RESEARCH ON FUNDAMENTAL PROPERTIES AND CHARACTERISTICS OF FROZEN SOILS

Raymond Yong

Soil Mechanics Series No. 3
April, 1962

SOIL MECHANICS LABORATORY

McGILL UNIVERSITY

DEPARTMENT OF CIVIL ENGINEERING AND APPLIED MECHANICS

MONTREAL, CANADA

PREFACE

The research work reported in this paper was performed under a continuing research grant from the Defence Research Board, in the form of a Grant-in-Aid of Research to the author (Grant No. 9511-28 [G. and C.]). The Grant was first given in April 1958 with subsequent yearly renewals.

The author wishes to acknowledge his indebtedness to the Defence Research Board for its support and interest - without which this research study would not have been possible. This paper, prepared for presentation at the First Canadian Conference on Permafrost concerns itself primarily with the understanding of frozen soil properties and characteristics.

Raymond Yong

Assistant Professor and Director
Soil Mechanics Laboratory

RESEARCH ON FUNDAMENTAL PROPERTIES AND CHARACTERISTICS OF FROZEN SOILS

by

RAYMOND YONG

Soil Mechanics Laboratory
Department of Civil Engineering
and Applied Mechanics
McGill University, Montreal

Paper prepared for presentation at
First Canadian Conference on Permafrost.
Ottawa, Canada
April 17-18, 1962.

RESEARCH ON FUNDAMENTAL PROPERTIES AND CHARACTERISTICS OF FROZEN SOILS

Raymond Yong*

ABSTRACT

The behaviour of frozen soil under loading conditions has been studied in terms of fundamental factors contributing to the strength of the soil. Electro-chemical theories based upon forces of interaction between charged particles have been applied by considering fine-grained soils as platelets with inherent unbalanced charges. It has been shown that the quantity of water remaining unfrozen in a soil-water system subject to prolonged freezing temperatures can be related to both inherent properties and external factors.

Properties or factors considered important in the consideration of unfrozen water content in a frozen soil are original water content, temperature, clay content, charge density, and electrolytic concentration. Partial freezing of the pore water affects the pressures exerted on the individual particles as a result of the freezing process.

The shearing strength of frozen soil is dependent upon ice content, temperature, lateral confinement, time rate of shear, and factors associated with partial freezing of the pore water.

* Assistant Professor and Director, Soil Mechanics Laboratory, McGill University

RESEARCH ON FUNDAMENTAL PROPERTIES AND CHARACTERISTICS OF FROZEN SOILS

Introduction

In the study of soil properties and characteristics, it is often considered useful to obtain fundamental relationships relating measured properties and characteristics with behaviour patterns. For soils existing at temperatures above freezing, of particular interest are such properties as soil strength and compressibility or deformation characteristics. - since in the final analysis these have the most direct bearing on engineering structures. The parameters involved in such behaviour characteristics are presently being subject to considerable study and scrutiny. For many clay soils, it is becoming more and more evident that the laws of mechanics applicable to granular soils may not be as easily applied to such clay soils. The surface forces existing in clay soils must now be considered.

In soil strength, there is evidence that the method of test evaluation plays an important part in the determination of the factors giving rise to soil strength. Between the limits established by granular soils and clays, it is thought that friction is primarily responsible for granular soil strength in the one instance, and "cohesion" is the other prime factor in clay soil strength. "Cohesion" however is an elusive parameter which seems best interpreted as an inherent property of clay soils dependent upon such factors or variables as:-

a) type of clay mineral and soil mass composition,
b) prestress history,
c) soil structure - particle orientation and arrangement,
d) nature of pore water and degree of saturation,
e) method of test evaluation.

Because of the lack of knowledge of clay soil-water interaction, it is apparent from the interest now shown in this important area of study that at the present time, it is more a problem of the definition of the term "cohesion". (See for example Lambe 1960, Schmertmann and Hall 1961 and Rosenquist 1959)

If the problem of defining and establishing the basic parameters involved in soil strength seems difficult for unfrozen soils, the case for frozen soils is most complex by comparison. Added to the complexities of unfrozen soil are such factors as temperature, ice content, partial freezing of the pore water resulting in the establishment of unfrozen water in frozen soils, number of ice crystals formed, orientation of ice crystals and size of ice crystals. It may be that some of the complexities of unfrozen soils will be obviated, but on the other hand, they may be multiplied.

Experimentation

To obtain an insight into the problem of frozen soil strength and its relationship with conventional measured properties and observed characteristics, three types of soils were used in the study - (sand, silt and clay - see Figure 1.). Two types of strength tests were used to measure shear strength of the frozen soils - unconfined compression test and ring shear test. A schematic representation of the ring shear test method is given in Figure 2. Restraint against axial elongation was provided and as part of the test technique, the test sample was subject to an axial force prior to application of the shear force.

Test samples were prepared in waxed containers in the case of sand samples, and the silt and clay samples were prepared either by consolidation or compaction. Sand samples in both the dense and loose states were fully saturated and only the consolidated clay samples were completely saturated. Clay and silt samples compacted by the Harvard Miniature method were compacted on the dry side and either frozen in that state or allowed to take up water for three days by controlled soaking prior to freezing.

Evaluation of unfrozen water content was by calorimetric means. Variation of initial water content was achieved only by means of moulding water content - (not by drying out from a uniform initial water content).

RESULTS AND DISCUSSION

Some of the data and results have been presented previously in primarily tabular form (Yong 1958, 1960) for strength tests on laboratory prepared samples. Subsequently, further experimentation has been undertaken on other more fundamental factors such as relationships between temperature, soil type and unfrozen water content. Only results and data pertinent to the discussion on a possible mechanism of shear strength of frozen soils will be presented herein.

It seems most appropriate to discuss the philosophy of frozen soil strength along the following lines:

a) What the strength tests indicate, and

b) The possible mechanics of the frozen system.

Rate of Loading in Unconfined Compression

Projecting from conventional strength tests on unfrozen soil, the logical procedure would be to determine strength of frozen soils initially in terms of unconfined compression tests. In the general understanding of strength of materials, this reasoning is both valid and sound. From previous studies (ACFEL 1951) on frozen soil strength in unconfined compression, the rate of load application was found to be important up to a rate of loading of approximately 400 psi. per minute. Beyond this, the strength increase realized from an increase in rate of loading was small and relatively insignificant.

At rates of loading in unconfined compression of approximately 60 psi. per minute and 500 psi. per minute, (designated as "slow" and "fast" respectively in Table 2) it was noticed that temperature was more effective in causing marked changes in ultimate strengths and stress-strain moduli - see Figures 3 and 4. Rate of loading plays a more dominant role at higher temperatures in the realization of ultimate strengths of clays and sands. At these temperatures (approximately -5°C), the higher rate of loading serves to decrease ultimate strength of the frozen sand soils while increasing their stress-strain moduli. On the other hand, while the ultimate strength of the clay soils decreased with the higher loading rate at the same high temperature, the stress-strain modulus of the test samples were increased.

Based upon limited studies of rate of strain loading on clay soils at normal above-freezing temperatures, the decrease in ultimate strength and stress-strain modulus with increased rates of loading experienced at temperatures just below freezing, indicate that it is not possible to explain frozen clay soil strength using the same model for both frozen and unfrozen soils. While this may seem intuitively obvious, there have been numerous suggestions proposing just such analyses. The decrease in ultimate strength of sand soils with a corresponding increase in rate of loading seems to justify the need for another mechanism or for the search for other factors hitherto unknown concerned with development of frozen soil strength. These will be discussed in the section on "General factors affecting Frozen Soil Strength".

Ring Shear Test

The ring shear test shown schematically in Figure 2 was used in an effort to learn more about the mechanics of shear failure of the frozen soils. Initially, no restraint from axial elongation was provided for, and under transverse shear, the tendency for axial elongation was noticed. Consequently, the shear test was refined to include axial prestressing - with the hope that more could be learnt about the relationship between confinement and shear stress. It must be pointed out that while this tries to emulate the conventional triaxial test, it in no way pretends to be such, since restraint and confinement can only be controlled positively in the axial direction. Confinement along the radial direction was controlled directly by the fit of the frozen soil specimen in the ring shear apparatus. At extremely low temperatures, this was not too critical, but at temperatures slightly below freezing, it seemed that the tendency for radial expansion induced both by shear and axial restraint could be the cause for some of the irreproducibility of results.

In Figures 5 through 9, some test results relating shear strength and final axial pressure for sands, silts and clay soils are given. Although initial axial confinement may be used as a relating factor in reporting the test results, it was felt that because of the axial elongation under shear, the results may be more meaningful if the final axial pressure was used to analyze the inter-relationships. To provide further data in the study of contribution to shear strength from ice strength, Figure 10 shows the influence of axial pressure on the shearing strength of ice. No attempt was made to control the growth or orientation of ice crystals - both for the soil samples and for the companion ice samples.

It may be argued from an examination of the ice curve in Figure 5 and those in Figure 10 that axial confinements above 50 psi. would begin to cause crushing of the ice in the soil voids. This cannot be denied. Failure in frozen soils however is not governed solely by the ice component - as witness the curves in Figures 5 through 9. Even in the case of ice specimens, while shear strength of the ice specimens averaged around 100 psi. with no initial axial confinement at -5°C, strength increase is noted with increasing axial confinement. It would seem that a "frictional" characteristic does exist in ice which tends to influence ice strength. It would seem obvious that there must be an optimum axial confinement which may be placed on the ice samples at any temperature - beyond which ice breakdown would be too great and failure would occur before any transverse shear can be effected. The curves for ice strength at -5°C and -8°C in Figure 10 show just this phenomenon.

How does this affect frozen soil strength? In frozen saturated granular soils, while it is not possible to separate the frictional characteristic of the ice from that of the soil grains, the evidence indicates that the total mass behaves similarly with frictional material. The slight aberrations from linearity must possibly arise from plastic yield and deformation of the ice phase.

While the clay soil used in the study showed very little frictional characteristic in the unfrozen state, the results shown in Figures 8 and 9 indicate otherwise. It must be concluded from these results that the major frictional contribution is derived from the ice whilst particle interaction and other undetermined factors could also provide some of this friction characteristic. For incomplete saturation, much remains to be learnt about interparticle action in clay soils in the unfrozen state. This lack of knowledge restricts intelligent speculation on the nature of interparticle action in the frozen state.

The two limits represented by frictional and frictionless soils (sand and clay) both demonstrated that the ice phase in the frozen soils contribute significantly to the development of frozen soil strength. Although there is difficulty in defining the actual contribution from the ice phase, the results obtained by decreasing the freezing temperature show increased strengths.

It would be expected that the frozen silt soils would also reflect the same trends shown in the clay soils. The influence of the ice component seems to be more noticeable - when the "dry" and "wet" silt samples are compared. This seems reasonable since it was shown from studies of normal above freezing temperatures that friction is the governing component in the silt soil. Hence if these same silt soils are prepared in the "dry" state, i.e. dry of optimum and at about 50% saturation, it would be reasonable to assume that increases in strength arising from corresponding increases in axial confinement would result primarily from mobilization of granular friction. By allowing the silt soils to take up water - up to about 90% saturation, the strength increases shown previously in the "dry" samples were not as pronounced in the "wet" samples. Whilst shear strength of the "wet" silt samples did increase with increasing axial confinement and also with decreasing temperature, these increases seem to depend more on the demonstrated strength properties of the pore ice.

Unfrozen Water Content

It became increasingly evident from observations on the behaviour of frozen saturated clay soils under unconfined compression, that some of the demonstrated yield and plastic deformation even at below freezing temperatures must be due to the presence of some water in the frozen samples. It was not clear whether this unfrozen water resulted from local melting at stress concentrations, or whether it existed despite freezing of the samples with no relation whatsoever with imposed radial shear.

In a detailed study on unfrozen water content, - some of the results of which are presented in graphical form in Figures 11 through 15, it is necessary to define certain limitations and conditions. Williams (1962 and personal communication) used the technique of drying out of samples from a constant initial high water content as standard procedure for sample preparation. For this study, variation in water content was achieved by varying initial moulding water content. The difference in technique here although seemingly slight has resulted in an interesting and meaningful development.

The results presented in Figures 11 through 15 show that variation in the initial moulding water content results in corresponding variations in the quantity of water remaining unfrozen measured at different subfreezing temperatures. Figure 15 shows this phenomenon. For clays and silts, it is a matter of great importance whether the specimen is prepared at above optimum, optimum, or below optimum water contents. Unfrozen water content decreases as temperature decreases, but the position of the curve depends upon the initial moulding water content. Further to this, unfrozen water content varies at the same temperature dependent upon whether the specimen is frozen to the test temperature or frozen at a lower temperature and allowed to thaw to the test temperature. This is demonstrated by the band lines or curves in Figures 11 through 14. The upper limits of the bands represent the unfrozen water content measured as the specimens were frozen directly to the test temperature shown, while the lower limits of the bands represent measurements of unfrozen water content as the specimens thawed to the test temperature from about 2°C lower than the test temperature. Similar hystereses were reported by Leonards and Andersland (1960) and Williams (1962).

By relating unfrozen water in terms of percent saturation or percent of original moulding water content remaining unfrozen, a better understanding of the phenomenon of partial freezing may be obtained.

Williams (loc.cit.) reports that the quantity of water remaining unfrozen is not dependant on initial water content. On the basis of drying out from a constant initial water content to different water contents prior to freezing, this may be expected. In terms of soil structure or orientation of soil particles, little particle re-arrangement occurs under slow drying (within limits) from the reported technique. Hence it would be expected that soil suction measured in terms of pF would not change significantly. It follows then that with this technique of sample preparation, the quantity of water remaining unfrozen at a constant pF would be dependent on the test temperature and the means of attainment or arriving at the test temperature.

On the other hand, with the technique of variation of initial moulding water content, individual specimen soil structures would be varied and from previous studies (Warkentin 1962, Schofield 1935) pF would correspondingly vary. Consequently, the results given in Figure 15 reflect unfrozen water contents based upon variations in pF's arising from differences in structural orientation.

The factors giving rise to partial freezing and unfrozen water content have been discussed in previous studies (e.g. Yong 1962). As expected, the silt soils prepared and tested do not show the same magnitudes of unfrozen water. However they showed the same inter-relationships between initial moulding water content, temperature, and unfrozen water content.

Factors affecting frozen soil-strength

At this present stage of research on frozen soil properties and characteristics, the evidence indicates that much remains to be done. Whilst it is not possible to give positive results or to draw conclusions, it is possible to examine the factors considered in the development of frozen soil strength.

It is evident that frozen soil strength increases as temperature is decreased and as restraint on axial elongation is increased. Projecting this further, it would seem feasible to suggest (based upon the data) that if normal pressure is increased, shear strength would correspondingly increase - or if volume change is restricted, shear strength would be increased. The ice "frictional" characteristic can be used to an advantage to develop greater strength potential in the frozen soil.

The quantity of water remaining unfrozen in partially frozen soils will affect strength development since it is fairly obvious that more unfrozen water means less pore ice present in the soil. Under load application, strength development is thought to depend upon not only shear strength of ice and soil particles, but also on the adhesion of ice to soil particles. Since unfrozen water and the concepts proposed for the existence of unfrozen water suggest that a film of water separates individual soil particles from the pore ice or ice phase, it follows that adhesion between ice and soil particles depends upon the properties of this unfrozen water. No results are available however to allow for any speculation on the properties of the unfrozen water.

Not only temperature, soil type, confinement, and water content affect frozen soil strength, the freezing or thawing history of the frozen soil mass must also be considered. It may be argued that present available test techniques do not measure or yield the necessary properties for interpretation of inherent parameters however these are the only ones available presently.

CONCLUSIONS

The present stage of knowledge of the mechanics of frozen soil leaves much to be desired. While studies and reports are available detailing strength of frozen soil as a function of soil type, temperature and a few other factors, a clear understanding of the mechanism involved therein is lacking. Much remains to be done and further study is presently under way to determine the more fundamental parameters thought to be important in the consideration of frozen soils.

BIBLIOGRAPHY

ACFEL (1951) "Investigation of Description, Classification and Strength Properties of Frozen Soils" SIPRE Report No.8.

Lambe, T.W. (1960) "Compacted Clay" - Symposium, Trans. ASCE. Vol. 125

Leonards, G.A. and Andersland, O.B. (1960) "The Clay-Water System and Shearing Resistance of Clays", ASCE Shear Conference.

Rosenquist, I. Th. (1959) "Physico - Chemical Properties of Soils" Journal ASCE, Soil Mech. and Founds, Vol. 85, No. SM2.

Schmertmann, J.H., and Hall, J.R. (1961) "Cohesion after Non-Hydrostatic Consolidation" Journal ASCE. Soil Mech. and Founds. Vol.87, SM4.

Schofield, R.K. (1935) "The pF of the Water in Soil" Trans. 3rd. Int.Congr. on Soil Science.

Warkentin, B.P. (1962) "Volume change in Clay Soils - Shrinking and Swelling" Soil Mech. Series No.2, McGill University.

Williams, P.J. (1962) "Specific Heat and Unfrozen Water Content in Frozen Soils" Paper for First Canadian Conf. on Permafrost.

Yong, R. (1958) "Some Physical Characteristics of Frozen Soil" Report DR 123, Directorate of Phys.Res. DRB.

Yong, R. (1960) "Some Shearing Characteristics of Frozen Soil - Part 1" Report No. D.Phys.R. (G) Misc. G.2, DRB.

Yong, R. (1962) "Soil Freezing and Permafrost" Soil Mech. Series No.1, McGill University.

TABLE 1

Properties of soils used for study

Sand. - $\phi = 37^{\circ}$, $c = o$, $S_s = 2.65$

	Silt.	Clay
LL	25.1	67.0
PL	17.0	28.8
S_s	2.68	2.73
Wopt.	16.5	28.5
Opt. dry density	114.5 pcf	87.8 pcf
Mineral Content in approx. %		
Chlorite	-	2 - 3
Biotite	-	10
Amphibole	-	2 - 3
Feldspar	20	50 - 60
Quartz	80	25

TABLE 2

Summary of unconfined compression results

NOTE: Groups consist of 5 individual samples.

Group No.	Sample Nos.	Test Temp. °C	Rate of Test	Ave. Density lbs/ft³	Ave. Void Ratio e	Ave. Water Content W%	Ave. Ultimate Strength K.S.F.	Ave. Stress Strain Mod. K.S.F.
1	LS-31-35	-17.8	Fast	119.3	0.784	29.8	311.2	14300
2	DS-31-35	-17.8	Fast	132.5	0.446	16.9	362.0	16700
3	LS-36-40	-17.8	Slow	118.5	0.810	30.8	269.0	11500
4	DS-36-40	-17.8	Slow	132.0	0.464	17.5	318.7	12600
5	LS-41-45	- 4.7	Fast	123.0	0.679	26.0	124.0	9300
6	DS-41-45	- 4.7	Fast	132.0	0.461	17.5	223.9	11200
7	LS-46-50	- 4.7	Slow	123.2	0.662	25.4	164.8	3300
8	DS-46-50	- 4.7	Slow	130.3	0.488	18.6	259.8	6100
9	CL-1-5	- 4.7	Fast	108.6	1.111	39.7	84.4	1910
10	CL-6-10	- 4.7	Slow	109.7	1.202	43.1	105.2	2570
11	CL-11-15	-17.8	Fast	111.5	1.123	40.3	236.7	6720
12	CL-16-20	-17.8	Slow	111.3	1.153	41.6	208.5	6780

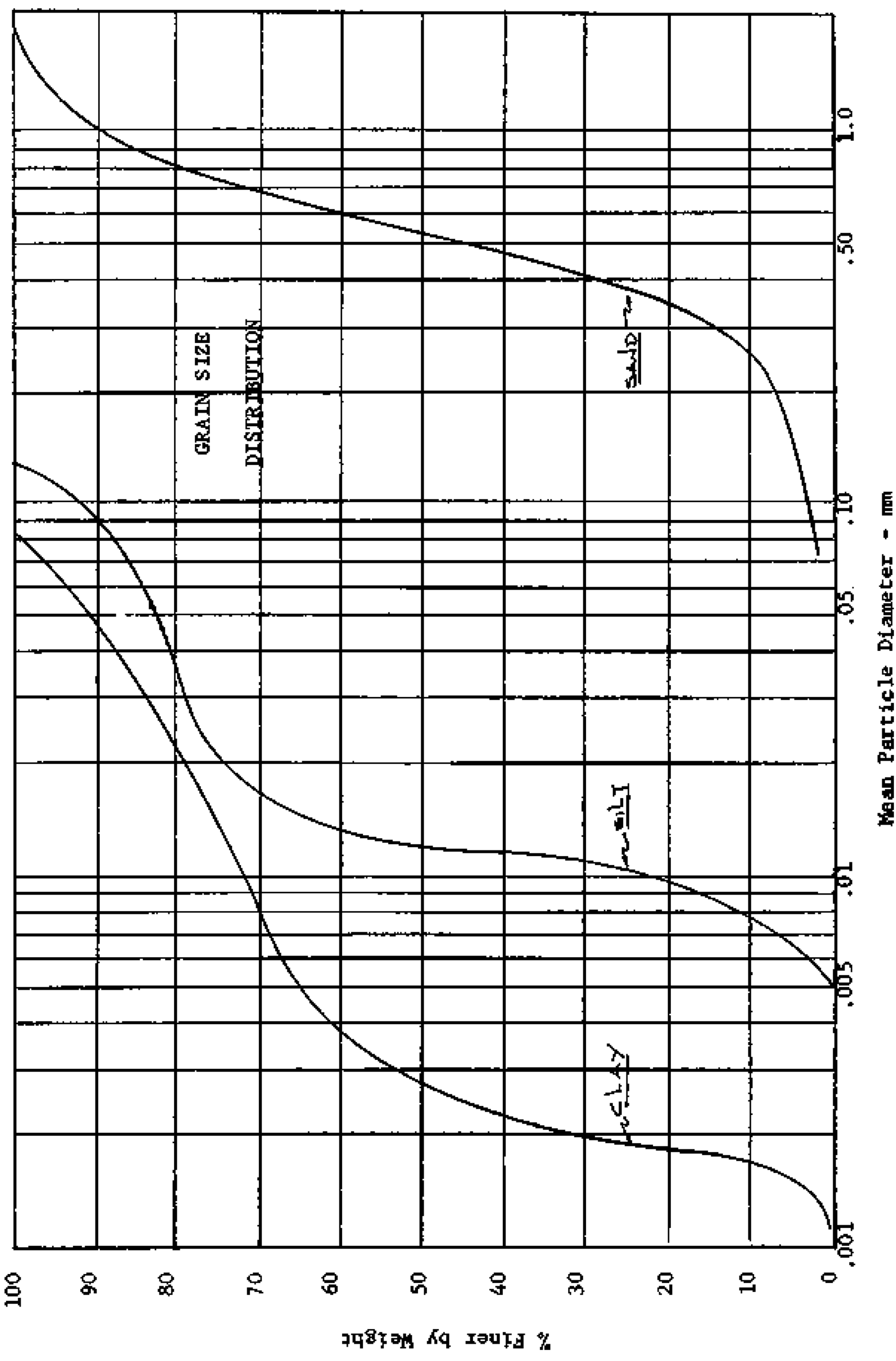

GRAIN SIZE
DISTRIBUTION
SAND
SILT
CLAY
100
90
80
70
60
50
40
30
20
10
0
% Finer by Weight
.001
.005
.01
.05
.10
.50
1.0
Mean Particle Diameter - mm

Figure 1

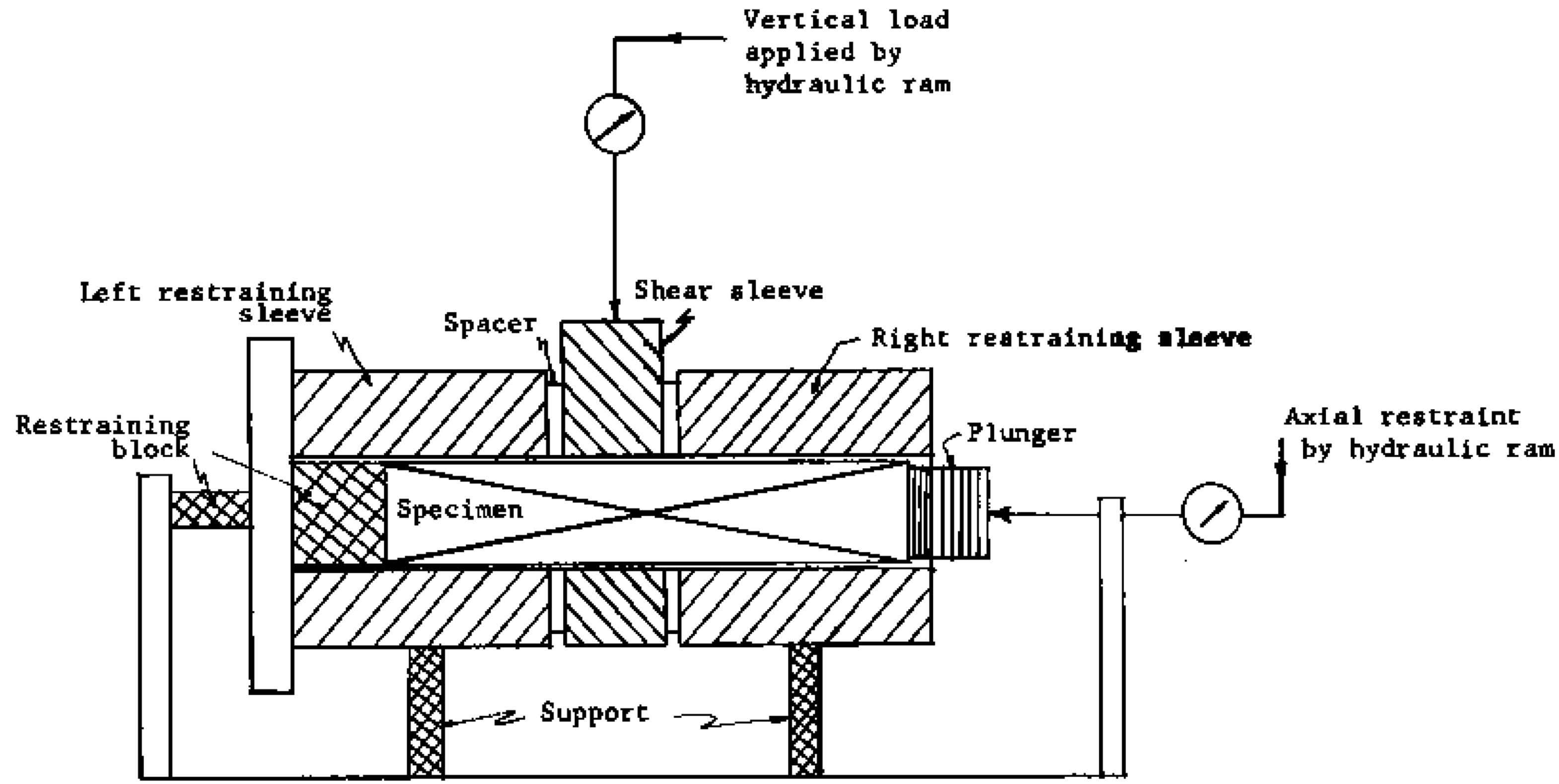


Figure 2

Schematic Picture of Double Shear Test

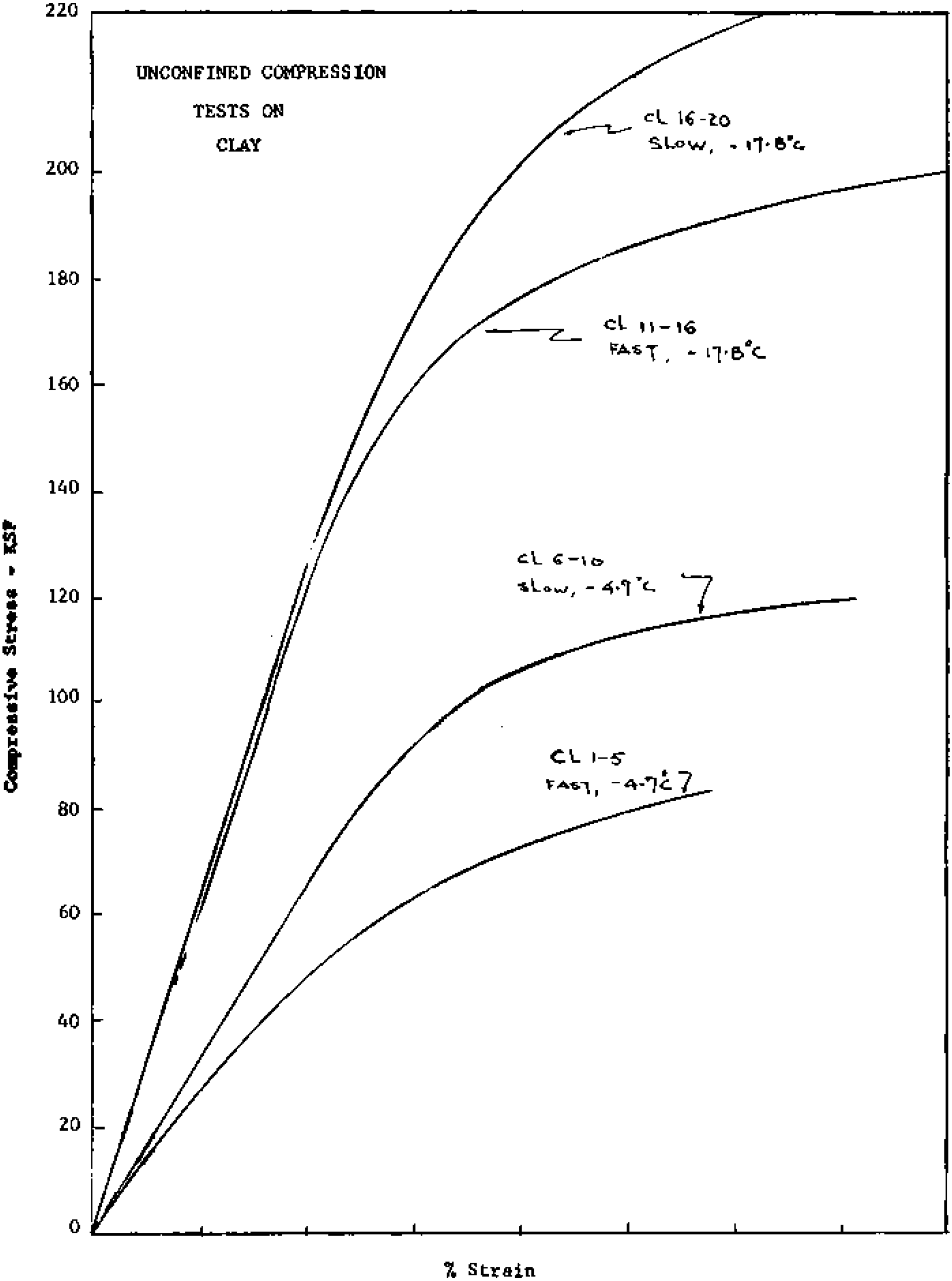

220
200
180
160
140
120
100
80
60
40
20
0
UNCONFINED COMPRESSION
TESTS ON
CLAY
CL 16-20
SLOW, -17.8°C
CL 11-16
FAST, -17.8°C
CL 6-10
SLOW, -4.9°C
CL 1-5
FAST, -4.7°C
Compressive Stress - KSF
% Strain

Figure 3

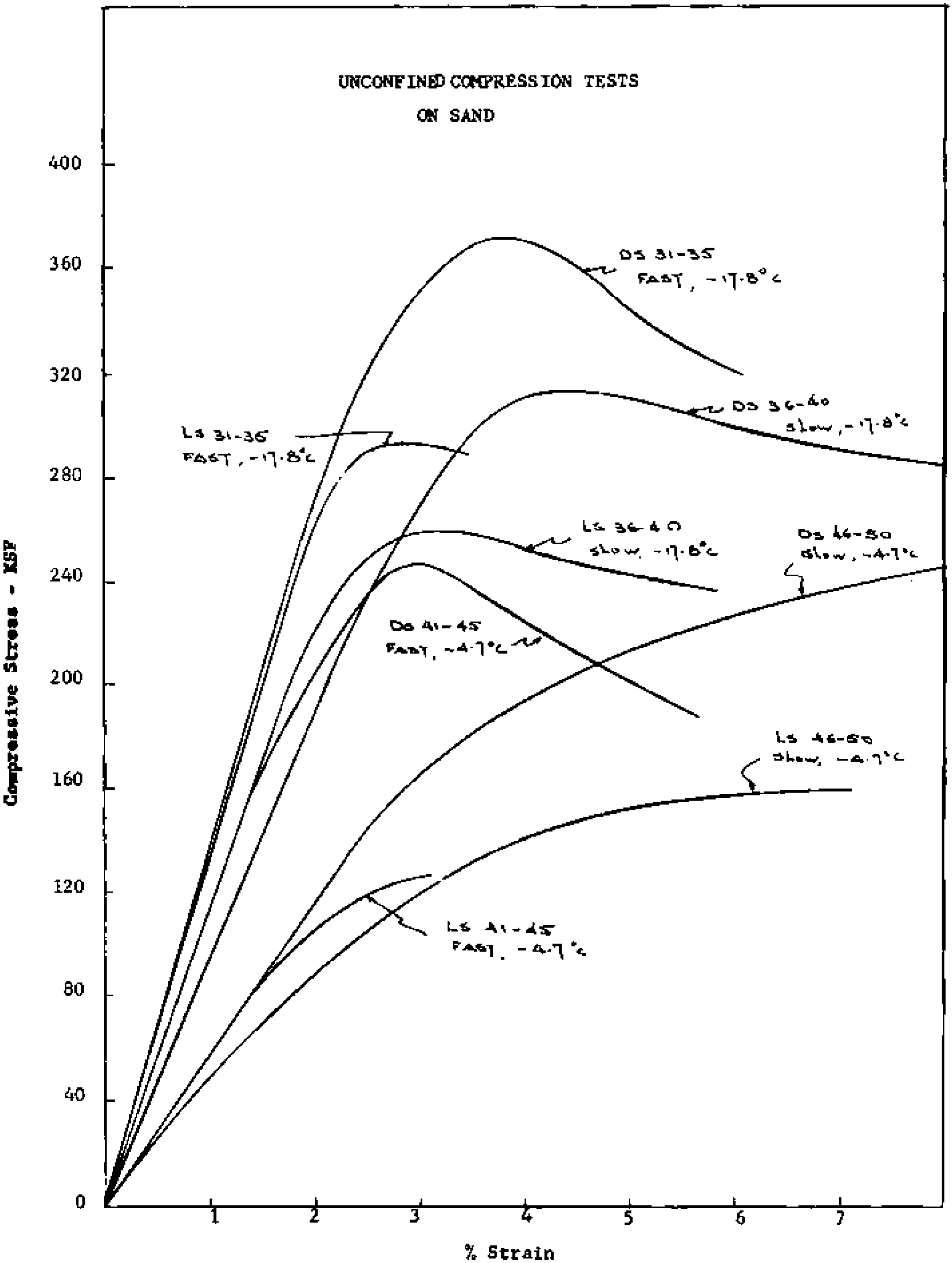

UNCONFINED COMPRESSION TESTS
ON SAND
Compressive Stress - KSF
400
360
320
280
240
200
160
120
80
40
0
1
2
3
4
5
6
7
% Strain
DS 31-35
FAST, -17.8°C
DS 36-40
slow, -17.8°C
LS 31-35
FAST, -17.8°C
LS 36-40
slow, -17.8°C
DS 46-50
slow, -4.7°C
DS 41-45
FAST, -4.7°C
LS 46-50
slow, -4.7°C
LS 41-45
FAST, -4.7°C

Figure 4

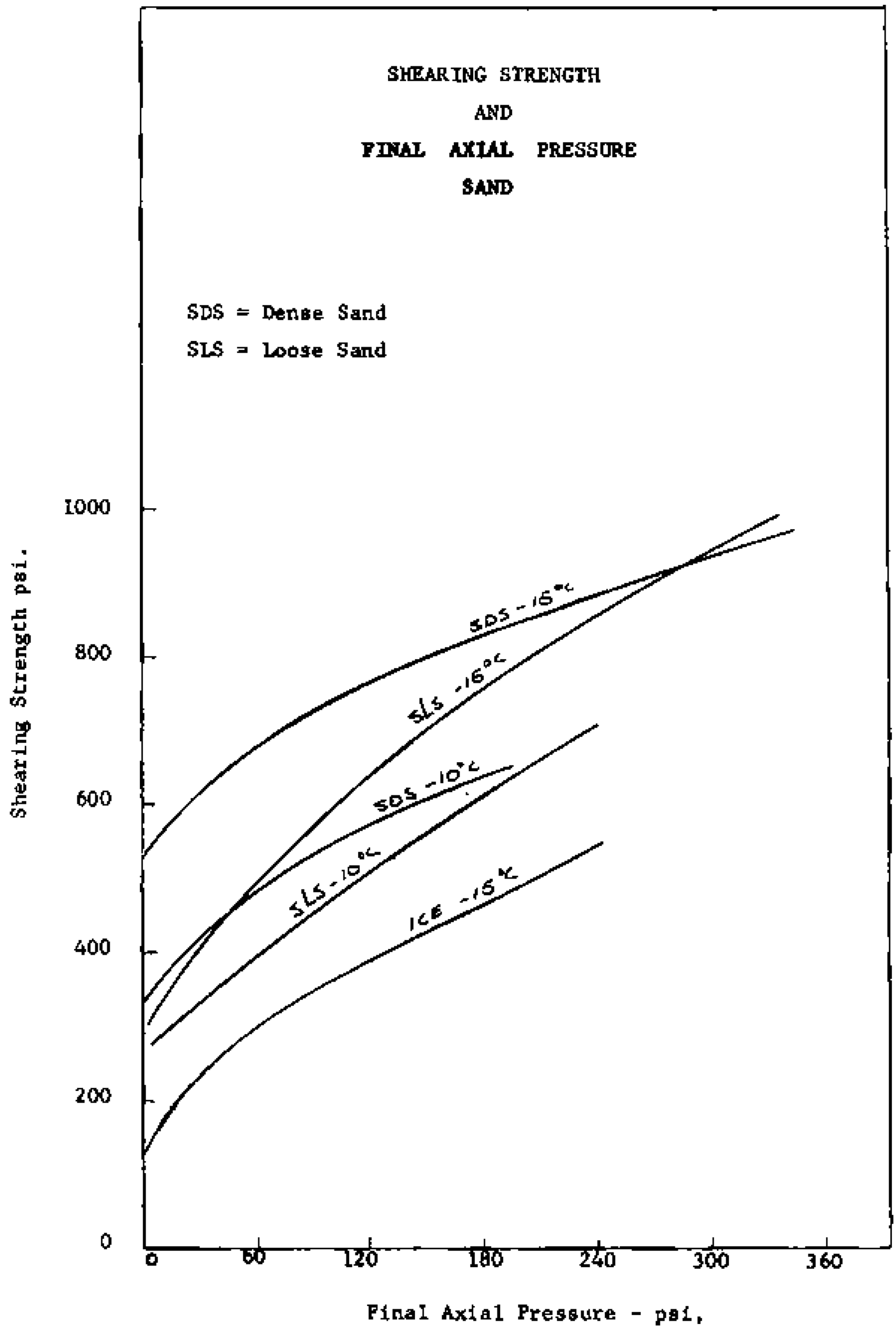

SHEARING STRENGTH
AND
FINAL AXIAL PRESSURE
SAND
SDS = Dense Sand
SLS = Loose Sand
SDS -16°c
SLS -16°c
SDS -10°c
SLS -10°c
ICE -15°c
Shearing Strength psi.
0
200
400
600
800
1000
0
60
120
180
240
300
360
Final Axial Pressure - psi.

Figure 5

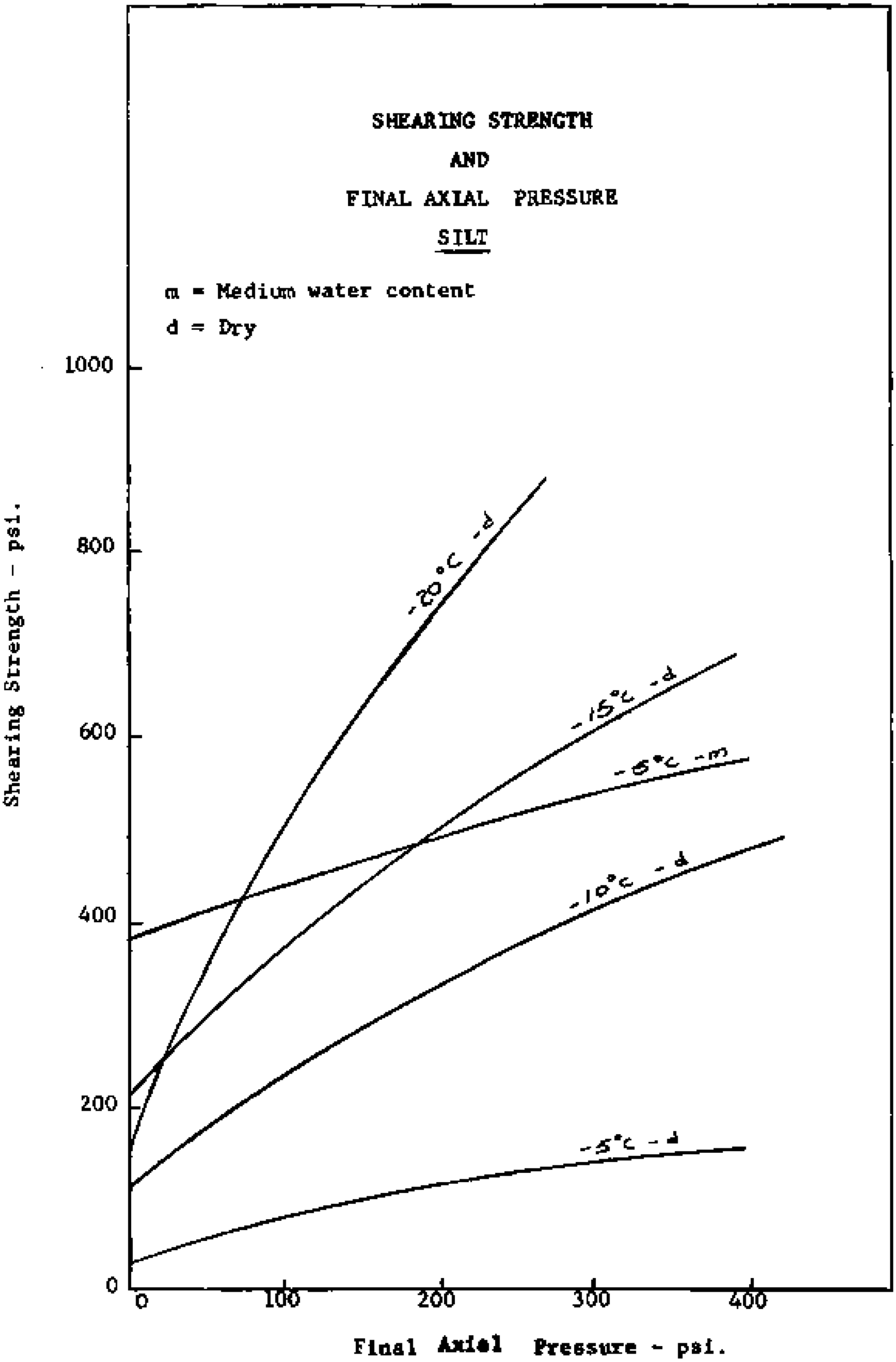

SHEARING STRENGTH
AND
FINAL AXIAL PRESSURE
SILT
m = Medium water content
d = Dry
Shearing Strength - psi.
1000
800
600
400
200
0
0
100
200
300
400
Final Axial Pressure - psi.

Figure 6

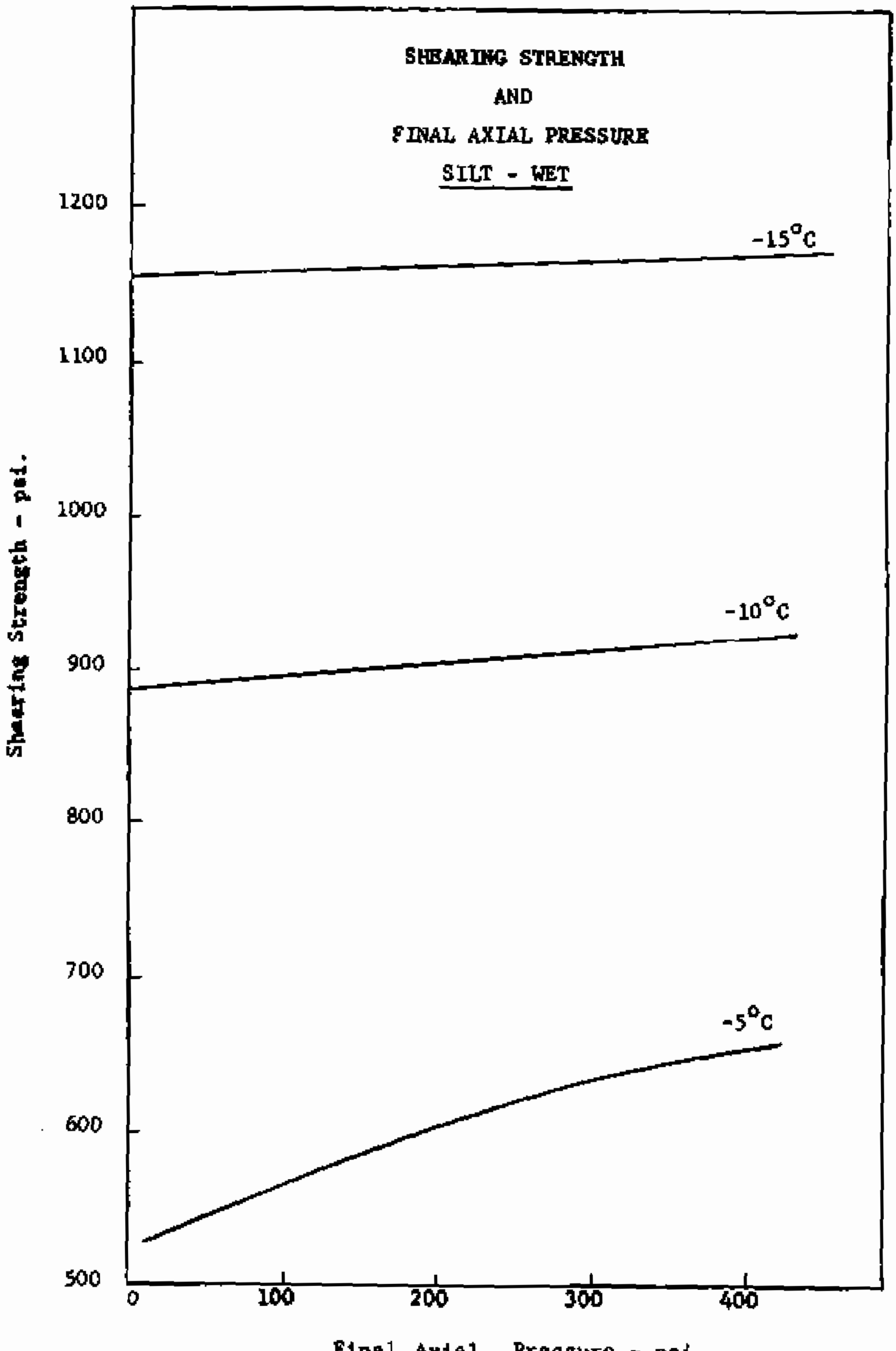

SHEARING STRENGTH
AND
FINAL AXIAL PRESSURE
SILT - WET
-15°C
-10°C
-5°C
1200
1100
1000
900
800
700
600
500
0
100
200
300
400
Shearing Strength - psi.
Final Axial Pressure - psi

Figure 7

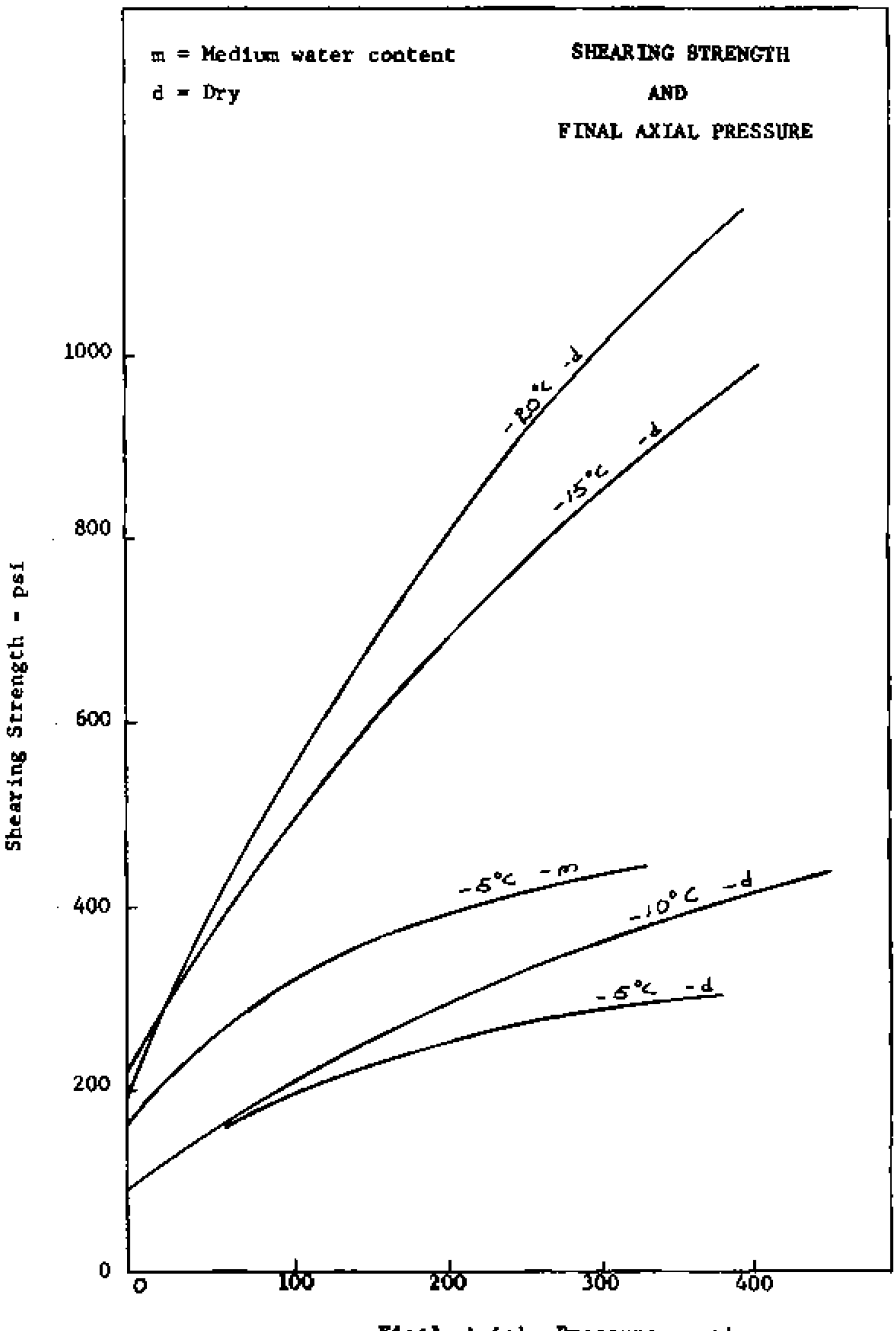

m = Medium water content
d = Dry
SHEARING STRENGTH
AND
FINAL AXIAL PRESSURE
Shearing Strength - psi
0
200
400
600
800
1000
0
100
200
300
400
-20°C -d
-15°C -d
-5°C -m
-10°C -d
-5°C -d
Final Axial Pressure - psi

Figure 8

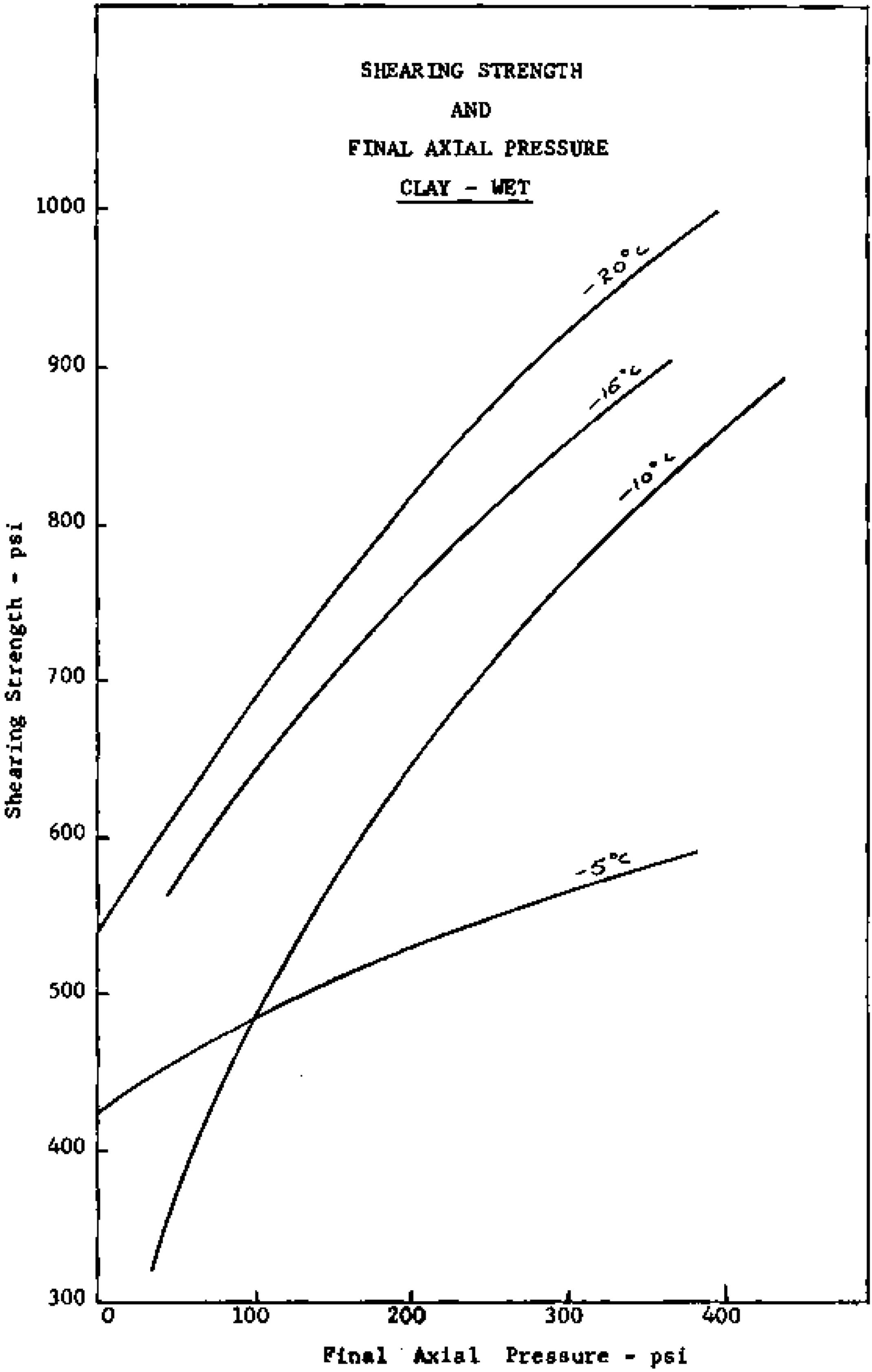

SHEARING STRENGTH
AND
FINAL AXIAL PRESSURE
CLAY - WET
-20°C
-16°C
-10°C
-5°C
1000
900
800
700
600
500
400
300
0
100
200
300
400
Shearing Strength - psi
Final Axial Pressure - psi

Figure 9

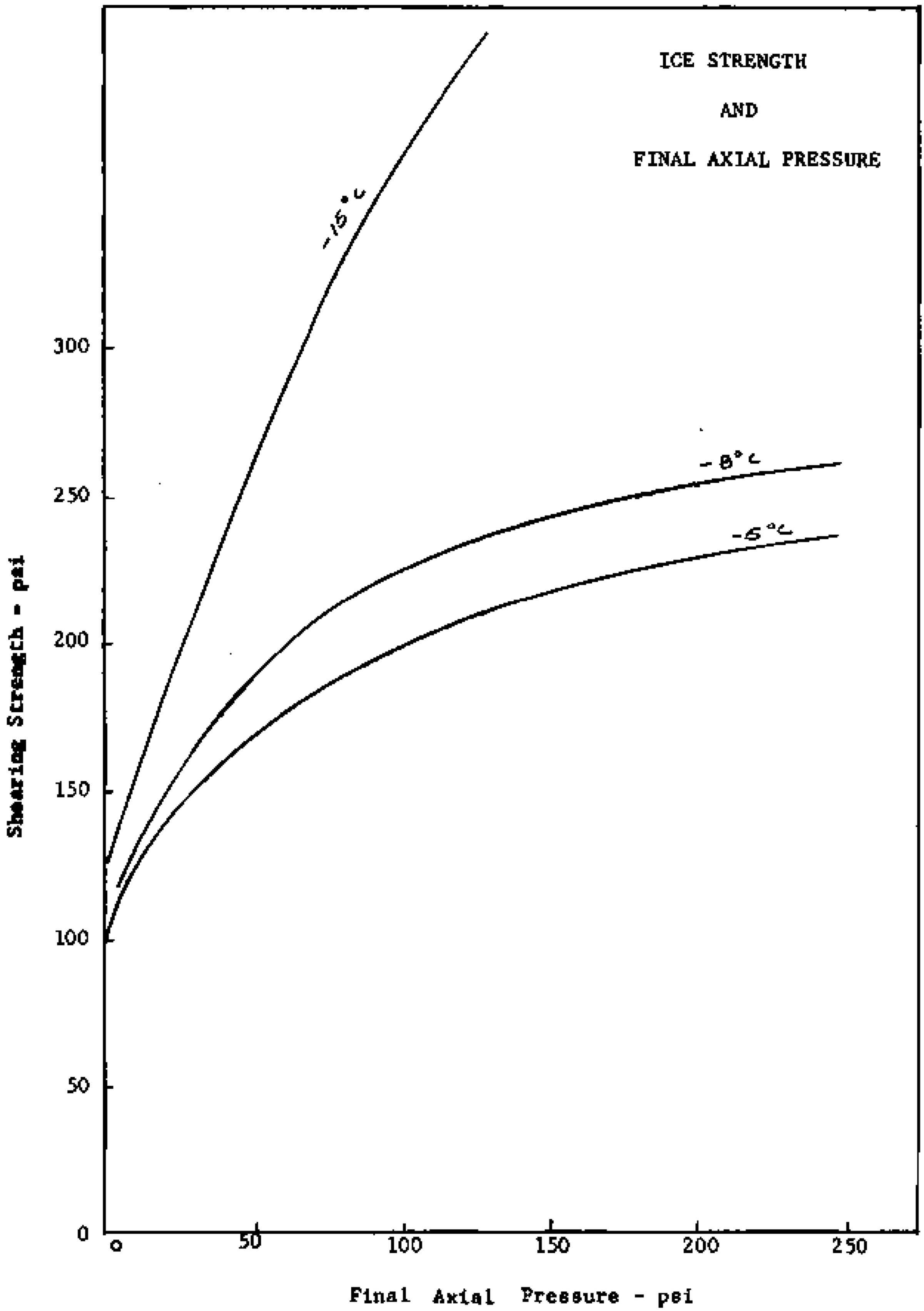
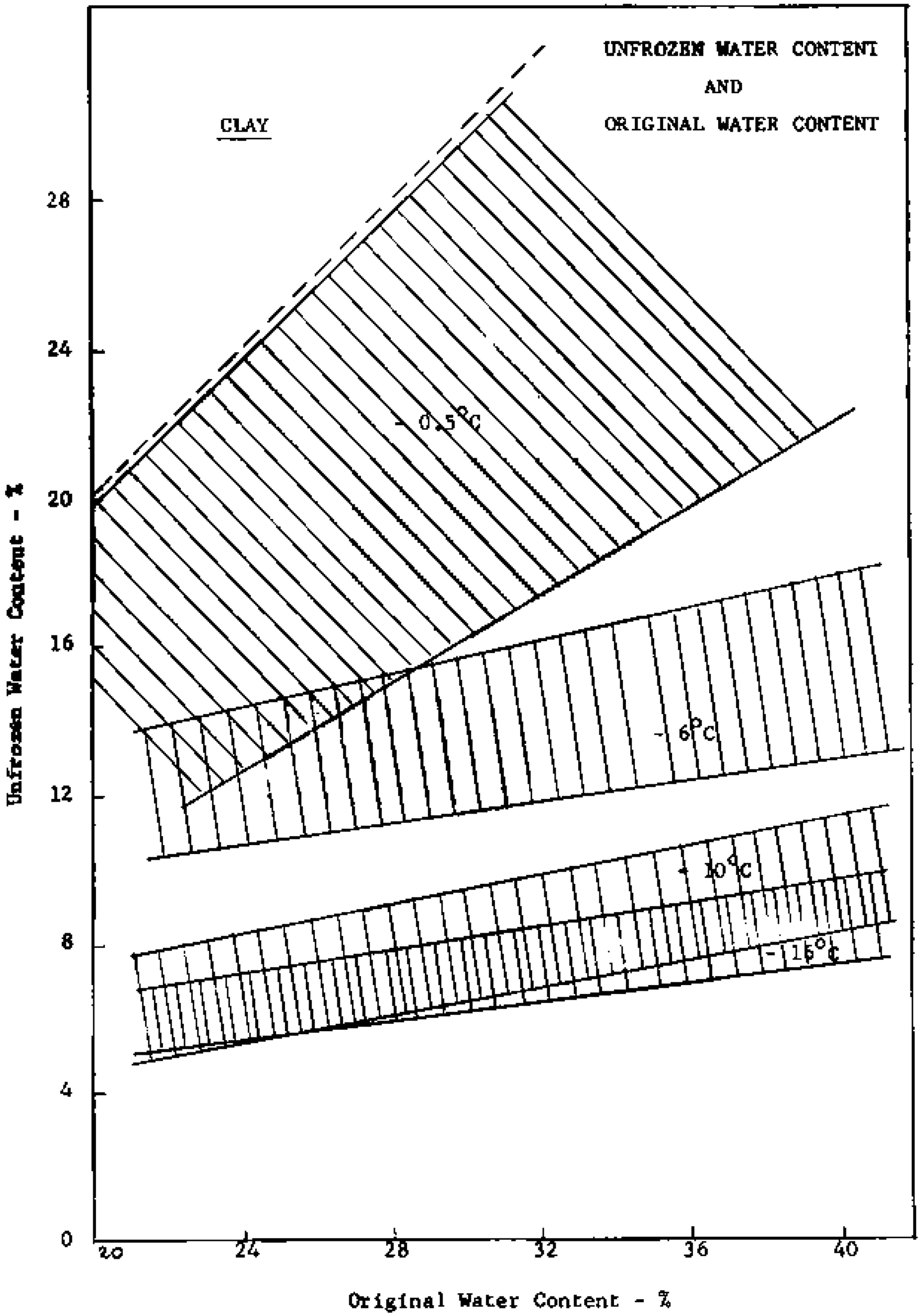

ICE STRENGTH
AND
FINAL AXIAL PRESSURE
-15°C
-8°C
-6°C
300
250
200
150
100
50
0
o
50
100
150
200
250
Shearing Strength - psi
Final Axial Pressure - psi

Figure 10



UNFROZEN WATER CONTENT
AND
ORIGINAL WATER CONTENT
CLAY
- 0.5°C
- 6°C
- 10°C
- 16°C
Unfrozen Water Content - %
0
4
8
12
16
20
24
28
20
24
28
32
36
40
Original Water Content - %

Figure 11

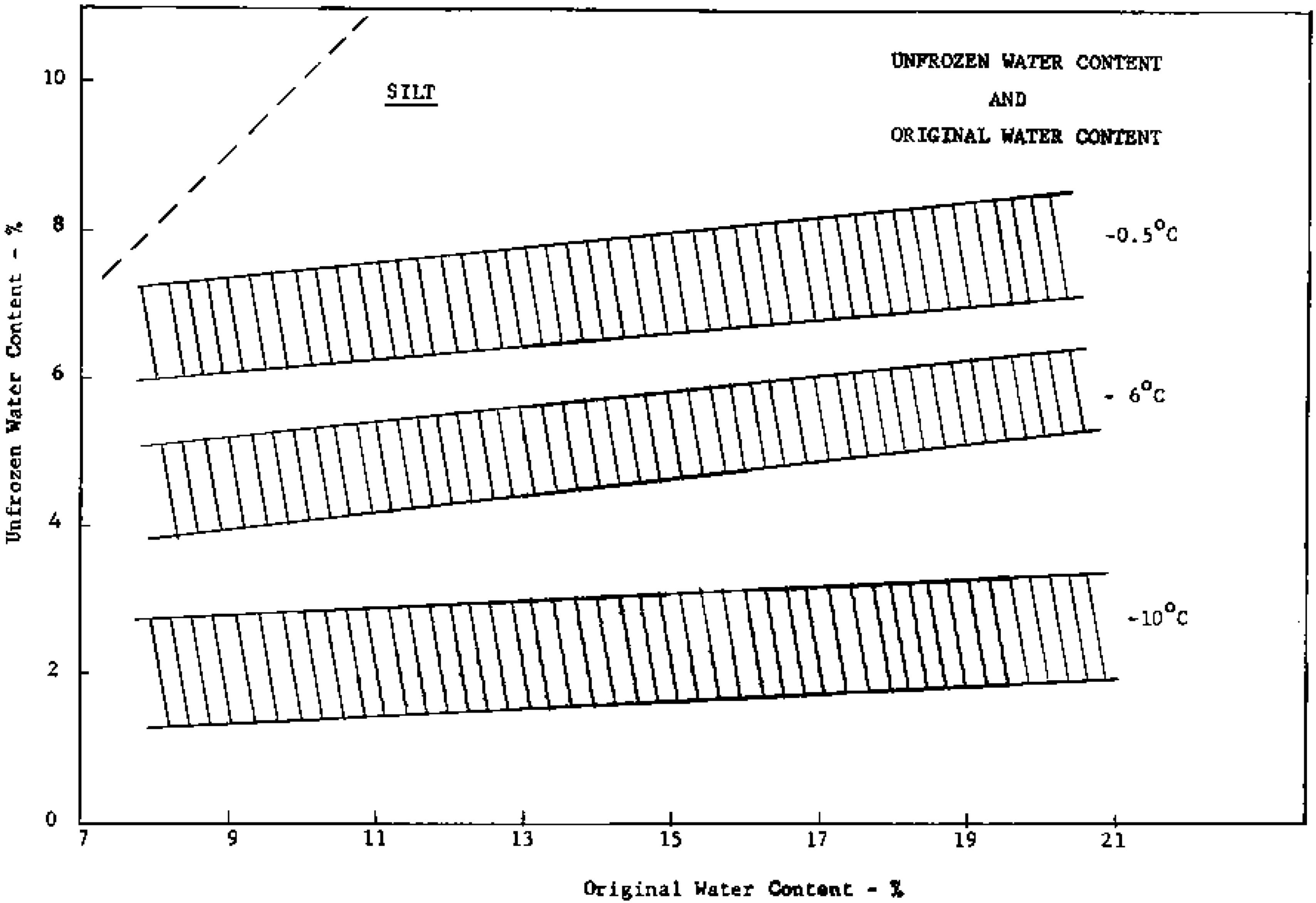

UNFROZEN WATER CONTENT
AND
ORIGINAL WATER CONTENT
SILT
-0.5°C
- 6°C
-10°C
Unfrozen Water Content - %
0
2
4
6
8
10
7
9
11
13
15
17
19
21
Original Water Content - %

Figure 12

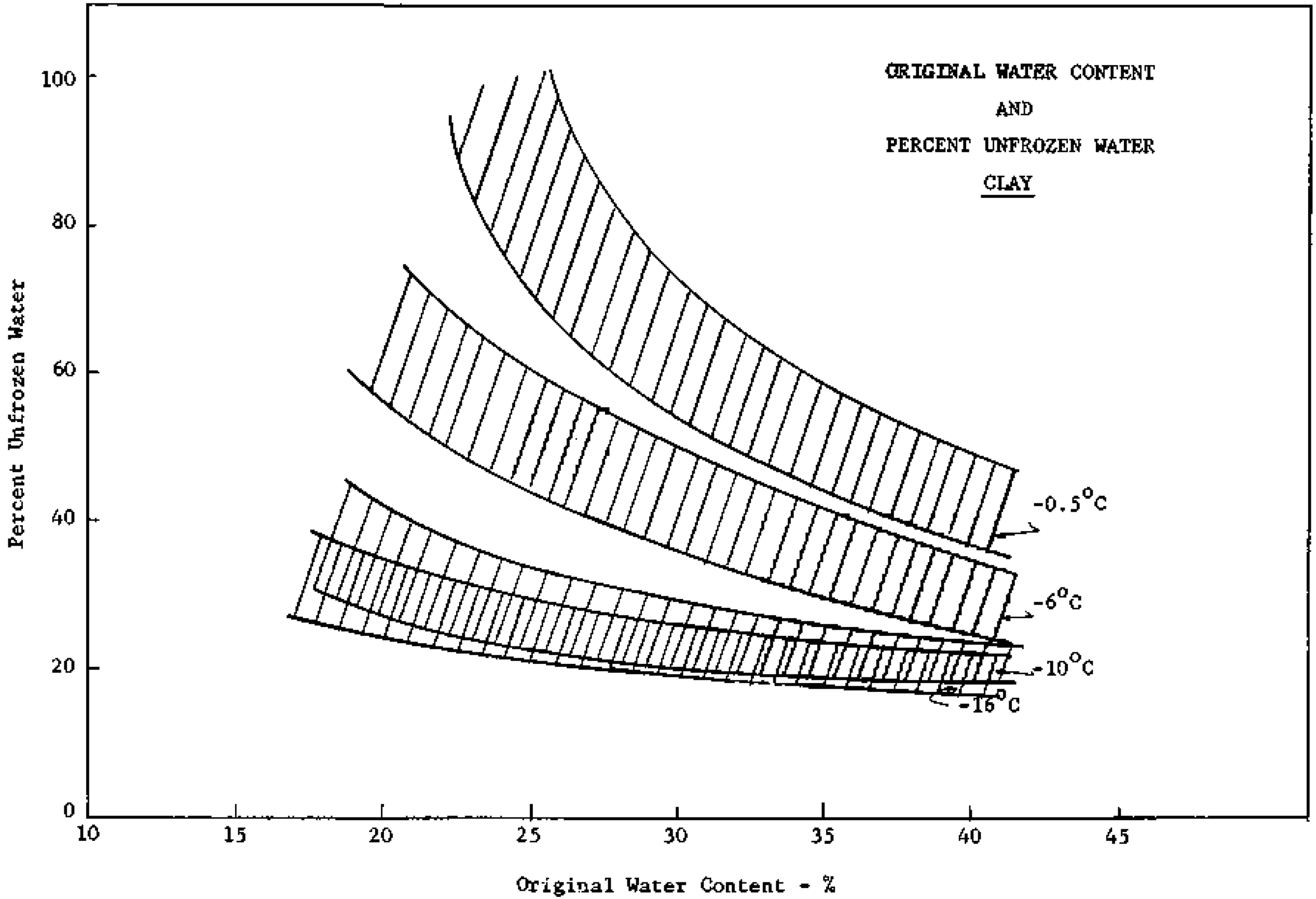

ORIGINAL WATER CONTENT
AND
PERCENT UNFROZEN WATER
CLAY
-0.5°C
-6°C
-10°C
-16°C
Percent Unfrozen Water
0
20
40
60
80
100
10
15
20
25
30
35
40
45
Original Water Content - %

Figure 13

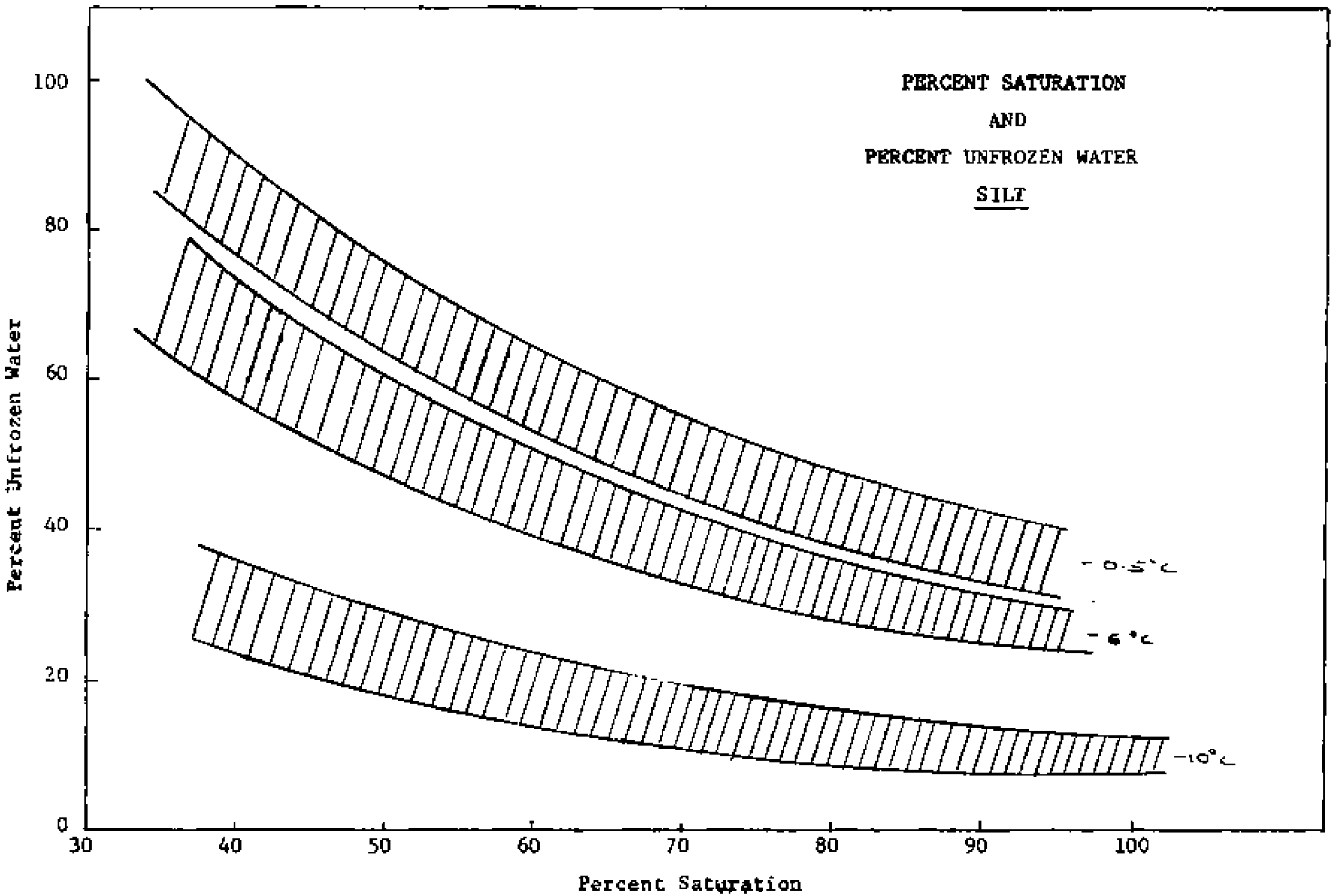

PERCENT SATURATION
AND
PERCENT UNFROZEN WATER
SILT
Percent Unfrozen Water
100
80
60
40
20
0
30
40
50
60
70
80
90
100
Percent Saturation
-0.5°C
-6°C
-10°C

Figure 14

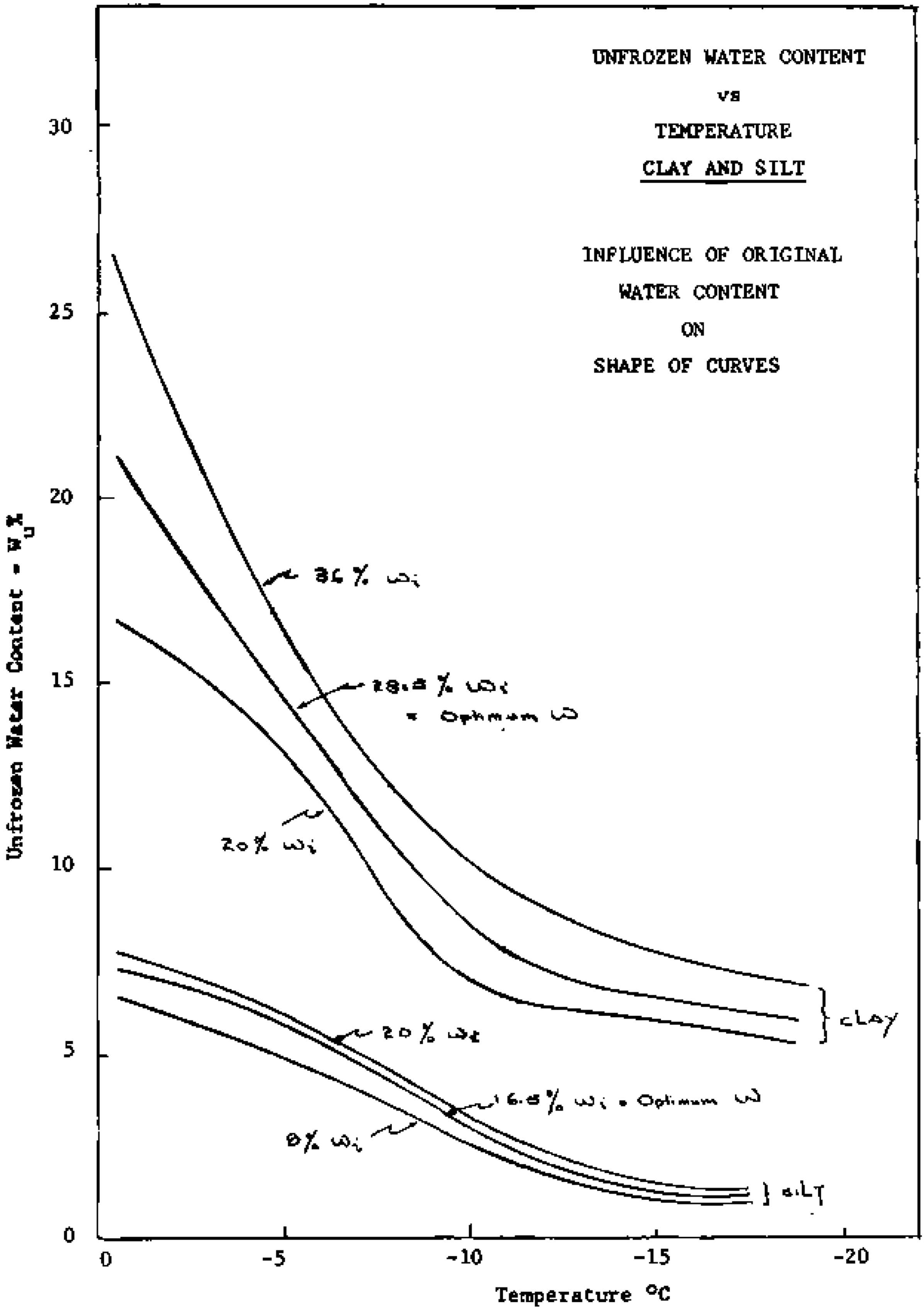

UNFROZEN WATER CONTENT
vs
TEMPERATURE
CLAY AND SILT
INFLUENCE OF ORIGINAL
WATER CONTENT
ON
SHAPE OF CURVES
Unfrozen Water Content - W_u%
30
25
20
15
10
5
0
0
-5
-10
-15
-20
Temperature °C
36% ωi
28.5% ωi
= Optimum ω
20% ωi
20% ωi
16.5% ωi = Optimum ω
8% ωi
clay
silt

Figure 15