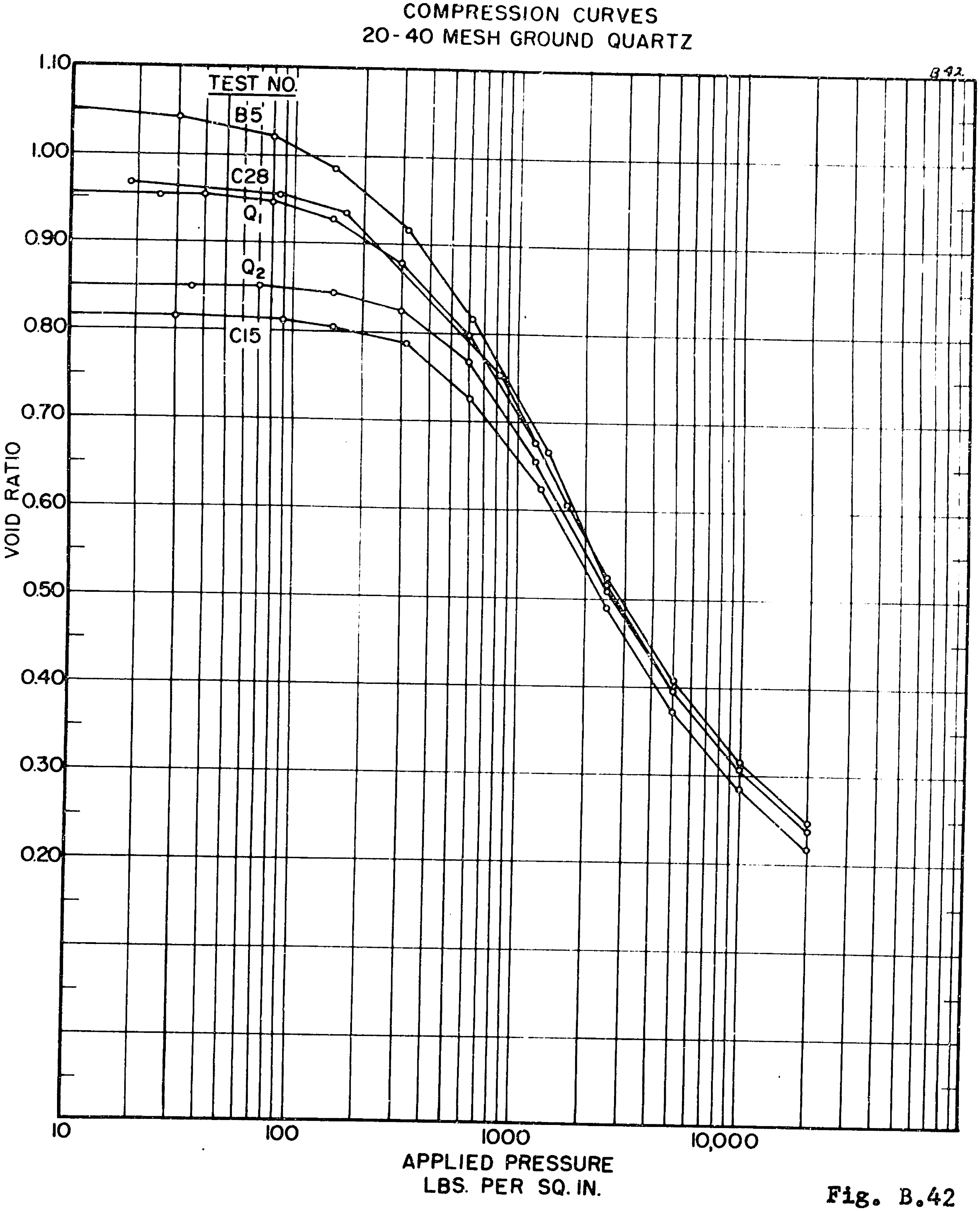

COMPRESSION CURVES
20-40 MESH GROUND QUARTZ
B42
TEST NO.
B5
C28
Q1
Q2
C15
VOID RATIO
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
10
100
1000
10,000
APPLIED PRESSURE
LBS. PER SQ. IN.

Fig. B.42

COMPRESSION CURVES
20-40 MESH GROUND FELDSPAR

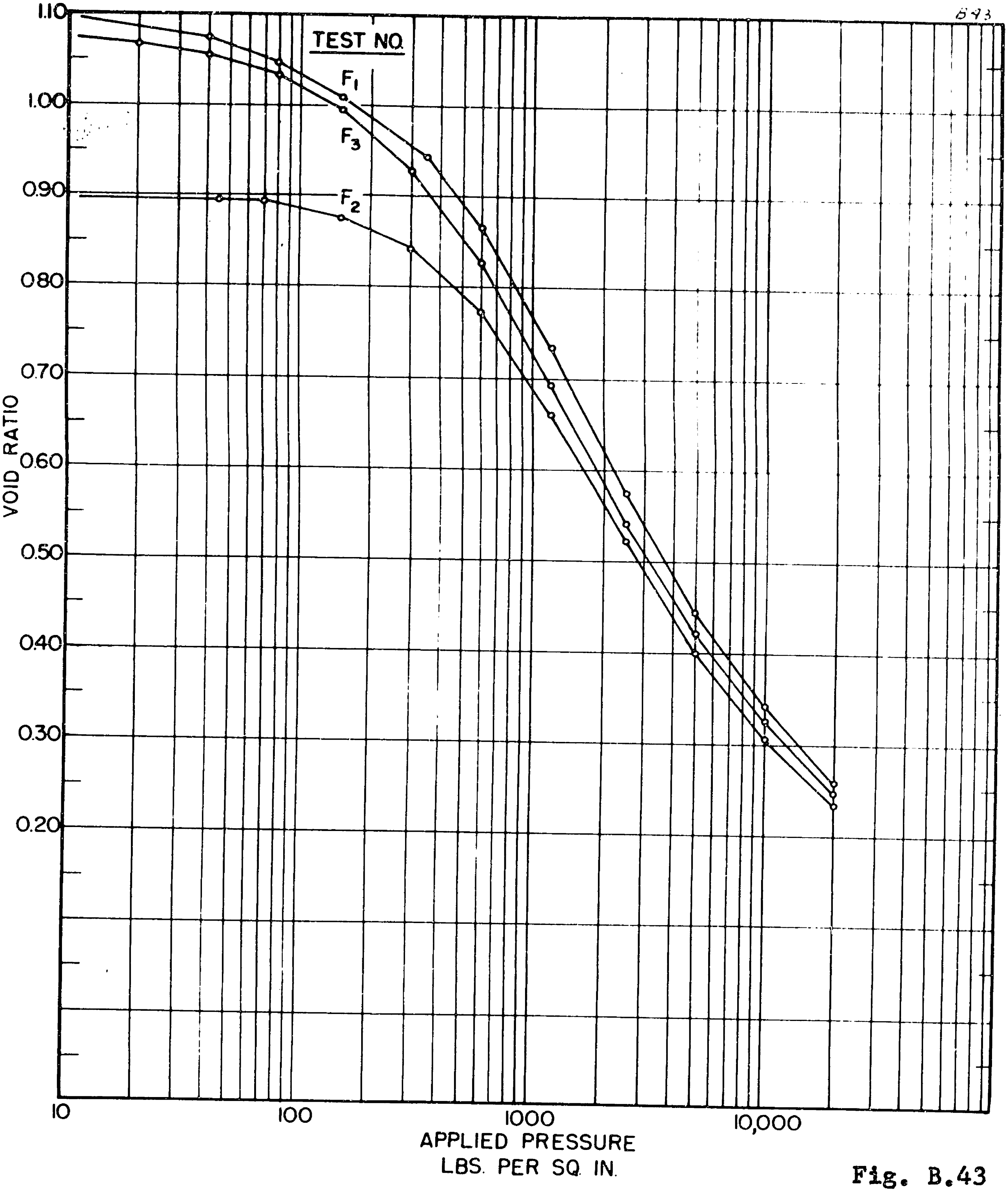


Fig. B.43

COMPRESSION CURVES
20-40 MESH GROUND DOLOMITE

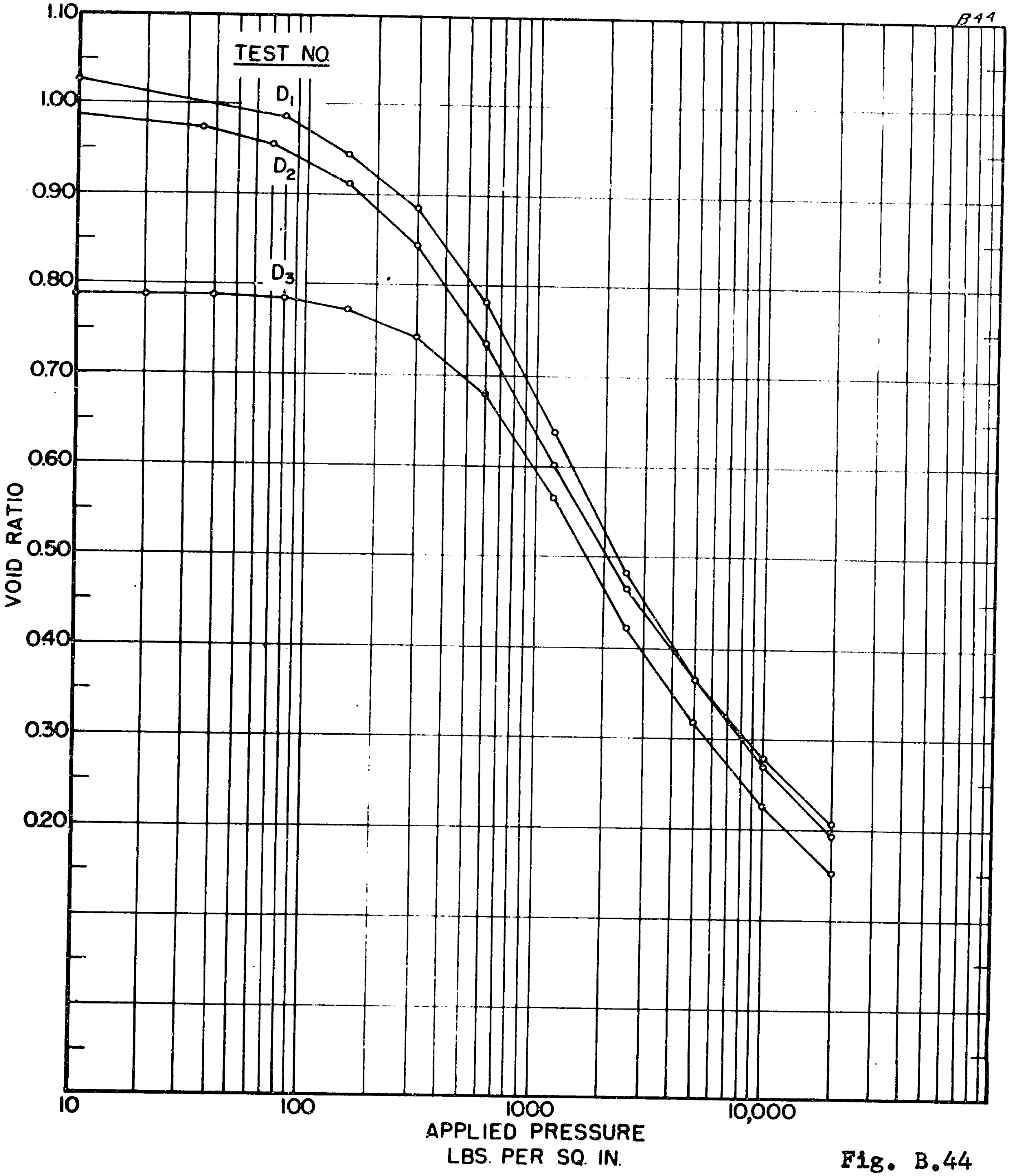


Fig. B.44

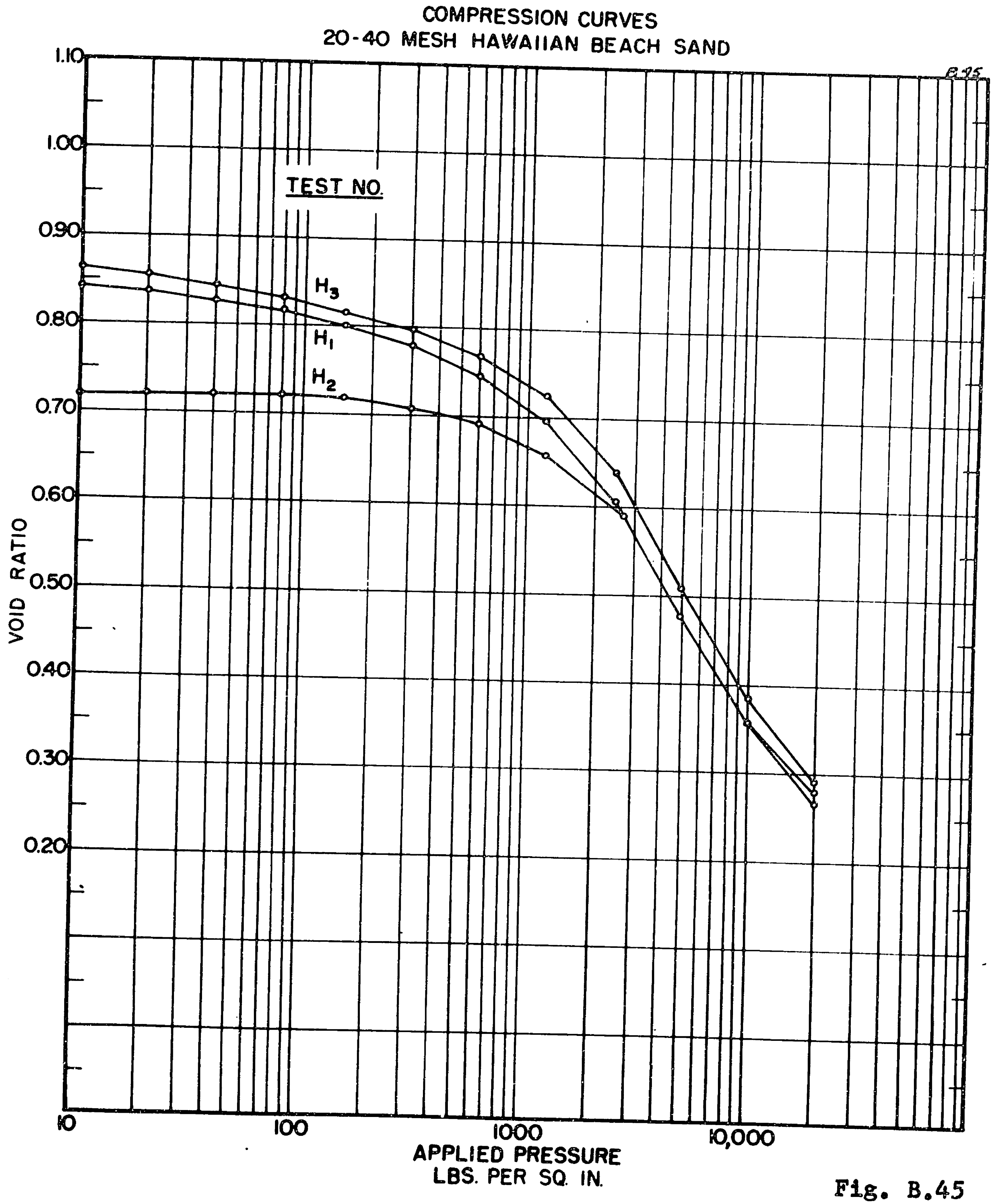

COMPRESSION CURVES
20-40 MESH HAWAIIAN BEACH SAND
B.45
TEST NO.
H3
H1
H2
VOID RATIO
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
10
100
1000
10,000
APPLIED PRESSURE
LBS. PER SQ. IN.

Fig. B.45

GRAIN SIZE DISTRIBUTION

Ground Quartz

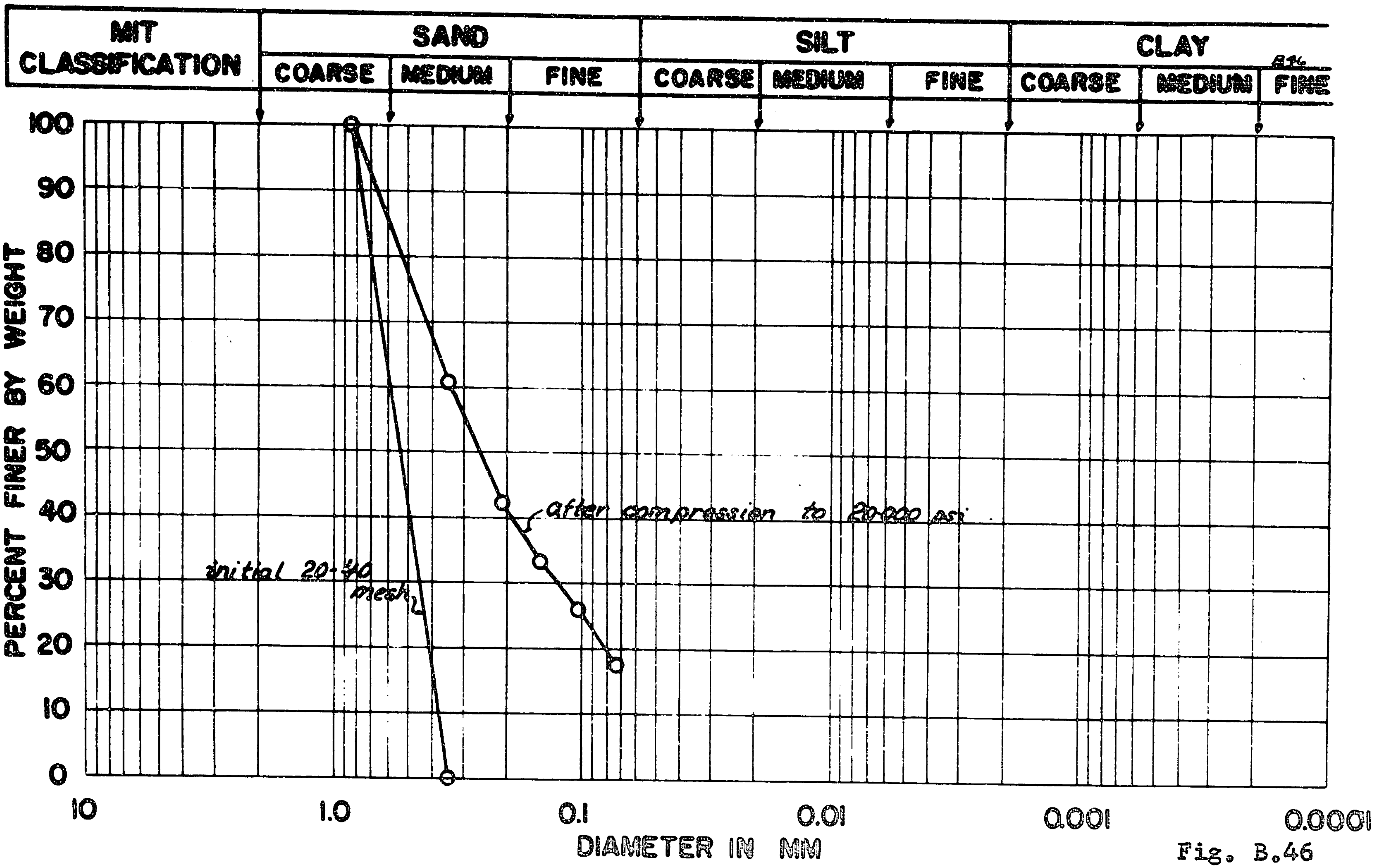


Fig. B.46

GRAIN SIZE DISTRIBUTION

Feldspar

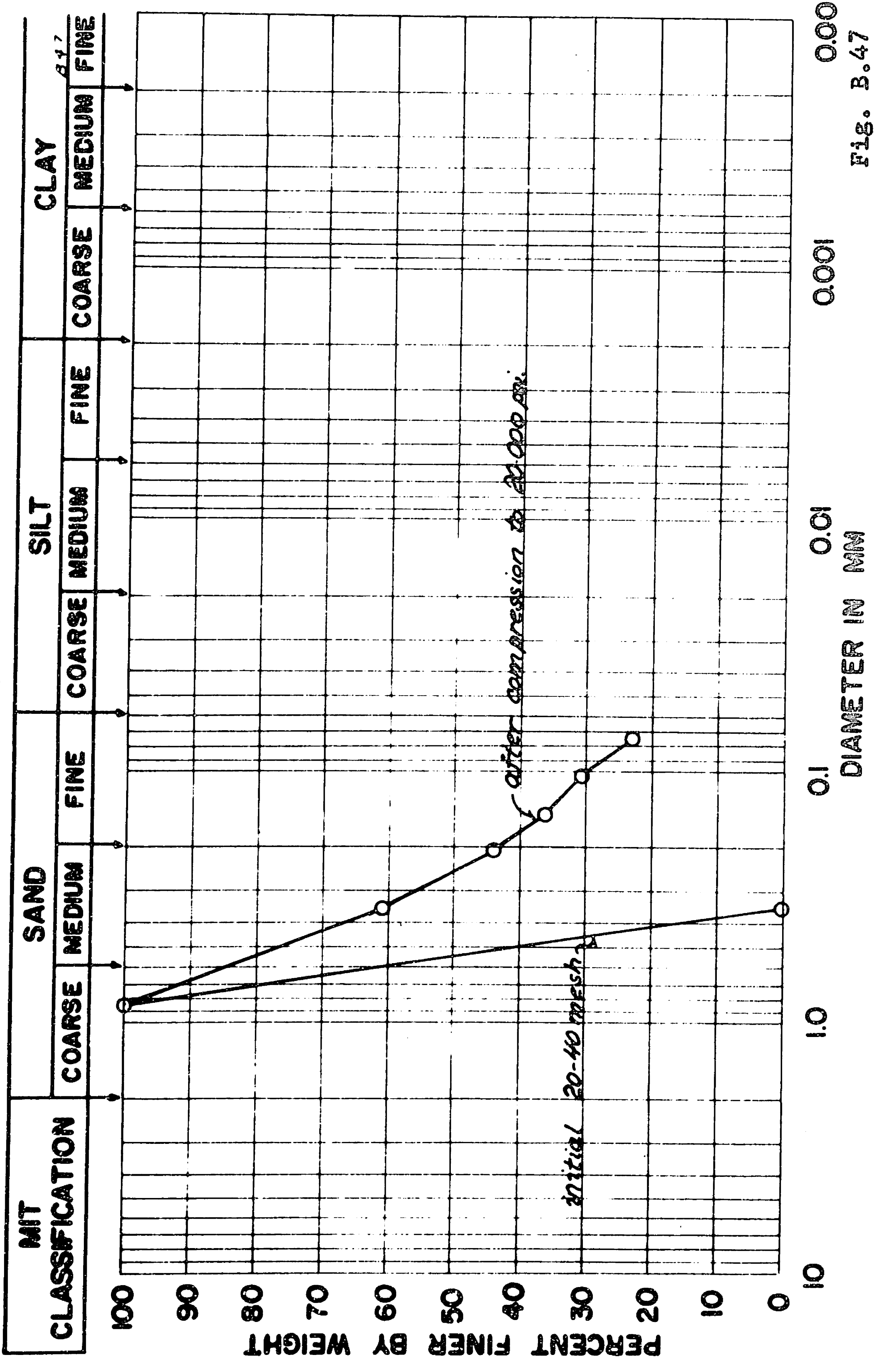


Fig. B.47

GRAIN SIZE DISTRIBUTION

DOLOMITE

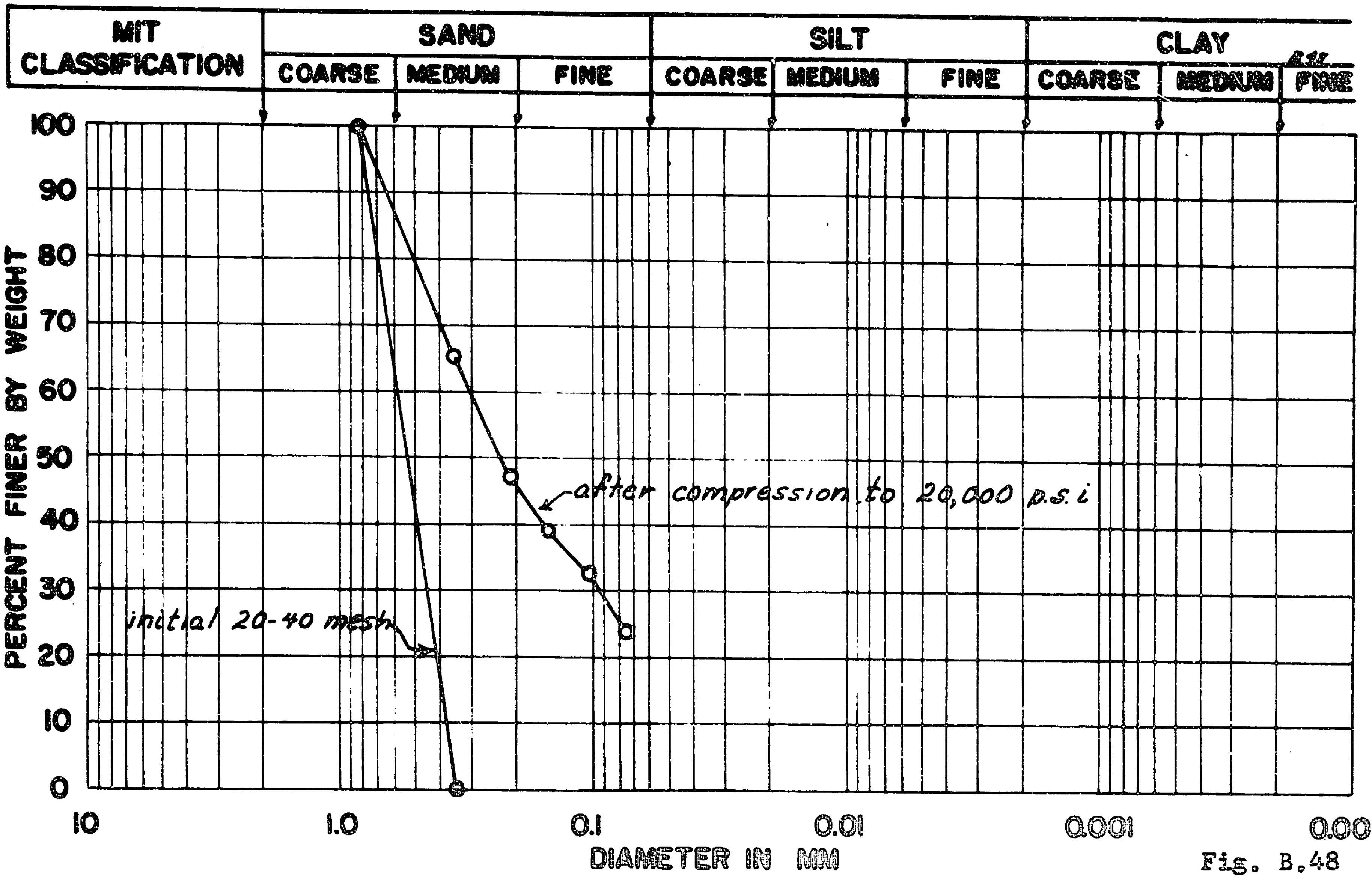


Fig. B.48

GRAIN SIZE DISTRIBUTION

Hawaiian Beach Sand

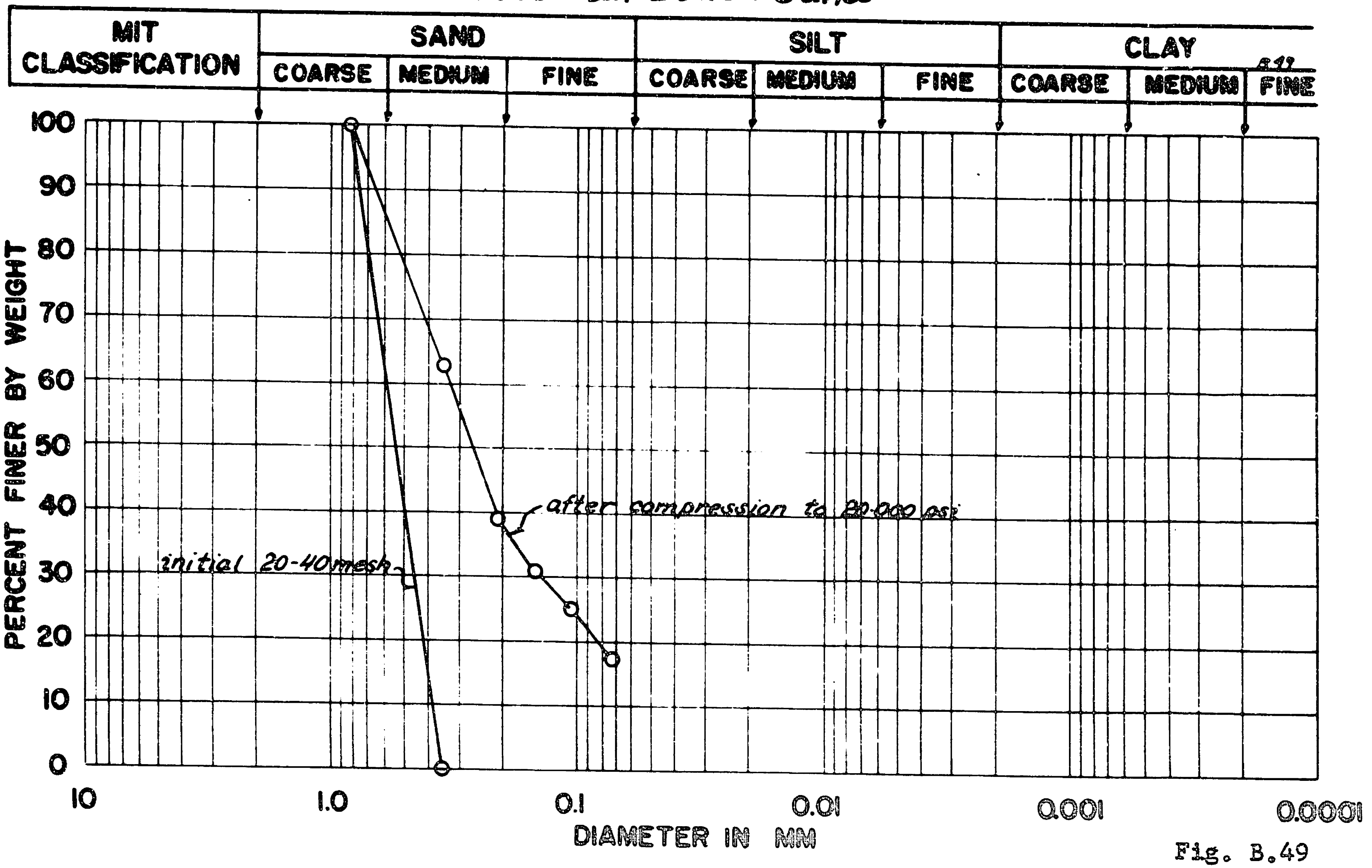
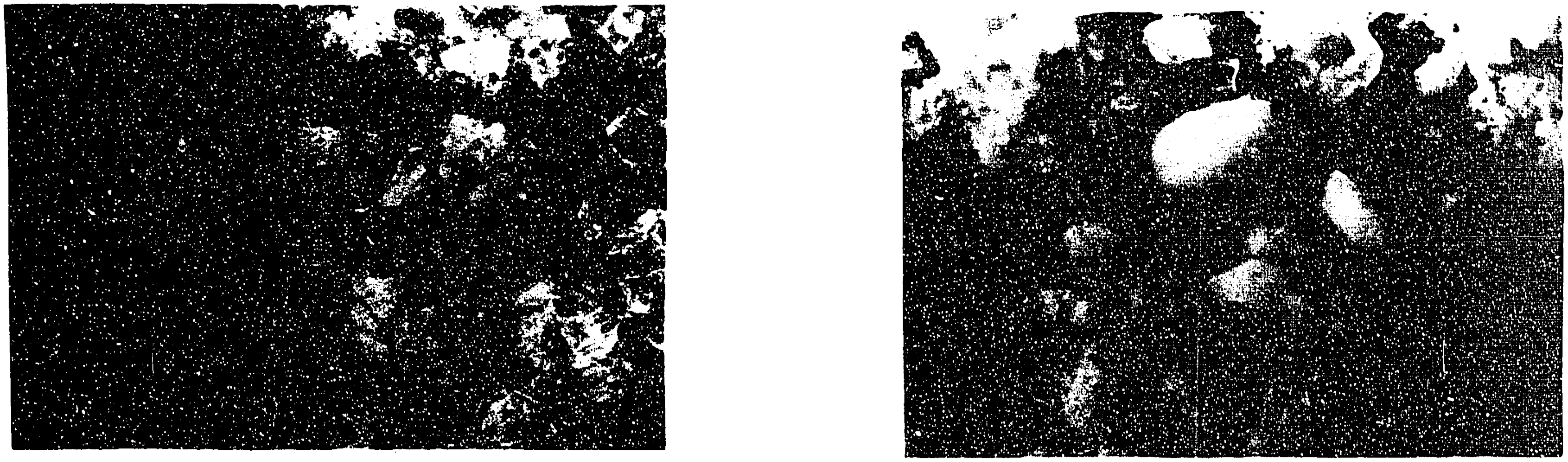
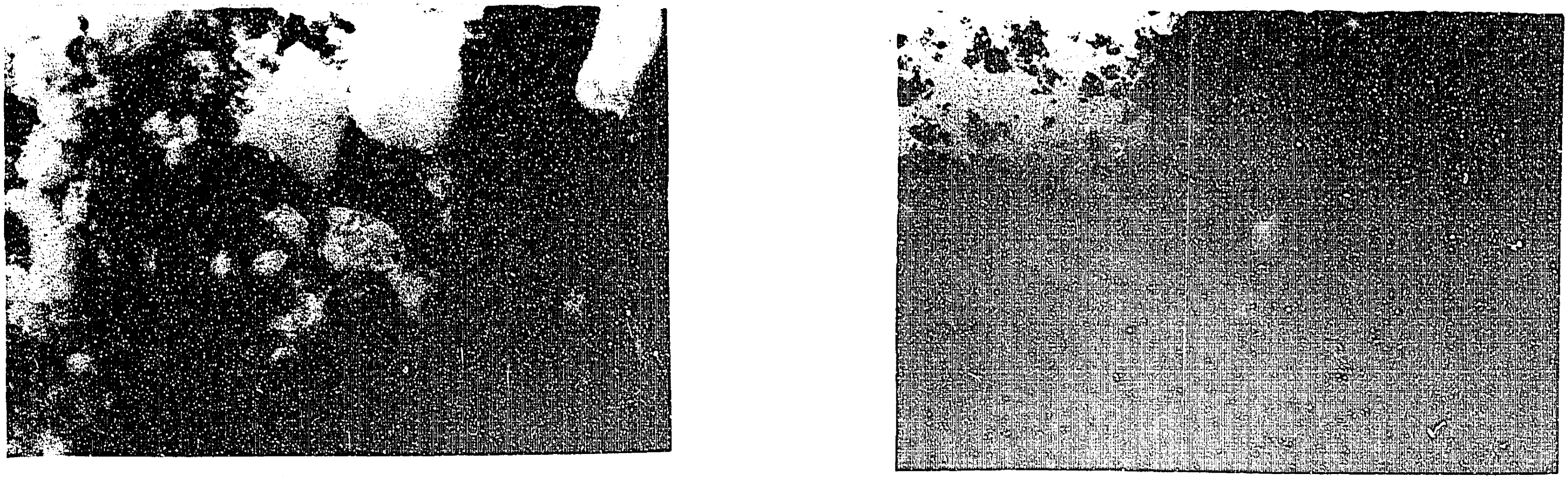


Fig. B.49



(a) Quartz

(b) Feldspar



(c) Dolomite

(d) Hawaiian Beach Sand

Fig. B.50 PHOTOMICROGRAPHS OF GROUND MINERALS COMPRESSED TO 20,000 psi.

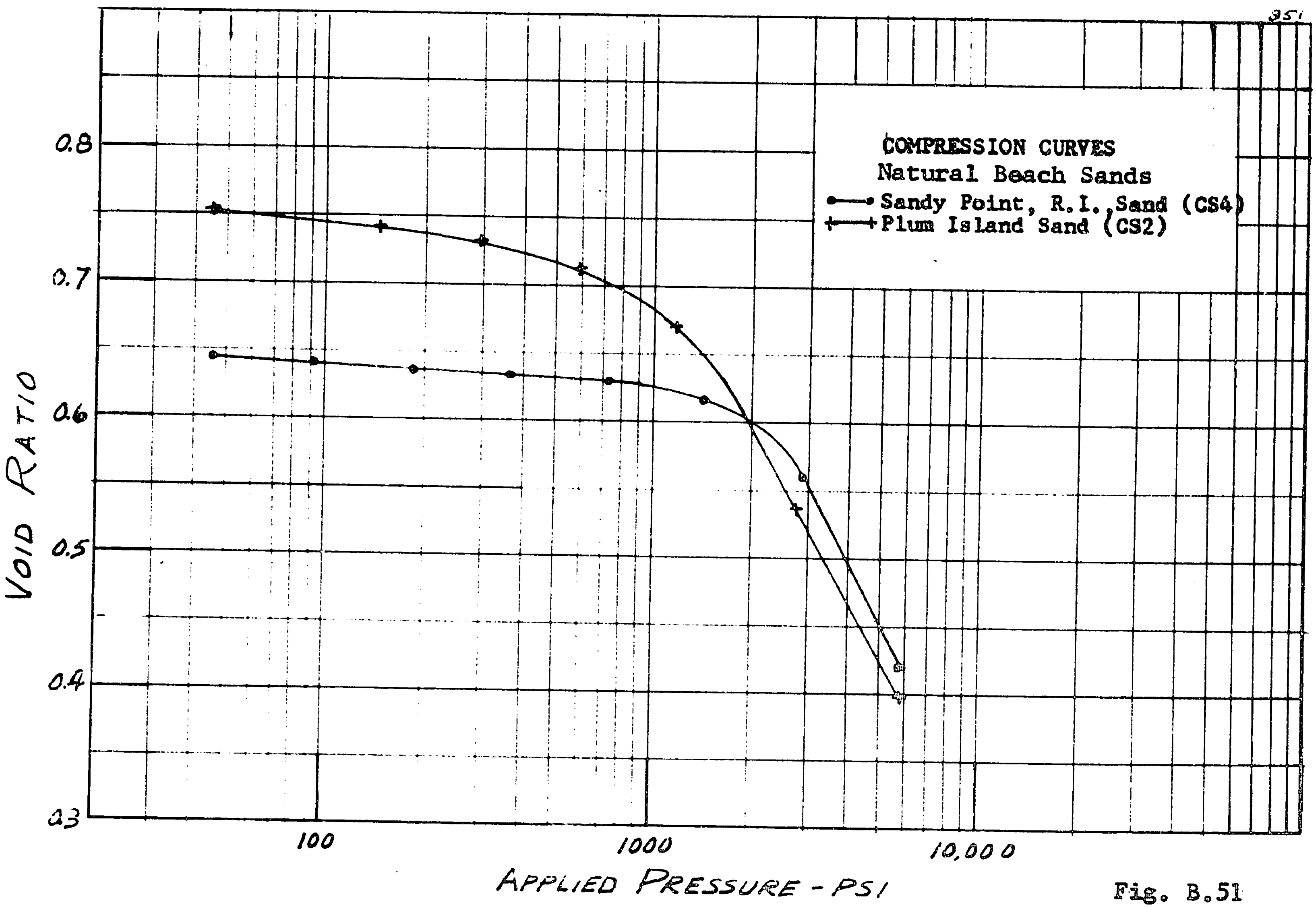

COMPRESSION CURVES
Natural Beach Sands
Sandy Point, R.I., Sand (CS4)
Plum Island Sand (CS2)
0.8
0.7
0.6
0.5
0.4
0.3
VOID RATIO
100
1000
10,000
APPLIED PRESSURE - PSI

Fig. B.51

GRAIN SIZE DISTRIBUTION

PLUM ISLAND SAND
BEFORE AND AFTER
COMPRESSION TO 6000 psi

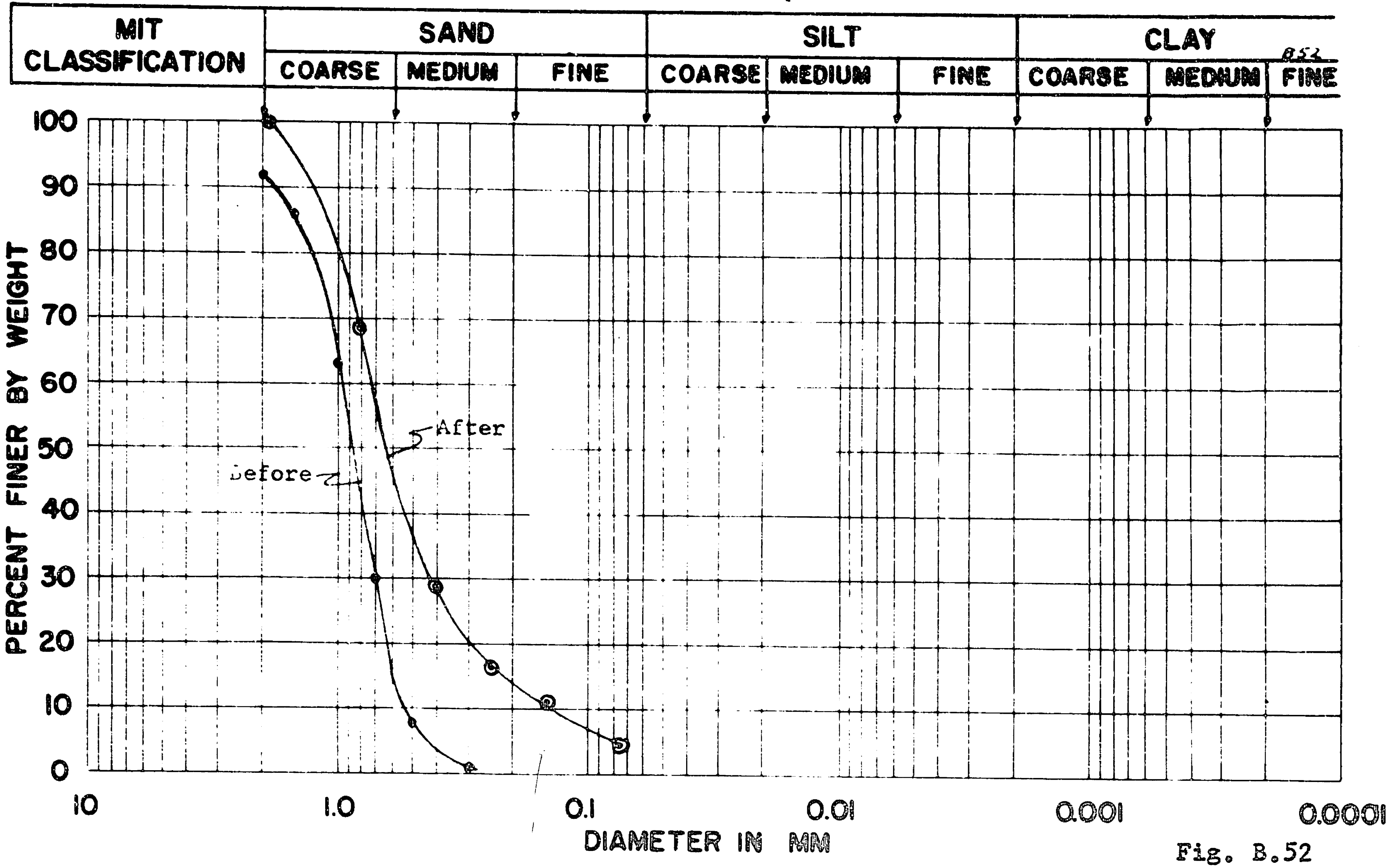
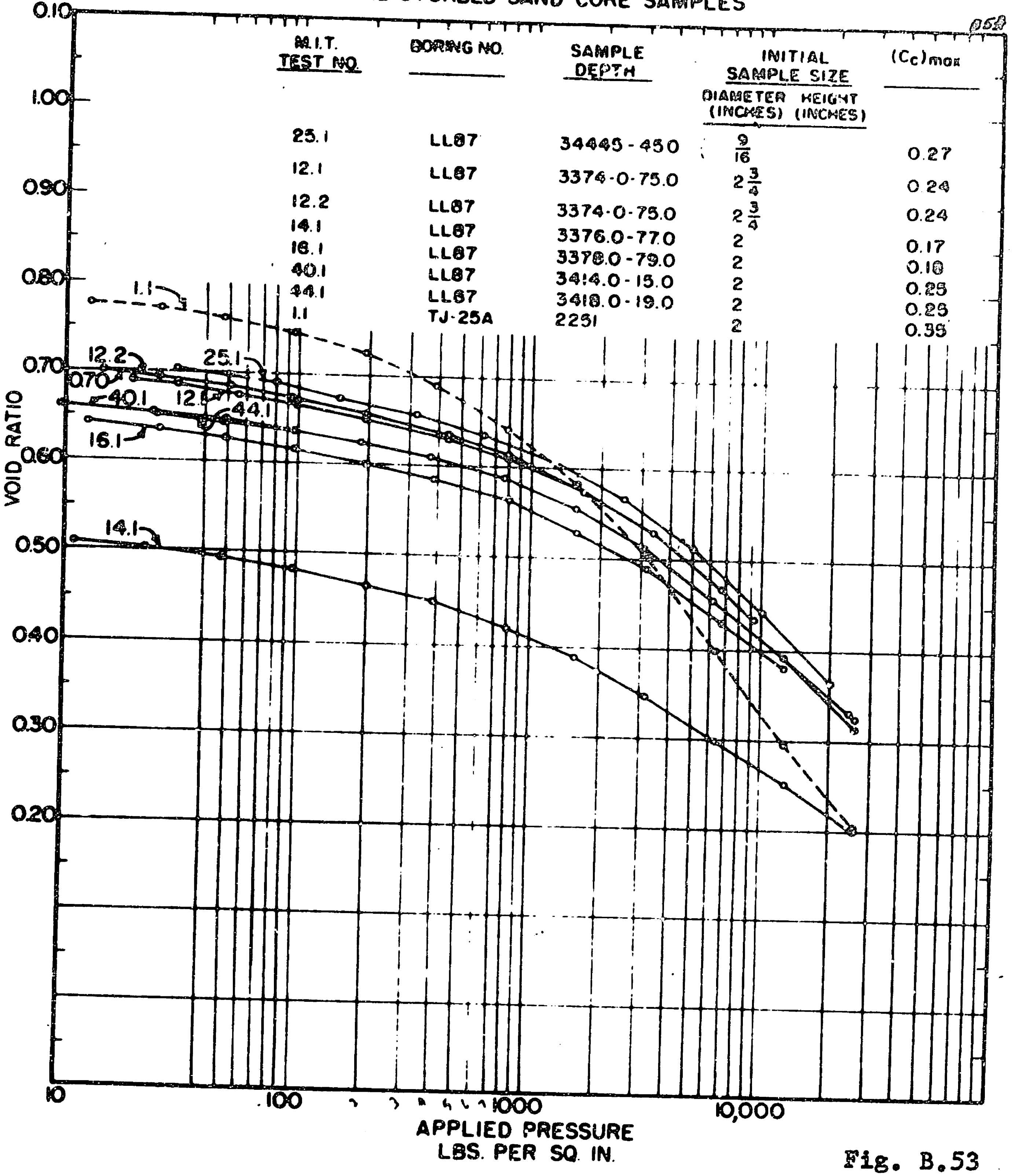


Fig. B.52



COMPRESSION CURVES
UNDISTURBED SAND CORE SAMPLES

M.I.T. TEST NO.	BORING NO.	SAMPLE DEPTH	INITIAL SAMPLE SIZE DIAMETER (INCHES)	INITIAL SAMPLE SIZE HEIGHT (INCHES)	$(C_c)_{max}$
25.1	LL87	34445-450	$\frac{9}{16}$		0.27
12.1	LL87	3374-0-75.0	$2\frac{3}{4}$		0.24
12.2	LL87	3374-0-75.0	$2\frac{3}{4}$		0.24
14.1	LL87	3376.0-77.0	2		0.17
16.1	LL87	3378.0-79.0	2		0.18
40.1	LL87	3414.0-15.0	2		0.25
44.1	LL87	3418.0-19.0	2		0.25
1.1	TJ-25A	2251	2		0.35

Fig. B.53

COMPRESSION CURVES
SAND-OIL MIXTURE
BORING NO: LL-87
SAMPLE NO: 25

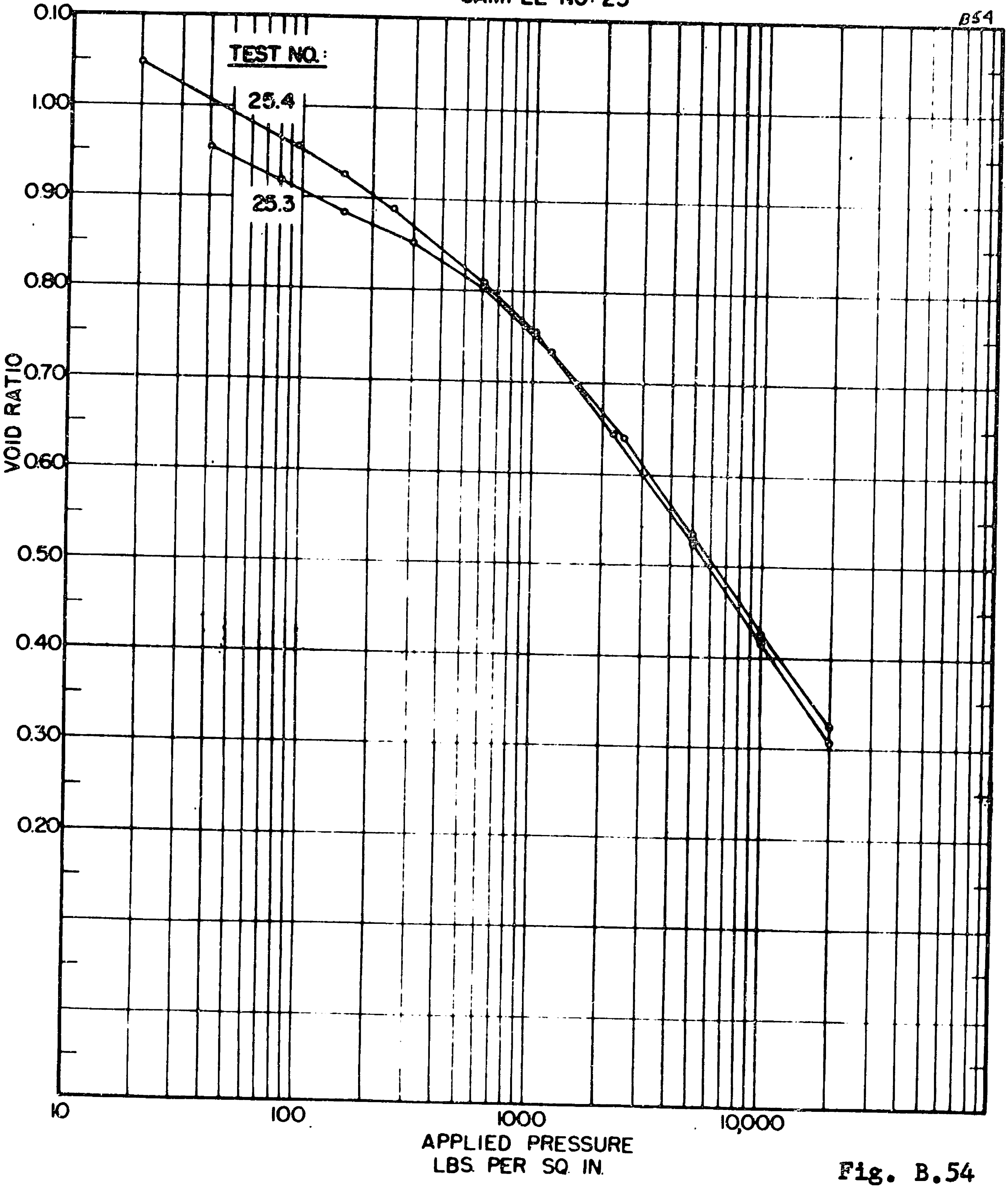


Fig. B.54

COMPRESSION CURVES
DRY SAND
(OIL REMOVED WITH XYLENE)
BORING NO.: LL-87
SAMPLE NO.: 25

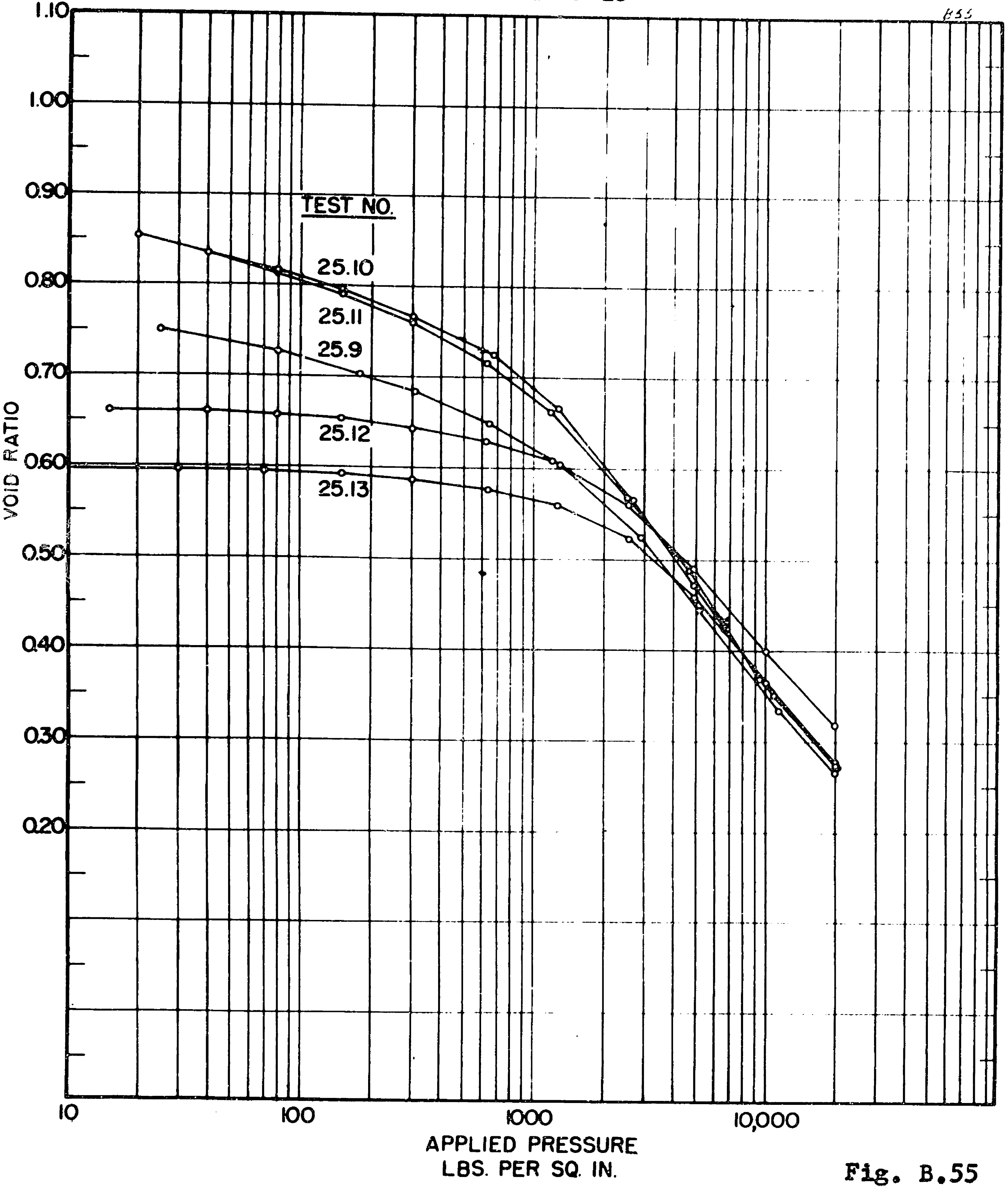


Fig. B.55

GRAIN SIZE DISTRIBUTION

SAMPLE LL87-25

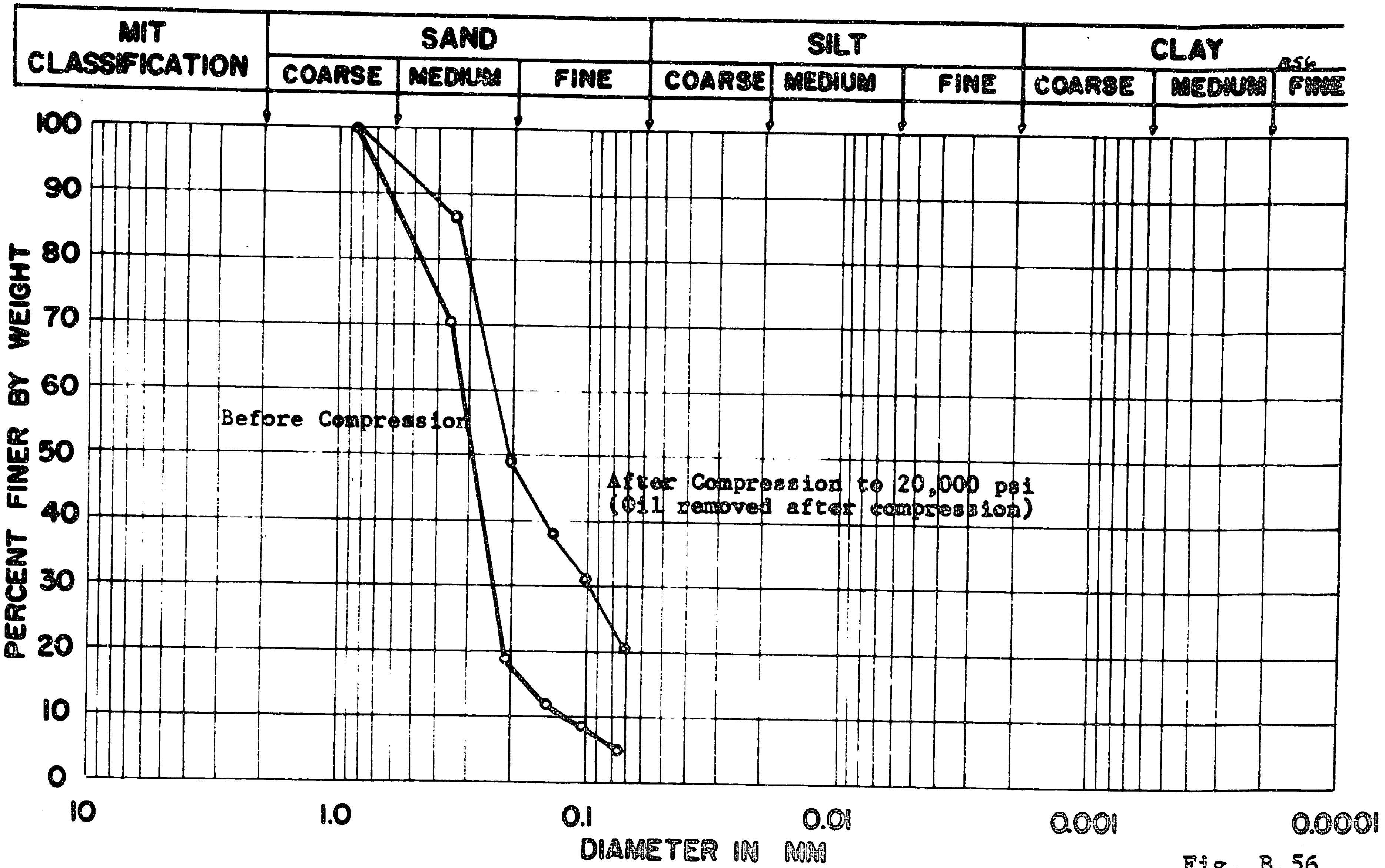
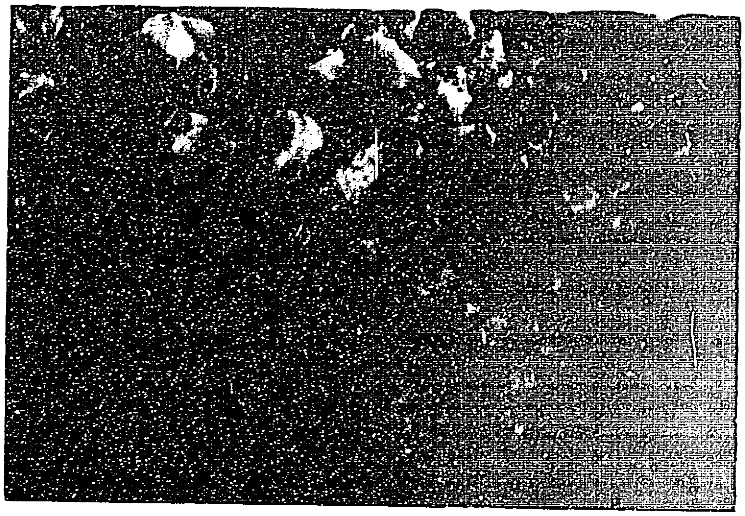
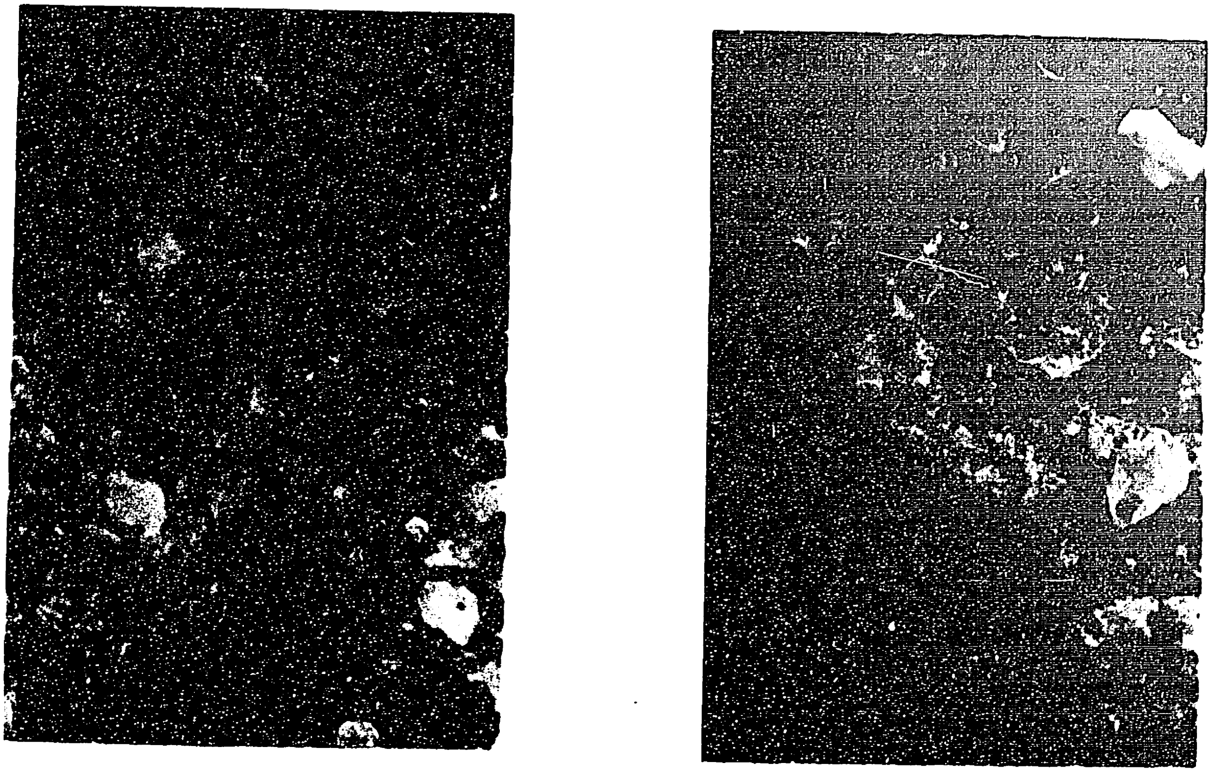


Fig. B.56



(a) Before Compression



(b) After Compression
to 20,000 psi
(Oil Removed with
Xylene after
Compression)

(c) After Compression
to 20,000 psi
(Oil Removed with
Xylene before
Compression)

Fig. B.57 PHOTOMICROGRAPHS, SAMPLE LL87-25

COMPRESSION CURVES
&
DISTURBED-PRECOMPRESSED SAND SAMPLES
BORING LL87
SAMPLE DEPTH 3374.0 - 75.0

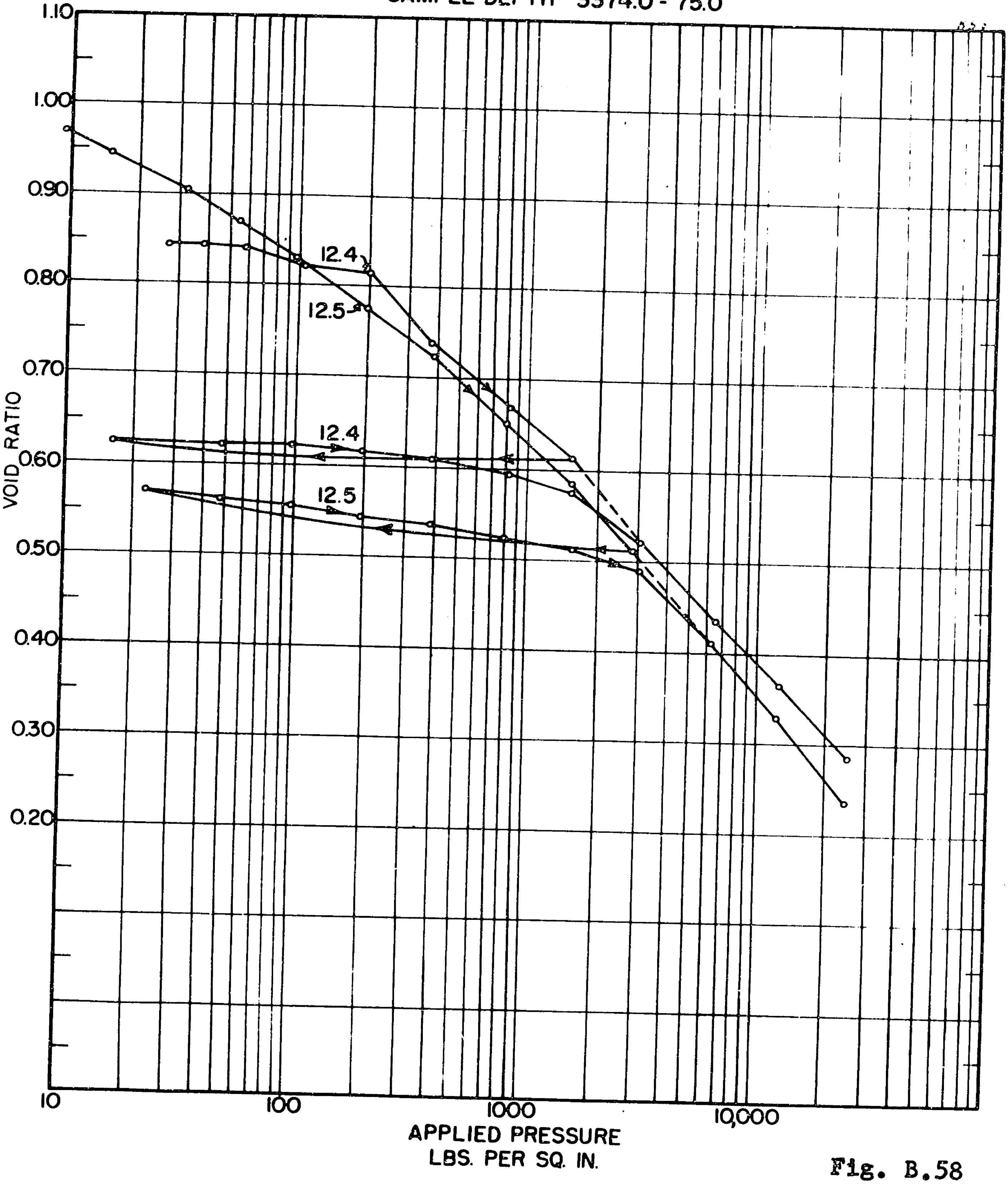


Fig. B.58

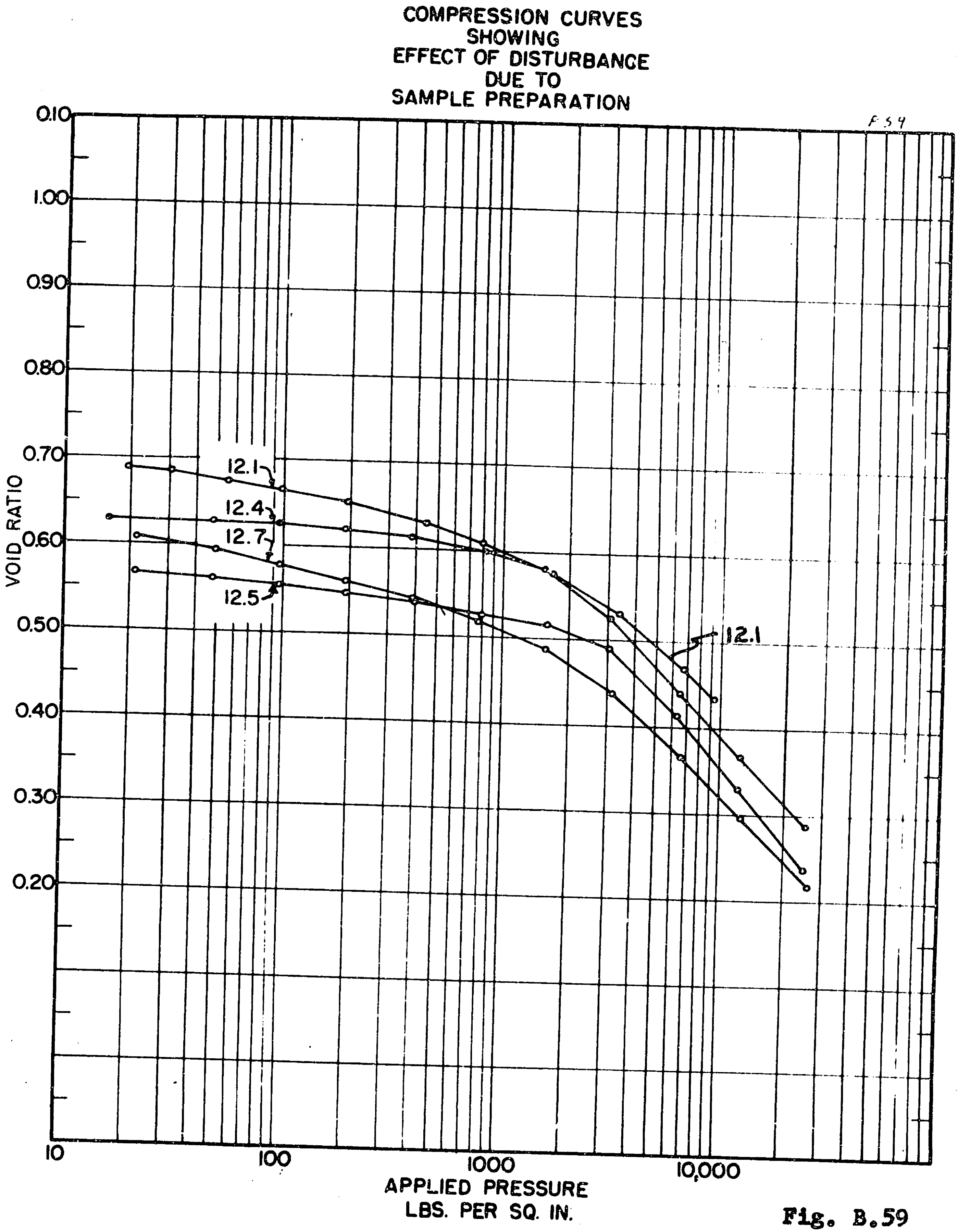

COMPRESSION CURVES
SHOWING
EFFECT OF DISTURBANCE
DUE TO
SAMPLE PREPARATION
F 59
VOID RATIO
0.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
12.1
12.4
12.7
12.5
12.1
10
100
1000
10,000
APPLIED PRESSURE
LBS. PER SQ. IN.

Fig. B.59

APPENDIX C: COMPRESSION OF INDIVIDUAL QUARTZ GRAINS

Several grains of 20-40 Ottawa sand were compressed individually between metal plates to evaluate the strength of grains of quartz sand. Grains with a mean diameter of approximately 0.84 mm shattered at loads varying between 10 and 17 pounds. Grains with a mean diameter of approximately 0.42 mm shattered at about 5 pounds.

Considering Test No. B2, the following comparison can be made:

Average diameter of grains	0.63 mm
Weight of average grain	0.00035 gms
Weight of sample in Test B2	10 gms
Thus, total number of grains	30,000
Height of sample	0.96 cm
Assuming regular stacking, number of layers of grains	15
Number of grains per layer	1900

If an average strength of 9 lbs is assumed for each grain, a total load of 17,000 pounds would be required to shatter all the grains simultaneously.

The crushing process in test B2 appears to have begun at about 3,000 lbs and was still proceeding at 20,000 lbs. This suggests that the load is carried by relatively few grains when fracturing starts and that the load is redistributed to an increasing number of the grains in any given average plane. A similar probable redistribution was noted even when a single layer of spherical glass beads was compressed. In the confined compression test, individual grains are supported by lateral confining pressures which are absent in the unconfined compression tests on individual grains. With a lateral force it would be expected that the shattering load of an individual grain would be higher because the presence of the lateral stress would reduce the average shear stress within an individual particle.

Preliminary measurements of the area of contact between quartz grains under compression were made by placing individual grains between two smooth quartz crystals and loading up to loads slightly less than the fracture load.

After removing the upper quartz crystal the grains were observed under the microscope and the flattened area of contact could be discerned and roughly measured.

The results of one such test were as follows:

Diameter of grain	0.8 mm
Load applied	10 lb
Approximate area of contact (measured)	$.22 \times 10^{-4}$ in^2
Load/area	450,000 psi

Other tests gave approximately the same value for load/area. This suggests that a pressure of at least 450,000 psi would be necessary to reduce the void ratio of a quartz sand to zero by pure mechanical compression.

APPENDIX D: BIOGRAPHICAL SKETCH OF THE AUTHOR

The author of this thesis, James E. Roberts, was born in Boston, Massachusetts, on February 6, 1928. He attended local schools in and around Boston and was graduated from Arlington High School, Arlington, Massachusetts, in June, 1945.

The author entered M.I.T. in July, 1945, took a leave of absence to serve two years in the Navy, returned to M.I.T. and received a Bachelor of Science Degree in Building Engineering and Construction in June 1951.

Subsequent to receiving his Bachelors Degree, the author spent nine years at M.I.T. in positions ranging from Research Assistant to Assistant Professor of Soil Engineering.

His engineering experience has included structural design for Cleverdon, Varney and Pike, and consulting soil and earthwork engineering for (1) Fay, Spofford and Thorndike; (2) Goldberg, LeMessurier and Associates; and (3) Schoenfeld Associates, Inc., all in Boston, Massachusetts.

Since June, 1960 he has been employed as Soil Engineer for Fruin-Colnon Contracting Company, St. Louis, Missouri, and as Chief Soil Engineer for Capitol Engineering Corporation in Dillsburg, Pennsylvania.

The author presently holds the rank of Associate Professor of Civil Engineering at San Jose State College, San Jose, California.

He is a registered professional engineer in Massachusetts, a member of the Boston Society of Civil Engineers, the American Society of Civil Engineers, Chi Epsilon, Tau Beta Pi and Sigma Xi.

The author has published, with J. M. DeSousa, a paper entitled "Compressibility of Sands", ASTM Proceedings, Vo. 58, 1958, p.1269.