

THE DYNAMIC PROPERTIES OF FROZEN SOILS
UNDER CYCLIC TRIAXIAL LOADING CONDITIONS

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ABSTRACT

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By

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Cyclic triaxial tests were conducted on laboratory prepared samples of frozen silt and clay to evaluate the dynamic properties of frozen silt and clay under simulated earthquake loading conditions. The testing apparatus consisted of an MTS electrohydraulic closed-loop test system, a triaxial cell, a refrigeration unit, and output recording devices.

Two silts - Hanover silt and Alaska silt - and a kaolinite clay were used in the research program. All soils were generally prepared at two water contents to assess the influence of water content on the dynamic properties of frozen silt and clay. The samples were tested at axial strain amplitudes from approximately 2×10^{-3} to $8 \times 10^{-2}\%$, temperatures from -1 to -10°C , frequencies from 0.05 to 10.0 cps, and confining pressures from 0 to 200 psi. Values of dynamic Young's modulus obtained ranged from 1×10^5 to 35×10^5 psi for Hanover silt, from 1×10^5 to 22×10^5 psi for Alaska silt, and from 1×10^5 to 14.5×10^5 psi for kaolinite. The test results indicate that dynamic Young's modulus decreases with increasing strain amplitude and increases with increasing frequency and decreasing

temperature. The relationship between dynamic Young's modulus and water content varies; in some cases dynamic Young's modulus increases with increasing water content and in other cases it decreases. Dynamic Young's modulus is apparently not affected by confining pressure. Values of damping ratio obtained ranged from .02 to .36 for Hanover silt, from .02 to .32 for Alaska silt, and from .01 to .22 for kaolin-ite. The test results indicate that damping ratio generally increases with increasing axial strain amplitude and decreases with increasing frequency and decreasing temperature. For frozen silt damping ratio decreases with increasing water content; for frozen clay there is only a slight influence of water content on damping ratio. Damping ratio is generally not significantly influenced by confining pressure.

The dynamic properties of frozen silt and clay obtained in the present study were compared to those obtained in previous studies. Values of dynamic Young's modulus for silt obtained in the present study were generally somewhat lower than the values obtained in previous studies while values of damping ratio were somewhat higher. Values of dynamic Young's modulus and damping ratio for clay obtained in the present study compared favorably with the values obtained in previous studies. The variation in the dynamic properties in the different studies may be due to differences in frequency, strain amplitude, and material characteristics between the present and previous studies.

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LIST OF SYMBOLS

c_p	confining pressure
D	damping ratio
E_d	dynamic Young's modulus
E^*	complex Young's modulus
f	frequency
G^*	complex shear modulus
LL	liquid limit
PI	plasticity index
PL	plastic limit
S -wave	shear wave velocity
$\tan \delta$	loss factor
V_L	longitudinal wave velocity
V_p	compression wave velocity
w_c	water content
δ	lag angle between stress vector and strain vector
μ	Poisson's ratio
ρ	density
σ_0	dynamic stress

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CHAPTER 1

INTRODUCTION

1.1 Statement of the Problem

Much attention has been focused in recent years on the evaluation of the dynamic properties of frozen soils. Such information is most appropriate when considering the future development of Alaska, where the design of structures may require knowledge of the mechanical properties of permafrost deposits on which structures may be founded. Since southern Alaska lies within one of the worlds major seismic zones, engineers should especially consider the dynamic properties of the frozen soil deposits under earthquake loading conditions.

While some field and laboratory work has been done to evaluate the dynamic properties of frozen soils, most of the work has been done over ranges of test parameters which might be inappropriate for use in a seismic analysis of a structure founded on a frozen soil deposit. Test strain amplitudes, for example, have generally been much lower than those associated with strong-motion earthquakes, while test frequencies have generally been much higher. Thus, an engineer might be unable to predict ground motions for a design earthquake in a permafrost region since the necessary dynamic properties of the soils have not been determined.

1.2 Purpose and Scope of Studies

The purpose of this research program is to:

- (1) Evaluate the dynamic Young's modulus and damping ratio of frozen silt and clay over ranges of test condition parameters that would be useful for ground motion

predictions of permafrost deposits during earthquakes.

- (2) Investigate the influence of various parameters that might affect the dynamic Young's modulus and damping ratio of frozen silt and clay.

The scope of this research program includes a description of sample preparation and experimental techniques used in evaluating the dynamic properties of frozen silt and clay, a discussion of the experimental results, and a comparison of the results obtained in this program with the results obtained by previous investigators. Information on the thermal and mechanical properties of ice and frozen soils and the dynamic properties of unfrozen soils - which is essential to an understanding of the dynamic properties of frozen soils - has been summarized by Chaichanavong (1976). To better understand the extent and nature of the soils tested in naturally occurring frozen deposits, the remainder of this chapter provides information on the distribution and structure of the various soil deposits in Alaska. Chapter 2 summarizes the results of previous research to evaluate the dynamic properties of frozen fine-grained soils. Chapter 3 provides information on the preparation of the frozen soil samples used in the research program, installation of the samples in a triaxial cell, and the test procedure employed. The test results for silt and clay are discussed in Chapters 4 and 5, respectively. The relationships between dynamic Young's modulus and damping ratio of the soils tested and confining pressure, strain amplitude, temperature, frequency, and water content are also presented in these chapters. Chapter 6

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provides a comparison between the results obtained in this research and the results obtained by previous investigators. A summary of the results obtained in the research program is provided in Chapter 7.

1.3 Distribution of Frozen Soil Deposits in Alaska

The unconsolidated surficial deposits in Alaska consist of soils of all types and of all origins. They have been described and mapped by many investigators and are summarized by Woods et al (1962) and Williams and Waller (1963). An evaluation of the various soil deposits in Alaska is best made on a regional basis; the basic physiographic regions of Alaska and corresponding soil deposits associated with each region are summarized in Figures 1.1 and 1.2.

1.3.1 Northern Alaska

Northern Alaska as discussed here includes three physiographic regions: the Arctic Rockies, the Arctic Foothills, and the Arctic Coastal Plain. The Arctic Rockies - loosely synonymous with the Brooks Range - is generally a mountainous area with little or no soil cover. The Arctic Foothills lie between the Arctic Rockies to the south and the Arctic Coastal Plain to the north and are characterized by erosional rather than depositional features; soil deposits are thin and generally consist of sand and silt, with some gravel associated with streams. The Arctic Coastal Plain is the northernmost region and contains extensive deposits of fluvial and marine sediments up to 150 feet thick. The sediments consist primarily of sands and silts with occasional gravel, clay, and peat. The soils are generally permanently frozen over their entire depth, with permafrost extending from 600 to 1300 feet beneath the ground surface.

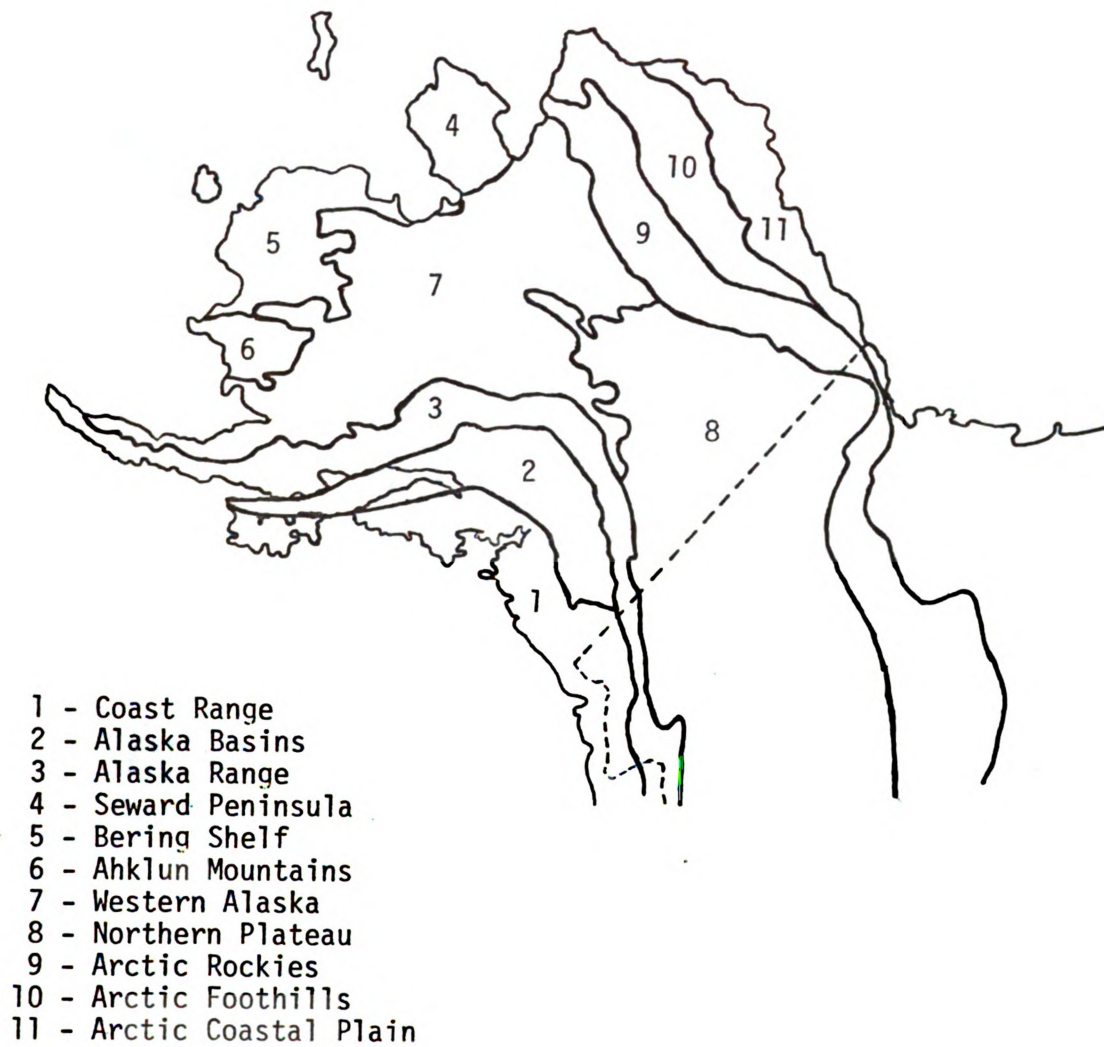


Figure 1.1 PHYSIOGRAPHIC REGIONS OF ALASKA (after Lovell and Roberts, 1975)

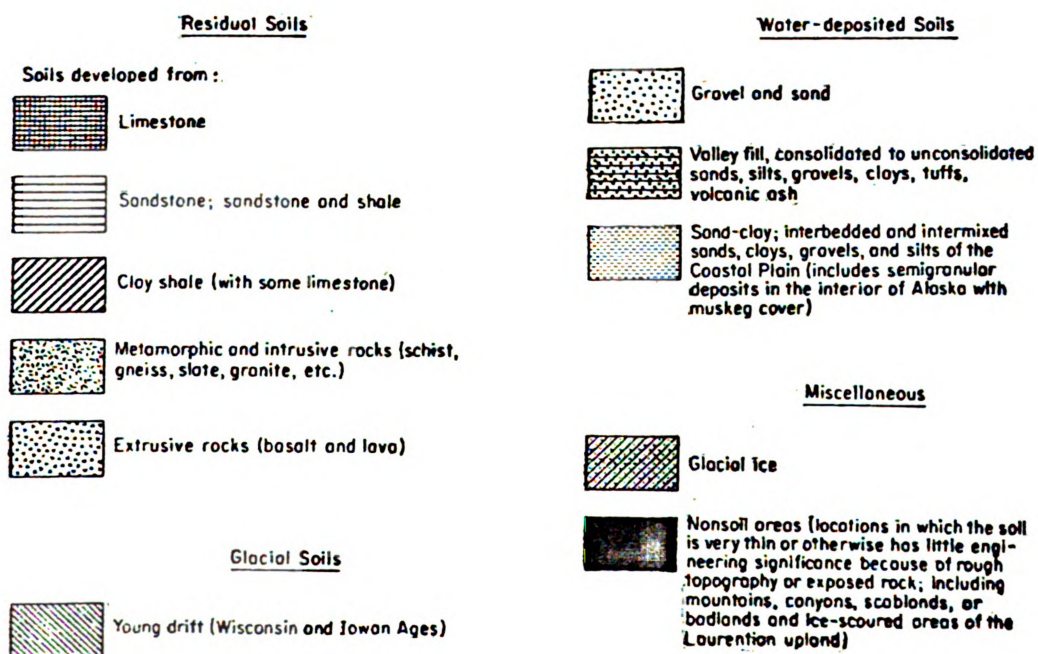
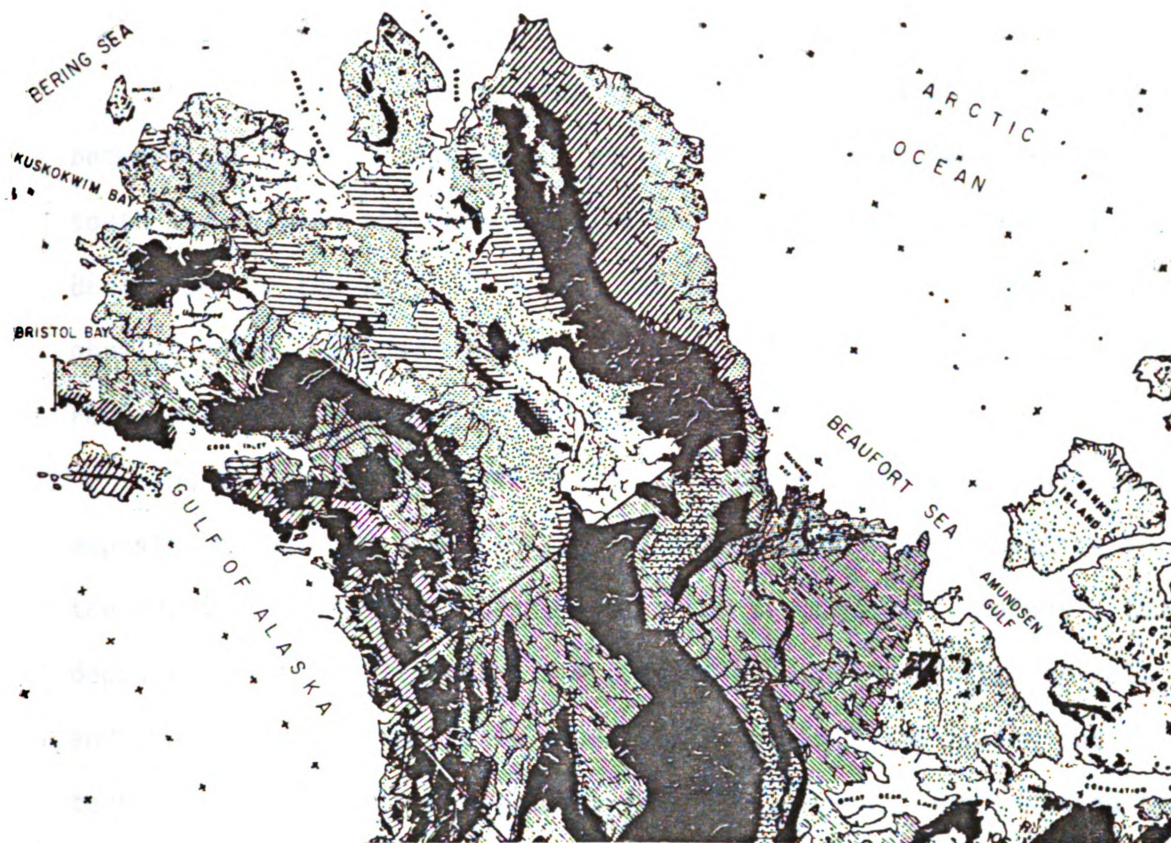


Figure 1.2 GENERALIZED SOILS MAP OF ALASKA (after Woods et al, 1962)

1.3.2 Central Alaska

Central Alaska as discussed here includes the area of Alaska between the Brooks Range in the north and the Alaska Range in the south and between the Canada-Alaska boundary in the east and the Bering Sea in the west. The area can be divided into the following physiographic regions: Northern Plateau, Western Alaska, Seward Peninsula, Bering Shelf, and Ahklun Mountains.

The most extensive soil deposits in Central Alaska are alluvial deposits associated with the Yukon and Kuskokwim drainage basins in the Northern Plateau, Western Alaska, and Bering Shelf regions. The deposits are generally thick and consist primarily of silt, gravel, and sand. The soil deposits generally occur in flood plains and terraces of valleys and outwash plains and alluvial fans fronting the mountains. The Yukon-Kuskokwim delta in the Bering Shelf region consists of silt, sand and gravel to a depth of almost 1000 ft. Coastal plain deposits occur over the entire Bering Sea coast; on the Seward Peninsula the deposits consist primarily of gravel on the southern coast and silt on the northern coast. Additional soil deposits which occur in local areas include lacustrine deposits, glacial drift in mountainous areas which had been glaciated, and eolian deposits of silt and sand, generally less than 60 ft. thick, over alluvial deposits and upland areas.

Central Alaska is generally an area of discontinuous permafrost. The depth of permafrost varies considerably throughout the area; deposits in the Yukon-Kuskokwim delta are frozen to depths of 350 to 600 ft. while deposits bordering Bristol Bay farther south are frozen in some places to depths of 150 ft. Alluvial deposits in Central

Alaska are generally unfrozen beneath river and stream channels and oxbow lakes and are frozen to depths ranging up to 300 ft. and more elsewhere. The depth and areal extent of permafrost is generally greater in higher flood-plain deposits than in lower deposits and is also greater in northern regions than in southern regions.

1.3.3 Southern Alaska

Southern Alaska includes the Alaska and Coast Ranges and the Alaska Basins. The Alaska and Coast Ranges consist of rugged mountainous topography and contain little or no soil cover except in low places, where gravelly glacial outwash occurs. The Alaska Basins lie between the Alaska and Coast Ranges and include the Copper River Valley in the eastern section and the Matanuska Valley in the western section. The Copper River Valley contains deposits of granular material up to several hundred feet in thickness; silt and sand cover the granular material in the flood plain and silty glacial till occurs in areas closer to mountains. The Matanuska Valley contains thick deposits of granular outwash covered in many places by thin deposits of fluvial and eolian silt.

Southern Alaska is near the southern boundary of the permafrost zone; permafrost in the area is thus discontinuous and generally thin. In the Matanuska Valley permafrost is sporadic; in the center of the Copper River Valley, sediments are frozen to depths of 100 to 200 ft.

1.4 Structure of Frozen Soil Deposits

Frozen soil deposits can occur in several forms determined by the amount and structure of interstitial ice. The structure of ice

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in frozen ground is dependent on soil type, availability of moisture, and other factors and can be classified as disseminated ice, ice gneiss, and massive ice. Disseminated ice typically occurs as ice uniformly distributed through a soil mass, resulting in a homogeneous appearance; the frozen soil may be saturated or unsaturated with ice generally taking up less volume than soil particles. Ice gneiss is characterized by foliated layers of ice and soil, with ice typically taking up from 30% to 90% of the total volume; ice gneiss is especially common in permafrost with a high silt content. Massive ice typically occurs as thick deposits containing relatively little soil, with ice contents ranging up to 1000% over depths of several tens of feet. Massive ice may be associated with variable soil types but is often found overlying sand and gravel deposits.

CHAPTER 2

DYNAMIC PROPERTIES OF FROZEN SILT AND CLAY

2.1 General

This chapter provides information on the results of previous investigations to evaluate the dynamic properties of frozen silt and clay. The dynamic properties that have been evaluated by various investigators using different testing techniques fall into two categories:

- (1) dynamic elastic properties and
- (2) damping properties.

Dynamic elastic properties are given in terms of dynamic Young's and shear moduli, complex Young's and shear moduli, sound velocity, and compression, dilatational, longitudinal, irrotational, primary, bulk, or "P" and shear, transverse, secondary, rotational, or "S" wave velocities. Damping properties are expressed in terms of angle of phase lag, attenuation coefficient, damping coefficient, loss factor, quality factor, log decrement, and damping ratio. Conversion equations between the various terms can be used to allow direct comparisons to be made between the results obtained by different investigators. These equations are given by Chaichanavong (1976).

2.2 Previous Research on the Dynamic Properties of Frozen Soils

A summary of the results from previous investigations to evaluate the dynamic properties of frozen clays has been presented by Chaichanavong (1976). The remainder of this chapter will concentrate

on the results of investigations to evaluate the dynamic properties of frozen silts.

Field techniques have been widely used to evaluate the dynamic elastic properties of frozen soils. The most common method used is the seismic method, which involves the measurement of compressional and shear wave velocities in naturally frozen soil deposits. A summary of wave velocities in frozen silt deposits obtained by several investigators is given in Table 2.1.

The dynamic properties of frozen silts have been investigated using various laboratory techniques by Kaplar (1969), Nakano and Froula (1973), and Stevens (1973). Silt samples tested in the laboratory have generally been artificially prepared; Stevens (1973), however, has tested silt which had been cored in a naturally frozen state. Kaplar (1969) and Stevens (1973) used a resonant frequency method in their testing programs; Nakano and Froula (1973) used an ultrasonic method. The apparatus and experimental technique used by each investigator is described in detail by Chaichanavong (1976).

2.3 Dynamic Elastic Properties of Frozen Silt

The influence of various parameters on the dynamic elastic properties of frozen silt has been investigated by Kaplar (1969), Nakano and Froula (1973), and Stevens (1973). The parameters considered include stress or strain amplitude, frequency of loading, temperature, void ratio or water content, and degree of ice saturation.

2.3.1 Effect of Void Ratio

The effect of void ratio on the dynamic elastic properties of frozen silt has been investigated by Stevens (1973) and is summarized

Table 2.1 FIELD MEASUREMENTS OF WAVE VELOCITY IN FROZEN SILT

REFERENCE	LOCATION	SOIL	COMPRESSIONAL WAVE VELOCITY	TEMPERATURE
Gagne and Hunter (1975)	Ellesmere Island	sandy silt silt and ice	1.8 km/sec 2.2 km/sec	
Hunter (1974)	Fairbanks	silt	2.69 to 3.29 km/sec	-4.2°C
Blouin (1976)	Eielson AFB, Alaska	silt with ice lenses	2.0 to 2.8 km/sec	-1.5°C

in Figure 2.1. The complex shear modulus decreases as the void ratio increases; as the volume of ice becomes significantly greater than the volume of soil, the modulus approaches the value for ice.

2.3.2 Effect of Ice Saturation

The effect of ice saturation on the dynamic elastic properties of frozen silt has been investigated by Stevens (1973). As shown in Figure 2.2, the complex shear modulus increases significantly as the degree of ice saturation in the voids increases. The complex shear modulus of frozen Manchester silt increases from about 0.1 GN/m^2 at 0% ice saturation to about 7.0 GN/m^2 at 100% ice saturation.

2.3.3 Effect of Temperature

The dynamic elastic properties of frozen silts tend to decrease with increasing temperature. The decrease is generally more pronounced at higher temperatures than at lower temperatures. Kaplar (1969) has determined the longitudinal wave velocity in beams of frozen silt as a function of temperature; the relationships for frozen New Hampshire silt, Fairbanks silt, and Yukon silt are shown in Figure 2.3. The longitudinal wave velocity decreases between -10°F and 30°F from 11.6×10^3 to 10.1×10^3 ft/sec for New Hampshire silt, from 11.5×10^3 to 8.3×10^3 ft/sec for Fairbanks silt, and from 11.0×10^3 to 8.0×10^3 ft/sec for Yukon silt.

Nakano and Froula (1973) have determined the shear wave velocity of frozen Hanover silt as a function of temperature. The results are summarized in Figure 2.4; the shear wave velocity of Hanover silt decreases from 2.1 km/sec at -14°C to 1.9 km/sec at -1°C .

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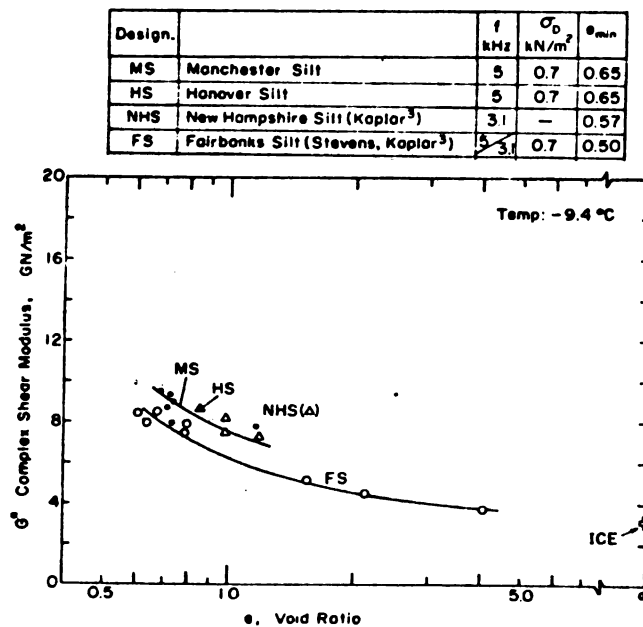


Figure 2.1 COMPLEX SHEAR MODULUS VERSUS VOID RATIO FOR FROZEN SILTS (after Stevens, 1973)

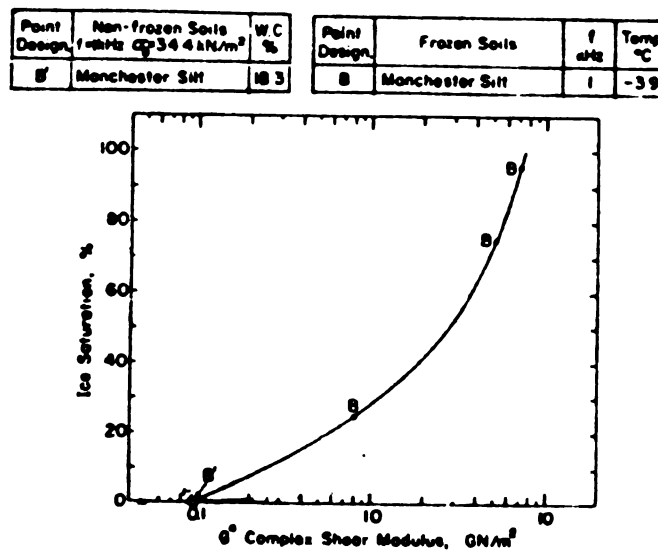


Figure 2.2 EFFECT OF ICE SATURATION ON COMPLEX SHEAR MODULUS OF FROZEN MANCHESTER SILT (after Stevens, 1973)

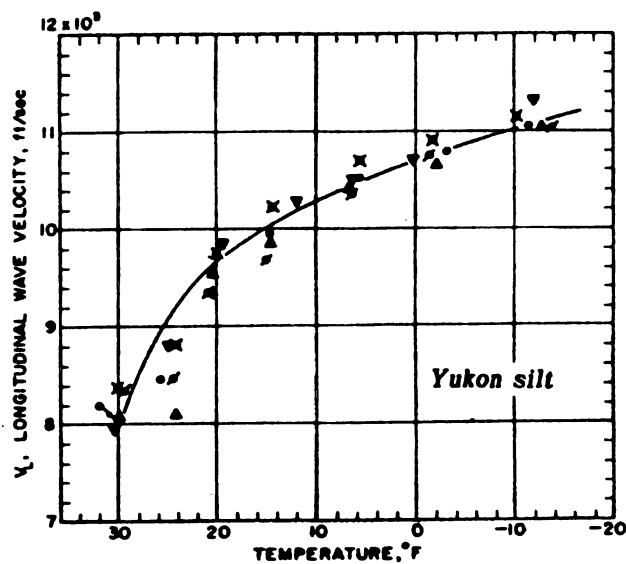
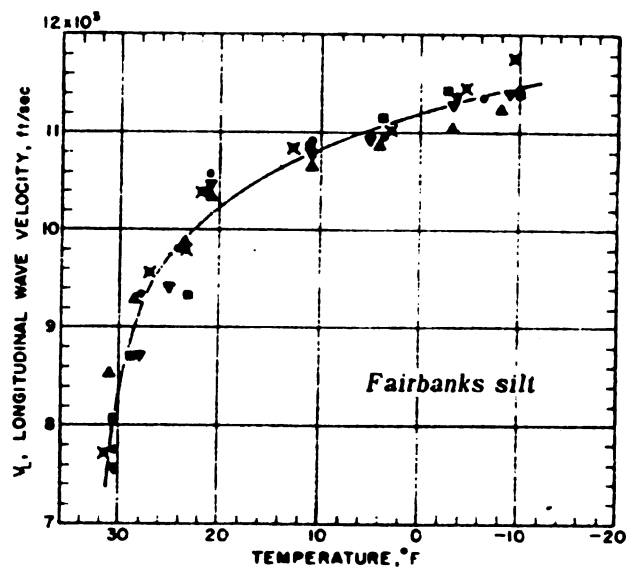
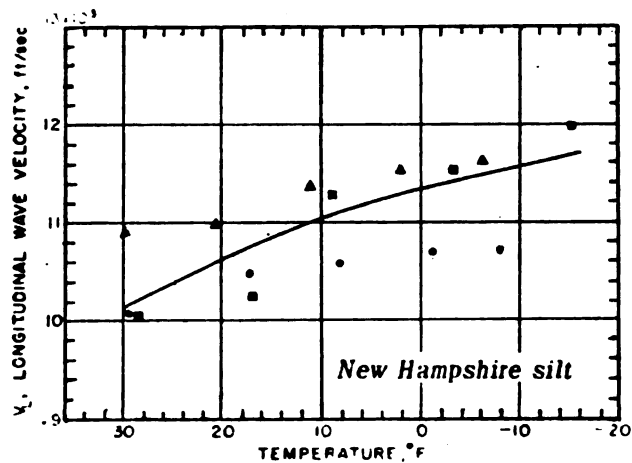


Figure 2.3 LONGITUDINAL WAVE VELOCITY VERSUS TEMPERATURE FOR FROZEN NEW HAMPSHIRE SILT, FAIRBANKS SILT, AND YUKON SILT (after Kaplar, 1969)

Figure

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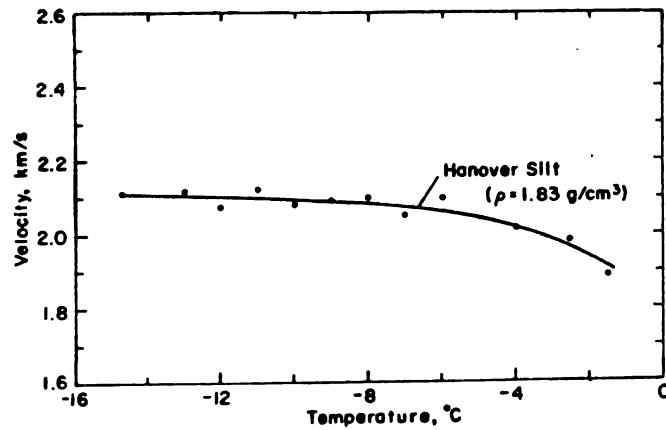


Figure 2.4 S-WAVE VELOCITY VERSUS TEMPERATURE FOR FROZEN HANOVER SILT (after Nakano and Froula, 1973)

Design.	S_1 %	S_w %	ν	
B	97.2	-	0.73	E° Manchester Silt
B'	-	91.4	0.73	
E	97.2	-	0.73	G° Manchester Silt
E'	-	91.4	0.73	

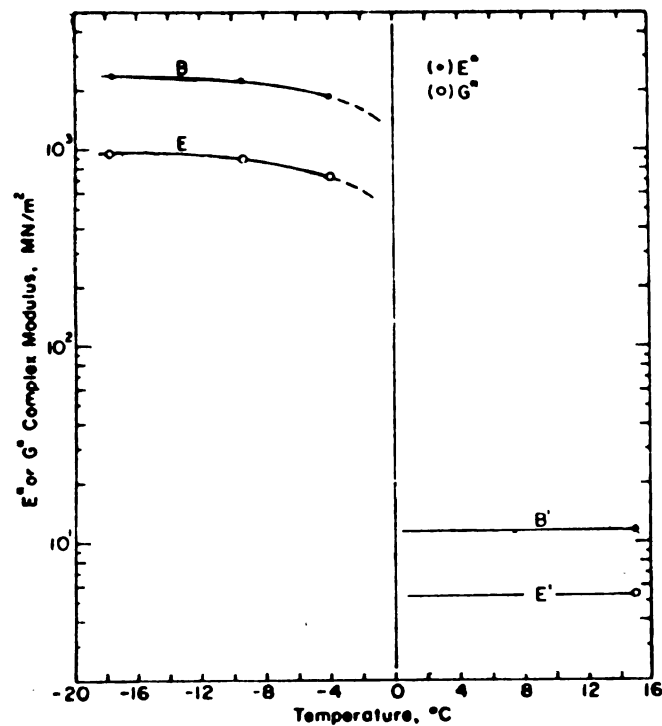


Figure 2.5 EFFECT OF TEMPERATURE ON COMPLEX MODULI OF FROZEN MANCHESTER SILT (after Stevens, 1973)

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Stevens (1973) has studied the influence of temperature on the dynamic complex Young's and shear moduli of Manchester silt. The results are shown in Figure 2.5. The dynamic complex Young's modulus decreases from $2.5 \times 10^3 \text{ MN/m}^2$ at -18°C to $1.9 \times 10^3 \text{ MN/m}^2$ at -4°C and to 11.0 MN/m^2 in the unfrozen state. The dynamic complex shear modulus decreases from $9.5 \times 10^2 \text{ MN/m}^2$ at -18°C to $7.5 \times 10^2 \text{ MN/m}^2$ at -4°C and to 5.5 MN/m^2 in the unfrozen state.

2.3.4 Effect of Frequency

The influence of frequency on the dynamic elastic properties of frozen silts has been studied by Stevens (1973). As shown in Figure 2.6, the complex shear modulus of frozen Hanover-Manchester silt increases slightly with increasing frequency between 1.0 kHz and 1000 kHz, with much of the increase occurring in the 1-5 kHz range. Stevens suggests that a significant decrease in shear modulus might result if testing was done at much lower frequencies.

2.3.5 Effect of Dynamic Stress or Strain

Information on the effect of dynamic stress on the dynamic elastic properties of frozen silts is given by Stevens (1973). As shown in Figure 2.7, the complex shear modulus of Manchester silt decreases slightly with increasing dynamic stress between 0.7 kN/m^2 and 34.5 kN/m^2 . In general, the influence of stress is greater at higher temperatures, lower frequencies, and higher stress levels.

2.4 Damping Properties of Frozen Silt

The damping properties of frozen silt have been studied by Stevens (1973). The influence of temperature on damping (in terms of $\tan \delta$) for Manchester silt is shown in Figure 2.8. The overall

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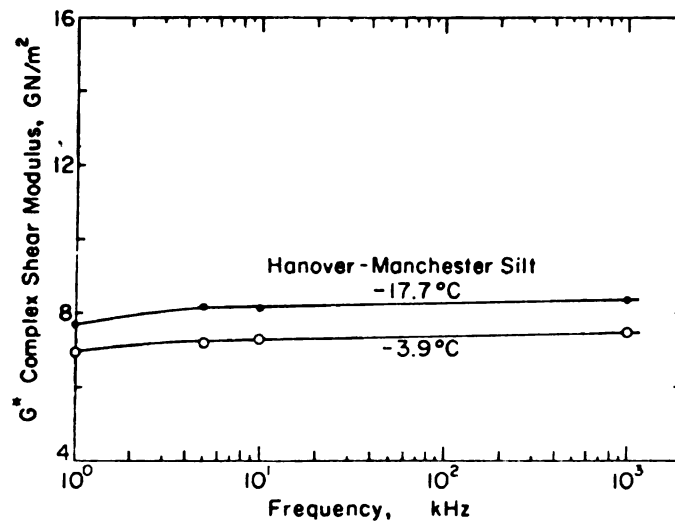


Figure 2.6 COMPLEX SHEAR MODULUS VERSUS FREQUENCY FOR FROZEN HANOVER-MANCHESTER SILT (after Stevens, 1973)

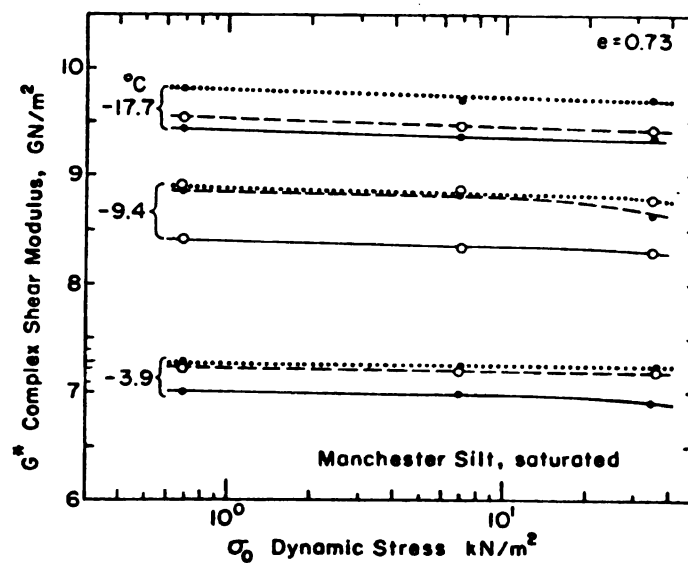


Figure 2.7 COMPLEX SHEAR MODULUS VERSUS DYNAMIC STRESS FOR FROZEN MANCHESTER SILT (after Stevens, 1973)

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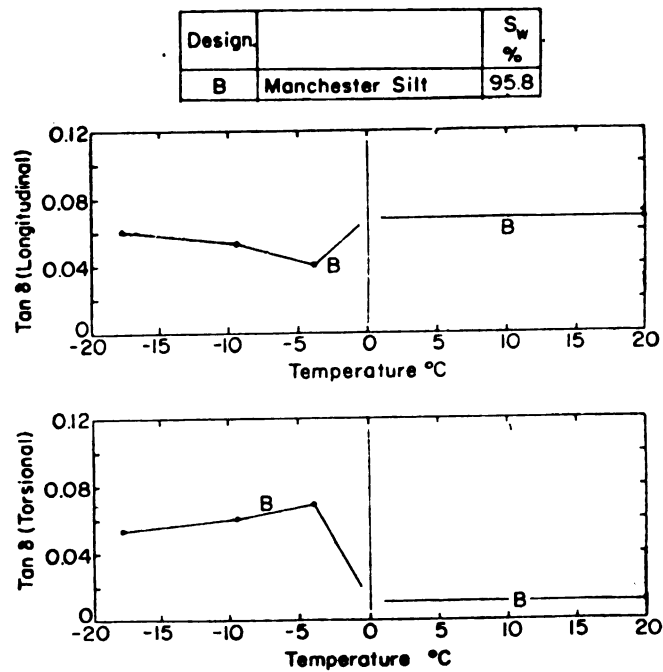


Figure 2.8 EFFECT OF TEMPERATURE ON $\tan \delta$ OF FROZEN MANCHESTER SILT (after Stevens, 1973)

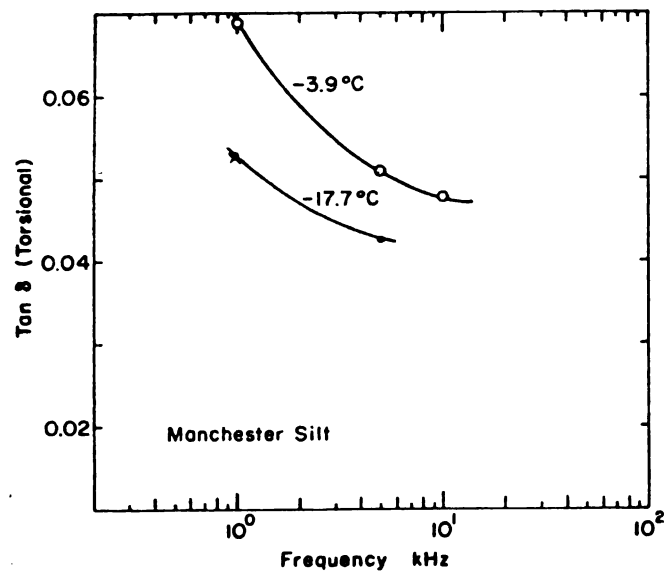


Figure 2.9 EFFECT OF FREQUENCY ON $\tan \delta$ OF FROZEN MANCHESTER SILT (after Stevens, 1973)

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relationship between damping and temperature is not entirely clear; it appears that longitudinal damping in frozen silt is less than in unfrozen silt and decreases with increasing temperature while torsional damping in frozen silt is greater than in unfrozen silt and increases with increasing temperature.

The influence of frequency on damping has been studied by Stevens (1973). As shown in Figure 2.9, damping of frozen Manchester silt decreases with increasing frequency between 1 and 10 kHz.

The influence of dynamic stress on damping of frozen silt has been studied by Stevens (1973) and is shown in Figure 2.10. Damping of frozen Manchester silt increases slightly with increasing dynamic stress between 0.7 kN/m^2 and 34.5 kN/m^2 ; the influence of dynamic stress on damping is generally greater at higher stress levels than at lower stress levels.

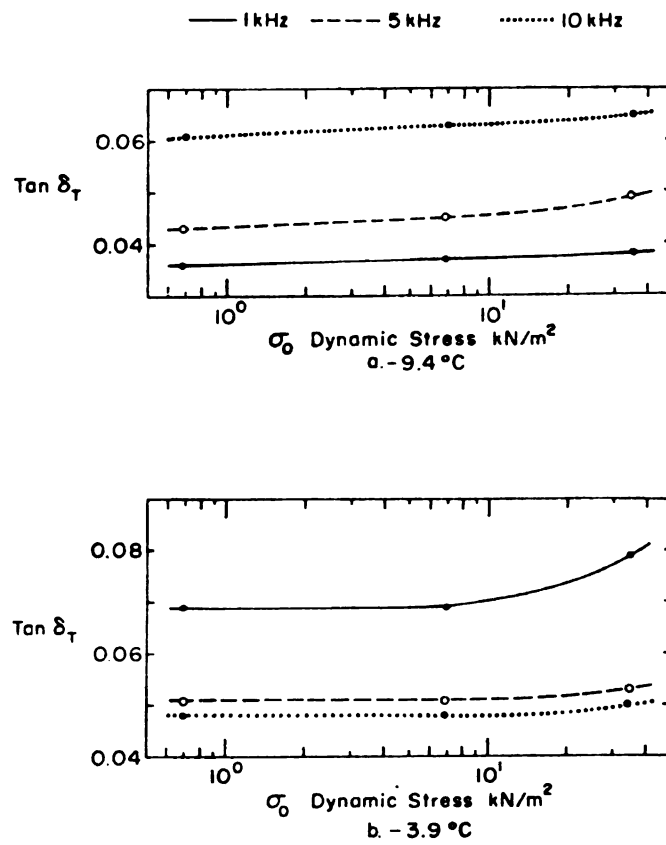


Figure 2.10 EFFECT OF DYNAMIC STRESS ON TAN δ OF FROZEN MANCHESTER SILT (after Stevens, 1973)

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CHAPTER 3

SAMPLE PREPARATION, SAMPLE INSTALLATION TRIAXIAL CELL ASSEMBLY AND TEST PROCEDURE

3.1 General

This chapter deals with the laboratory preparation of frozen silt and clay samples, installation of the samples in a triaxial cell, triaxial cell assembly, and the test procedure used in the program. A basic knowledge of the components of the test system is assumed. The MTS electrohydraulic closed-loop test system, the refrigeration unit, the triaxial cell, and the output recording devices used in the testing program are described in detail by Chaichanavong (1976).

3.2 Preparation of Frozen Silt Sample

Two types of silt were used in the testing program: Hanover silt, termed HS, and Alaska silt, termed AS. Physical properties of both silts are given in Figure 3.1. Samples were prepared at two water contents for each of the two silts to assess the influence of water content and dry density on the dynamic properties of silts. All samples were formed and frozen to aluminum coupling devices in a hollow cylindrical teflon mold 30.5 cm high, 7.1 cm in inside diameter, and 1.3 cm thick.

The high density (low water content) samples for both Hanover silt and Alaska silt were prepared as follows:

(1) A silt slurry with a water content of approximately 36% was made by adding distilled water to oven-dried silt and mixing thoroughly. The slurry was then placed in a triaxial cell and consolidated

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Percent Finer by Weight

Design.	Soil	LL	PL	PI
HS	Hanover Silt	22	--	NP
AS	Alaska Silt	28	23	5
K	Kaolinite	40	23	17

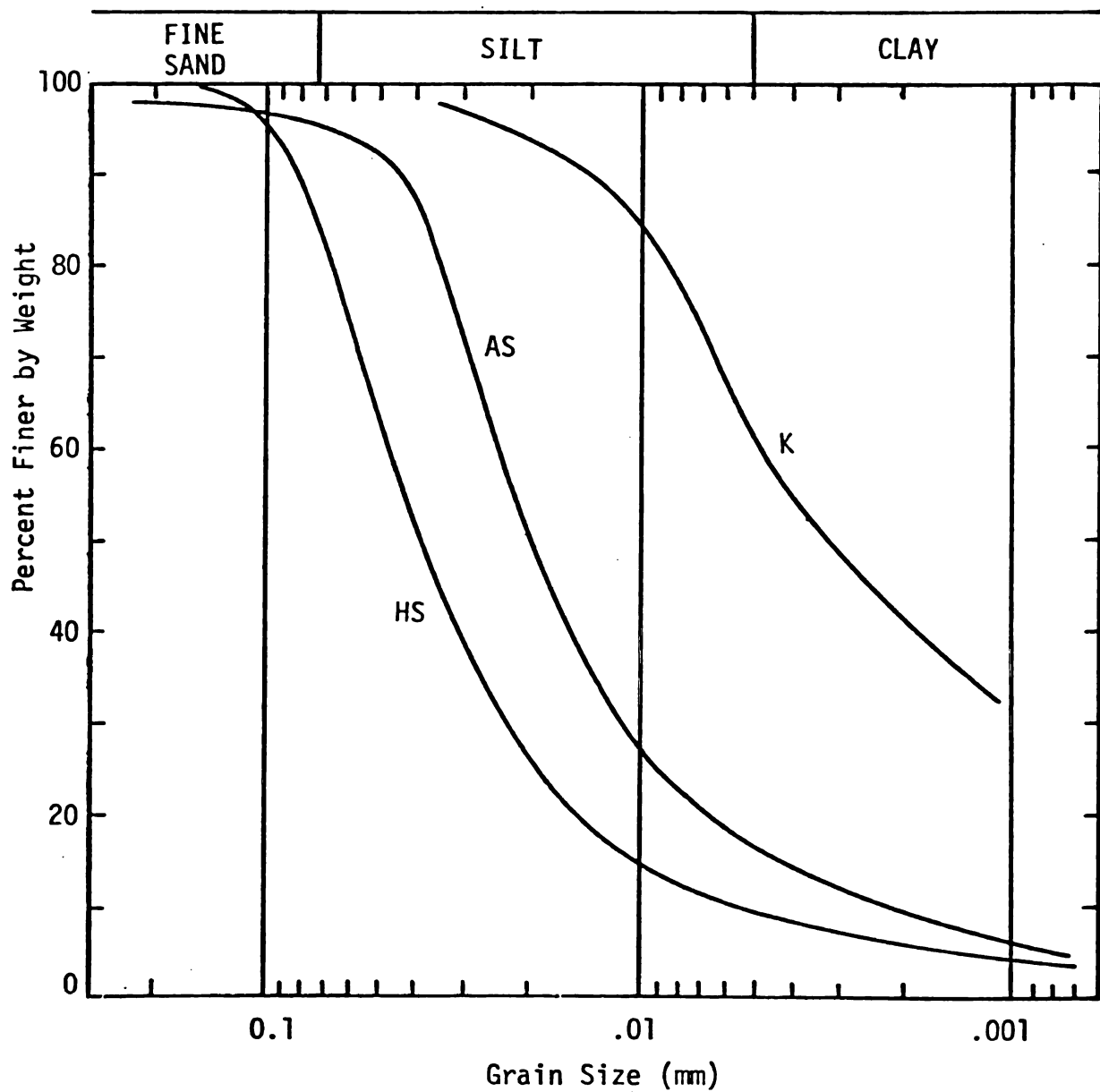


Figure 3.1 GRADATION CURVES FOR SOILS

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isotropically under a cell pressure of 40 psi for 24 hours.

(2) The sample was removed from the consolidation cell and trimmed to a diameter approximately equal to the inside diameter of the mold. Material trimmed from the sample was packed tightly around the couplings on the caps; the sample and the caps were then placed in the mold. The caps were then hammered vigorously to assure a good bond between the main portion of the sample and the material around the couplings and to allow any entrapped air to escape. A small hole near the top of the mold facilitated the removal of air. The mold was then placed in a freezer at -30°C and left for 24 hours.

(3) The mold was then removed from the freezer. The sample was extruded from the mold as quickly as possible, weighed, transferred to a freezer, and jacketed with two rubber membranes. The sample was now ready for installation in the triaxial cell.

A typical frozen sample is as shown in figure 3.2. The high density frozen silt samples were uniform in appearance with occasional ice lenses in the outer portion of the sample and were classified as ML, Nbn (Linell and Kaplar, 1966). The water content was reasonably uniform over the length of the sample, with a slightly higher water content in the vicinity of the caps. Average water contents were 21.4% for Hanover silt and 20.5% for Alaska silt.

The low density (high water content) samples for both Hanover silt and Alaska silt were prepared as follows:

(1) A silt slurry with a water content of 51% was made by adding the appropriate amount of distilled water to oven-dried silt

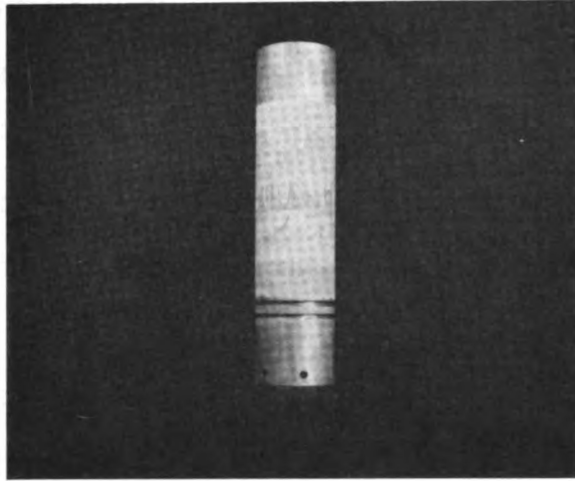


Figure 3.2 TYPICAL FROZEN KAOLINITE SAMPLE

and mixing thoroughly. The slurry was stored at a temperature slightly above 0°C for 24 hours.

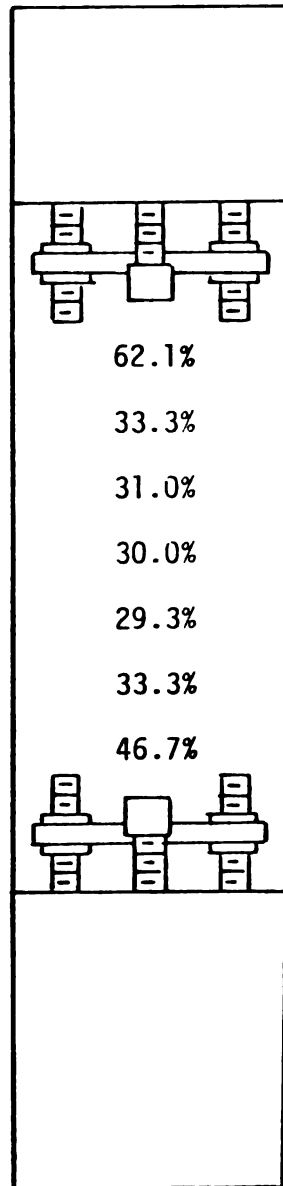
(2) The teflon mold and aluminum caps were precooled to -30°C. The slurry was mixed again and poured into the mold with the bottom cap in place. Additional slurry was packed around the coupling of the top cap, which was then set in the mold and hammered to remove any entrapped air. The mold was then placed on its side in a freezer at -30°C for 24 hours. In order to prevent settlement of the silt particles before freezing, the sample was rotated 180° every 10 minutes for the first three hours after being placed in the freezer.

(3) The mold was removed from the freezer and the sample was extruded, weighed, and jacketed with membranes as described above.

The resulting low density frozen silt samples were classified ML, Nbe. They contained a layer approximately .1" thick consisting of silt with ice lenses around the entire sample. While the interior of the sample appeared to be uniformly frozen with no ice lenses, the water content varied significantly from the center to the ends of the sample. The distribution of water content over the effective length of the sample (between top and bottom coupling) for both Hanover silt and Alaska silt is shown in Figure 3.3.

It is apparent that the permeability of both silts was great enough to allow significant migration of water in both a radial direction and along the length of the sample during the freezing process. This movement occurred despite efforts to freeze the sample as quickly as possible by precooling the slurry, mold, and caps. Since a uniform water content could not be obtained, the water con-

Hanover silt



Alaska silt

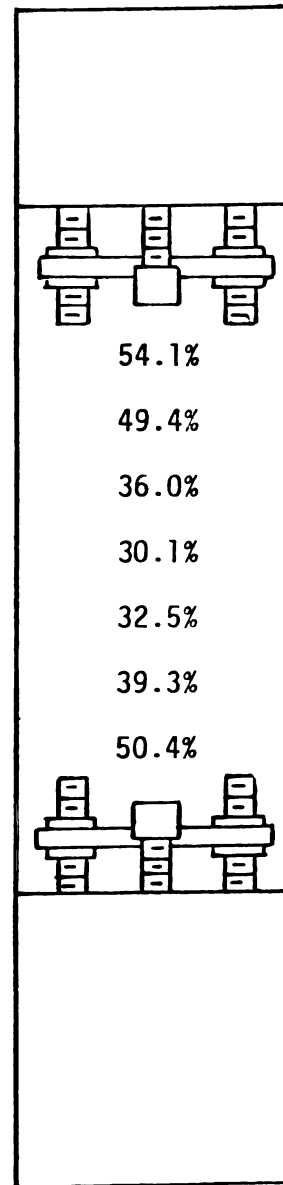


Figure 3.3 DISTRIBUTION OF WATER CONTENT OVER LENGTH OF HIGH WATER CONTENT FROZEN SILT SAMPLE

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tent was taken as the weighted average water content of the material over the effective length of the sample excluding the silt-ice layer around the outside of the sample. Average water contents determined using this technique were 35.5% for Hanover silt and 38.9% for Alaska silt.

Two samples of Alaska silt were prepared at water contents intermediate between high and low water contents. The procedure used was similar to the method used in preparation of the high water content samples, with the major difference being the use of a slurry with a water content of 36%. The frozen sample was similar in appearance to the high water content sample and had an average water content of 29.2%.

3.3 Preparation of Frozen Clay Sample

The clay used in the testing program was a commercial kaolinite, termed K. Physical properties of the kaolinite are given in Figure 3.1. Clay samples were prepared at two water contents to assess the influence of water content on the dynamic properties of frozen clay. The same mold and caps used in the preparation of frozen silt samples were used in the preparation of frozen clay samples.

The low water content clay samples were prepared with a procedure similar to that used in the preparation of high density frozen silt samples. A clay slurry of 50% water content was made by adding the appropriate amount of distilled water to dry clay and mixing thoroughly. After setting for a minimum of three days, the slurry was consolidated isotropically under a cell pressure of 40 psi for

24 hours; the final water content after consolidation was 35%. The sample was then removed from the consolidation cell, trimmed, placed in the mold, and frozen as described previously.

The resulting low water content frozen clay samples were classified CL, Nbn. They contained a layer approximately .1" thick consisting of ice and clay with ice lenses around the entire sample. The interior of the sample had few apparent ice lenses and a reasonably uniform water content over the effective length of the sample. The average water content of the sample excluding the clay-ice layer in the outer portion was 28.1%.

It was found that high water content clay samples could not be prepared in the same way as low density silt samples due to the resulting large degree of non-uniformity in both structure and water content over the length of the frozen sample. Significant migration of water during the freezing process resulted in a sample which had a uniformly frozen structure with a water content of about 30% in the central part and a structure consisting of horizontal layers of ice and frozen clay with a total water content of about 110% near the outer portions of the sample. To alleviate this problem, high water content clay samples were prepared by adding clay slurry in layers, with each layer added after the previous layer had frozen.

The high water content clay samples were prepared with the following procedure:

- (1) A clay slurry with a water content of 75% was made by adding the appropriate amount of distilled water to dry clay and mixing thoroughly. The slurry was stored for a minimum of two days and precooled to a temperature slightly above 0°C before use.

(2) The aluminum caps were precooled to -30°C . Clay slurry was packed around the coupling on the bottom cap, which was then placed in the mold. Additional slurry was poured into the mold to the top of the coupling and the mold was placed in the freezer at -30°C . The mold in this case was not precooled and was surrounded radially by additional insulation; the purpose of this was to assure that the sample would freeze vertically rather than radially.

(3) After the slurry above the coupling had formed a crust, a second layer of slurry was added to a depth of approximately $3/4$ ". Additional $3/4$ " layers of slurry were added in succession after a crust had formed on each previous layer. After the last layer was in place, slurry was packed around the coupling of the top cap; the top cap was then set in the mold and hammered as described previously.

(4) After 24 hours, the mold was removed from the freezer and the sample was extruded, weighed, and jacketed with membranes as described earlier.

The resulting high water content frozen clay sample was classified CL, Vs and had a structure consisting of predominantly horizontal layers of ice and clay throughout. Ice lenses, which varied from $.02$ " to $.04$ " in thickness, were generally non-uniformly distributed over the length of the sample, resulting in a water content which varied over the length of the sample; a typical water content distribution is as shown in Figure 3.4. The average water content of the sample obtained using a weighted average technique was 71.3%.

Kaolinite

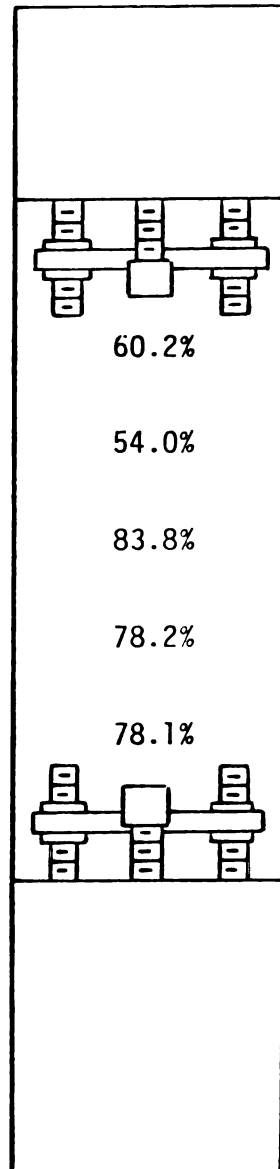


Figure 3.4 DISTRIBUTION OF WATER CONTENT OVER LENGTH OF HIGH WATER CONTENT FROZEN CLAY SAMPLE

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A summary of all silt and clay samples made and tested is given in Table 3.1.

3.4 Sample Installation and Triaxial Cell Assembly

The base clamp of the anti-tilt device was fastened to the bottom cap of the frozen silt or clay sample which had been previously jacketed with rubber membranes. The sample was then placed in the cold bath of the testing apparatus and connected to the load cell at the bottom. A spring-loaded LVDT was then attached to the anti-tilt device. An anti-tilt ring was fastened to the top cap of the sample; one end of the anti-tilt ring was fastened to a spring steel clip which extended from the base of the anti-tilt device and the opposite end contained a flat-headed bearing screw which bore directly on the core of the LVDT. The voltage output from the LVDT was then adjusted close to zero by adjusting the bearing screw or by sliding the opposite end of the anti-tilt ring along the spring clip and tightening. The sample with the anti-tilt device and LVDT connected is shown in Figure 3.5.

After the LVDT was adjusted, the aluminum cylinder of the triaxial cell was set in the base plate and the thermistor wires were set in place around the top and bottom of the sample. The top plate of the cell was then set in place and tightened and a connecting rod was screwed into the top cap of the sample through the top plate. Coolant was circulated over the top plate and the cold bath was covered with styrofoam.

The sample was allowed to sit in the cold bath for at least one hour prior to testing to bring the temperature of the sample into equilibrium with the cold bath. Temperatures within the cell were

Table 3.1 SUMMARY OF SAMPLES MADE AND TESTED

Soil	Average water content (%)	Testing temperature (°C)	Sample number	Water content (%)	Density (g/cc)
Hanover silt	21.4	-1	HS-14	21.7	2.04
			HS-15	22.1	2.08
		-4	HS-6	24.5	2.01
			HS-7	24.5	2.04
			HS-11	24.2	2.05
		-10	HS-21	20.9	2.06
			HS-22	21.8	2.05
	35.5	-1	HS-13	*	1.74
			HS-16	*	1.67
			HS-17	*	1.66
		-4	HS-3	*	1.87
			HS-4	*	1.85
			HS-5	*	1.78
			HS-8	*	1.77
			HS-10	*	1.72
			HS-12	*	1.72
			HS-18	*	1.71
		-10	HS-19	*	1.67
			HS-20	*	1.68
Alaska silt	20.5	-1	AS-3	22.1	2.07
			AS-4	21.9	2.06
		-4	AS-10	20.8	2.06
			AS-11	21.5	2.06
		-10	AS-13	19.7	2.09
			AS-15	19.8	2.09
	29.2	-1	AS-5	27.1	1.90
			AS-6	31.2	1.86
			AS-7	31.7	1.74
	38.9	-1	AS-1	*	1.59
			AS-2	*	1.65
		-4	AS-8	*	1.69
			AS-9	*	1.69
		-10	AS-12	*	1.66
			AS-14	*	1.66
Kaolinite	28.1	-1	K-7	28.1	1.84
			K-8	27.2	1.86
		-4	K-5	28.8	1.83
			K-6	28.0	1.82

Table 3.1 (cont'd)

Soil	Average water content (%)	Testing temperature (°C)	Sample number	Water Content (%)	Density (g/cc)
Kaolinite	28.1	-10	K-1	31.7	1.75
			K-2	28.1	1.82
			K-3	28.4	1.82
	71.3	-1	K-11	78.9	1.50
			K-12	75.9	1.51
		-4	K-10	71.9	1.50
			K-13	66.5	1.50
		-10	K-9	63.9	1.52
			K-14	70.9	1.49

* Average water content determined from weighted average technique using single sample rather than individual samples.



Figure 3.5 FROZEN SAMPLE WITH LVDT AND ANTI-TILT DEVICE CONNECTED

monitored by means of the thermistors before and during testing to assure that testing was done at the proper temperature.

3.5 Test Procedure

After the sample was installed and the triaxial cell was assembled, the sample was subjected to cyclic loading using an electrohydraulic closed-loop test system. The start-up procedure for the testing of each sample was as follows:

(1) The power was turned on and the electrohydraulic system was allowed to warm up for 15 minutes. The set point knob on the control unit was then used to lower the actuator rod to approximately 1/2" above the connecting rod. An LDVT in the actuator was used to provide the control at this point.

(2) The system was turned off and the control was switched to the LVDT attached to the sample; the voltage output from the load cell and the LVDT were then adjusted to zero. The supply valve to the actuator was closed and the actuator rod was connected to the rod attached to the sample. A confining pressure of 200 psi was then applied to the cell.

(3) The power was turned on again and the supply valve to the actuator was opened. Movement of the actuator was now controlled by the LVDT attached to the sample.

(4) Any load in the sample as measured by the voltage output from the load cell was adjusted close to zero in compression by adjusting the set point knob on the control unit. In general, the LVDT output was non-zero; a voltage offset was used to bring the net LVDT output on the recording devices close to zero.

(5) The desired strain amplitude and frequency for each test were selected by adjusting the span knob on the control unit and the frequency selector on the function generator, respectively. A sinusoidal strain wave of the selected amplitude and frequency was then applied to the sample by pressing the run button on the function generator. Output was recorded in the form of load and deformation sine waves on a strip-chart recorder and in the form of hysteresis loops on a storage oscilloscope.

CHAPTER 4

DYNAMIC PROPERTIES OF FROZEN SILT UNDER CYCLIC TRIAXIAL LOADING CONDITIONS

4.1 General

Cyclic triaxial tests were conducted on the frozen Hanover and Alaska silt samples described in Chapter 3. Samples of both silts were tested at two water contents to determine the influence of sample density on the dynamic properties. To determine the influence of other parameters which might affect the dynamic properties of frozen silts, samples were tested at temperatures of -1, -4, and -10°C, confining pressures of 0, 50, and 200 psi, frequencies of 0.05, 0.3, 1.0, 5.0, and 10.0 cps, and over a range of axial strain amplitudes from .002 to .08%.

4.2 Testing Sequence

The test history (i.e. the sequence in which the various test condition parameters - confining pressure, frequency, and strain amplitude - were applied) used on the frozen silt samples in the research program is shown in Figure 4.1. The test history was similar to one used in previous research by Chaichanavong (1976). Chaichanavong found that with a test sequence similar to that used, the influence of sample disturbance on the measured dynamic properties was negligible.

The ranges of the various test condition parameters were as follows:

(1) Temperature - three temperatures (-1, -4, and -10°C) were used in the testing program; each sample was tested at only one

Constant temperature

Approximate axial strain = $2.0 \times 10^{-3}\%$

→ cp=200 psi → f=0.05 cps → f=0.3 cps → f=1.0 cps → f=5.0 cps → f=10.0 cps
 → cp= 50 psi → f=0.05 cps → f=0.3 cps → f=1.0 cps → f=5.0 cps → f=10.0 cps
 → cp= 0 psi → f=0.05 cps → f=0.3 cps → f=1.0 cps → f=5.0 cps → f=10.0 cps

Approximate axial strain = $5.0 \times 10^{-3}\%$

→ cp=200 psi → f=0.05 cps → f=0.3 cps → f=1.0 cps → f=5.0 cps → f=10.0 cps
 → cp= 50 psi → f=0.05 cps → f=0.3 cps → f=1.0 cps → f=5.0 cps → f=10.0 cps
 → cp= 0 psi → f=0.05 cps → f=0.3 cps → f=1.0 cps → f=5.0 cps → f=10.0 cps

Approximate axial strain = $1.8 \times 10^{-2}\%$

→ cp=200 psi → f=0.05 cps → f=0.3 cps → f=1.0 cps → f=5.0 cps → f=10.0 cps
 → cp= 50 psi → f=0.05 cps → f=0.3 cps → f=1.0 cps → f=5.0 cps → f=10.0 cps
 → cp= 0 psi → f=0.05 cps → f=0.3 cps → f=1.0 cps → f=5.0 cps → f=10.0 cps

Approximate axial strain = $8.0 \times 10^{-2}\%$

→ cp=200 psi → f=0.05 cps → f=0.3 cps → f=1.0 cps → f=5.0 cps → f=10.0 cps

Figure 4.1 DIAGRAM OF TEST HISTORY FOR FROZEN SILT AND CLAY

temperature.

(2) Strain amplitude - each sample was tested at four strain amplitudes ranging from approximately .002 to .08% axial strain. In general, the strain amplitude of .08% was applied only at 200 psi confining pressure; the strain amplitude at 0 and 50 psi was limited to approximately .02% axial strain.

(3) Confining pressure - the samples were tested at three confining pressures (0, 50, and 200 psi).

(4) Frequency - each sample was tested at five loading frequencies (.05, .3, 1.0, 5.0, and 10.0 cps).

(5) Number of cycles - each sample was generally subjected to a maximum of 10 cycles per loading condition.

(6) Water content - both silts were prepared at two water contents; average water contents were 21.4 and 35.6% for Hanover silt and 20.5 and 38.9% for Alaska silt. Two samples of Alaska silt tested at -1°C were prepared at an intermediate water content (29.2%).

The dynamic Young's modulus for each loading condition was calculated from the amplitude of the load and deformation sine waves from the strip-chart recorder output. Research by Chaichanavong (1976) indicated that the dynamic Young's modulus does not vary significantly with the number of cycles of loading up to 20 cycles of loading. Therefore, a representative cycle of loading less than 20 was selected to determine the dynamic Young's modulus for each loading condition.

The damping ratio for each loading condition was calculated from a hysteresis loop recorded on the storage oscilloscope. A

cycle of loading within the first ten cycles was chosen and recorded; the trace on the oscilloscope was then observed for subsequent cycles to assure that the loop recorded did not differ from loops at other cycles for the particular loading condition. The loops on the oscilloscope were then photographed, enlarged, and projected onto sheets of paper and traced; areas of the traced loops were found with a planimeter and damping ratios were calculated. Typical hysteresis loops recorded in this manner are shown in Figure 4.2. Any deviations from symmetry in the loops generally indicated imminent sample failure, melting at the couplings, or off scale.

4.3 Dynamic Young's Modulus of Frozen Silt

Values of dynamic Young's modulus were plotted versus the log of axial strain expressed as a percent for all loading conditions. Plots for both silts at all water contents are given in Appendix A. Each plot represents a silt at a particular water content, temperature, and frequency. Data from at least two samples are included in each plot. It can be seen that, in general, data points from duplicate samples are in good agreement. There is somewhat more scatter in the data points for high water content samples; this is due perhaps to the lack of uniformity and the difficulty in reproducing the high water content samples.

It was apparent early in the testing program that confining pressure had a negligible influence on dynamic Young's modulus regardless of strain amplitude, frequency, temperature, or water content. A typical plot of dynamic Young's modulus versus confining pressure for a single sample is shown in Figure 4.3. Since dynamic

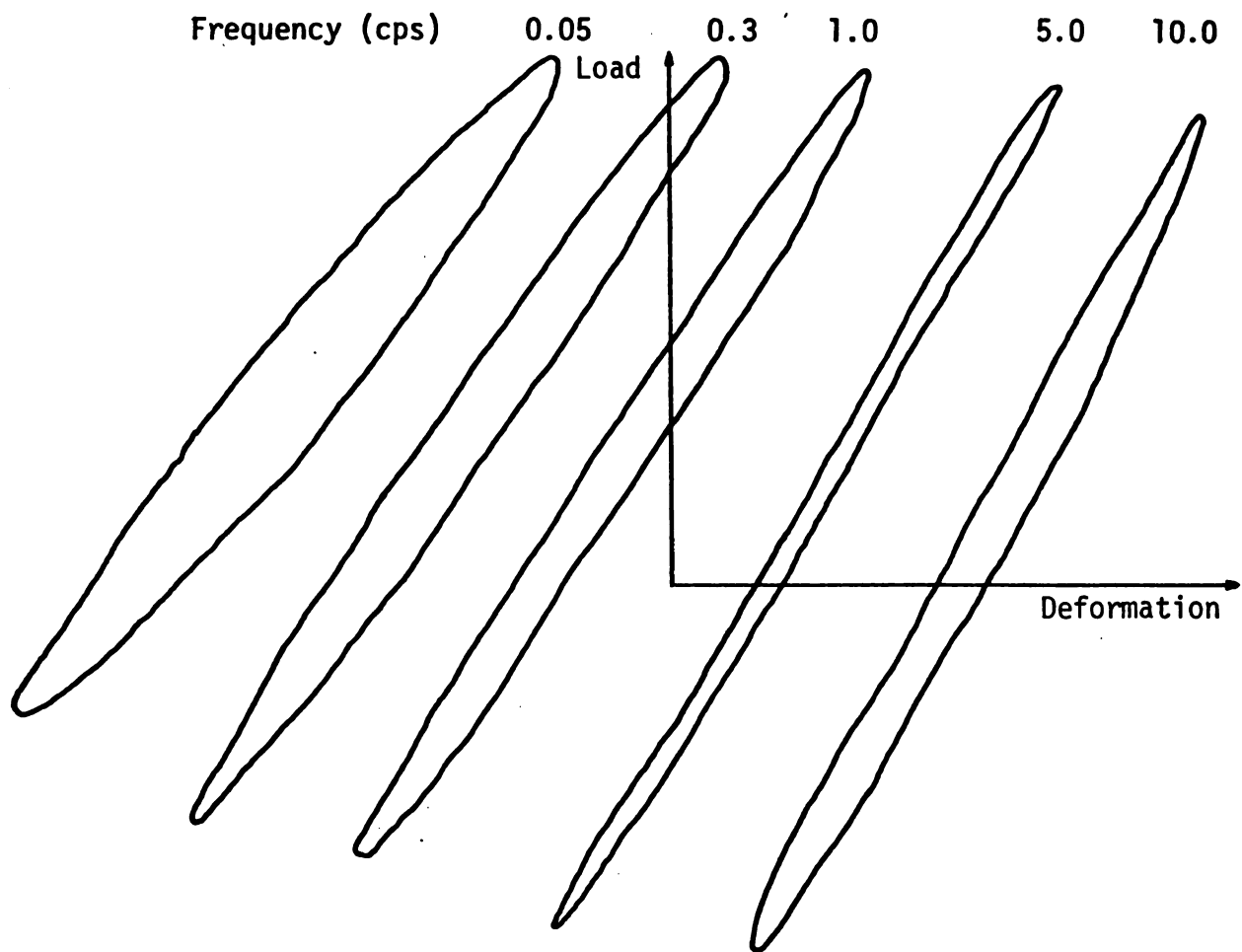


Figure 4.2 TYPICAL HYSTERESIS LOOPS OBTAINED DURING CYCLIC TRIAXIAL TESTING

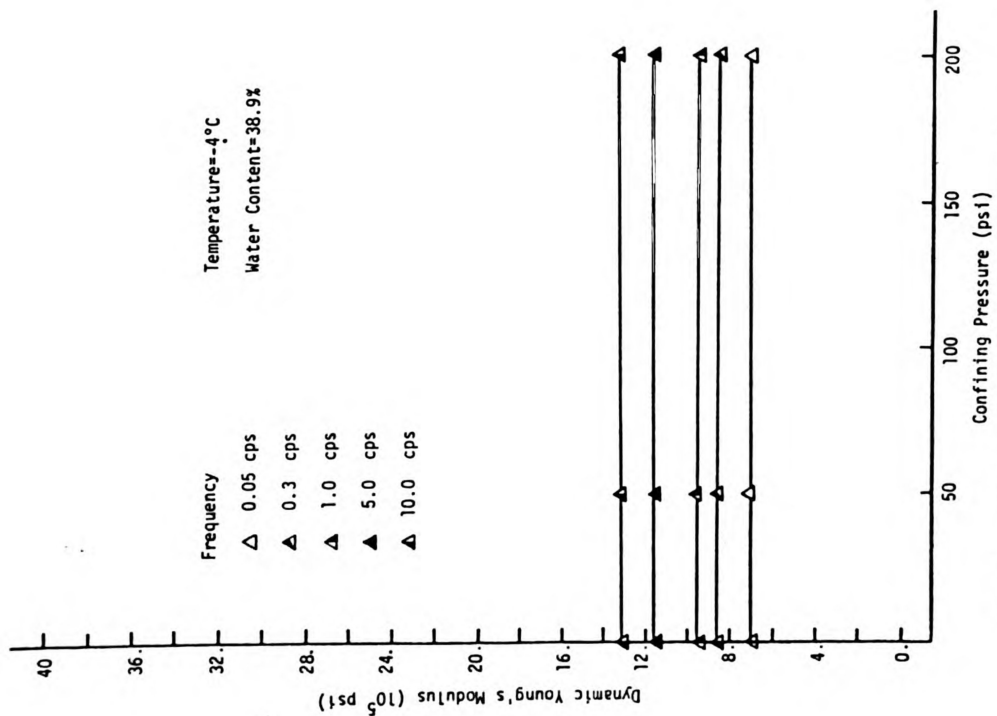


Figure 4.3 DYNAMIC YOUNG'S MODULUS VERSUS CONFINING PRESSURE FOR ALASKA SILT AT AN AXIAL STRAIN OF $5.0 \times 10^{-3}\%$.

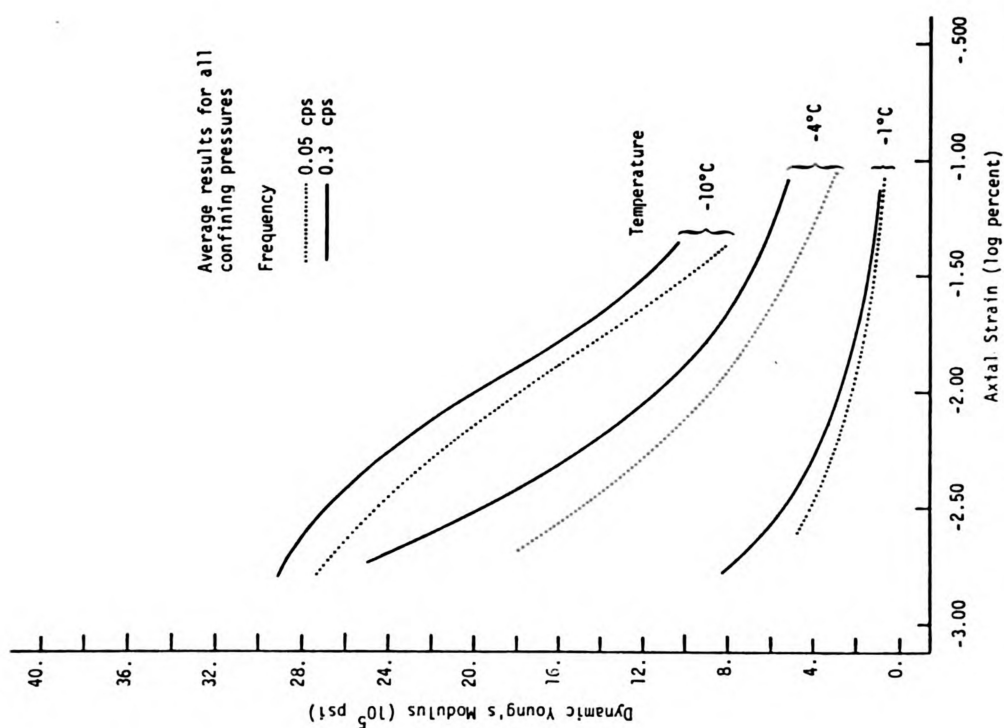


Figure 4.4 DYNAMIC YOUNG'S MODULUS VERSUS AXIAL STRAIN FOR HANOVER SILT AT 21.4% WATER CONTENT

Young's modulus was not influenced by confining pressure, data points for all confining pressures were plotted together in the graphs of dynamic Young's modulus versus axial strain amplitude.

4.3.1 Effect of Strain Amplitude

To assess the influence of strain amplitude on dynamic Young's modulus, a "best fit" line was drawn through the data points shown on the plots given in Appendix A. The relationships between dynamic Young's modulus and strain amplitudes for both silts are summarized in Figures 4.4 to 4.12. Each graph represents one silt at a particular water content, at three temperatures (-1 , -4 , and -10°C), and at least two frequencies. Values for dynamic Young's modulus range from 1×10^5 to 35×10^5 psi for Hanover silt and 1×10^5 to 22×10^5 psi for Alaska silt.

The dynamic Young's modulus for both silts decreases as the axial strain amplitude increases; the decrease is more pronounced at -4 and -10°C than at -1°C . The relationship between dynamic Young's modulus and strain amplitude appears to be independent of water content and frequency,

To assess the influence of frequency, temperature, and water content on dynamic Young's modulus, values of dynamic Young's modulus were obtained from Figures 4.4 to 4.12 at axial strain amplitudes of $3.16 \times 10^{-3}\%$ ($\log$ axial strain = -2.50) and $3.16 \times 10^{-2}\%$ ($\log$ axial strain = -1.50). The modulus values were then plotted versus frequency, temperature, and water content.

4.3.2 Effect of Frequency

The relationship between dynamic Young's modulus and frequency

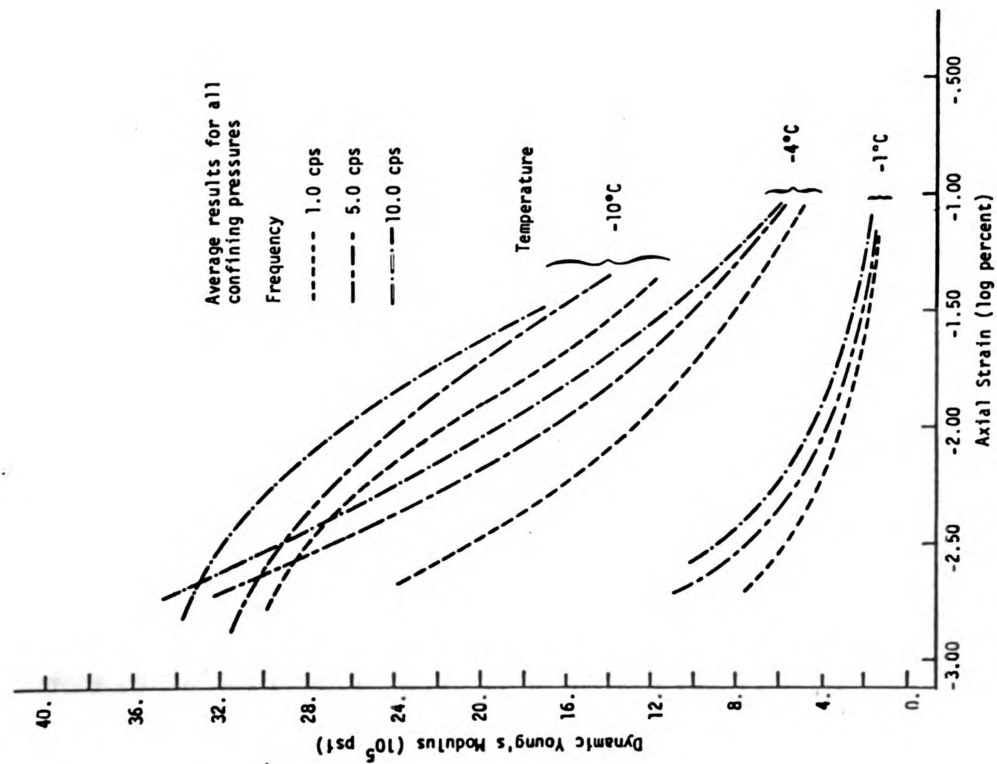


Figure 4.5 DYNAMIC YOUNG'S MODULUS VERSUS AXIAL STRAIN FOR HANOVER SILT
AT 21.4% WATER CONTENT

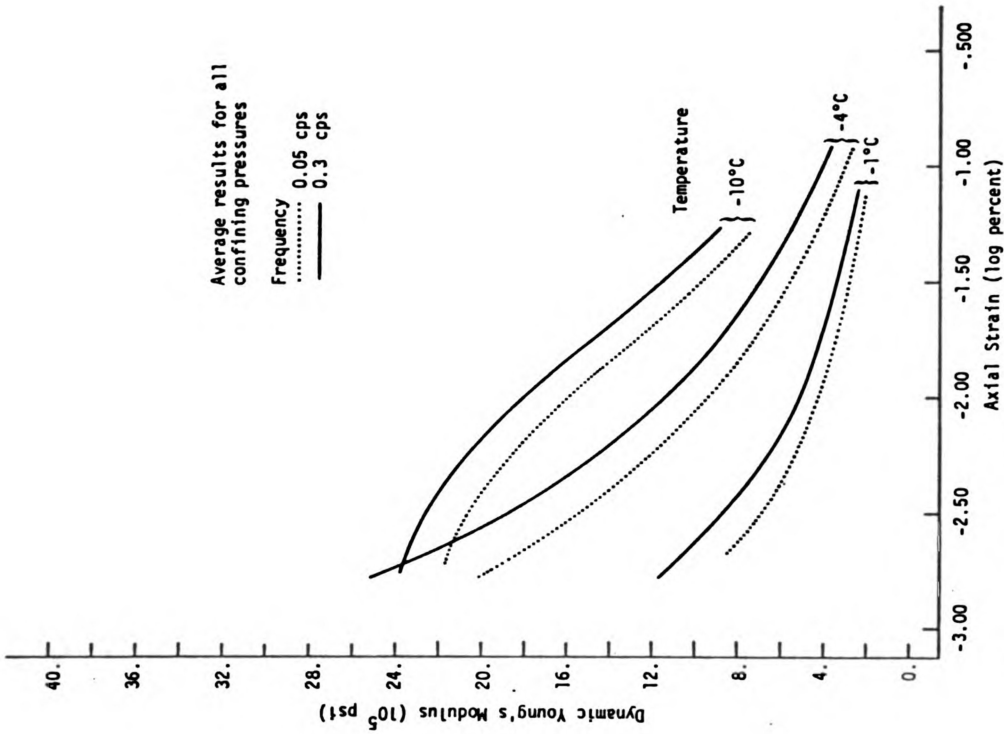


Figure 4.6 DYNAMIC YOUNG'S MODULUS VERSUS AXIAL STRAIN FOR HANOVER
SILT AT 35.5% WATER CONTENT

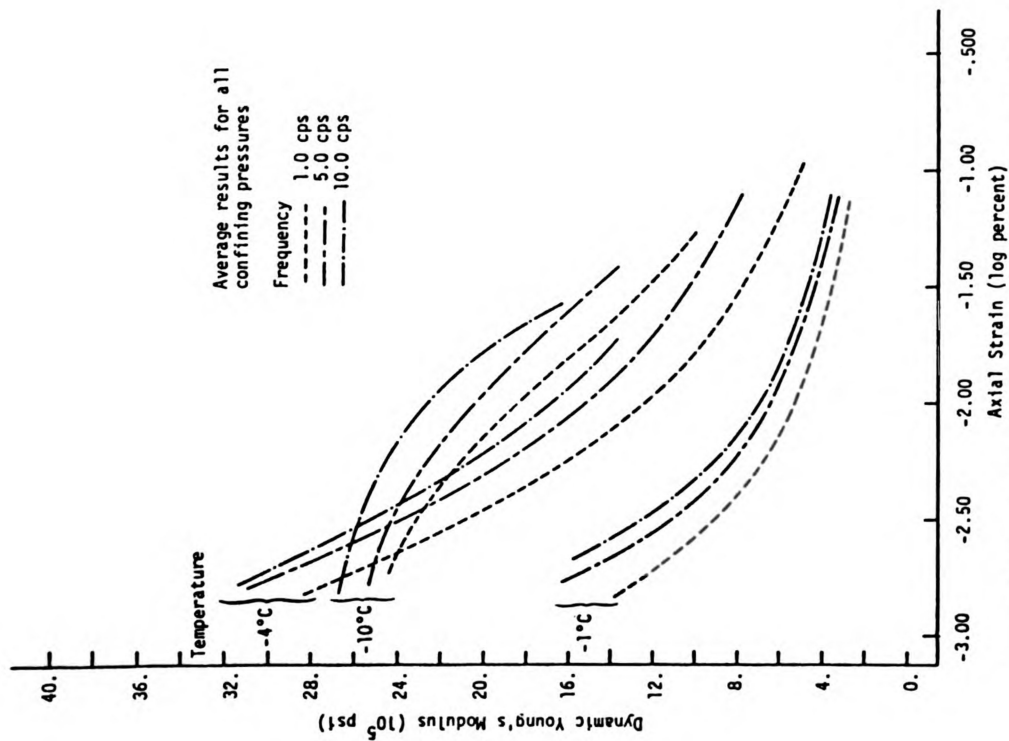


Figure 4.7 DYNAMIC YOUNG'S MODULUS VERSUS AXIAL STRAIN FOR HANOVER SILT AT 35.5% WATER CONTENT

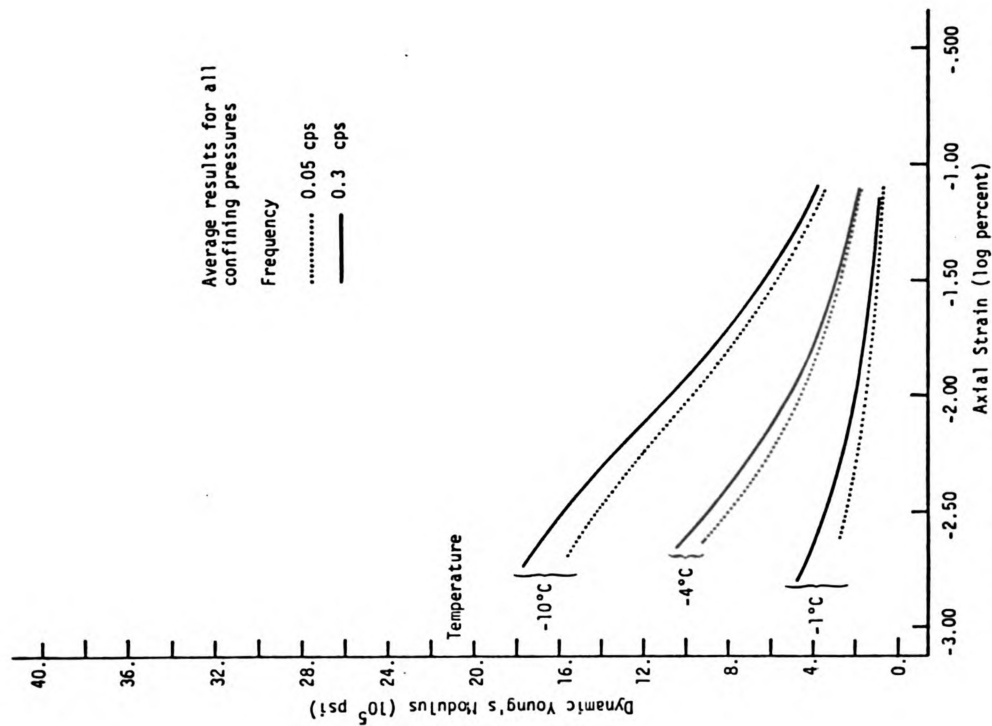


Figure 4.8 DYNAMIC YOUNG'S MODULUS VERSUS AXIAL STRAIN FOR ALASKA SILT AT 20.5% WATER CONTENT

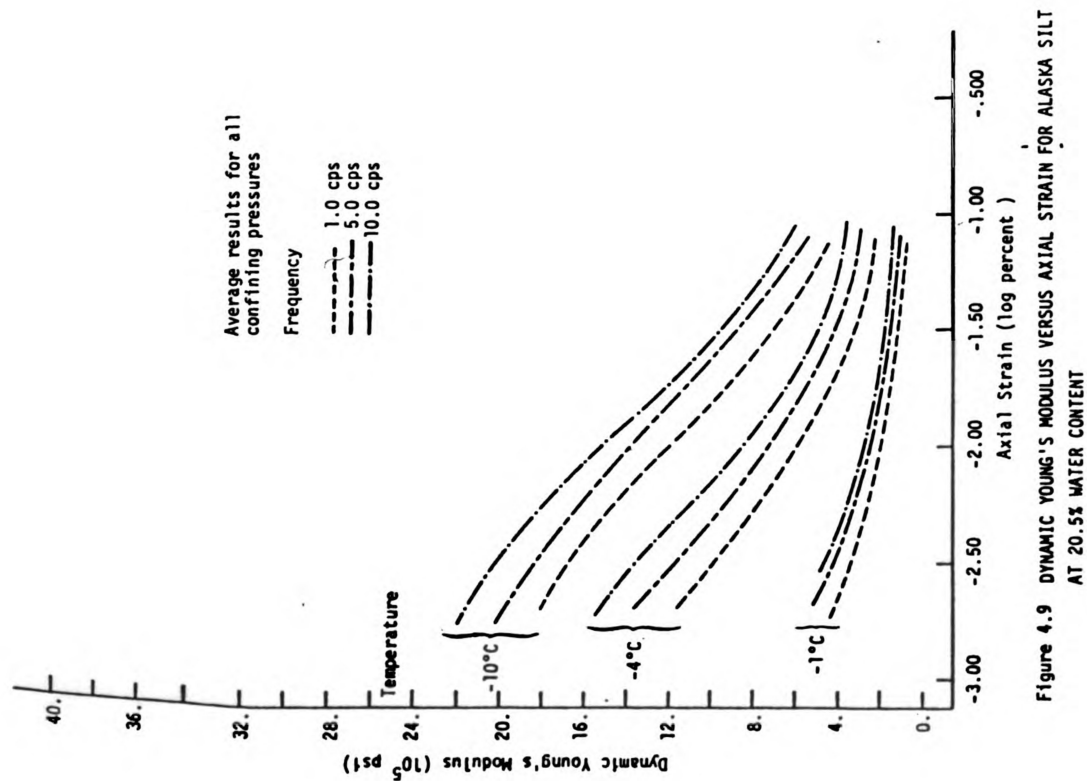


Figure 4.9 DYNAMIC YOUNG'S MODULUS VERSUS AXIAL STRAIN FOR ALASKA SILT AT 20.5% WATER CONTENT

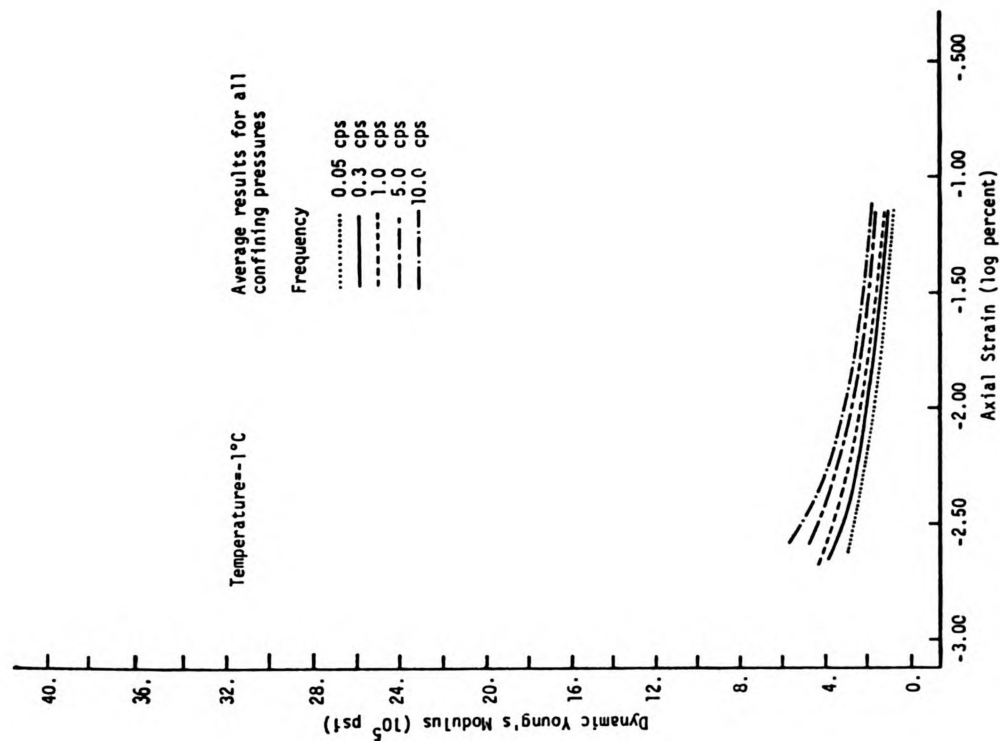


Figure 4.10 DYNAMIC YOUNG'S MODULUS VERSUS AXIAL STRAIN FOR ALASKA SILT AT 29.2% WATER CONTENT

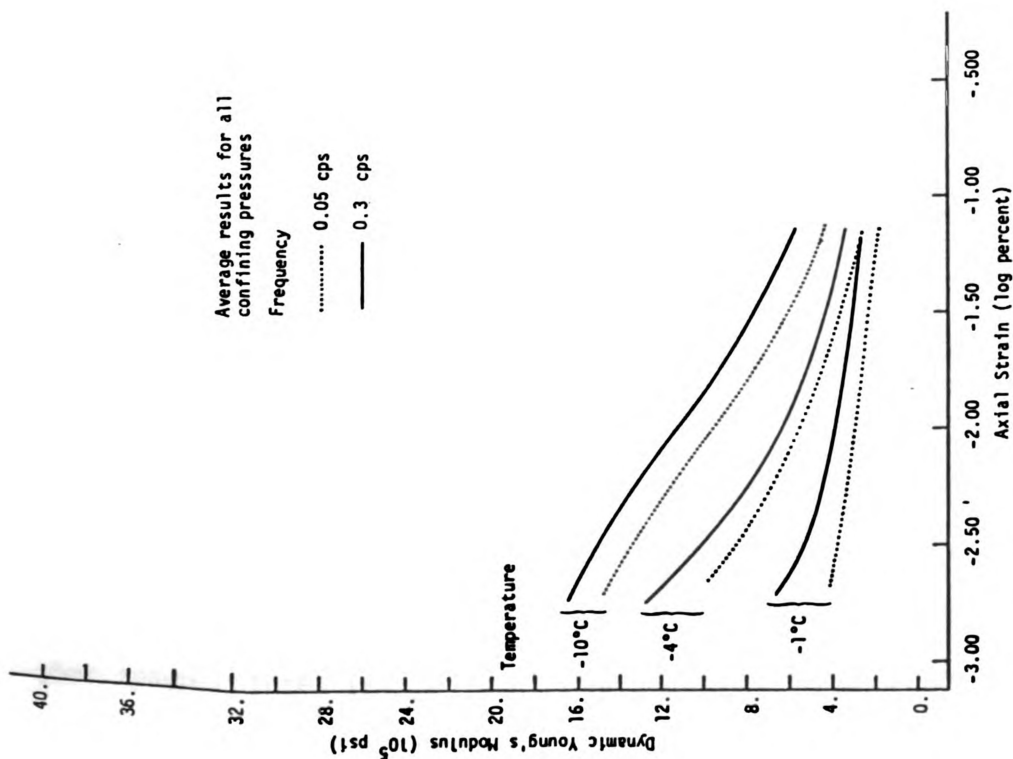


Figure 4.11 DYNAMIC YOUNG'S MODULUS VERSUS AXIAL STRAIN FOR ALASKA SILT
AT 38.9% WATER CONTENT

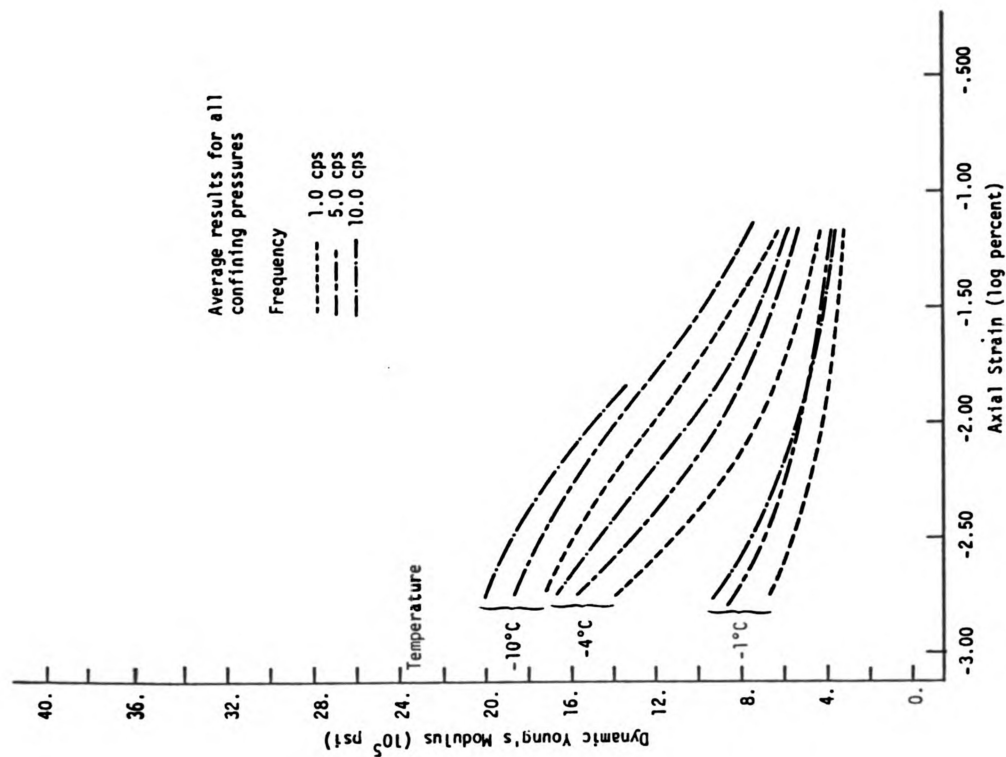


Figure 4.12 DYNAMIC YOUNG'S MODULUS VERSUS AXIAL STRAIN FOR ALASKA
SILT AT 38.9% WATER CONTENT

for both silts is given in Figures 4.13 to 4.22; each plot represents the relationship for a silt at a single water content at all three temperatures (-1, -4, and -10°C). Dynamic Young's modulus increases with increasing frequency. In general, the rate of increase is slightly greater at very low and very high frequencies than at intermediate frequencies. At a high strain amplitude, the relationship between dynamic Young's modulus and frequency appears to be independent of water content and temperature. At a low strain amplitude, the rate of increase of dynamic Young's modulus with frequency is somewhat greater at -4°C than at -1 and -10°C. In the case of Hanover silt, the value of dynamic Young's modulus at -4°C approaches the value at -10°C at high frequencies.

4.3.3 Effect of Temperature

The relationship between dynamic Young's modulus and temperature for both silts is given in Figures 4.23 to 4.30. Each plot represents the relationship for a silt at a particular water content, at five frequencies (0.05, 0.3, 1.0, 5.0, and 10.0 cps), and at one of two axial strain amplitudes ($3.16 \times 10^{-3}\%$ or $3.16 \times 10^{-2}\%$). In all cases, dynamic Young's modulus increases significantly with decreasing temperature. The rate of increase is fairly constant at a high strain amplitude ($3.16 \times 10^{-2}\%$), with a slightly greater rate of increase at higher temperatures (-1 to -4°C) than at lower temperatures (-4 to -10°C). At a lower strain amplitude ($3.16 \times 10^{-3}\%$) the rate of increase is generally significantly greater at higher temperatures (-1 to -4°C) than at lower temperatures (-4 to -10°C). The rate of increase of dynamic Young's modulus with de-

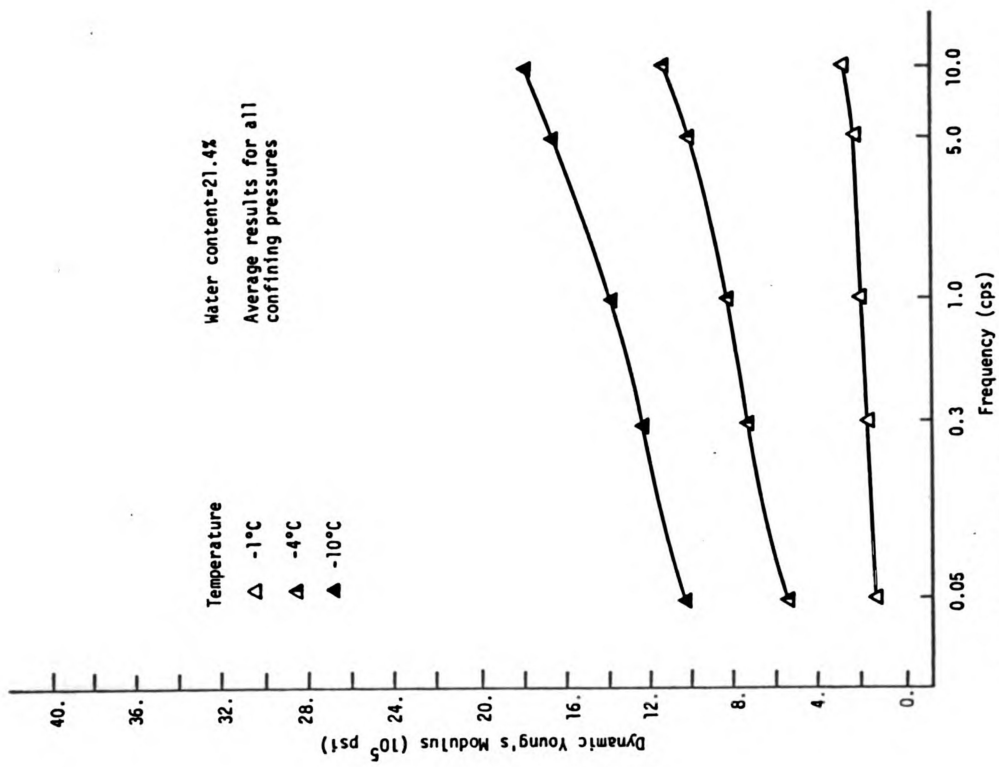


Figure 4.13 DYNAMIC YOUNG'S MODULUS VERSUS FREQUENCY FOR HANOVER SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

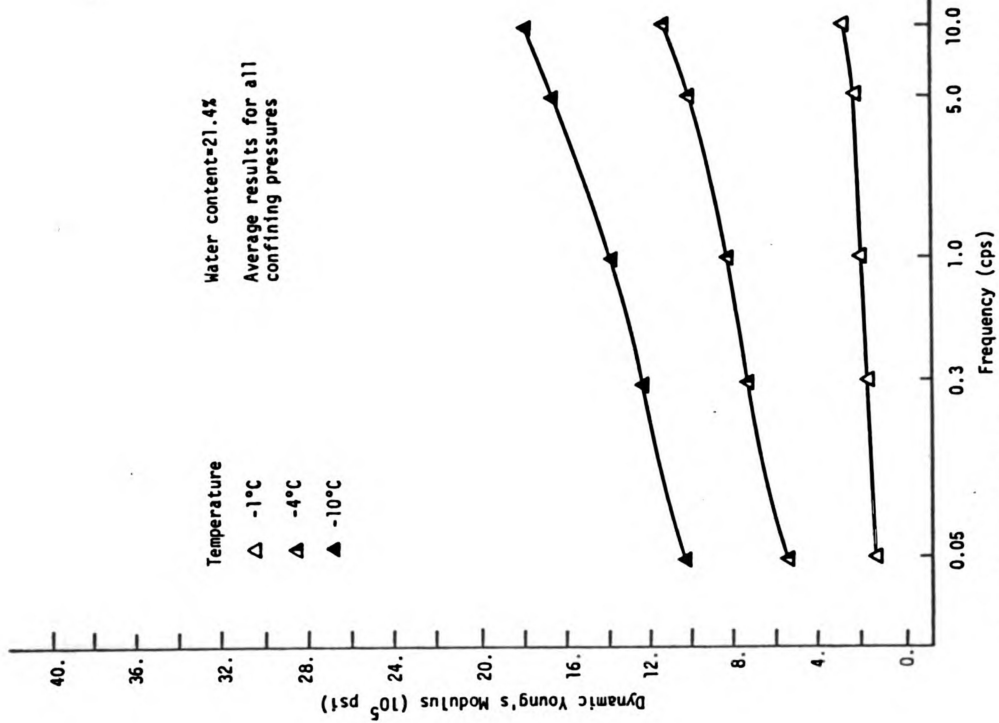


Figure 4.14 DYNAMIC YOUNG'S MODULUS VERSUS FREQUENCY FOR HANOVER SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

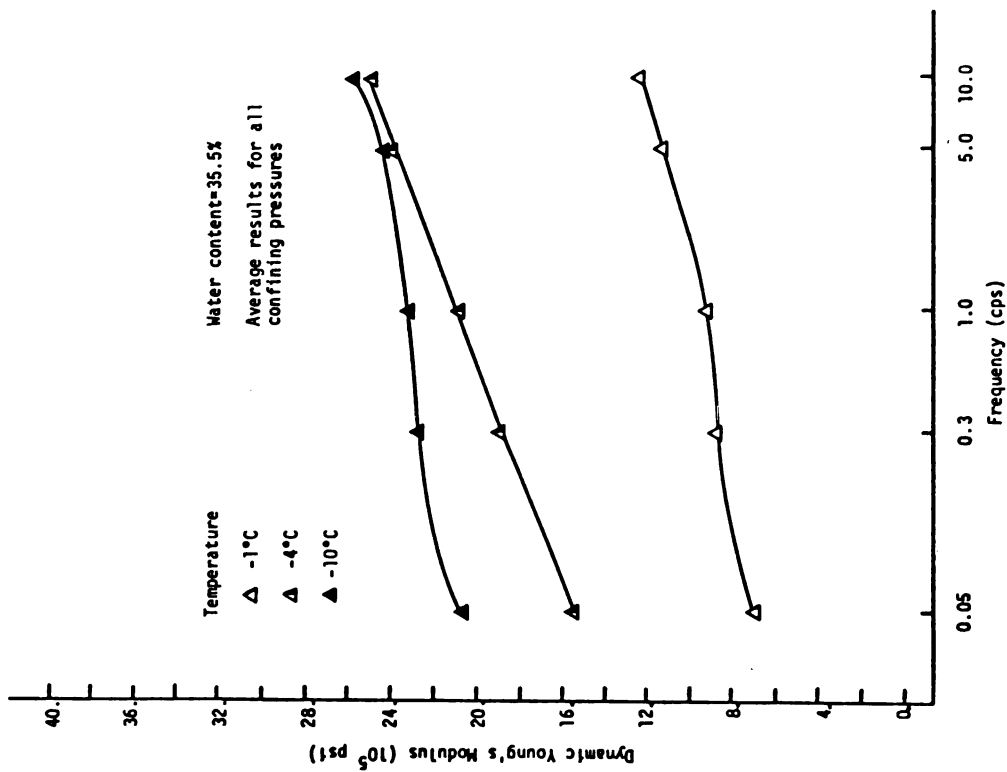


Figure 4.15 DYNAMIC YOUNG'S MODULUS VERSUS FREQUENCY FOR HANOVER SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

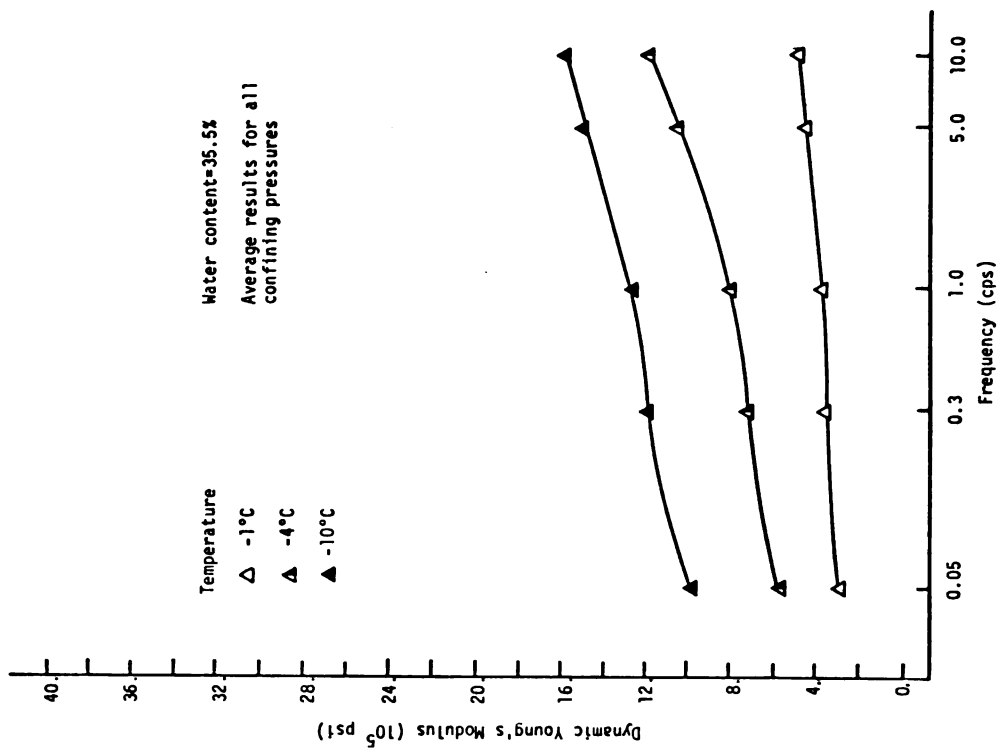


Figure 4.16 DYNAMIC YOUNG'S MODULUS VERSUS FREQUENCY FOR HANOVER SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

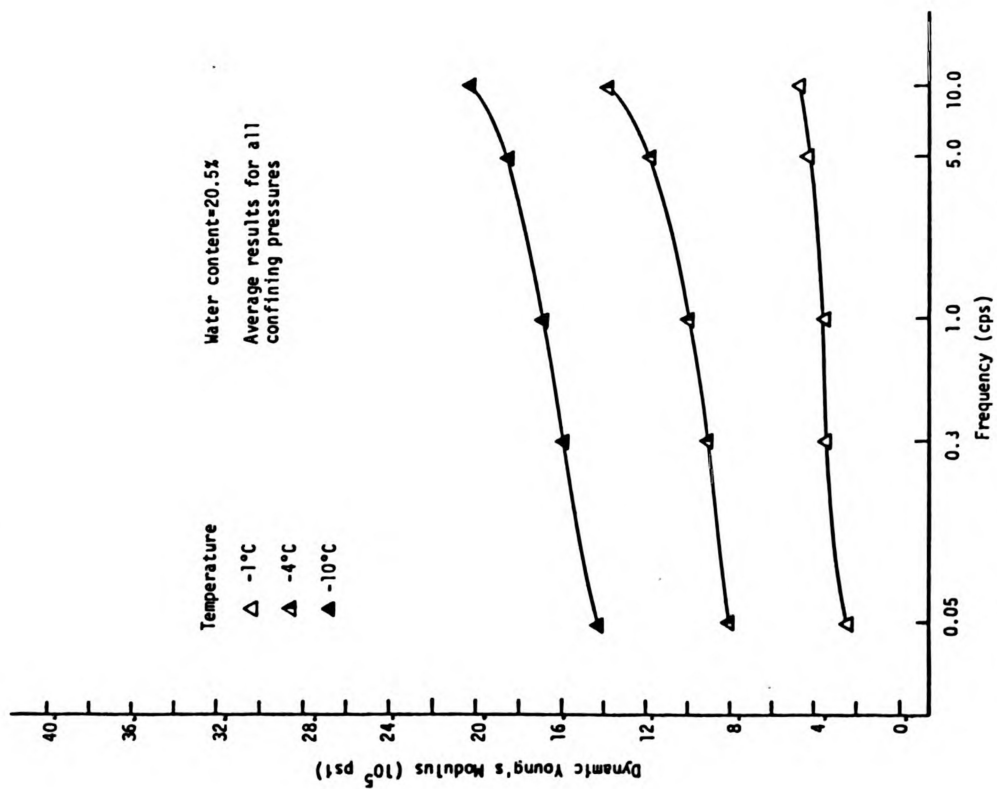


Figure 4.17 DYNAMIC YOUNG'S MODULUS VERSUS FREQUENCY FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

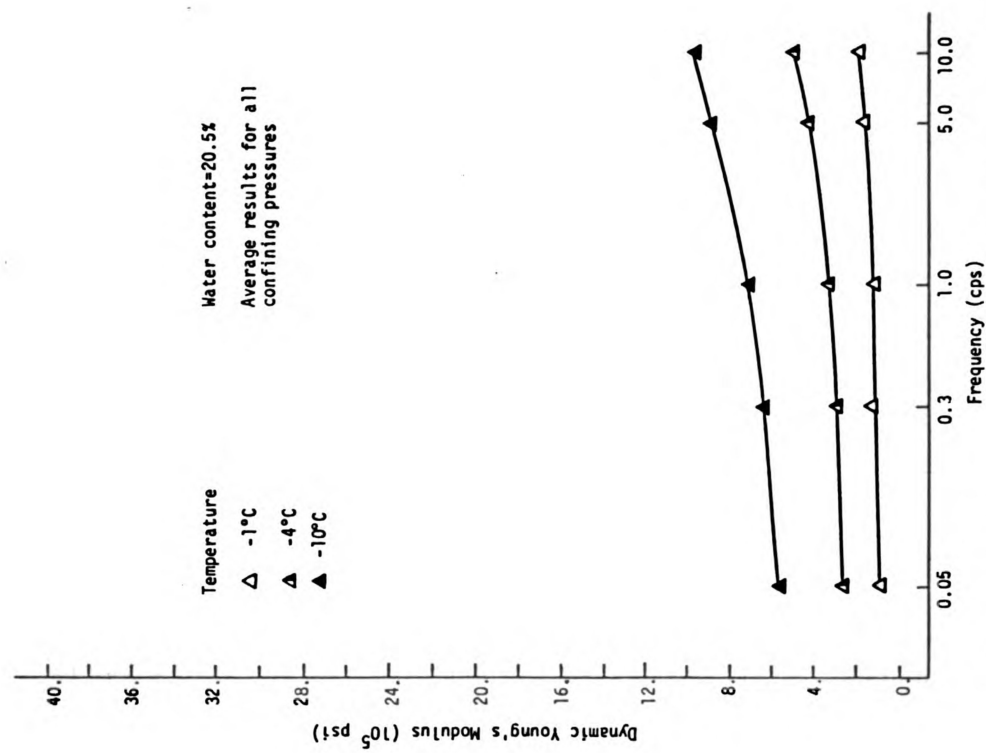


Figure 4.18 DYNAMIC YOUNG'S MODULUS VERSUS FREQUENCY FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

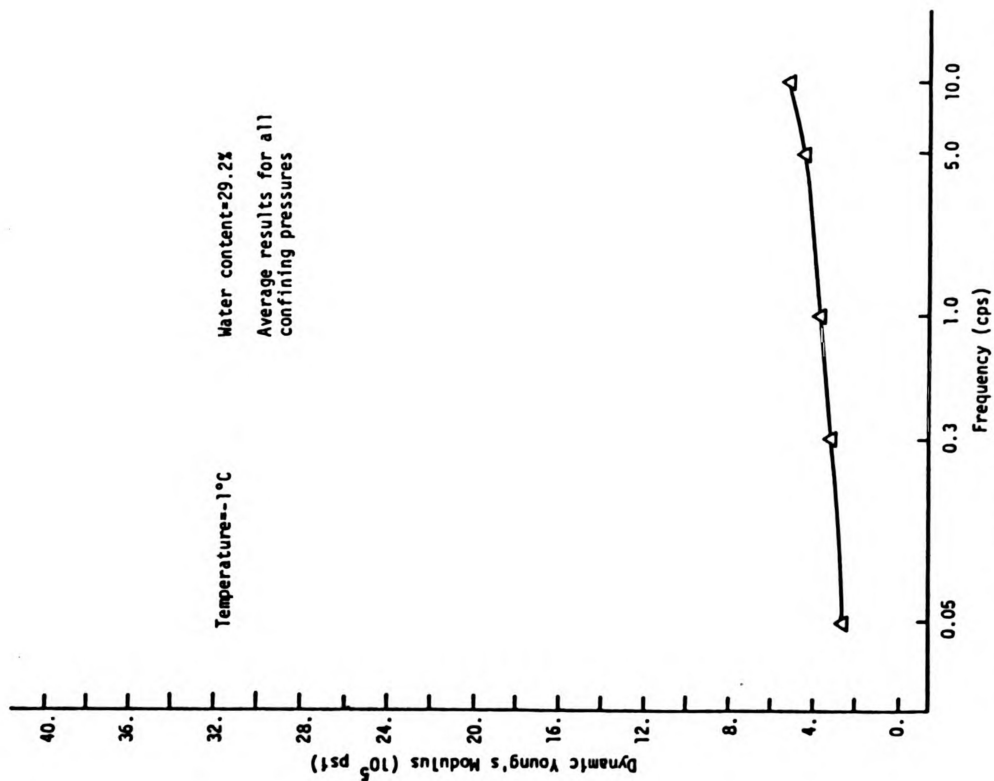


Figure 4.19 DYNAMIC YOUNG'S MODULUS VERSUS FREQUENCY FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

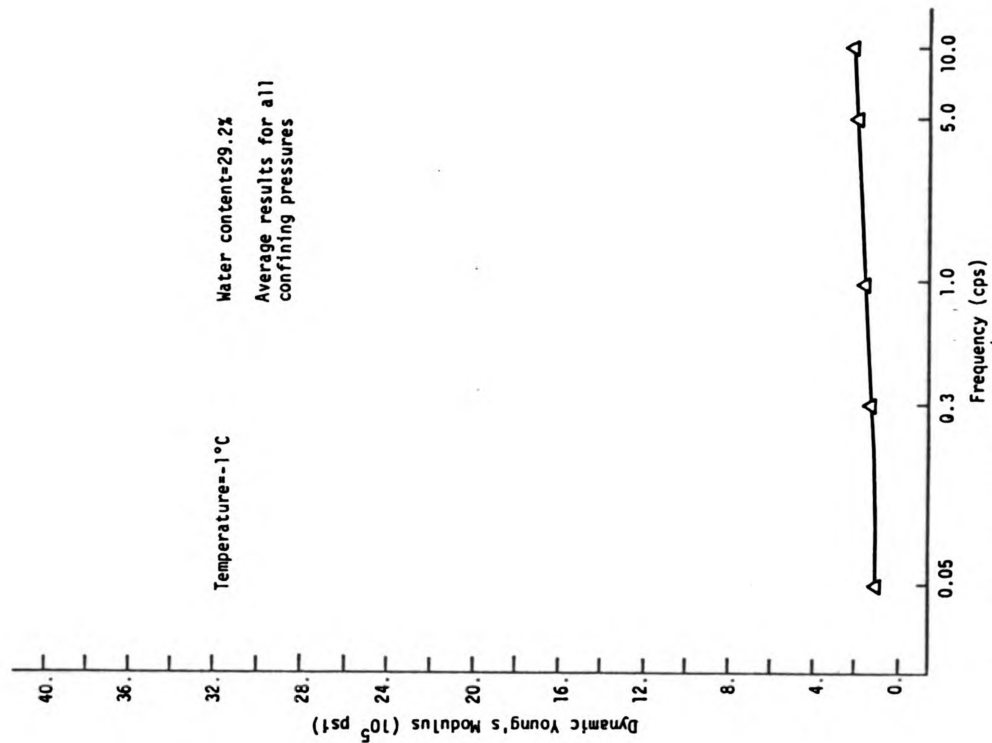


Figure 4.20 DYNAMIC YOUNG'S MODULUS VERSUS FREQUENCY FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

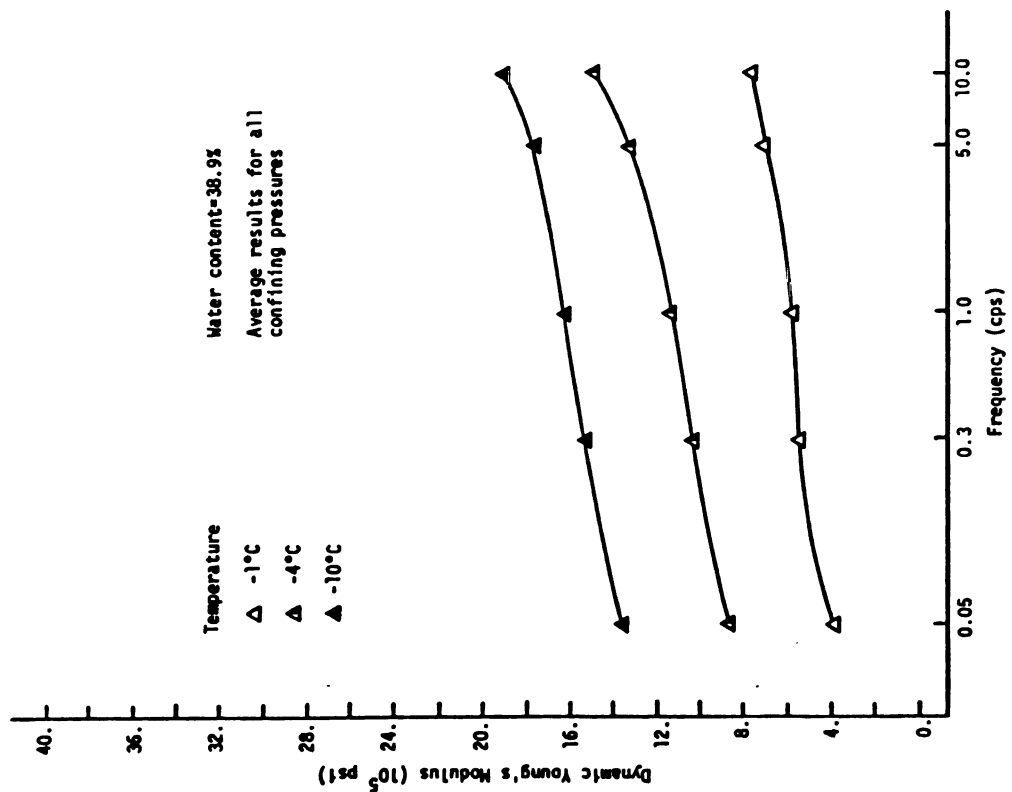


Figure 4.21 DYNAMIC YOUNG'S MODULUS VERSUS FREQUENCY FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

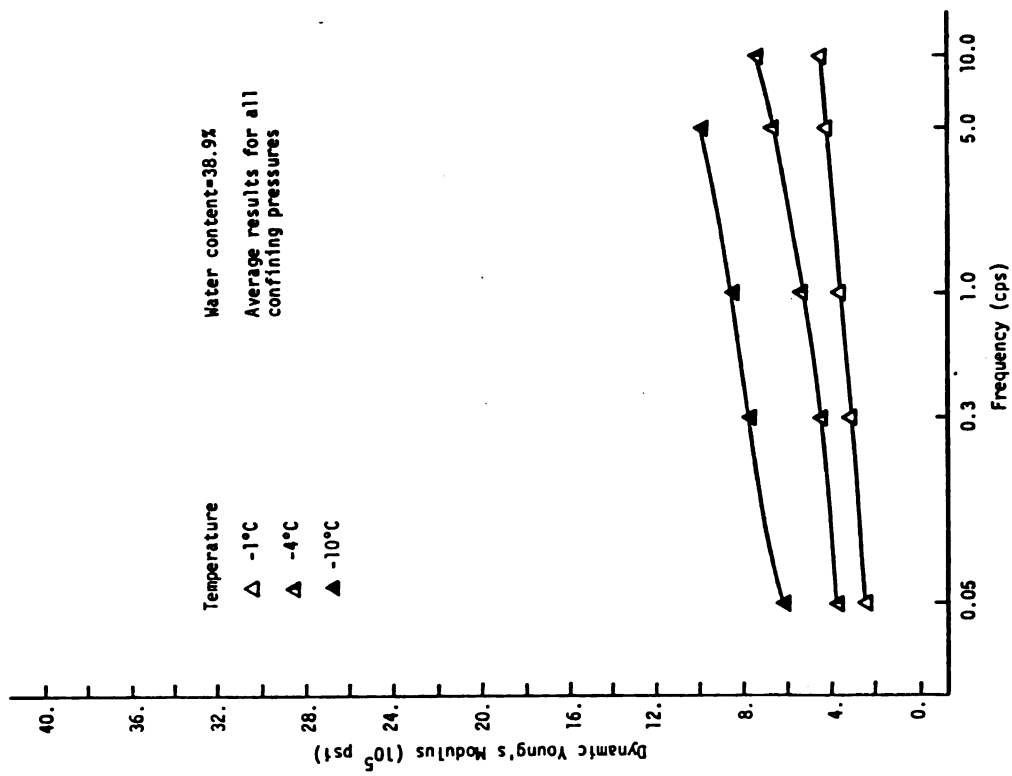


Figure 4.22 DYNAMIC YOUNG'S MODULUS VERSUS FREQUENCY FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

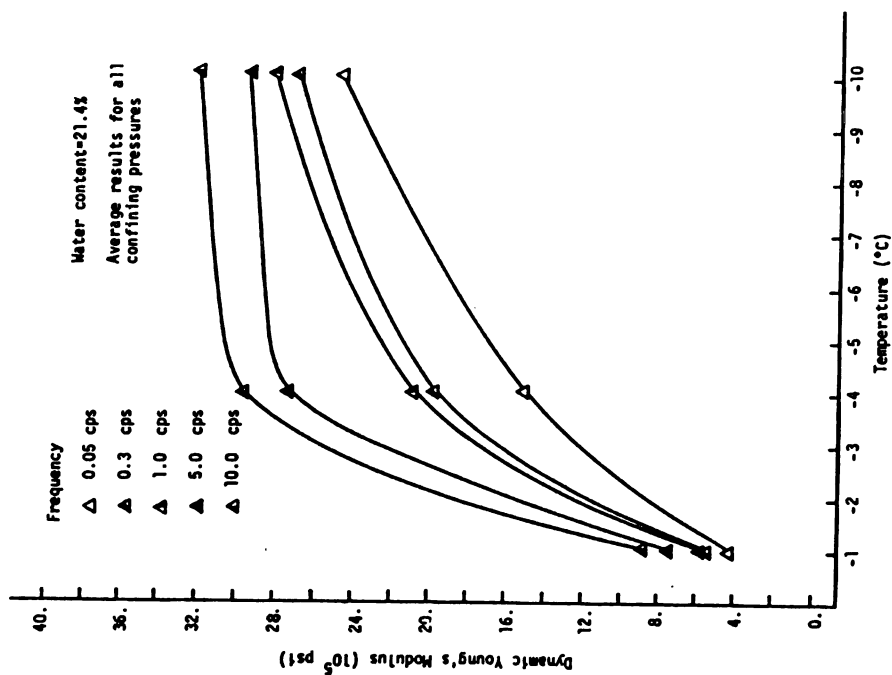


Figure 4.23 DYNAMIC YOUNG'S MODULUS VERSUS TEMPERATURE FOR HANOVER SILT AT AN AXIAL STRAIN OF 3.16×10^{-3}

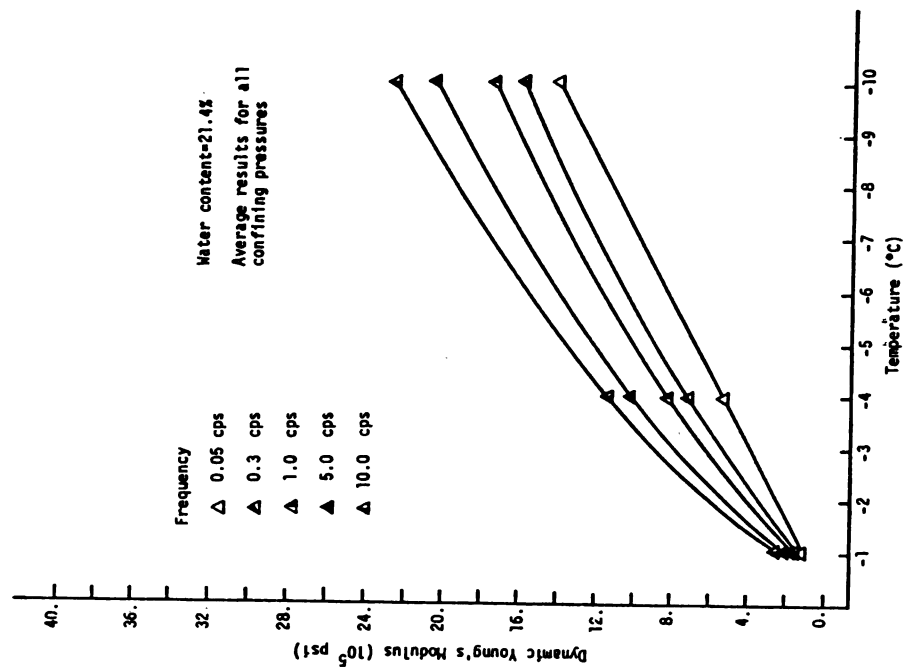


Figure 4.24 DYNAMIC YOUNG'S MODULUS VERSUS TEMPERATURE FOR HANOVER SILT AT AN AXIAL STRAIN OF 3.16×10^{-2}

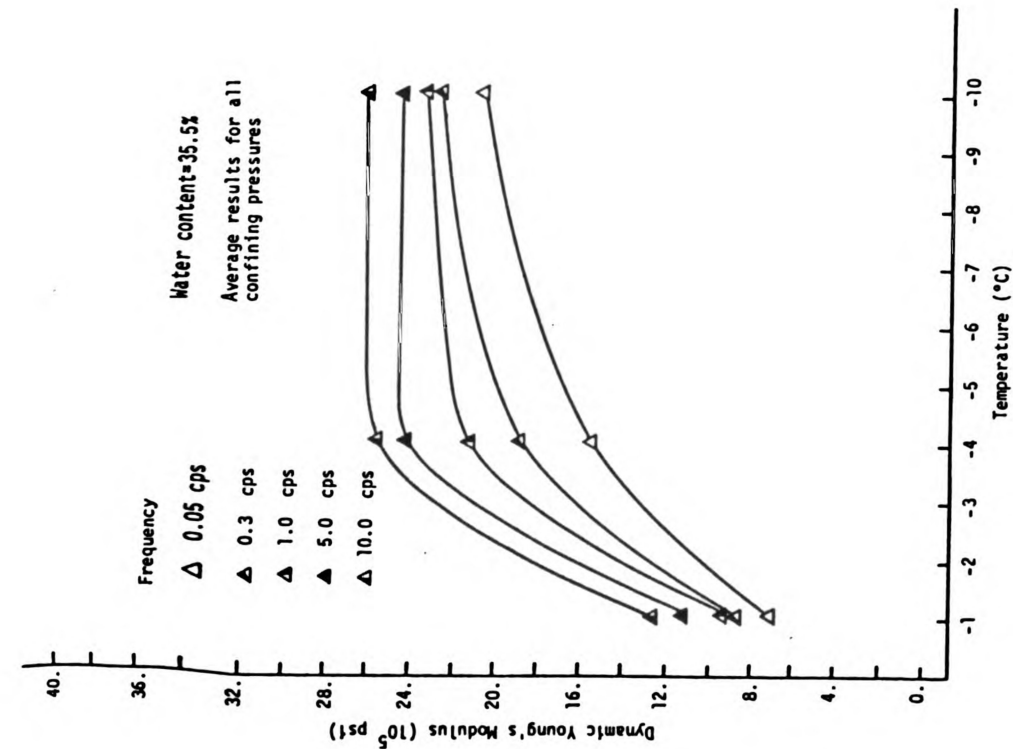


Figure 4.25 DYNAMIC YOUNG'S MODULUS VERSUS TEMPERATURE FOR HANOVER SILT AT AN AXIAL STRAIN OF 3.16×10^{-3}

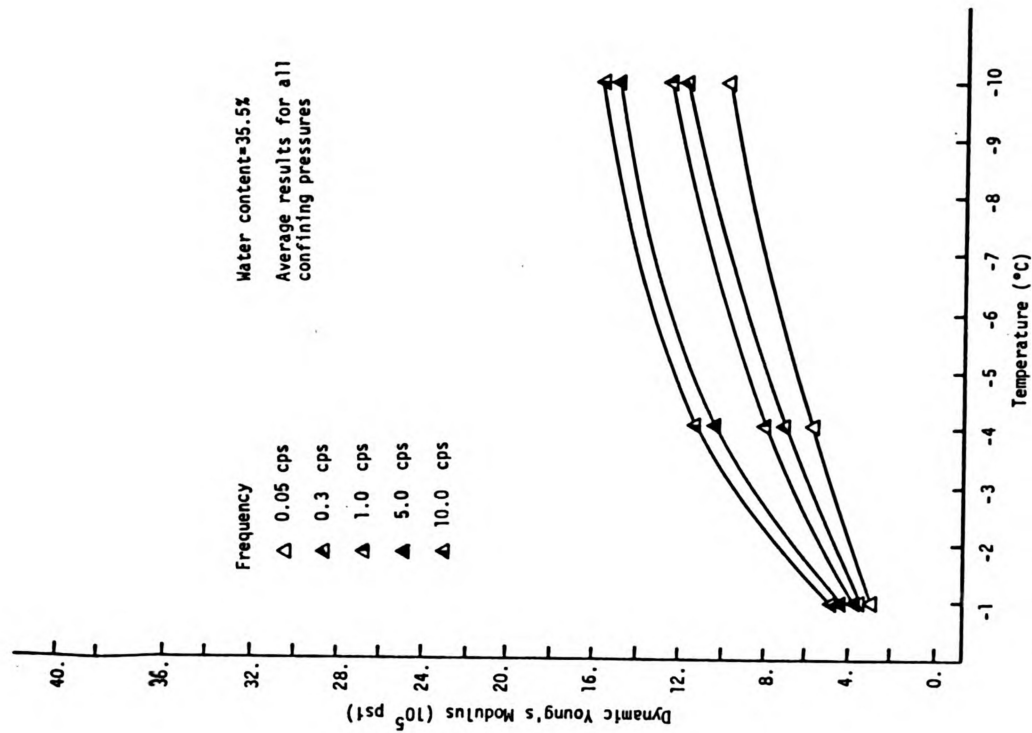


Figure 4.26 DYNAMIC YOUNG'S MODULUS VERSUS TEMPERATURE FOR HANOVER SILT AT AN AXIAL STRAIN OF 3.16×10^{-2}

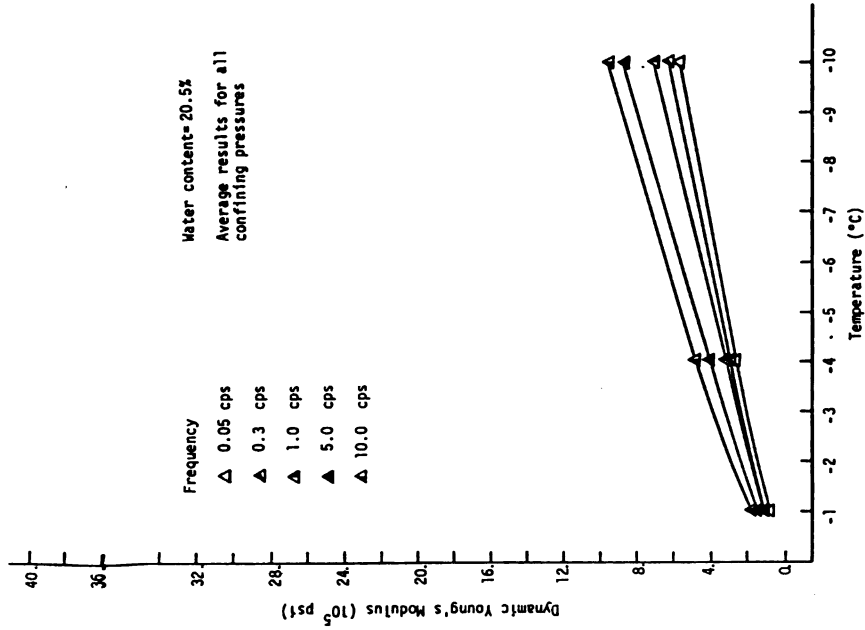


Figure 4.27 DYNAMIC YOUNG'S MODULUS VERSUS TEMPERATURE FOR ALASKA SILT
AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

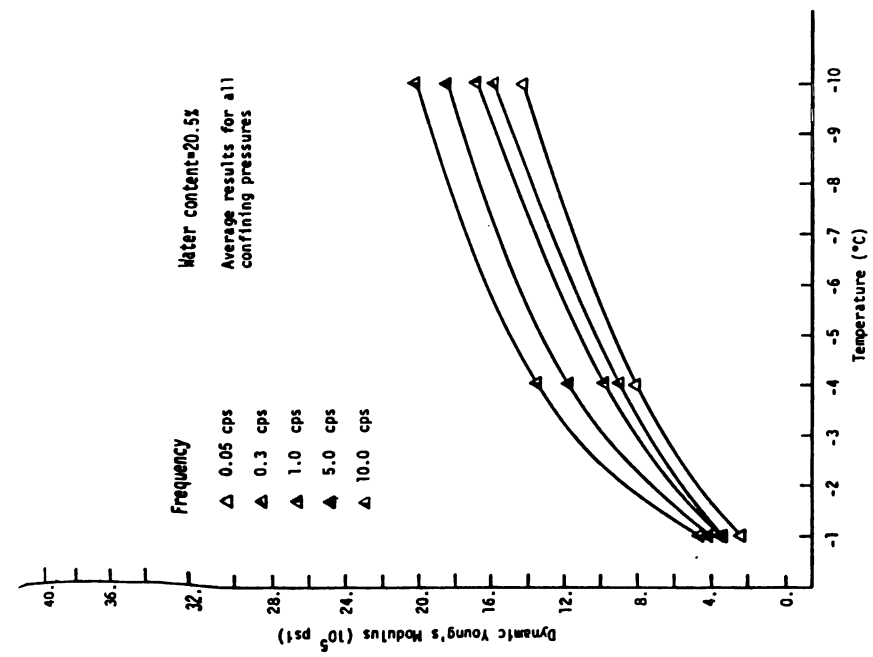


Figure 4.28 DYNAMIC YOUNG'S MODULUS VERSUS TEMPERATURE FOR ALASKA
SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

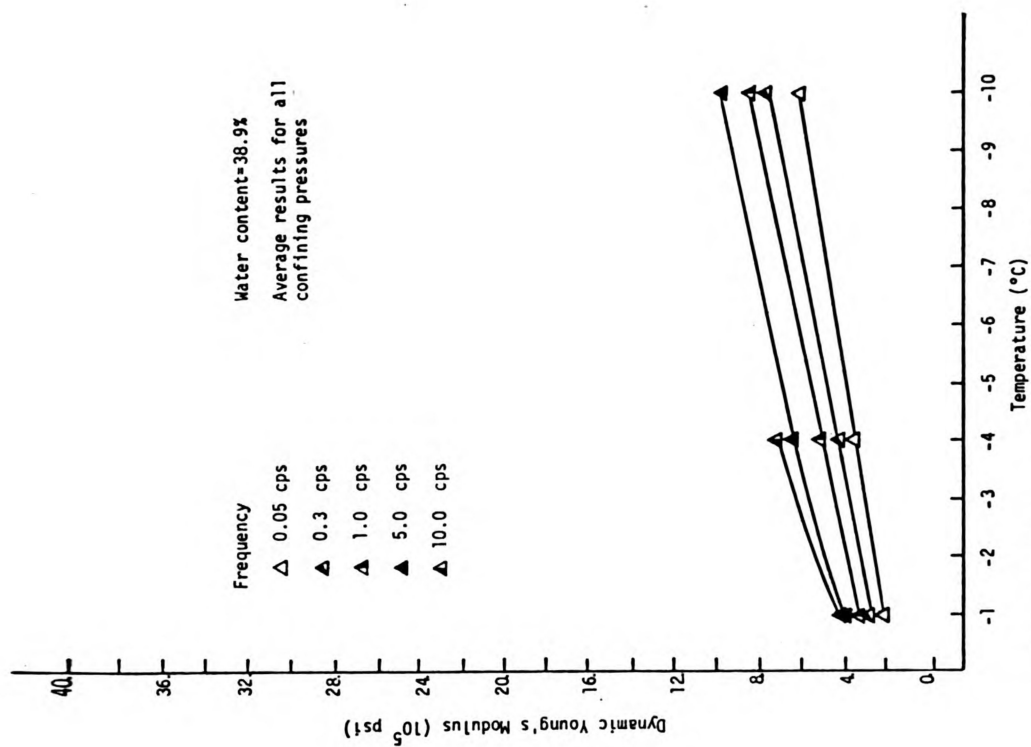


Figure 4.29 DYNAMIC YOUNG'S MODULUS VERSUS TEMPERATURE FOR ALASKA SILT
AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

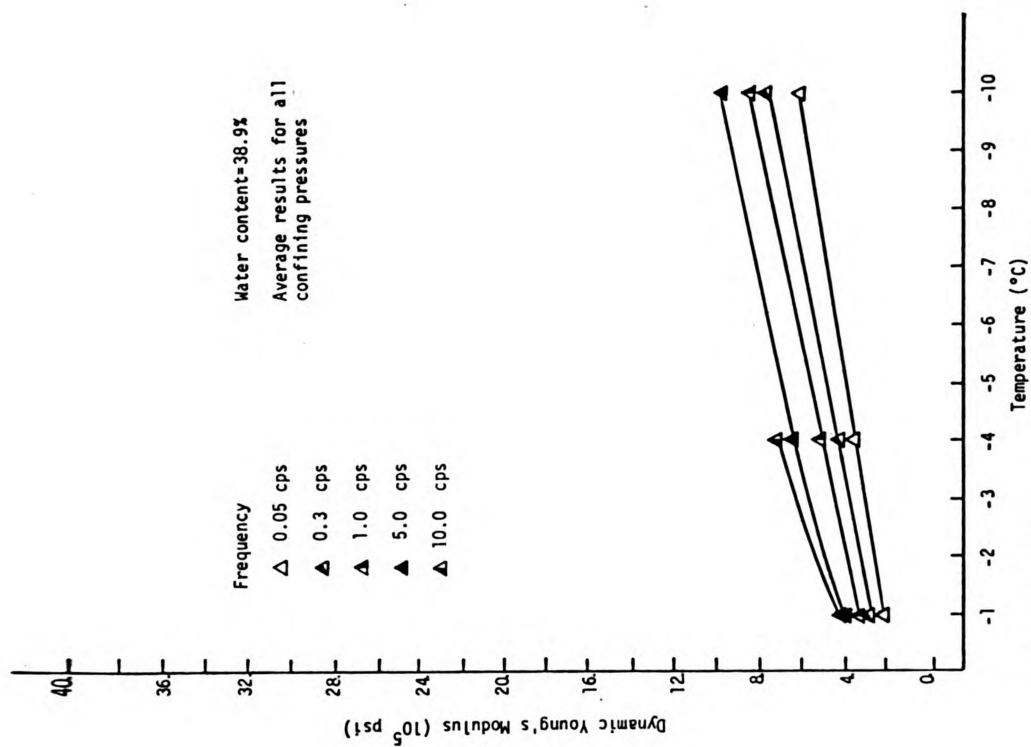


Figure 4.30 DYNAMIC YOUNG'S MODULUS VERSUS TEMPERATURE FOR ALASKA
SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

creasing temperature is generally more uniform over the entire range of temperatures (-1 to -10°C) at lower frequencies than at higher frequencies.

4.3.4 Effect of Water Content

The relationship between dynamic Young's modulus and water content is given in Figures 4.31 to 4.36. Each graph represents a silt at a given temperature at two strain amplitudes (3.16×10^{-3} and $3.16 \times 10^{-2}\%$) and five frequencies (0.05, 0.3, 1.0, 5.0, and 10.0 cps). Each relationship shown is based on only two points with the exception of the relationship for Alaska silt at -1°C (Figure 4.34) which is based on three points. At a temperature of -1°C, dynamic Young's modulus increases by a moderate amount as the water content increases (from 21.4 to 35.5% for Hanover silt and from 20.5 to 38.9% for Alaska silt) for both strain amplitudes (3.16×10^{-3} and $3.16 \times 10^{-2}\%$); this relationship does not appear to be affected by frequency. In the case of Alaska silt, most of the increase in dynamic Young's modulus with water content occurs in the higher water content range (29.2 to 38.9%).

At lower temperatures (-4 and -10°C) there appears to be little or no significant influence of water content on dynamic Young's modulus at a higher strain amplitude ($3.16 \times 10^{-2}\%$). At a lower strain amplitude ($3.16 \times 10^{-3}\%$) the relationship between dynamic Young's modulus and water content is not clear. In the case of Hanover silt, dynamic Young's modulus decreases by a small amount as the water content increases at both -4 and -10°C; in the case of Alaska silt, dynamic Young's modulus appears to increase by a small amount at -4°C and decrease by a small amount at -10°C as the water

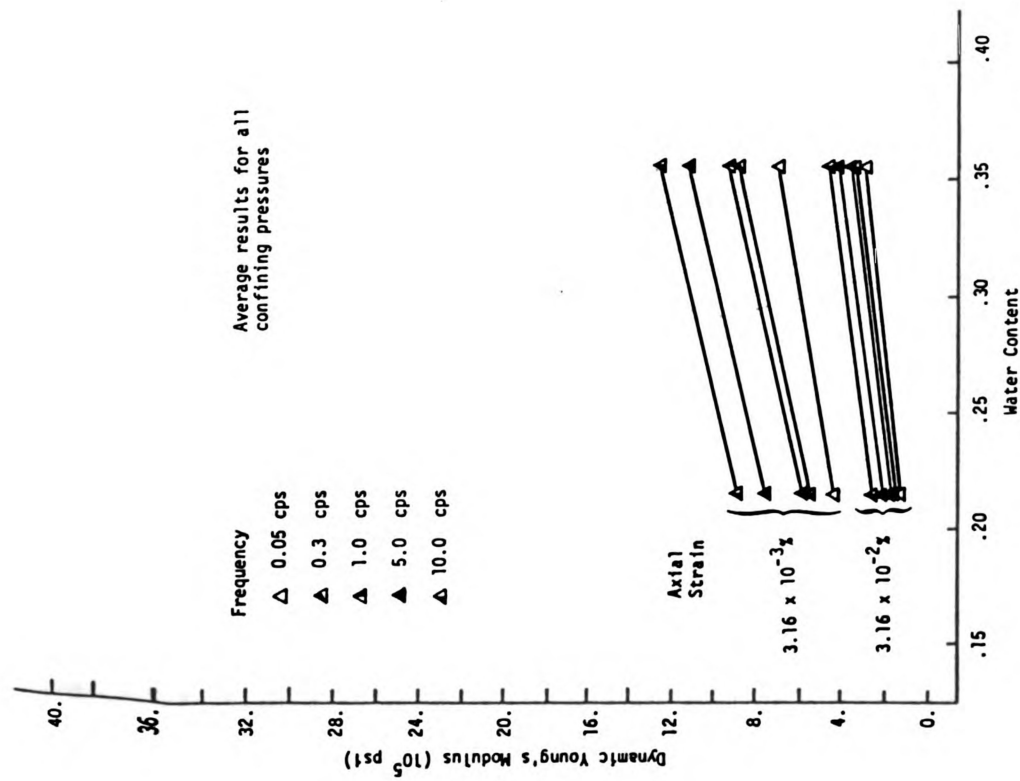


Figure 4.31 DYNAMIC YOUNG'S MODULUS VERSUS WATER CONTENT FOR HANOVER SILT AT A TEMPERATURE OF -1°C

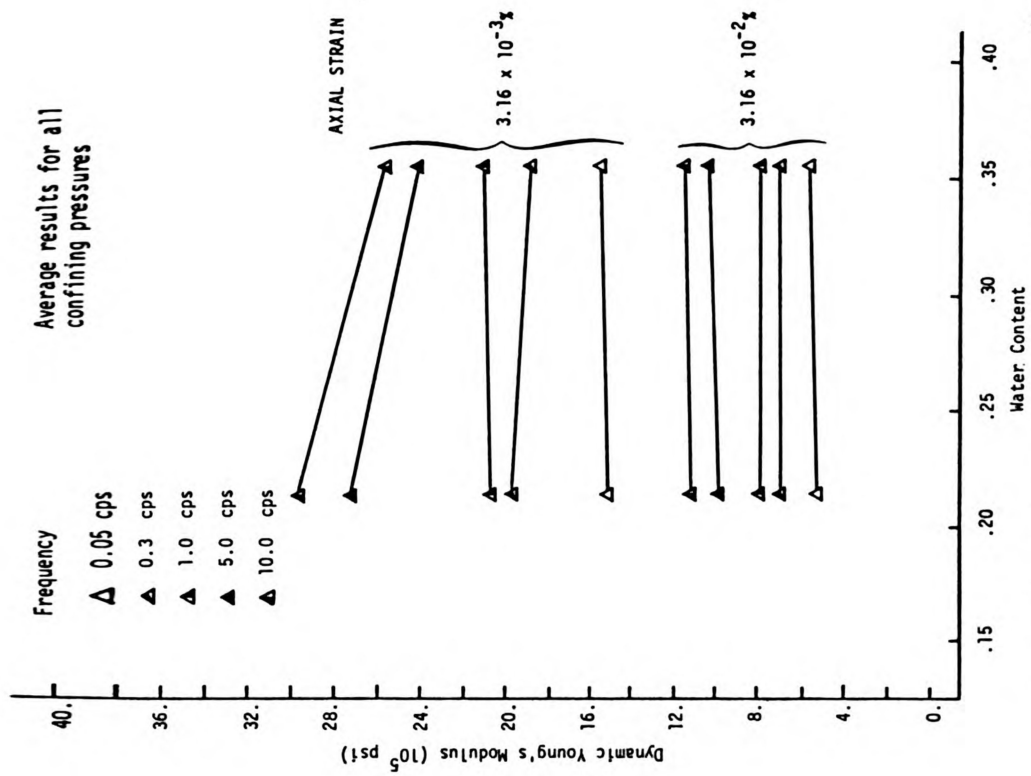


Figure 4.32 DYNAMIC YOUNG'S MODULUS VERSUS WATER CONTENT FOR HANOVER SILT AT A TEMPERATURE OF -4°C

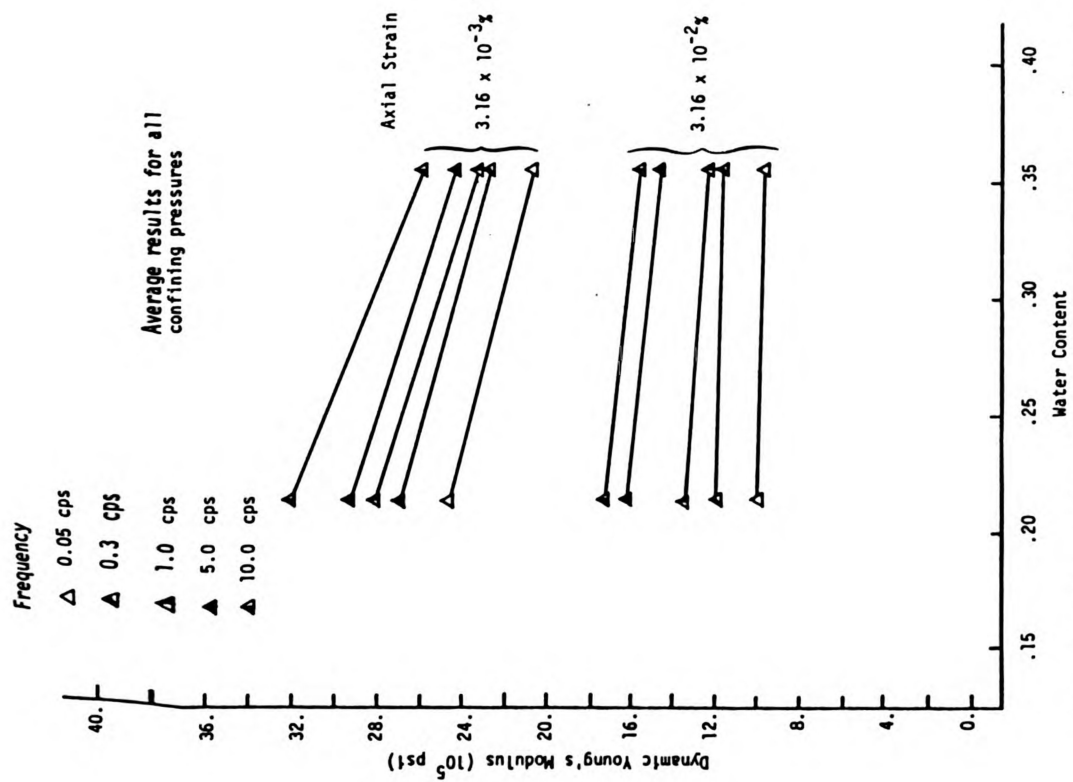


Figure 4.33 DYNAMIC YOUNG'S MODULUS VERSUS WATER CONTENT FOR HANOVER SILT AT A TEMPERATURE OF -10°C

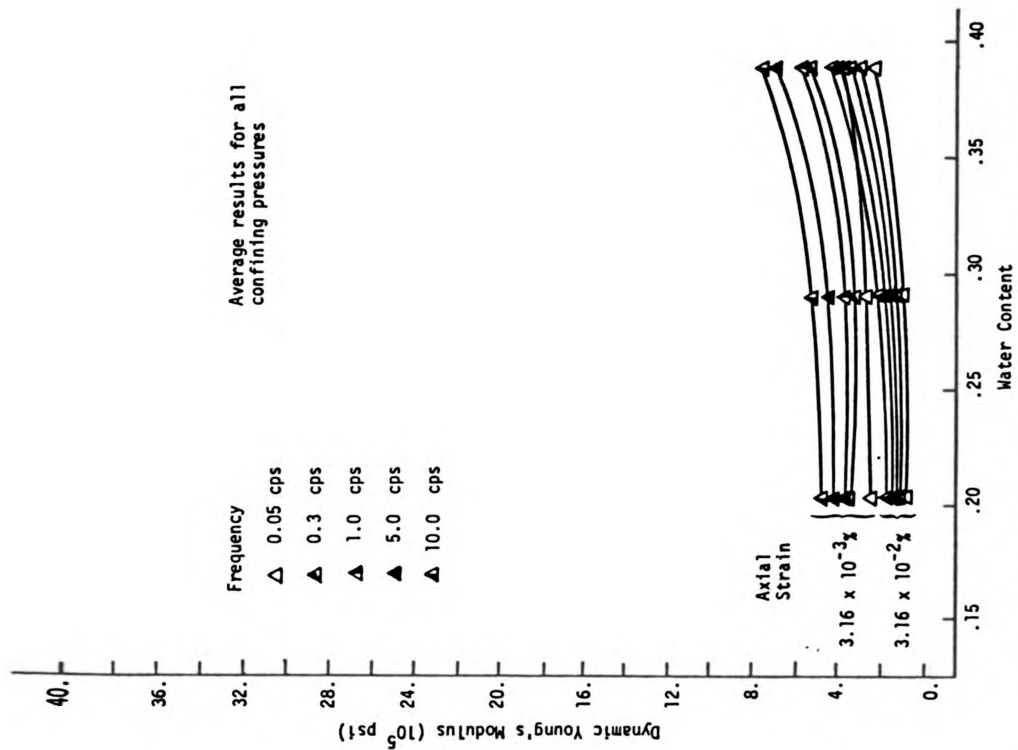


Figure 4.34 DYNAMIC YOUNG'S MODULUS VERSUS WATER CONTENT FOR ALASKA SILT AT A TEMPERATURE OF -1°C

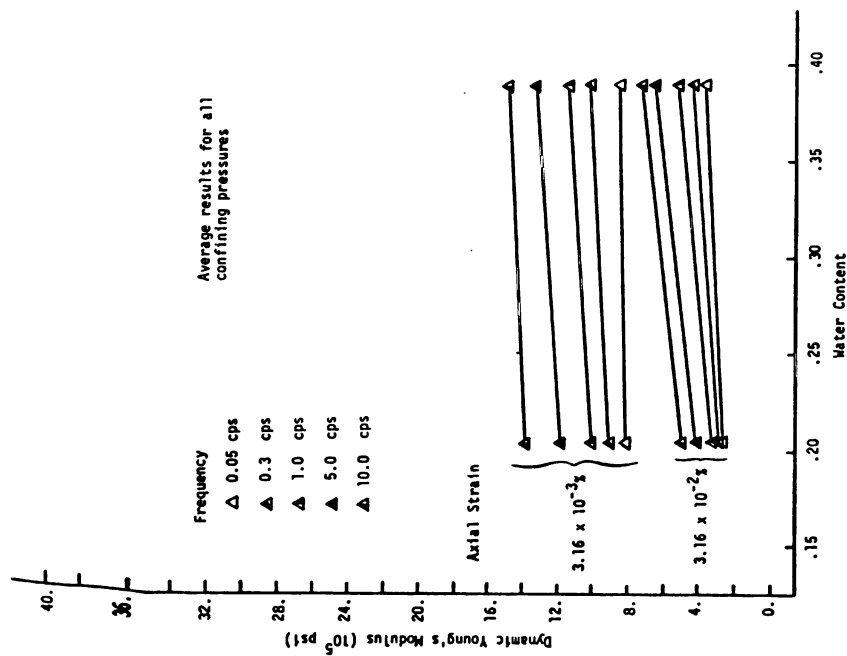


Figure 4.35 DYNAMIC YOUNG'S MODULUS VERSUS WATER CONTENT FOR ALASKA SILT AT A TEMPERATURE OF -4°C

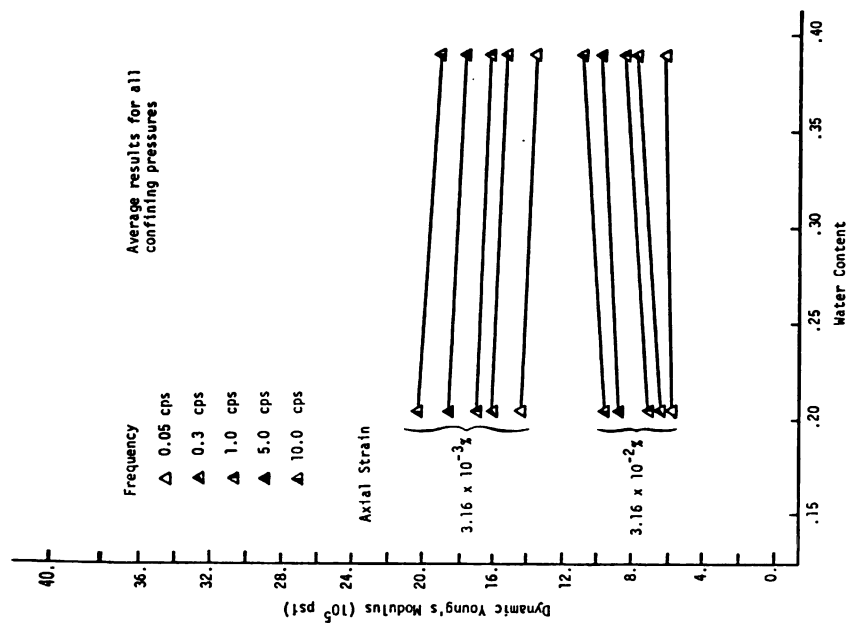


Figure 4.36 DYNAMIC YOUNG'S MODULUS VERSUS WATER CONTENT FOR ALASKA SILT AT A TEMPERATURE OF -10°C

content increases.

The influence of temperature on the relationship between dynamic Young's modulus and water content may be a function of the unfrozen water content of the silt. At a low temperature (-10°C) where the influence of unfrozen water content is small, dynamic Young's modulus tends to decrease with increasing water content. At higher temperatures where the unfrozen water content is greater, dynamic Young's modulus increases with increasing water content; this may be due to the relatively larger proportion of water in the form of ice in the higher water content samples than in the lower water content samples.

4.4 Damping Ratio of Frozen Silt

Values of damping ratio were plotted against the log of axial strain amplitude expressed as a percent for all loading conditions. Plots for both silts at all water contents are given in Appendix B. Each plot represents data points for a silt at a particular water content, temperature, and frequency. Data points for all three confining pressures (0, 50, and 200 psi) are included in each plot. Each plot represents at least two samples; in general, there is good agreement between data points from duplicate samples. At very low strains, the scatter of the data points is due to the influence of background "noise" during testing, which results in difficulty in accurately measuring damping from the single hysteresis loop recorded for each loading condition. The scatter of data at the high water contents is due to the lack of uniformity and the difficulty in reproducing the high water content samples.

4.4.1 Effect of Strain Amplitude

To determine the influence of strain amplitude on damping ratio, a "best fit" line was drawn through the data points given in the plots in Appendix B. The relationship between damping ratio and strain amplitude is summarized in Figures 4.37 to 4.58. Each graph represents a silt at a given loading frequency at each of three temperatures (-1, -4, and -10°C). In cases where damping ratio was influenced by confining pressure, a separate curve was drawn for each confining pressure.

In general, damping ratio increases as strain amplitude increases. At a temperature of -1°C, the rate of increase is moderate at low frequencies and somewhat greater at higher frequencies for low water contents. For higher water contents, the rate of increase is moderate at all frequencies. At lower temperatures (-4 and -10°C) damping increases significantly with increasing strain amplitude at low frequencies. At high frequencies, damping ratio increases by a smaller amount and in some cases decreases by a small amount with increasing strain amplitude. In some instances, the relationship becomes U-shaped with a slight decrease in damping followed by an increase with increasing strain amplitude.

To assess the influence of confining pressure, frequency, temperature, and water content on damping ratio, values of damping ratio were obtained from Figures 4.37 to 4.58 and Appendix B at axial strain amplitudes of $3.16 \times 10^{-3}\%$ (log axial strain = -2.50) and $3.16 \times 10^{-2}\%$ (log axial strain = -1.50). The damping ratio values were then plotted versus confining pressure, frequency, temperature, and water content.

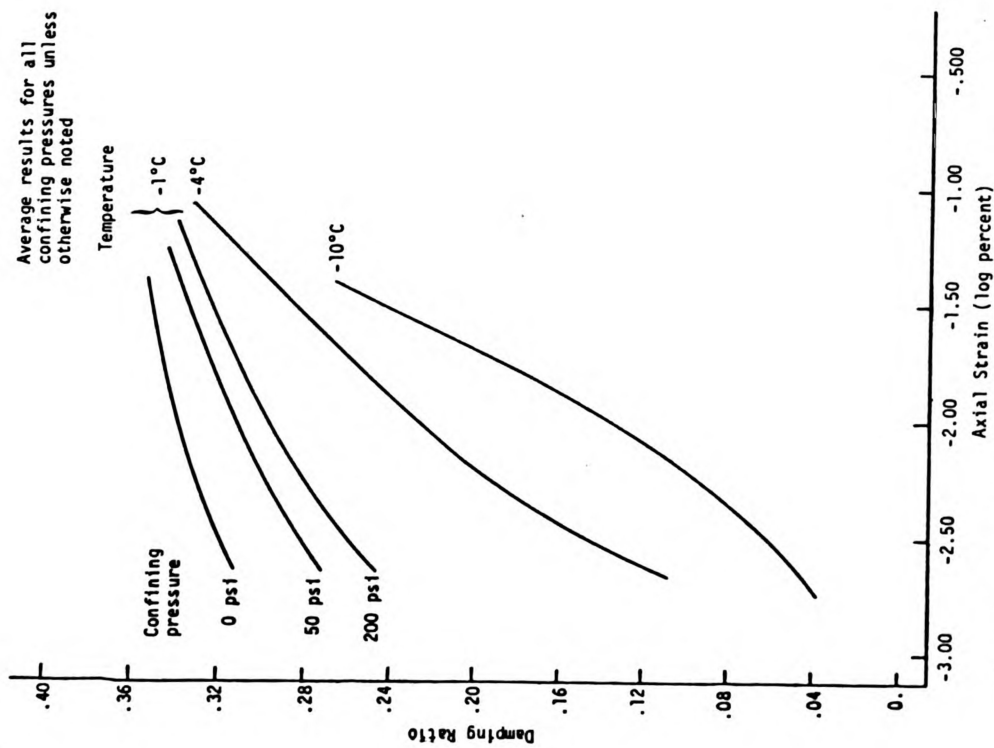


Figure 4.37 DAMPING RATIO VERSUS AXIAL STRAIN FOR HANOVER SILT AT 0.05cps FREQUENCY AND 21.4% WATER CONTENT

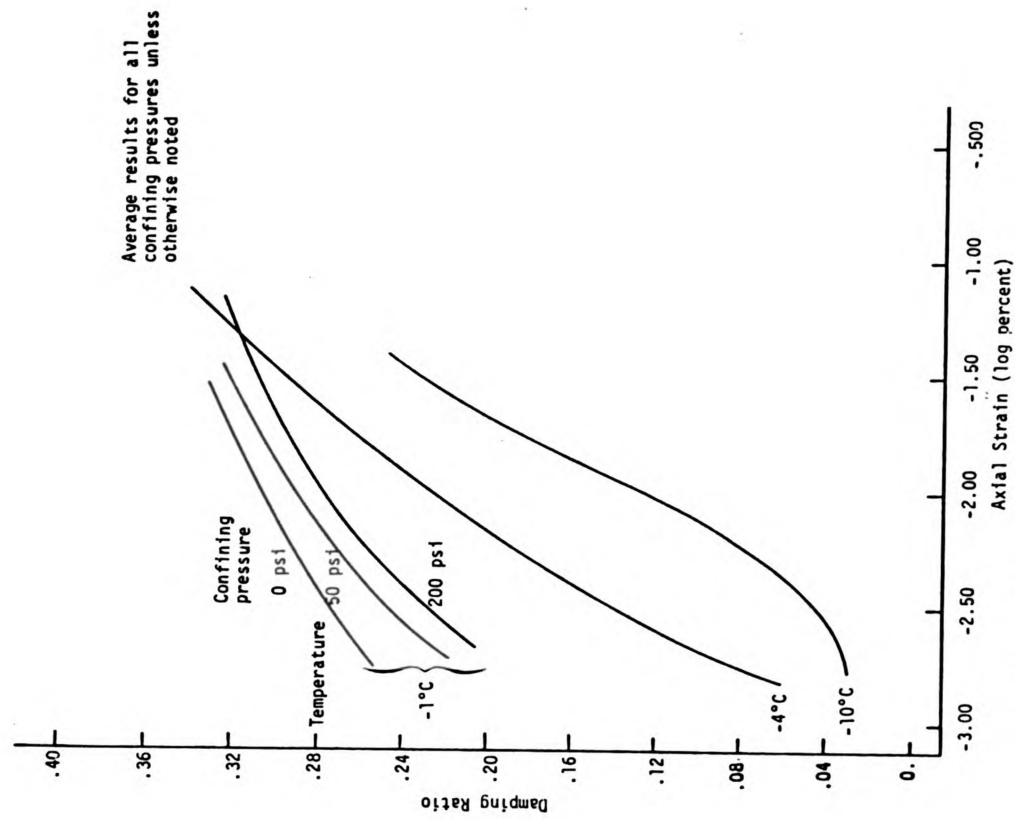


Figure 4.38 DAMPING RATIO VERSUS AXIAL STRAIN FOR HANOVER SILT AT 0.3 cps FREQUENCY AND 21.4% WATER CONTENT

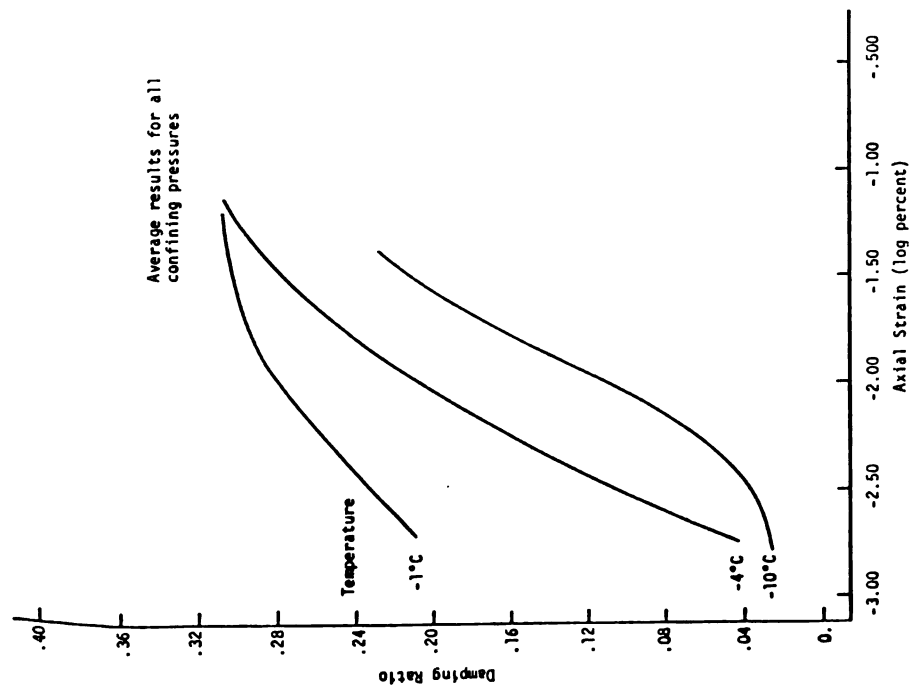


Figure 4.39 DAMPING RATIO VERSUS AXIAL STRAIN FOR HANOVER SILT AT 1.0 cps FREQUENCY AND 21.4% WATER CONTENT

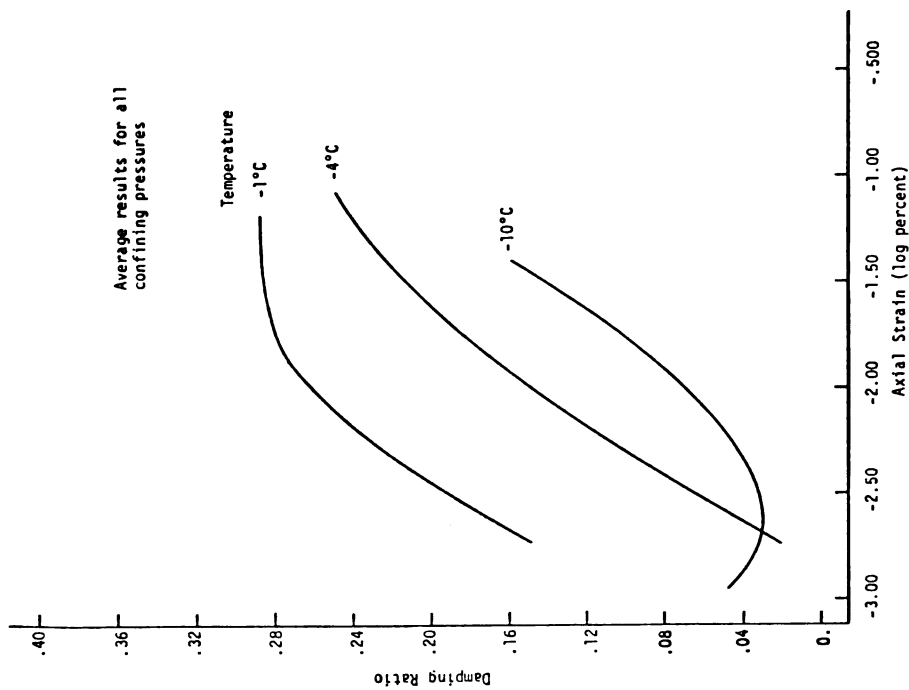


Figure 4.40 DAMPING RATIO VERSUS AXIAL STRAIN FOR HANOVER SILT AT 5.0 cps FREQUENCY AND 21.4% WATER CONTENT

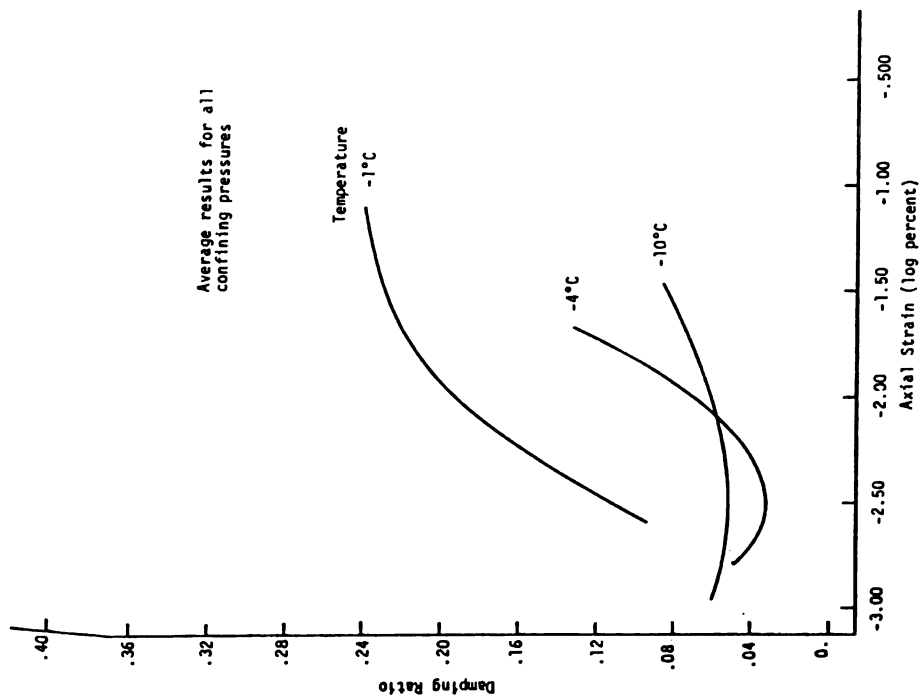


Figure 4.41 DAMPING RATIO VERSUS AXIAL STRAIN FOR HANOVER SILT AT 10.3 cps FREQUENCY AND 21.4% WATER CONTENT

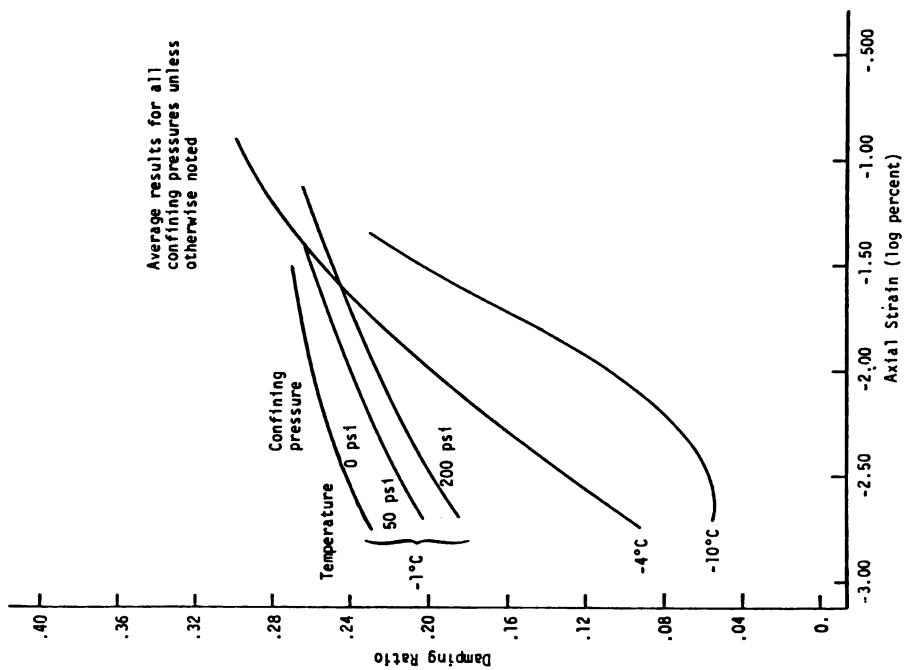
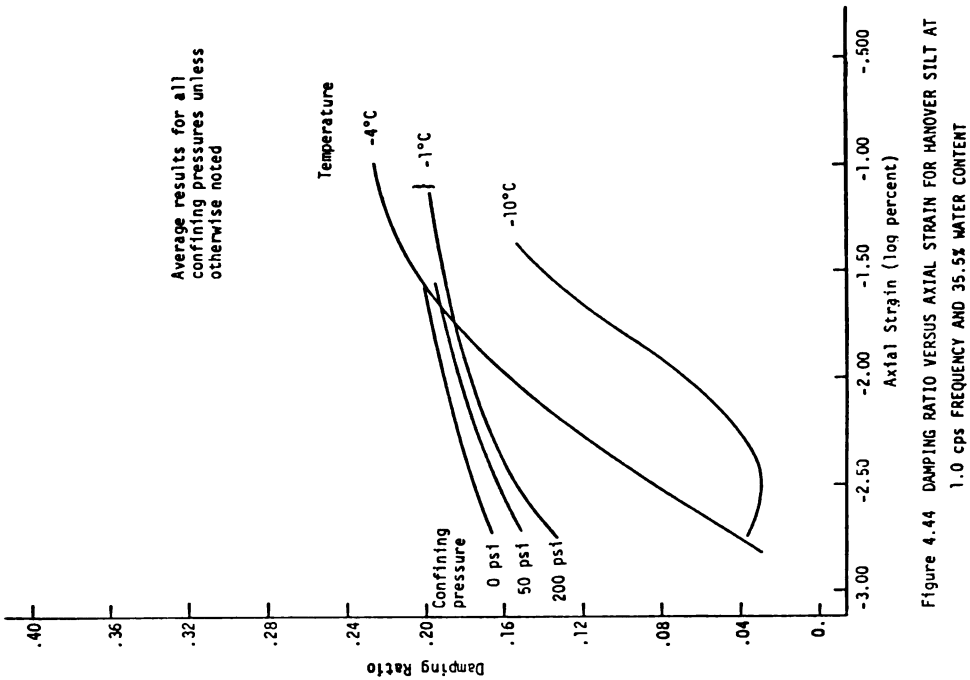
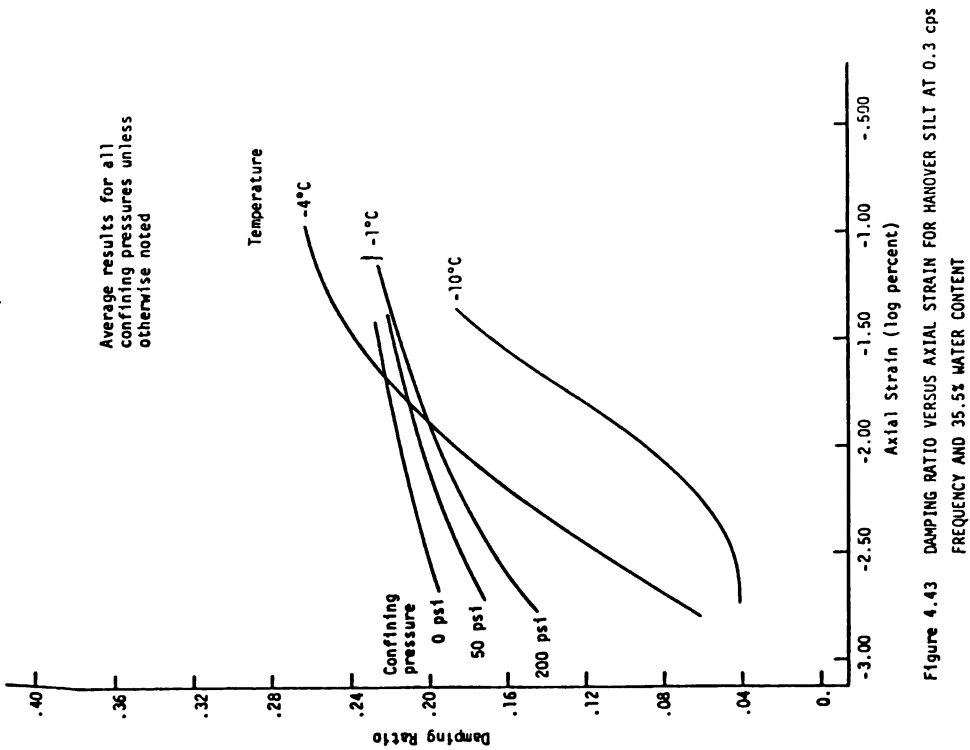


Figure 4.42 DAMPING RATIO VERSUS AXIAL STRAIN FOR HANOVER SILT AT 0.05 cps FREQUENCY AND 35.5% WATER CONTENT

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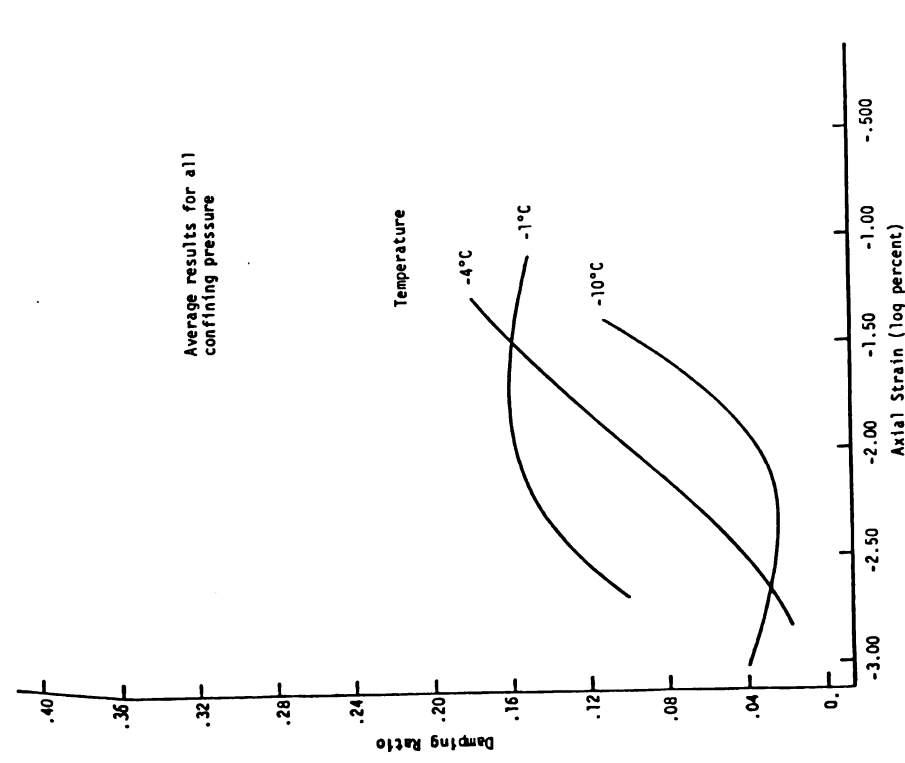


Figure 4.45 DAMPING RATIO VERSUS AXIAL STRAIN FOR HANOVER SILT AT 5.0 cps FREQUENCY AND 35.5% WATER CONTENT

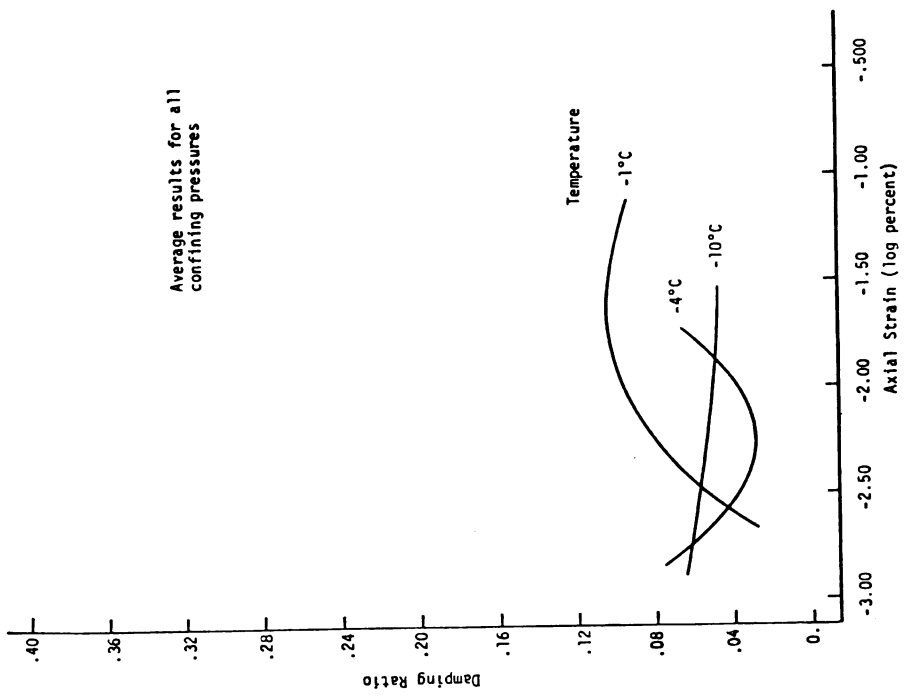


Figure 4.46 DAMPING RATIO VERSUS AXIAL STRAIN FOR HANOVER SILT AT 10.0 cps FREQUENCY AND 35.5% WATER CONTENT

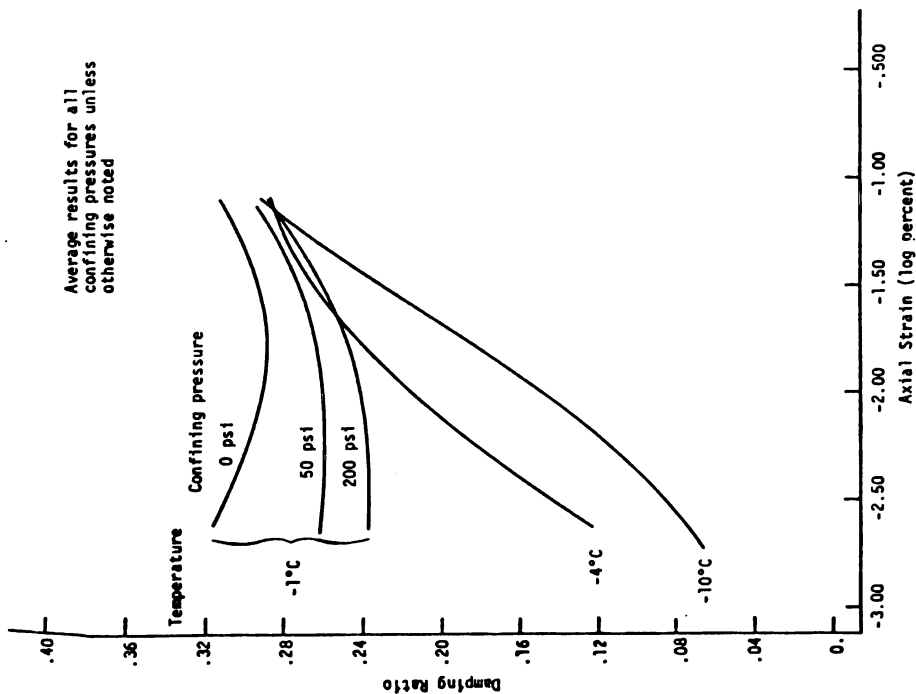


Figure 4.47 DAMPING RATIO VERSUS AXIAL STRAIN FOR ALASKA SILT AT 0.05 cps
FREQUENCY AND 20.5% WATER CONTENT

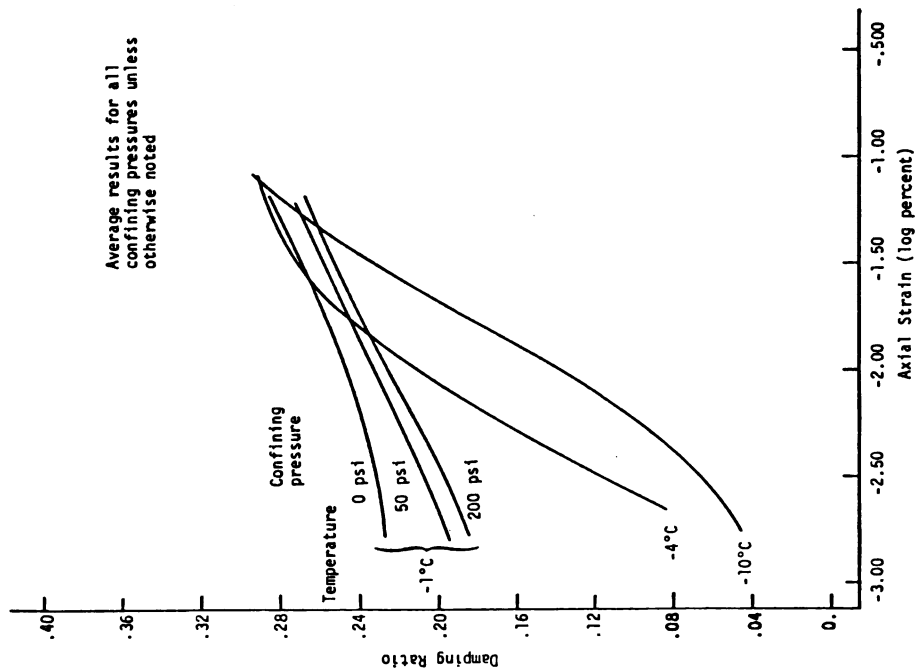


Figure 4.48 DAMPING RATIO VERSUS AXIAL STRAIN FOR ALASKA SILT AT
0.3 cps FREQUENCY AND 20.5% WATER CONTENT

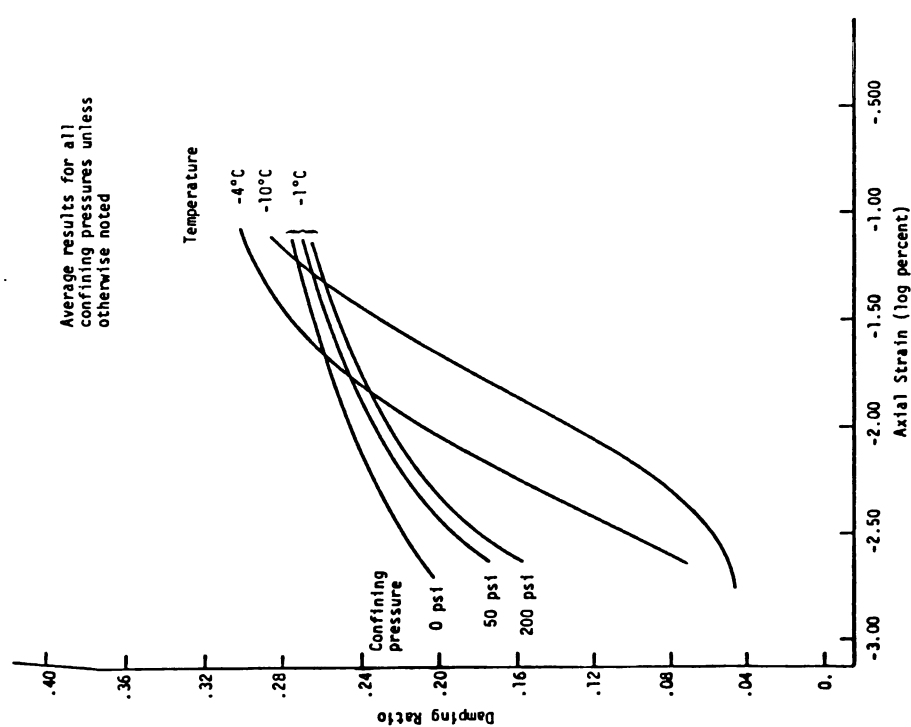


Figure 4.49 DAMPING RATIO VERSUS AXIAL STRAIN FOR ALASKA SILT AT 1.0 cps FREQUENCY AND 20.5% WATER CONTENT

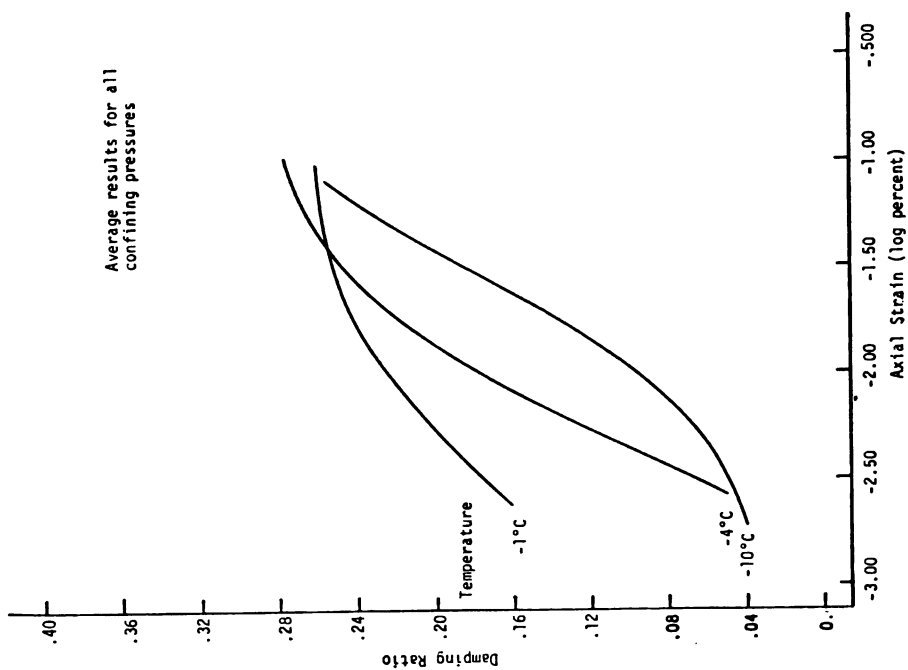


Figure 4.50 DAMPING RATIO VERSUS AXIAL STRAIN FOR ALASKA SILT AT 5.0 cps FREQUENCY AND 20.5% WATER CONTENT

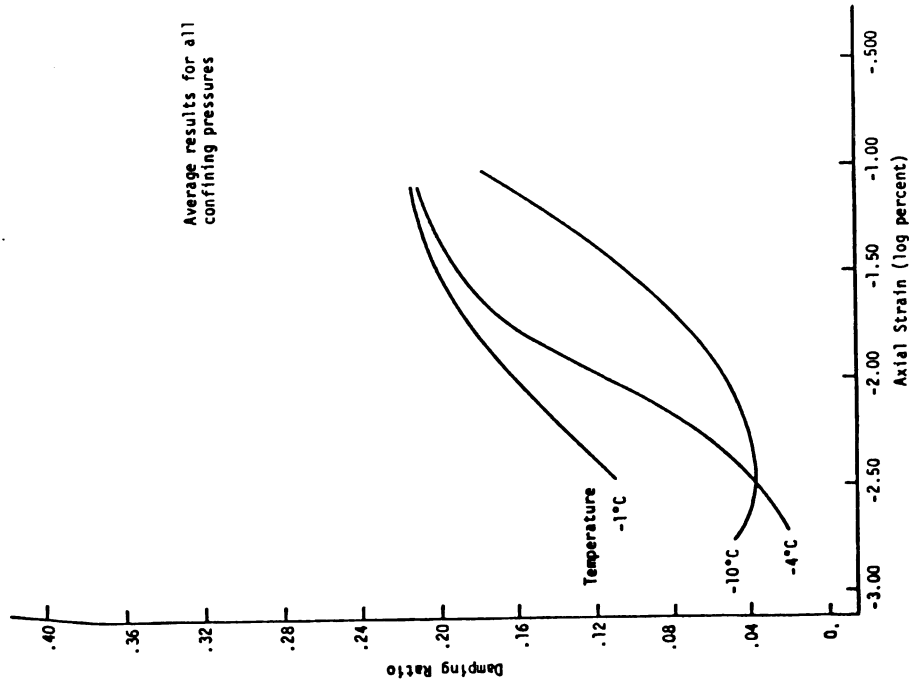


Figure 4.51 DAMPING RATIO VERSUS AXIAL STRAIN FOR ALASKA SILT AT 10.0 cps FREQUENCY AND 20.5% WATER CONTENT

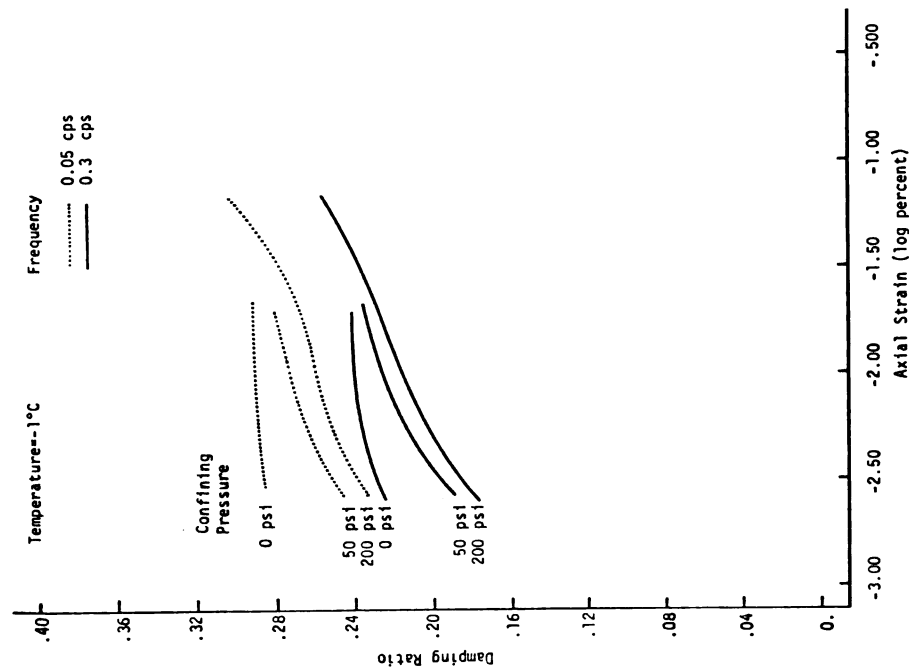


Figure 4.52 DAMPING RATIO VERSUS AXIAL STRAIN FOR ALASKA SILT AT 29.2% WATER CONTENT

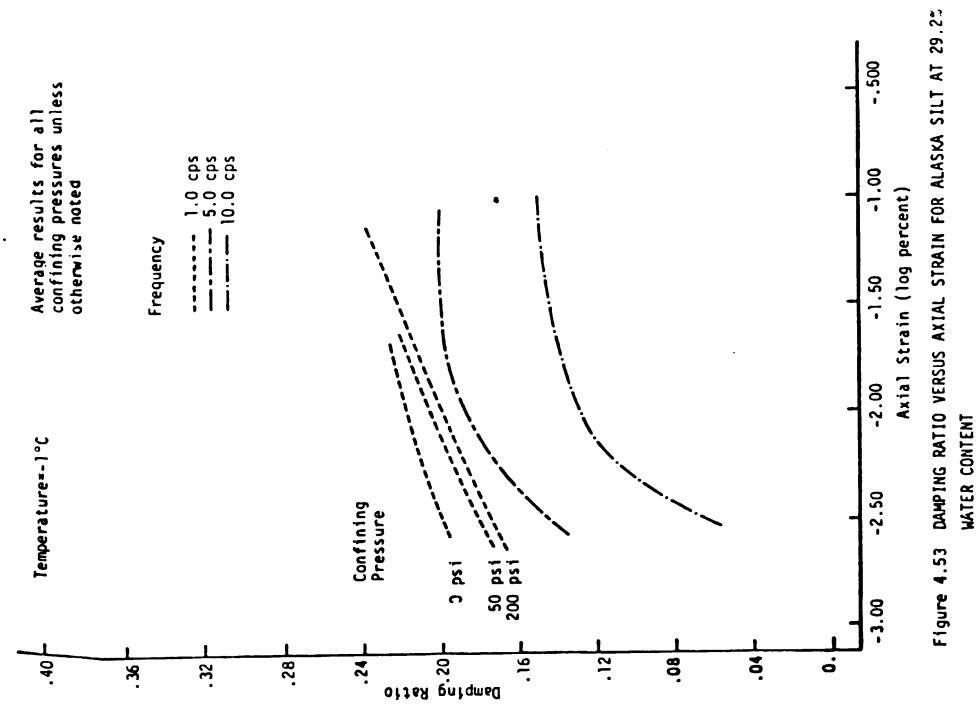


Figure 4.53 DAMPING RATIO VERSUS AXIAL STRAIN FOR ALASKA SILT AT 29.2% WATER CONTENT

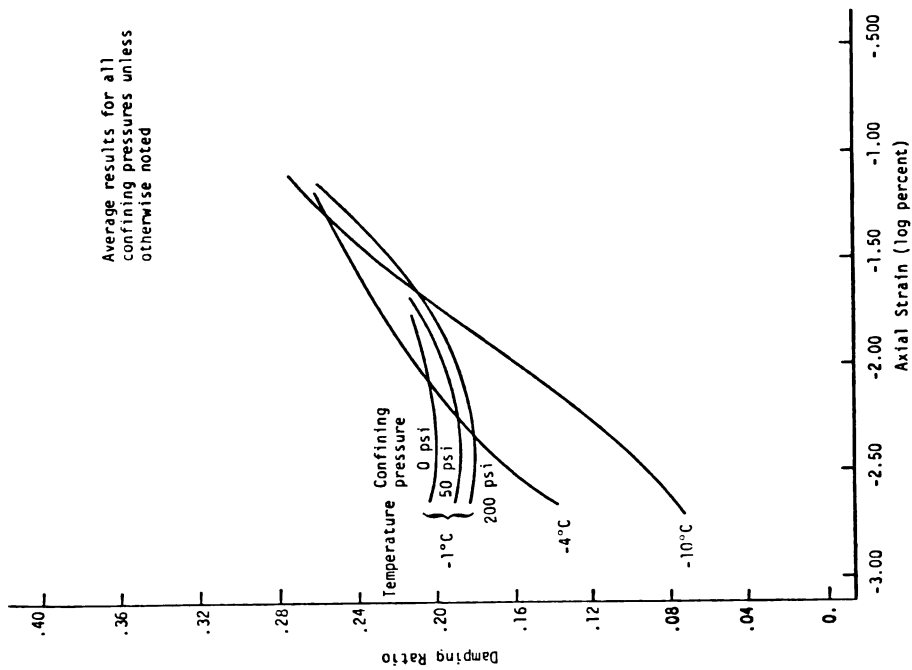


Figure 4.54 DAMPING RATIO VERSUS AXIAL STRAIN FOR ALASKA SILT AT 0.05 cps FREQUENCY AND 38.9% WATER CONTENT

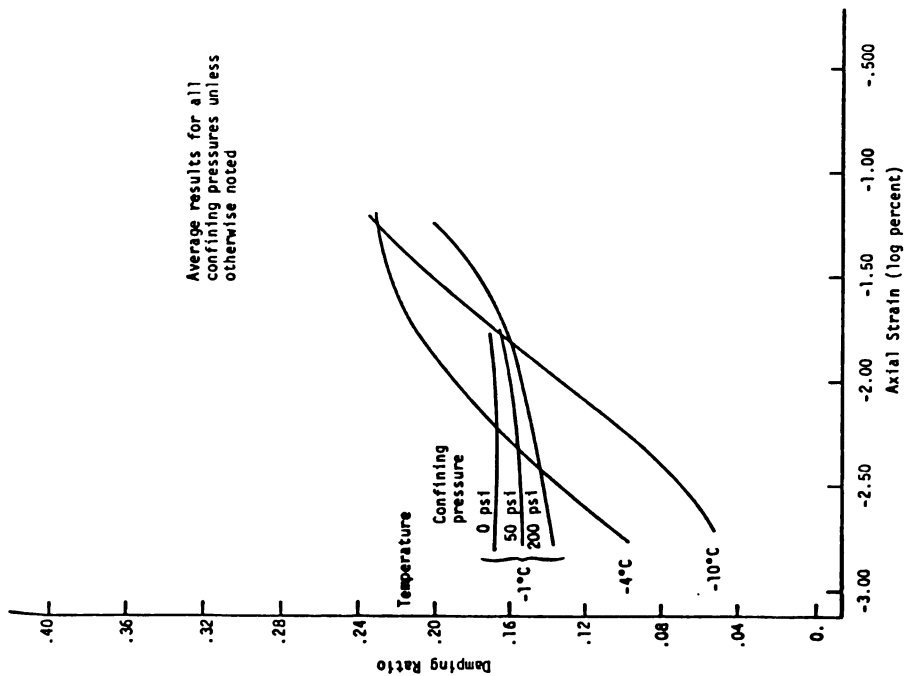


Figure 4.55 DAMPING RATIO VERSUS AXIAL STRAIN FOR ALASKA SILT AT 0.3 cps FREQUENCY AND 38.9% WATER CONTENT

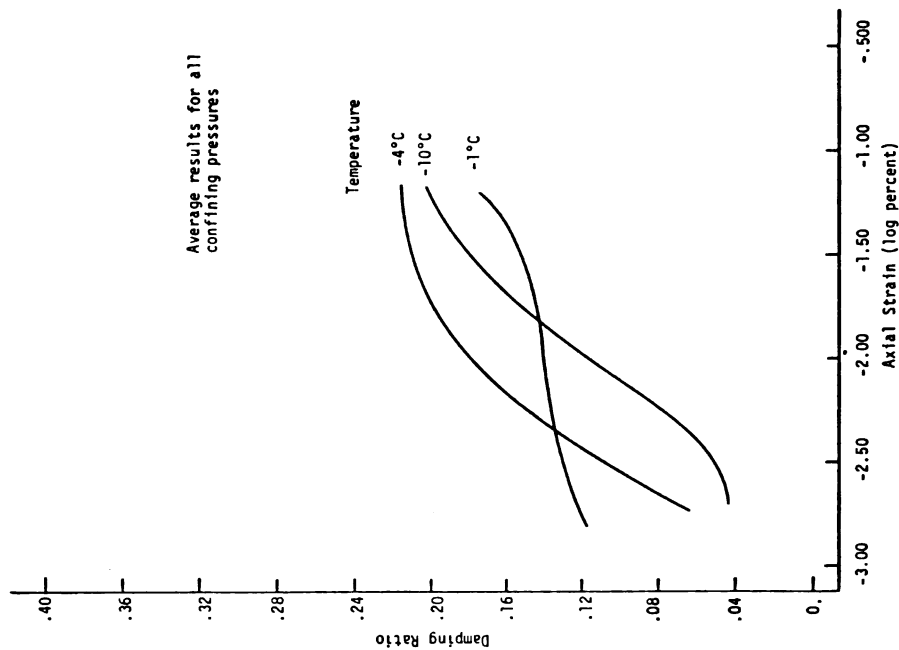
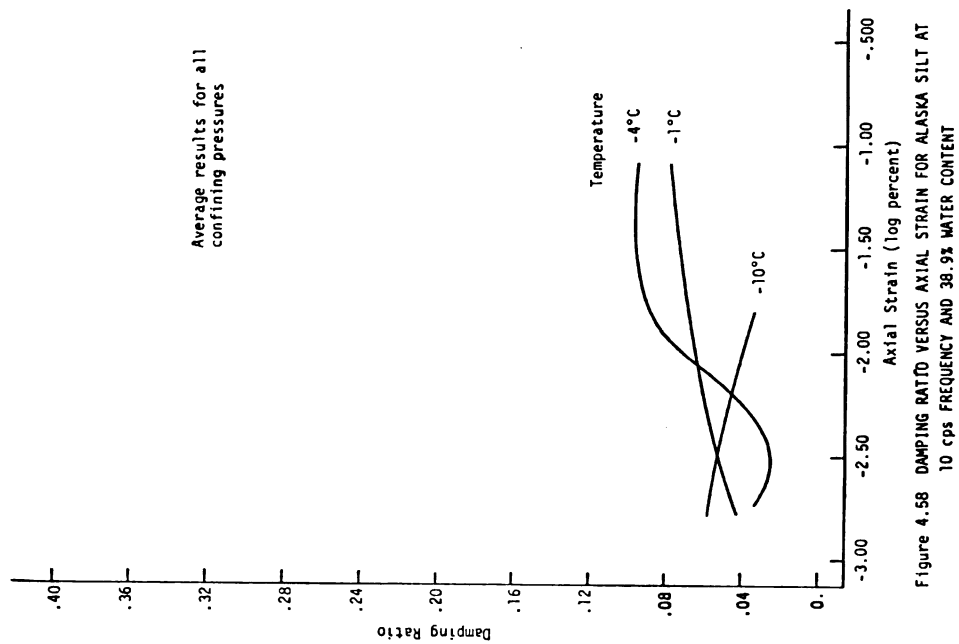
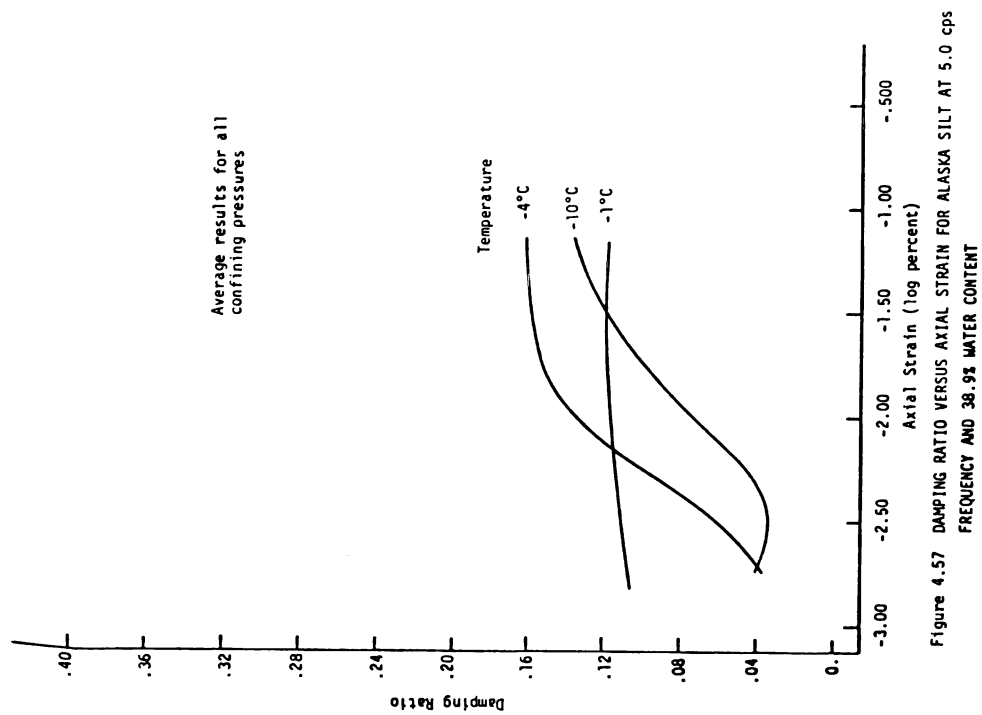


Figure 4.56 DAMPING RATIO VERSUS AXIAL STRAIN FOR ALASKA SILT AT 1.0 cps FREQUENCY AND 38.9% WATER CONTENT



4.4.2 Effect of Confining Pressure

The relationships between damping ratio and confining pressure are summarized in Figures 4.59 to 4.63. Since it was apparent that confining pressure did not influence damping ratio at low temperatures (-4 and -10°C), plots were prepared only for a temperature of -1°C. In general, at a temperature of -1°C and at a low strain amplitude ($3.16 \times 10^{-3}\%$) damping ratio decreases with increasing confining pressure at low frequencies and is not significantly affected by confining pressure at higher frequencies. At a high strain amplitude ($3.16 \times 10^{-2}\%$) damping ratio decreases slightly with increasing confining pressure at low frequencies and is not affected by confining pressure at higher frequencies. Since the change in damping ratio with confining pressure is small to negligible at a high strain amplitude, only one curve has been shown for the damping ratio-confining pressure relationship at a high strain amplitude (Figure 4.61). In general, the rate of decrease of damping ratio is more pronounced at low confining pressures (0 to 50 psi) than at high confining pressures (50 to 200 psi). It appears that confining pressure has a more significant influence on damping ratio at low water contents than at high water contents.

4.4.3 Effect of Frequency

The relationships between damping ratio and frequency are given in Figures 4.64 to 4.73. Each graph represents the relationship for a silt at a particular water content at three temperatures (-1, -4, and -10°C) and, where applicable, at three confining pressures (0, 50, and 200 psi). At a temperature of -1°C, the damping ratio de-

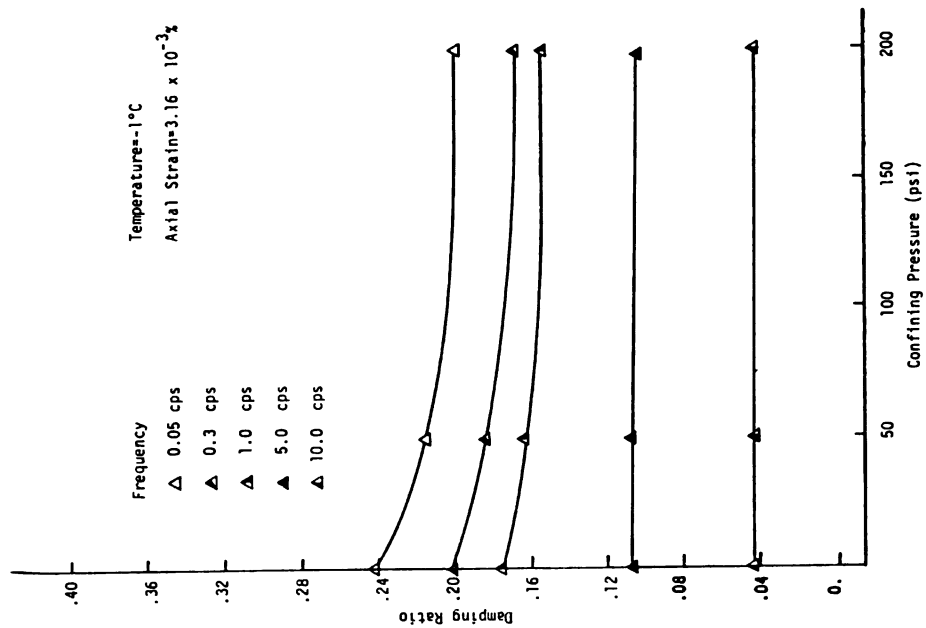


Figure 4.60 DAMPING RATIO VERSUS CONFINING PRESSURE FOR HANOVER SILT AT A WATER CONTENT OF 35.5%

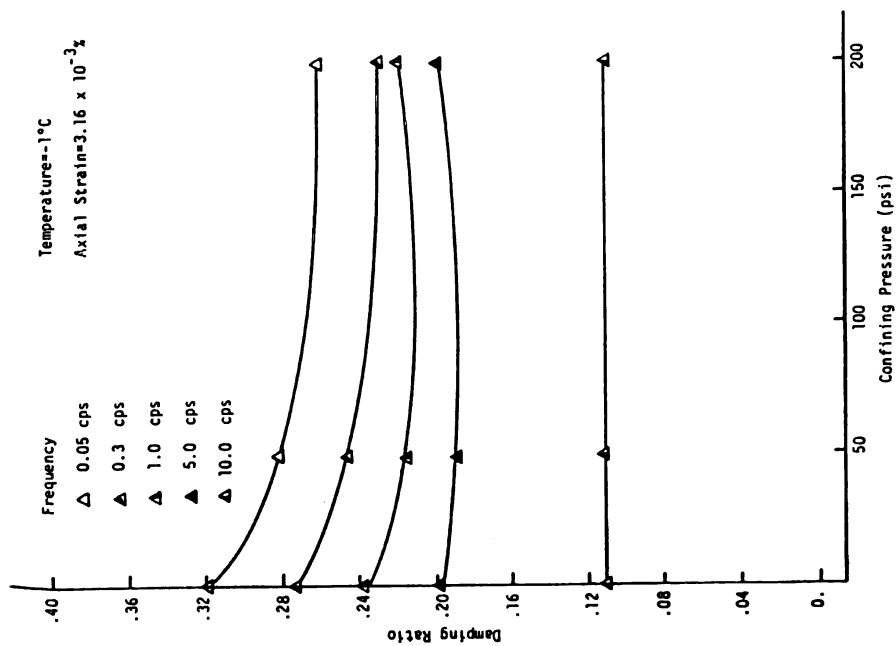


Figure 4.59 DAMPING RATIO VERSUS CONFINING PRESSURE FOR HANOVER SILT AT A WATER CONTENT OF 21.4%

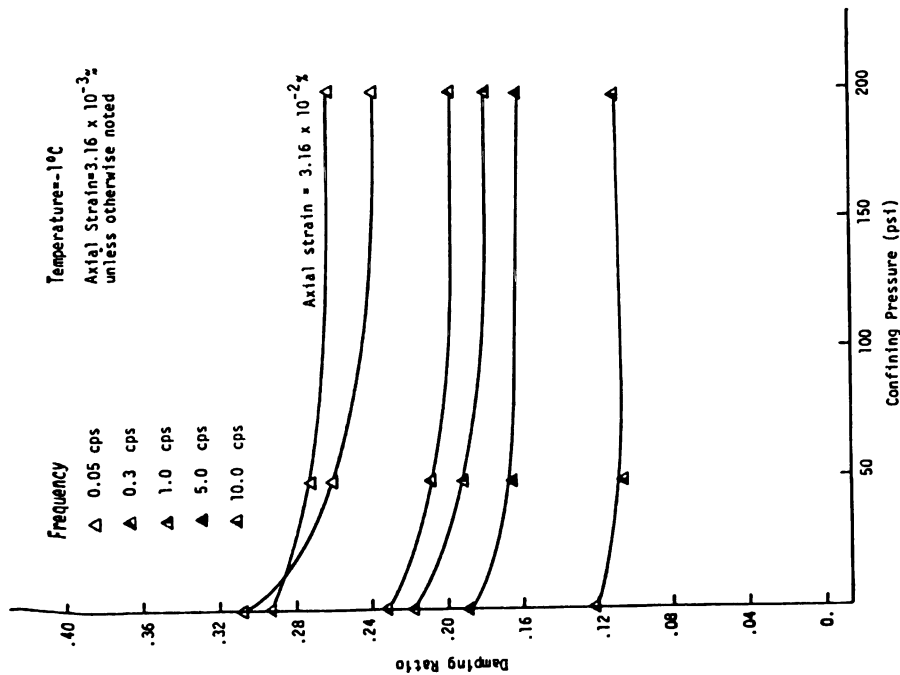


Figure 4.61 DAMPING RATIO VERSUS CONFINING PRESSURE FOR ALASKA SILT AT A WATER CONTENT OF 20.5%

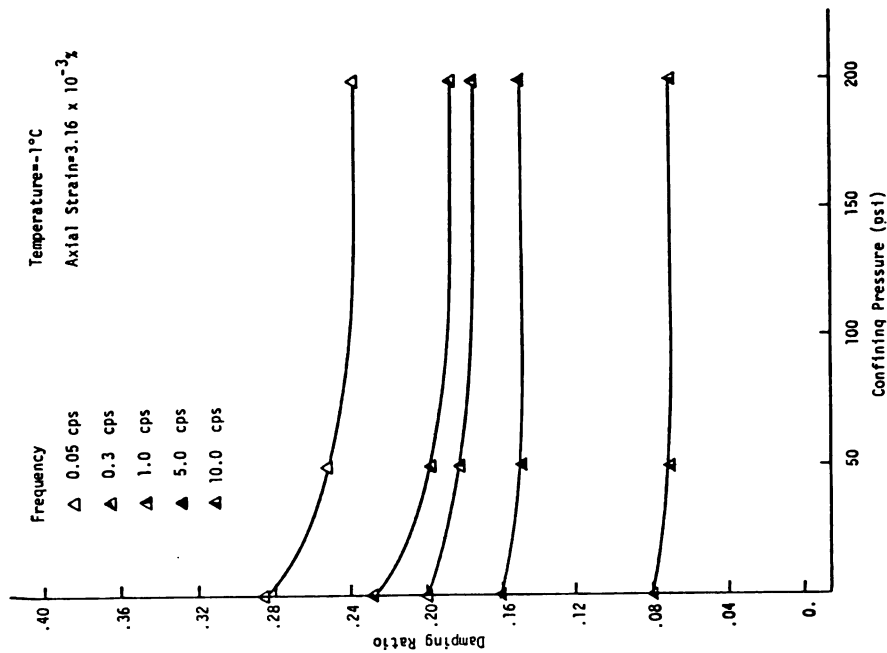


Figure 4.62 DAMPING RATIO VERSUS CONFINING PRESSURE FOR ALASKA SILT AT A WATER CONTENT OF 29.2%

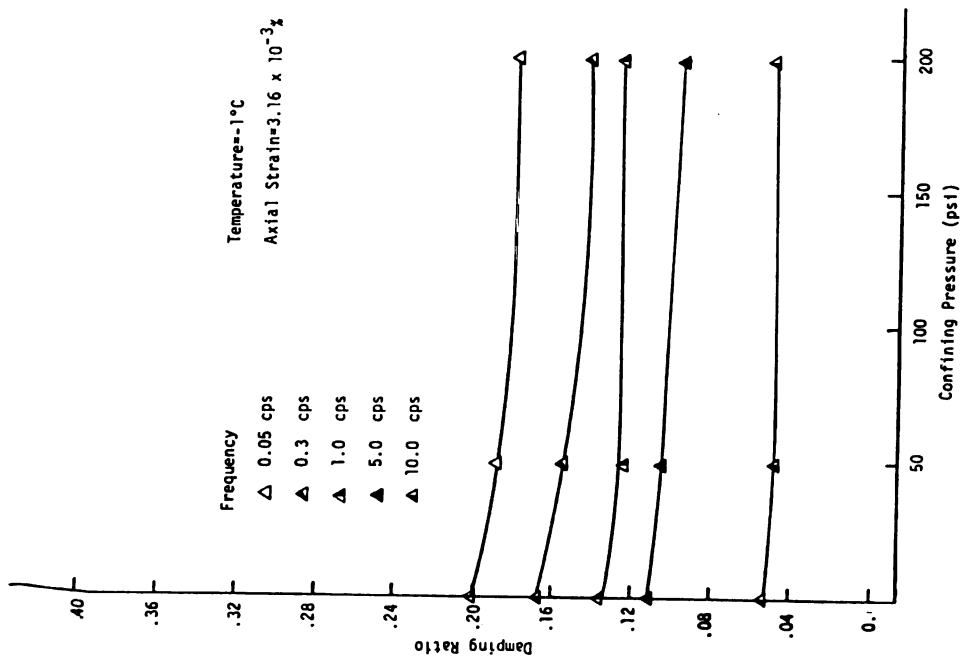


Figure 4.63 DAMPING RATIO VERSUS CONFINING PRESSURE FOR ALASKA SILT AT A WATER CONTENT OF 38.9%

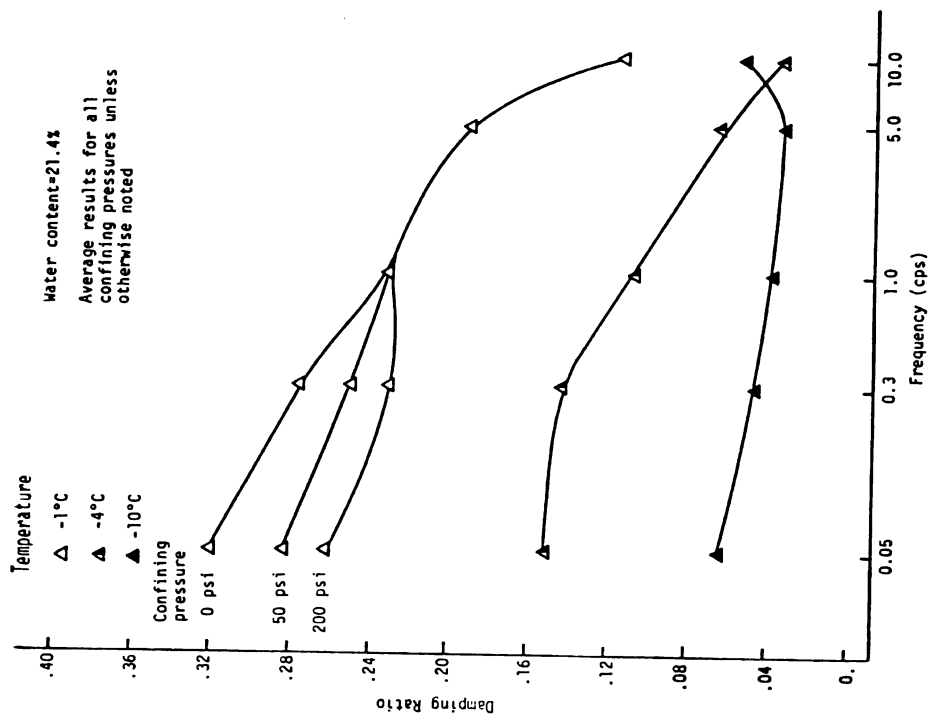


Figure 4.64 DAMPING RATIO VERSUS FREQUENCY FOR HANOVER SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

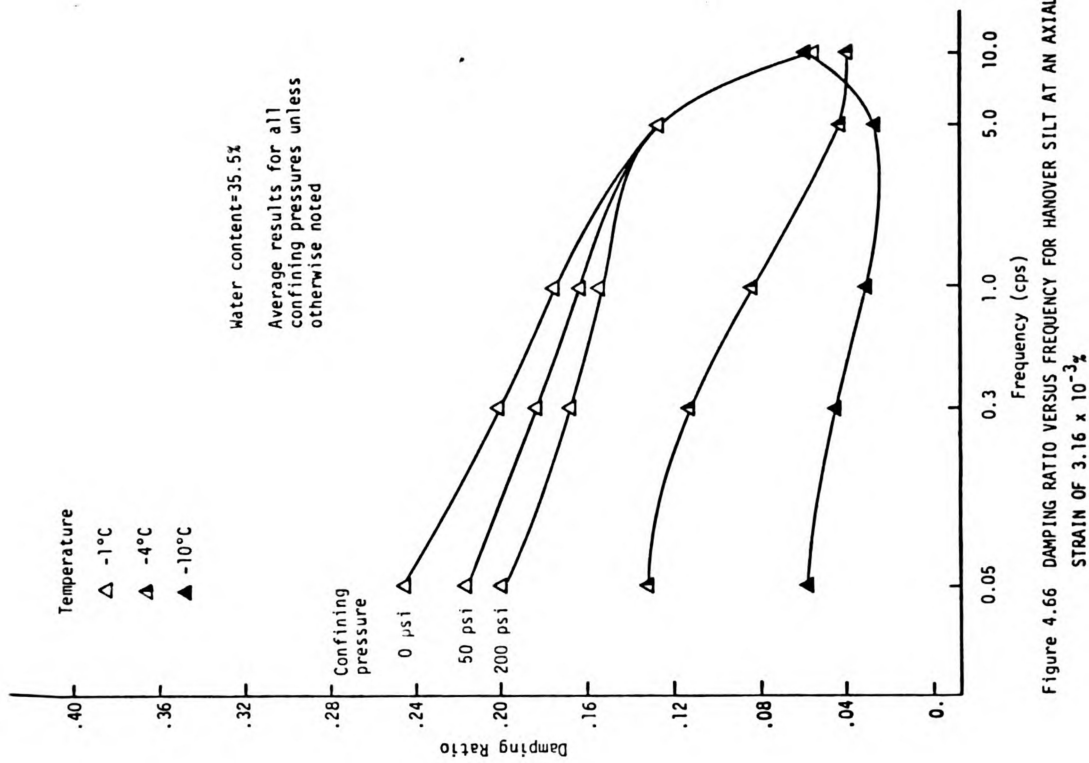


Figure 4.65 DAMPING RATIO VERSUS FREQUENCY FOR HANOVER SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

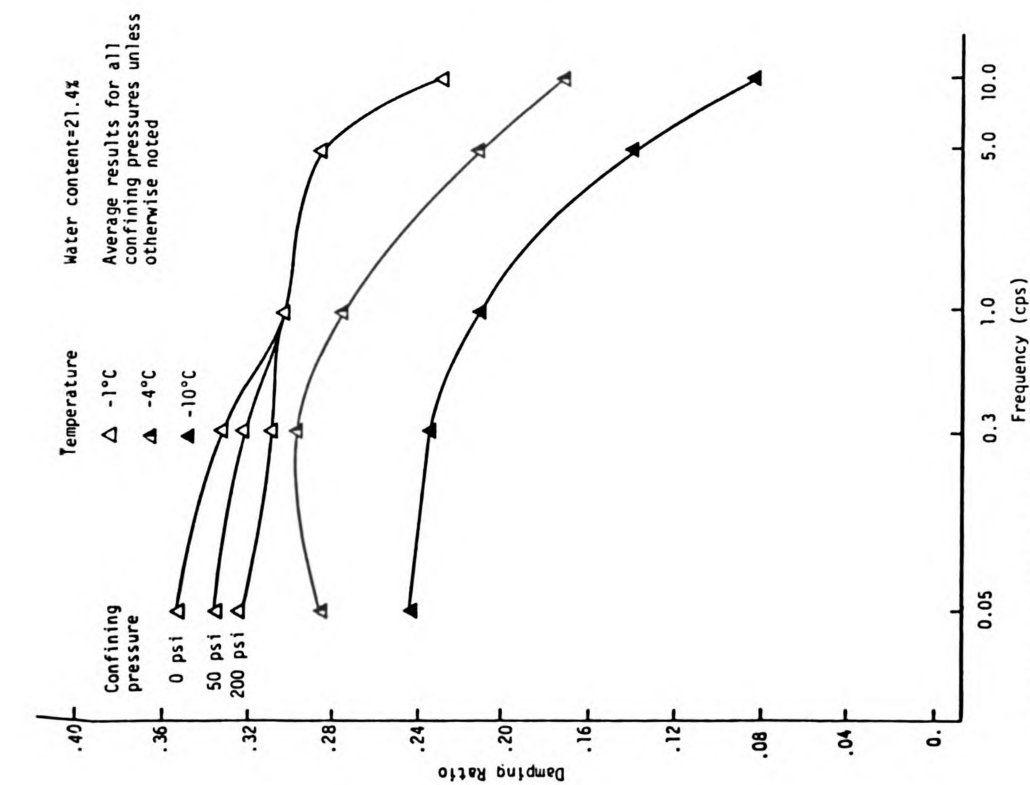


Figure 4.66 DAMPING RATIO VERSUS FREQUENCY FOR HANOVER SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

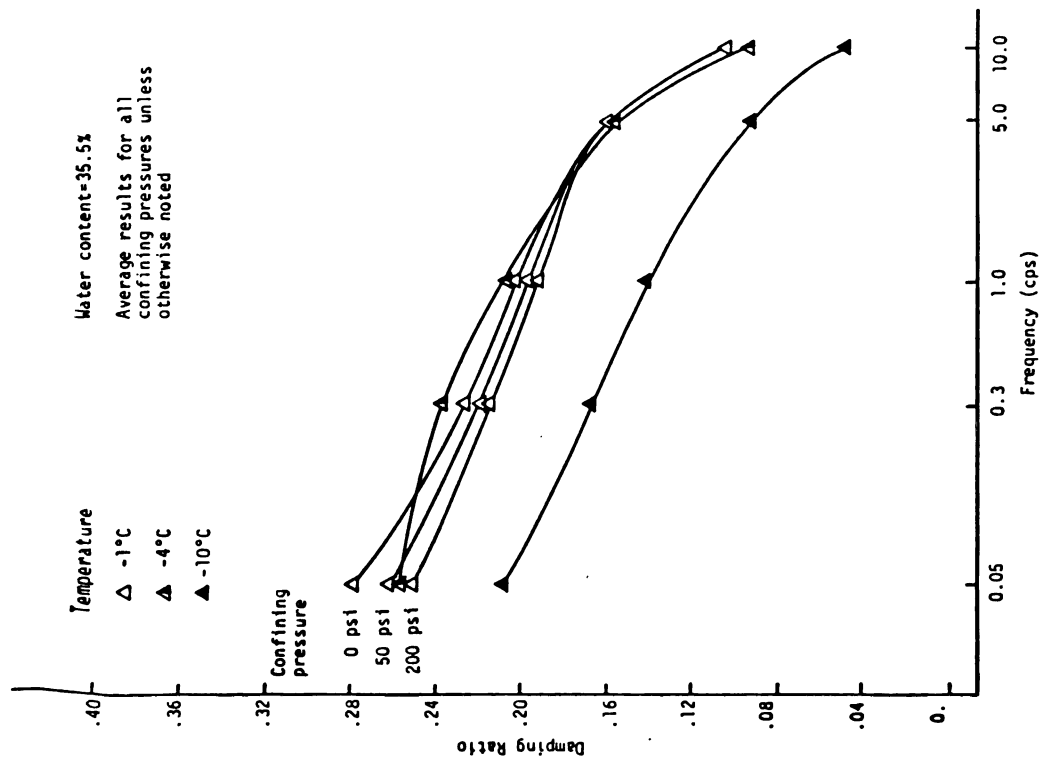


Figure 4.67 DAMPING RATIO VERSUS FREQUENCY FOR HANOVER SILT AT AN AXIAL STRAIN OF 3.16×10^{-2}

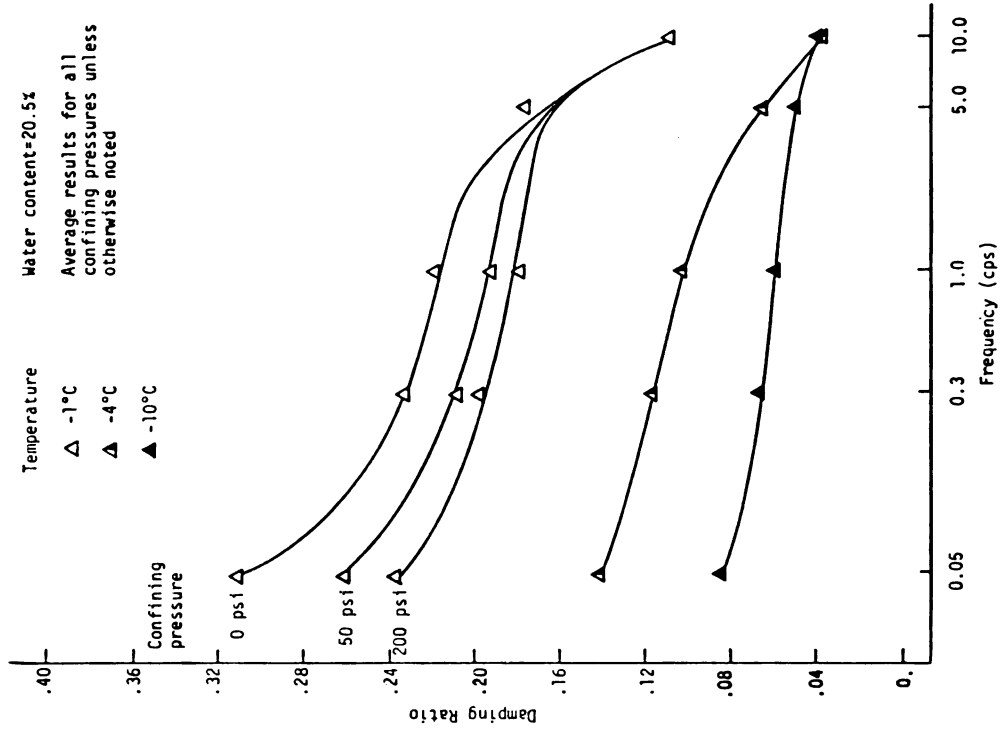


Figure 4.68 DAMPING RATIO VERSUS FREQUENCY FOR ALASKA SILT AT AN AXIAL STRAIN OF 3.16×10^{-3}

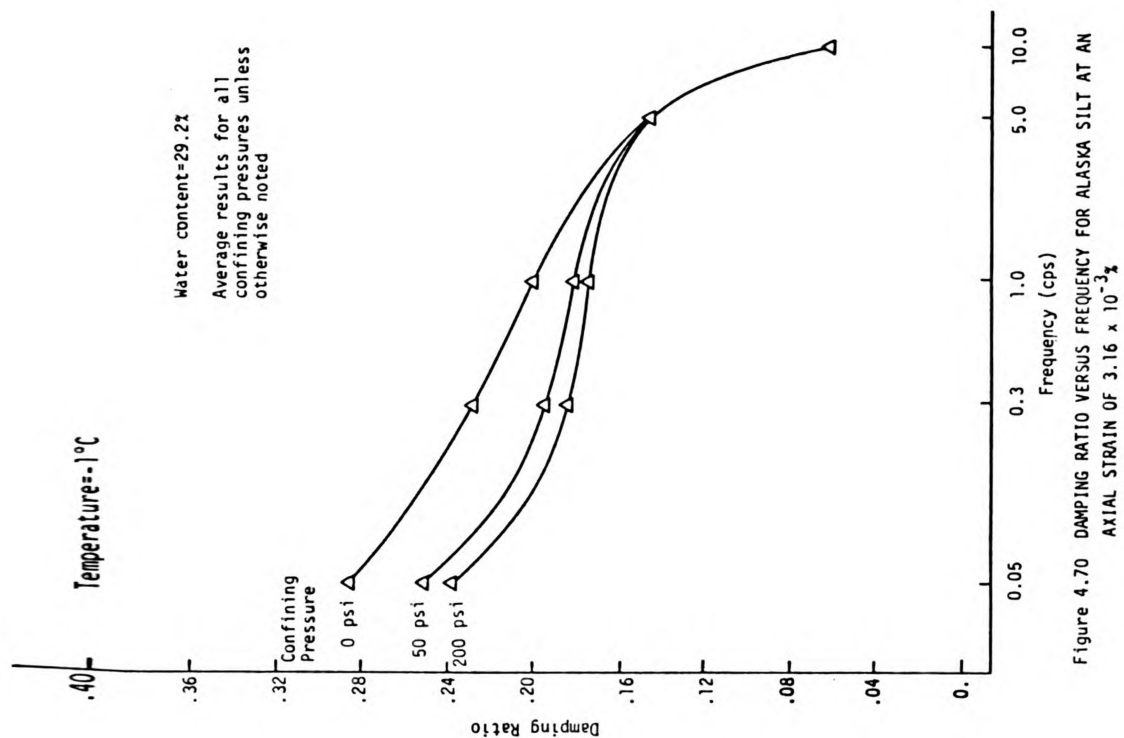


Figure 4.70 DAMPING RATIO VERSUS FREQUENCY FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

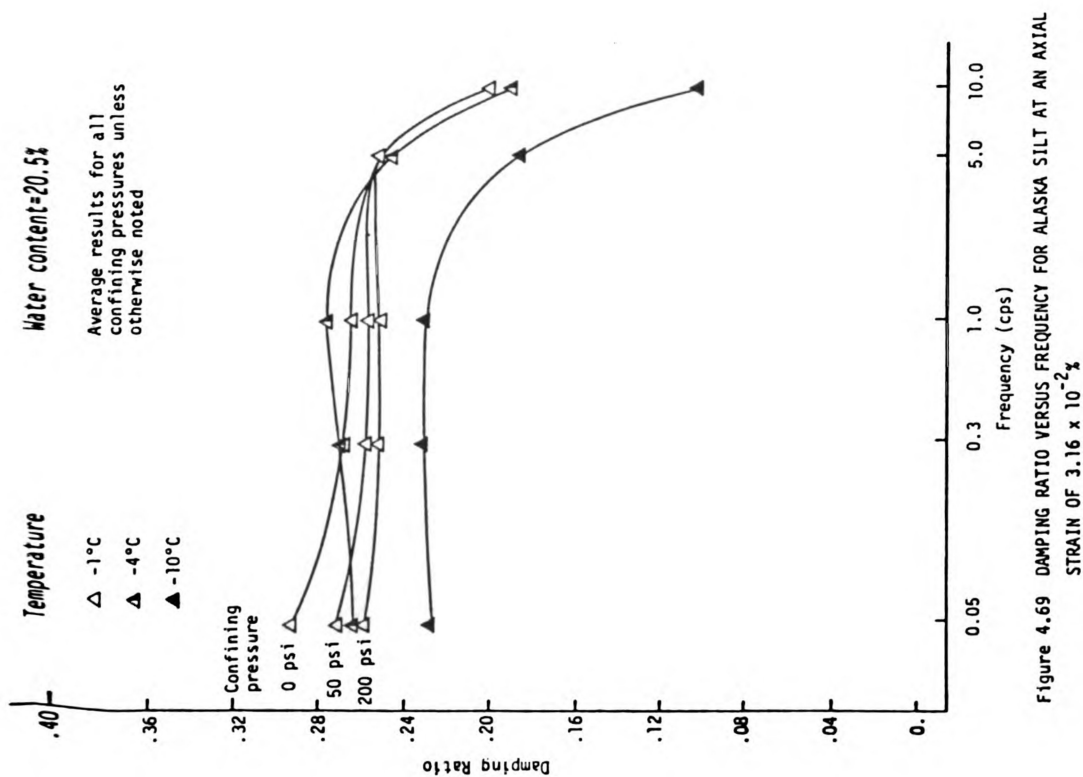


Figure 4.69 DAMPING RATIO VERSUS FREQUENCY FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

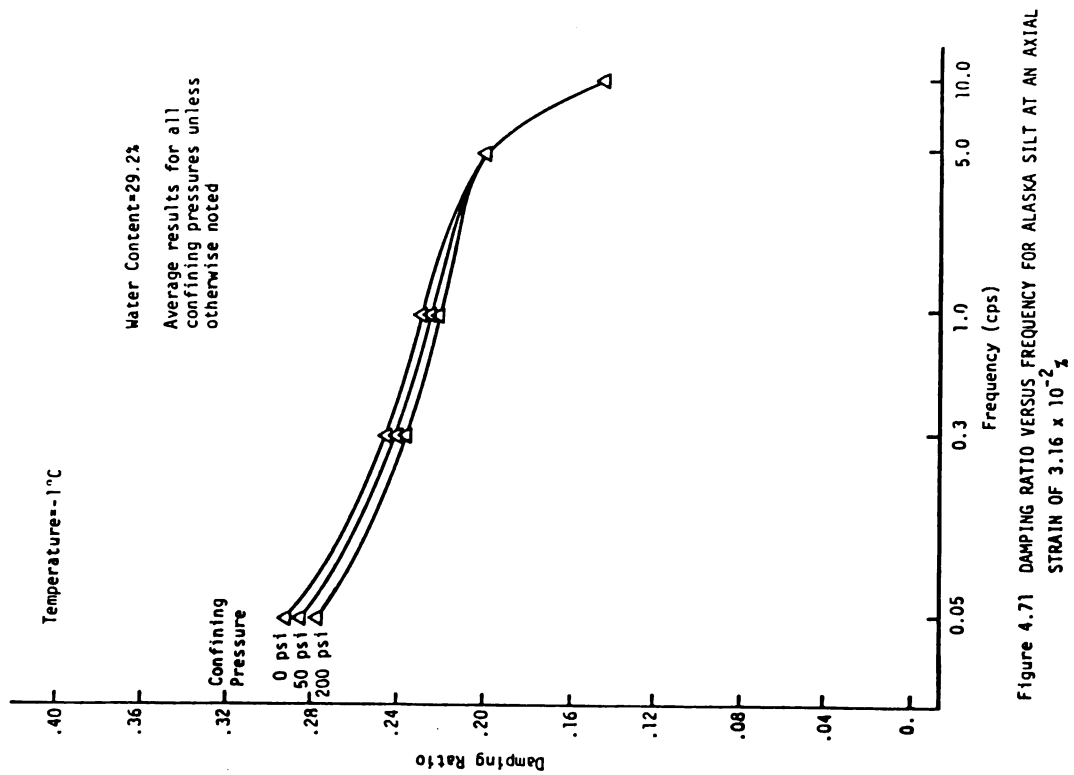


Figure 4.71 DAMPING RATIO VERSUS FREQUENCY FOR ALASKA SILT AT AN AXIAL STRAIN OF 3.16×10^{-2}

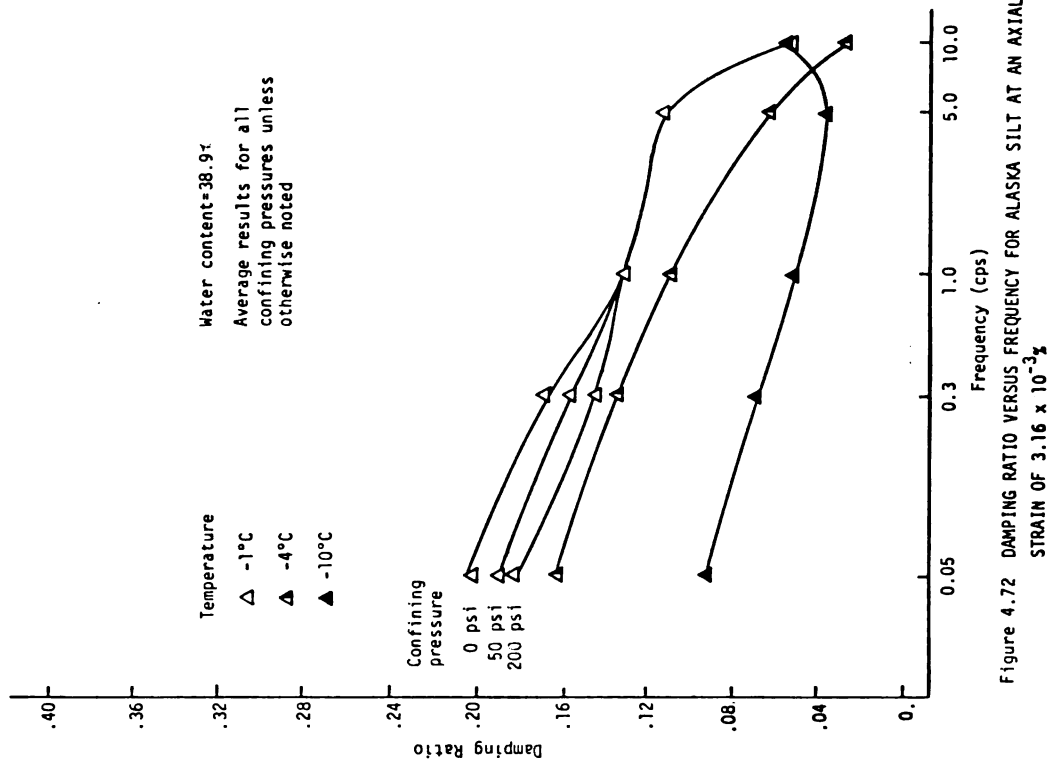


Figure 4.72 DAMPING RATIO VERSUS FREQUENCY FOR ALASKA SILT AT AN AXIAL STRAIN OF 3.16×10^{-3}

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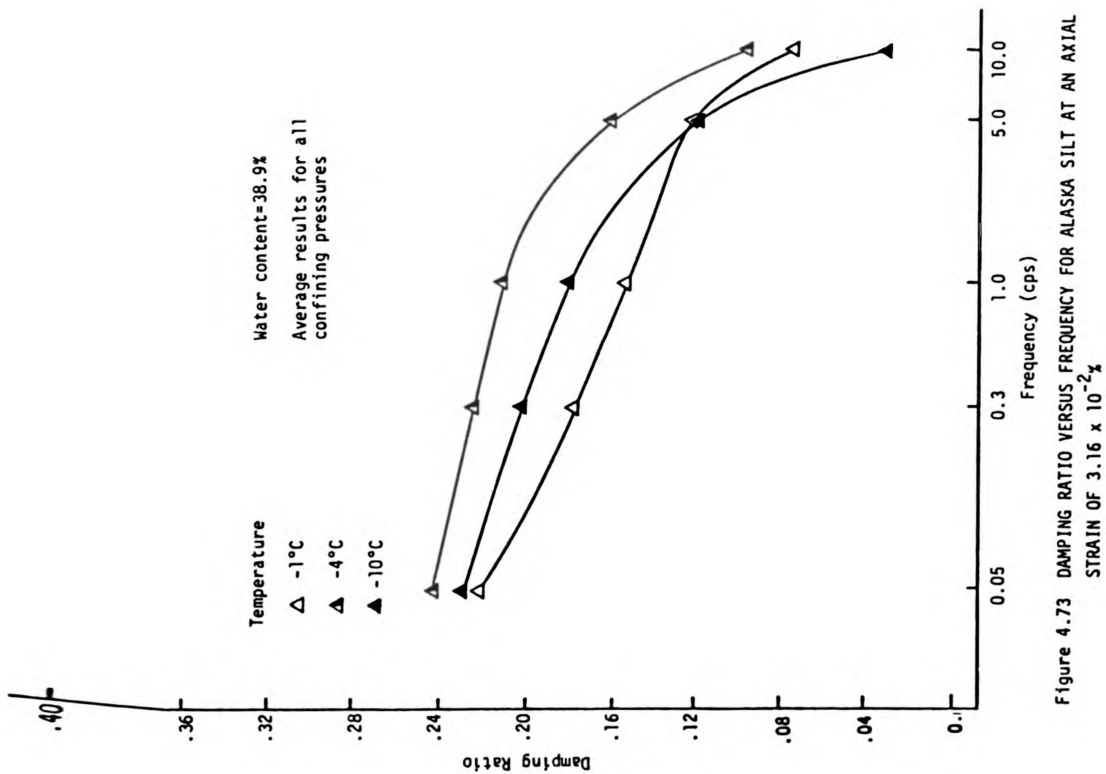


Figure 4.74 DAMPING RATIO VERSUS TEMPERATURE FOR HANOVER SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

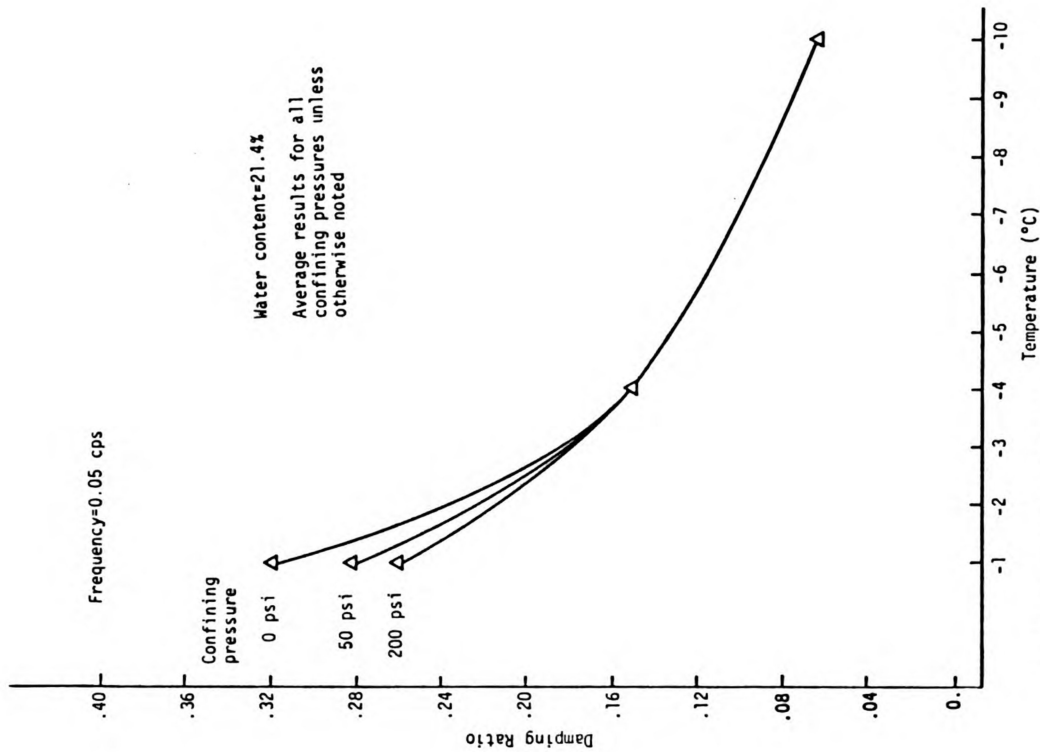


Figure 4.73 DAMPING RATIO VERSUS FREQUENCY FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

creases by a moderate amount in the frequency range 0.05 to 5.0 cps and decreases sharply from 5.0 to 10.0 cps. In general, at low water contents the influence of frequency on damping ratio is more significant at a low strain amplitude ($3.16 \times 10^{-3}\%$) than at a high strain amplitude ($3.16 \times 10^{-2}\%$). At higher water contents, the rate of decrease of damping ratio with frequency is not significantly influenced by strain amplitude.

At a temperature of -4°C , damping ratio decreases with increasing frequency at a low strain amplitude ($3.16 \times 10^{-3}\%$) at a rate somewhat more uniform than at -1°C . At a higher strain amplitude ($3.16 \times 10^{-2}\%$) the damping ratio-frequency relationship is similar to that at -1°C with a more pronounced decline in damping ratio at high frequencies than at low frequencies. At a low water content for both silts, there appears to be an initial increase in damping ratio at low frequencies followed by a sharp decrease at high frequencies.

At a temperature of -10°C and at a low strain amplitude ($3.16 \times 10^{-3}\%$) damping ratio generally decreases by a small amount with increasing frequency at low frequencies (0.05 to 5.0 cps) and increases at higher frequencies (5.0 to 10.0 cps). At a high strain amplitude ($3.16 \times 10^{-2}\%$) the damping ratio-frequency relationship is similar to that at -1 and -4°C . The rate of decrease of damping ratio is greater at high frequencies than at low frequencies.

4.4.4 Effect of Temperature

The relationship between damping ratio and temperature is given in Figures 4.74 to 4.90. Each graph represents the relationship for a silt at a particular water content, at one of two axial strain

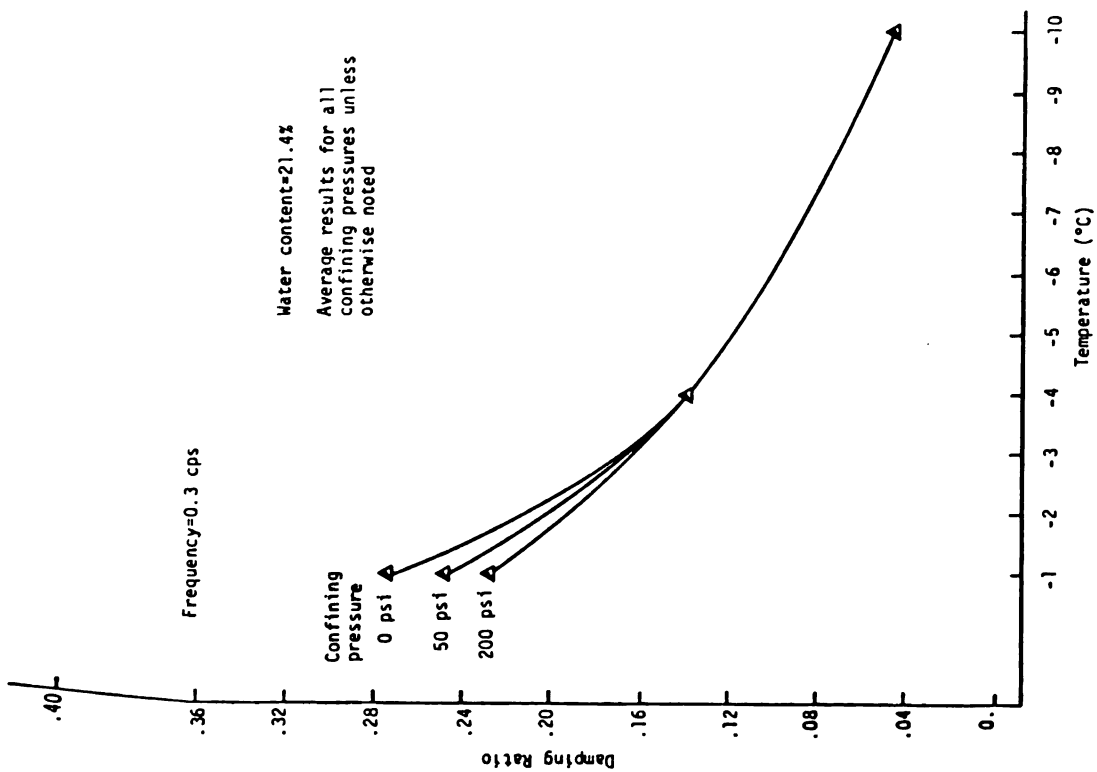


Figure 4.75 DAMPING RATIO VERSUS TEMPERATURE FOR HANOVER SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

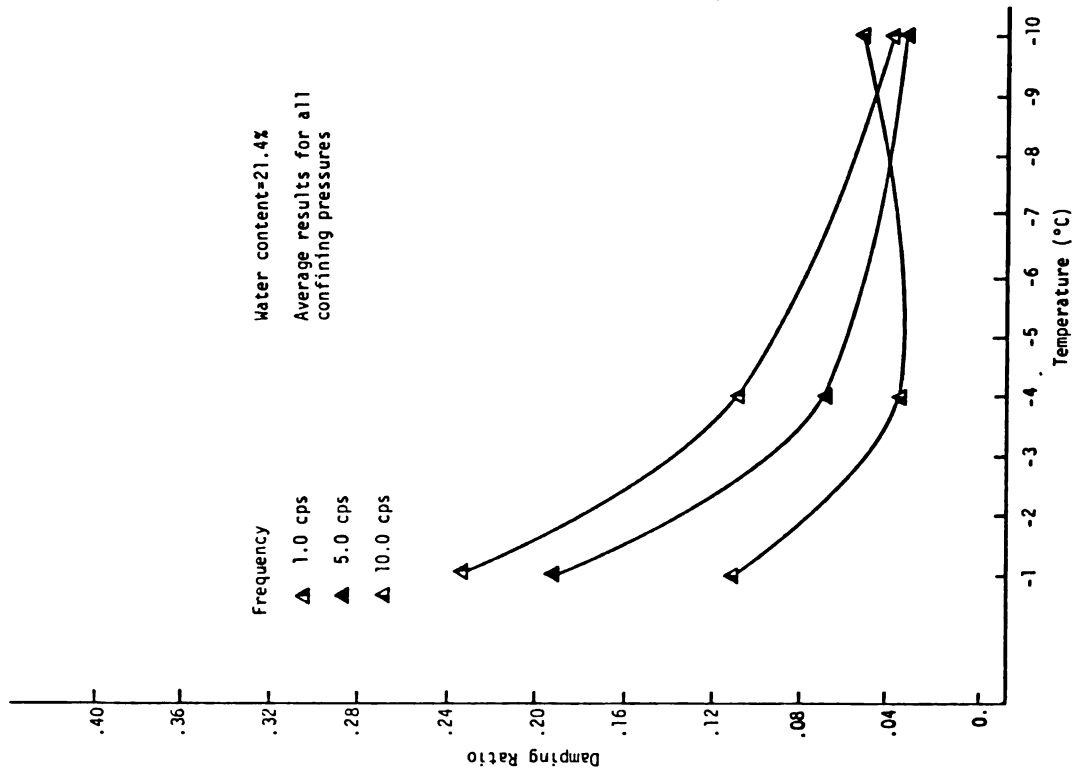


Figure 4.76 DAMPING RATIO VERSUS TEMPERATURE FOR HANOVER SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

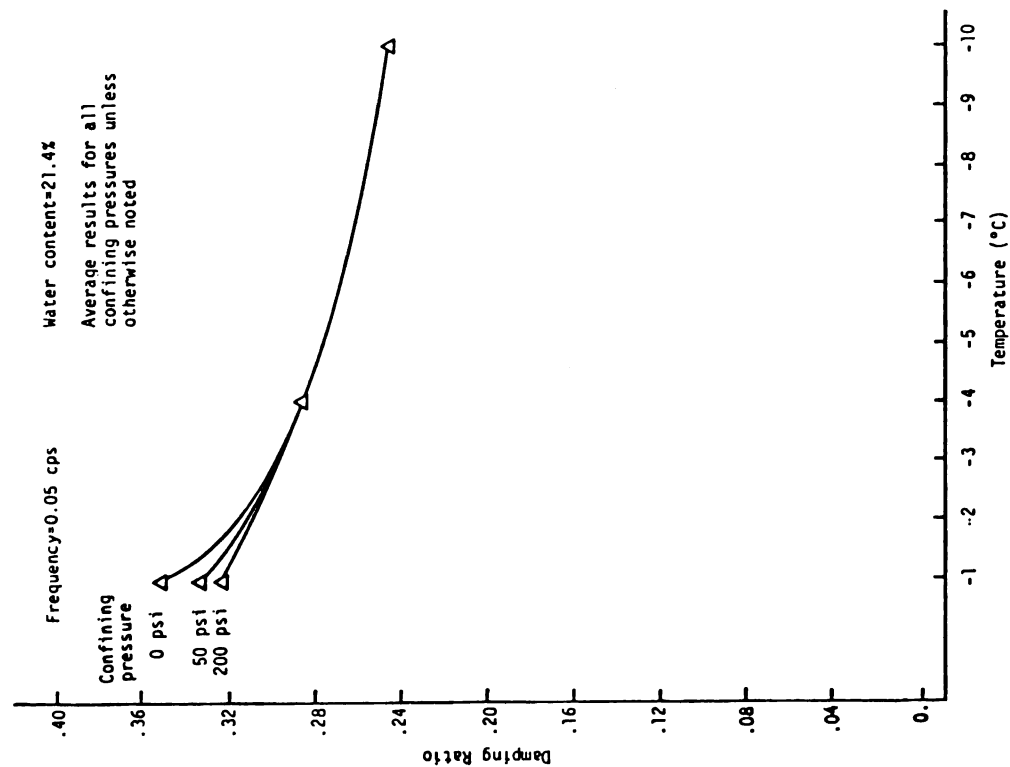


Figure 4.77 DAMPING RATIO VERSUS TEMPERATURE FOR HANOVER SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

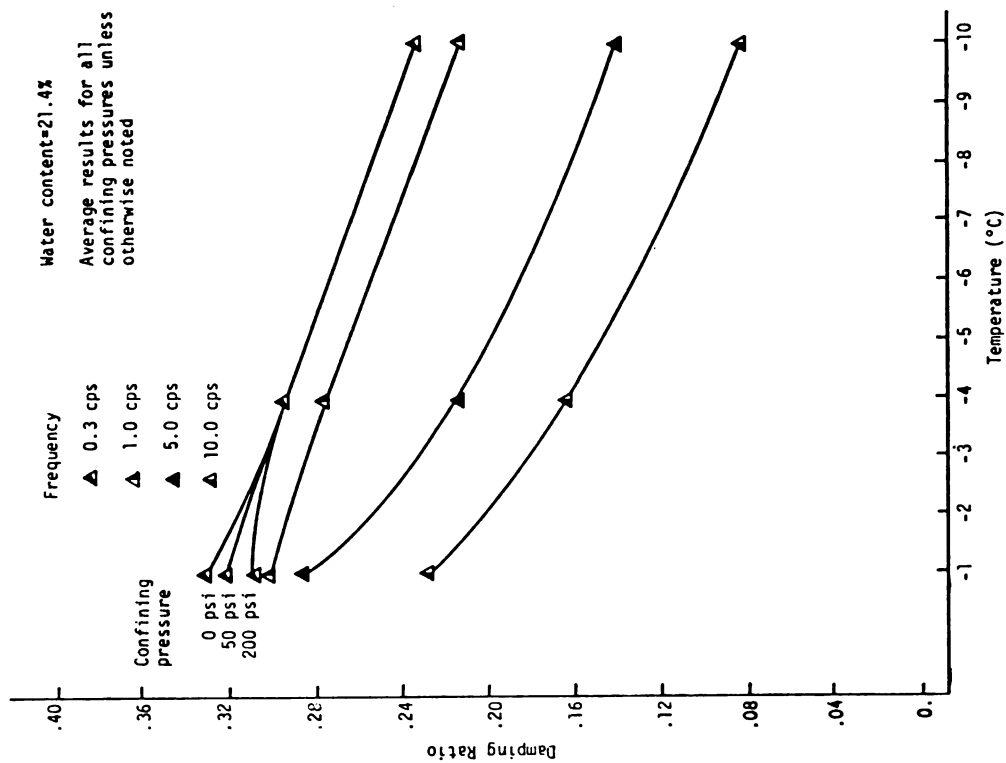


Figure 4.78 DAMPING RATIO VERSUS TEMPERATURE FOR HANOVER SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

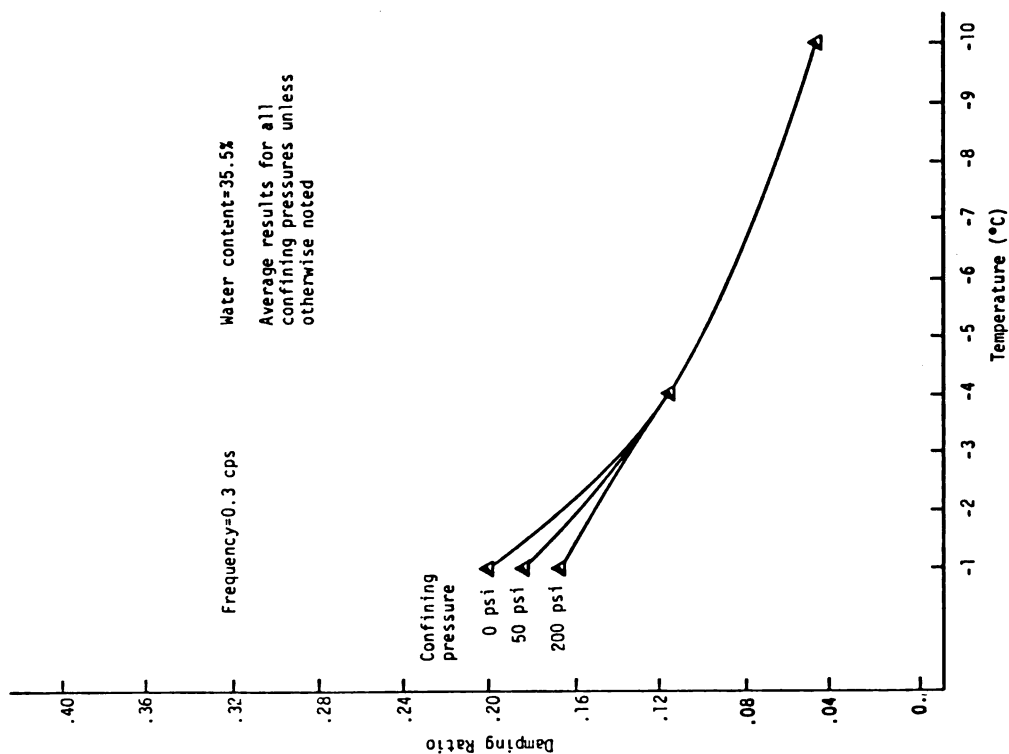


Figure 4.80 DAMPING RATIO VERSUS TEMPERATURE FOR HANOVER SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

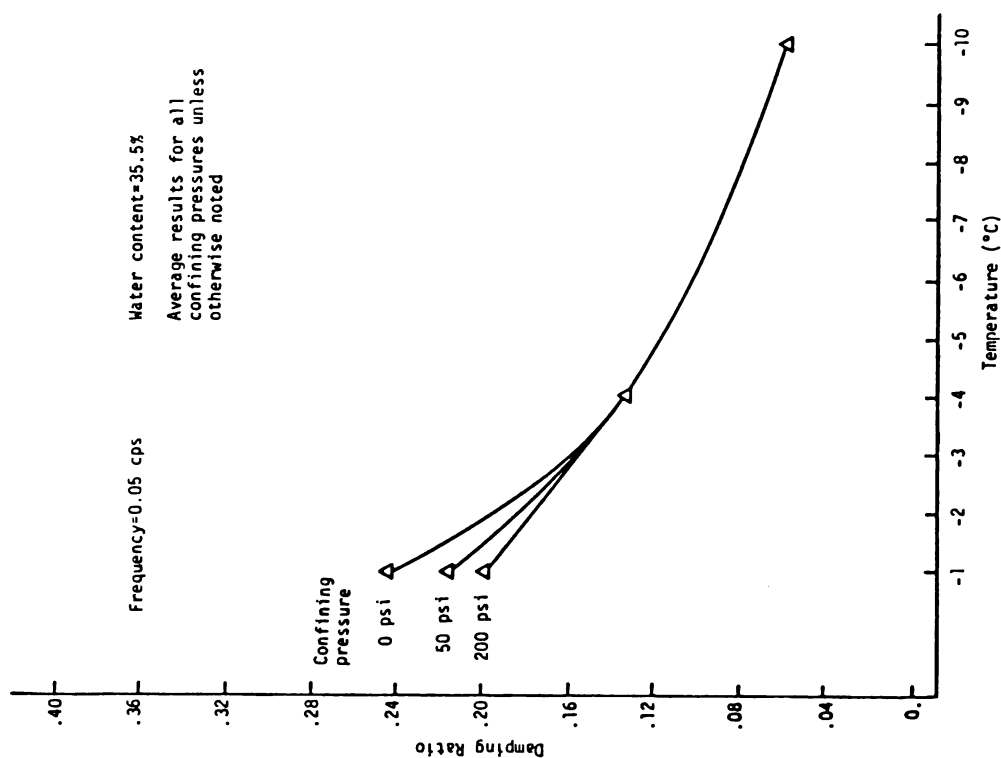


Figure 4.79 DAMPING RATIO VERSUS TEMPERATURE FOR HANOVER SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

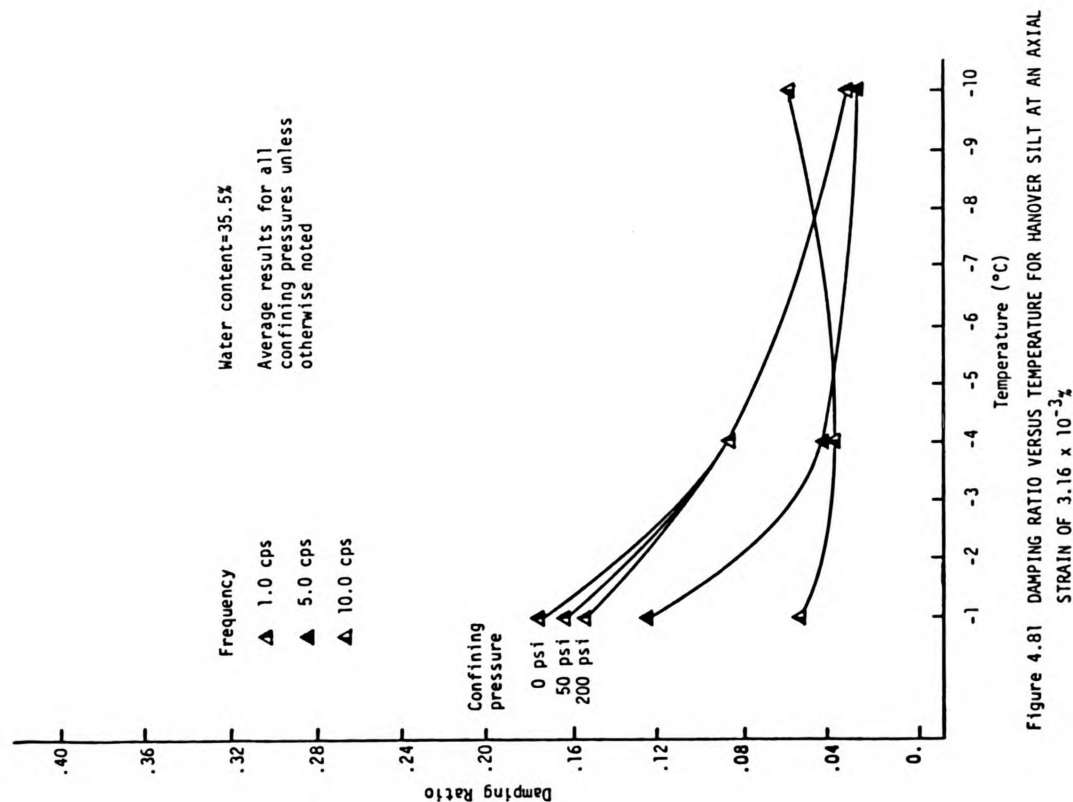


Figure 4.81 DAMPING RATIO VERSUS TEMPERATURE FOR HANOVER SILT AT AN AXIAL STRAIN OF 3.16×10^{-3}

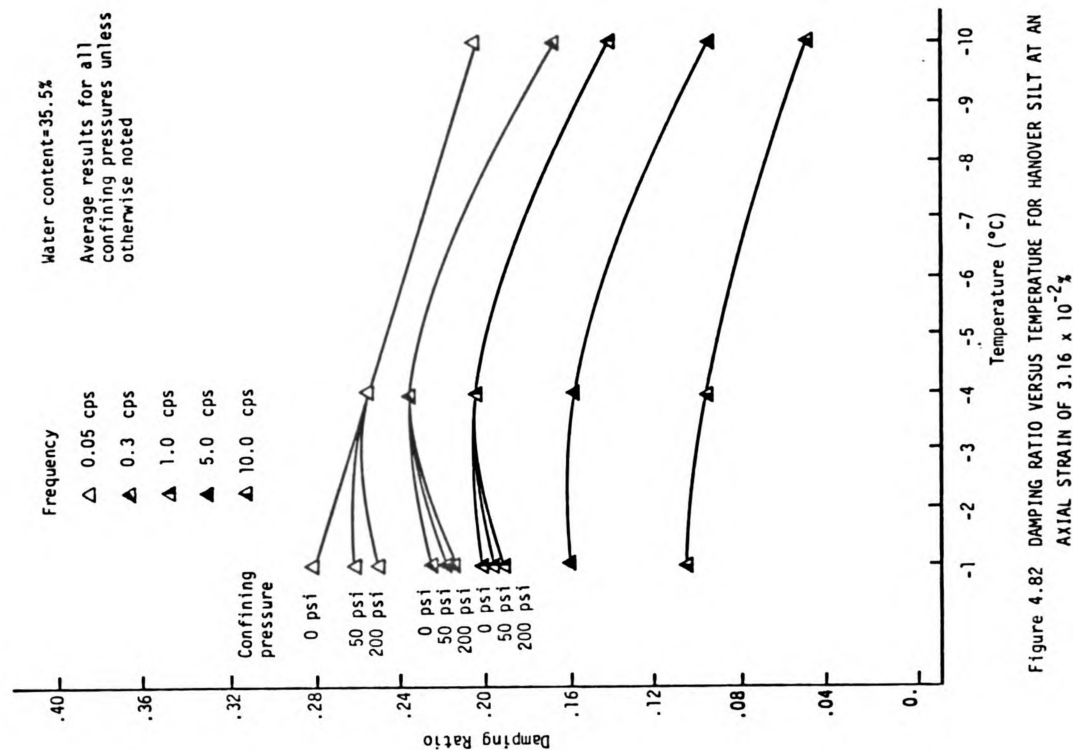


Figure 4.82 DAMPING RATIO VERSUS TEMPERATURE FOR HANOVER SILT AT AN AXIAL STRAIN OF 3.16×10^{-2}

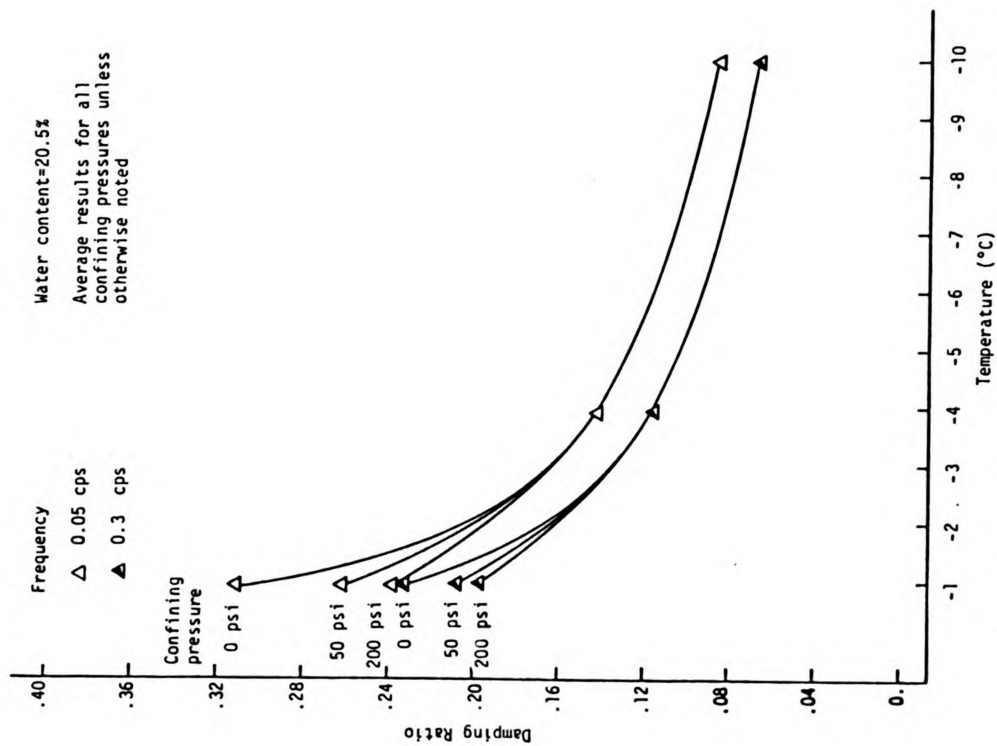


Figure 4.83 DAMPING RATIO VERSUS TEMPERATURE FOR ALASKA SILT AT AN AXIAL STRAIN OF 3.16×10^{-3}

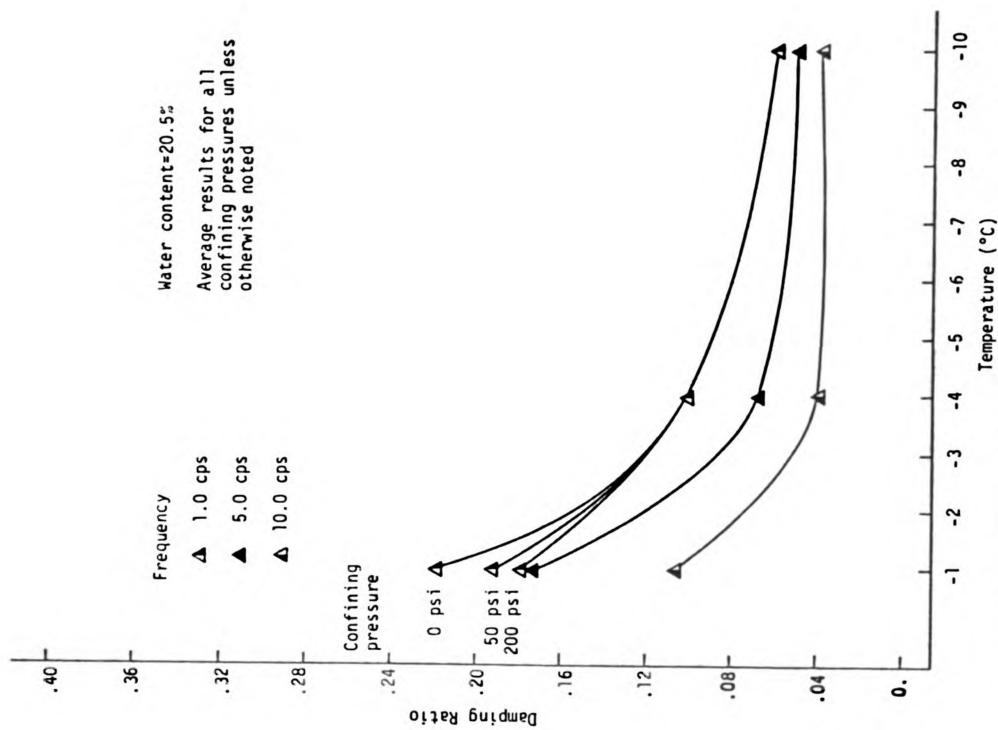


Figure 4.84 DAMPING RATIO VERSUS TEMPERATURE FOR ALASKA SILT AT AN AXIAL STRAIN OF 3.16×10^{-3}

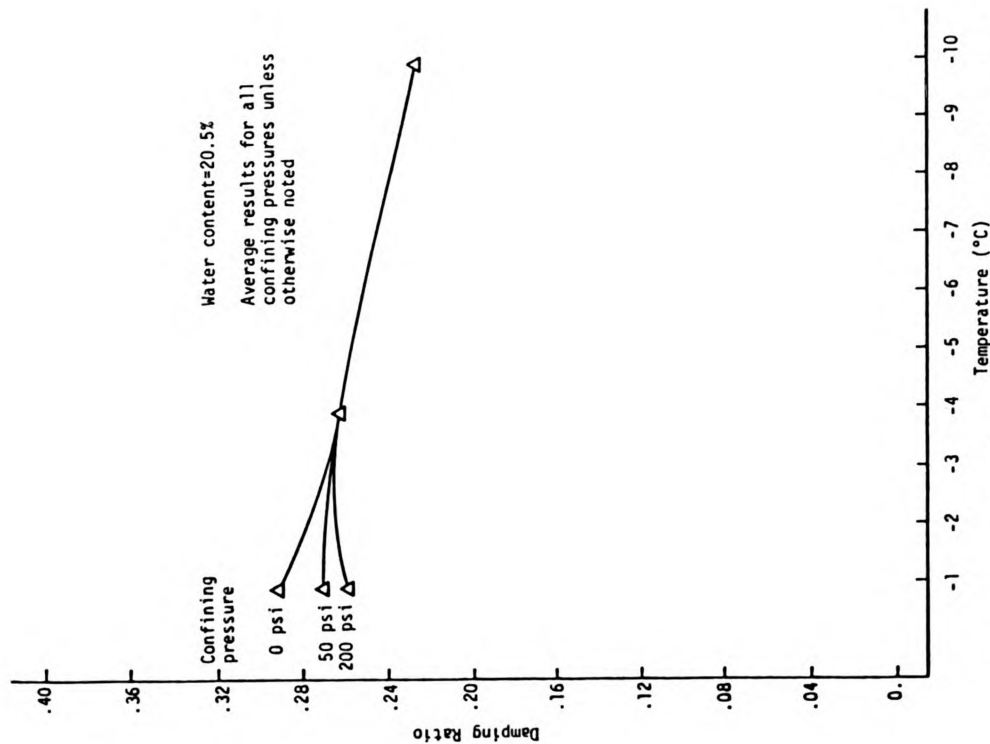


Figure 4.85 DAMPING RATIO VERSUS TEMPERATURE FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$ AND 0.05 cps FREQUENCY

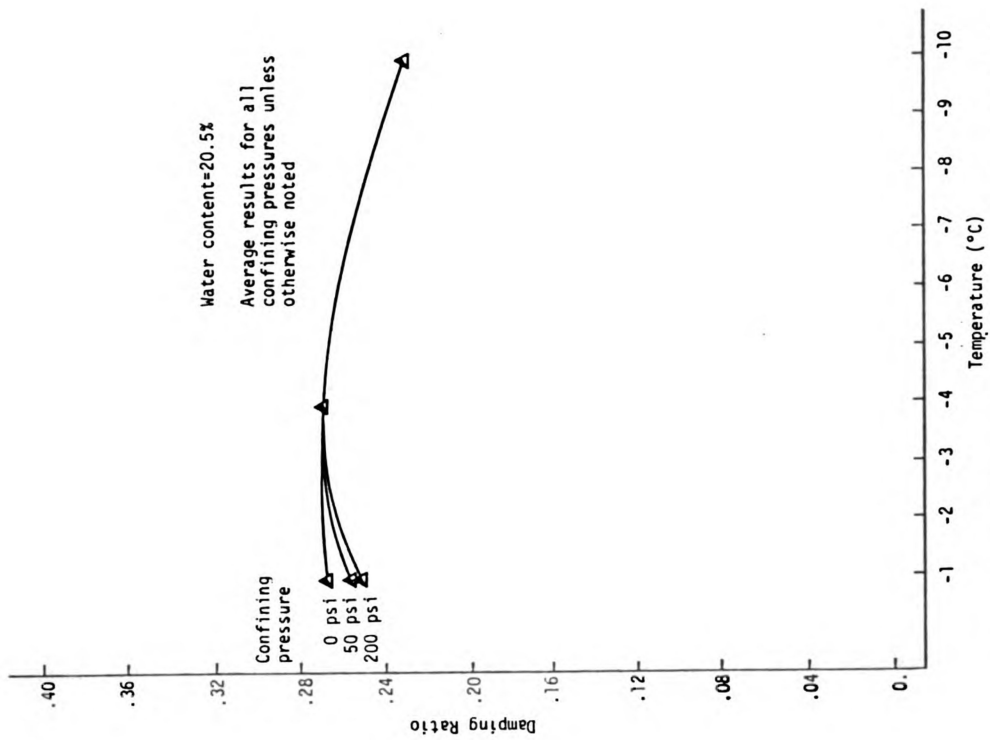


Figure 4.86 DAMPING RATIO VERSUS TEMPERATURE FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$ AND 0.3 cps FREQUENCY

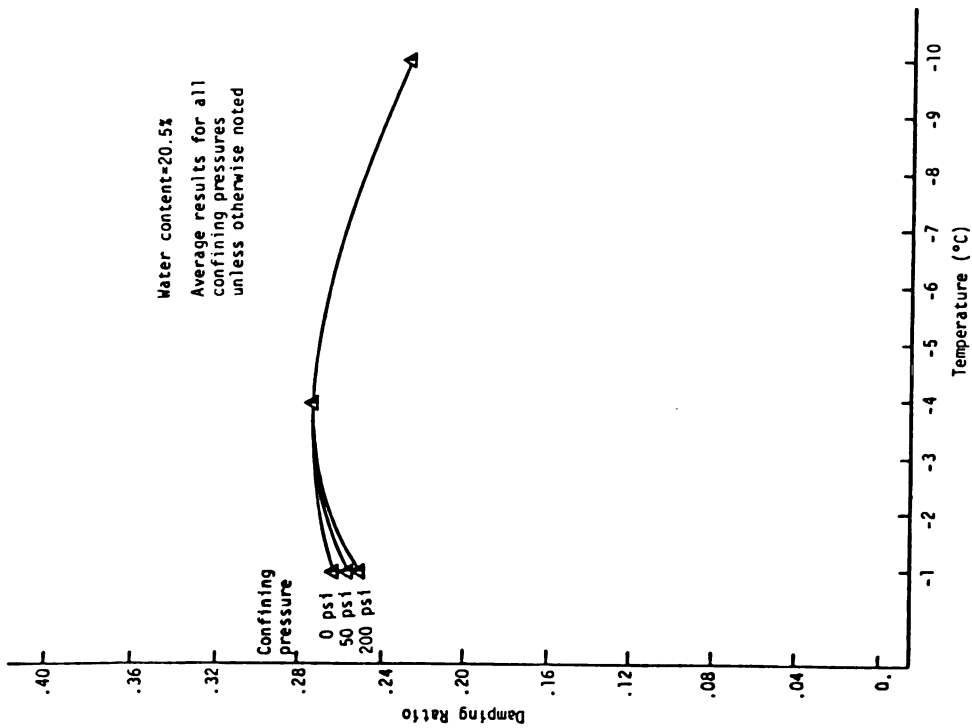


Figure 4.87 DAMPING RATIO VERSUS TEMPERATURE FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$ AND 1.0 cps FREQUENCY

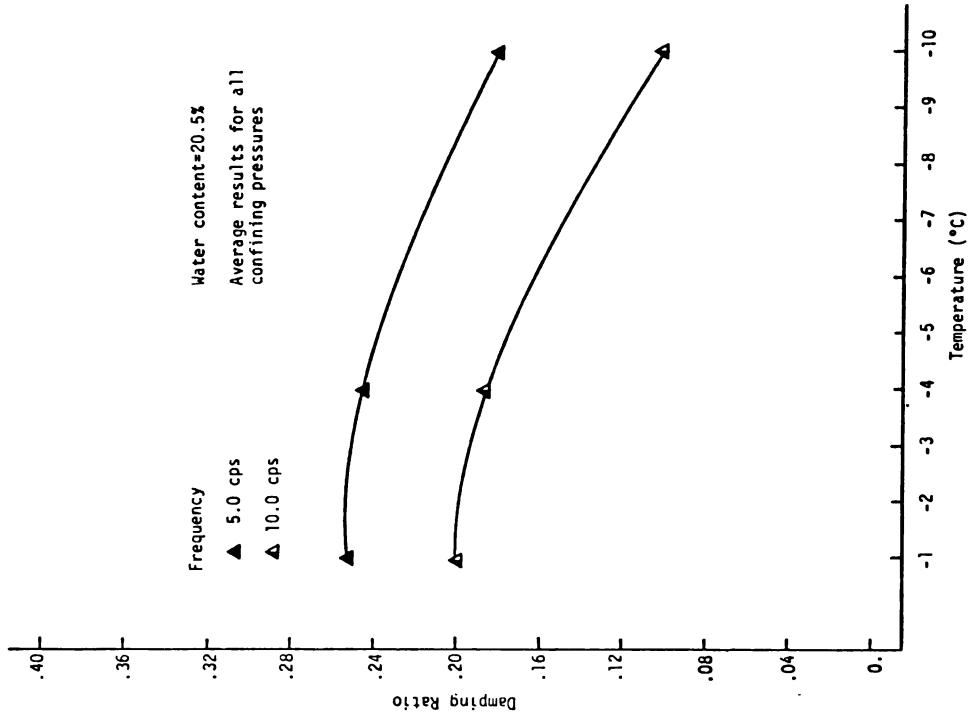


Figure 4.88 DAMPING RATIO VERSUS TEMPERATURE FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

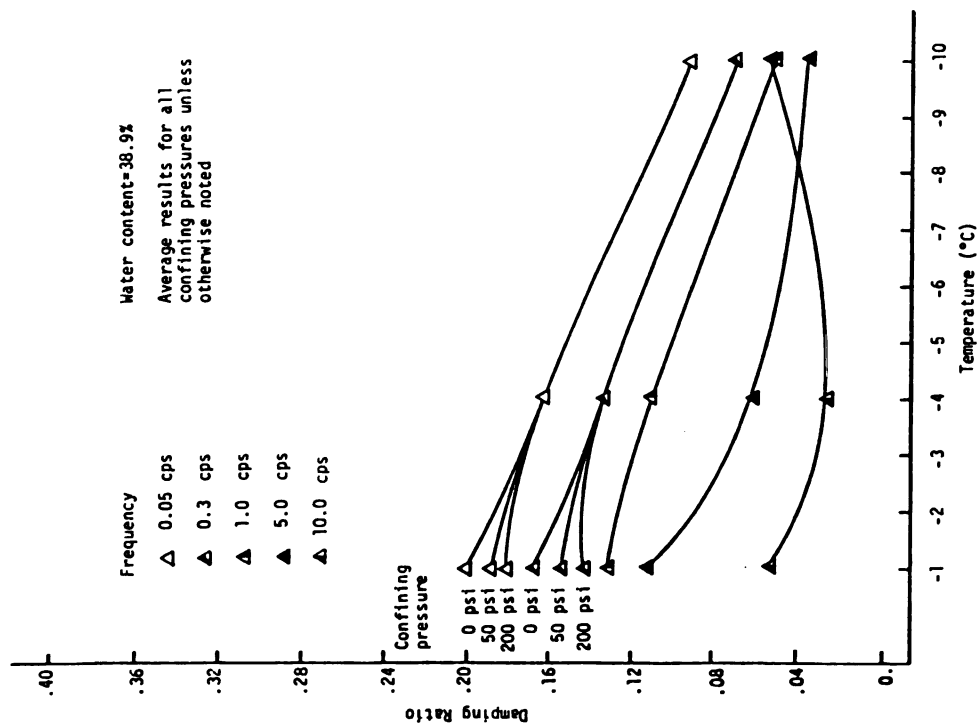


Figure 4.89 DAMPING RATIO VERSUS TEMPERATURE FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

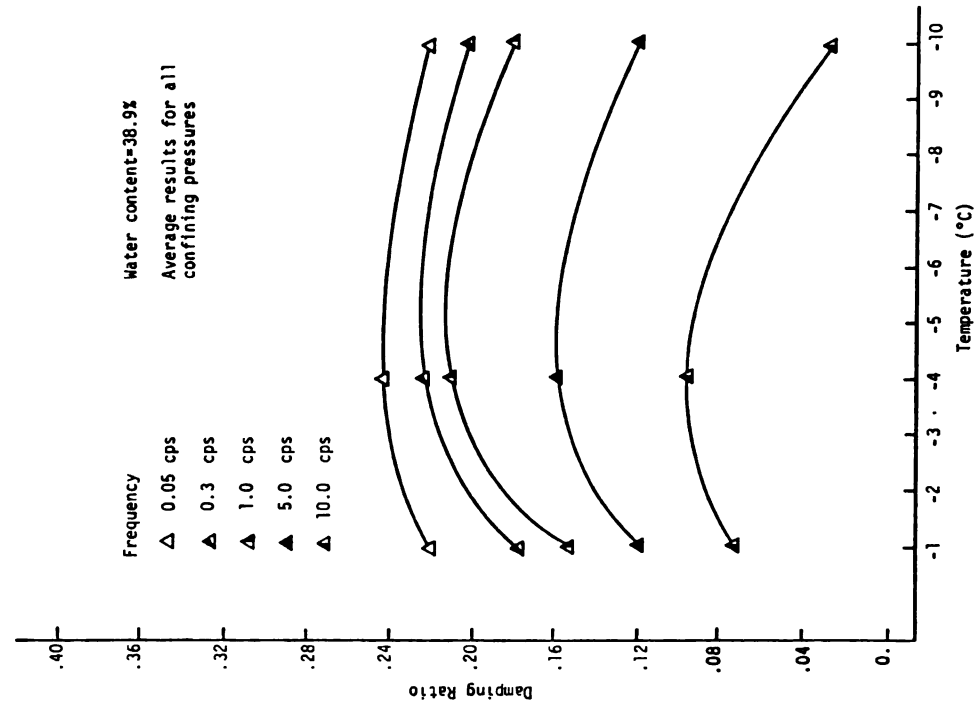


Figure 4.90 DAMPING RATIO VERSUS TEMPERATURE FOR ALASKA SILT AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

amplitudes (3.16×10^{-3} or $3.16 \times 10^{-2}\%$), and at one or more frequencies. In general, damping ratio decreases with decreasing temperature. The influence of temperature on damping ratio appears to be more significant at low water contents than at high water contents. At a low strain amplitude ($3.16 \times 10^{-3}\%$) at low water contents, the rate of decrease of damping ratio is generally greater in the high temperature range (-1 to -4°C) than in the low temperature range (-4 to -10°C); at high water contents the rate of decrease appears to be more uniform over the entire range of temperatures (-1 to -10°C). At a very high frequency (10.0 cps) there is an initial decrease in damping ratio from -1°C to -4°C followed by an increase from -4°C to -10°C .

At a high strain amplitude ($3.16 \times 10^{-2}\%$) the rate of decrease in damping ratio with decreasing temperature is generally somewhat less than at a low strain amplitude ($3.16 \times 10^{-3}\%$). In many cases, there appears to be either little change or a slight increase in damping ratio from -1 to -4°C followed by a gradual decrease from -4 to -10°C .

4.4.5 Effect of Water Content

The relationship between damping ratio and water content is given in Figures 4.91 to 4.102. Each figure represents the relationship for a silt at a particular temperature, at two axial strain amplitudes (3.16×10^{-3} and $3.16 \times 10^{-2}\%$), and at one or more frequencies. The relationships are based on only two data points with the exception of those for Alaska silt at a temperature of -1°C , which are based on three data points. At a temperature of -1°C ,

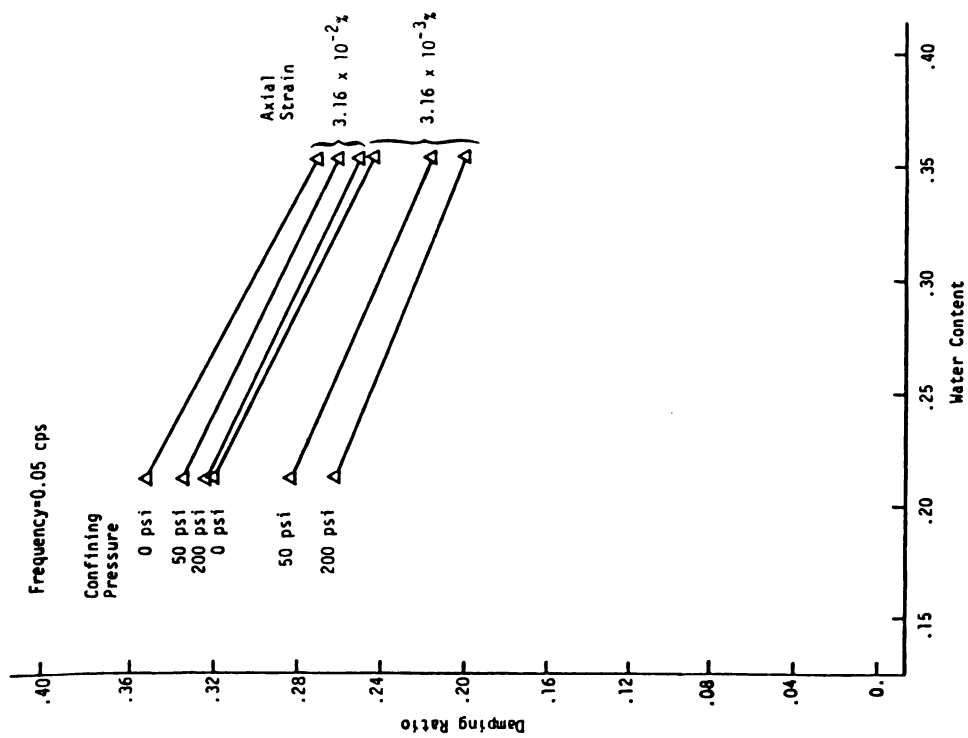


Figure 4.91 DAMPING RATIO VERSUS WATER CONTENT FOR HANOVER SILT AT A TEMPERATURE OF -1°C

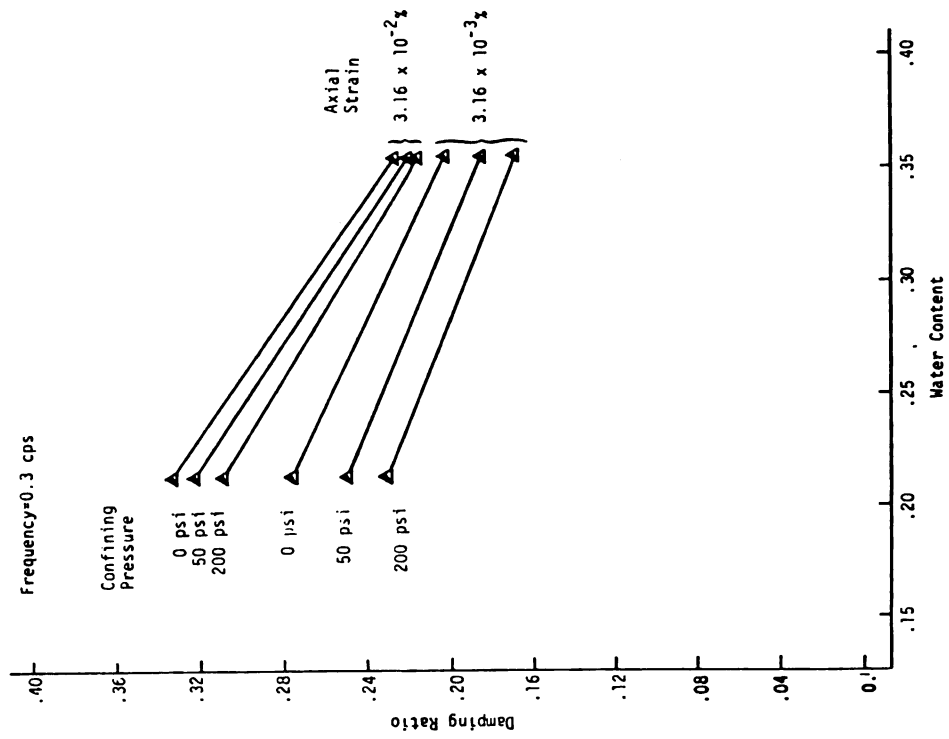


Figure 4.92 DAMPING RATIO VERSUS WATER CONTENT FOR HANOVER SILT AT A TEMPERATURE OF -1°C

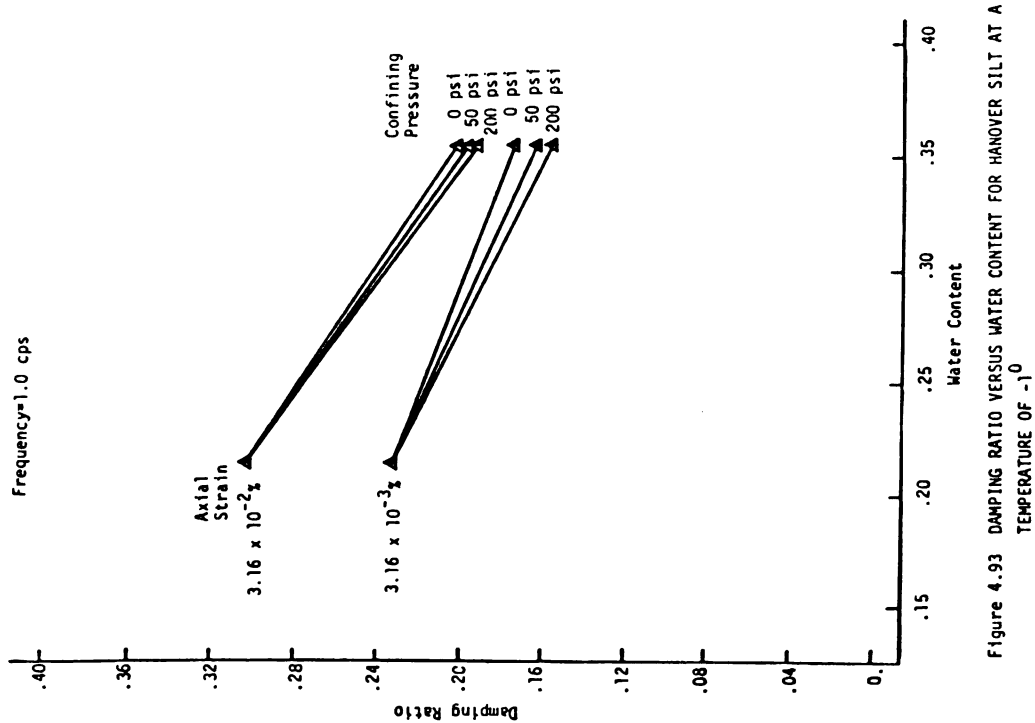


Figure 4.93 DAMPING RATIO VERSUS WATER CONTENT FOR HANOVER SILT AT A TEMPERATURE OF -10°C

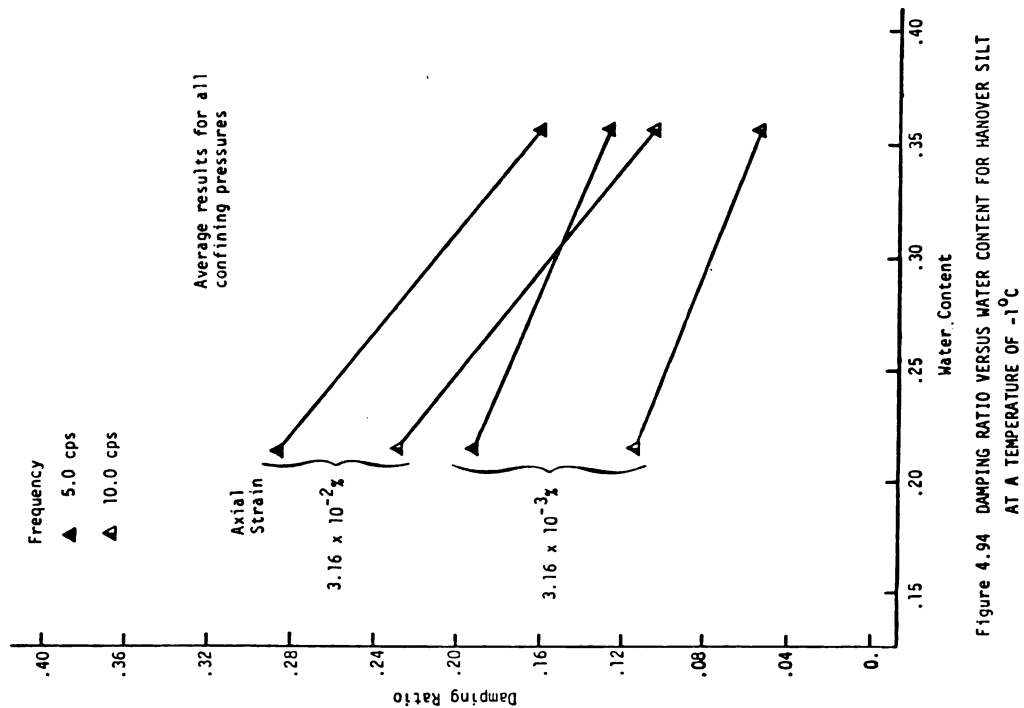


Figure 4.94 DAMPING RATIO VERSUS WATER CONTENT FOR HANOVER SILT AT A TEMPERATURE OF -1°C

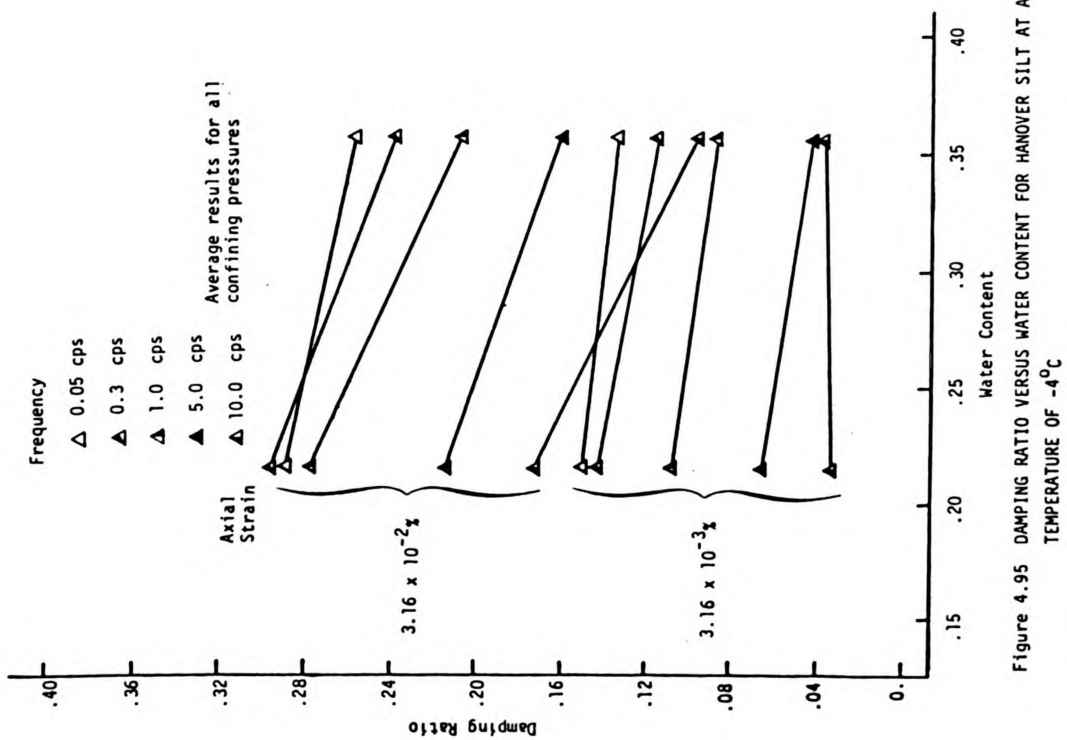


Figure 4.95 DAMPING RATIO VERSUS WATER CONTENT FOR HANOVER SILT AT A TEMPERATURE OF -4°C

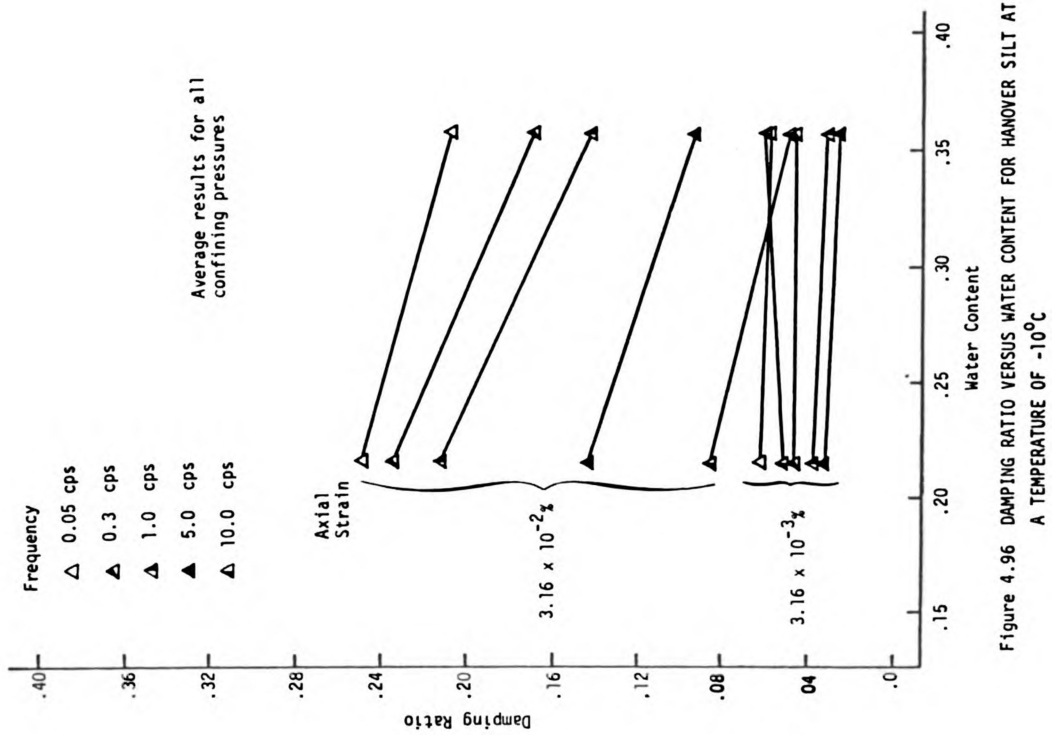


Figure 4.96 DAMPING RATIO VERSUS WATER CONTENT FOR HANOVER SILT AT A TEMPERATURE OF -10°C

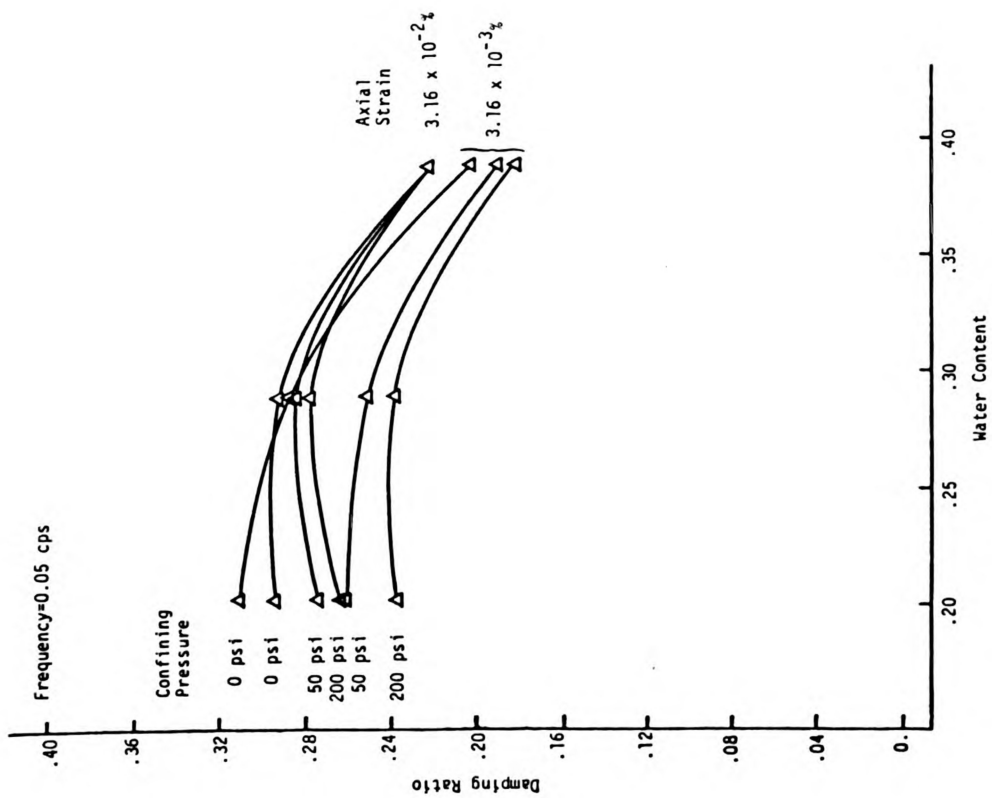


Figure 4.97 DAMPING RATIO VERSUS WATER CONTENT FOR ALASKA SILT
AT A TEMPERATURE OF -1°C

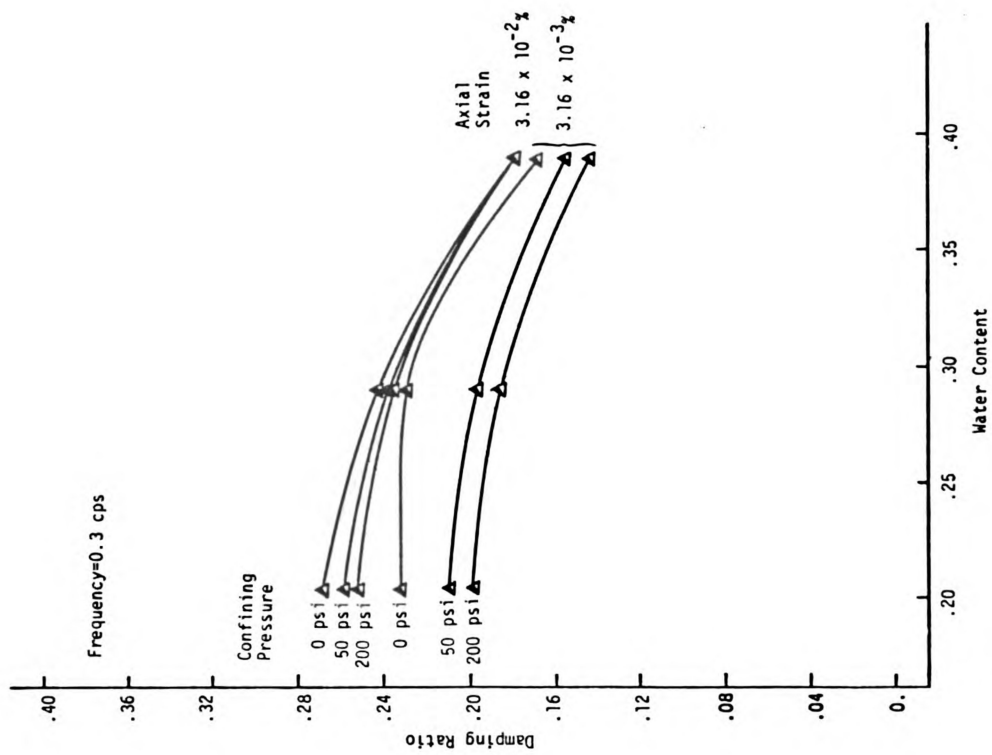


Figure 4.98 DAMPING RATIO VERSUS WATER CONTENT FOR ALASKA SILT
AT A TEMPERATURE OF -1°C

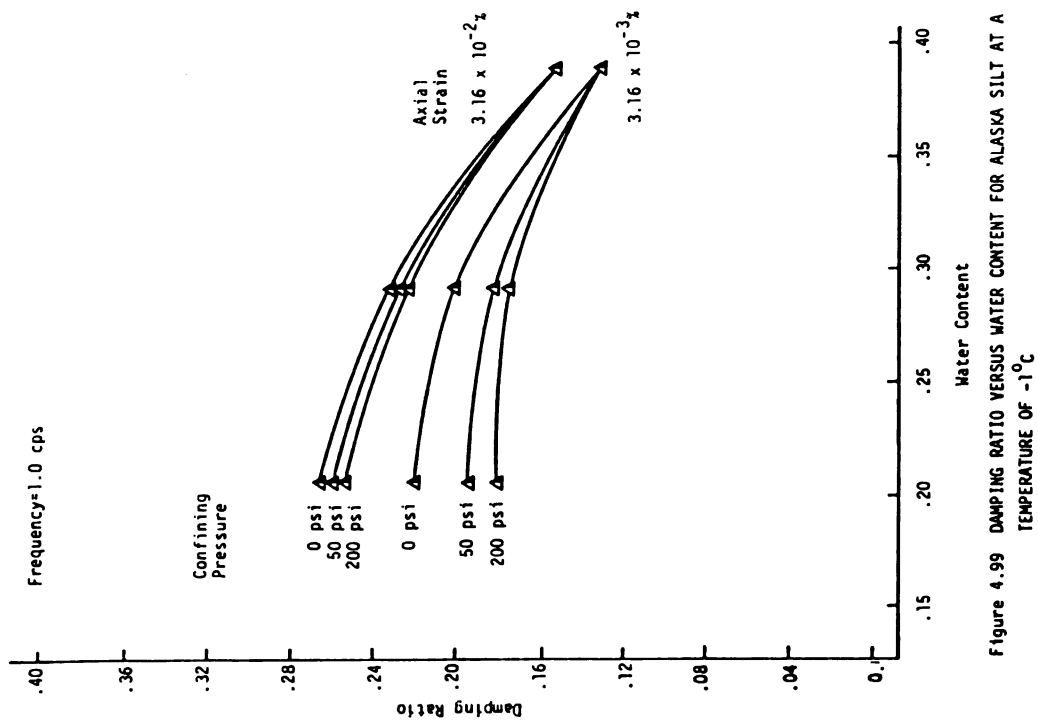


Figure 4.99 DAMPING RATIO VERSUS WATER CONTENT FOR ALASKA SILT AT A TEMPERATURE OF -1°C

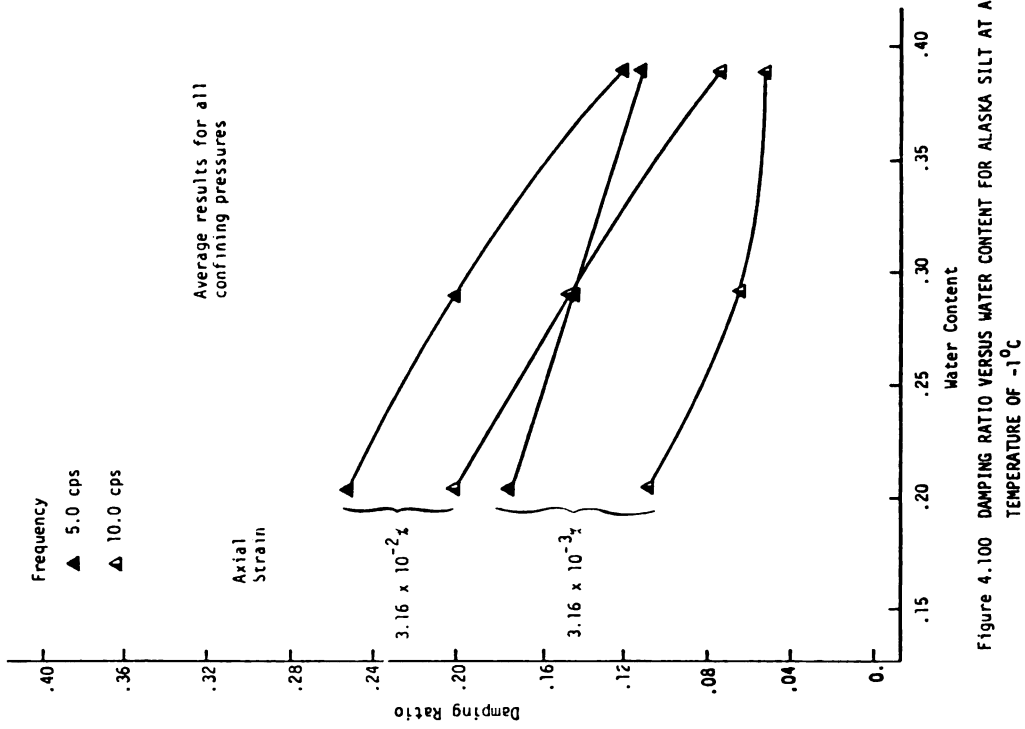


Figure 4.100 DAMPING RATIO VERSUS WATER CONTENT FOR ALASKA SILT AT A TEMPERATURE OF -1°C

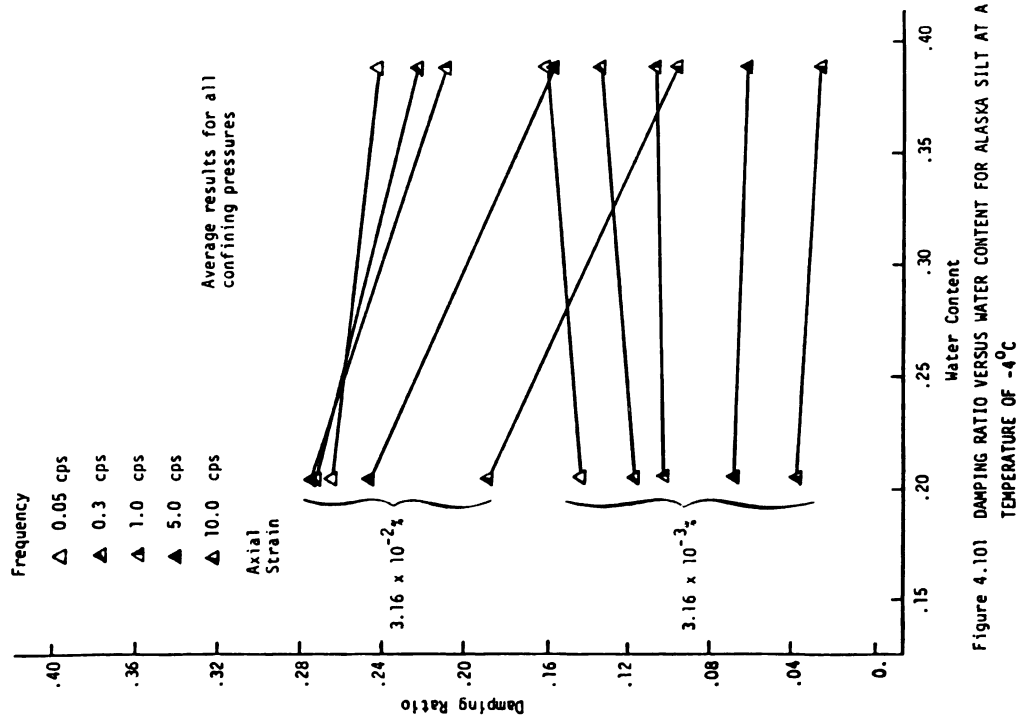


Figure 4.101 DAMPING RATIO VERSUS WATER CONTENT FOR ALASKA SILT AT A TEMPERATURE OF -4°C

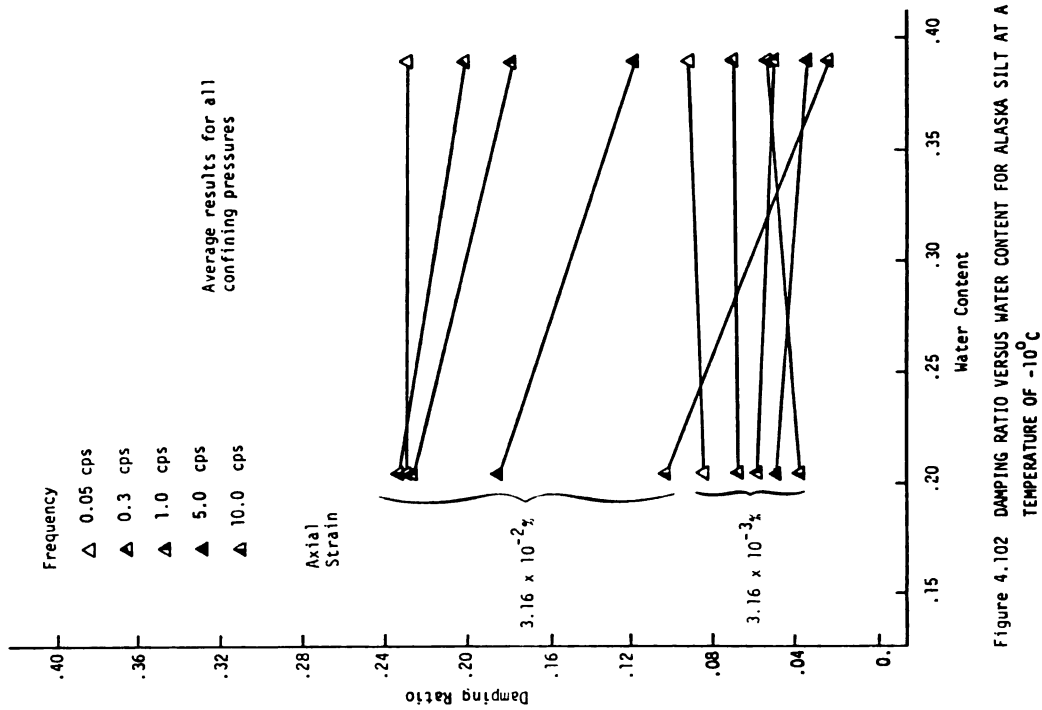


Figure 4.102 DAMPING RATIO VERSUS WATER CONTENT FOR ALASKA SILT AT A TEMPERATURE OF -10°C

damping ratio decreases significantly with increasing water content. The relationship does not seem to be significantly affected by strain amplitude. It appears that at low frequencies most of the decrease in damping ratio occurs in the higher water content range while at high frequencies the rate of decrease is more uniform over the entire range of water contents.

At lower temperatures (-4 and -10°C) there appears to be no significant influence of water content on damping ratio at a low strain amplitude ($3.16 \times 10^{-3}\%$). At a high strain amplitude ($3.16 \times 10^{-2}\%$) damping ratio decreases with increasing water content; the relationship appears to be dependent on frequency, with a slight decrease occurring at low frequencies and a more significant decrease at high frequencies.

CHAPTER 5

DYNAMIC PROPERTIES OF FROZEN CLAY UNDER CYCLIC TRIAXIAL LOADING CONDITIONS

5.1 General

Cyclic triaxial tests were conducted on the frozen kaolinite clay samples described in Chapter 3. The kaolinite samples were tested at two water contents to determine the influence of water content on the dynamic properties. To determine the influence of additional parameters which might affect the dynamic properties of frozen clay, samples were tested at temperatures of -1, -4, and -10°C, confining pressures of 0, 50, and 200 psi, frequencies of 0.05, 0.3, 1.0, 5.0, and 10.0 cps, and axial strain amplitudes from .002 to .08%.

5.2 Testing Sequence

The testing history used on the frozen clay samples was the same as that used for the frozen silt samples and is shown in Figure 4.1. The ranges of the various test condition parameters (temperature, axial strain amplitude, confining pressure, frequency, and number of cycles of loading) were also the same as those for the frozen silt samples. The clay samples were tested at water contents of 28.1 and 71.3%. The testing apparatus, procedure, and data recording and reduction methods are as described in Chapter 4.

5.3 Dynamic Young's Modulus of Frozen Clay

Values of dynamic Young's modulus were plotted versus the log of axial strain amplitude expressed as a percent for all loading conditions. The plots for clay at both water contents are given in

Appendix C. Each plot represents clay at a particular water content, temperature, and frequency. Data from at least two samples are included in each plot; in general, there is good agreement between data points from duplicate samples.

It was apparent from the test results that confining pressure had a negligible influence on dynamic Young's modulus of frozen clay. A typical relationship between dynamic Young's modulus and confining pressure is shown in Figure 5.1. Since dynamic Young's modulus was not significantly influenced by confining pressure, data points for all three confining pressures were plotted together.

5.3.1 Effect of Strain Amplitude

To assess the influence of axial strain amplitude on dynamic Young's modulus of frozen clay, average "best fit" curves were drawn through the data points given in the plots in Appendix C. The relationships obtained are summarized in Figures 5.2 to 5.4. Each curve represents the relationship between dynamic Young's modulus and axial strain amplitude for clay at a particular water content, temperature, and frequency. Values of dynamic Young's modulus for frozen clay range from 1×10^5 to 14.5×10^5 psi.

Dynamic Young's modulus decreases with increasing axial strain amplitude. At a temperature of -1°C , the rate of decrease is fairly uniform over the range of strain amplitudes while at a temperature of -10°C the rate of decrease increases significantly at higher strain amplitudes. The relationship at -4°C is intermediate between those at -1 and -10°C . The relationship between dynamic Young's modulus and strain amplitude does not appear to be affected by frequency or water content.

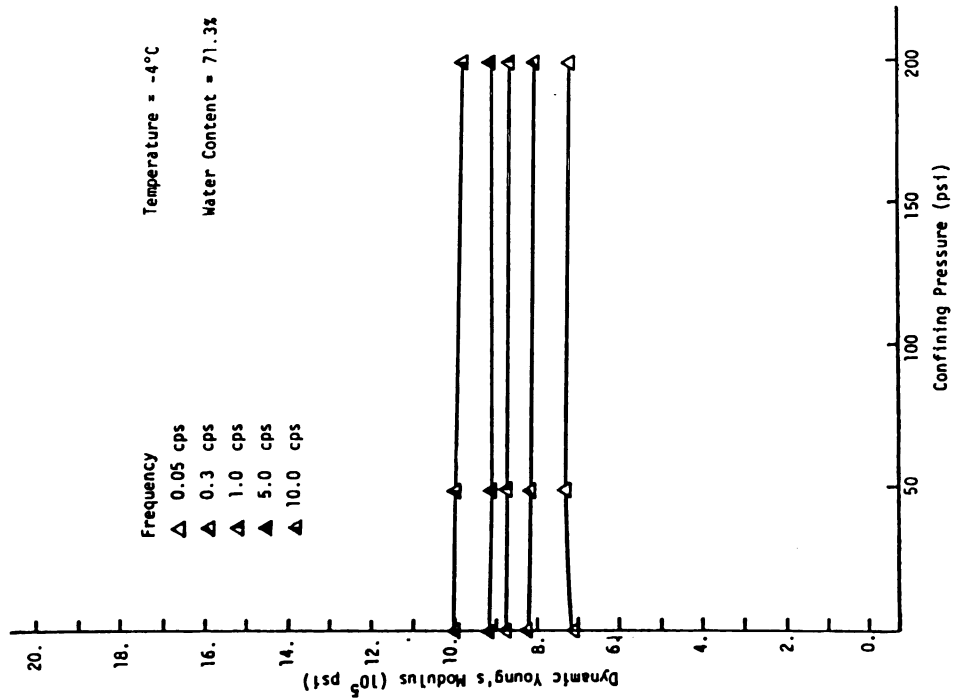


Figure 5.1 DYNAMIC YOUNG'S MODULUS VERSUS CONFINING PRESSURE FOR KAOLINITE AT AN AXIAL STRAIN OF 5.0×10^{-3}

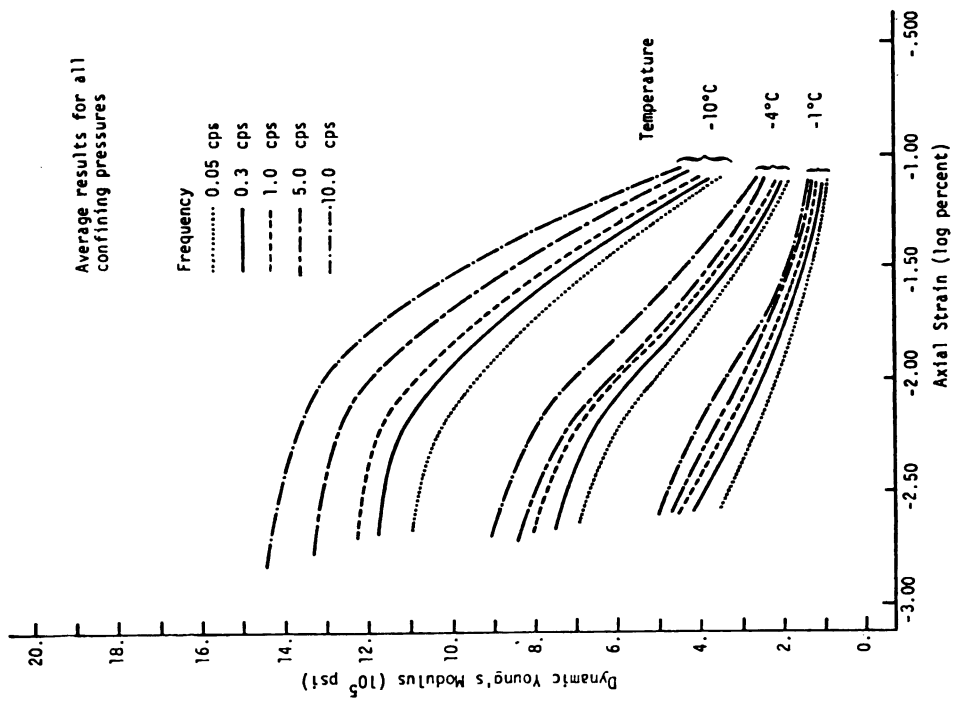


Figure 5.2 DYNAMIC YOUNG'S MODULUS VERSUS AXIAL STRAIN FOR KAOLINITE AT 28.1% WATER CONTENT

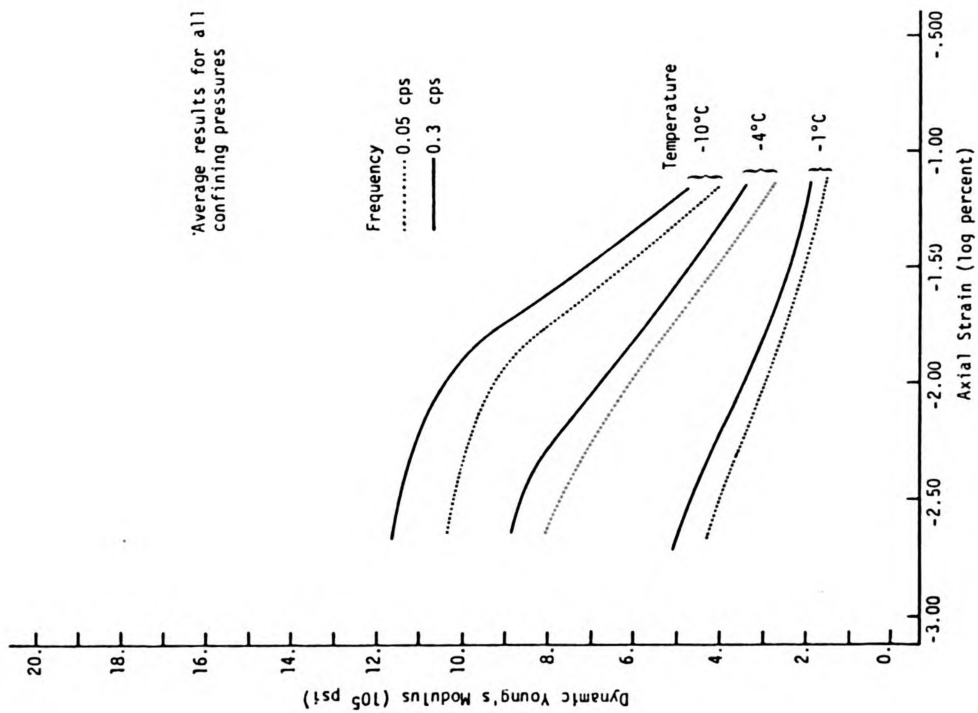


Figure 5.3 DYNAMIC YOUNG'S MODULUS VERSUS AXIAL STRAIN FOR KAOLINITE AT 71.3% WATER CONTENT

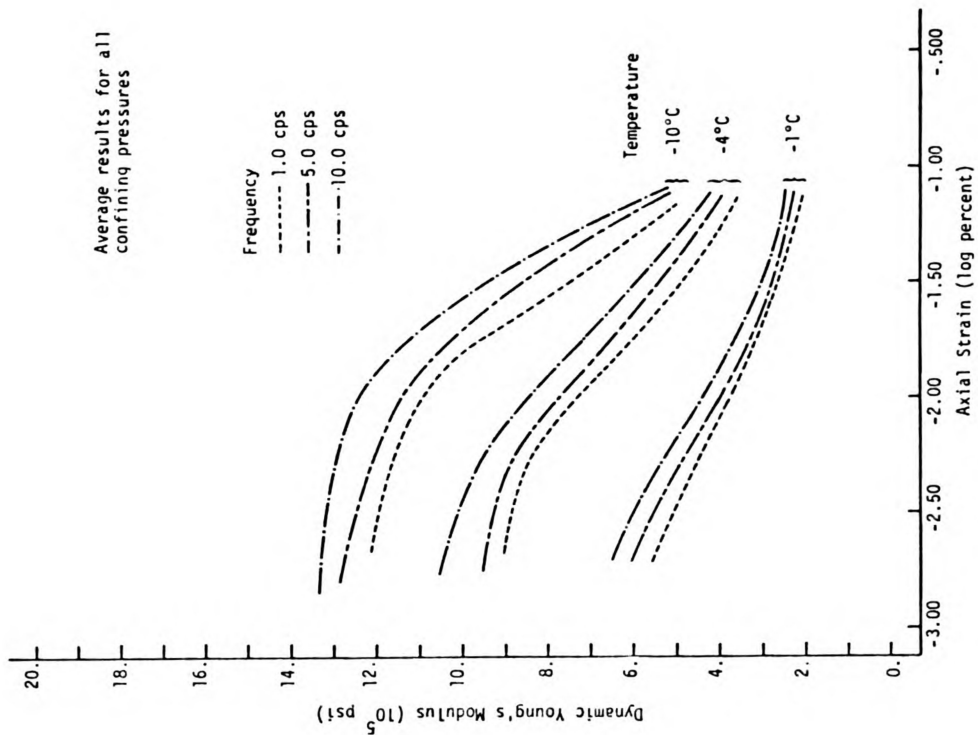


Figure 5.4 DYNAMIC YOUNG'S MODULUS VERSUS AXIAL STRAIN FOR KAOLINITE AT 71.3% WATER CONTENT

To assess the influence of frequency, temperature, and water content on dynamic Young's modulus, values of dynamic Young's modulus were obtained from the plots of dynamic Young's modulus versus axial strain amplitude and plotted versus frequency, temperature, and water content, respectively. The modulus values were chosen at axial strain amplitudes of 3.16×10^{-3} and $3.16 \times 10^{-2}\%$.

5.3.2 Effect of Frequency

The relationship between dynamic Young's modulus and frequency is shown in Figures 5.5 to 5.8. Each graph represents the relationship at a given strain amplitude and water content at all three temperatures (-1, -4, and -10°C). In general, dynamic Young's modulus increases by a small amount as frequency increases. The rate of increase is fairly constant over the frequency range 0.05 to 5.0 cps, but increases somewhat in the frequency range 5.0 to 10.0 cps. The relationship does not appear to be significantly influenced by temperature, strain amplitude, or water content.

5.3.3 Effect of Temperature

The relationship between dynamic Young's modulus and temperature is shown in Figures 5.9 to 5.12; each graph represents the relationship at a given strain amplitude and water content at all frequencies (0.05, 0.3, 1.0, 5.0, and 10.0 cps). Dynamic Young's modulus increases significantly with decreasing temperature. The rate of increase is generally more uniform over the entire temperature range (-1 to -10°C) at a high strain amplitude ($3.16 \times 10^{-2}\%$) and a low water content (28.1%). At a low strain amplitude ($3.16 \times 10^{-3}\%$) the rate of increase is somewhat greater in the high tempera-

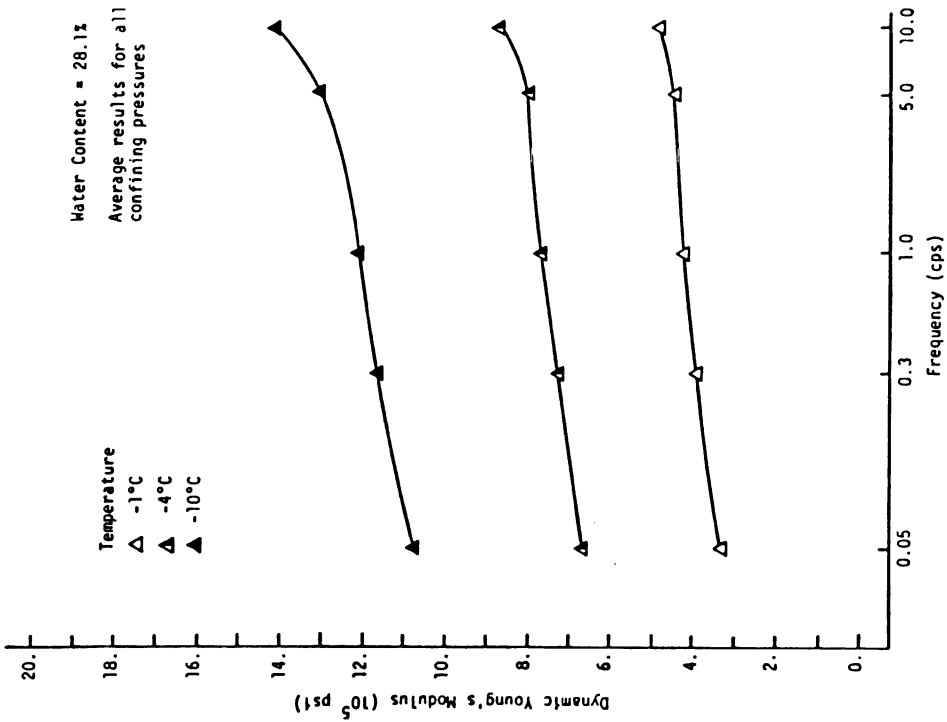


Figure 5.5 DYNAMIC YOUNG'S MODULUS VERSUS FREQUENCY FOR KAOLINITE
AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

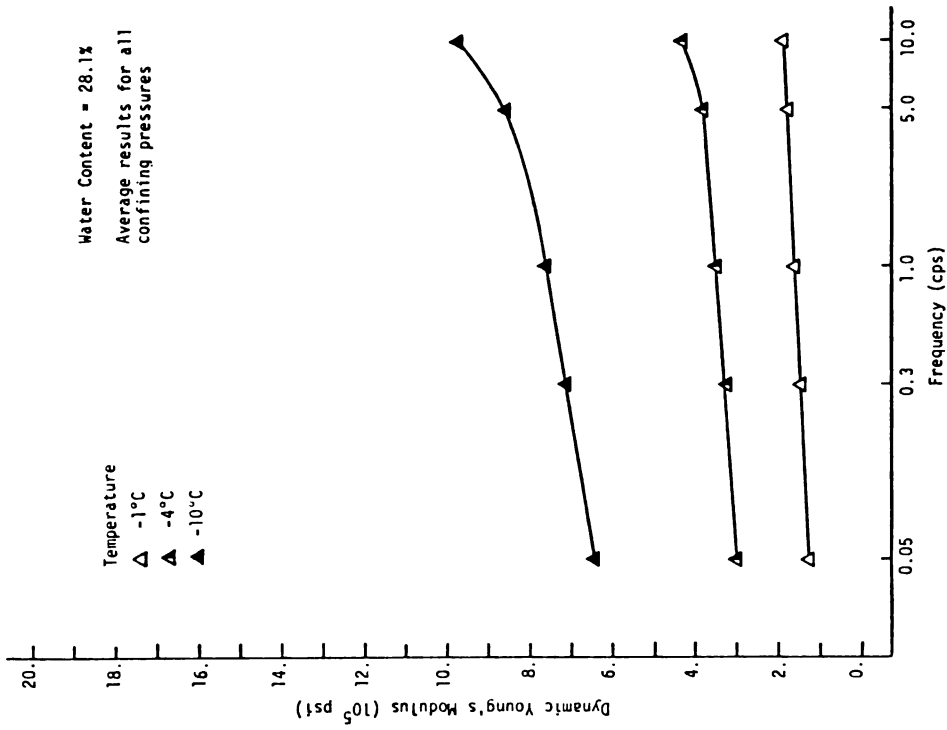


Figure 5.6 DYNAMIC YOUNG'S MODULUS VERSUS FREQUENCY FOR KAOLINITE
AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

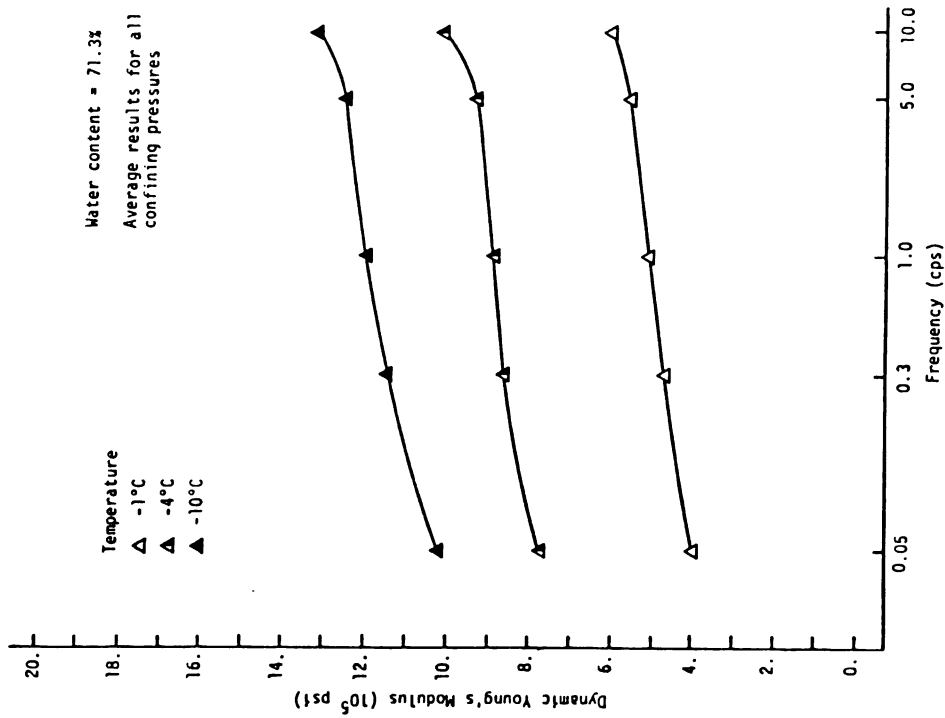


Figure 5.7 DYNAMIC YOUNG'S MODULUS VERSUS FREQUENCY FOR KAOLINITE
AT AN AXIAL STRAIN OF 3.16×10^{-3}

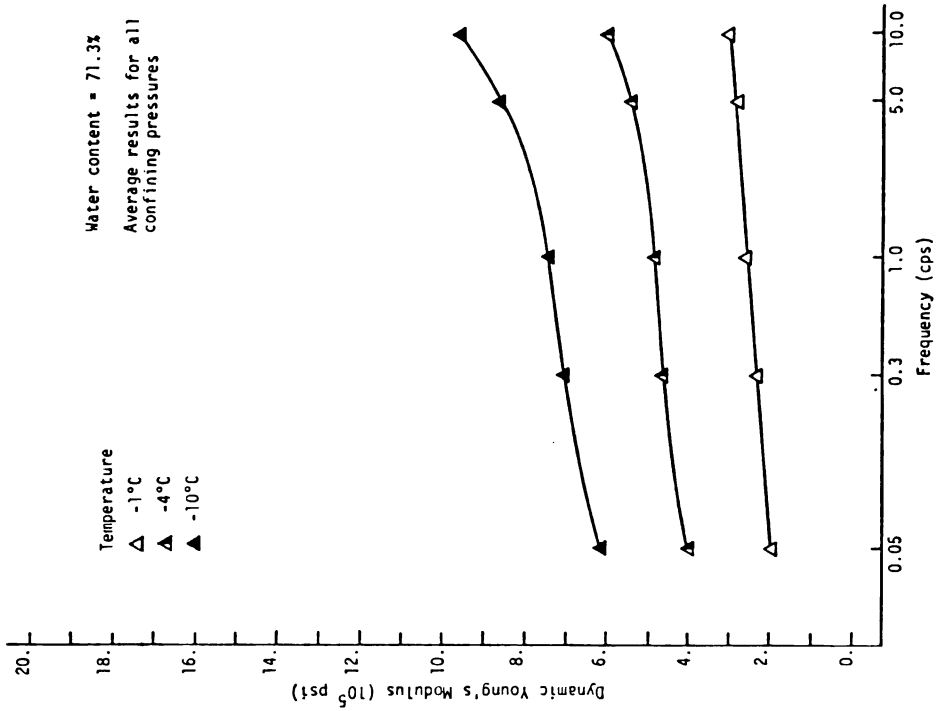


Figure 5.8 DYNAMIC YOUNG'S MODULUS VERSUS FREQUENCY FOR KAOLINITE
AT AN AXIAL STRAIN OF 3.16×10^{-2}

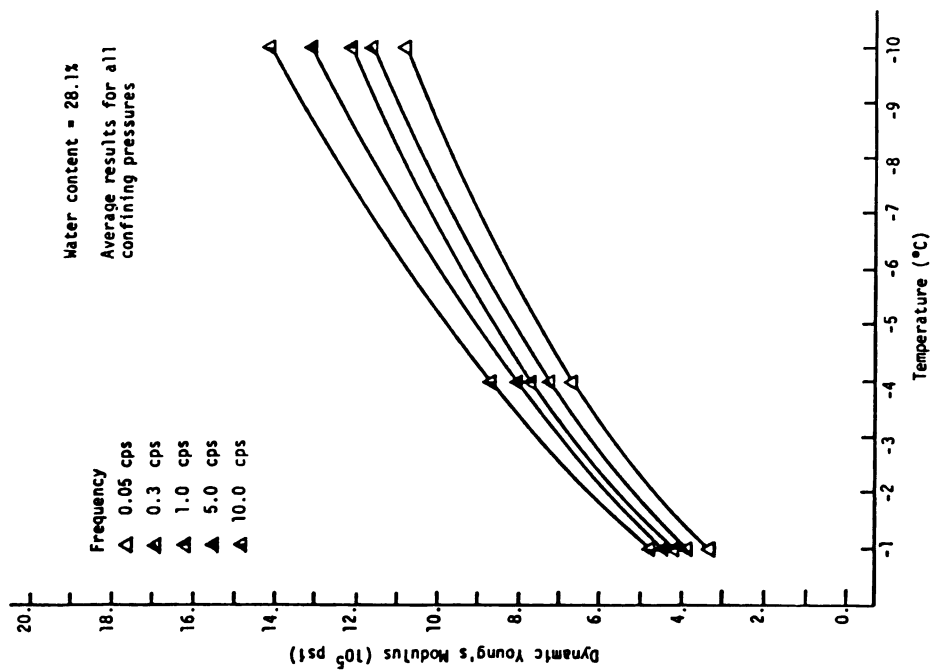


Figure 5.9 DYNAMIC YOUNG'S MODULUS VERSUS TEMPERATURE FOR
KAOLINITE AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

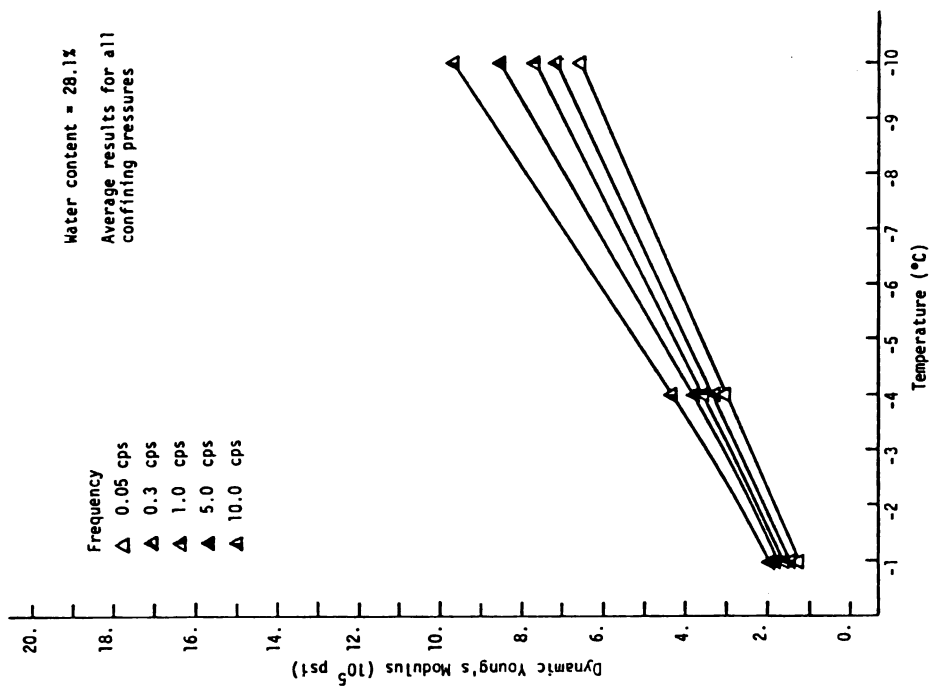


Figure 5.10 DYNAMIC YOUNG'S MODULUS VERSUS TEMPERATURE FOR
KAOLINITE AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

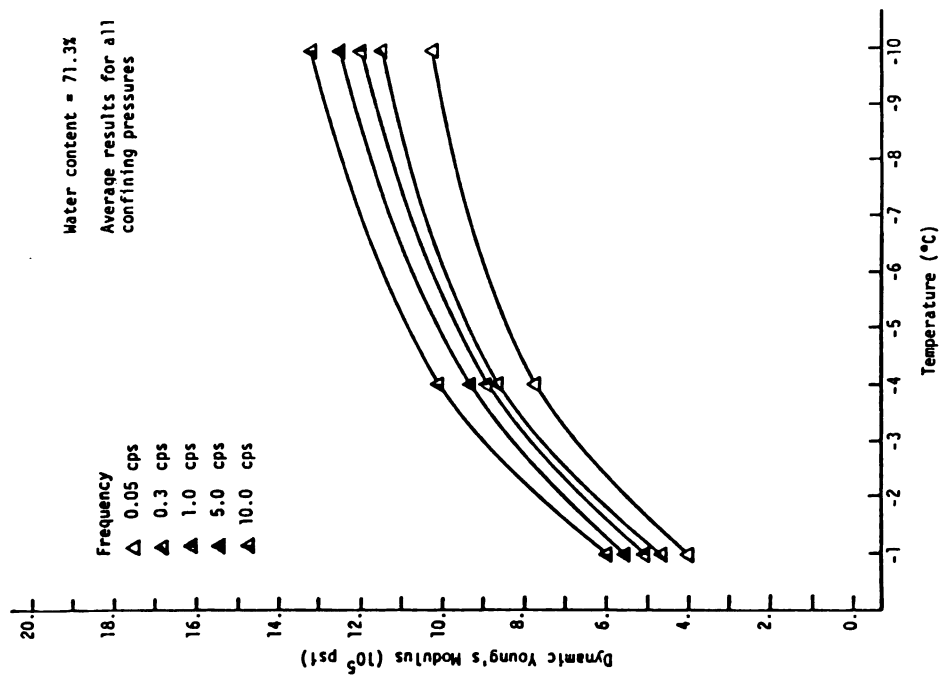


Figure 5.11 DYNAMIC YOUNG'S MODULUS VERSUS TEMPERATURE FOR
KAOLINITE AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

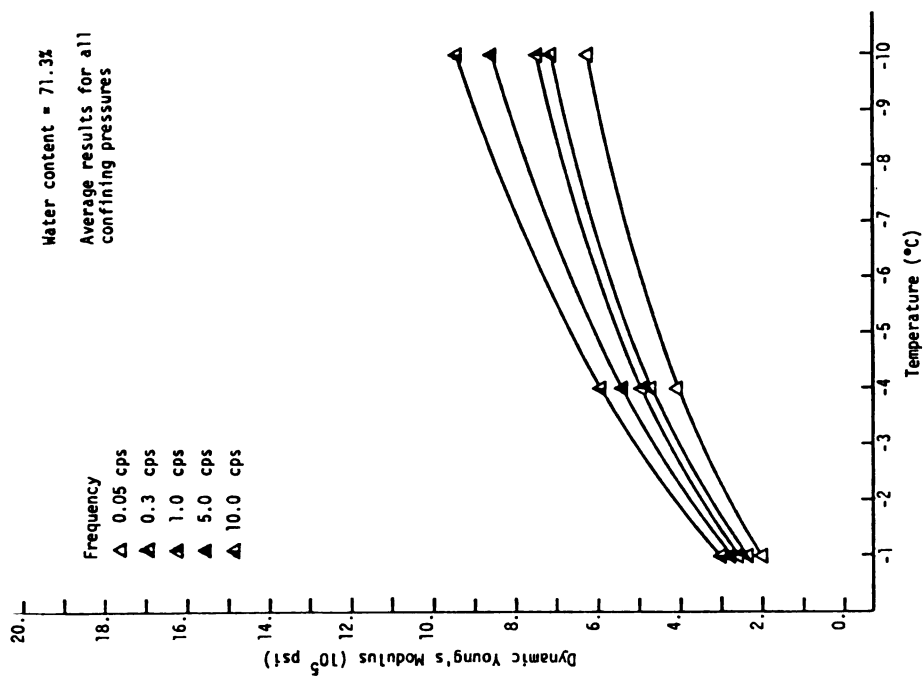


Figure 5.12 DYNAMIC YOUNG'S MODULUS VERSUS TEMPERATURE FOR
KAOLINITE AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

ture range (-1 to -4°C) than in the low temperature range (-4 to -10°C). The relationship does not appear to be influenced by frequency.

5.3.4 Effect of Water Content

The relationship between dynamic Young's modulus and water content is shown in Figures 5.13 and 5.14. Each curve is based on two points and represents the relationship at a given strain amplitude, temperature, and frequency. At higher temperatures (-1 and -4°C) dynamic Young's modulus increases by a small amount with increasing water content. The relationship is not influenced by frequency or strain amplitude. At a low temperature (-10°C) dynamic Young's modulus appears to decrease slightly with increasing water content at a low strain amplitude ($3.16 \times 10^{-3}\%$) and is not significantly influenced by water content at a high strain amplitude ($3.16 \times 10^{-2}\%$).

5.4 Damping Ratio of Frozen Clay

Values of damping ratio were plotted versus the log of axial strain expressed as a percent for all loading conditions. The plots for clay at both water contents are given in Appendix D. Each plot represents clay at a particular water content, temperature, and frequency. Data points for all three confining pressures (0, 50, and 200 psi) are included in each plot. Each plot represents at least two samples; the agreement between the data points of duplicate samples is generally good. Some minor scatter of data points at low damping ratio values is probably due to limitations in the recording and reduction methods. In general, however, the data is considered

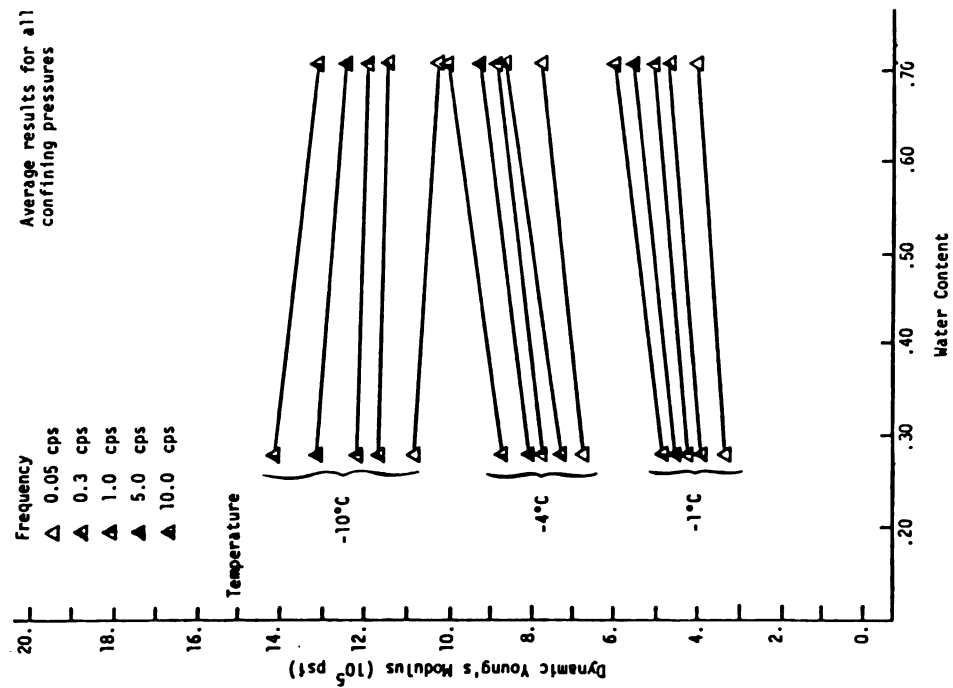


Figure 5.13 DYNAMIC YOUNG'S MODULUS VERSUS WATER CONTENT FOR KAOLINITE AT AN AXIAL STRAIN OF 3.16×10^{-3}

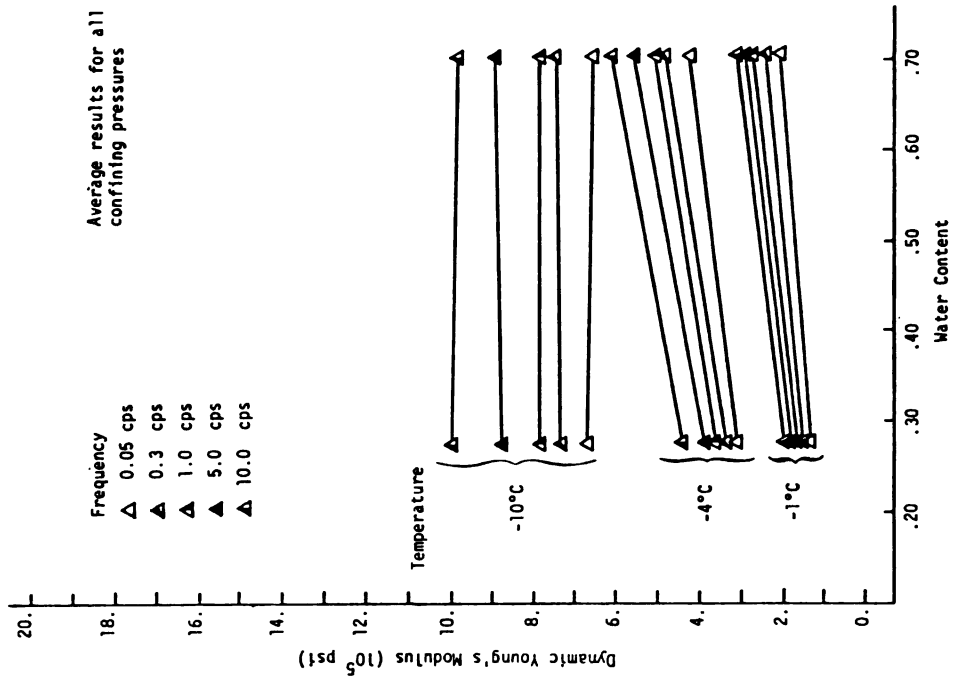


Figure 5.14 DYNAMIC YOUNG'S MODULUS VERSUS WATER CONTENT FOR KAOLINITE AT AN AXIAL STRAIN OF 3.16×10^{-2}

quite reliable.

5.4.1 Effect of Strain Amplitude

To assess the influence of axial strain amplitude on the damping ratio of frozen clay, average "best fit" curves were drawn through the data points given in the plots in Appendix D. The relationship between damping ratio and strain amplitude is summarized in Figures 5.15 to 5.24. Each graph represents the relationship for clay at a particular water content and frequency at each of three temperatures (-1, -4, and -10°C). In cases where confining pressure appeared to have an influence on damping ratio, separate curves are given for each confining pressure (0, 50, and 200 psi).

Damping ratio generally increases with increasing strain amplitude. In most instances, the rate of increase is greater at higher strain amplitudes than at lower strain amplitudes. The influence of strain amplitude on damping ratio is greater at lower frequencies than at higher frequencies; at the highest frequency (10.0 cps) there is an initial decrease in damping ratio at low strain amplitudes followed by an increase at higher strain amplitudes. The relationship between damping ratio and strain amplitude does not appear to be significantly influenced by water content or temperature.

To assess the influence of confining pressure, frequency, temperature, and water content on damping ratio, values of damping ratio were obtained from the plots of damping ratio versus axial strain amplitude in Figures 5.15 to 5.24 and Appendix D and plotted versus confining pressure, frequency, temperature, and water content, respectively. Damping ratio values were obtained at strain amplitudes of 3.16×10^{-3} and $3.16 \times 10^{-2}\%$.

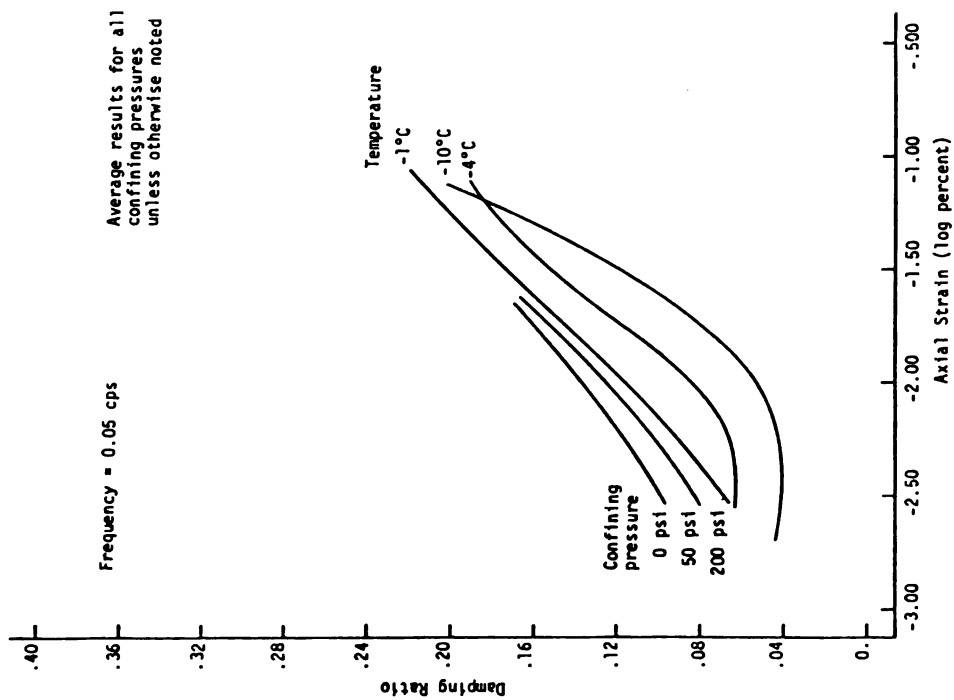


Figure 5.15 DAMPING RATIO VERSUS AXIAL STRAIN FOR KAOLINITE AT 28.1% WATER CONTENT

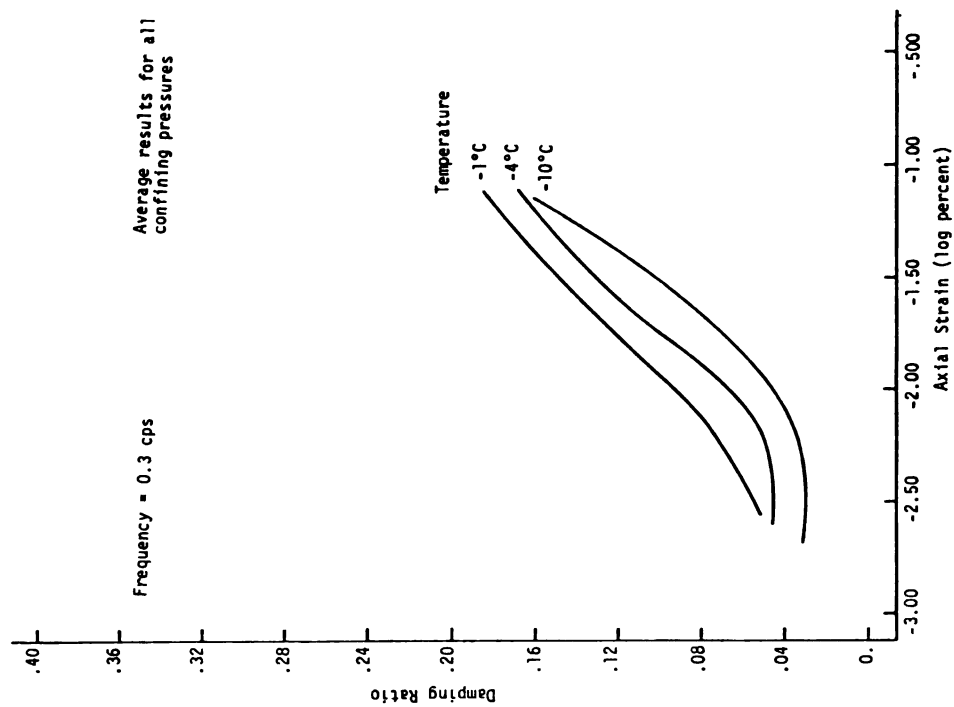


Figure 5.16 DAMPING RATIO VERSUS AXIAL STRAIN FOR KAOLINITE AT 28.1% WATER CONTENT

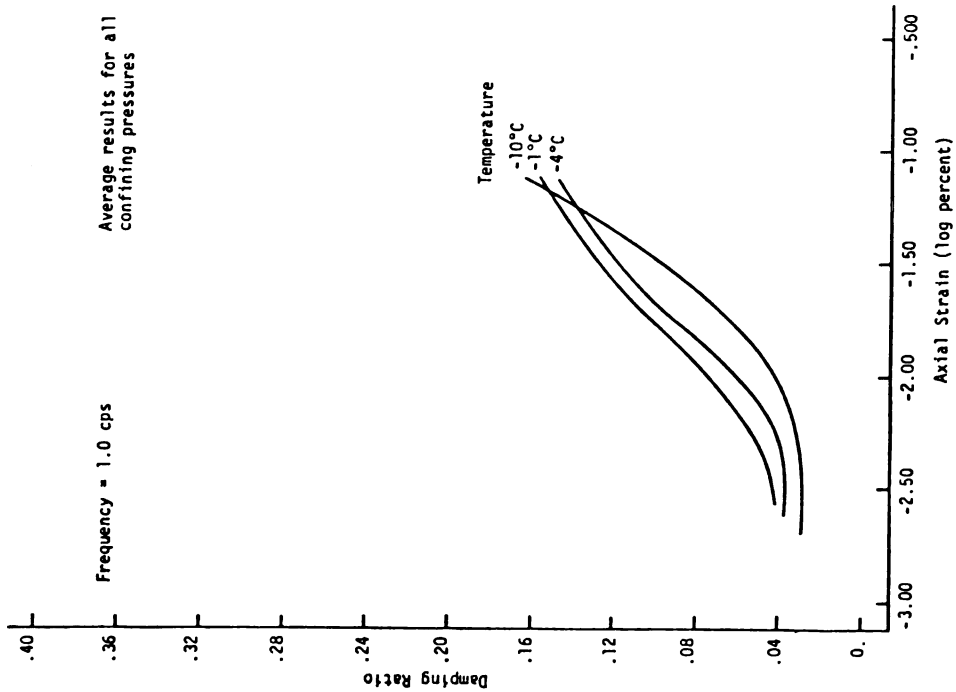


Figure 5.17 DAMPING RATIO VERSUS AXIAL STRAIN FOR KAOLINITE AT
28.1% WATER CONTENT

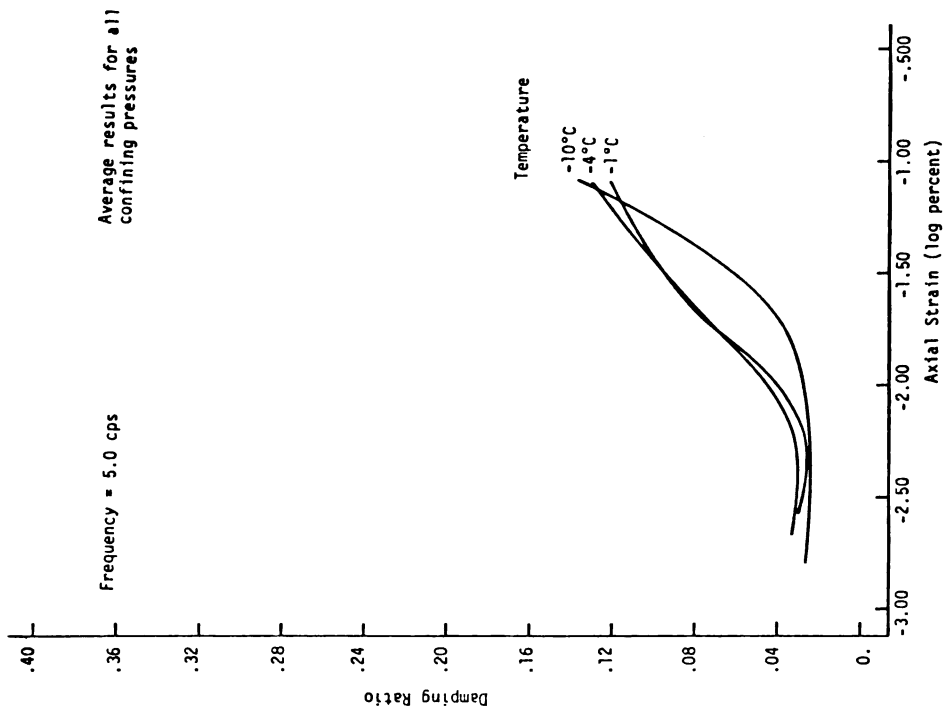


Figure 5.18 DAMPING RATIO VERSUS AXIAL STRAIN FOR KAOLINITE AT
28.1% WATER CONTENT

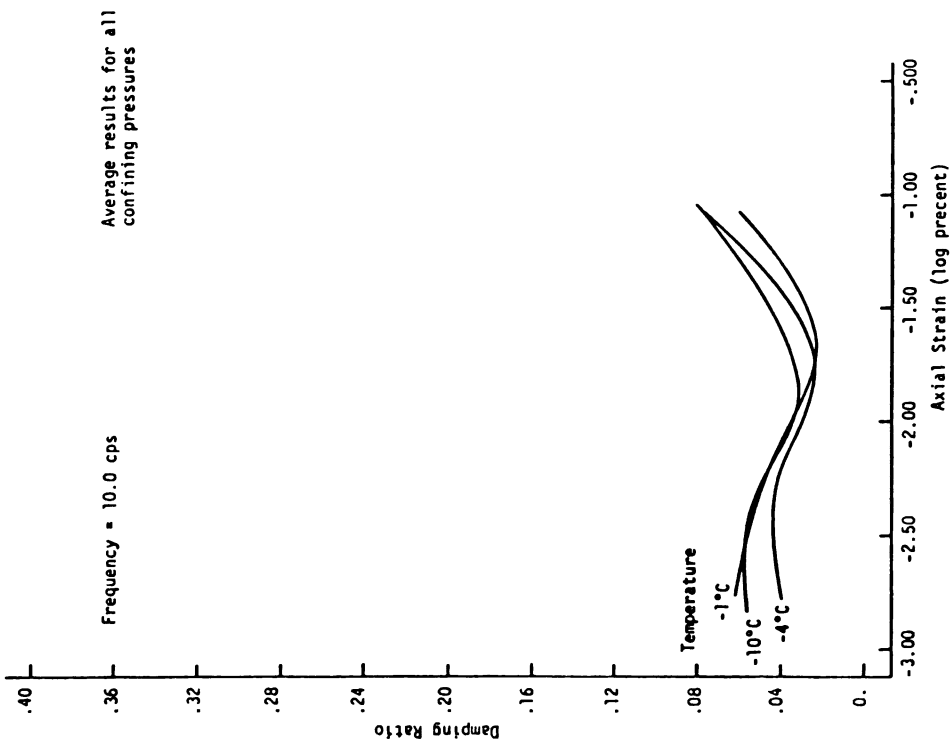


Figure 5.19 DAMPING RATIO VERSUS AXIAL STRAIN FOR KAOLINITE AT
28.1 WATER CONTENT

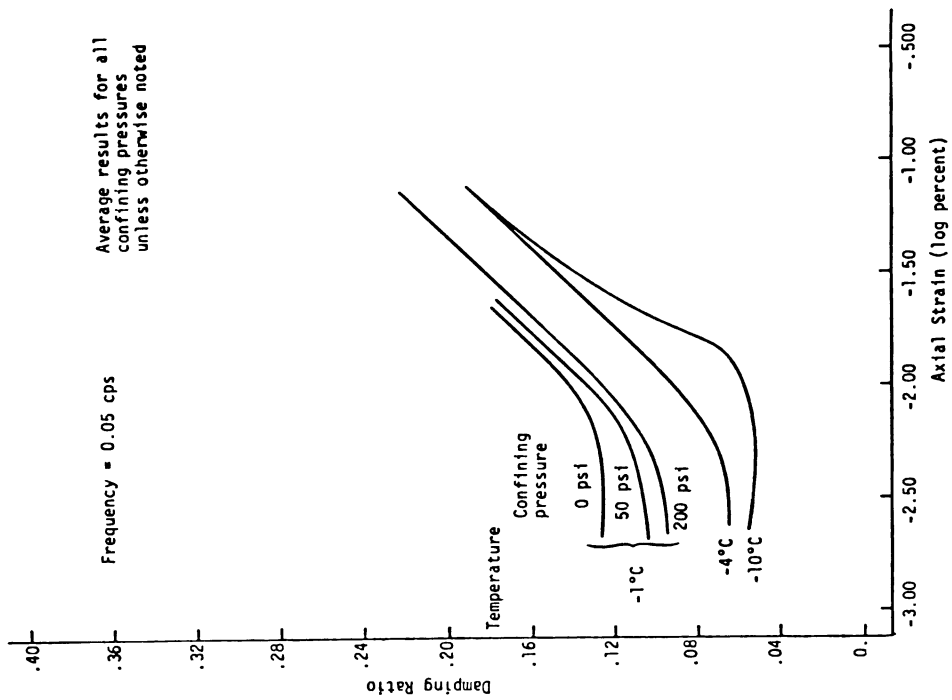


Figure 5.20 DAMPING RATIO VERSUS AXIAL STRAIN FOR KAOLINITE AT
71.3% WATER CONTENT

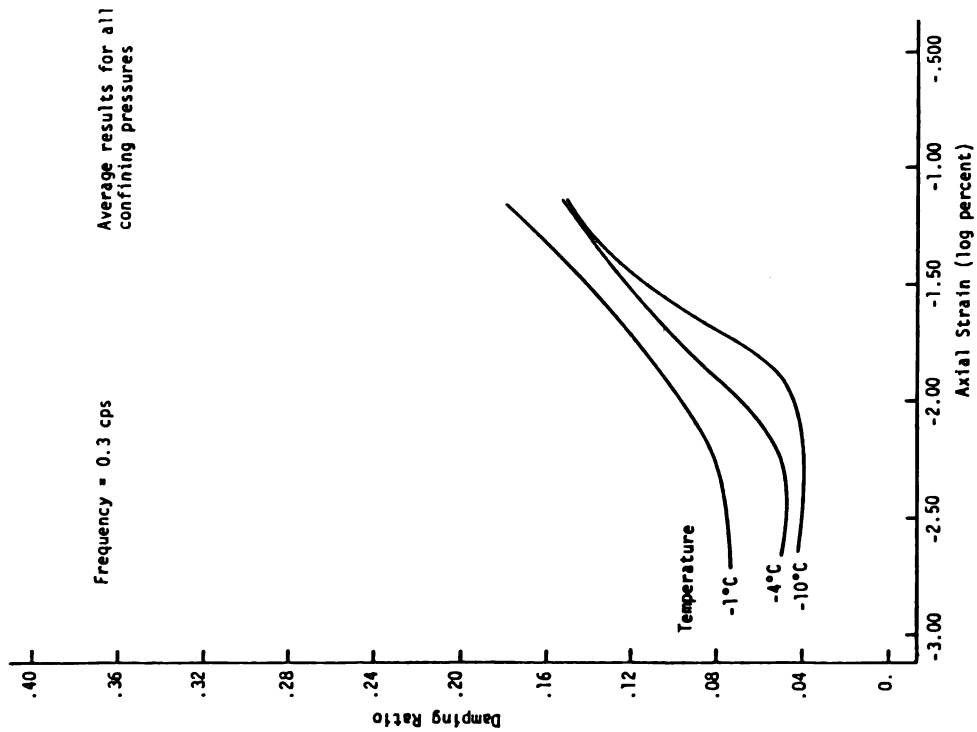


Figure 5.21 DAMPING RATIO VERSUS AXIAL STRAIN FOR KAOLINITE AT
71.3% WATER CONTENT

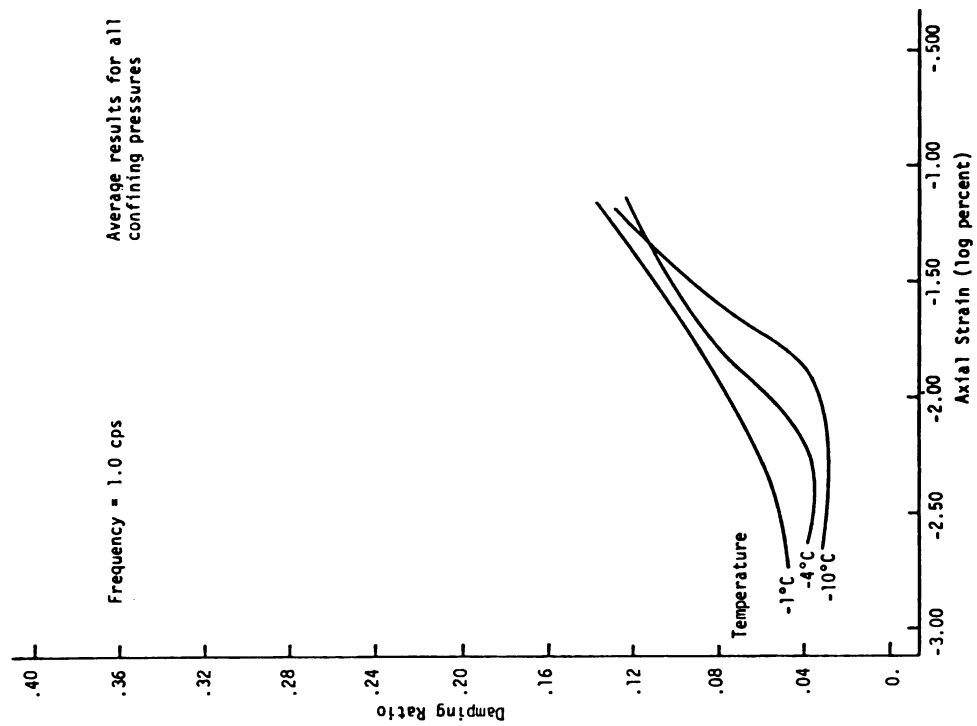


Figure 5.22 DAMPING RATIO VERSUS AXIAL STRAIN FOR KAOLINITE AT
71.3% WATER CONTENT

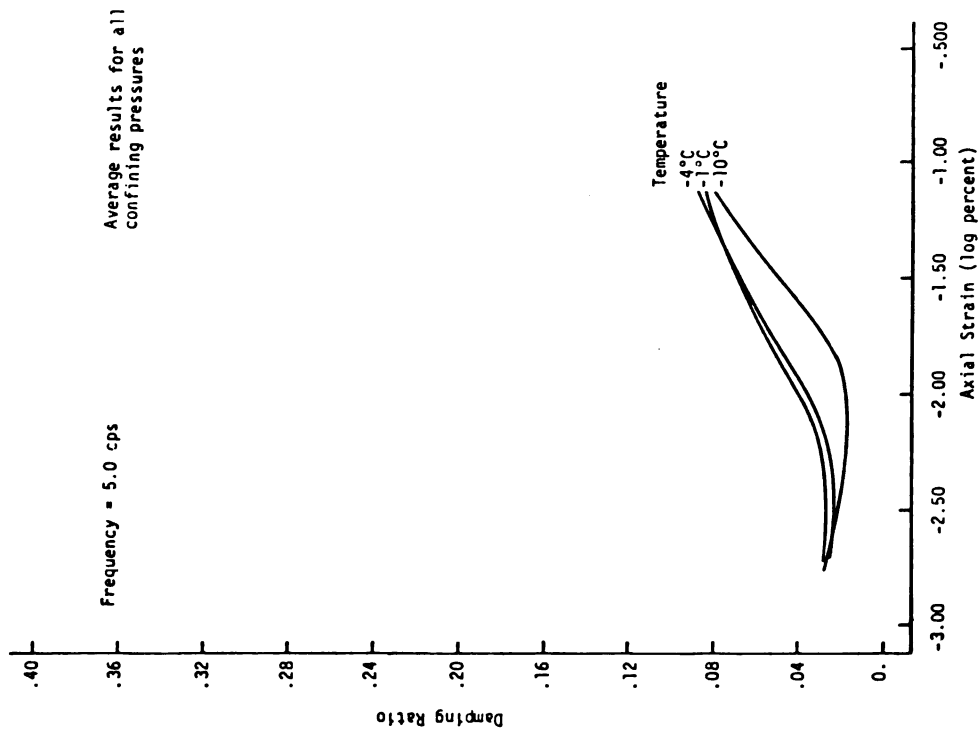


Figure 5.23 DAMPING RATIO VERSUS AXIAL STRAIN FOR KAOLINITE AT 71.3% WATER CONTENT

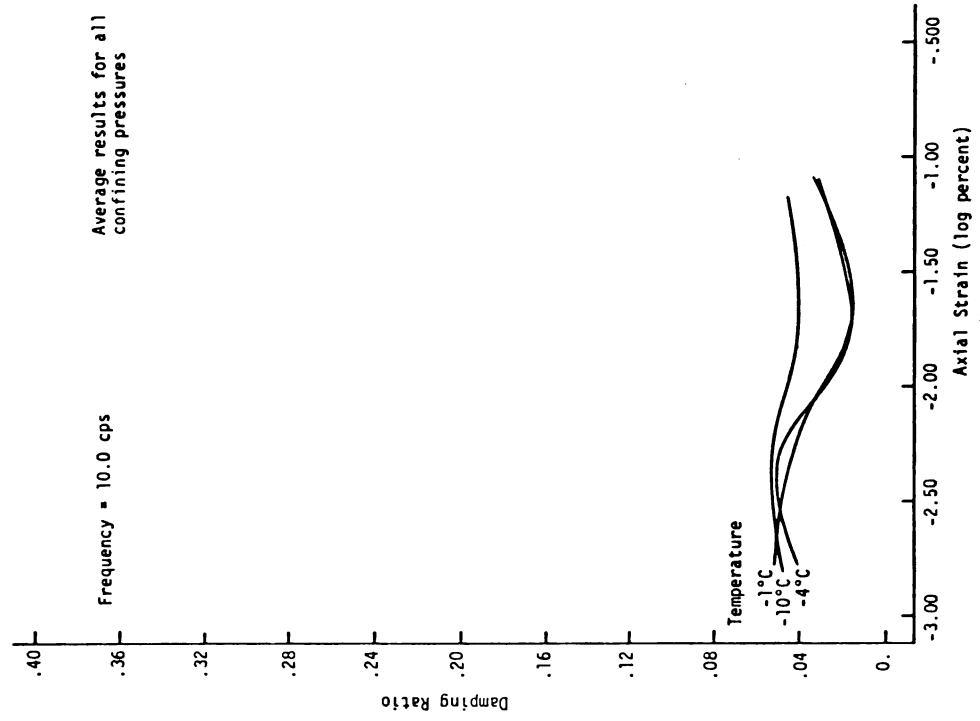


Figure 5.24 DAMPING RATIO VERSUS AXIAL STRAIN FOR KAOLINITE AT 71.3% WATER CONTENT

5.4.2 Effect of Confining Pressure

The influence of confining pressure on damping ratio is summarized in Figures 5.25 and 5.26. Since it was apparent that confining pressure did not influence damping ratio at low temperatures (-4 and -10°C), plots are shown only for the relationships at -1°C. At a low strain amplitude ($3.16 \times 10^{-3}\%$) damping ratio decreases slightly with increasing confining pressure at the lowest frequency (0.05 cps). The rate of decrease is greater in the low confining pressure range (0 to 50 psi) than in the high confining pressure range (50 to 200 psi). At frequencies greater than 0.05 cps and at a higher strain amplitude ($3.16 \times 10^{-2}\%$) confining pressure does not have a significant influence on damping ratio. The relationship is not influenced by water content.

5.4.3 Effect of Frequency

The relationship between damping ratio and frequency is summarized in Figures 5.27 to 5.30. Each graph represents the relationship at a given water content and strain amplitude at all three temperatures (-1, -4, and -10°C). At a low strain amplitude ($3.16 \times 10^{-3}\%$) damping ratio decreases by a small amount with increasing frequency to a minimum value at approximately 5.0 cps and then increases sharply between 5.0 and 10.0 cps. The relationship at a low strain amplitude is not influenced significantly by water content or temperature. At a high strain amplitude ($3.16 \times 10^{-2}\%$) damping ratio decreases with increasing frequency over the entire range of frequencies. At higher temperatures (-1 and -4°C) the rate of decrease is fairly uniform from 0.05 to 5.0 cps and significantly greater from 5.0 to 10.0 cps. At a low temperature (-10°C) the rate

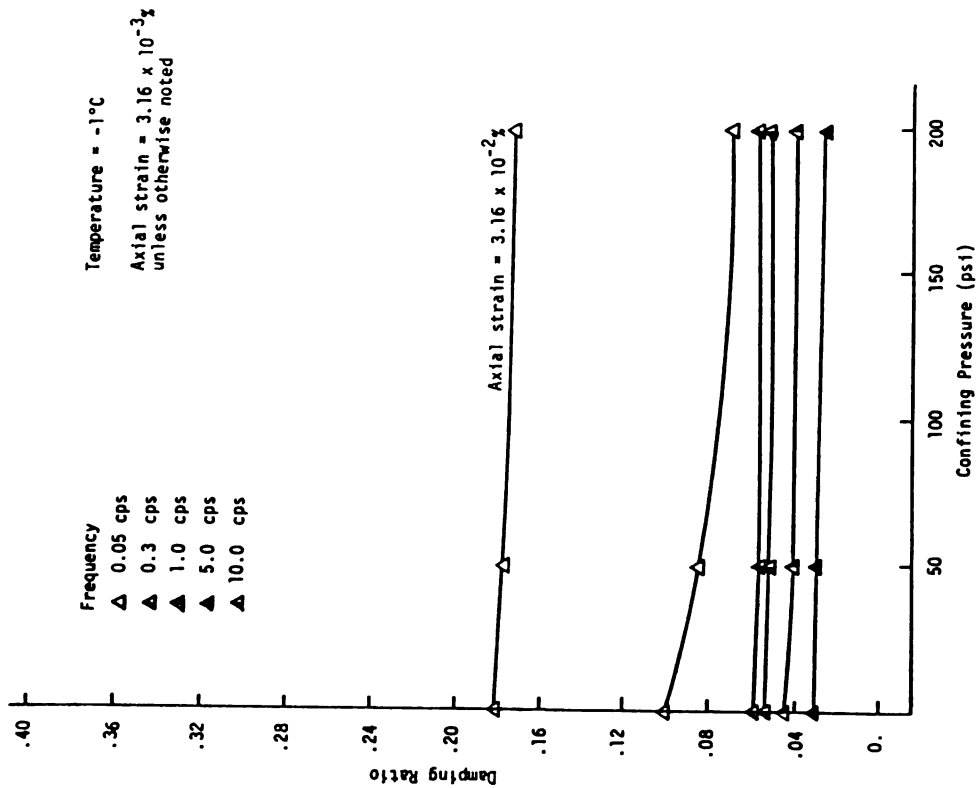


Figure 5.25 DAMPING RATIO VERSUS CONFINING PRESSURE FOR KAOLINITE
 AT A WATER CONTENT OF 28.1%

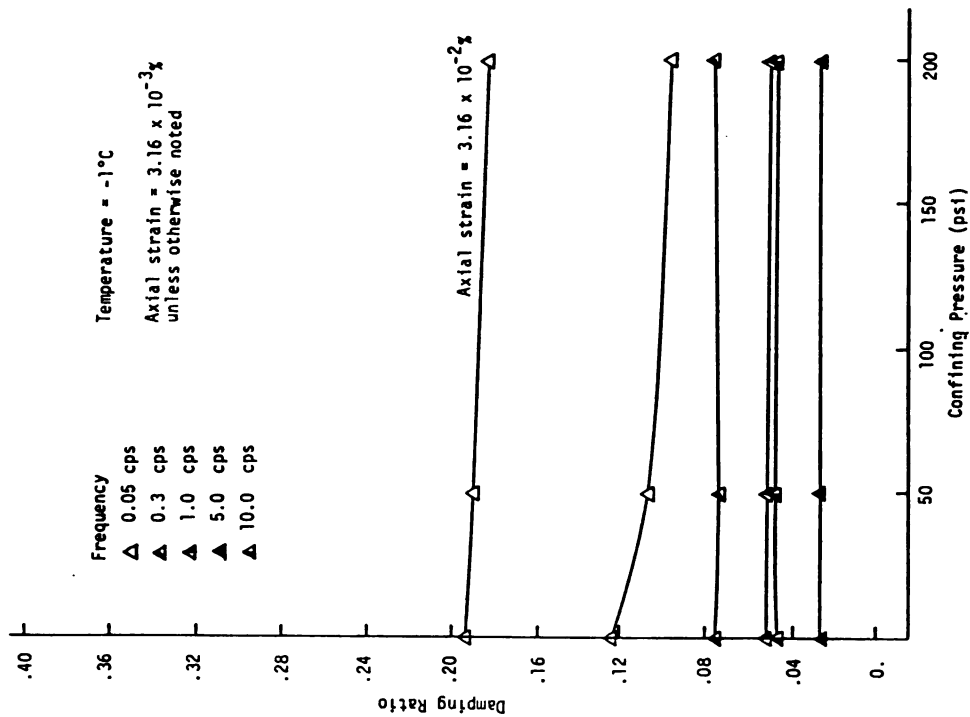


Figure 5.26 DAMPING RATIO VERSUS CONFINING PRESSURE FOR KAOLINITE
 AT A WATER CONTENT OF 71.3%

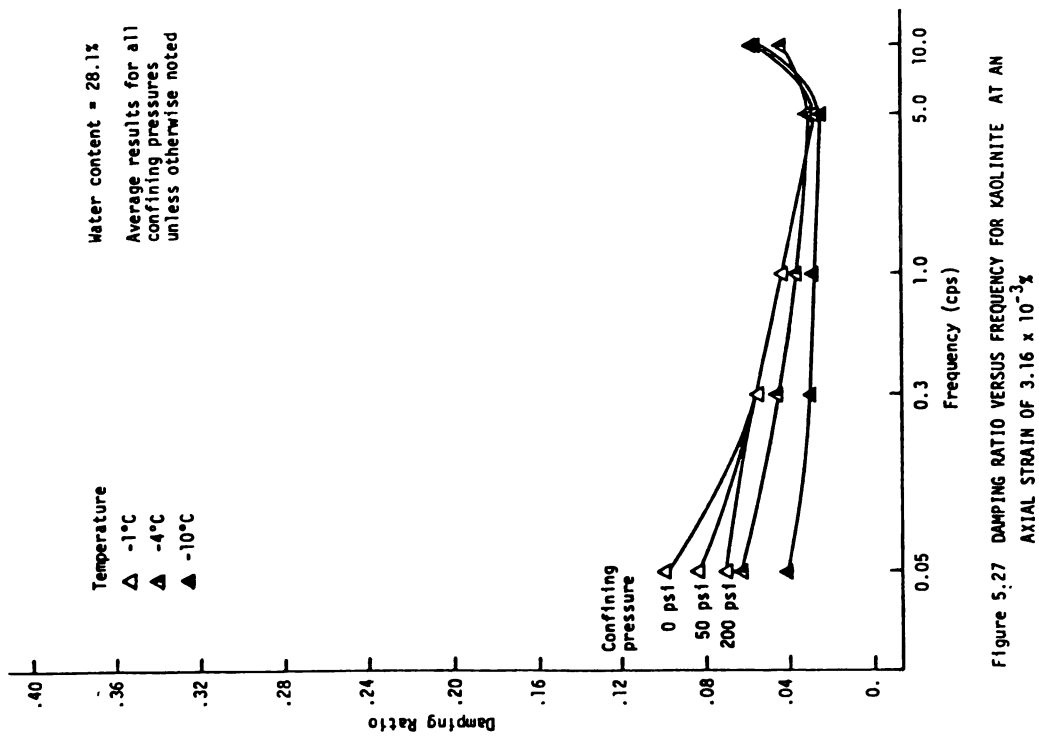


Figure 5.27 DAMPING RATIO VERSUS FREQUENCY FOR KAOLINITE AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

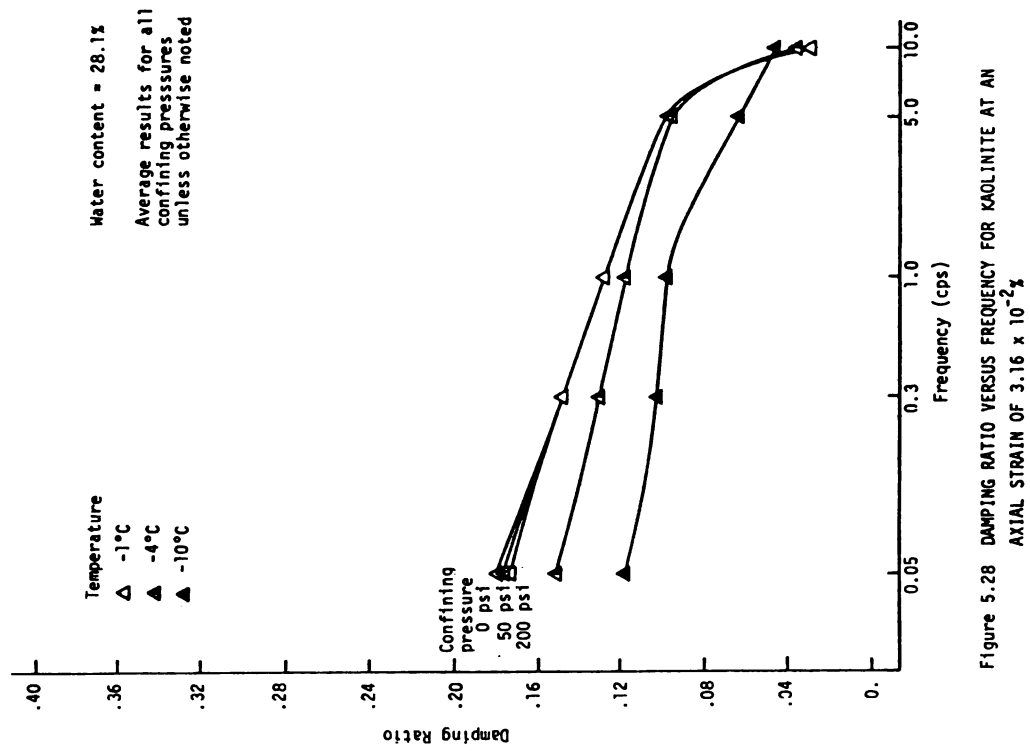


Figure 5.28 DAMPING RATIO VERSUS FREQUENCY FOR KAOLINITE AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

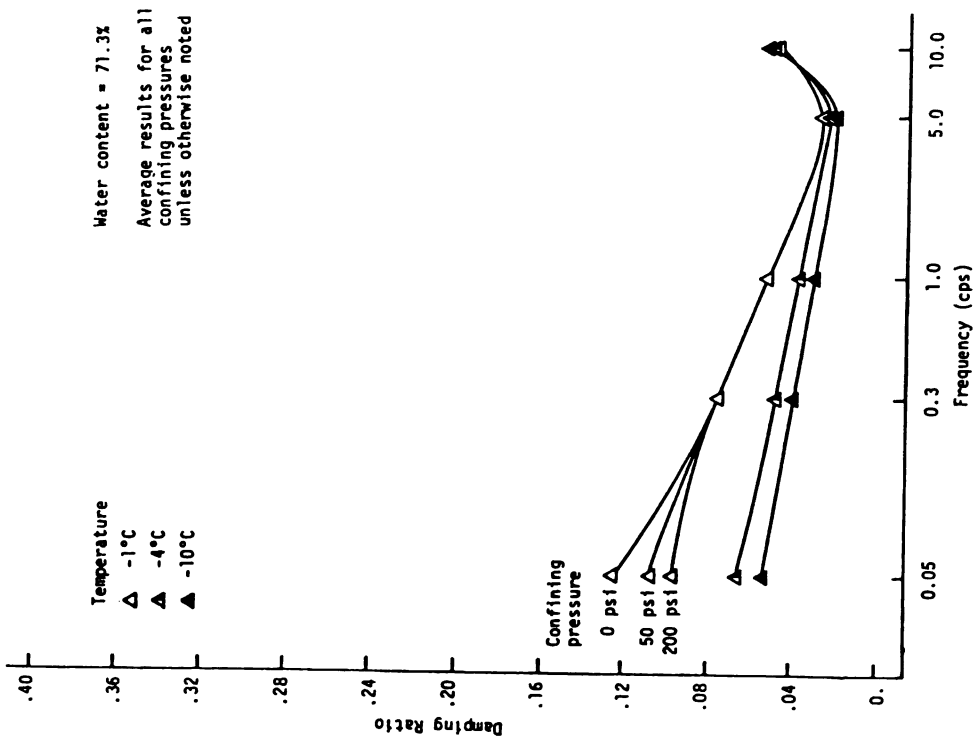


Figure 5.29 DAMPING RATIO VERSUS FREQUENCY FOR KAOLINITE AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

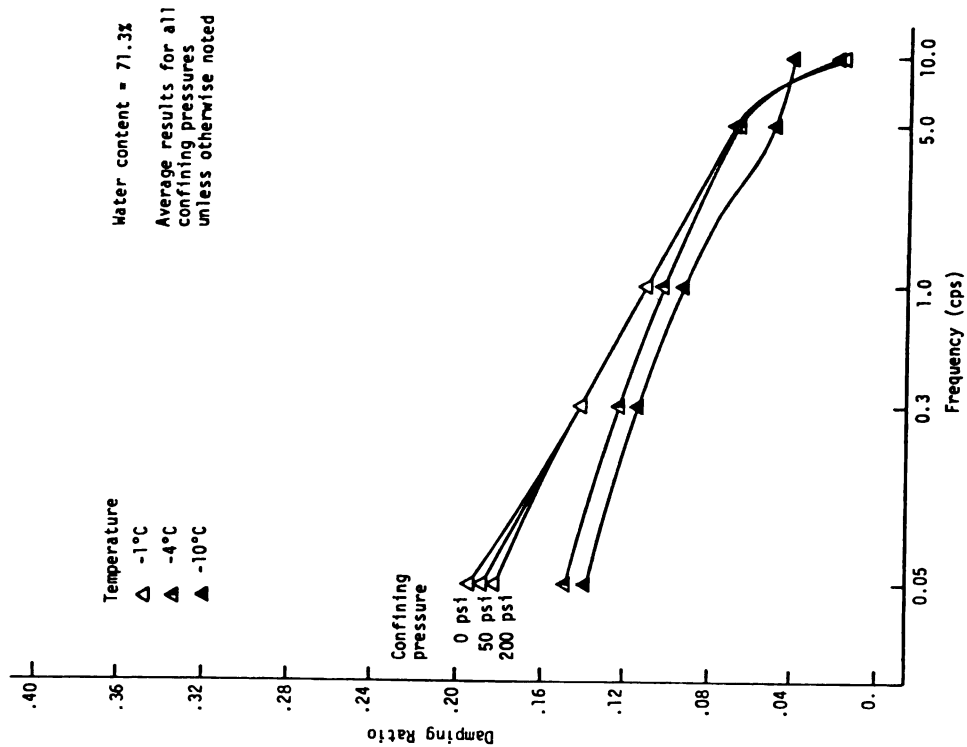


Figure 5.30 DAMPING RATIO VERSUS FREQUENCY FOR KAOLINITE AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

of decrease is somewhat more uniform over the entire range of frequencies. The relationship at a high strain amplitude does not appear to be influenced significantly by water content.

5.4.4 Effect of Temperature

The relationship between damping ratio and temperature is summarized in Figures 5.31 to 5.34. Each graph represents the relationship at a given water content and strain amplitude at all five frequencies (0.05, 0.3, 1.0, 5.0, and 10.0 cps). In general, damping ratio decreases slightly with decreasing temperature. In most instances, the decrease appears to be more pronounced at lower frequencies than at higher frequencies. At the highest frequency (10.0 cps) the relationship reverses as damping ratio increases by a small amount with decreasing temperature. At a low water content (28.1%) and low strain amplitude ($3.16 \times 10^{-3}\%$) at 10.0 cps there is an initial decrease in damping ratio between -1 and -4°C followed by an increase between -4 and -10°C. In general, the rate of change in damping ratio is somewhat greater in the high temperature range (-1 to -4°C) than in the low temperature range (-4 to -10°C) at a high water content (71.3%). At a low water content, the rate of change is somewhat more uniform over the entire range of temperatures. The influence of strain amplitude on the relationship between damping ratio and temperature is not clear.

5.4.5 Effect of Water Content

The relationship between damping ratio and water content is summarized in Figures 5.35 to 5.40. Each graph represents the relationship at a given temperature and strain amplitude at all five

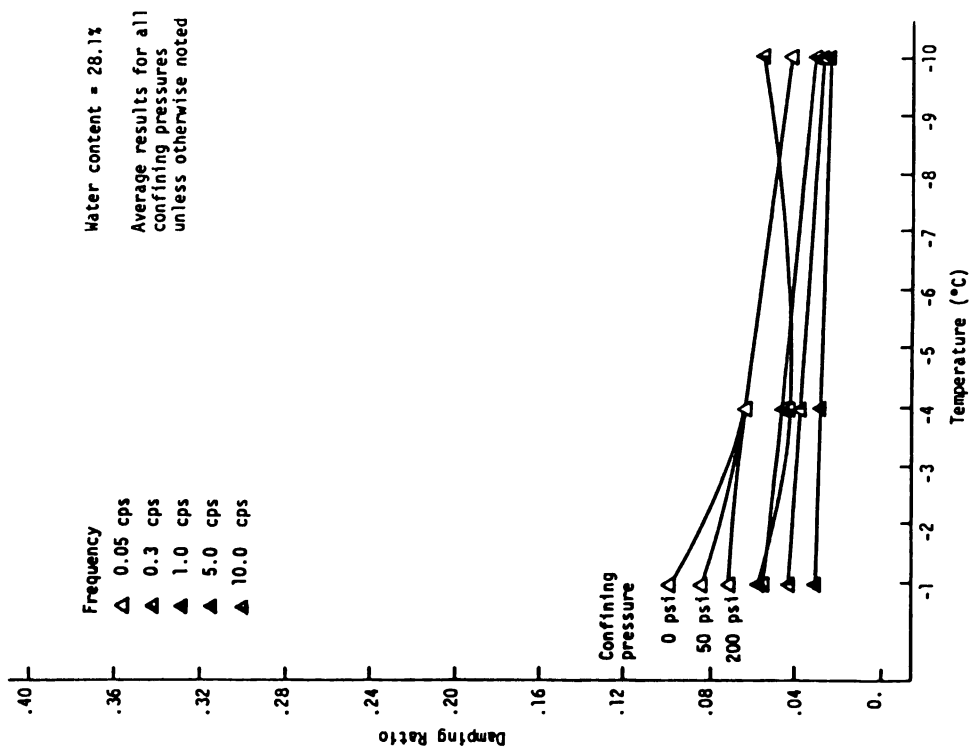


Figure 5.31 DAMPING RATIO VERSUS TEMPERATURE FOR KAOLINITE AT AN AXIAL STRAIN OF 3.16×10^{-3}

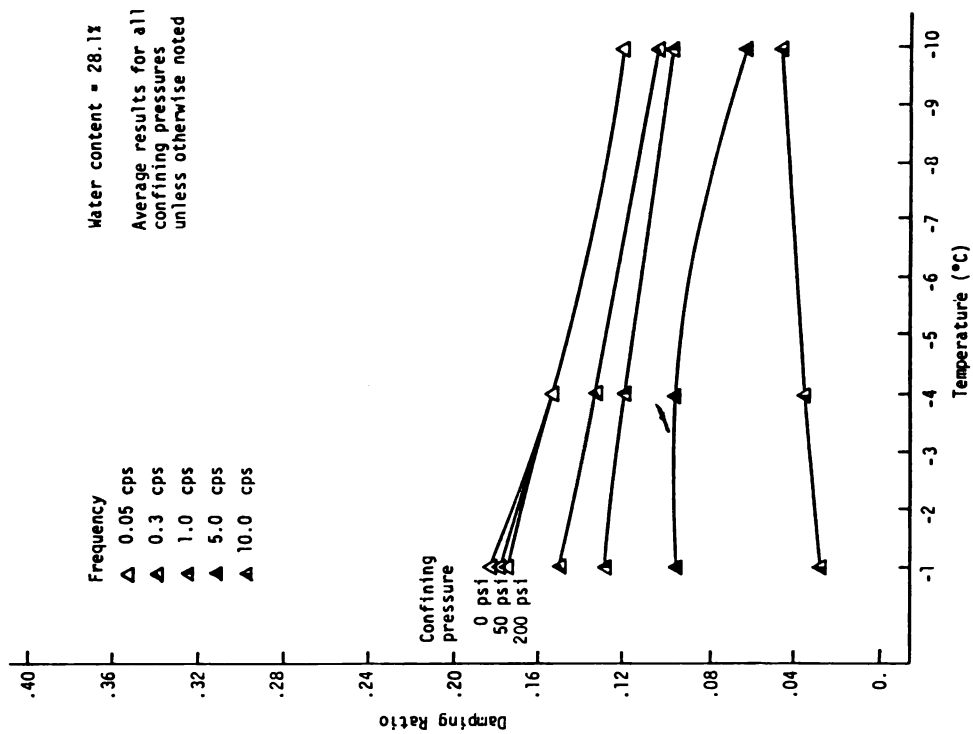


Figure 5.32 DAMPING RATIO VERSUS TEMPERATURE FOR KAOLINITE AT AN AXIAL STRAIN OF 3.16×10^{-2}

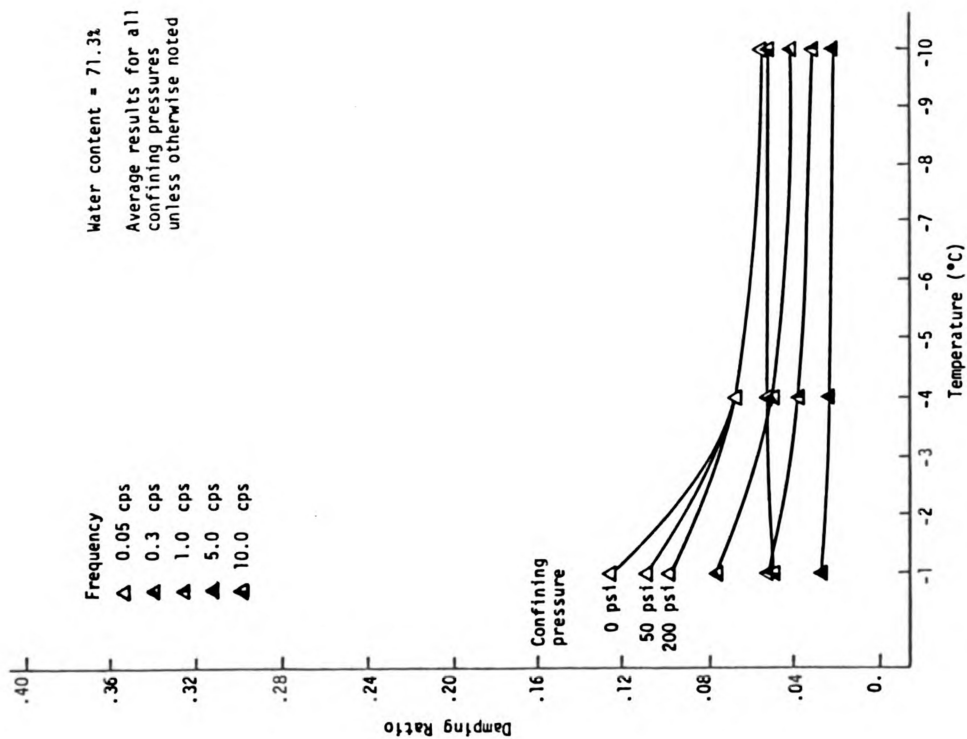


Figure 5.33 DAMPING RATIO VERSUS TEMPERATURE FOR KAOLINITE AT AN AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

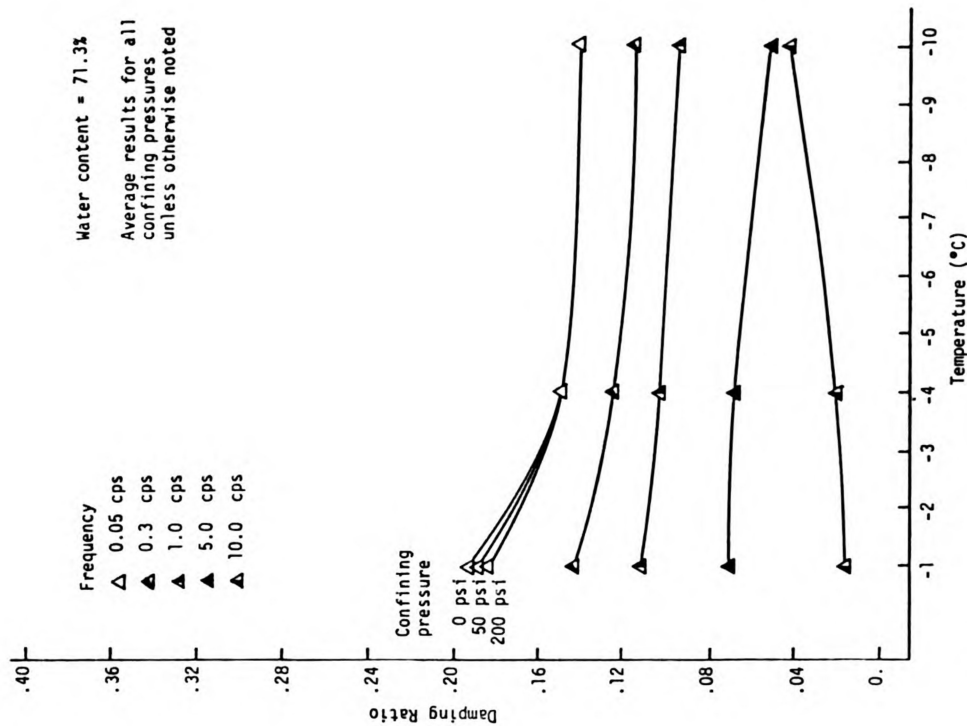


Figure 5.34 DAMPING RATIO VERSUS TEMPERATURE FOR KAOLINITE AT AN AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

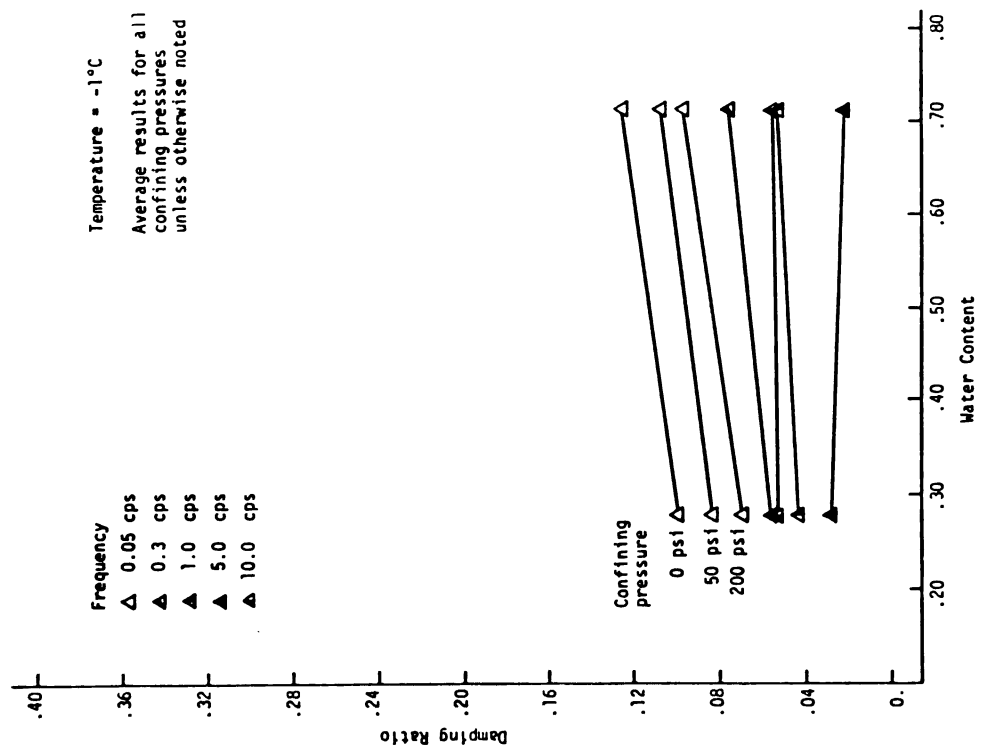


Figure 5.35 DAMPING RATIO VERSUS WATER CONTENT FOR KAOLINITE AT AN
AXIAL STRAIN OF 3.16×10^{-3}

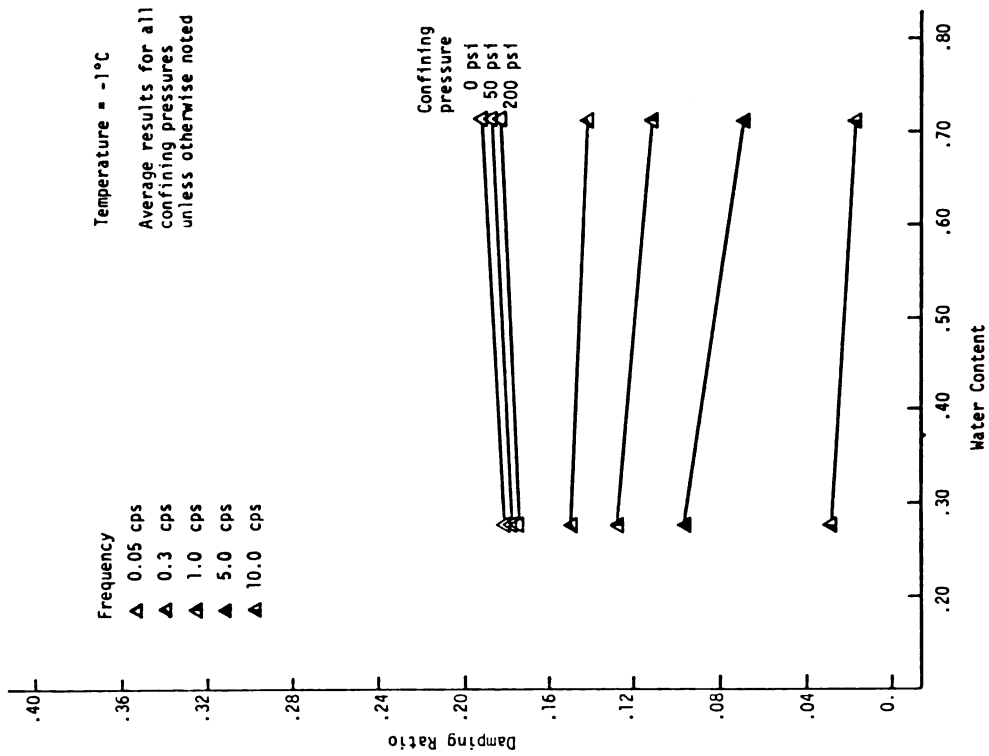


Figure 5.36 DAMPING RATIO VERSUS WATER CONTENT FOR KAOLINITE AT AN
AXIAL STRAIN OF 3.16×10^{-2}

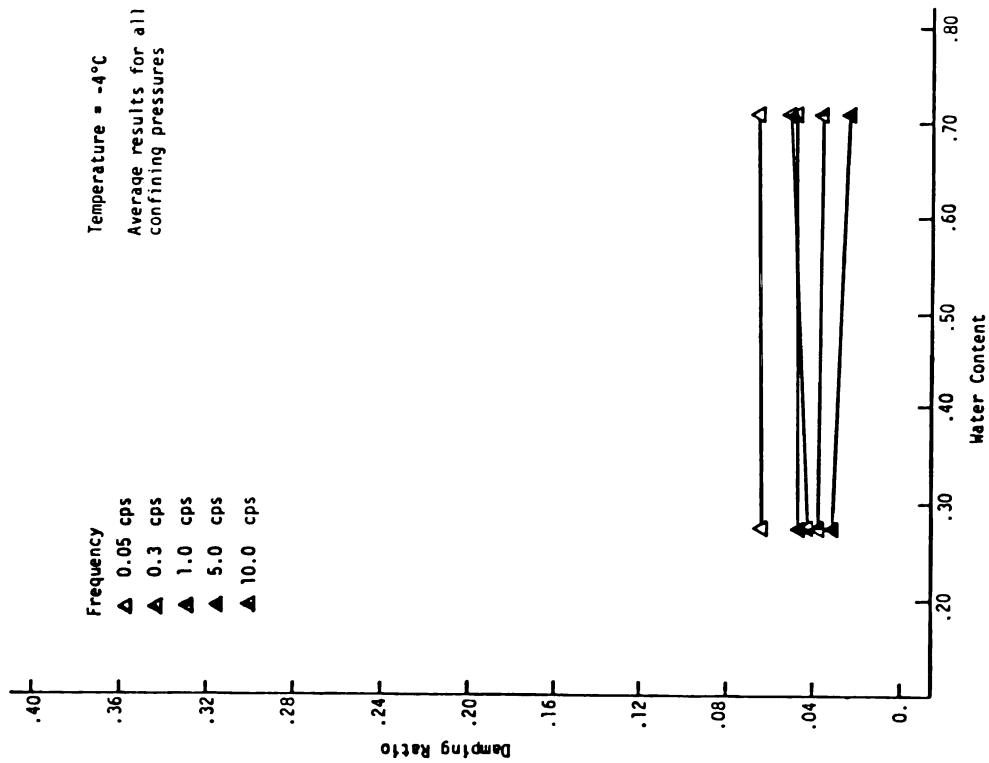


Figure 5.37 DAMPING RATIO VERSUS WATER CONTENT FOR KAOLINITE AT AN AXIAL STRAIN OF 3.16×10^{-3}

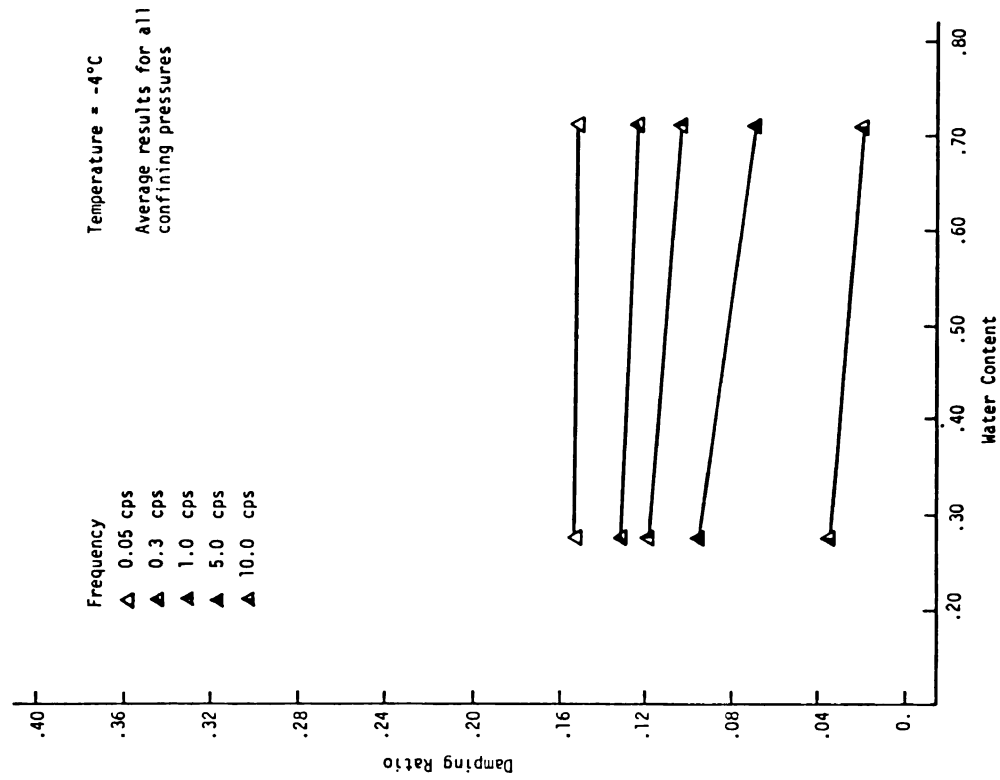


Figure 5.38 DAMPING RATIO VERSUS WATER CONTENT FOR KAOLINITE AT AN AXIAL STRAIN OF 3.16×10^{-2}

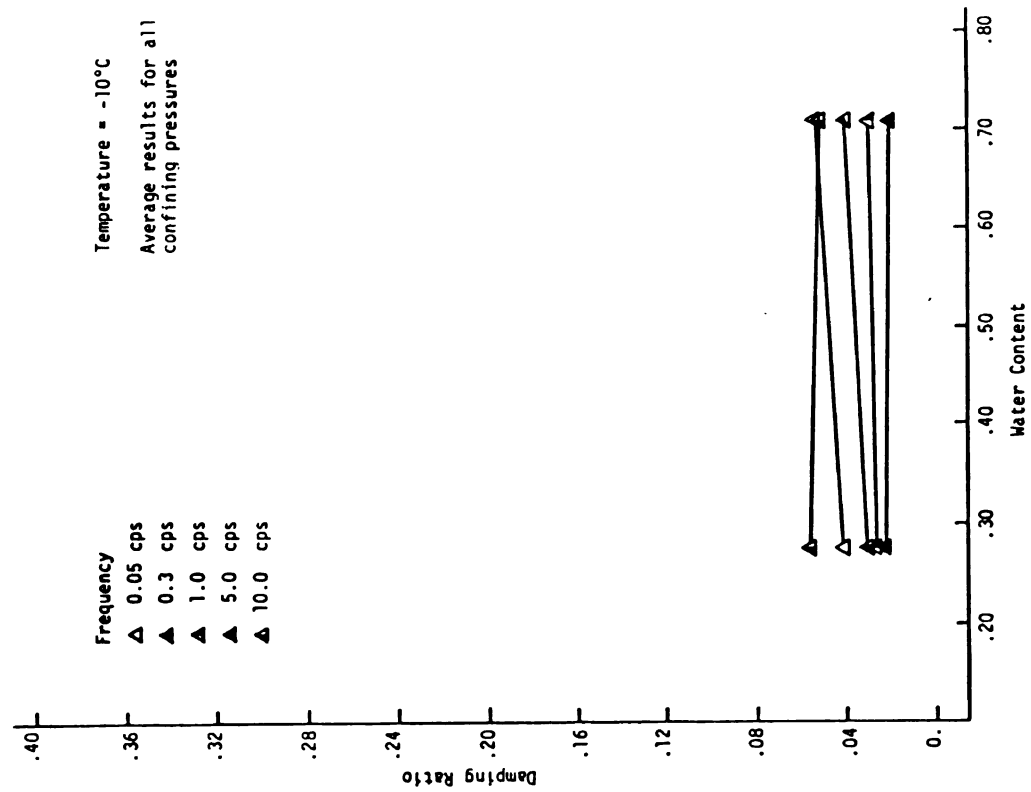


Figure 5.39 DAMPING RATIO VERSUS WATER CONTENT FOR KAOLINITE AT AN
AXIAL STRAIN OF $3.16 \times 10^{-3}\%$

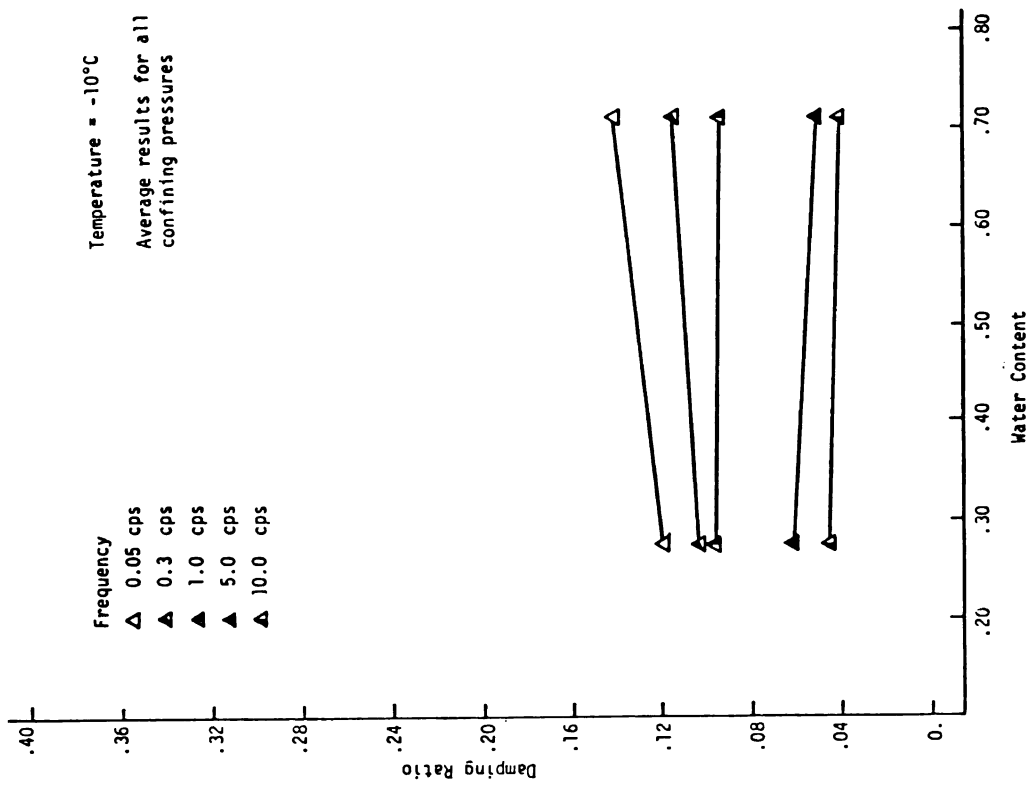


Figure 5.40 DAMPING RATIO VERSUS WATER CONTENT FOR KAOLINITE AT AN
AXIAL STRAIN OF $3.16 \times 10^{-2}\%$

frequencies (0.05, 0.3, 1.0, 5.0, and 10.0 cps). In general, it appears that water content has at most only a slight influence on damping ratio over the range of water contents tested. At a high temperature (-1°C) and a low strain amplitude ($3.16 \times 10^{-3}\%$) damping ratio increases by a small amount with increasing water content. The change is most significant at lower frequencies and becomes negligible at higher frequencies. At a high strain amplitude ($3.16 \times 10^{-2}\%$) damping ratio increases by a slight amount with increasing water content at the lowest frequency (0.05 cps) and decreases by a slight amount at higher frequencies. At lower temperatures (-4 and -10°C) the relationship between damping ratio and water content and the influence of frequency and strain amplitude on the relationship are not entirely clear; it appears that, in general, water content has a slight to negligible influence on damping ratio.

CHAPTER 6

COMPARISONS OF DYNAMIC PROPERTIES OF FROZEN SILT AND CLAY

6.1 General

This chapter presents a comparison of the dynamic properties of frozen silt and clay obtained in this study with the results obtained in previous studies.. To allow a direct comparison to be made, the dynamic properties obtained in all of the studies were converted to common units. Thus, dynamic elastic properties are presented in terms of compressional or longitudinal wave velocities and damping properties are presented in terms of damping ratios. Values of dynamic Young's modulus obtained in the present study were converted to longitudinal wave velocities using:

$$V_L = \sqrt{\frac{E_d}{\rho}} \quad (6.1)$$

in which

V_L = longitudinal wave velocity,

E_d = dynamic Young's modulus, and

ρ = material density.

Results of field investigations are presented in terms of compressional wave velocities, which are related to longitudinal wave velocities as follows:

$$V_P = V_L \sqrt{\frac{(1 - \mu)}{(1 + \mu)(1 - 2\mu)}} \quad (6.2)$$

in which

V_P = compressional wave velocity and

μ = Poisson's ratio.

Values of damping ratio were calculated from loss factors determined in previous investigations using:

$$D = \sin \frac{\delta}{2} \quad (6.3)$$

in which

D = damping ratio and

δ = phase lag.

6.2 Comparison of Dynamic Properties of Frozen Silt

6.2.1 Longitudinal and Compression Wave Velocity

The relationship between longitudinal or compressional wave velocity and temperature for frozen silt obtained in the present study and in previous studies is summarized in Figure 6.1. In general, there is fairly good agreement among the basic wave velocity-temperature relationships obtained in the several studies. The variation in the magnitude of the wave velocities may be attributed to differences in testing technique and material characteristics and may be summarized as follows:

(1) Frequency - the range of frequencies associated with the present study using cyclic triaxial equipment (0.05 to 10.0 Hz) is significantly less than the frequencies associated with the testing techniques used in the previous studies (resonant frequency, approximately 1 to 10 kHz; seismic, approximately 150 Hz; ultrasonic, approximately 50 to 1000 kHz). It was shown in the present study that dynamic Young's modulus of frozen silt increases with increasing frequency between 0.05 and 10.0 cps. The relationship between longitudinal wave velocity and frequency determined in the present study and by Stevens (1973) is shown in Figure 6.2. Since the wave velocity decreases at frequencies

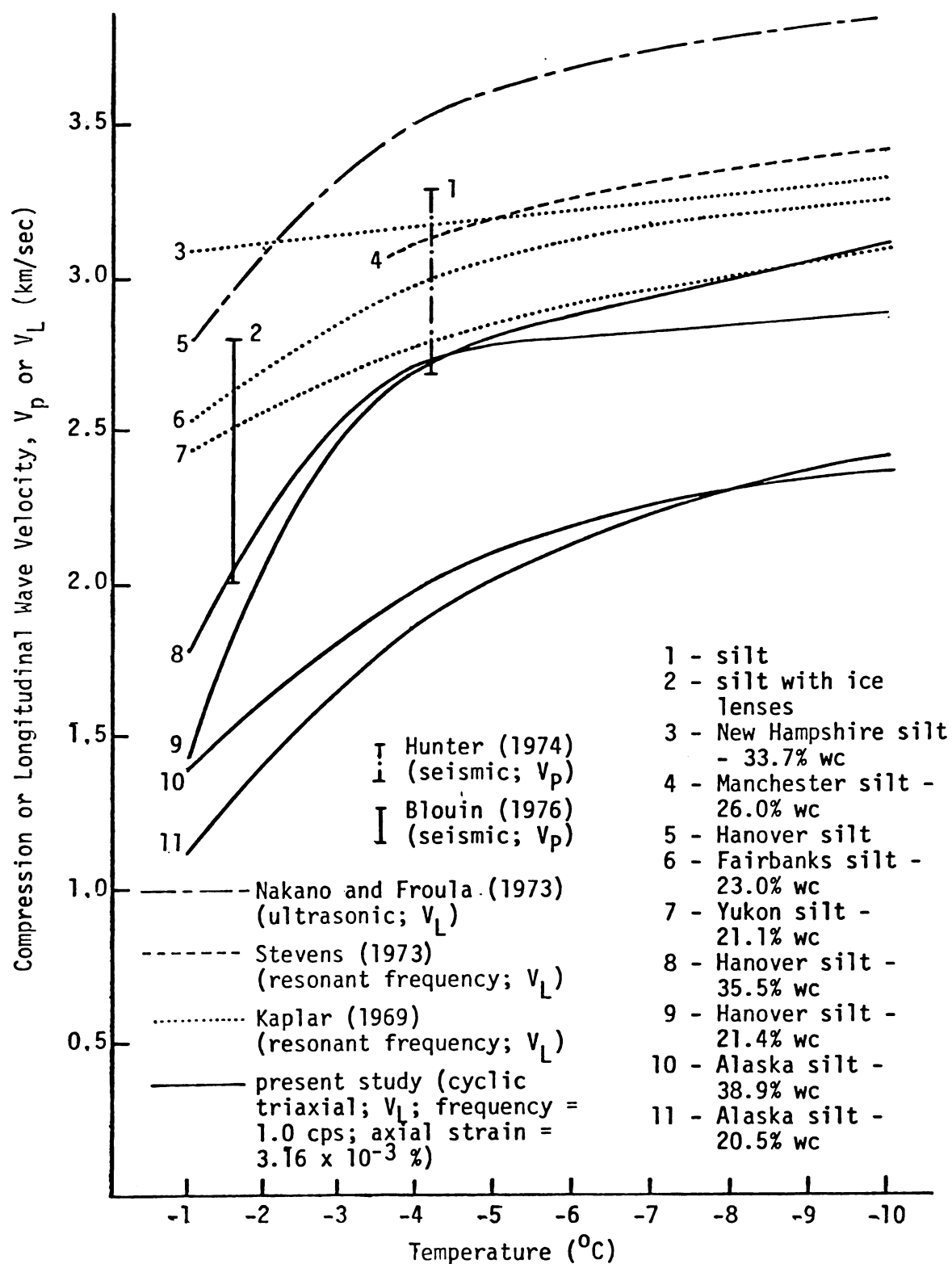


Figure 6.1 WAVE VELOCITY VERSUS TEMPERATURE OF FROZEN SILT

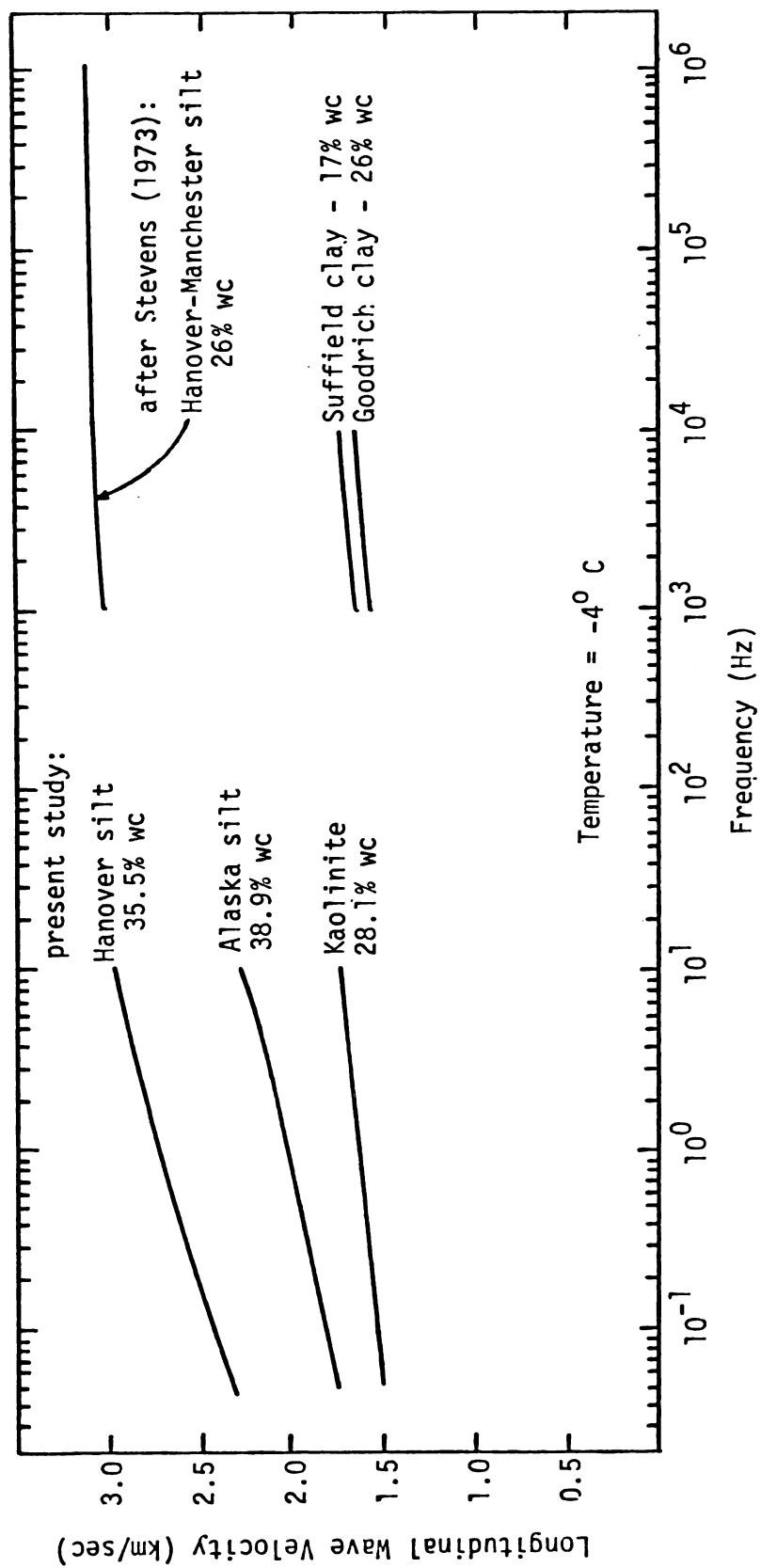


Figure 6.2 LONGITUDINAL WAVE VELOCITY VERSUS FREQUENCY OF FROZEN SILT AND CLAY

less than 10.0 cps, the longitudinal wave velocities obtained in the present study should be lower than those obtained in previous studies.

(2) Strain amplitude - the strain amplitudes associated with the cyclic triaxial method (approximately 2×10^{-3} to $8 \times 10^{-2}\%$) are greater than the strain amplitudes associated with the other methods (resonant frequency, approximately 10^{-6} to $10^{-3}\%$; ultrasonic and seismic methods, approximately 10^{-7} to $10^{-4}\%$). It was shown in the present study that the dynamic Young's modulus of frozen silt decreases with increasing strain amplitude over the entire range of strain amplitudes in the testing program. The relationship between longitudinal wave velocity and axial strain amplitude obtained in the present study and by Stevens (1973) is summarized in Figure 6.3. Since the longitudinal wave velocity is higher at very low strain amplitudes than at high strain amplitudes, the longitudinal wave velocities obtained in the present study at an axial strain amplitude of $3.16 \times 10^{-3}\%$ should be lower than the wave velocities obtained by other methods at lower strain amplitudes.

(3) Material characteristics - in general, the wave-velocity-temperature relationships from the several studies shown in Figure 6.1 are associated with frozen silts over a relatively narrow range of water contents. It can be seen from the relationships obtained for Hanover and Alaska silt in the present study that water content did not influence the longitudinal wave velocities to a large extent; it is, therefore, not likely that the differences in wave velocities among the several laboratory studies are due to the relatively small differences in water contents. On the other hand, it appears that the wave velocity can be influenced to a larger extent by the nature of the silt itself, such as the grain size characteristics. In the present study,

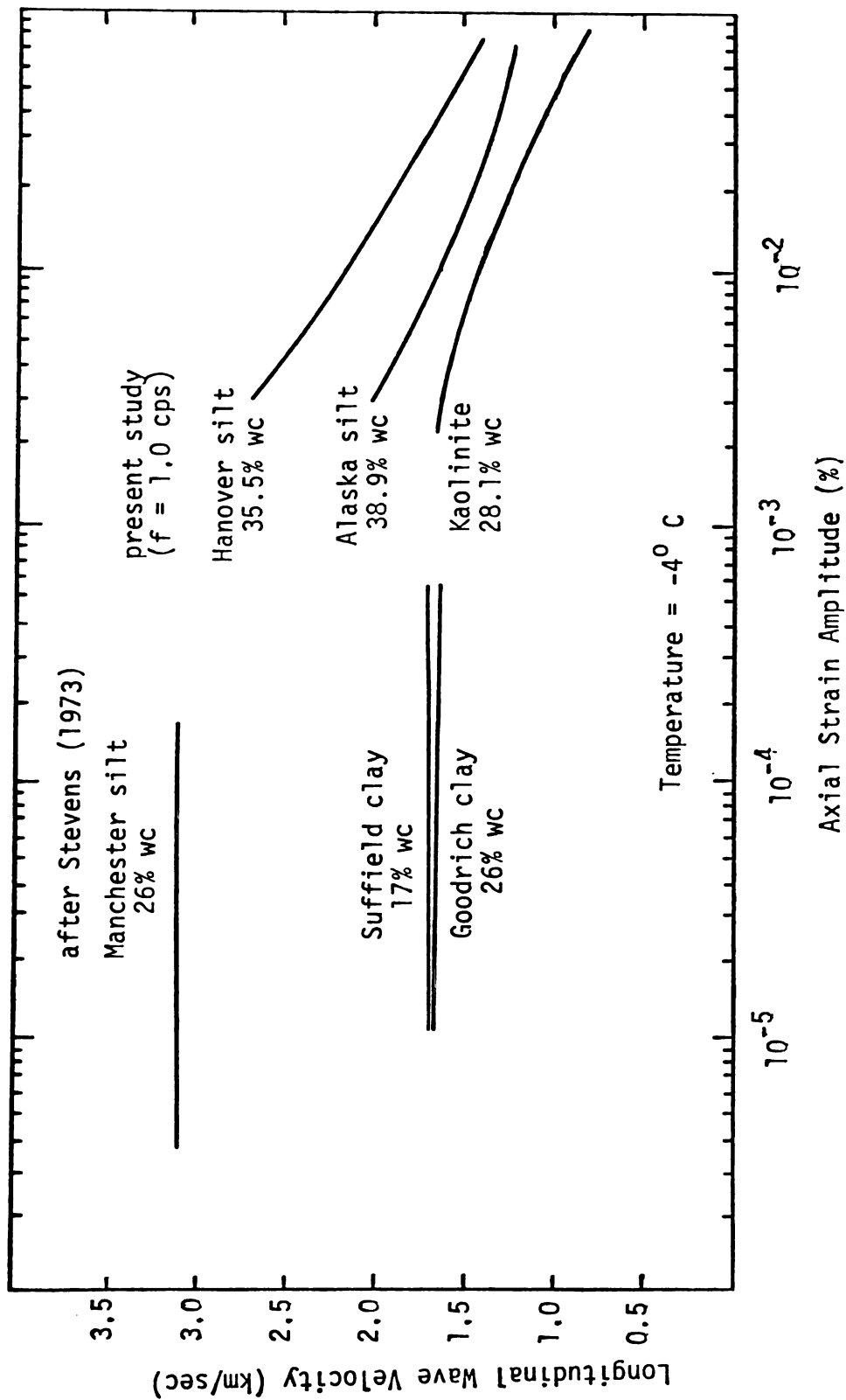


Figure 6.3 LONGITUDINAL WAVE VELOCITY VERSUS AXIAL STRAIN AMPLITUDE OF FROZEN SILT AND CLAY

for example, the lower longitudinal wave velocity obtained in Alaska silt than in Hanover silt may be a function of the finer grain size and corresponding large clay content in the Alaska silt.

Overall, the wave velocities obtained in the present study appear to be in good agreement with the wave velocities obtained in the previous studies.

6.2.2 Damping Ratio

The relationship between damping ratio and temperature for frozen silt obtained in the present study and in a previous study by Stevens (1973) is summarized in Figure 6.4. The values of damping ratio obtained by Stevens (1973) are lower than the values obtained in the present study. This variation may be attributed to differences in the testing technique in the two studies and may be explained as follows:

(1) Frequency - the frequency associated with Stevens' (1973) resonant frequency procedure is much greater than that associated with the present study. It was shown in the present study that the damping ratio of frozen silt decreases with increasing frequency between 0.05 and 10.0 cps. The relationship between damping ratio and frequency obtained in both studies is summarized in Figure 6.5. Since the damping ratio is smaller at high frequencies than at low frequencies, the values of damping ratio obtained in the present study should be higher than those obtained by Stevens (1973).

(2) Strain amplitude - the strain amplitude associated with the present study are greater than the strain amplitudes associated with the resonant frequency method. It was shown in the present

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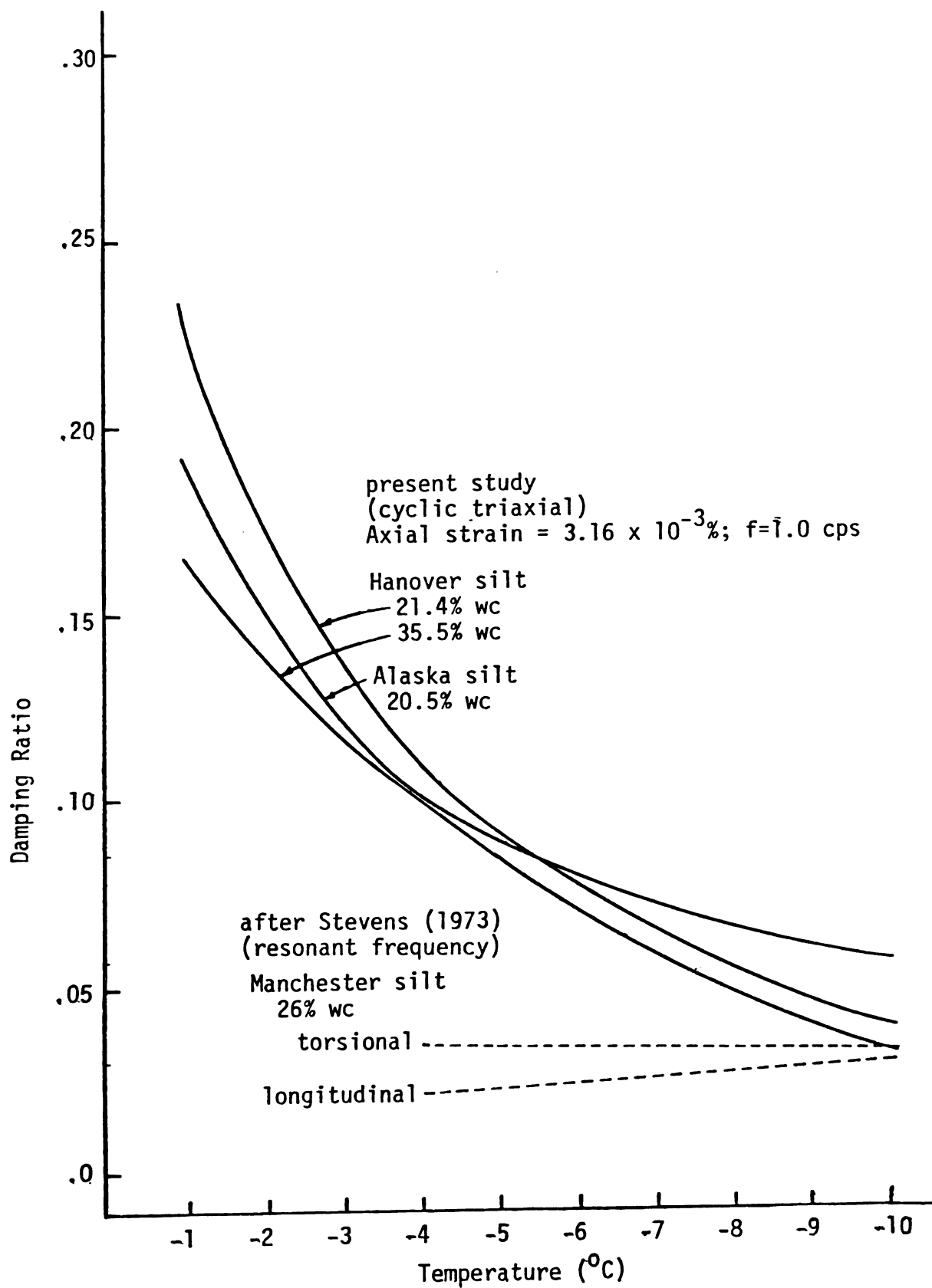


Figure 6.4 DAMPING RATIO VERSUS TEMPERATURE OF FROZEN SILT

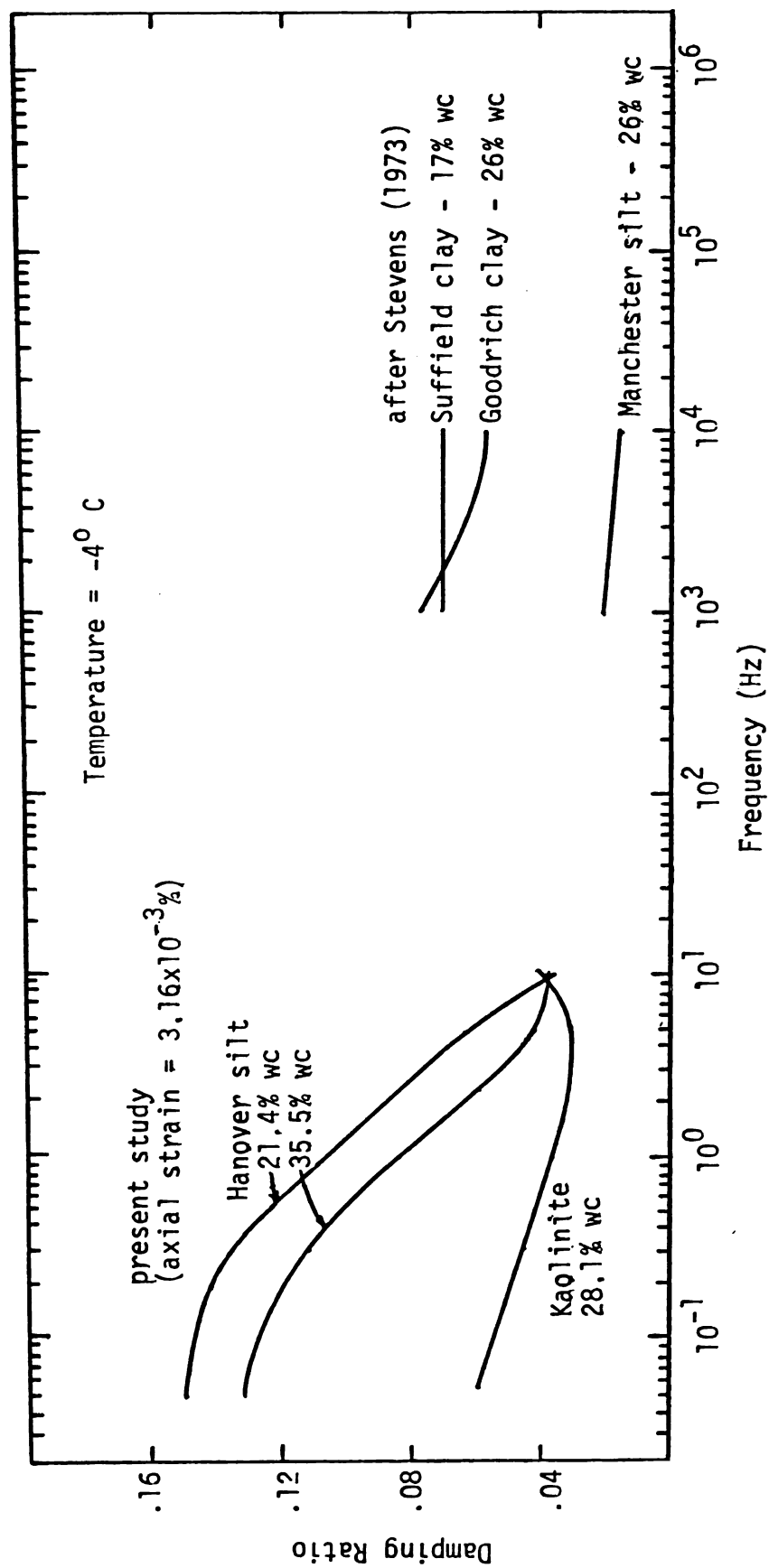


Figure 6.5 DAMPING RATIO VERSUS FREQUENCY OF FROZEN SILT AND CLAY

study that damping ratio of frozen silt increases with increasing axial strain amplitude between approximately 2×10^{-3} and $8 \times 10^{-2}\%$. The relationship between damping ratio and strain amplitude obtained in the present study and by Stevens (1973) is shown in Figure 6.6. Since the damping ratio is less at low strain amplitudes than at high strain amplitudes, the values of damping ratio obtained in the present study should be greater than those obtained by Stevens (1973).

Overall, it is felt that the comparison between the damping ratios obtained in the present study and by Stevens (1973) is reasonable.

6.3 Comparison of Dynamic Properties of Frozen Clay

6.3.1 Longitudinal and Compression Wave Velocity

The relationship between longitudinal or compressional wave velocity and temperature for frozen clay obtained in the present study and in previous studies is summarized in Figure 6.7. In general, the longitudinal wave velocities obtained in the present study compare favorably with the wave velocities obtained in previous studies. The variation in wave velocity from different studies can be attributed to differences in testing technique and material characteristics and may be summarized as follows:

(1) Frequency - as in the case of frozen silt, the frozen clay in the present study was tested at frequencies significantly lower than the frequencies associated with the testing techniques used in most of the previous studies. As shown in Figure 6.2, the longitudinal wave velocity of frozen clay increases slightly with increasing frequency in both high and low frequency ranges. Therefore, the wave

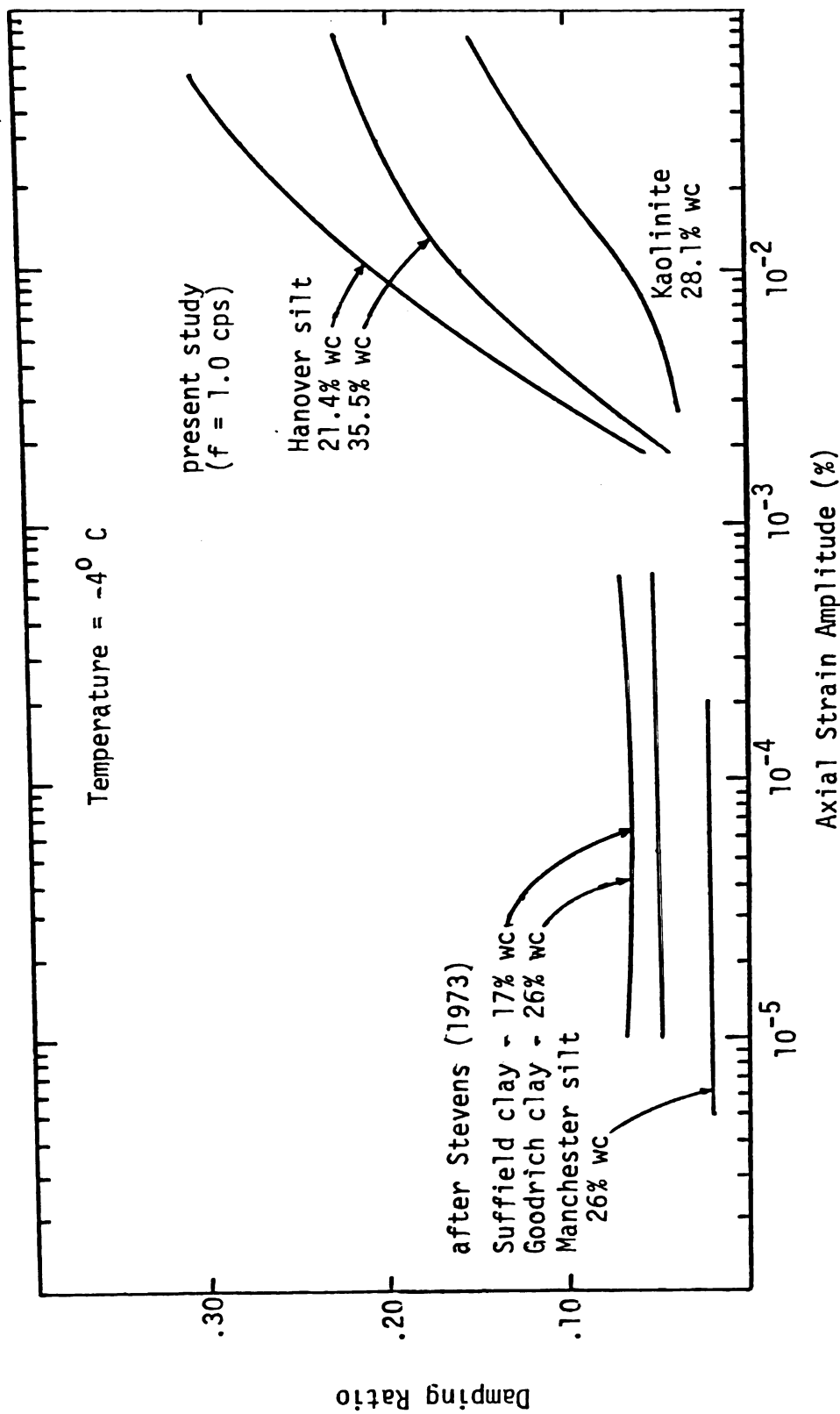


Figure 6.6 DAMPING RATIO VERSUS AXIAL STRAIN AMPLITUDE OF FROZEN SILT AND CLAY

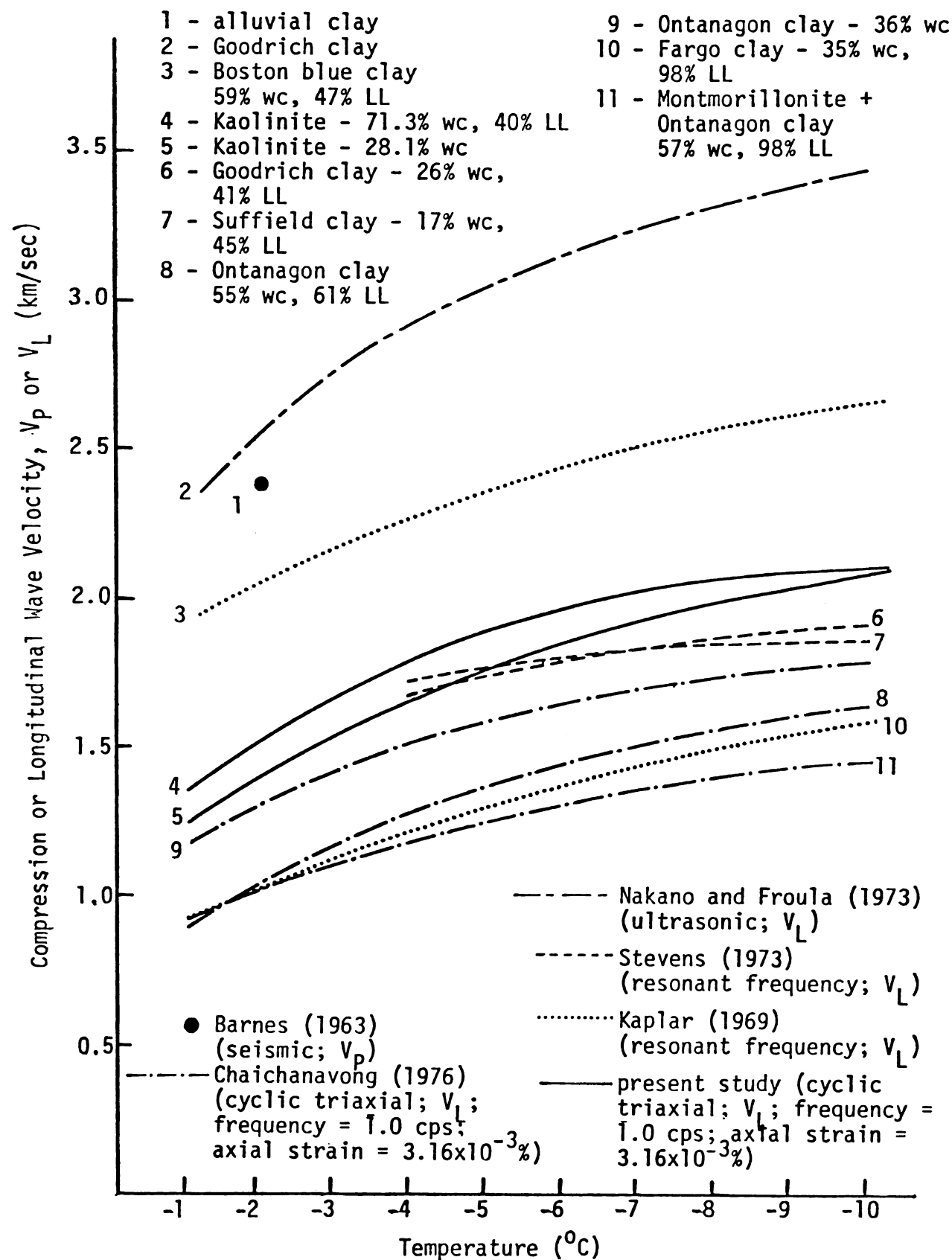


Figure 6.7 WAVE VELOCITY VERSUS TEMPERATURE OF FROZEN CLAY

velocities obtained in the present study should tend to be somewhat lower than wave velocities obtained in previous studies using high-frequency techniques.

(2) Strain amplitude - the strain amplitudes associated with the present study are higher than the strain amplitudes associated with most of the previous studies. The relationship between longitudinal wave velocity and strain amplitude for frozen clay determined in the present study and by Stevens (1973) is summarized in Figure 6.3. It can be seen that the wave velocity decreases with increasing strain amplitude at high strain amplitudes, but is not significantly influenced by strain amplitude at lower strain amplitudes. Since the values of wave velocity in the present study were chosen at a sufficiently low strain amplitude ($3.16 \times 10^{-3}\%$) for purposes of comparison, it appears unlikely that differences in strain amplitude can account to a large extent for the significant variation in wave velocity among the several studies shown in Figure 6.7.

(3) Material characteristics - the wave velocity-temperature relationships shown in Figure 6.7 are associated with frozen clays with wide variation in plasticities and water contents. Results obtained by Chaichanavong (1976) and in the present study indicate that water content has a relatively small influence on longitudinal wave velocity. It appears that the wave velocity in frozen clay is influenced to a larger extent by the properties of the clay particles. A general relationship between wave velocity and liquid limit using the data of Kaplar (1969), Chaichanavong (1976), and the present study is shown in Figure 6.8; while an exact relationship cannot be determined from the data given, it appears that the wave velocity

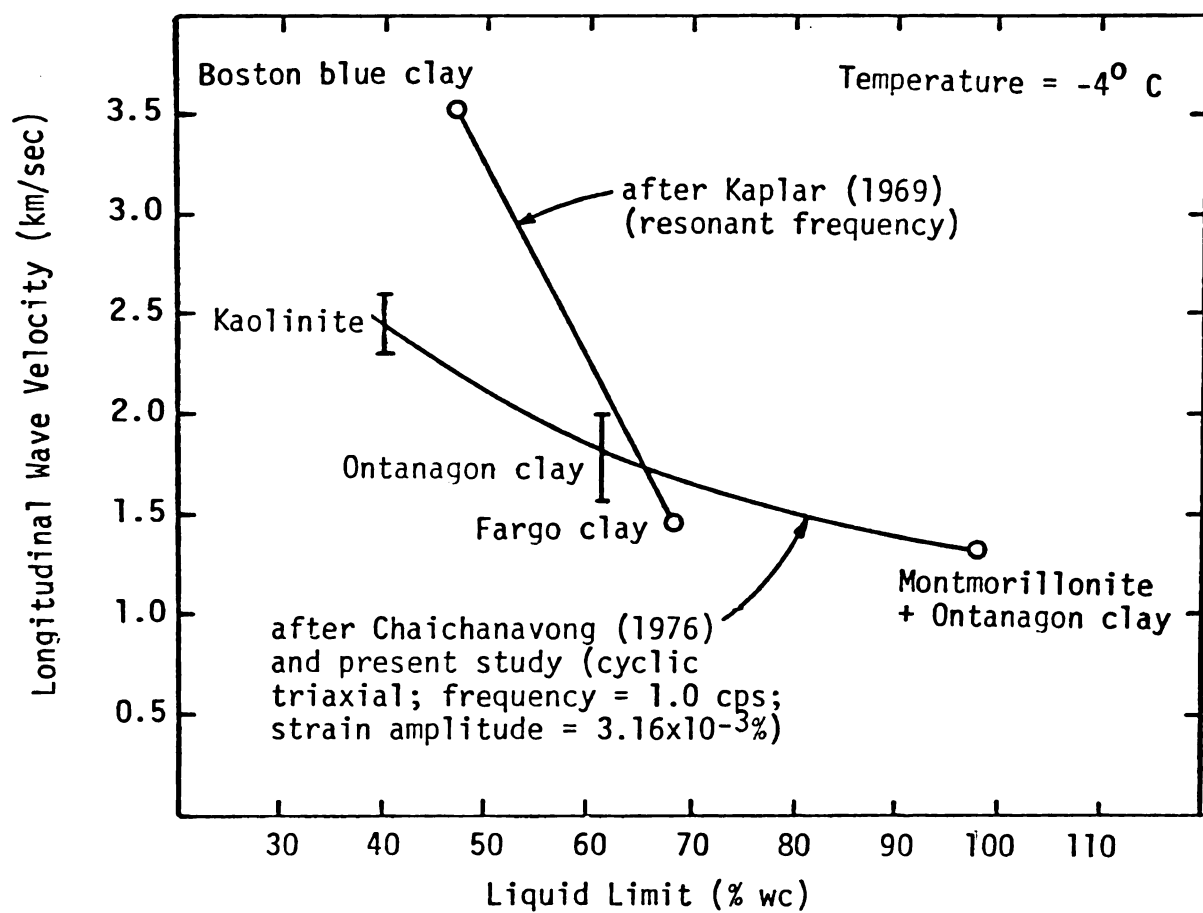


Figure 6.8 LONGITUDINAL WAVE VELOCITY VERSUS LIQUID LIMIT OF FROZEN CLAY

is significantly greater in clays with lower liquid limits than in clays with higher liquid limits. This may be an indication of the influence of the unfrozen water content on the wave velocity in frozen clay, since the liquid limit is related to the specific surface area of the clay which is in turn related to the unfrozen water content.

Overall, the longitudinal wave velocities for frozen clay obtained in the present study appear to be very reasonable in comparison with the wave velocities obtained in previous studies.

6.3.2 Damping Ratio

The relationship between damping ratio and temperature for frozen clay obtained in the present study and in previous studies by Chaichanavong (1976) and Stevens (1973) is summarized in Figure 6.9. It can be seen that the damping ratio values obtained in the present study compare favorably with the values obtained by Chaichanavong (1976) but are significantly less than the values obtained by Stevens (1973); this variation may be attributed to differences in the testing techniques and material characteristics in the studies and may be explained as follows:

(1) Frequency - the frequency associated with Stevens' (1973) resonant frequency procedure is much greater than that associated with the present study and the study by Chaichanavong (1976). It was shown in the present study that the damping ratio of frozen clay at a strain amplitude of $3.16 \times 10^{-3}\%$ decreases with increasing frequency between 0.05 and 5.0 cps and increases with increasing frequency between 5.0 and 10.0 cps. The relationship between damping ratio and frequency obtained in the present study and by

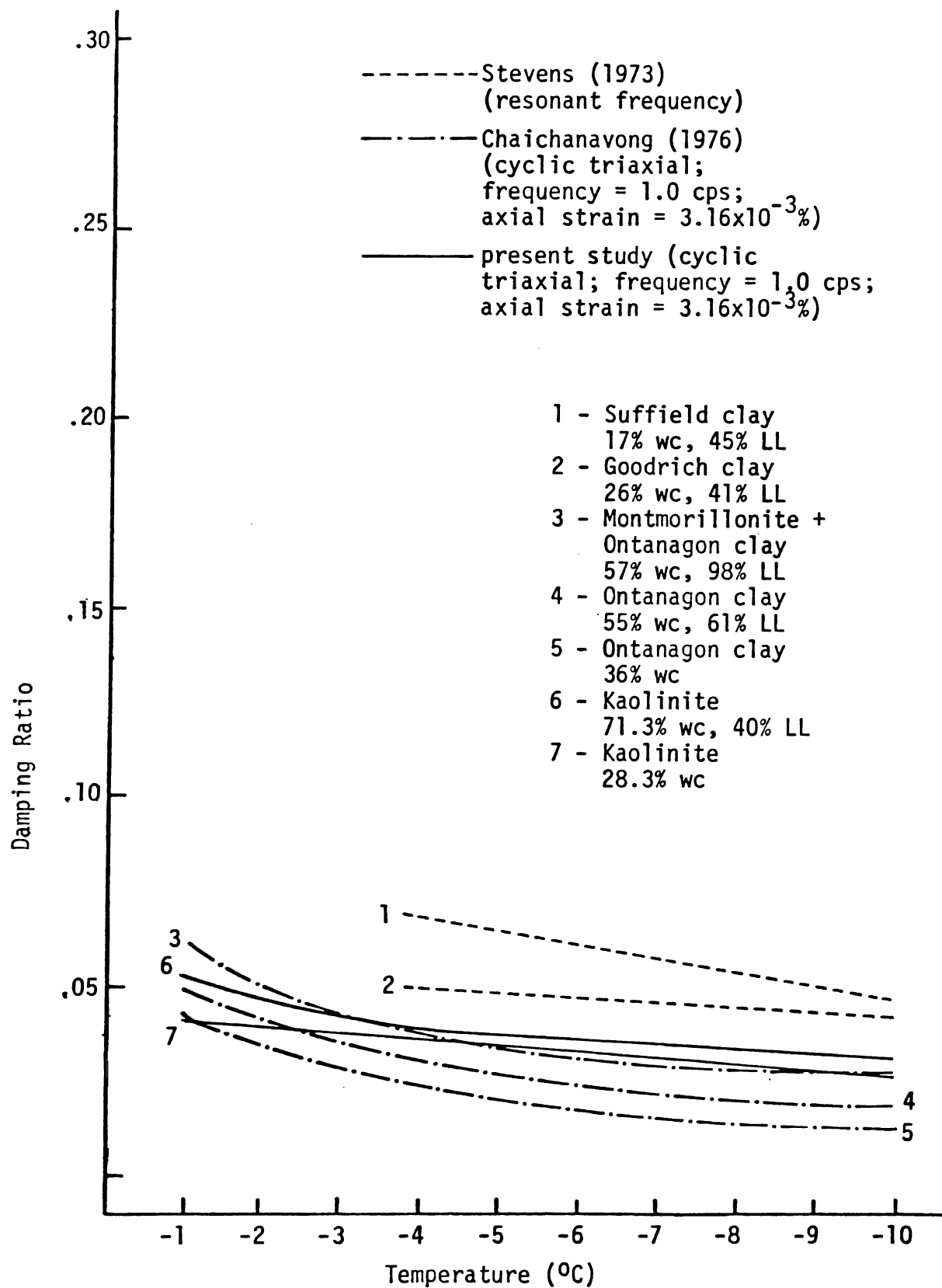


Figure 6.9 DAMPING RATIO VERSUS TEMPERATURE OF FROZEN CLAY

Stevens (1973) is summarized in Figure 6.5; it can be seen that the damping ratio of frozen clay associated with higher frequencies (10^3 to 10^4 Hz) is greater than the damping ratio associated with the upper limit of lower frequencies (5 to 10 Hz). Therefore, since it appears that the damping ratio of frozen clay will continue to increase to a certain extent at frequencies greater than 10 cps, the damping ratios obtained in the present study should be lower than those obtained by Stevens (1973).

(2) Strain Amplitude - the strain amplitudes associated with the present study are higher than the strain amplitudes associated with Stevens' (1973) studies. It was shown in the present study that the damping ratio of frozen clay increases with increasing strain amplitude and that the rate of increase is less at low strain amplitudes than at high strain amplitudes. The relationship between damping ratio and strain amplitude obtained both in the present study and by Stevens (1973) is shown in Figure 6.6. It can be seen that the damping ratio of frozen clay is not significantly influenced by strain amplitude at very low strain amplitudes (10^{-5} to $6 \times 10^{-4}\%$). Therefore, since the damping ratios in the present study and in the study by Chaichanavong (1976) were chosen at a sufficiently small strain amplitude ($3.16 \times 10^{-3}\%$) for purposes of comparison, it is not likely that the variation in damping ratio among the several studies is due to differences in strain amplitude.

(3) Material characteristics - it was shown in the present study that the damping ratio of frozen clay is not significantly influenced by water content. While the influence of the type of clay on damping ratio is not clear from the data shown in Figure 6.9, it appears that

the influence of clay type is relatively small. Therefore, it is not likely that the variation in damping ratio among the several studies is due primarily to differences in material characteristics.

Overall, the damping ratios of frozen clay obtained in the present study appear reasonable in comparison with the damping ratios obtained in previous studies.

CHAPTER 7

SUMMARY AND CONCLUSIONS

Cyclic triaxial tests were conducted on samples of frozen Hanover silt, Alaska silt, and kaolinite. Values of dynamic Young's modulus and damping ratio were obtained for each soil as a function of strain amplitude, temperature, frequency, confining pressure, and water content. The test results may be summarized as follows:

(1) Values of dynamic Young's modulus obtained for the range of test strain amplitudes (approximately 2×10^{-3} to $8 \times 10^{-2}\%$), frequencies (0.05 to 10.0 cps), temperatures (-1 to -10°C), confining pressures (0 to 200 psi), and sample water contents (21.4 and 35.5% for Hanover silt and 20.5, 29.2, and 38.9% for Alaska silt) ranged from 1×10^5 to 35×10^5 psi for Hanover silt and 1×10^5 to 22×10^5 psi for Alaska silt. Values of damping ratio ranged from .02 to .36 for Hanover silt and .02 to .32 for Alaska silt.

(2) The influence of the various parameters on the dynamic Young's modulus of frozen silt in the order of their importance is as follows:

- (a) Strain amplitude - the dynamic Young's modulus of both silts decreases as the axial strain amplitude increases, with a more pronounced effect at low temperatures (-4 and -10°C) than at high temperatures (-1°C). The relationship between dynamic Young's modulus and strain amplitude appears to be independent of frequency and water content.
- (b) Temperature - the dynamic Young's modulus increases significantly with decreasing temperature. At a low strain amplitude ($3.16 \times 10^{-3}\%$) the rate of increase is generally greater at

higher temperatures (-1 to -4°C) than at lower temperatures (-4 to -10°C); at a high strain amplitude ($3.16 \times 10^{-2}\%$), the rate of increase is more uniform over the entire temperature range. The rate of increase of dynamic Young's modulus with decreasing temperature is generally more uniform over the entire range of temperatures (-1 to -10°C) at low frequencies than at high frequencies.

- (c) Frequency - dynamic Young's modulus increases with increasing frequency. The rate of increase is slightly greater at very low and very high frequencies than at intermediate frequencies. At a high strain amplitude ($3.16 \times 10^{-2}\%$) the relationship between dynamic Young's modulus and frequency appears to be independent of water content and temperature. At a low strain amplitude ($3.16 \times 10^{-3}\%$) the rate of increase of dynamic Young's modulus with frequency is somewhat greater at -4°C than at -1 and -10°C .
- (d) Water content - the dynamic Young's modulus increases by a moderate amount as the water content increases at a high temperature (-1°C); this relationship does not appear to be affected by frequency. At lower temperatures (-4 and -10°C) there appears to be little or no significant influence of water content on dynamic Young's modulus at a high strain amplitude ($3.16 \times 10^{-2}\%$). At a lower strain amplitude ($3.16 \times 10^{-3}\%$) the relationship between dynamic Young's modulus and water content is not clear. In the case of Hanover silt, dynamic Young's modulus decreases by a small amount as the water content increases at both -4 and -10°C ; in the case of Alaska silt,

dynamic Young's modulus appears to increase by a small amount at -4°C and decrease by a small amount at -10°C as the water content increases.

(e) Confining pressure - the dynamic Young's modulus does not appear to be influenced by confining pressure under any test conditions.

(3) The influence of the various parameters on the damping ratio of frozen silt in the order of their importance is as follows:

(a) Strain amplitude - in general, the damping ratio increases as strain amplitude increases. At a high temperature (-1°C) the rate of increase is moderate at low frequencies and somewhat greater at higher frequencies for low water contents; for higher water contents the rate of increase is moderate at all frequencies. At lower temperatures (-4 and -10°C) damping increases significantly with increasing strain amplitude at low frequencies. At high frequencies the damping ratio increases by a smaller amount and in some cases decreases by a small amount with increasing strain amplitude; in some instances the relationship becomes U-shaped, with a slight decrease in damping followed by an increase with increasing strain amplitude.

(b) Temperature - damping ratio generally decreases with decreasing temperature. The influence of temperature on damping ratio appears to be more significant at low water contents than at high water contents. At a low strain amplitude ($3.16 \times 10^{-3}\%$) at low water contents the rate of decrease of damping ratio is generally greater in the high temperature range (-1 to -4°C) than in the low temperature range (-4 to -10°C); at high water contents the rate of decrease appears to be more uniform over the entire temperature

range (-1 to -10°C). At a high strain amplitude ($3.16 \times 10^{-2}\%$) the rate of decrease in damping ratio with decreasing temperature is generally somewhat less than at a low strain amplitude ($3.16 \times 10^{-3}\%$). In many cases, there appears to be either little change or a slight increase in damping ratio from -1 to -4°C followed by a gradual decrease from -4 to -10°C.

- (c) Frequency - damping ratio generally decreases with increasing frequency. At a high strain amplitude ($3.16 \times 10^{-2}\%$) at all temperatures and at a lower strain amplitude ($3.16 \times 10^{-3}\%$) at a high temperature (-1°C) the damping ratio generally decreases by a smaller amount in the frequency range 0.05 to 5.0 cps than in the frequency range 5.0 to 10.0 cps. At a low strain amplitude ($3.16 \times 10^{-3}\%$) at a temperature of -4°C, the damping ratio decreases with increasing frequency at a rate somewhat more uniform than at -1°C. At a low temperature (-10°C) at a low strain amplitude ($3.16 \times 10^{-3}\%$) the damping ratio generally decreases by a small amount with increasing frequency at low frequencies (0.05 to 5.0 cps) and increases with increasing frequency at higher frequencies (5.0 to 10.0 cps).
- (d) Water content - damping ratio decreases significantly with increasing water content at a high temperature (-1°C); the relationship does not seem to be significantly affected by strain amplitude. It appears that at low frequencies most of the decrease in damping ratio occurs in the high water content range while at high frequencies the rate of decrease is more uniform over the entire range of water contents. At lower temperatures (-4 and -10°C) there appears to be no significant influence of

water content on damping ratio at a low strain amplitude ($3.16 \times 10^{-3}\%$). At a high strain amplitude ($3.16 \times 10^{-2}\%$) the damping ratio decreases with increasing water content; the relationship appears to be dependent on frequency, with a slight decrease occurring at low frequencies and a more significant decrease at higher frequencies.

- (e) Confining pressure - damping ratio is not influenced by confining pressure at low temperatures (-4 and -10°C). At a high temperature (-1°C) and a low strain amplitude ($3.16 \times 10^{-3}\%$) damping ratio decreases with increasing confining pressure at low frequencies and is not significantly affected by confining pressure at higher frequencies. At a high strain amplitude ($3.16 \times 10^{-2}\%$) damping ratio decreases slightly with increasing confining pressure at low frequencies and is unaffected by confining pressure at higher frequencies. In general, the rate of decrease of damping ratio is greater at low confining pressures (0 to 50 psi) than at high confining pressures (50 to 200 psi). Confining pressure appears to have a more significant influence on damping ratio at low water contents than at high water contents.

(4) Values of dynamic Young's modulus obtained for kaolinite for the range of test strain amplitudes (approximately 2×10^{-3} to $8 \times 10^{-2}\%$), frequencies (0.05 to 10.0 cps), temperatures (-1 to -10°C), confining pressures (0 to 200 psi), and sample water contents (28.1 and 71.3%) ranged from 1×10^5 to 14.5×10^5 psi. Values of damping ratio ranged from .01 to .22.

(5) The influence of the various parameters on the dynamic Young's modulus of frozen clay in the order of their importance is as follows:

- (a) Strain amplitude - the dynamic Young's modulus decreases with increasing axial strain amplitude. At a high temperature (-1°C) the rate of decrease is fairly uniform over the range of strain amplitudes while at a low temperature (-10°C) the rate of decrease increases significantly with increasing strain amplitude. The relationship at -4°C is intermediate between those at -1 and -10°C . The relationship between dynamic Young's modulus and strain amplitude does not appear to be affected by frequency or water content.
- (b) Temperature - dynamic Young's modulus increases significantly with decreasing temperature. The rate of increase is generally more uniform over the entire temperature range (-1 to -10°C) at a high strain amplitude ($3.16 \times 10^{-2}\%$) and a low water content. At a low strain amplitude ($3.16 \times 10^{-3}\%$) the rate of increase is somewhat greater in the high temperature range (-1 to -4°C) than in the low temperature range (-4 to -10°C). The relationship does not appear to be influenced by frequency.
- (c) Frequency - in general, dynamic Young's modulus increases with increasing frequency. The rate of increase is somewhat greater in the frequency range 5.0 to 10.0 cps than in the frequency range 0.05 to 5.0 cps. The relationship does not appear to be influenced by temperature, strain amplitude, or water content.
- (d) Water content - at higher temperatures (-1 and -4°C) dynamic Young's modulus increases by a small amount with increasing

water content. The relationship is not influenced by frequency or strain amplitude. At a low temperature (-10°C) dynamic Young's modulus appears to decrease slightly with increasing water content at a low strain amplitude ($3.16 \times 10^{-3}\%$) and is not significantly influenced by water content at a high strain amplitude ($3.16 \times 10^{-2}\%$).

(e) Confining pressure - dynamic Young's modulus does not appear to be influenced by confining pressure under any test conditions.

(6) The influence of the various parameters on the damping ratio of frozen clay in the order of their importance is as follows:

- (a) Strain amplitude - damping ratio generally increases with increasing strain amplitude. In most instances the rate of increase is greater at higher strain amplitudes than at lower strain amplitudes. The influence of strain amplitude on damping ratio is greater at lower frequencies than at higher frequencies; at the highest frequency (10.0 cps) there is an initial decrease in damping ratio at low strain amplitudes followed by an increase at high strain amplitudes. The relationship between damping ratio and strain amplitude does not appear to be significantly influenced by water content or temperature.
- (b) Temperature - in general damping ratio decreases slightly with decreasing temperature. In most instances the decrease appears to be more pronounced at lower frequencies than at higher frequencies. At the highest frequency (10.0 cps) the relationship deviates somewhat as damping ratio tends to increase by a small amount with decreasing temperature. In general, the rate of change in damping ratio is somewhat greater in the high

temperature range (-1 to -4°C) than in the low temperature range (-4 to -10°C) at a high water content (71.3%). At a low water content (28.1%) the rate of change is somewhat more uniform over the entire range of temperatures. The influence of strain amplitude on the relationship between damping ratio and temperature is not clear.

- (c) Frequency - at a low strain amplitude ($3.16 \times 10^{-3}\%$) damping ratio decreases by a small amount with increasing frequency to a minimum value at approximately 5.0 cps and then increases sharply between 5.0 and 10.0 cps. The relationship at a low strain amplitude is not influenced significantly by water content or temperature. At a high strain amplitude ($3.16 \times 10^{-2}\%$) damping ratio decreases with increasing frequency over the entire range of frequencies. At higher temperatures (-1 and -4°C) the rate of decrease is fairly uniform from 0.05 to 5.0 cps and significantly greater from 5.0 to 10.0 cps. At a lower temperature (-10°C) the rate of decrease is somewhat more uniform over the entire range of frequencies. The relationship at a high strain amplitude does not appear to be influenced significantly by water content.
- (d) Water content - in general, it appears that water content has at most only a slight influence on damping ratio over the range of water contents considered. At a high temperature (-1°C) and a low strain amplitude ($3.16 \times 10^{-3}\%$) damping ratio increases by a small amount with increasing water content. The change is most significant at lower frequencies and becomes negligible at higher frequencies. At a high strain amplitude ($3.16 \times 10^{-2}\%$)

damping ratio increases by a slight amount with increasing water content at the lowest frequency (0.05 cps) and decreases by a slight amount at higher frequencies. At lower temperatures (-4 and -10°C) the relationship between damping ratio and water content and the influence of frequency and strain amplitude on the relationship are not entirely clear; it appears that, in general, water content has a slight to negligible influence on damping ratio.

- (e) Confining pressure - damping ratio is not influenced by confining pressure at low temperatures (-4 and -10°C). At a high temperature (-1°C) and a low strain amplitude ($3.16 \times 10^{-3}\%$) damping ratio decreases with increasing confining pressure at the lowest frequency (0.05 cps). The rate of decrease is greater in the low confining pressure range (0 to 50 psi) than in the high confining pressure range (50 to 200 psi). At frequencies greater than 0.05 cps and at higher strain amplitudes ($3.16 \times 10^{-2}\%$) confining pressure does not have a significant influence on damping ratio. The relationship is not influenced by water content.

A comparison of the dynamic properties of frozen silt and clay obtained in the present study with those obtained in previous studies may be summarized as follows:

- (1) The values of longitudinal and compression wave velocities of frozen silt obtained in the present study are somewhat lower than those obtained in previous studies. This may be due to the much lower frequencies and higher strain amplitudes associated with the present study than with previous studies. Differences in the types of silts

used in the several studies may also contribute somewhat to the variation in values of wave velocity.

(2) The values of damping ratio of frozen silt obtained in the present study are somewhat higher than those obtained in a previous study. This may be due to the much lower frequencies and higher strain amplitudes associated with the present study than with the previous study.

(3) The values of longitudinal and compression wave velocities of frozen clay obtained in the present study generally compare favorably with those obtained in previous studies. The variation in wave velocity from the different studies may be due to the much lower frequencies associated with the present study than with previous studies. In addition, it appears that differences in the types of clays tested have a significant influence on the wave velocities obtained in the several studies.

(4) The values of damping ratio of frozen clay obtained in the present study compare favorably with those obtained in previous studies. The variation in damping ratio between the present study and the study by Stevens (1973) may be due to the much lower frequencies associated with the present study.

APPENDIX A
CYCLIC TRIAXIAL TEST RESULTS -
DYNAMIC YOUNG'S MODULUS OF FROZEN SILT

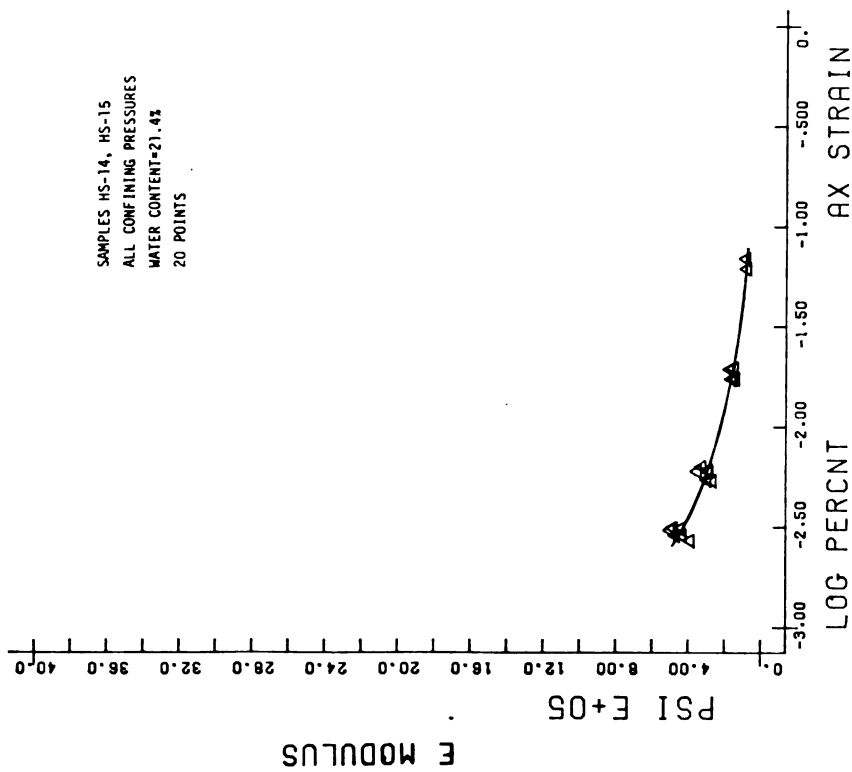


Fig. A-1 H-SILTT-1F.05

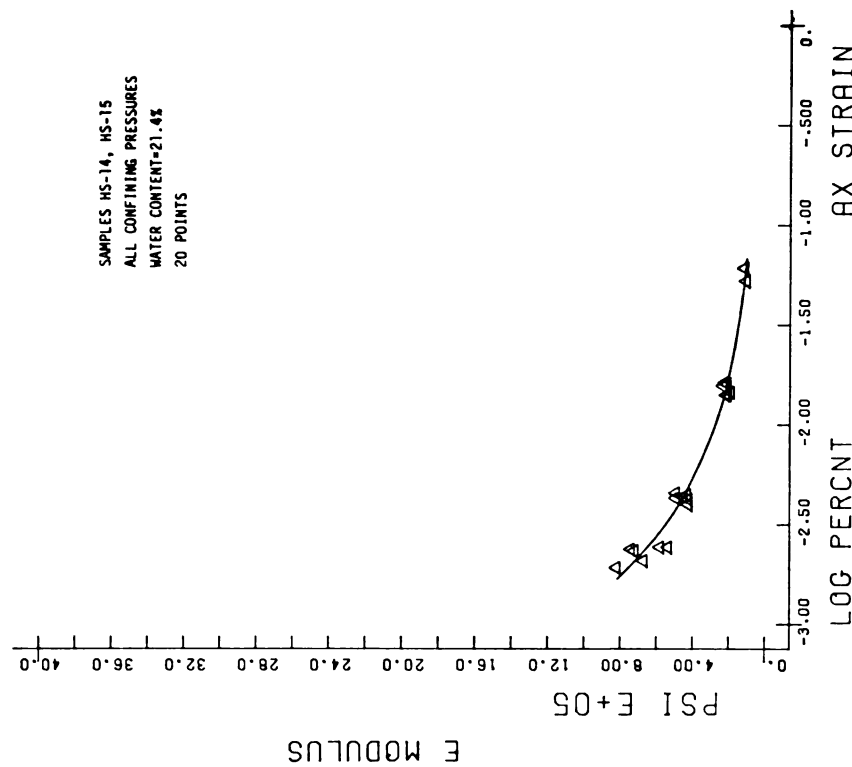


Fig. A-2 H-SILTT-1F.3

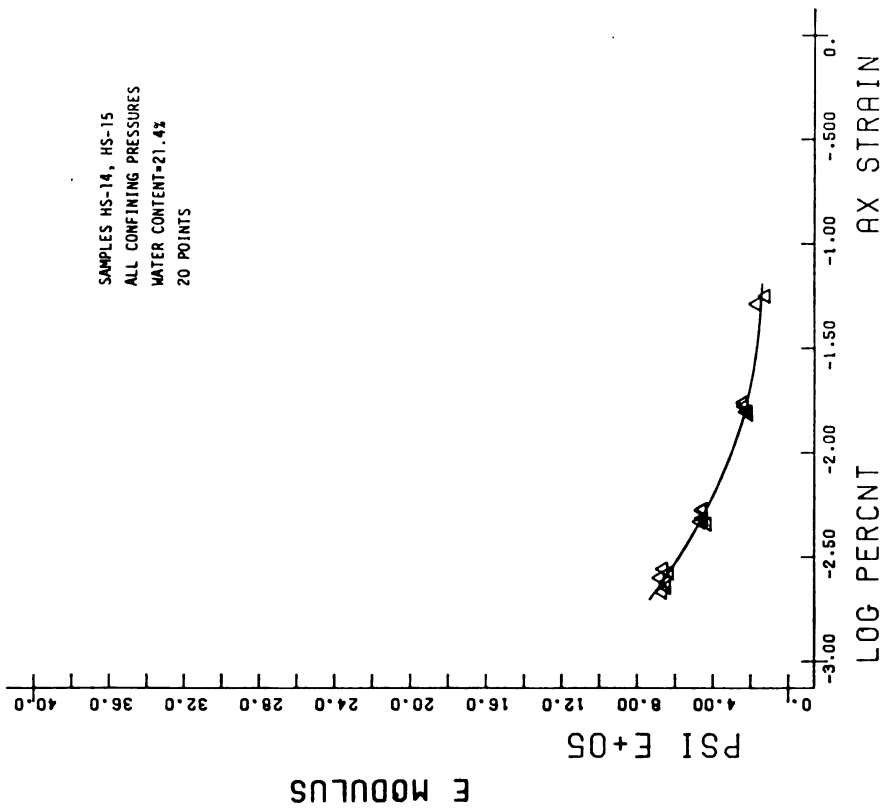


Fig. A-3 H-SILTT-1F1

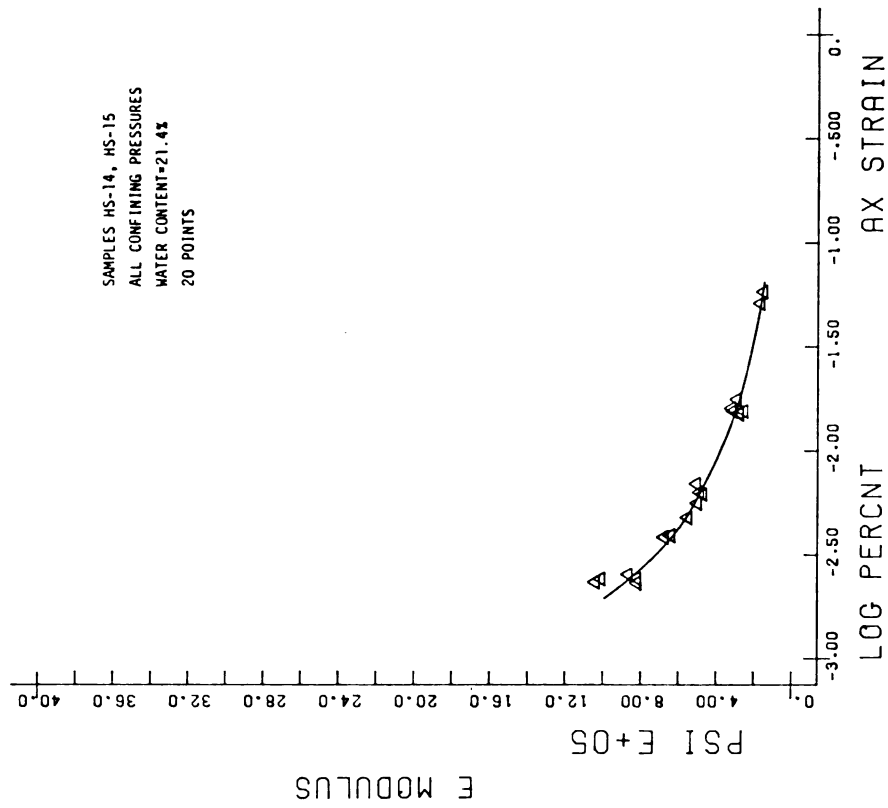


Fig. A-4 H-SILTT-1F5

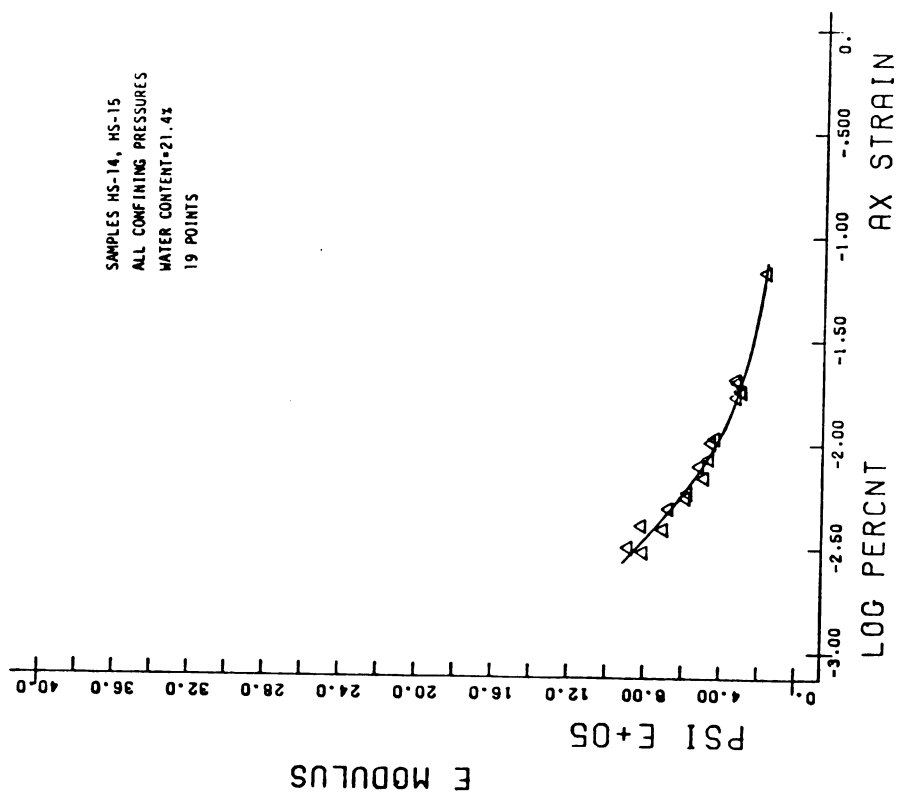


Fig. A-5 H-SILTT-1F10

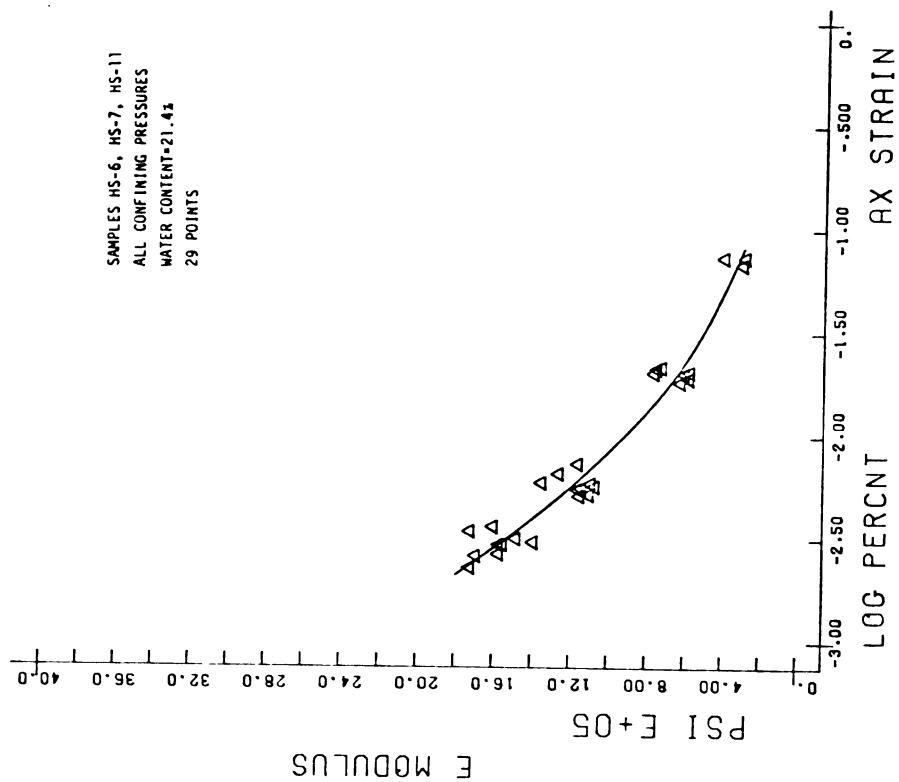


Fig. A-6 H-SILTT-4F05

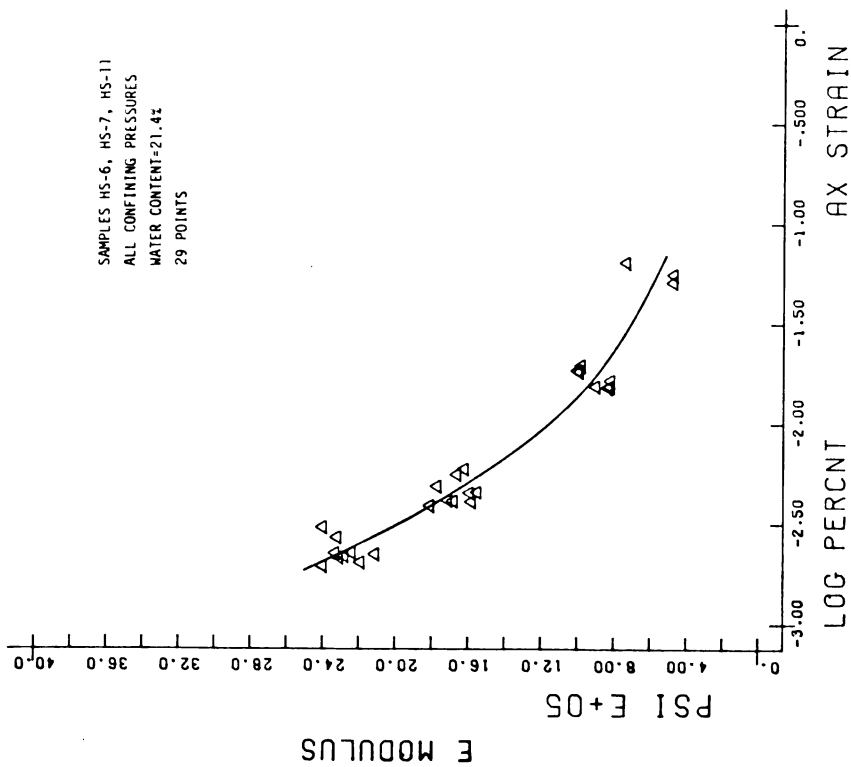


Fig. A-7 H-SILT-4F.3

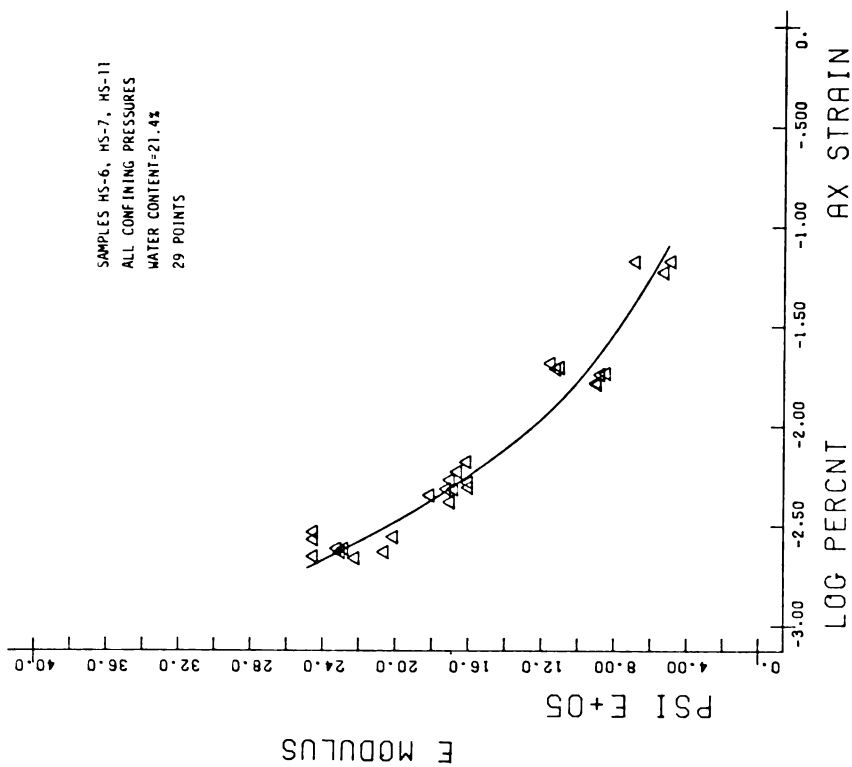


Fig. A-8 H-SILT-4F1

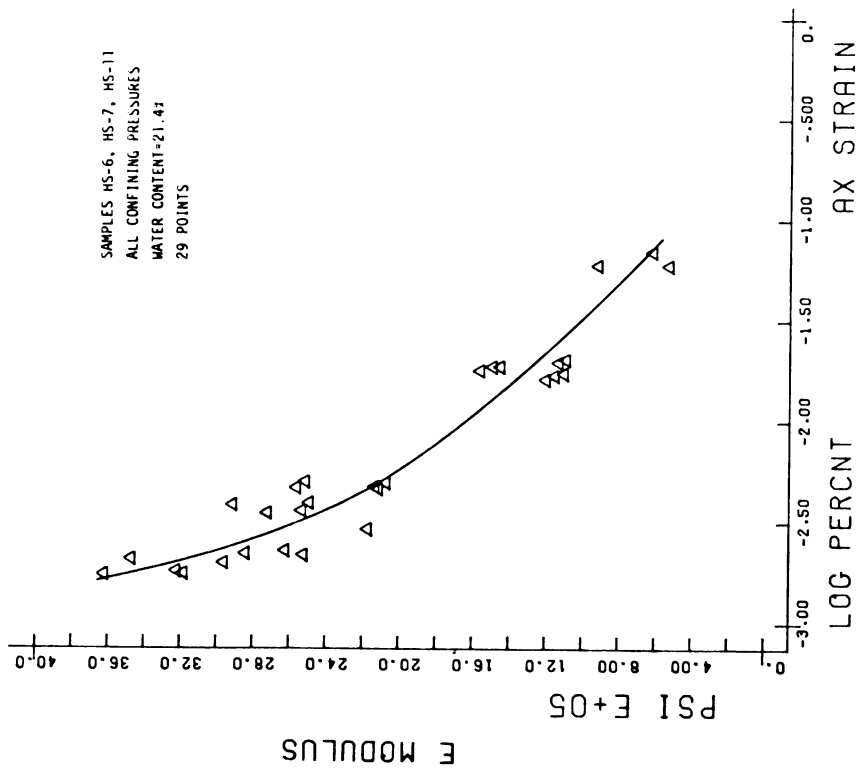


Fig. A-9 H-SILTT-4F5

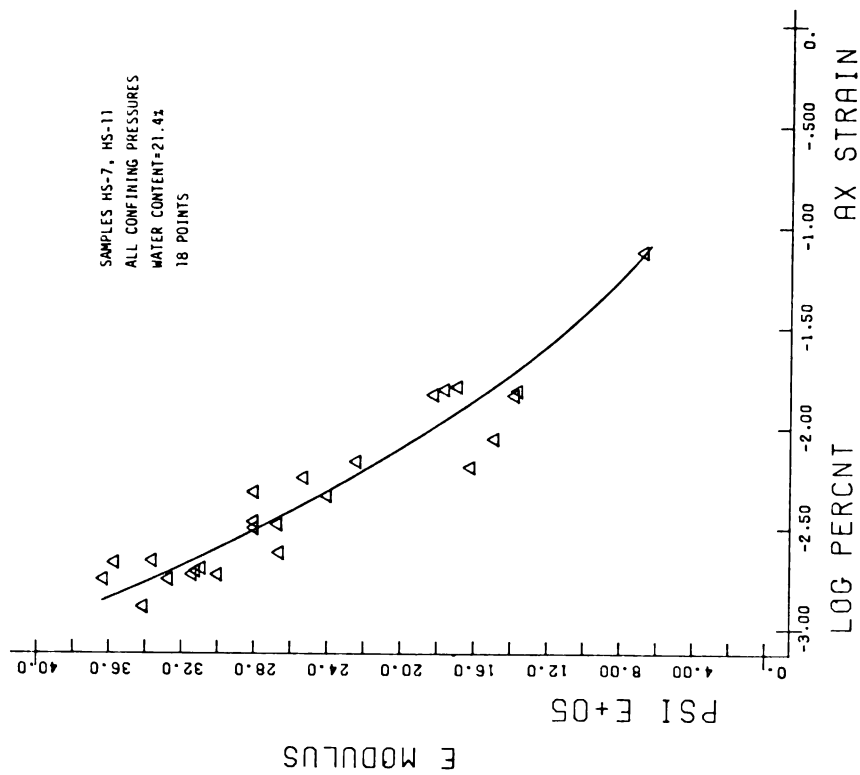


Fig. A-10 H-SILTT-4F10

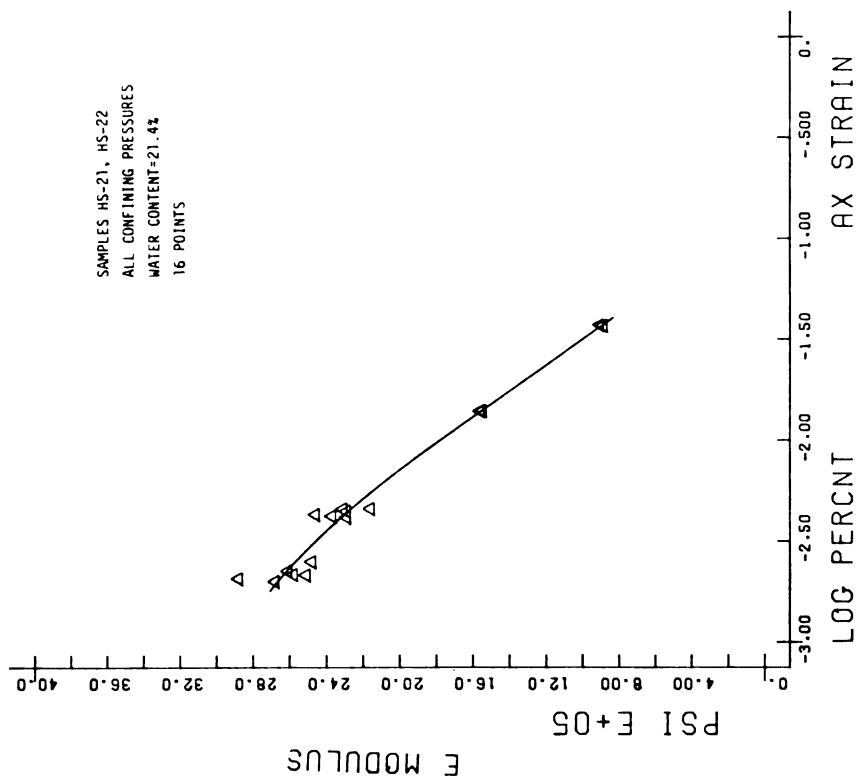


Fig. A-17 H-SILT-10F.05

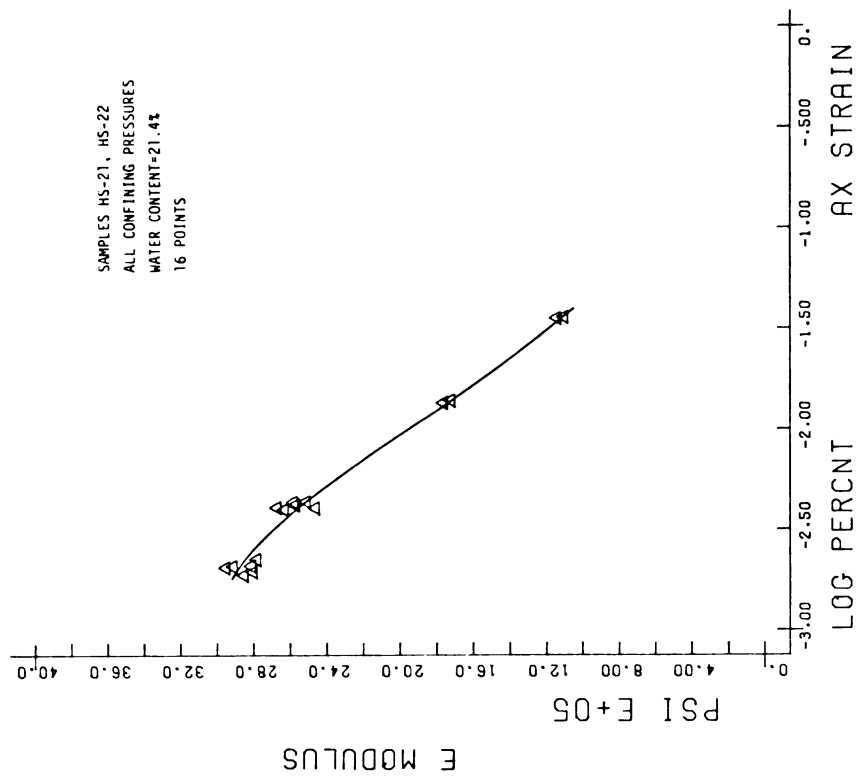


Fig. A-12 H-SILT-10F.3

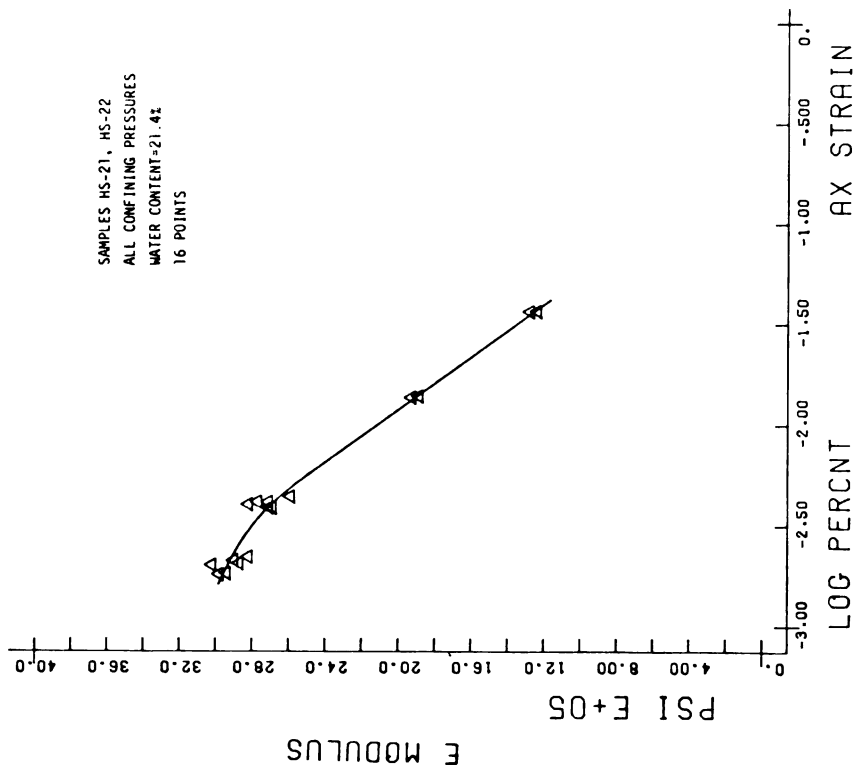


Fig. A-13 H-SILTT-10F1

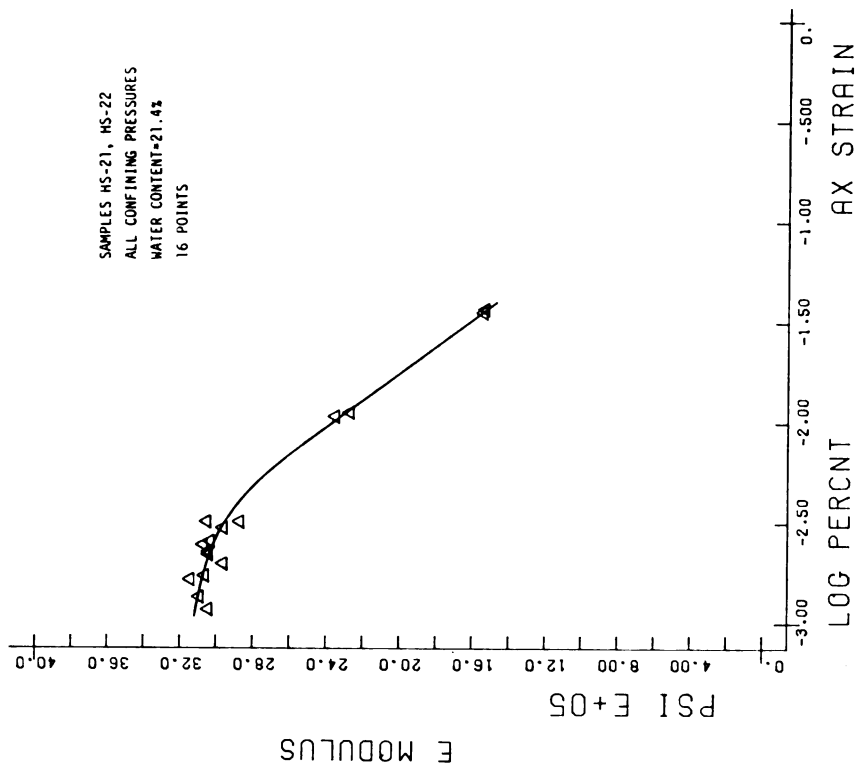


Fig. A-14 H-SILTT-10F5

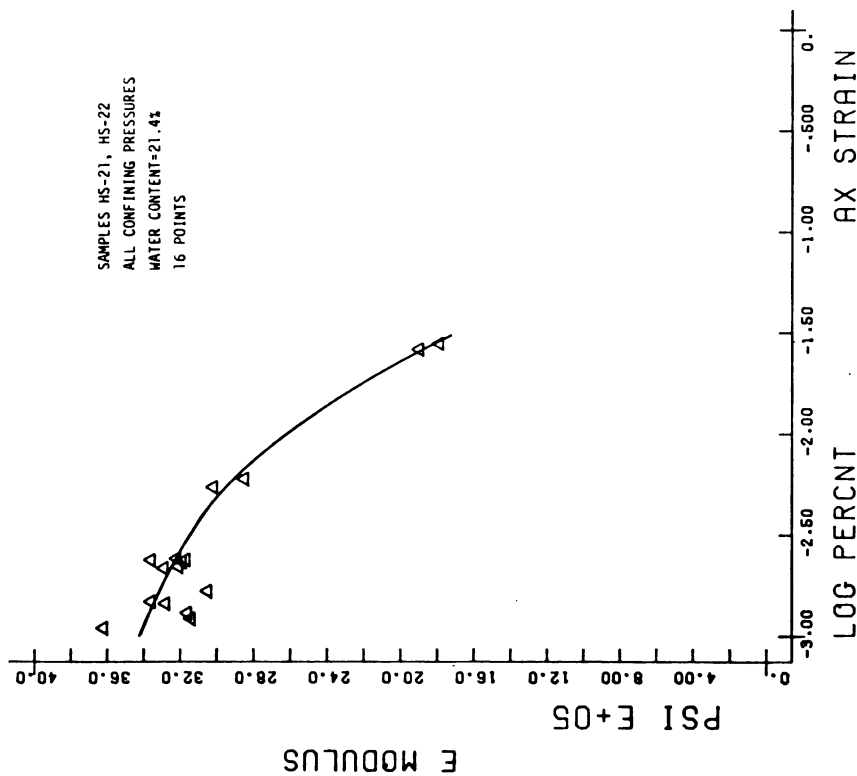


Fig. A-15 H-SILTT-10F10

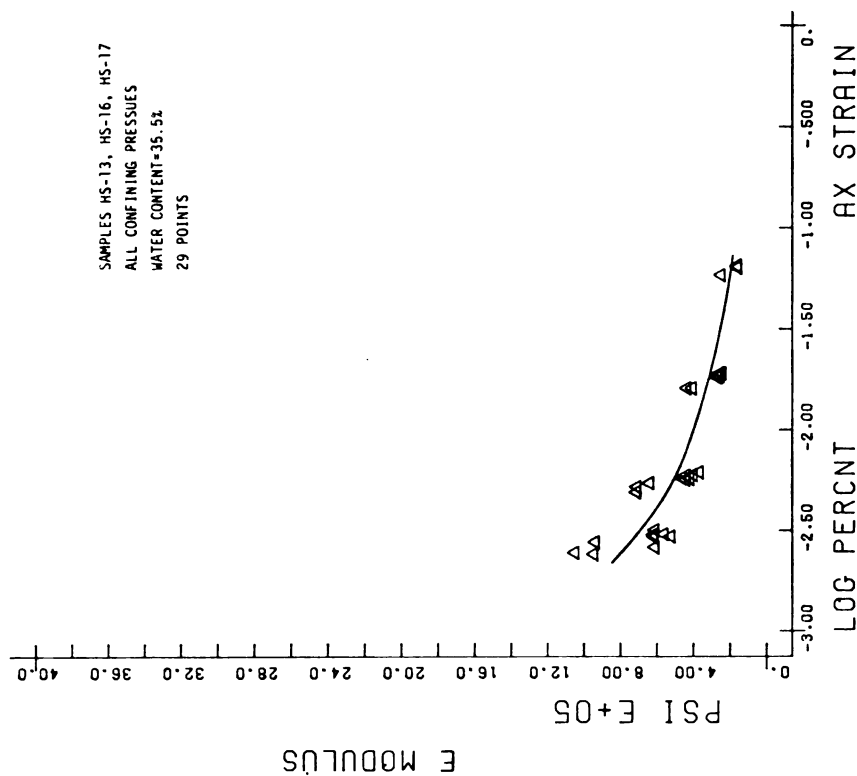


Fig. A-16 H-SILTT-1F05

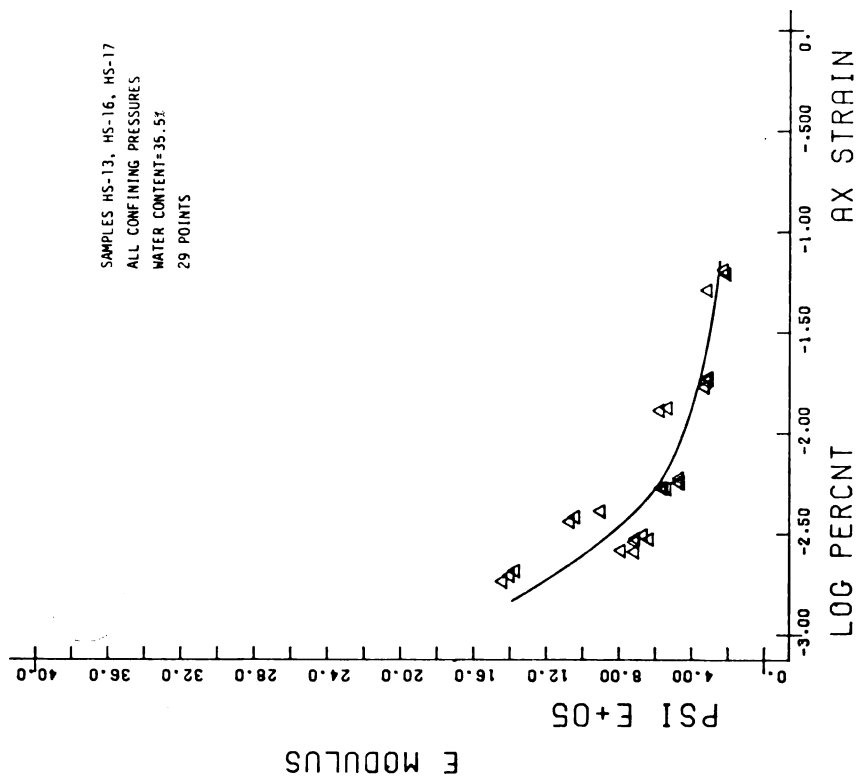


Fig. A-17 H-SILTT-1F.3

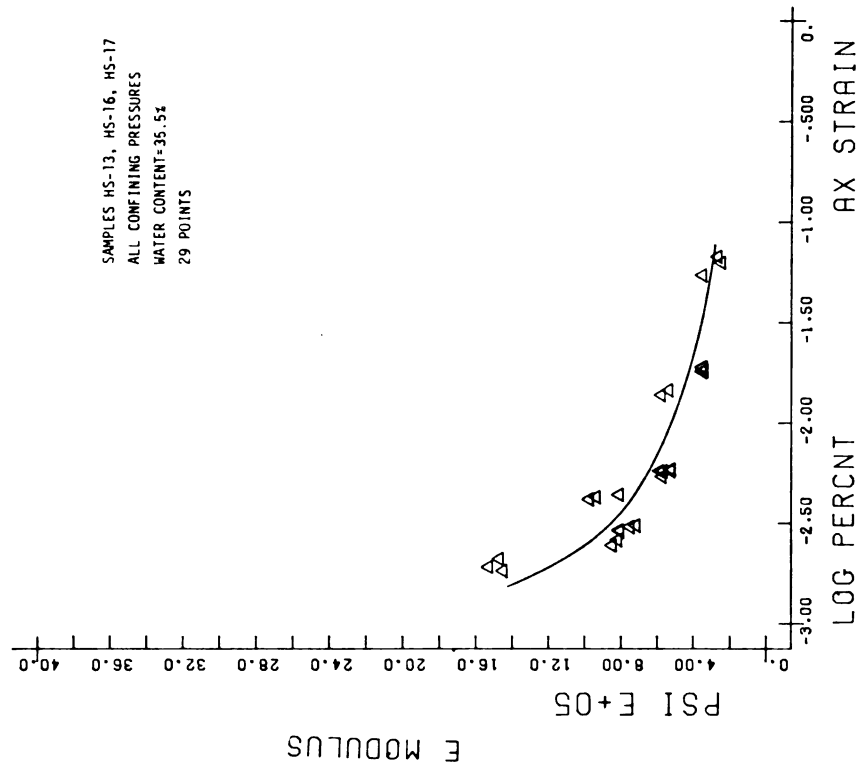


Fig. A-18 H-SILTT-1F1

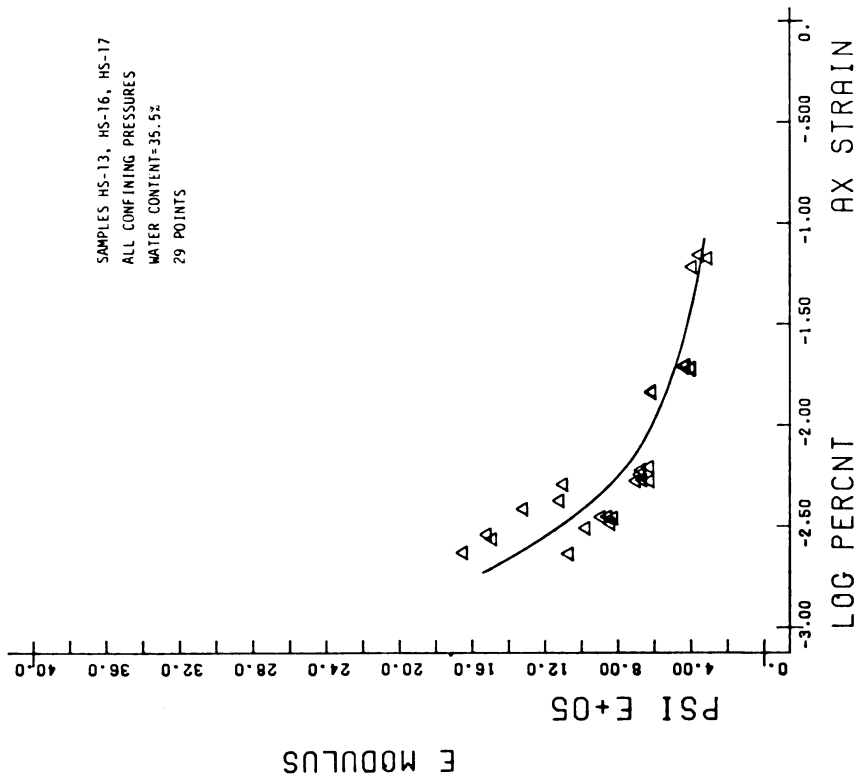


Fig. A-19 H-SILT-1F5

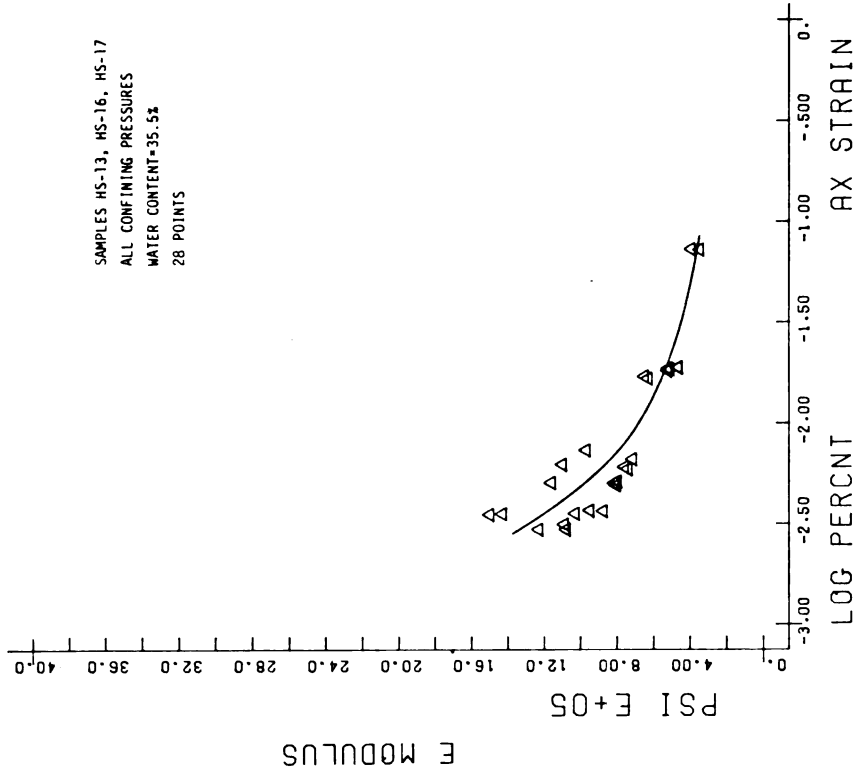


Fig. A-20 H-SILT-1F10

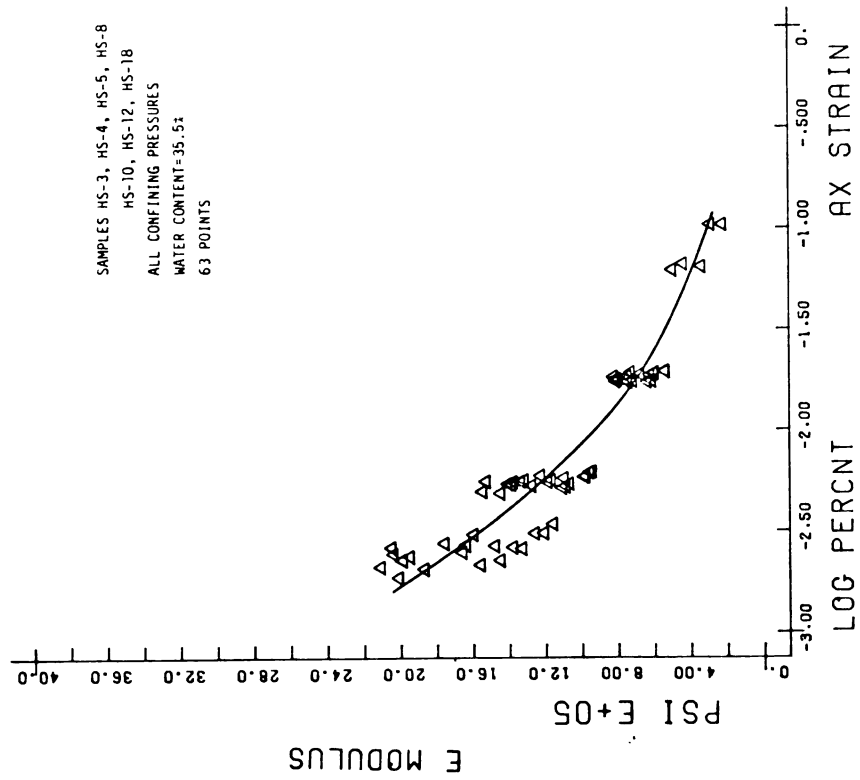


Fig. A-21H-SILTT-4F05

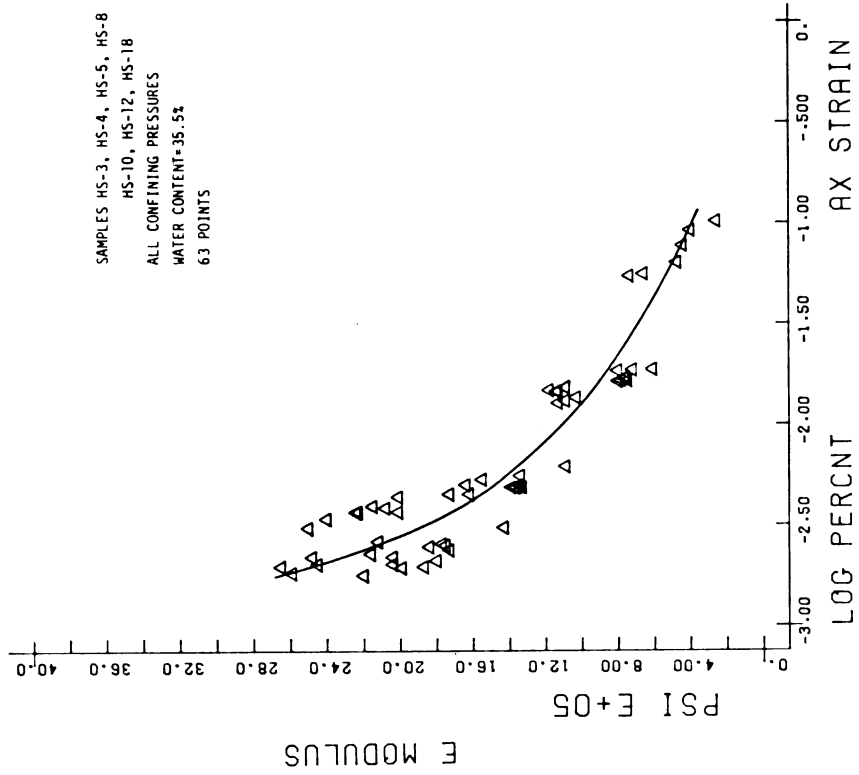


Fig. A-22H-SILTT-4F3

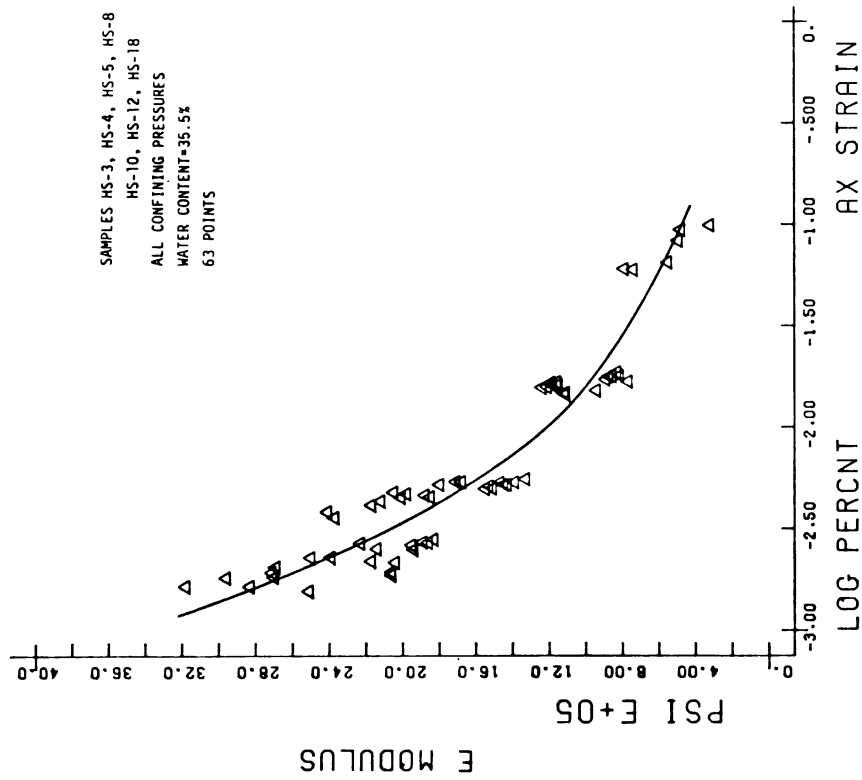


Fig. A-23 H-SILT-4F1

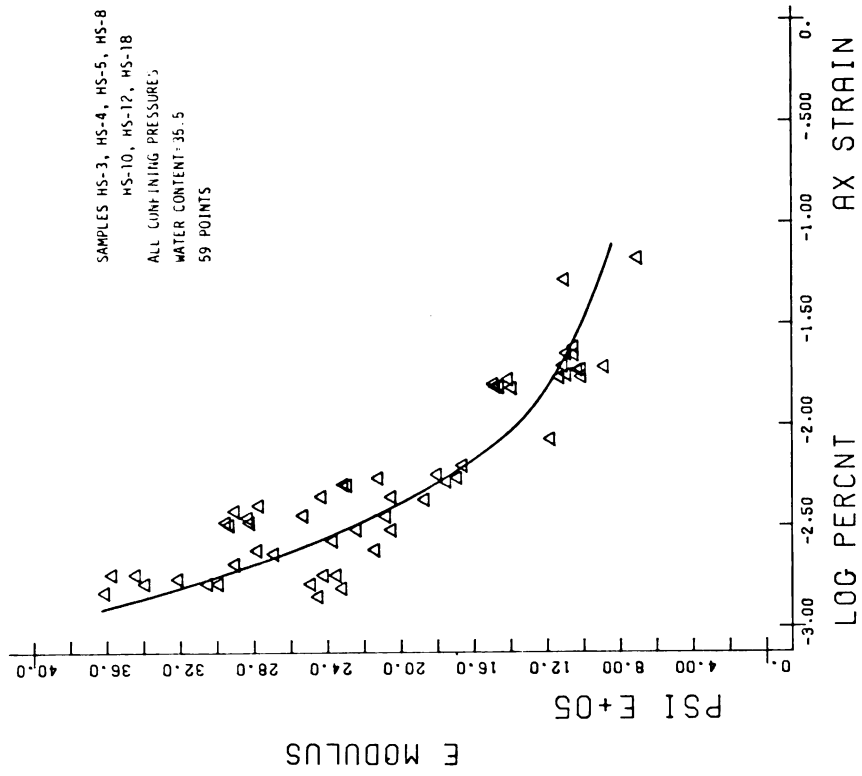


Fig. A-24 H-SILT-4F5

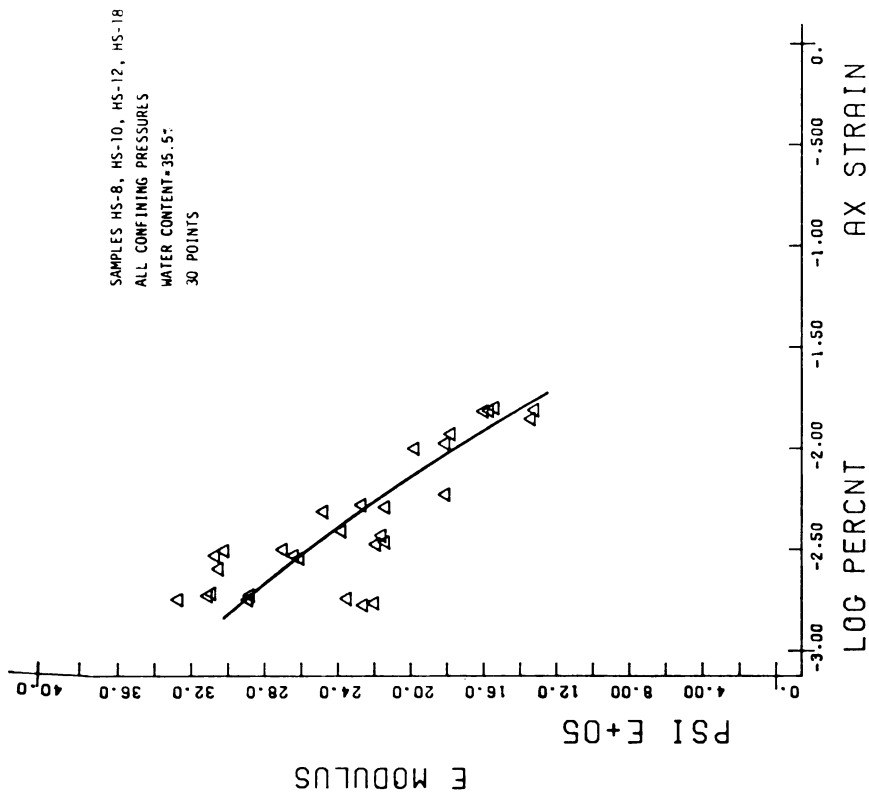


Fig. A-25 H-SILTT-4F10

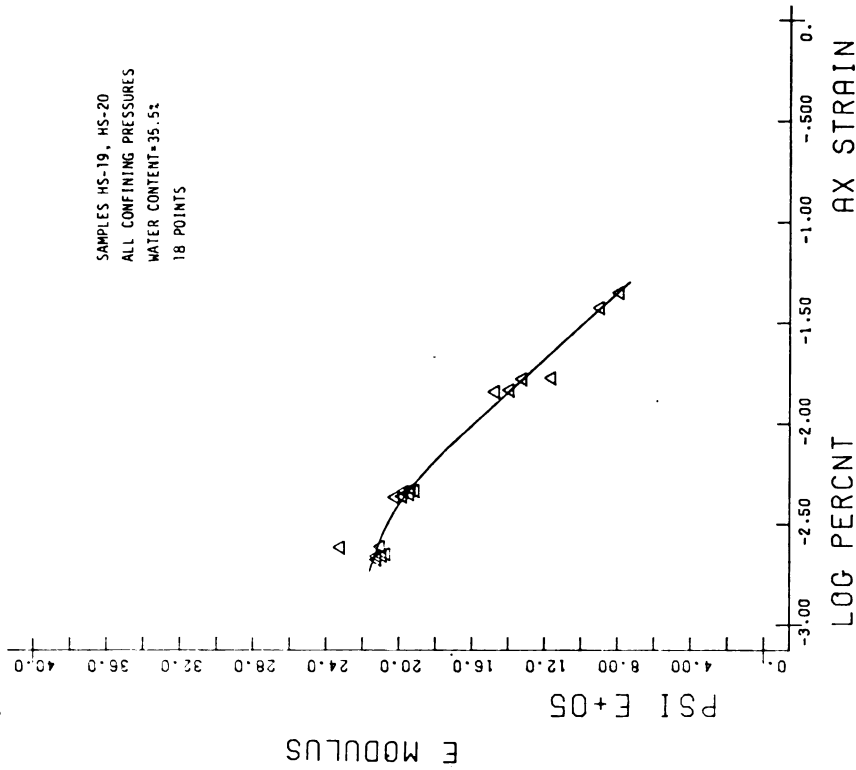


Fig. A-26 H-SILTT-10F05

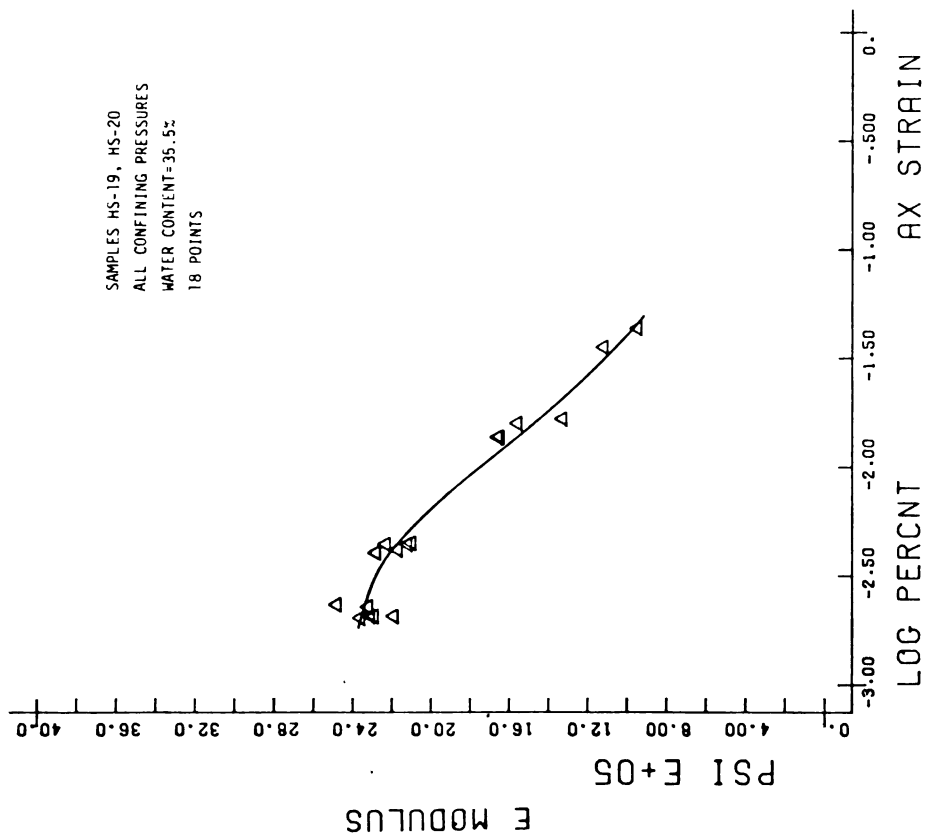


Fig. A-27H-SILTT-10F.3

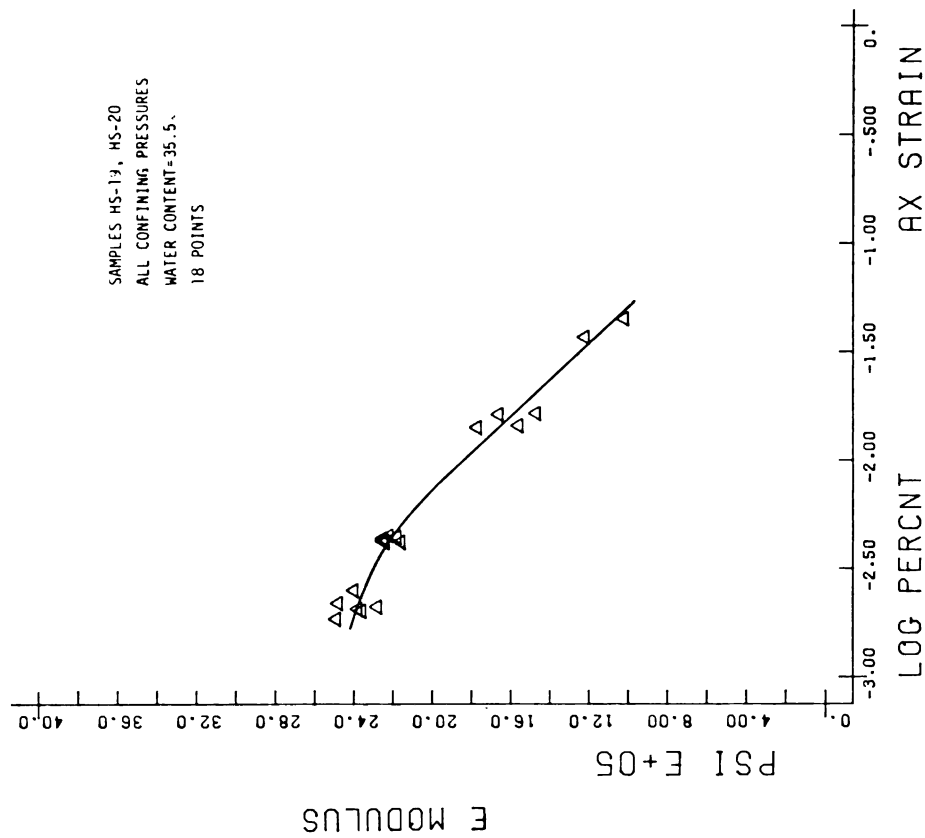


Fig. A-28H-SILTT-10F1

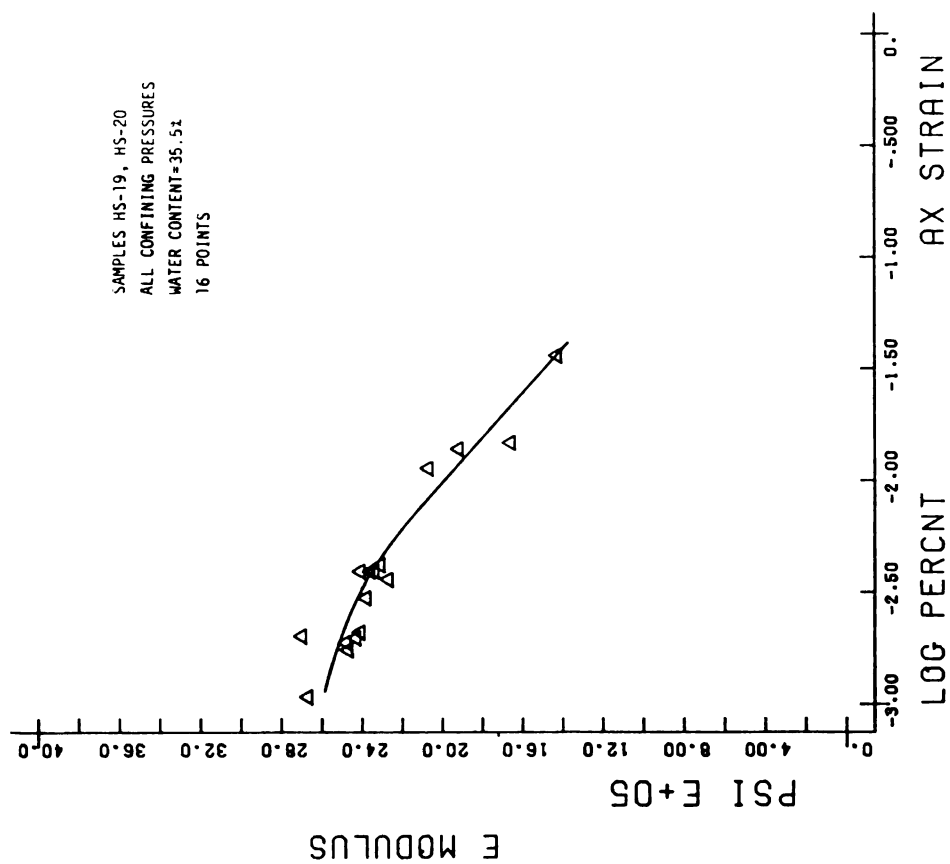


Fig. A-29H-SILTT-10F5

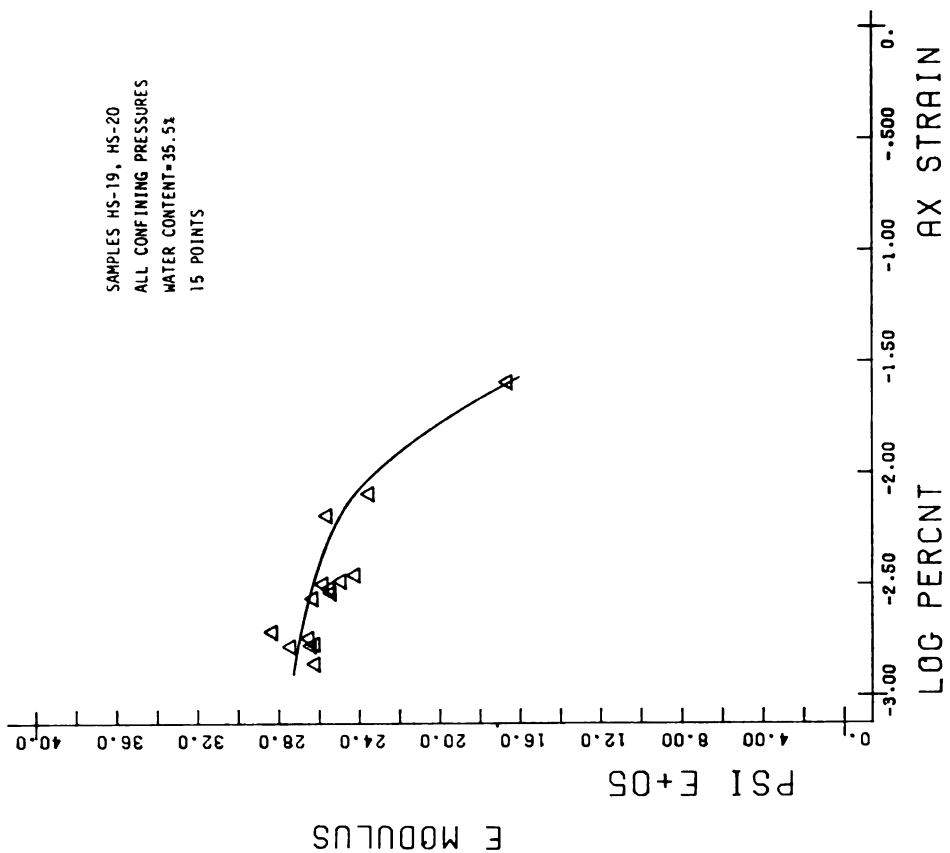


Fig. A-30H-SILTT-10F10

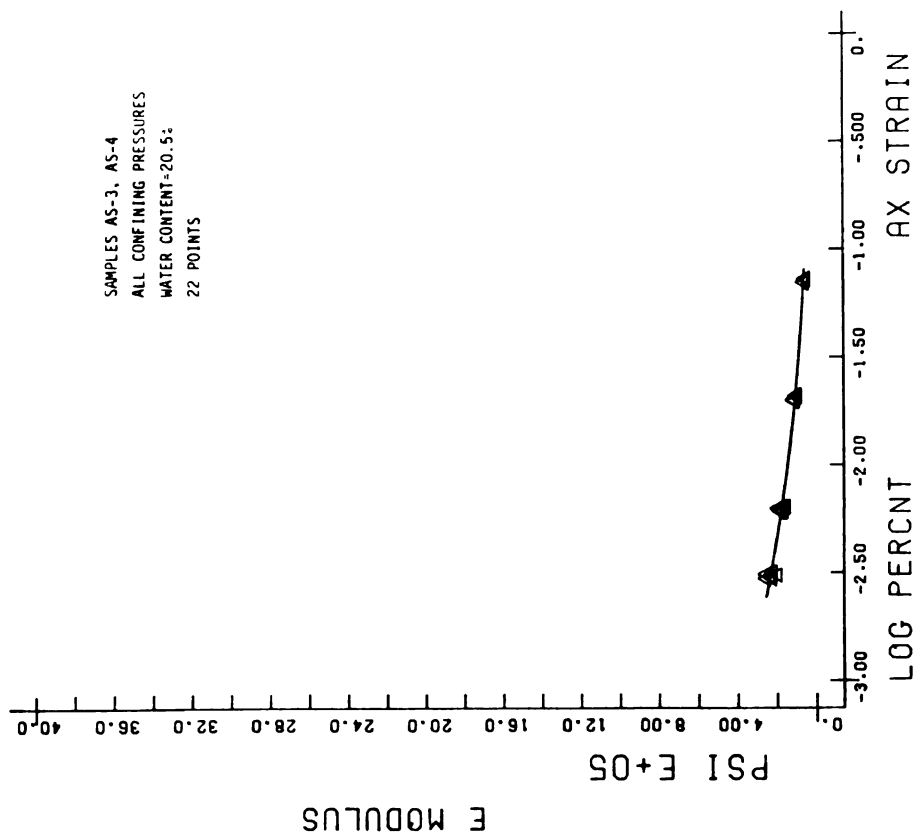


Fig. A-31 A-SILTT-1F.05

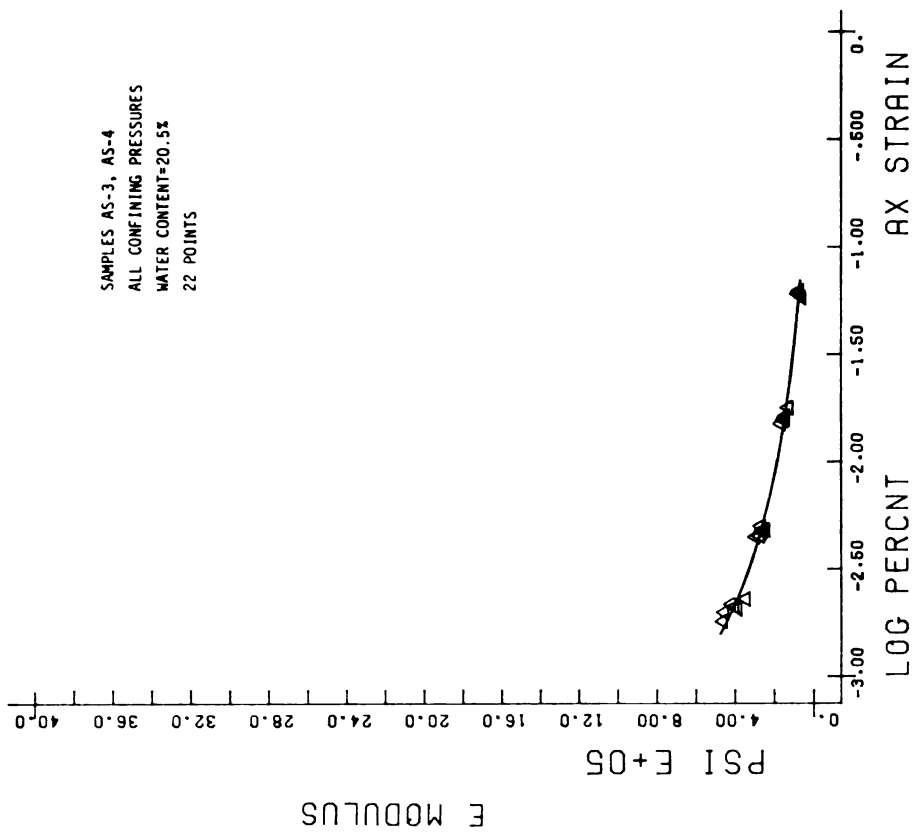


Fig. A-32 A-SILTT-1F.3

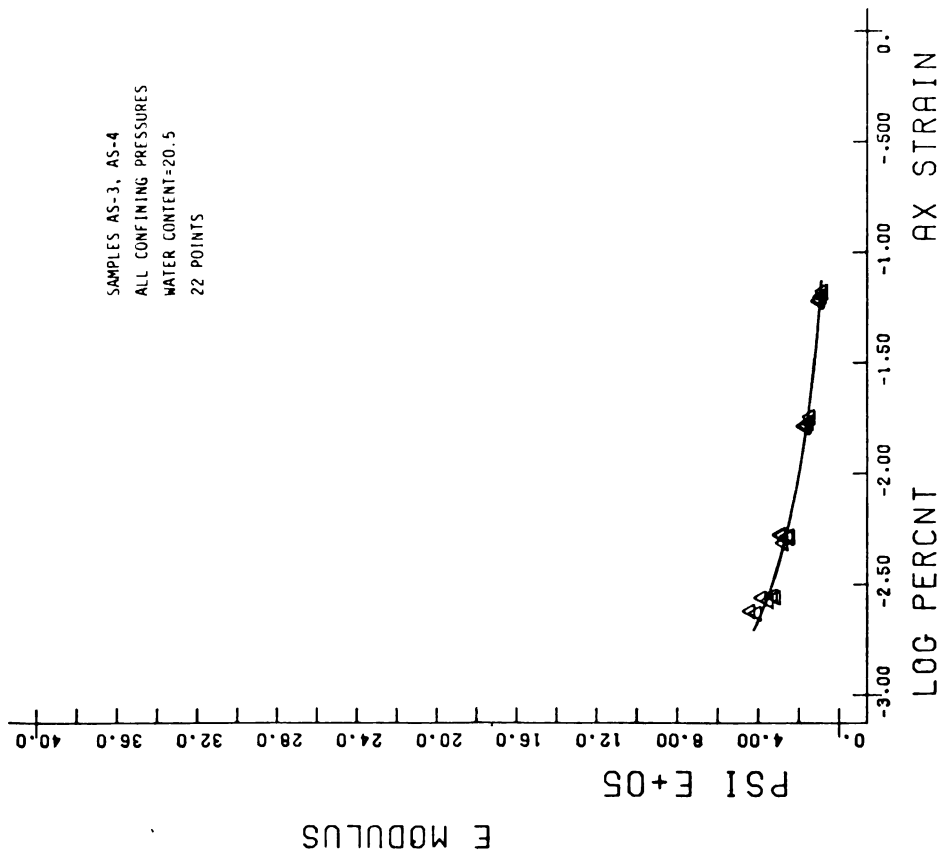


Fig. A-33A-SILTT-1F1

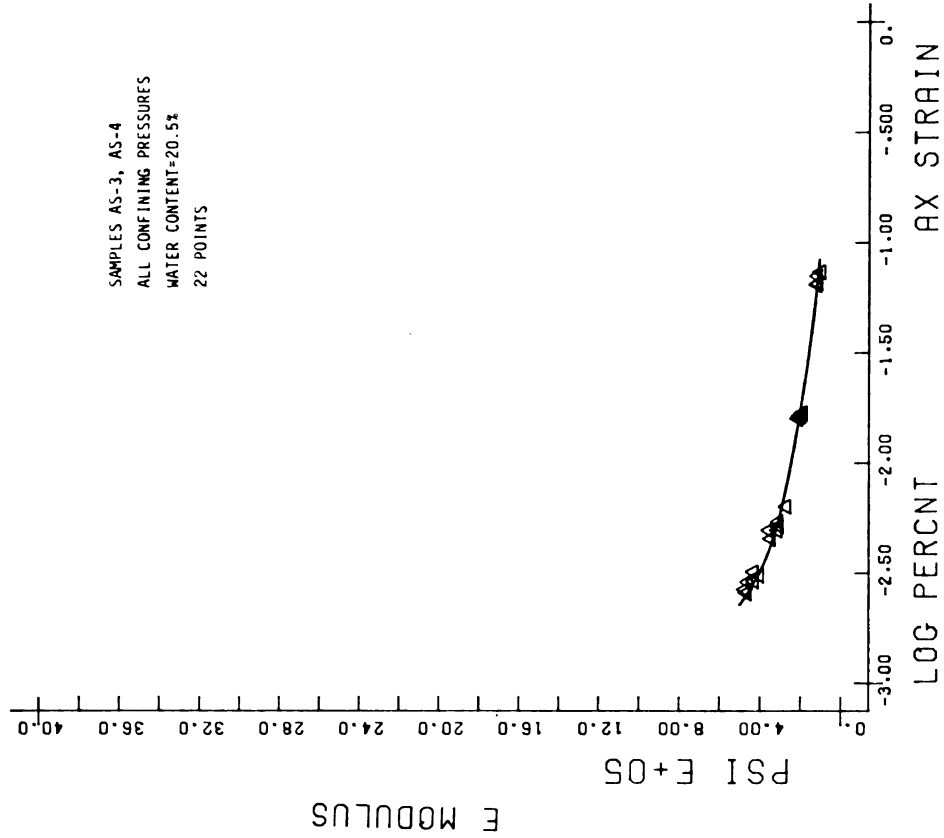


Fig. A-34A-SILTT-1F5

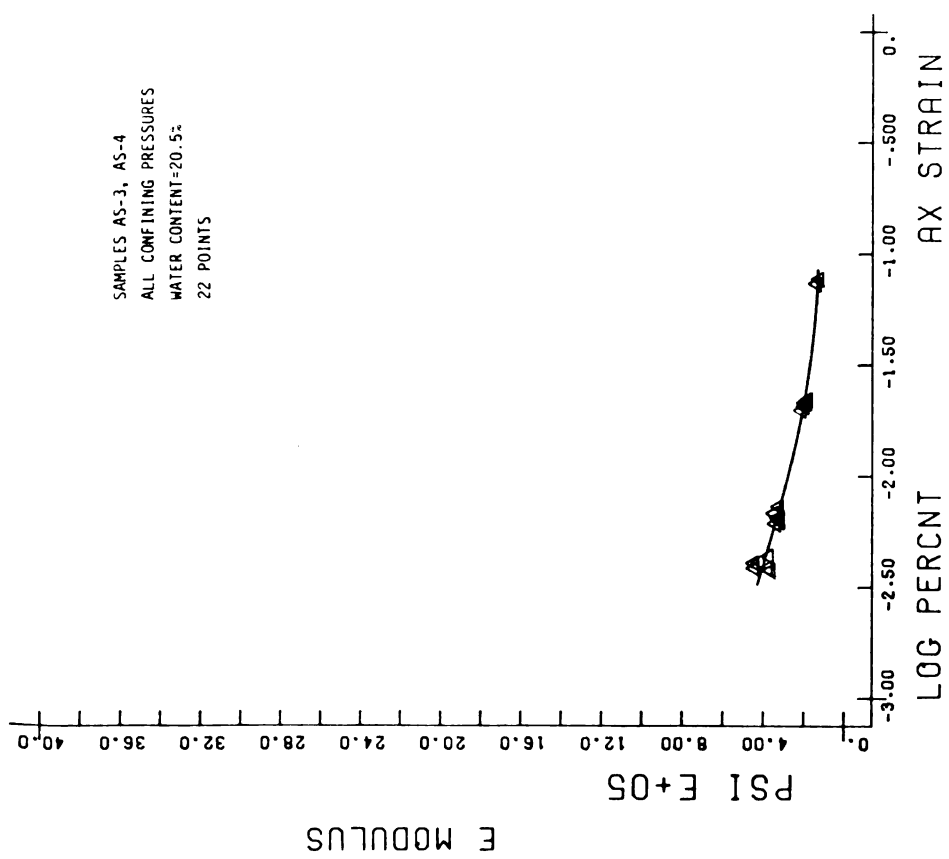


Fig. A-35 A-SILTT-1F10

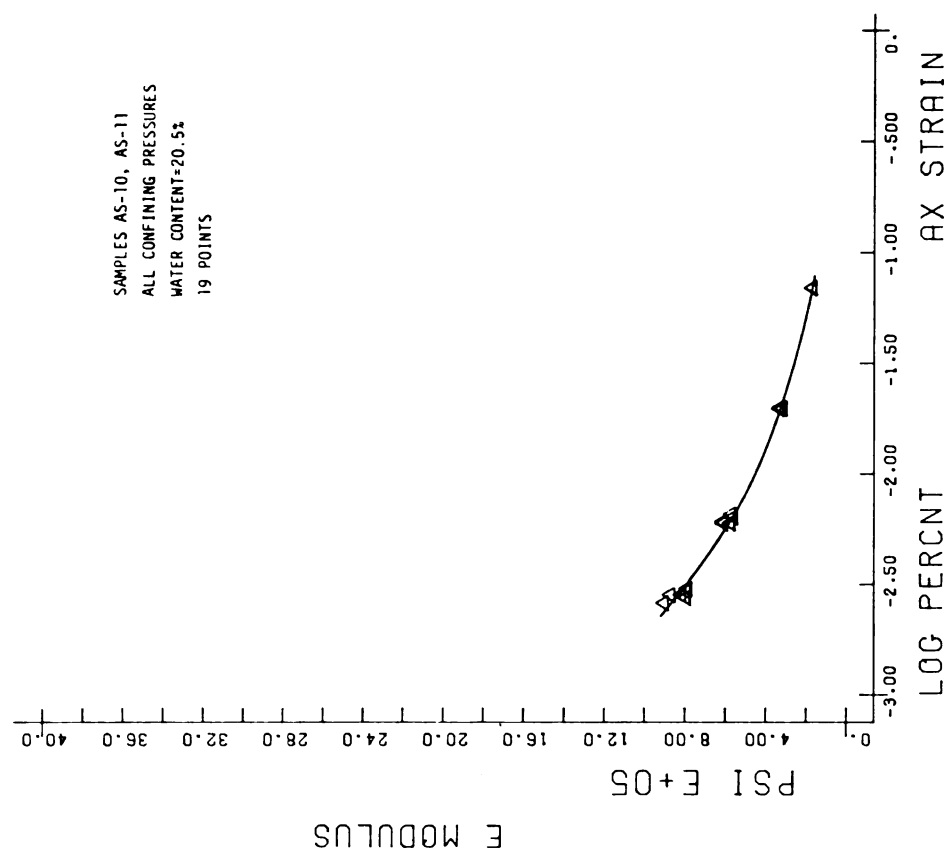


Fig. A-36 A-SILTT-4F05

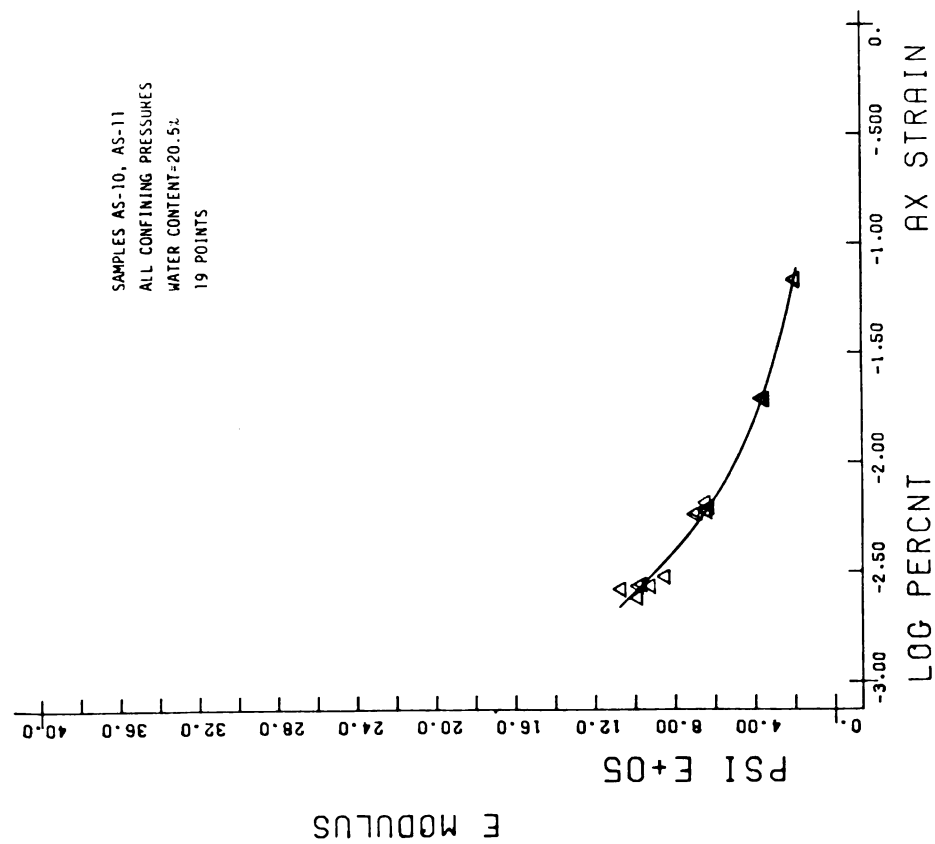


Fig. A-37A-SILTT-4F3

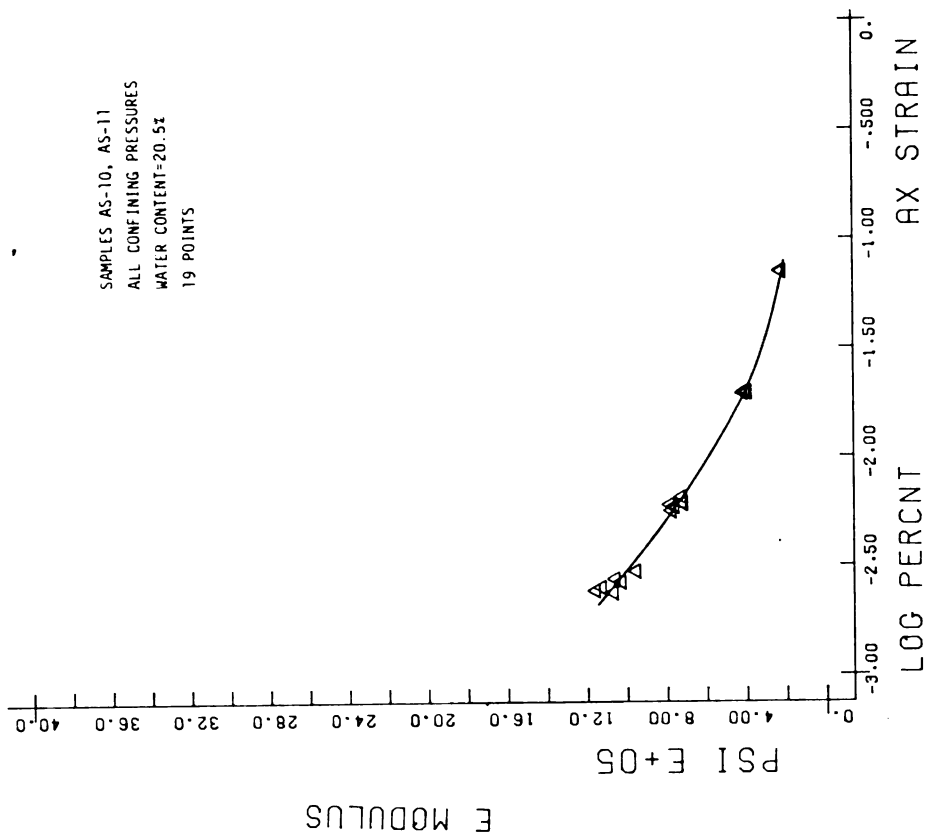


Fig. A-38A-SILTT-4F1

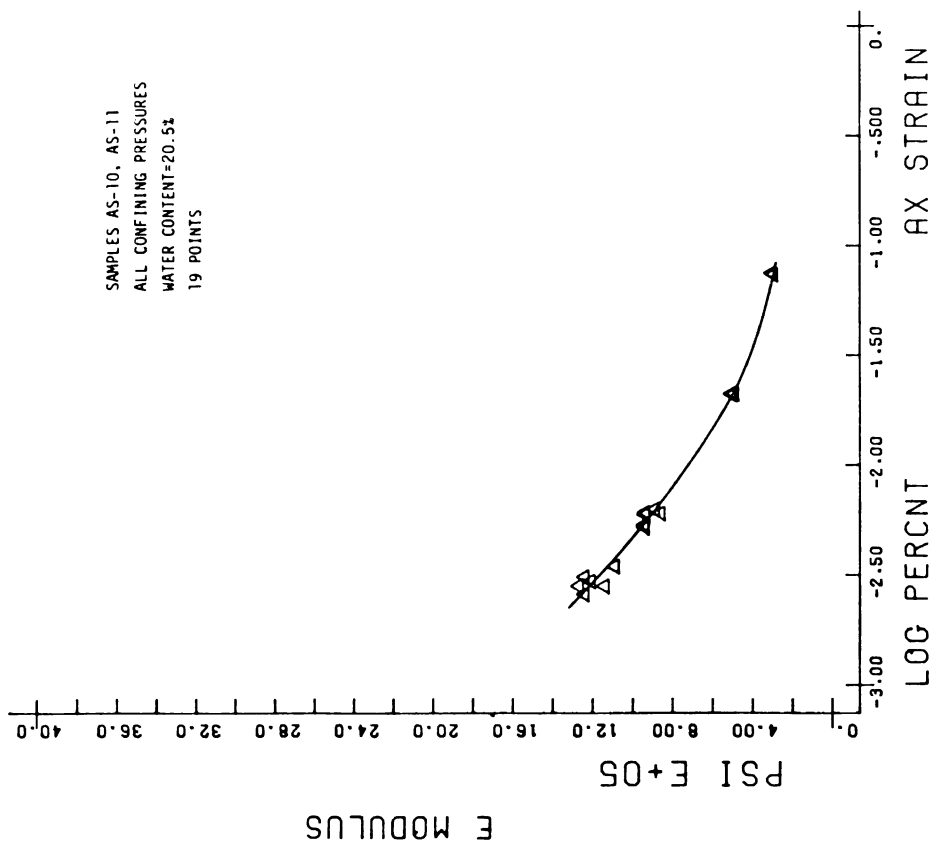


Fig. A-39 A-SILTT-4F5

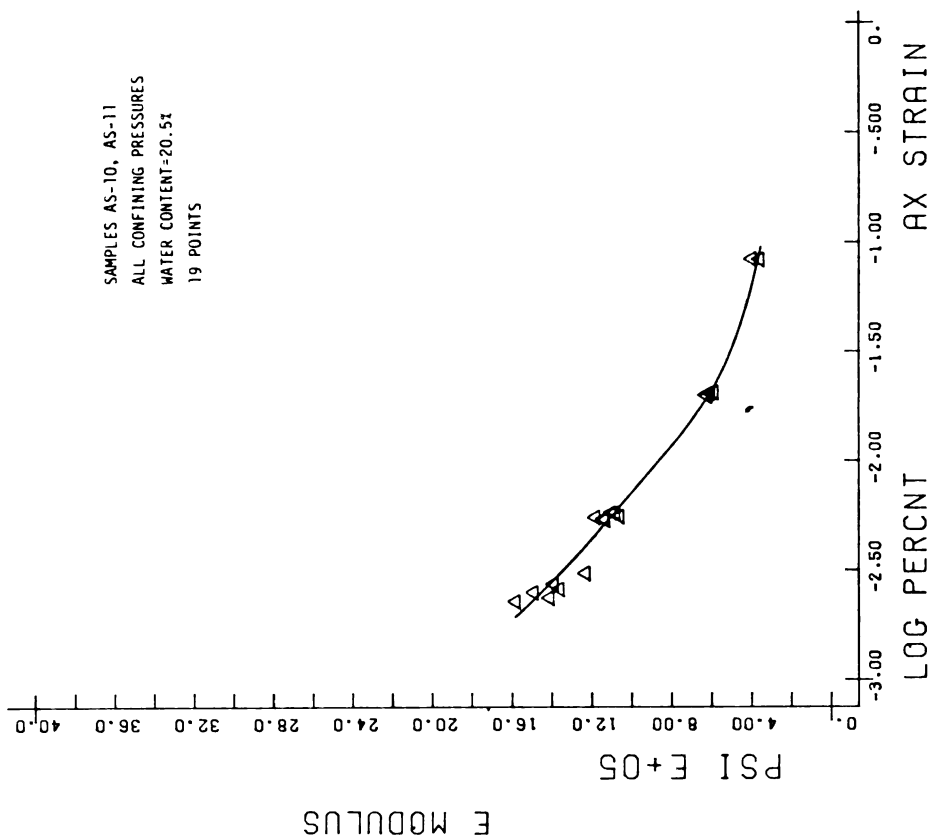


Fig. A-40 A-SILTT-4F10

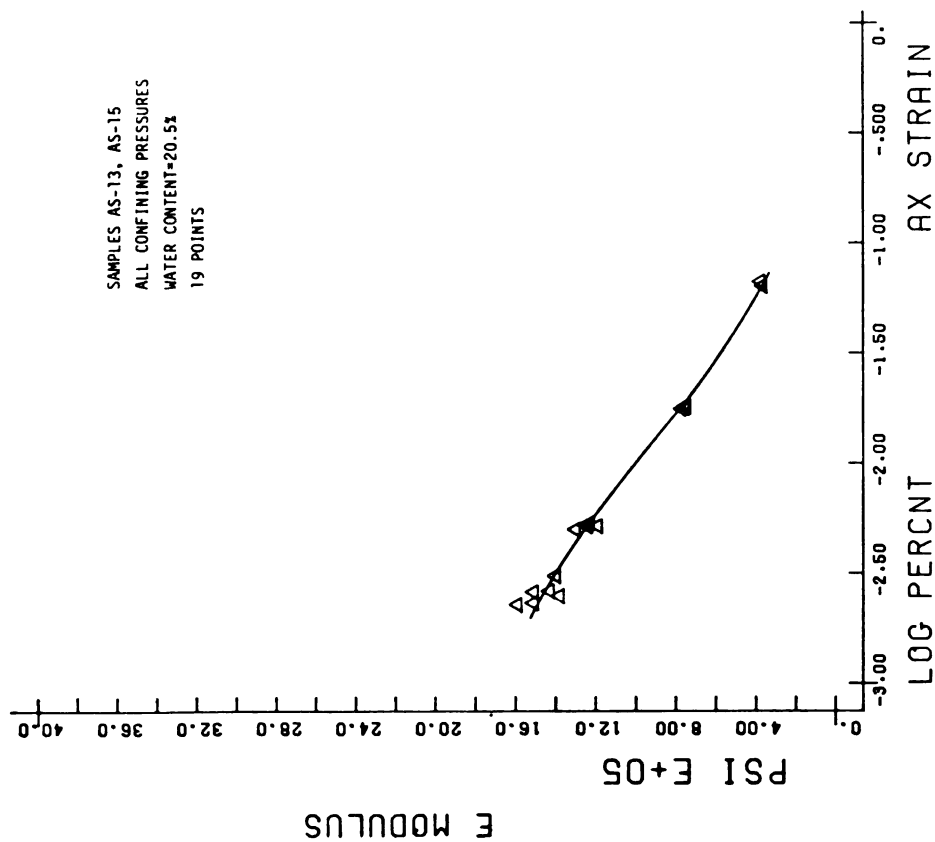


Fig. A-41 A-SILT-10F.05

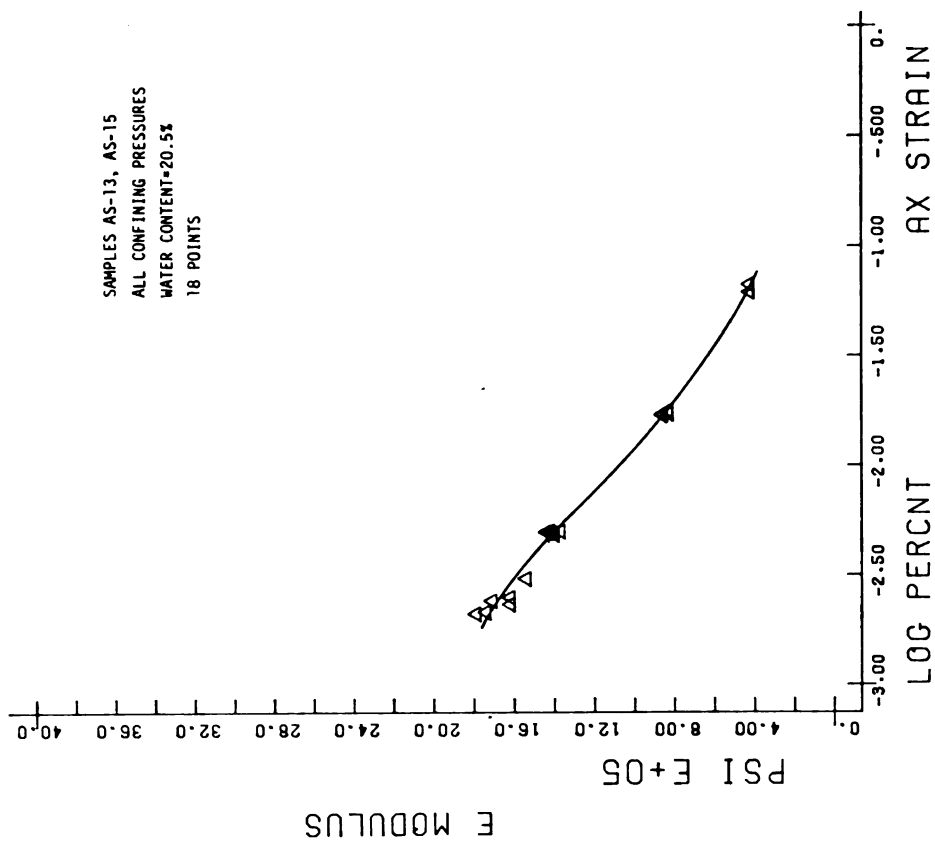


Fig. A-42 A-SILT-10F.3

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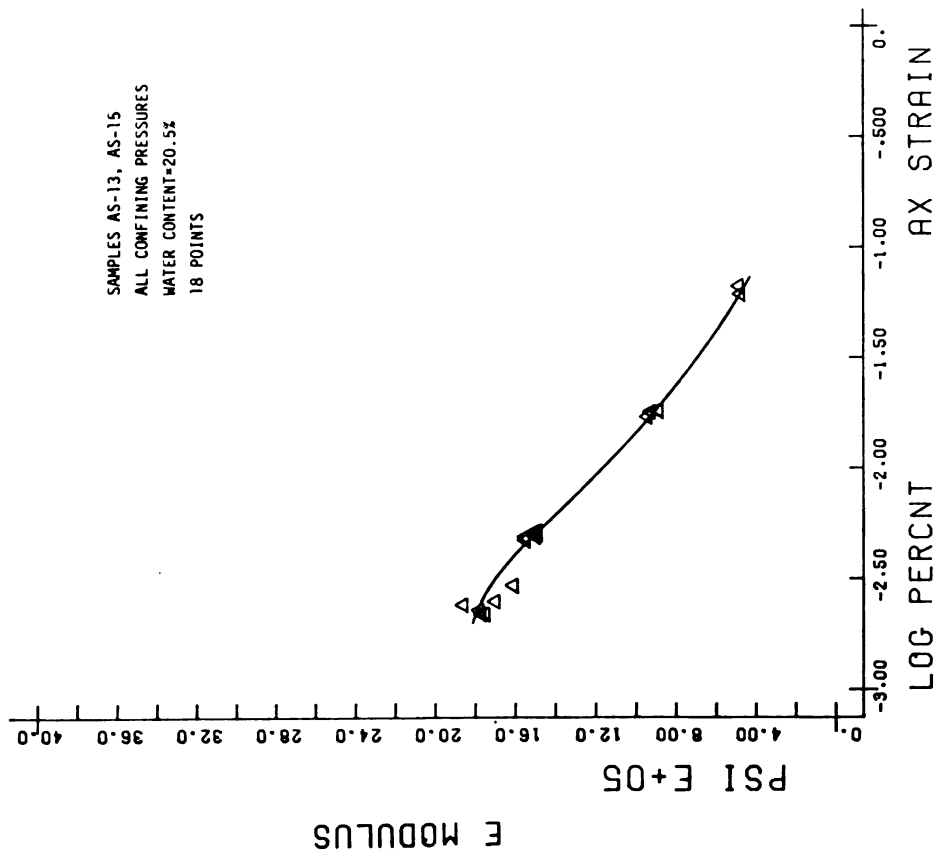


Fig. A-43 A-SILTT-10F1

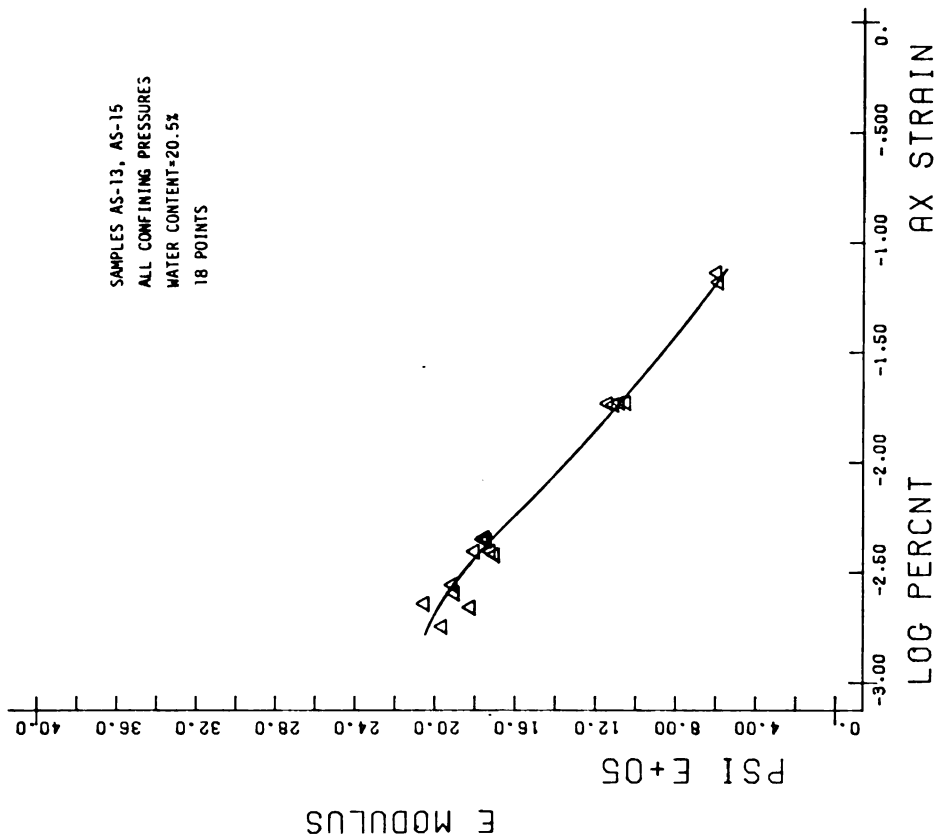


Fig. A-44 A-SILTT-10F5

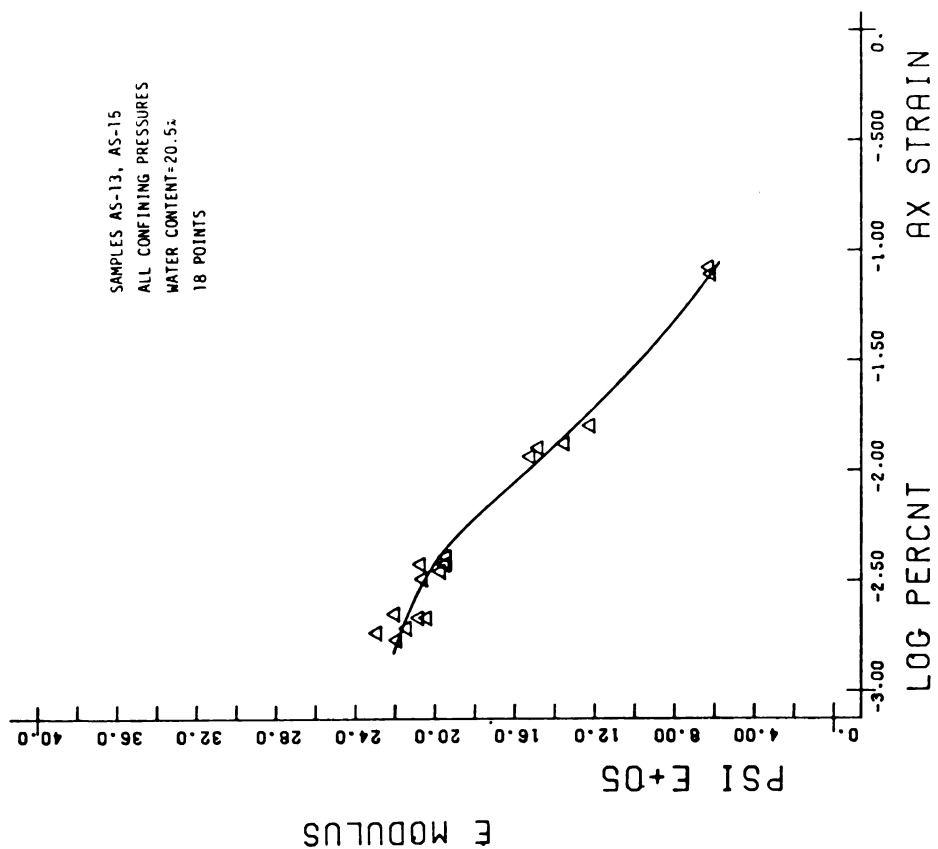


Fig. A-45 A-SILTT-10F10

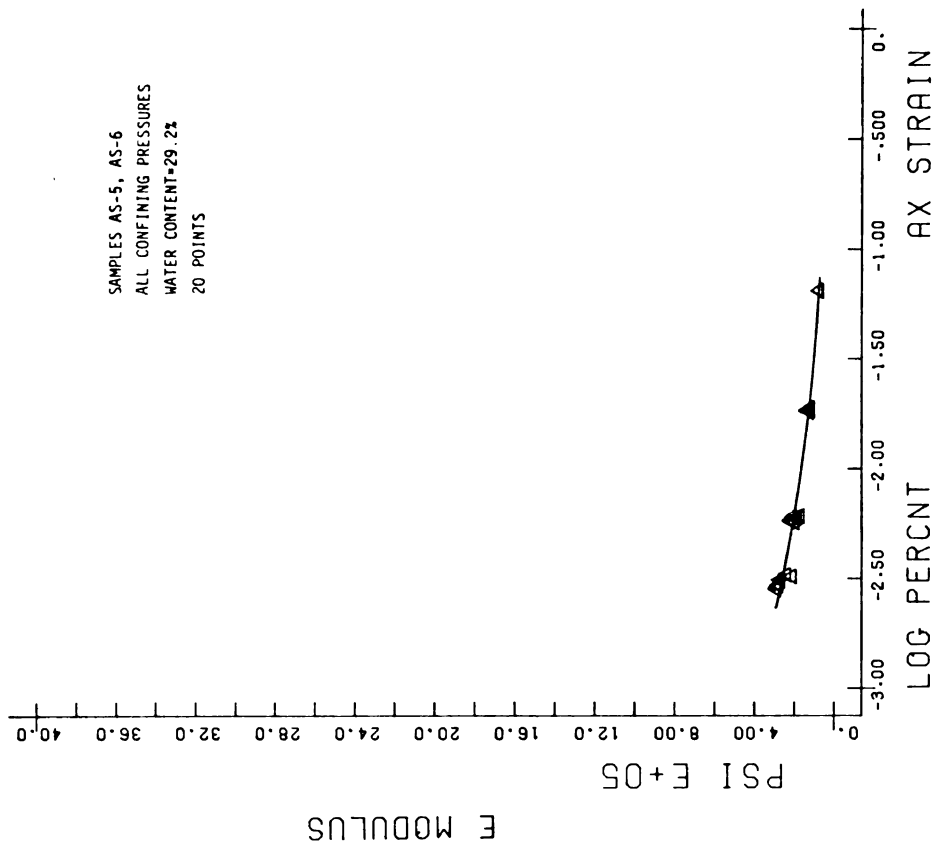


Fig. A-46 A-SILTT-1F05

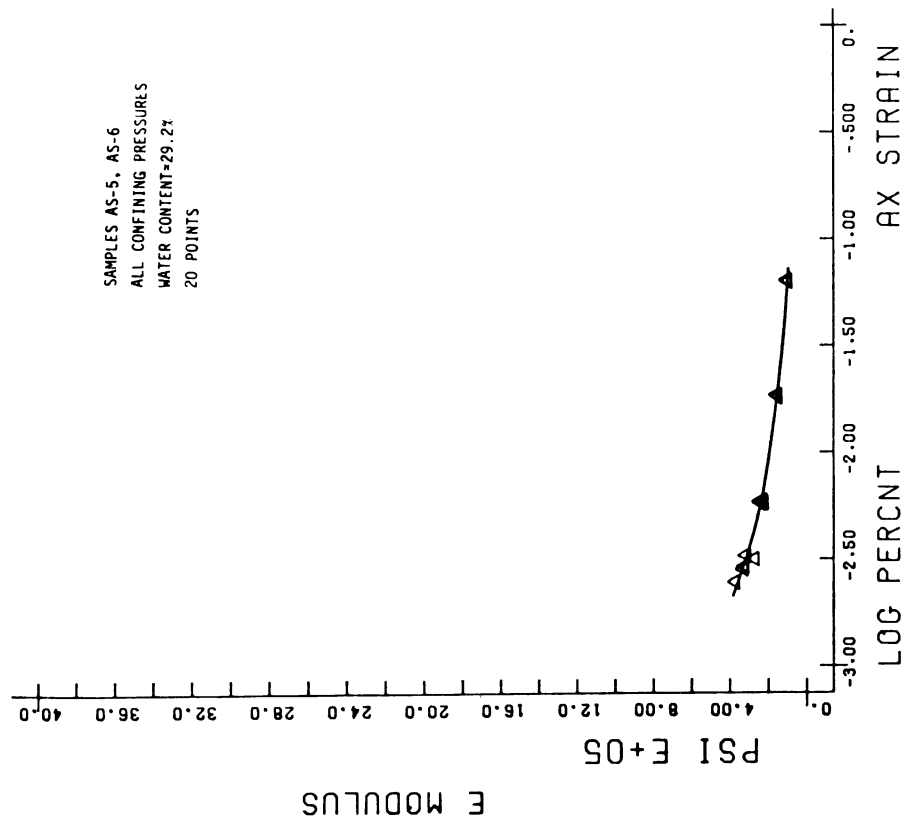


Fig. A-47 A-SILTT-1F.3

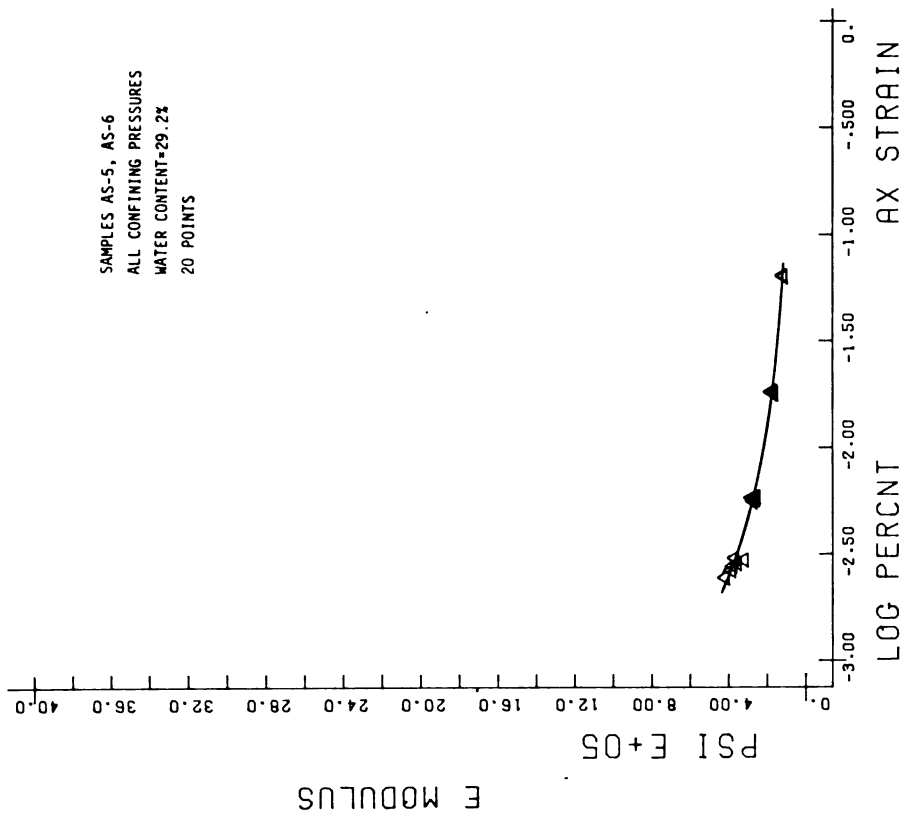


Fig. A-48 A-SILTT-1F1

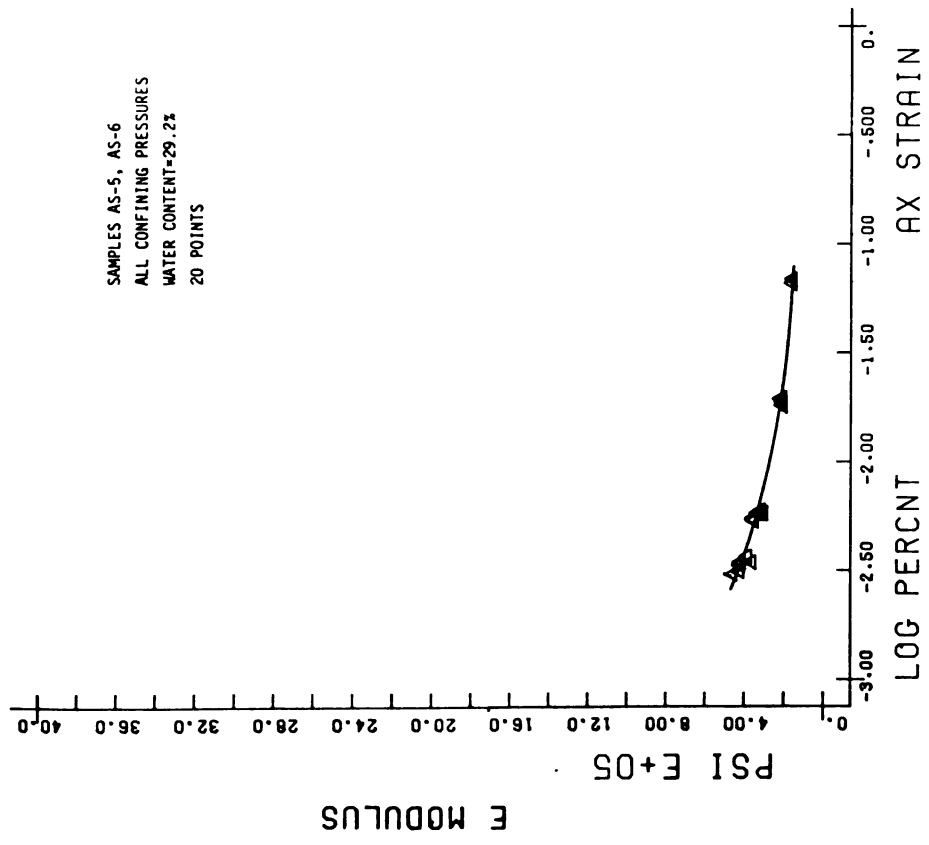


Fig. A-49 A-SILTT-1F5

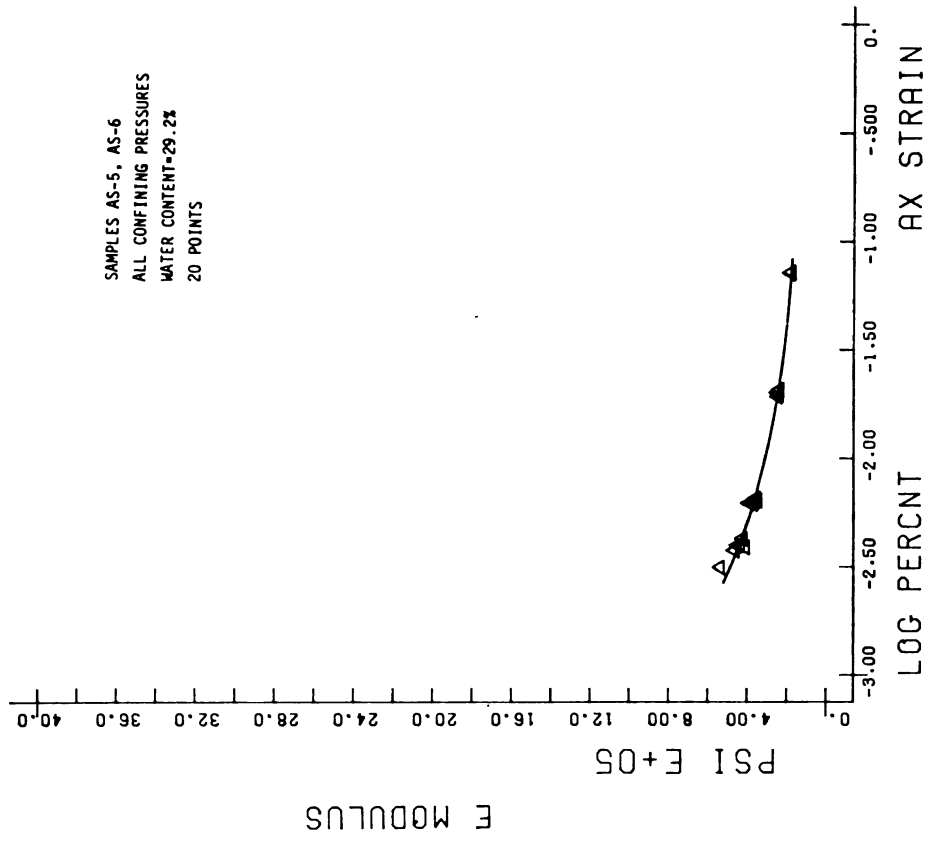


Fig. A-50 A-SILTT-1F10

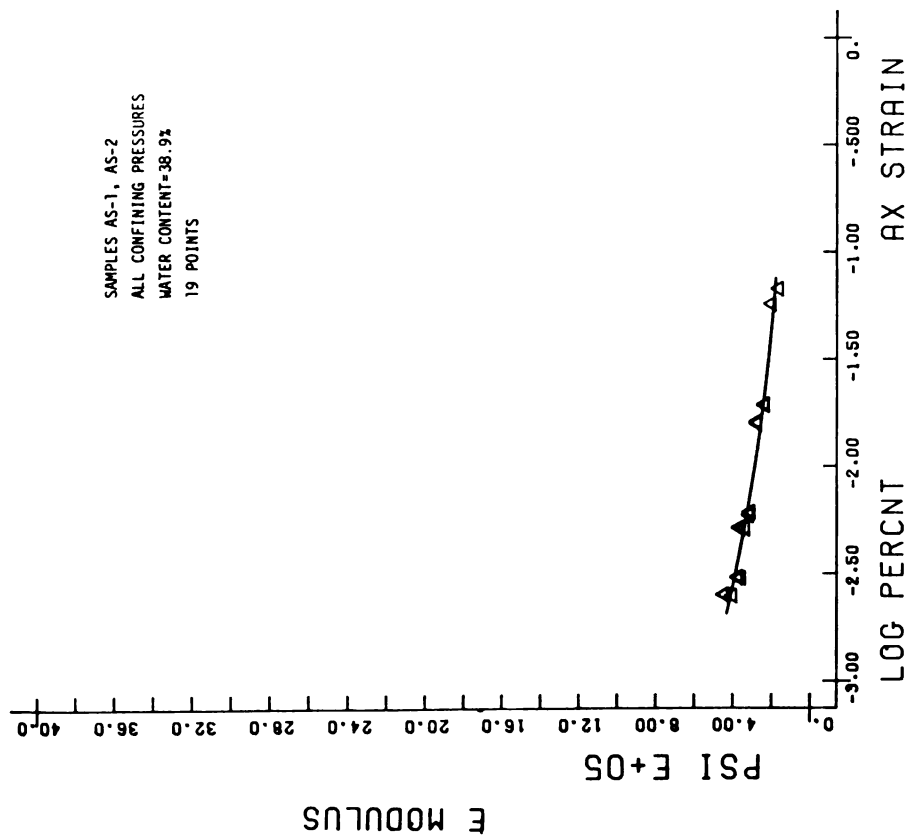


Fig. A-51 A-SILTT-1F.05

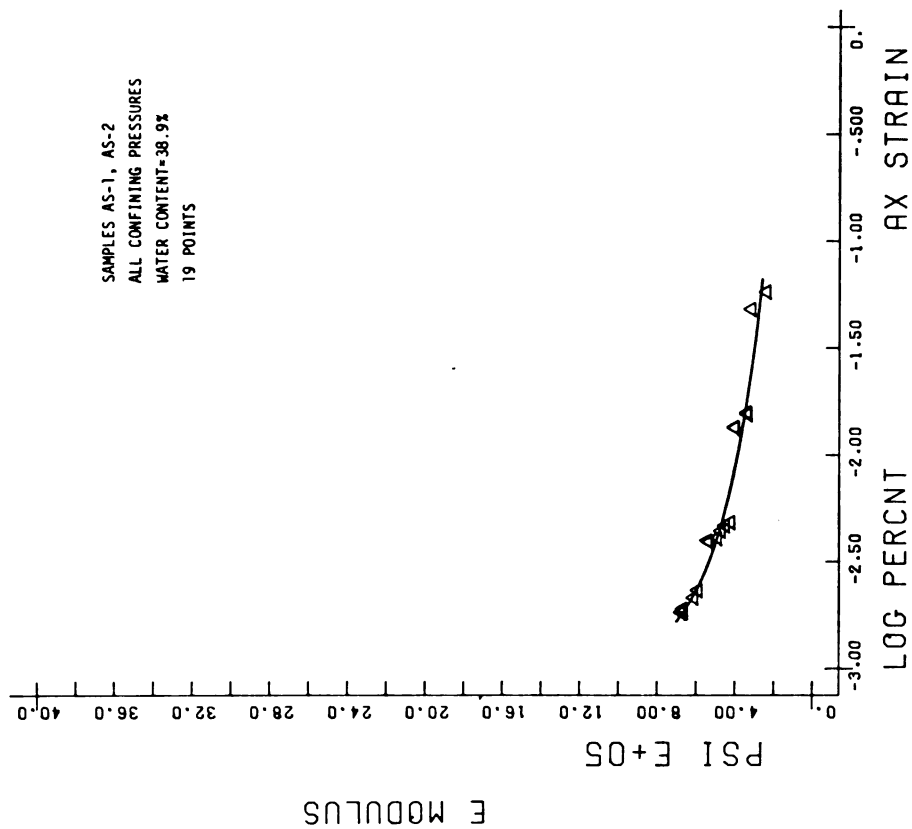


Fig. A-52 A-SILTT-1F.3

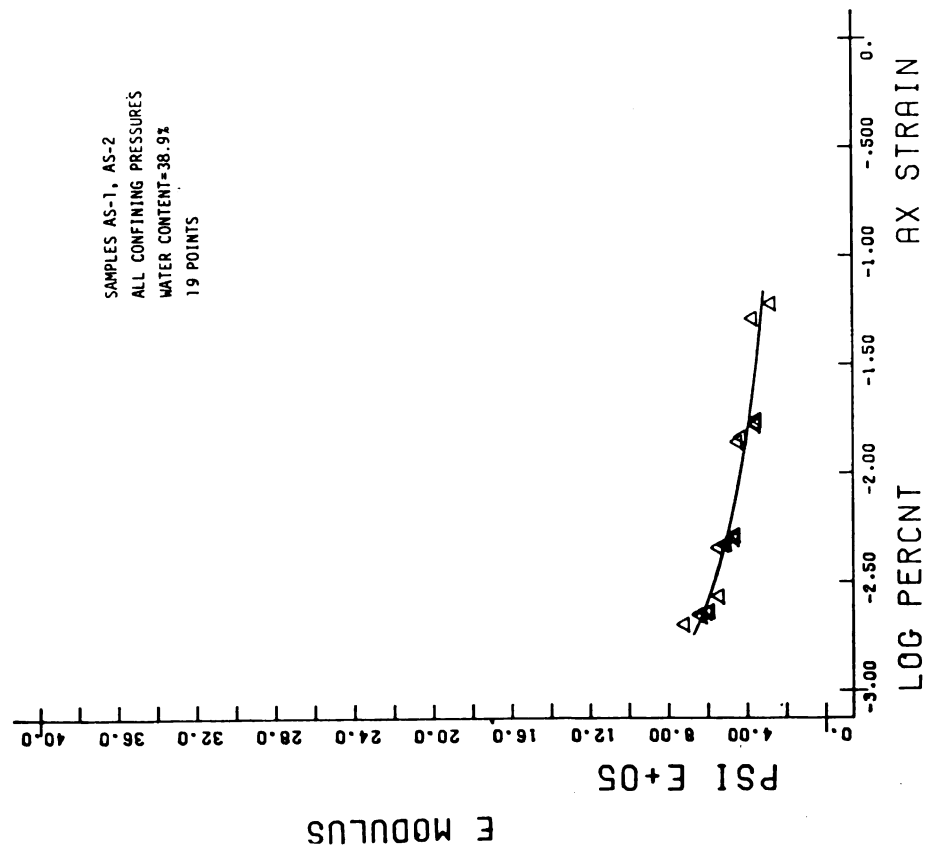


Fig. A-53 A-SILTT-1F1

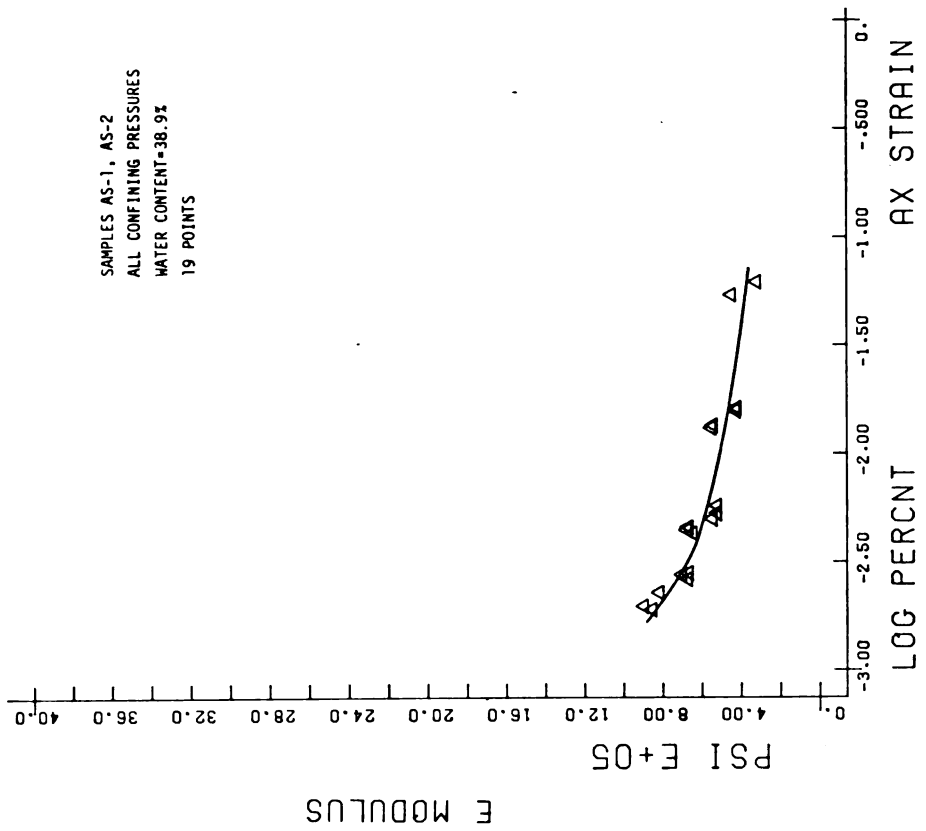


Fig. A-54 A-SILTT-1F5

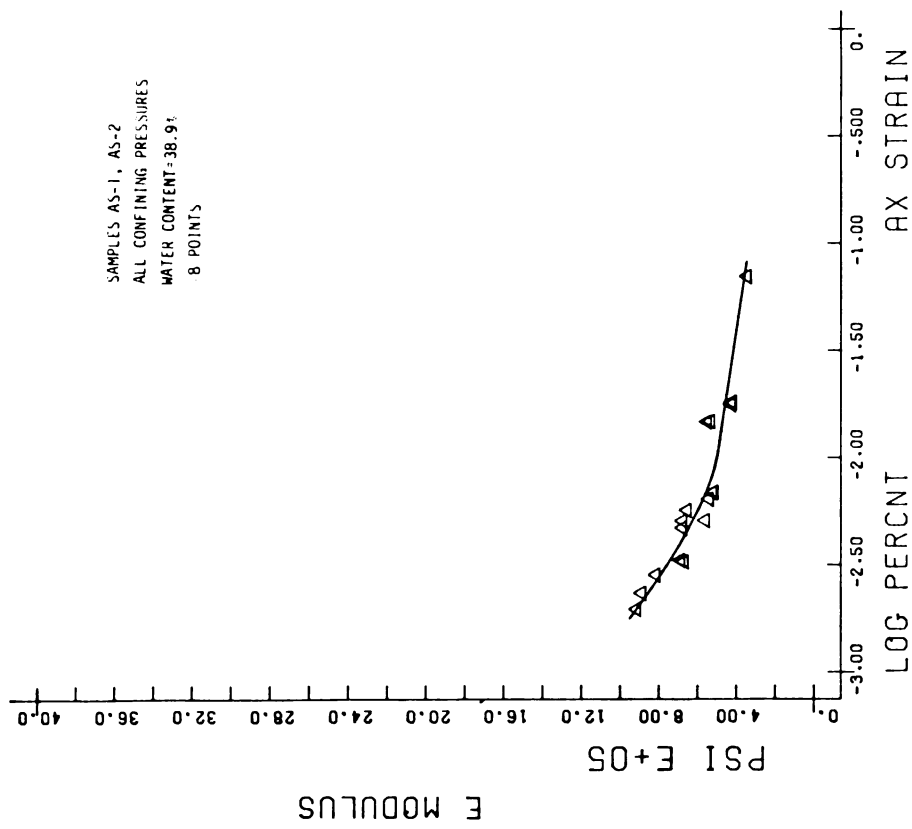


Fig. A-55 A-SILTT-1F10

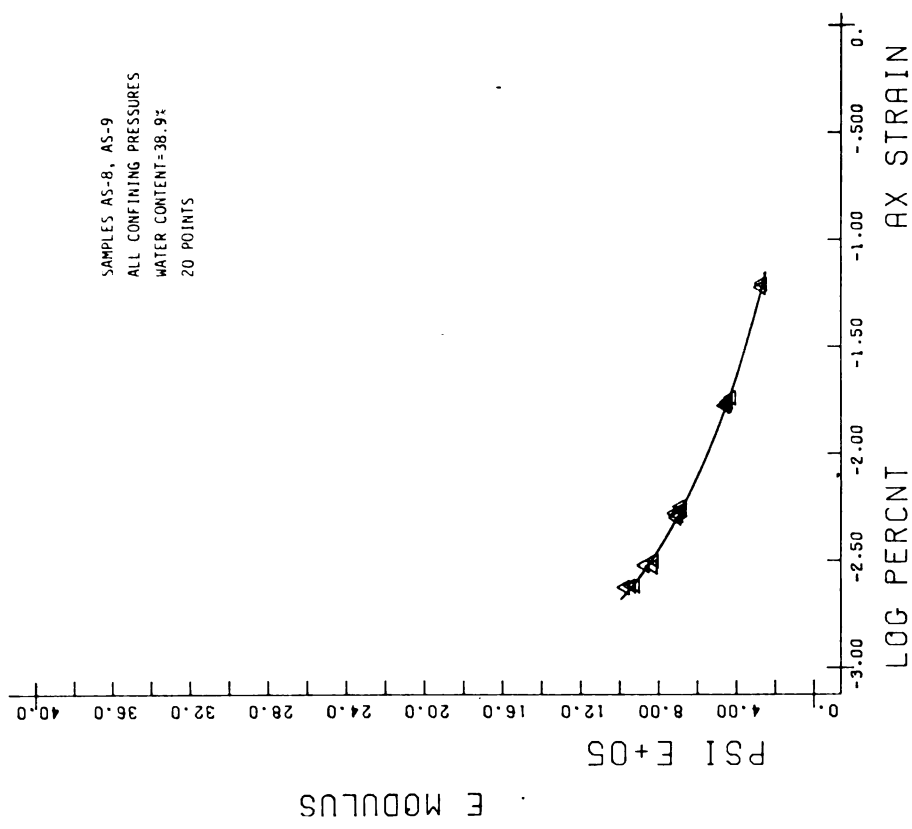


Fig. A-56 A-SILTT-4F05

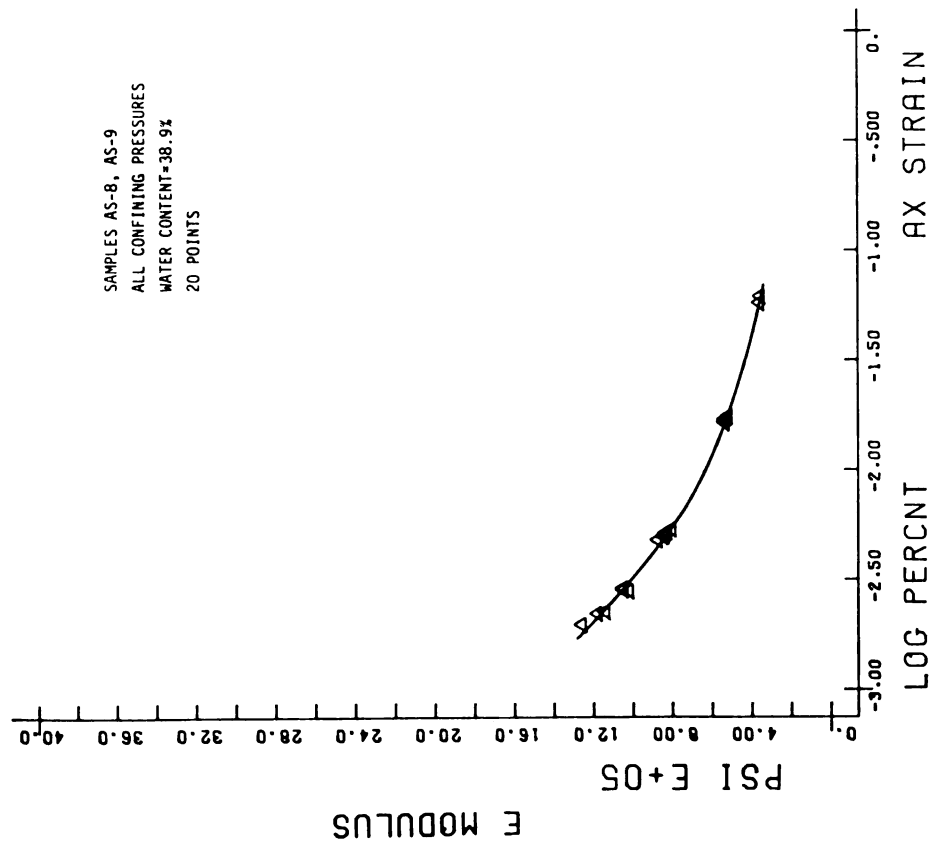


Fig. A-57 A-SILTT-4F.3

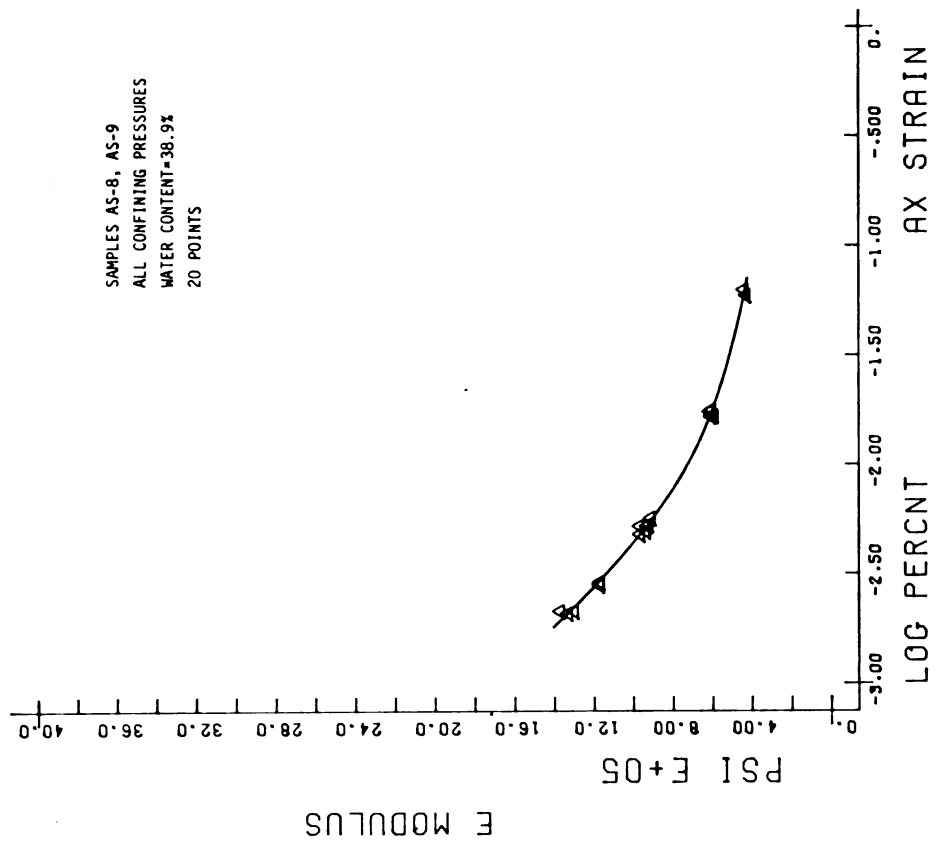


Fig. A-58 A-SILTT-4F1

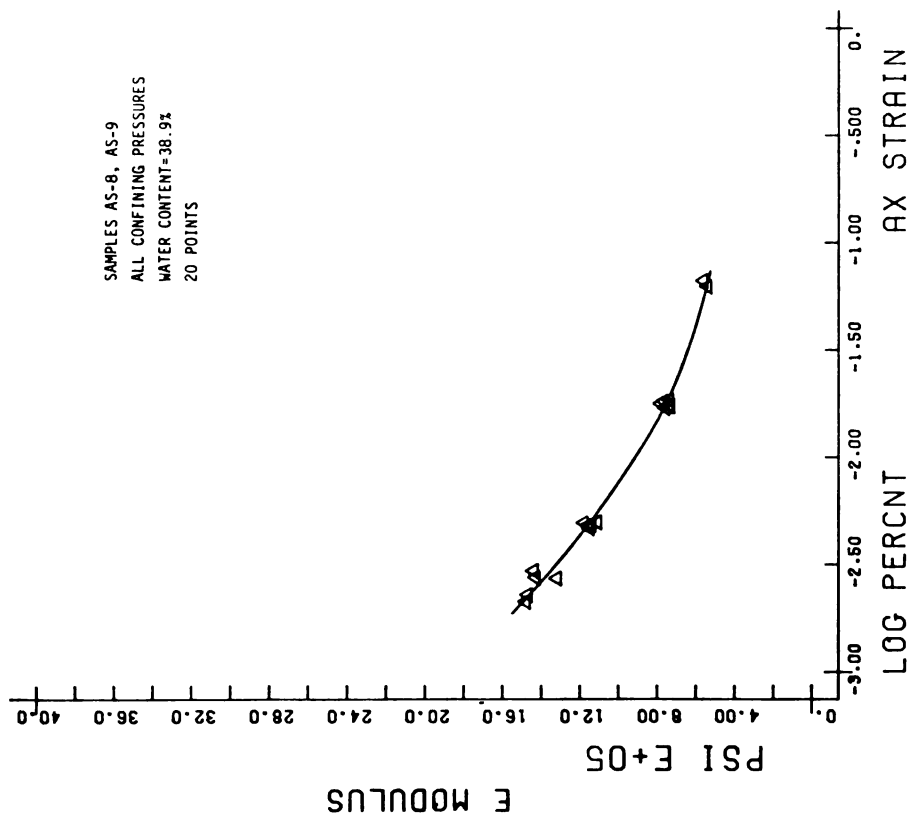


Fig. A-59 A-SILTT-4F5

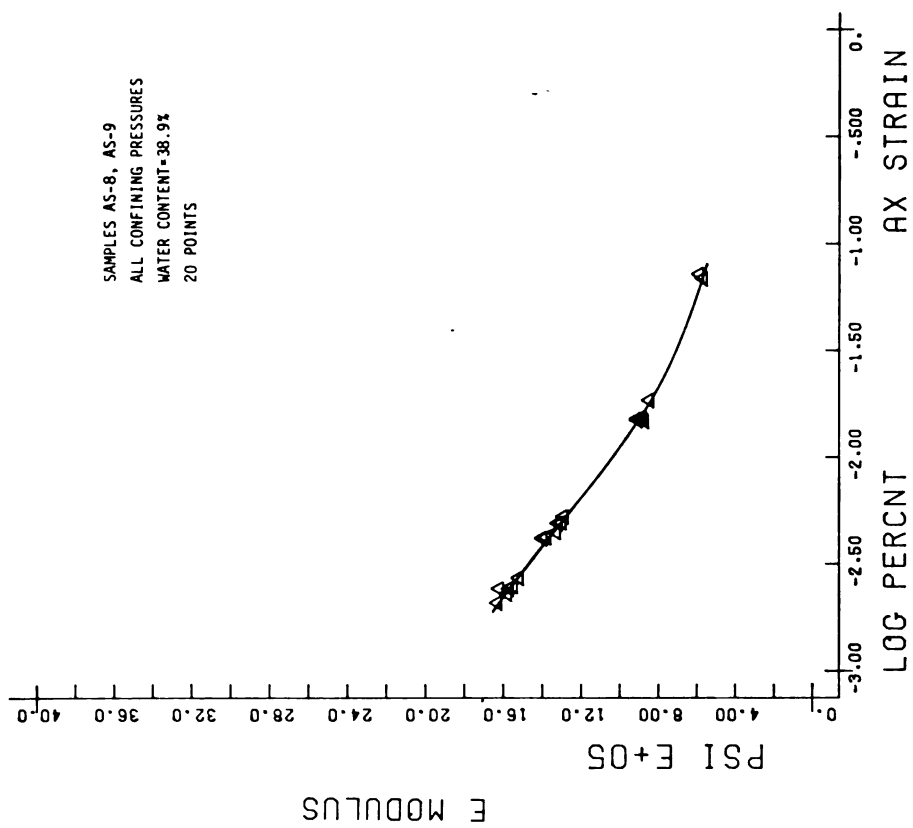


Fig. A-60 A-SILTT-4F10

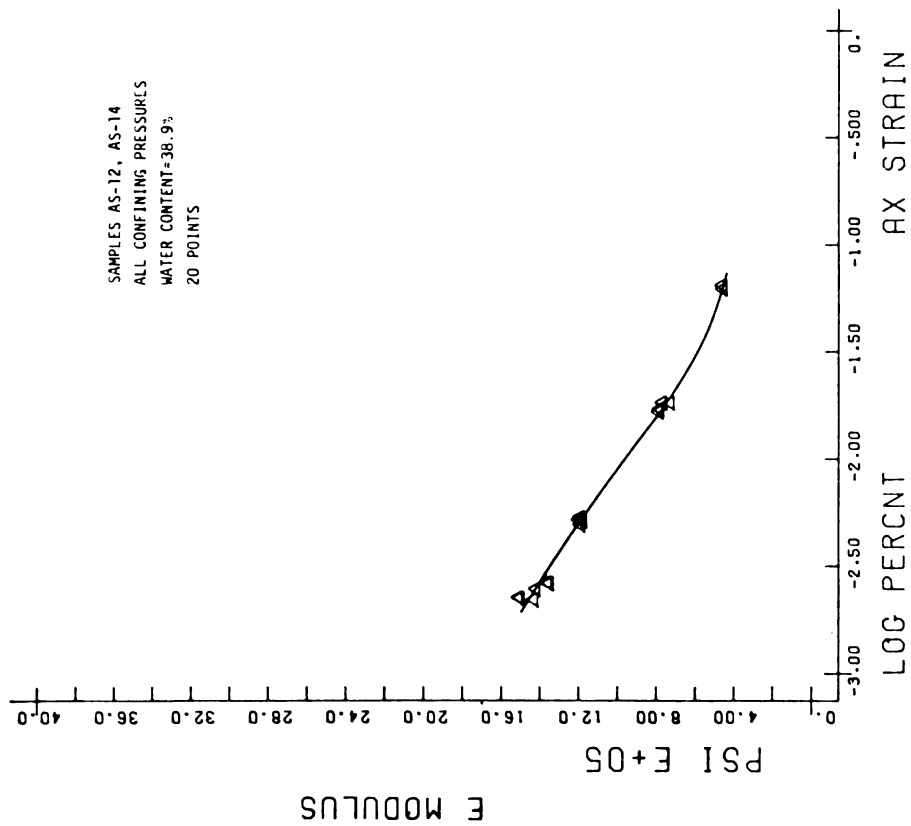


Fig. A-67 A-SILTT-10F.05

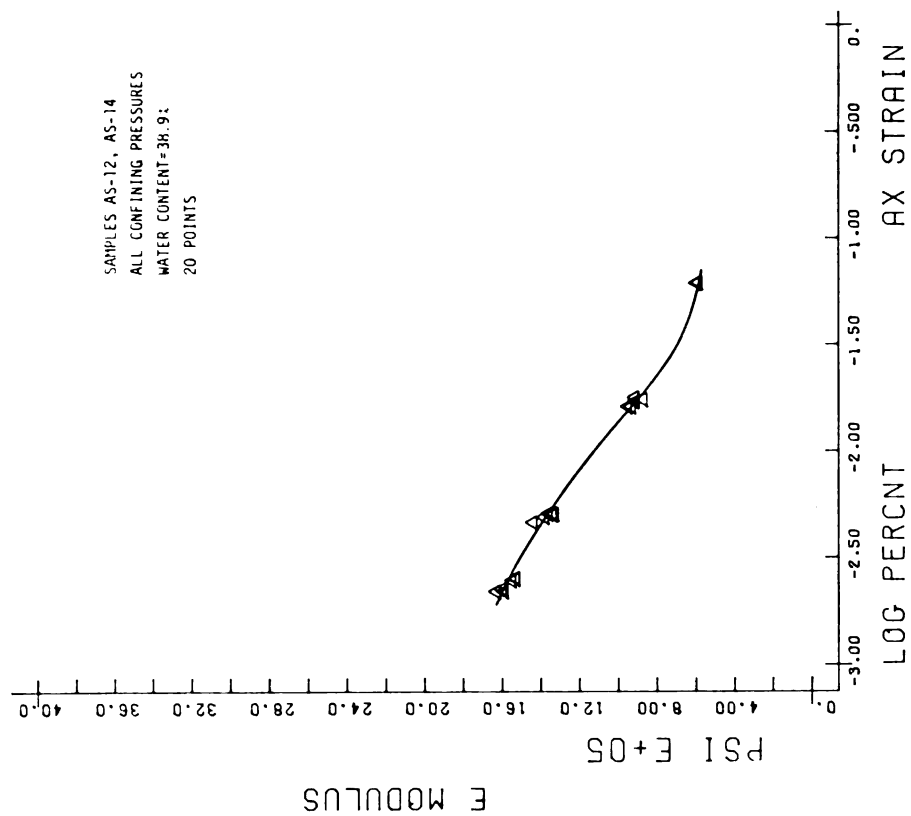


Fig. A-62 A-SILTT-10F.3

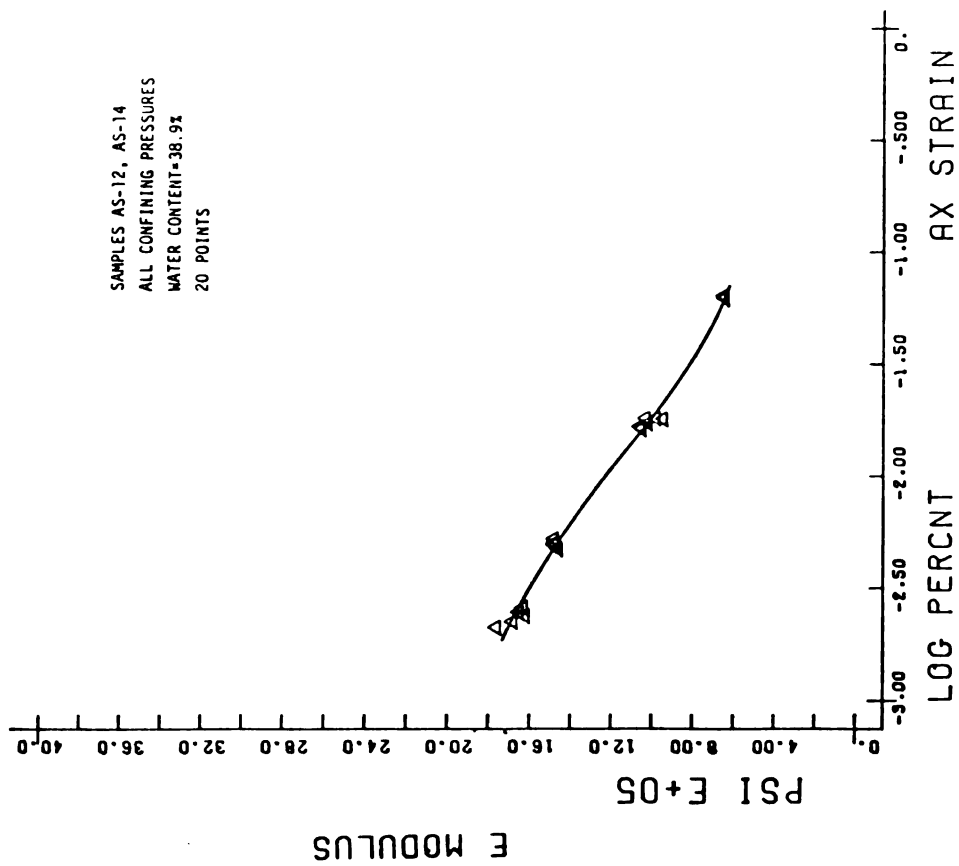


Fig. A-63 A-SILTT-10F1

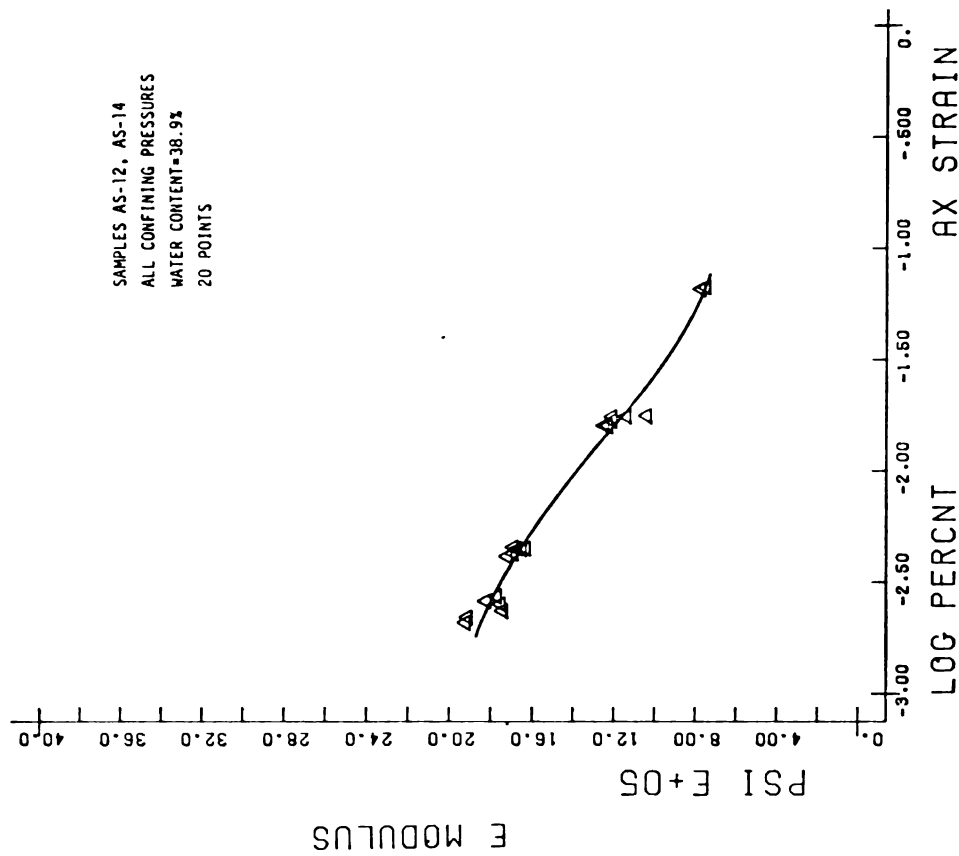


Fig. A-64 A-SILTT-10F5

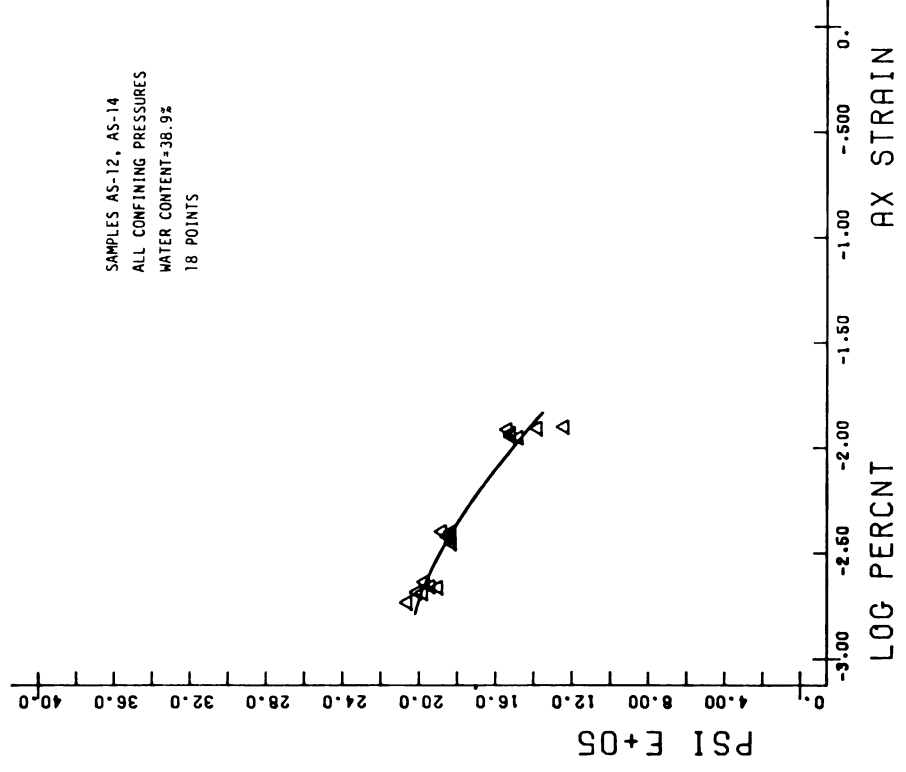


Fig. A-65A-SILTT-10F10

APPENDIX B
CYCLIC TRIAXIAL TESTS RESULTS -
DAMPING RATIO OF FROZEN SILT

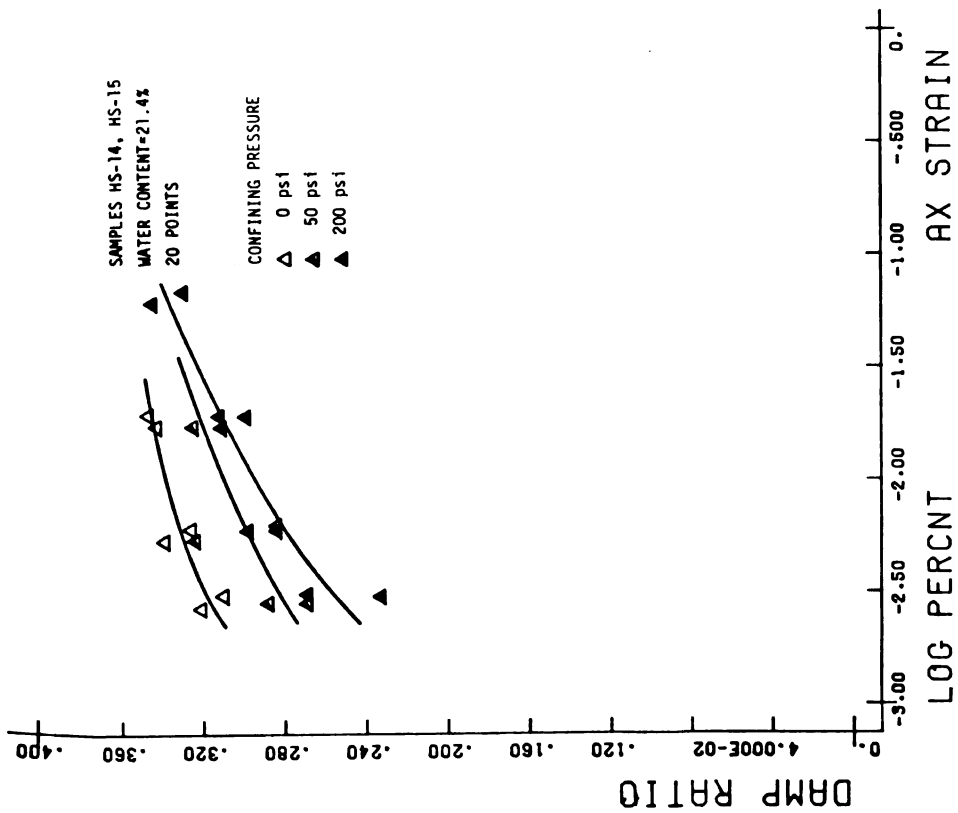


Fig. B-1H-SILTT-1F05

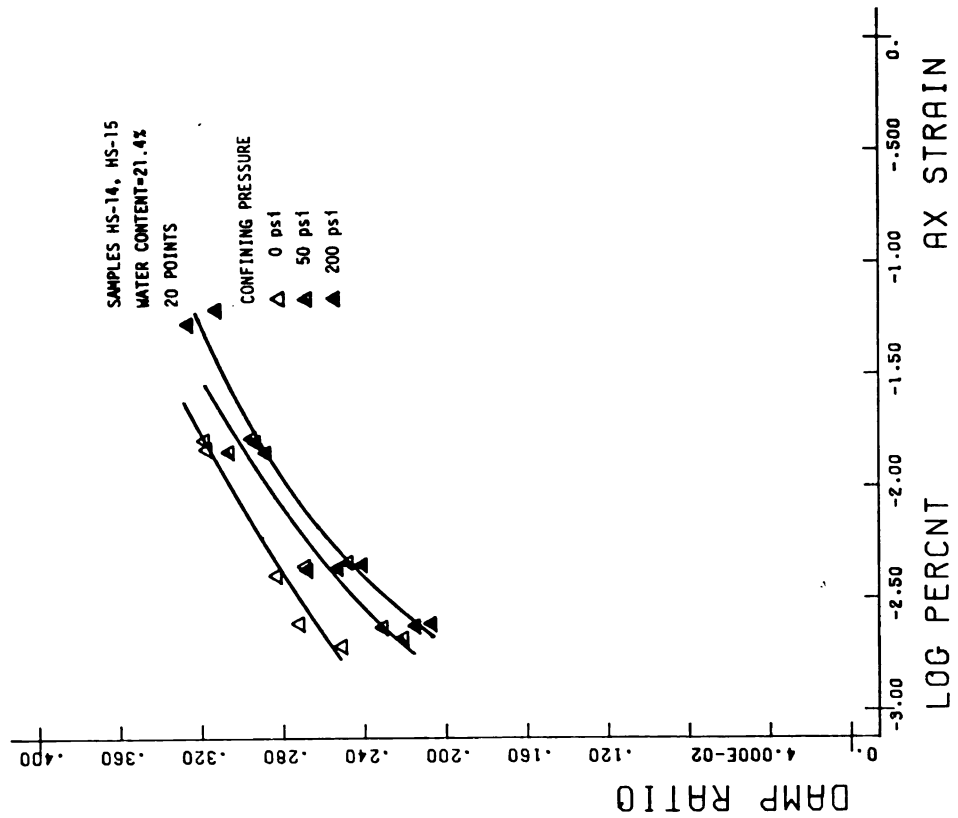


Fig. B-2H-SILTT-1F03

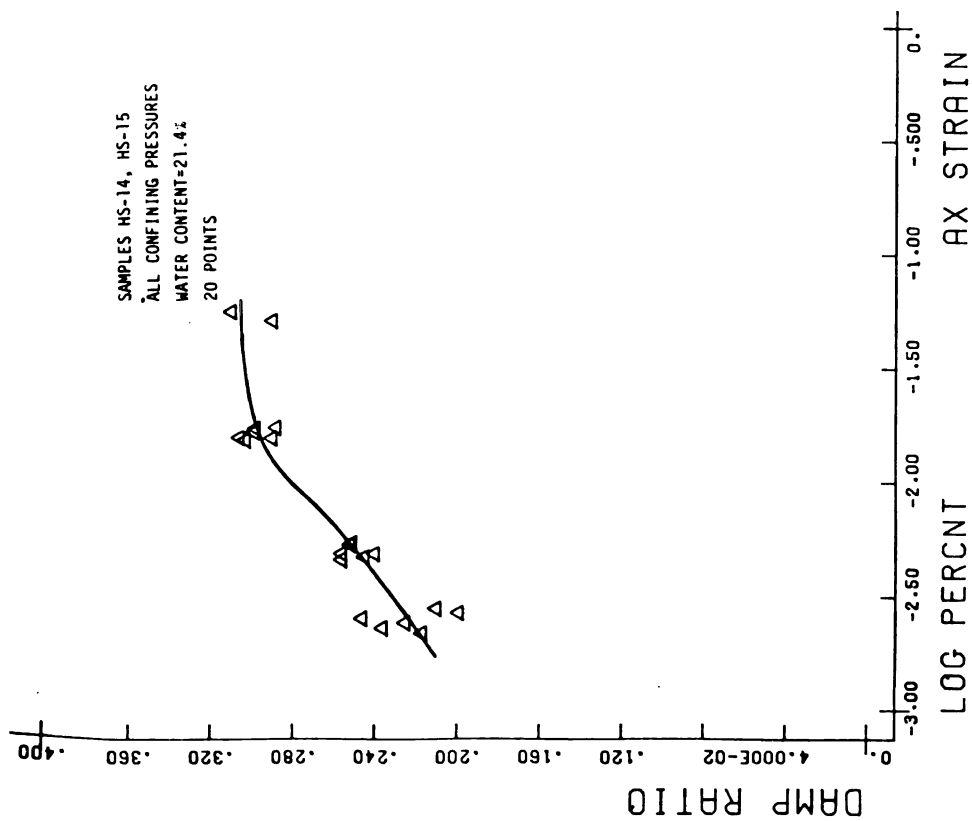


Fig. B-3H-SILTT-1F1

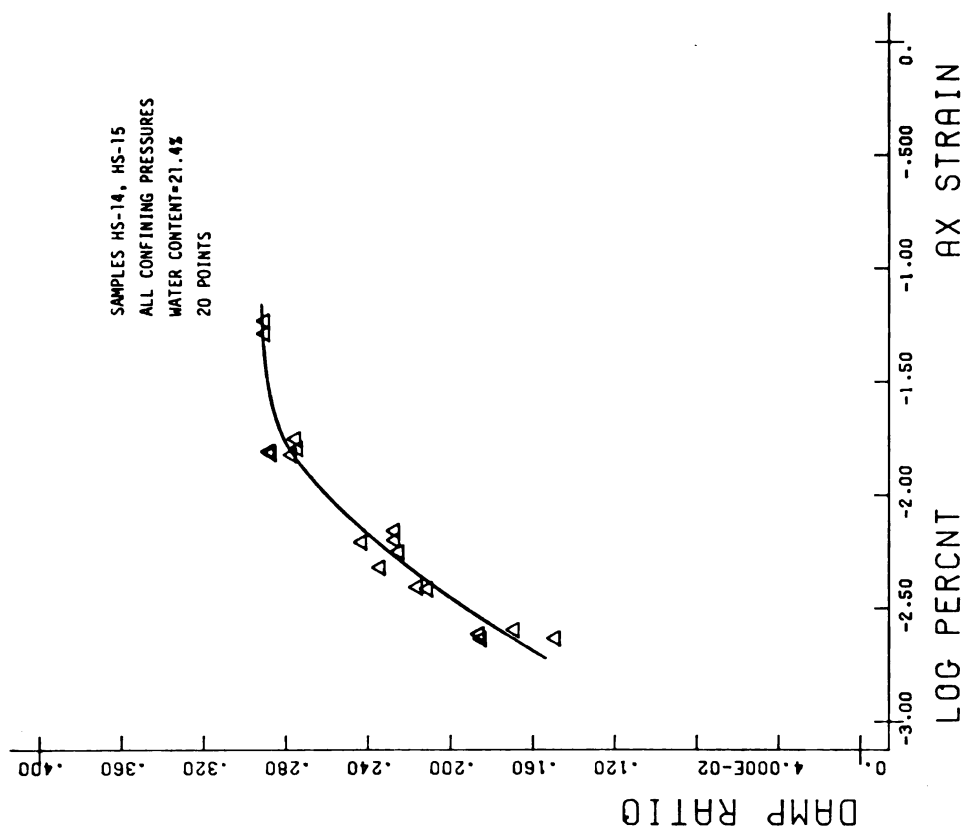


Fig. B-4H-SILTT-1F5

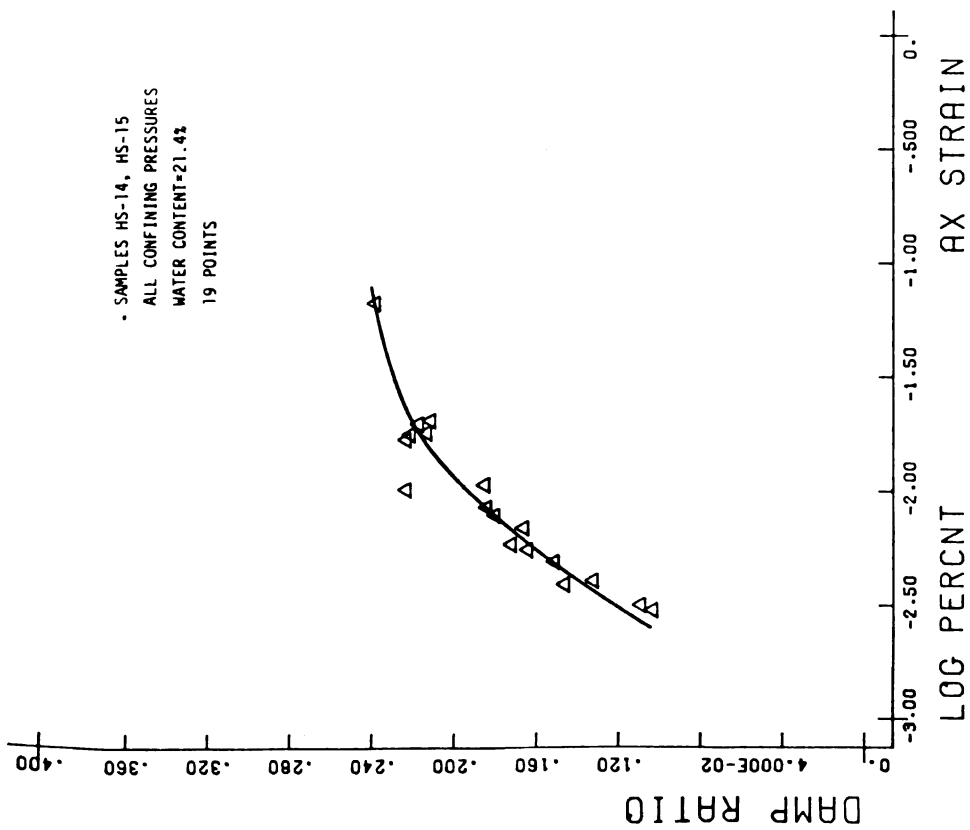


Fig. B-5 H-SILT-1F10

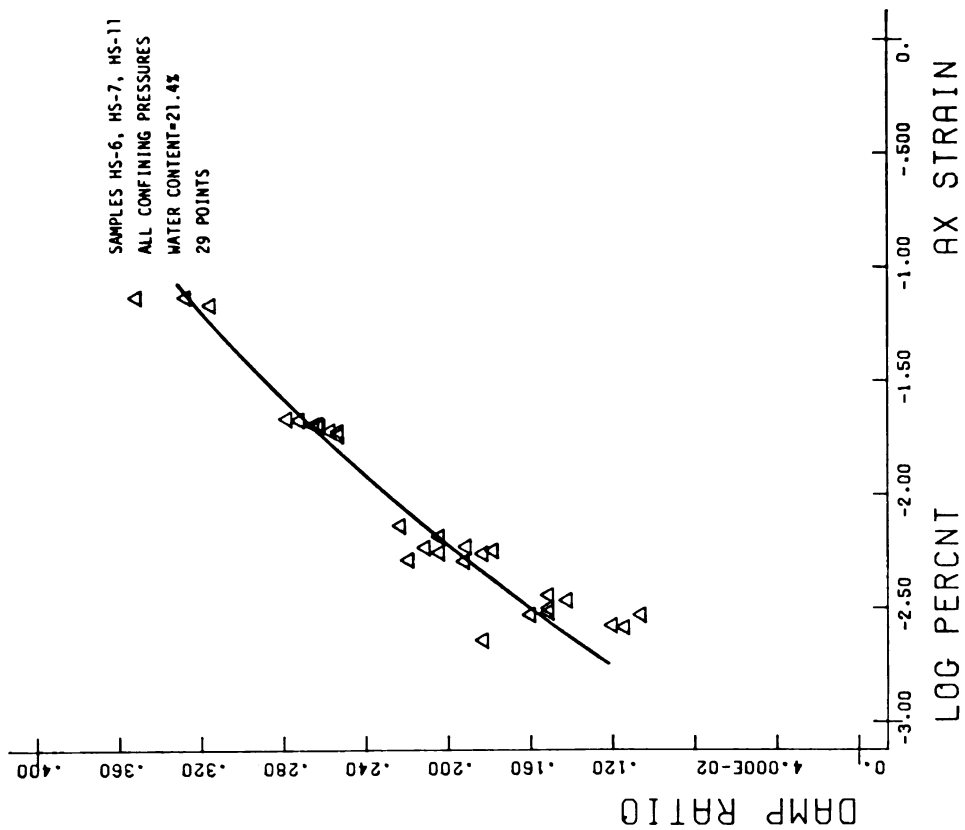


Fig. B-6 H-SILT-4F05

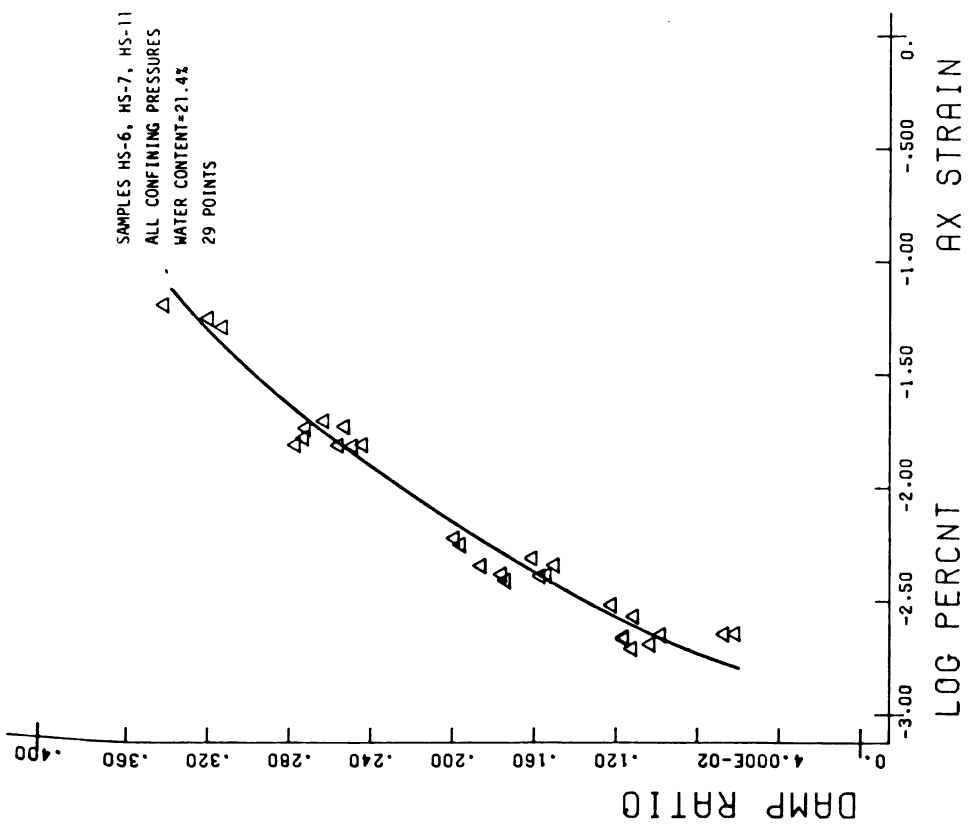


Fig. B-7H-SILTT-4F3

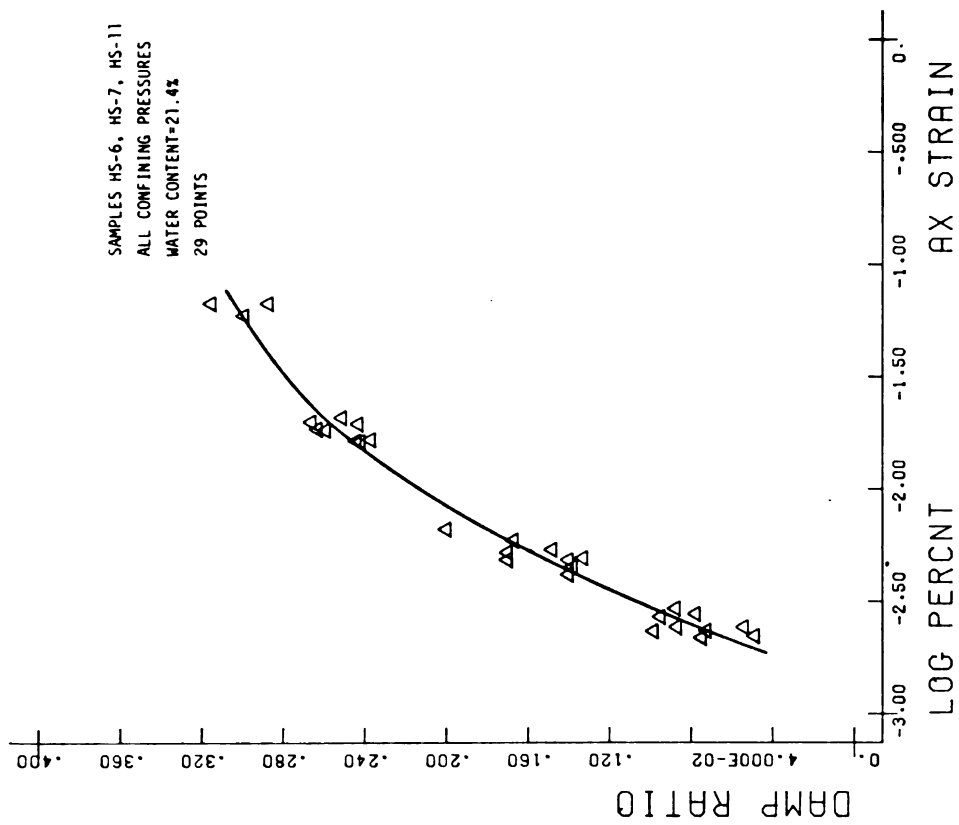


Fig. B-8H-SILTT-4F1

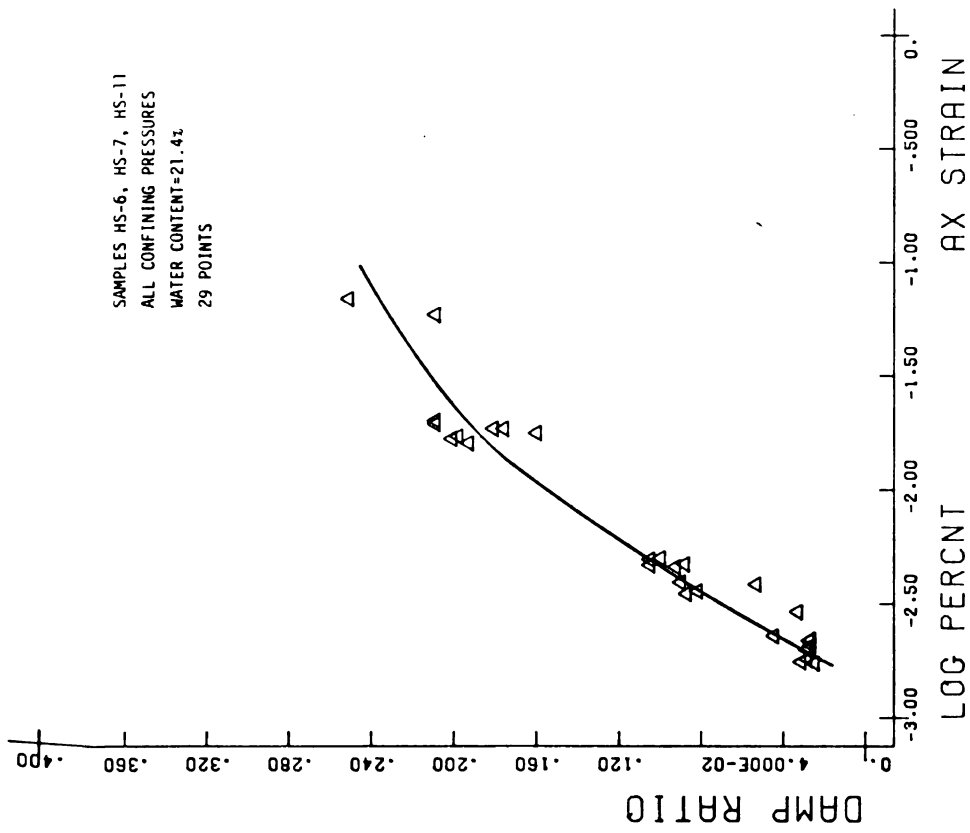


Fig. B-9 H-SILT-4F5

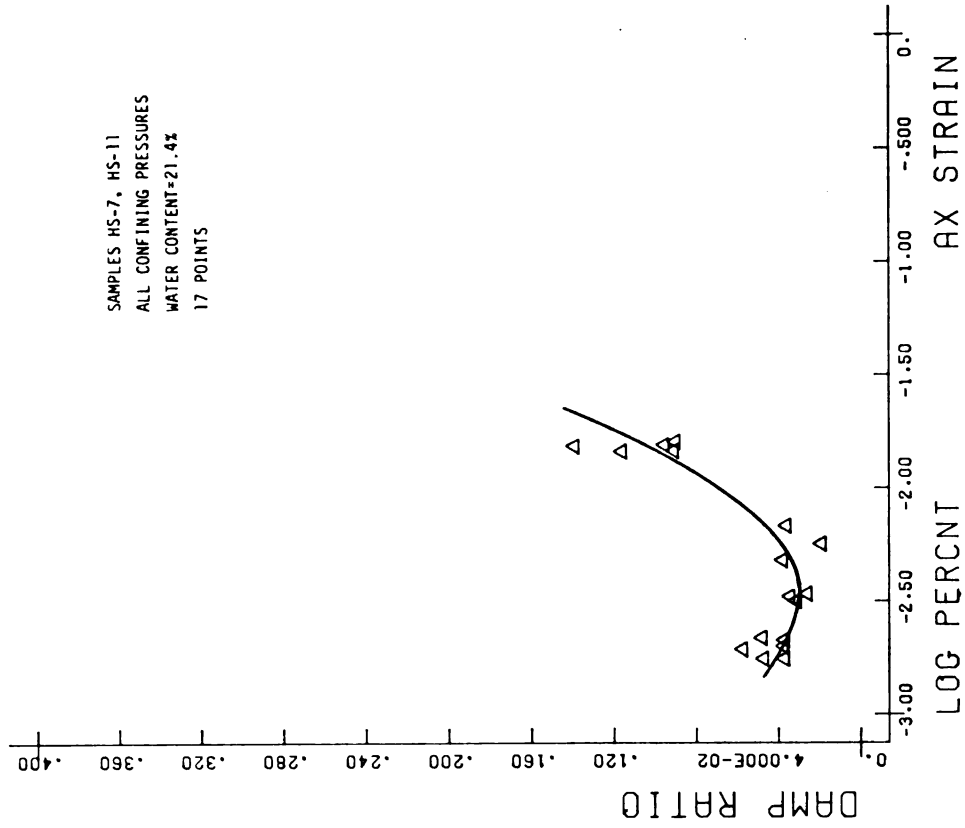


Fig. B-10 H-SILT-4F10

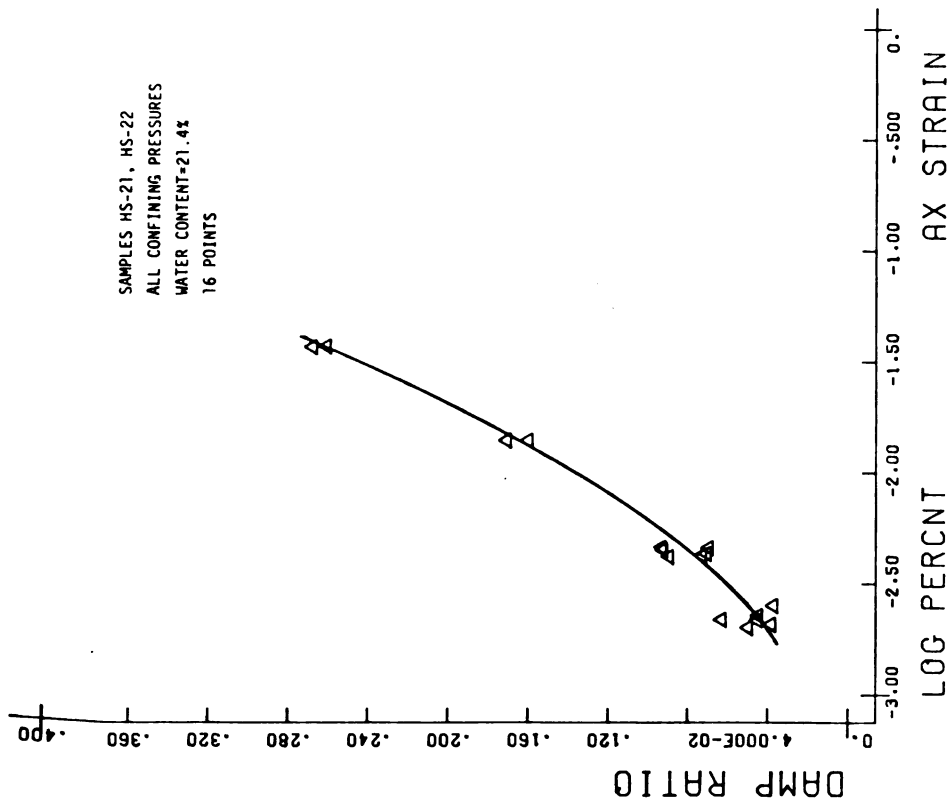


Fig. B-11 H-SILTT-10F.05

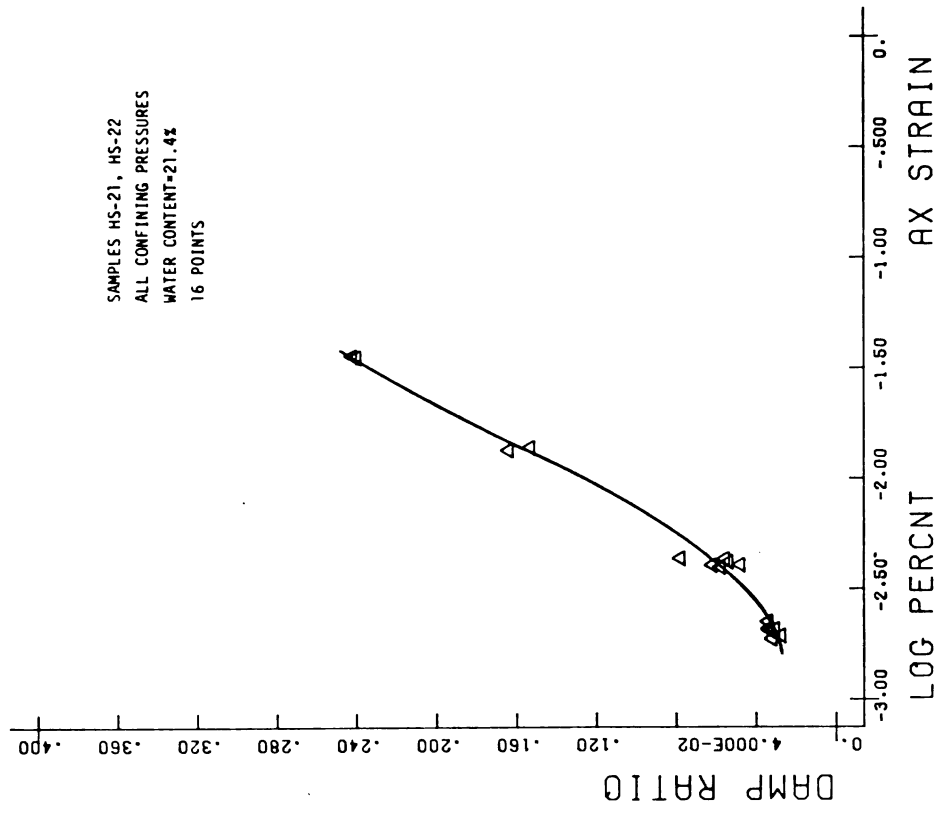


Fig. B-12 H-SILTT-10F.3

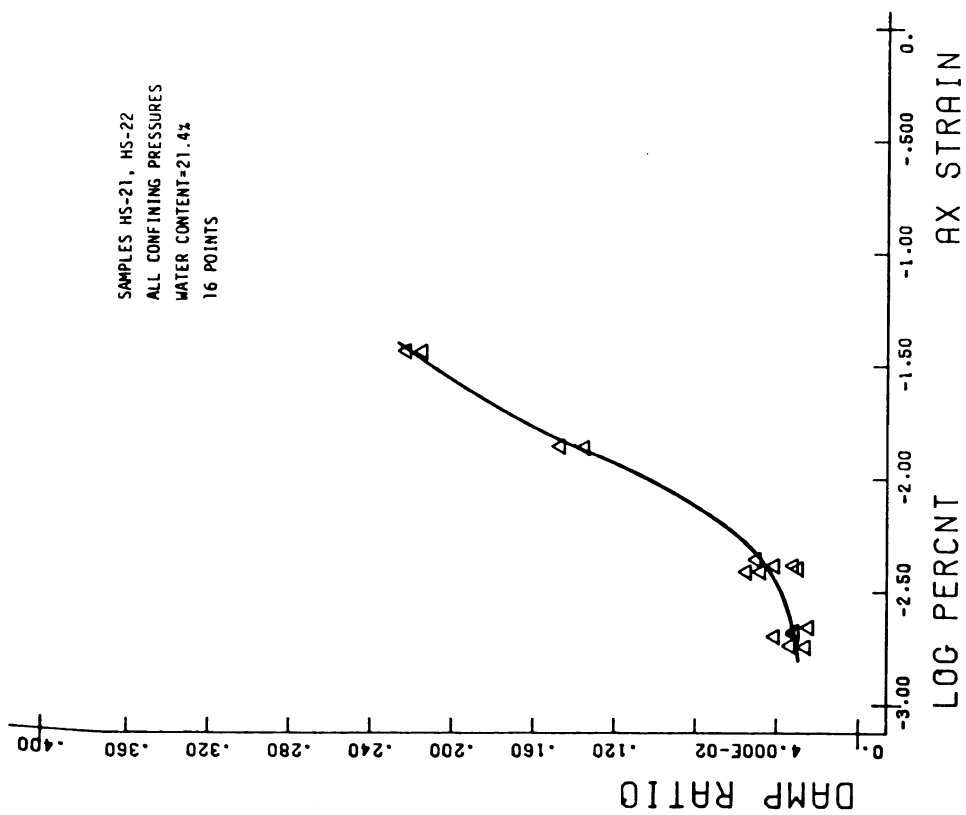


Fig. B-13H-SILTT-10F1

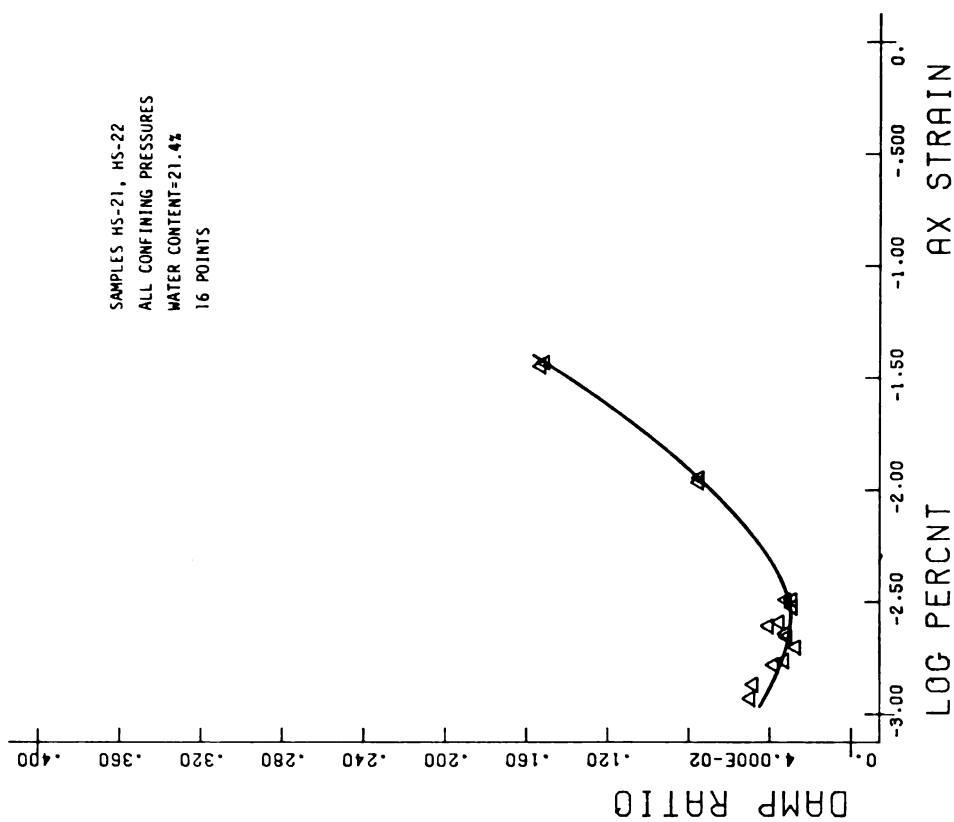


Fig. B-14H-SILTT-10F5

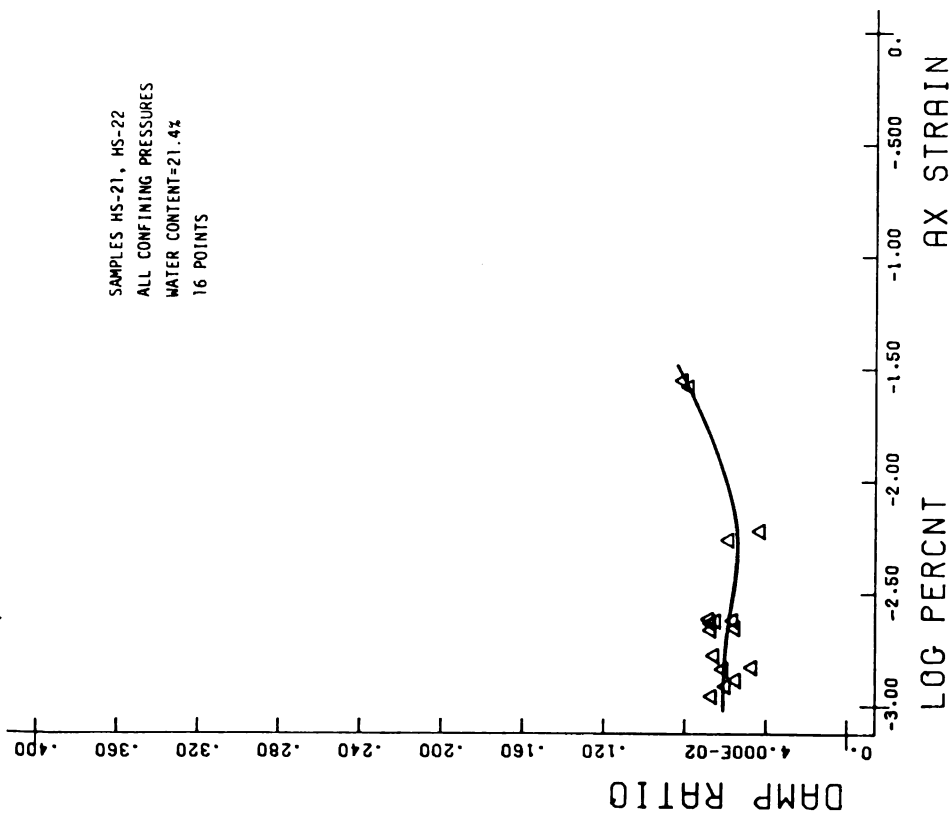


Fig. B-15H-SILTT-10F10

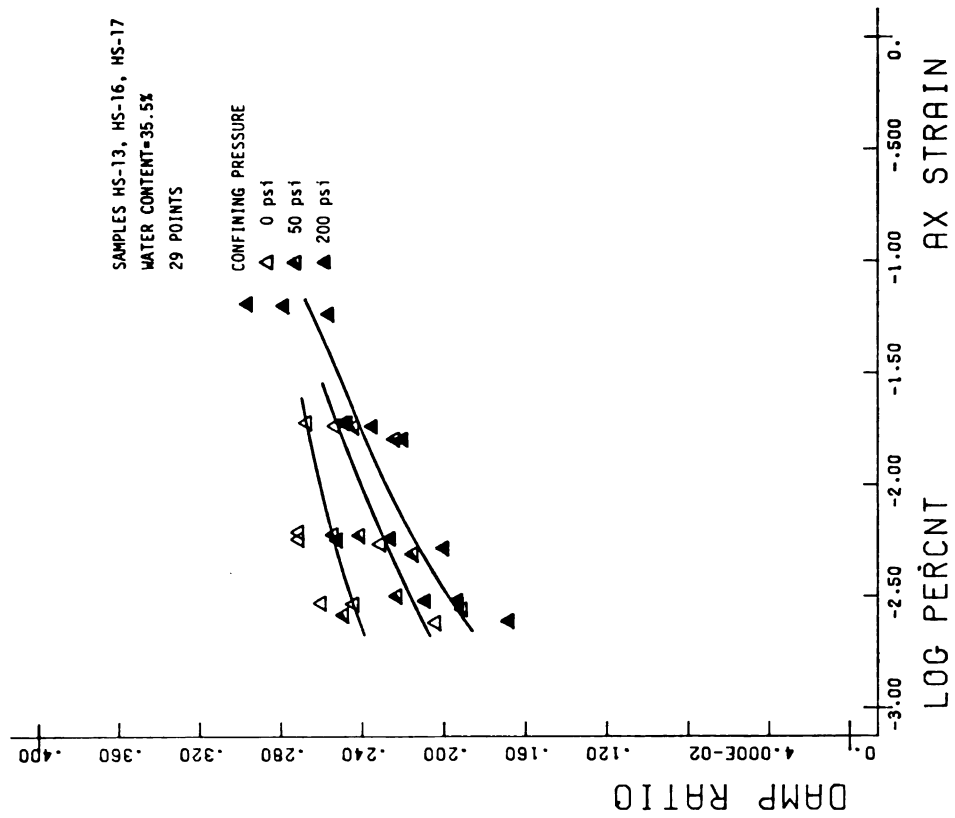


Fig. B-16H-SILTT-1F05

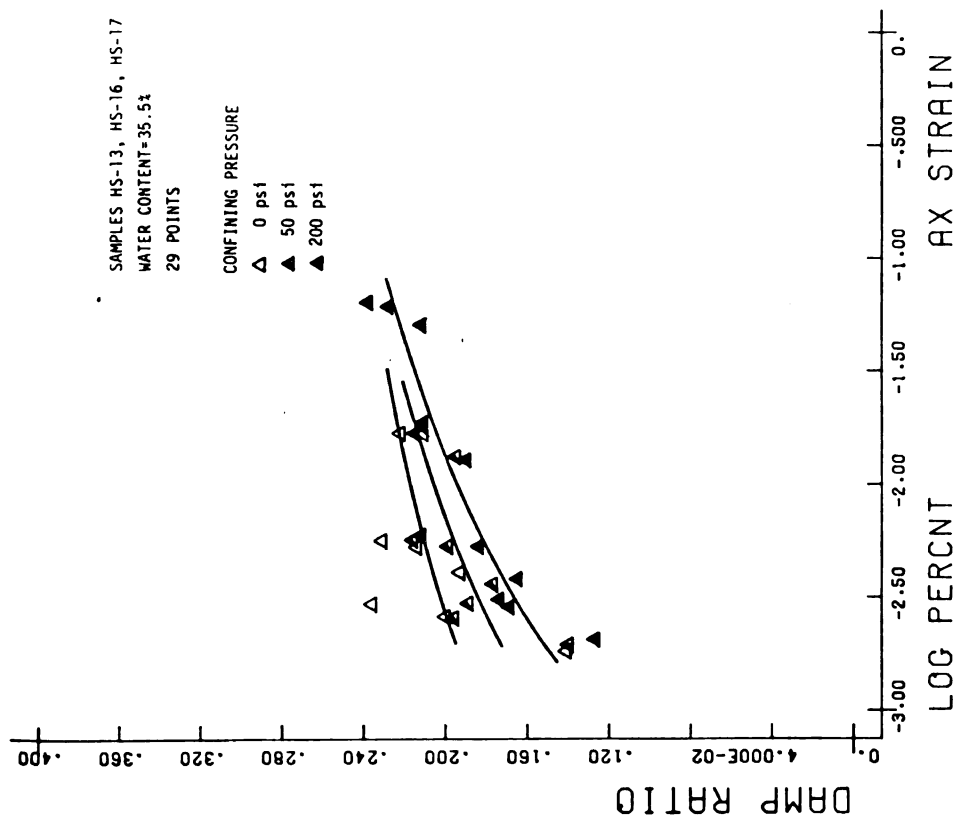


Fig. B-17H-SILTT-1F.3

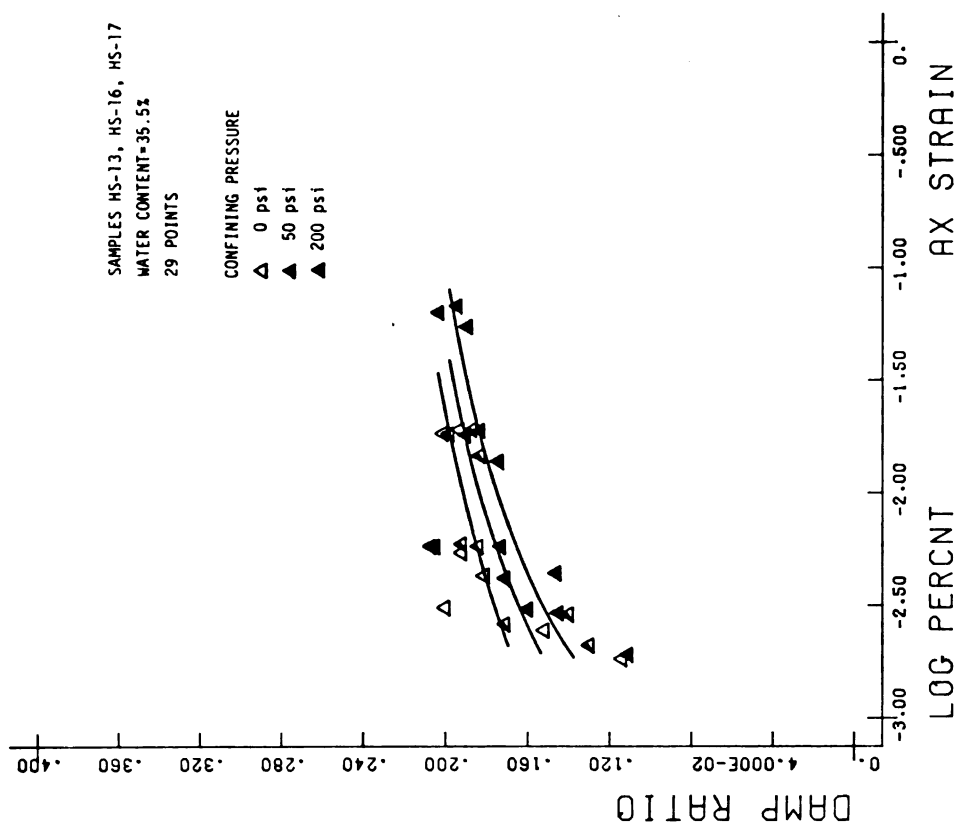


Fig. B-18H-SILTT-1F.1

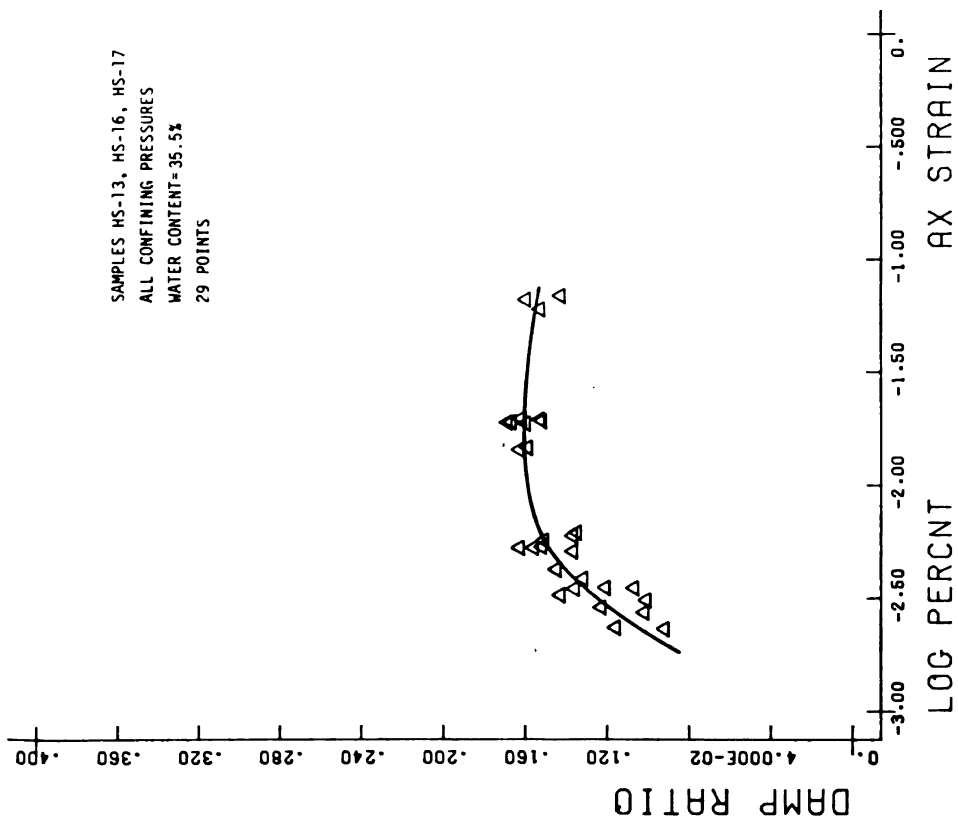


Fig. B-19 H-SILT-1F5

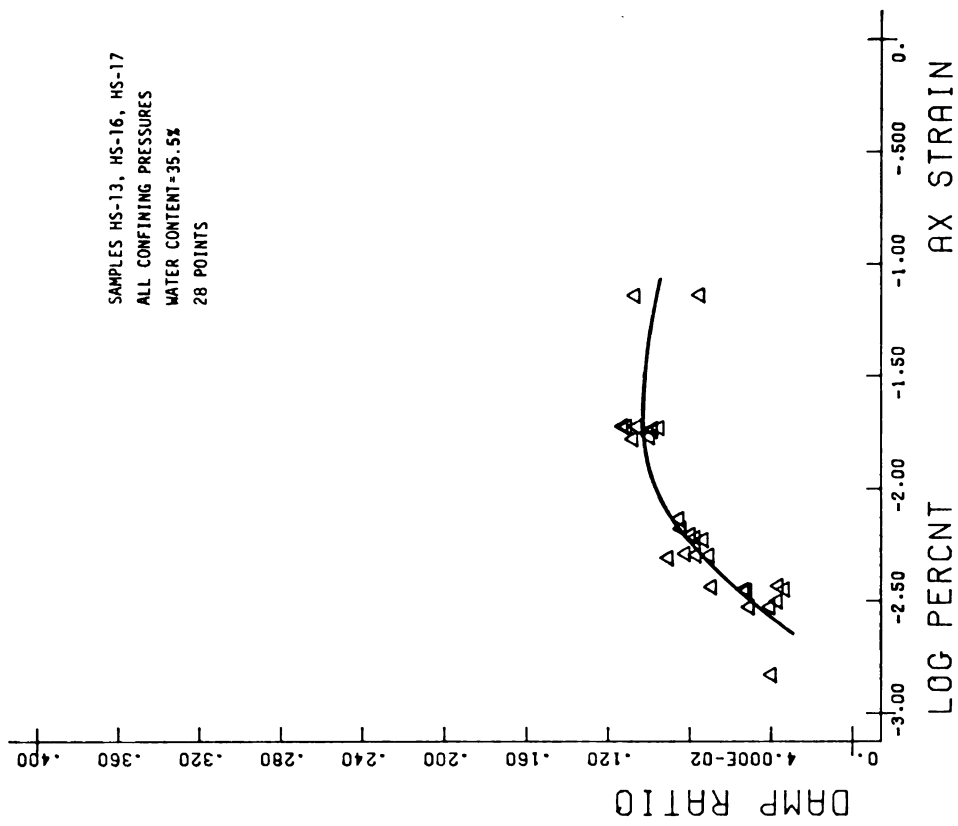


Fig. B-20 H-SILT-1F10

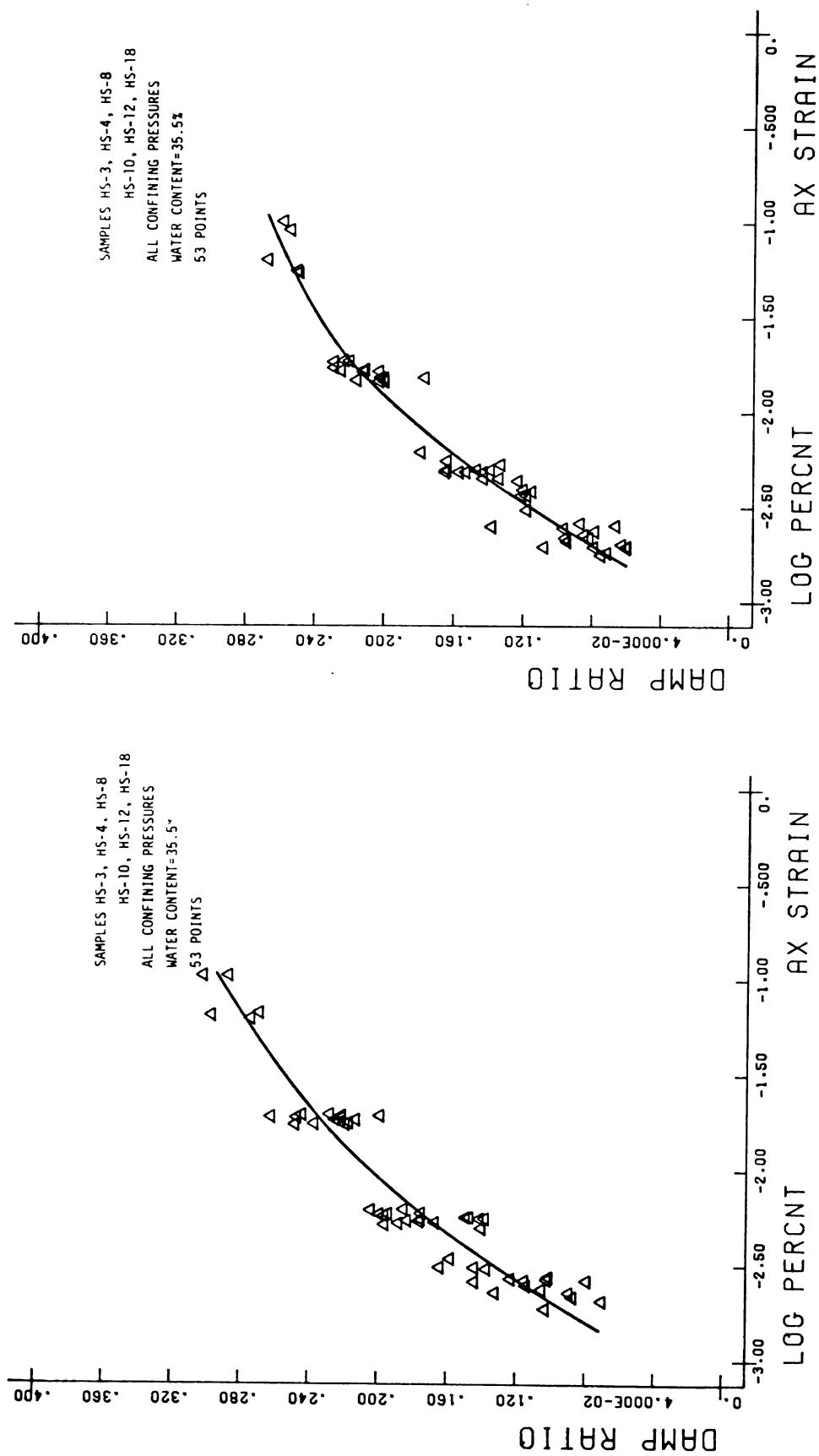


Fig. B-21H-SILTT-4F05

Fig. B-22H-SILTT-4F03

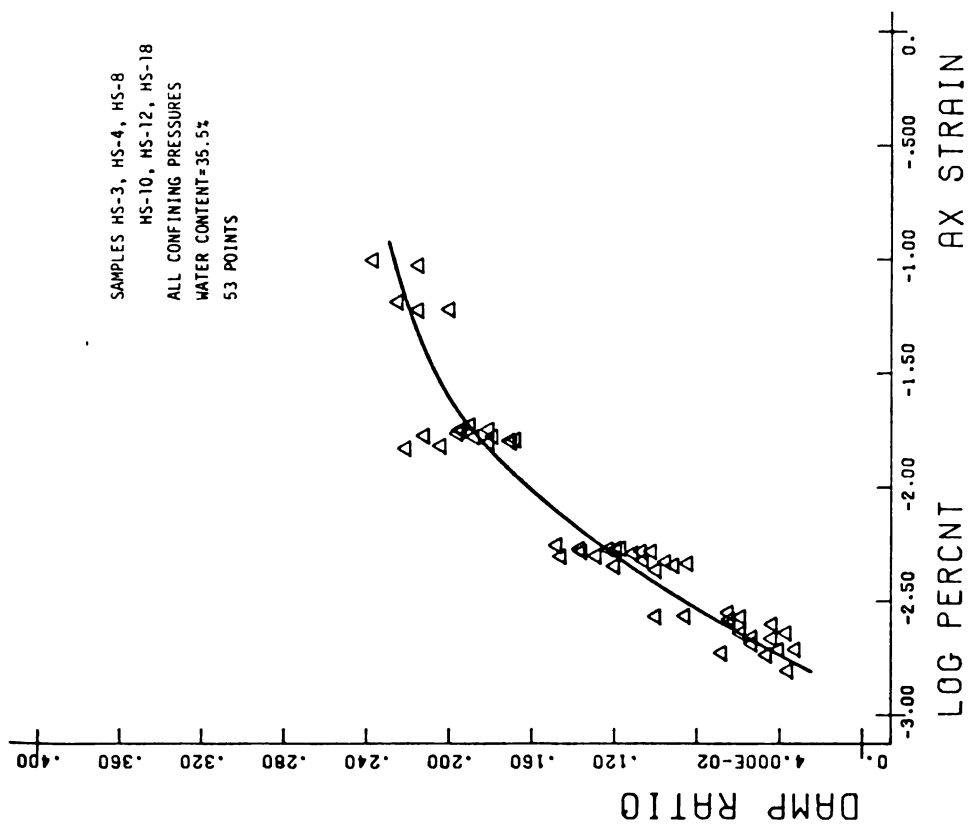


Fig. B-23H-SILTT-4F1

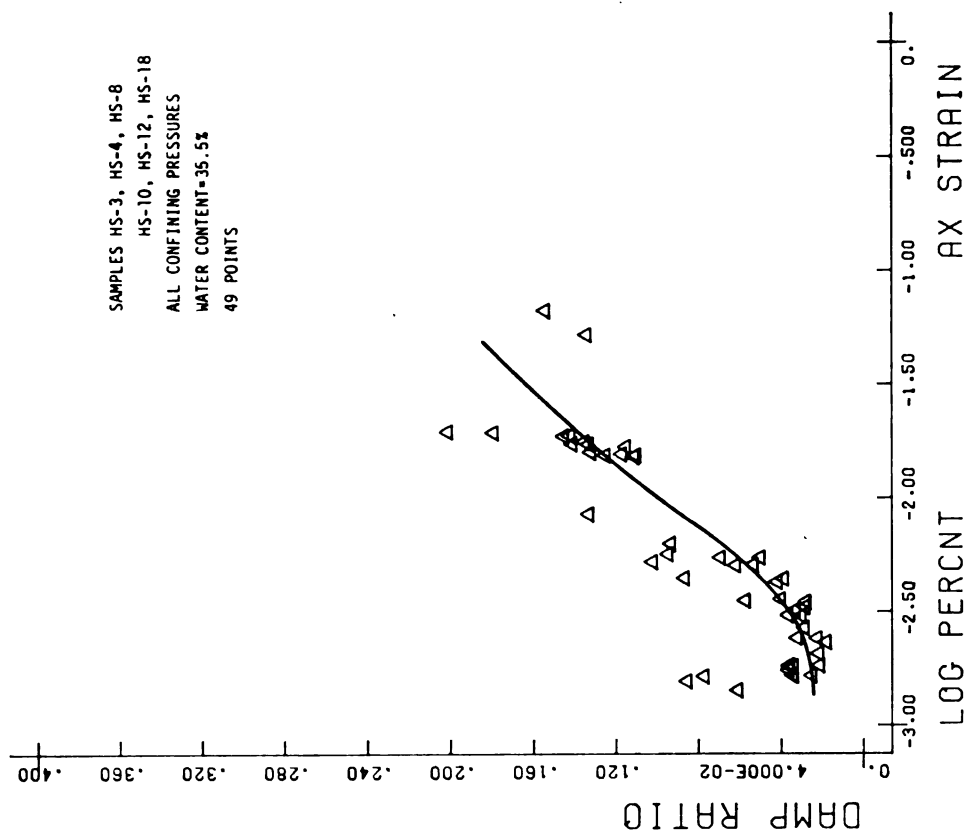


Fig. B-24H-SILTT-4F5

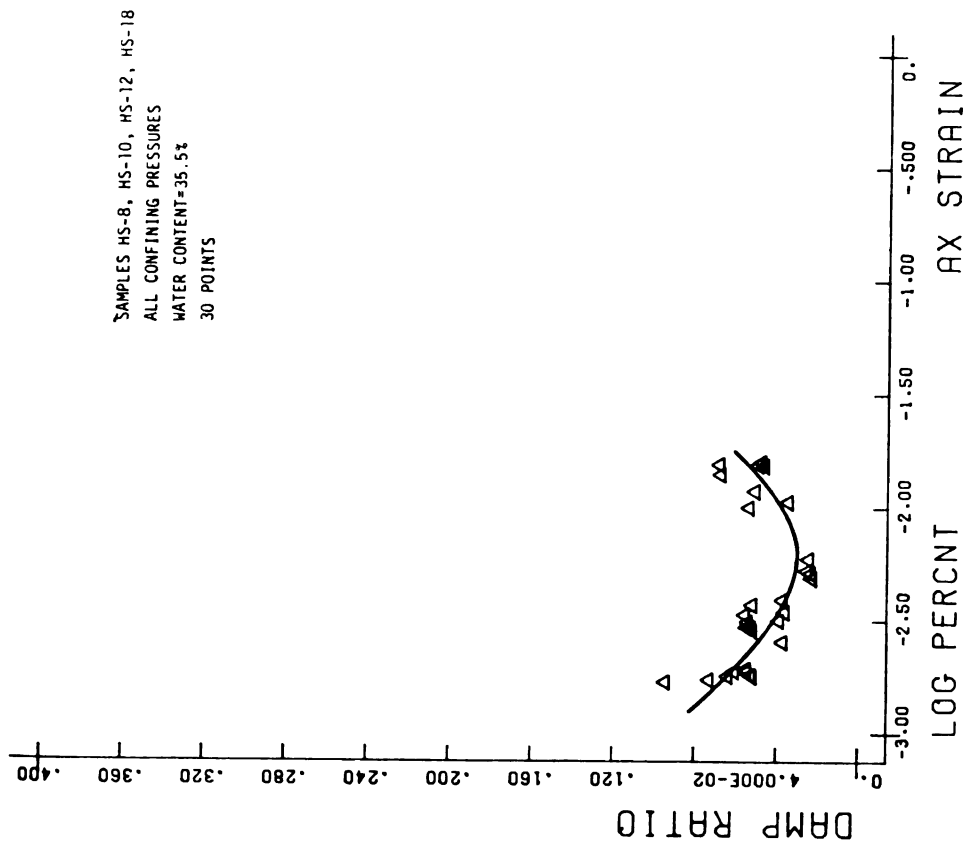


Fig. B-25H-SILTT-4F10

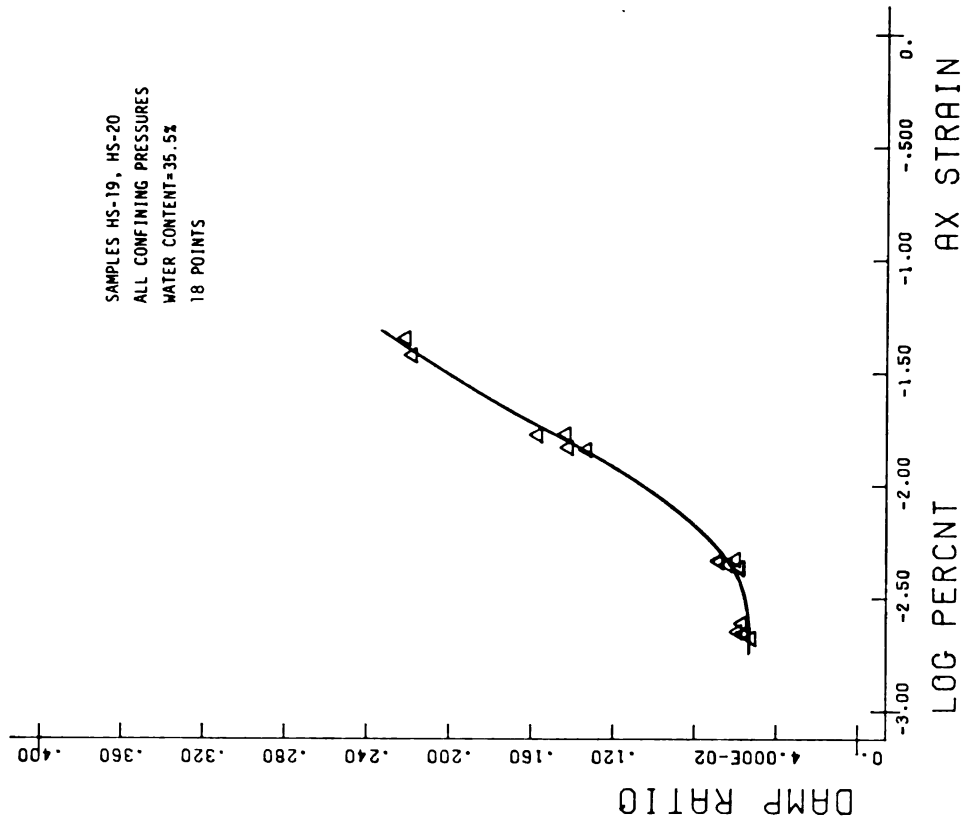


Fig. B-26H-SILTT-10F05

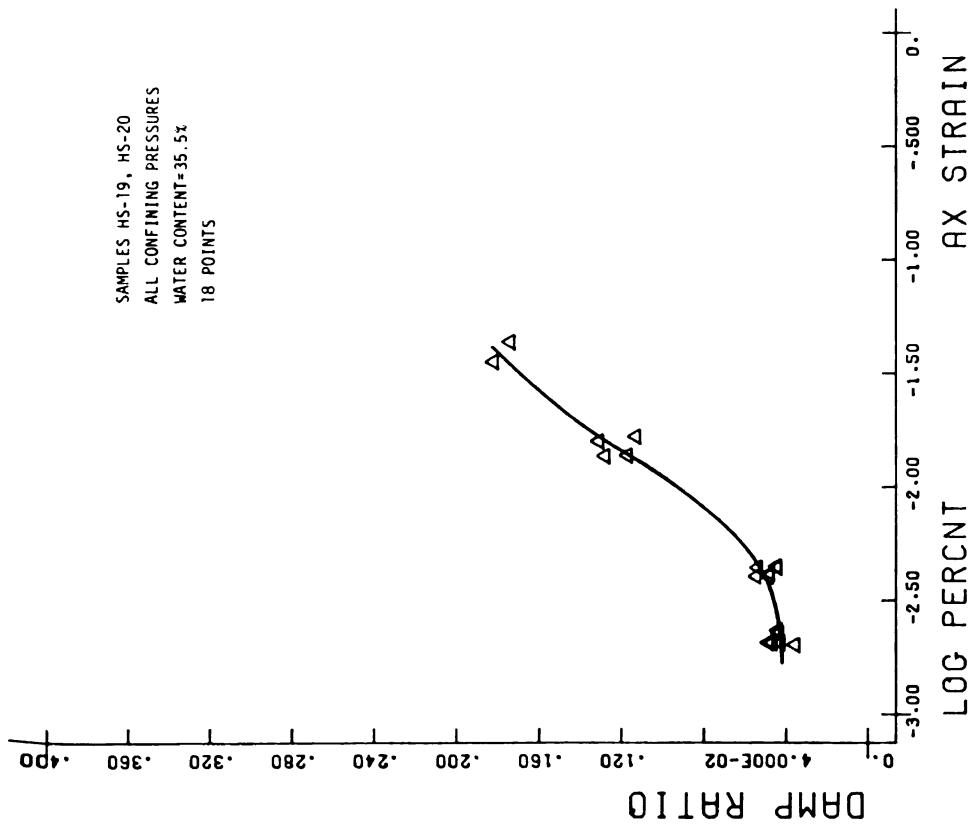


Fig. B-27H-SILTT-10F3

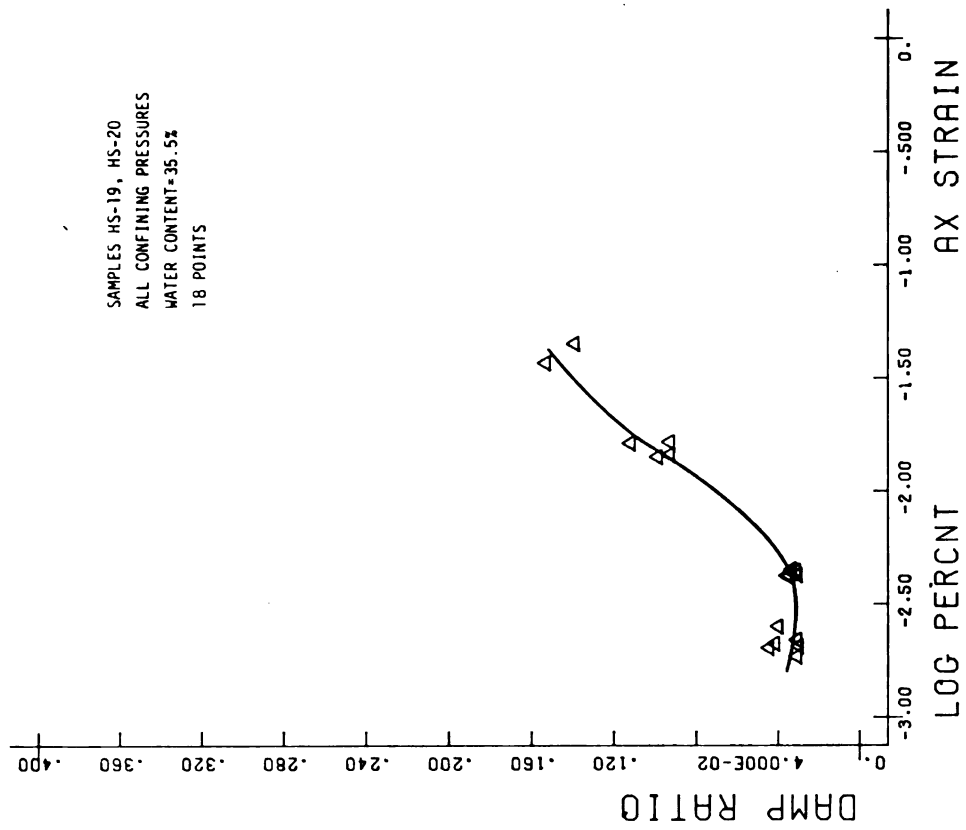


Fig. B-28H-SILTT-10F1

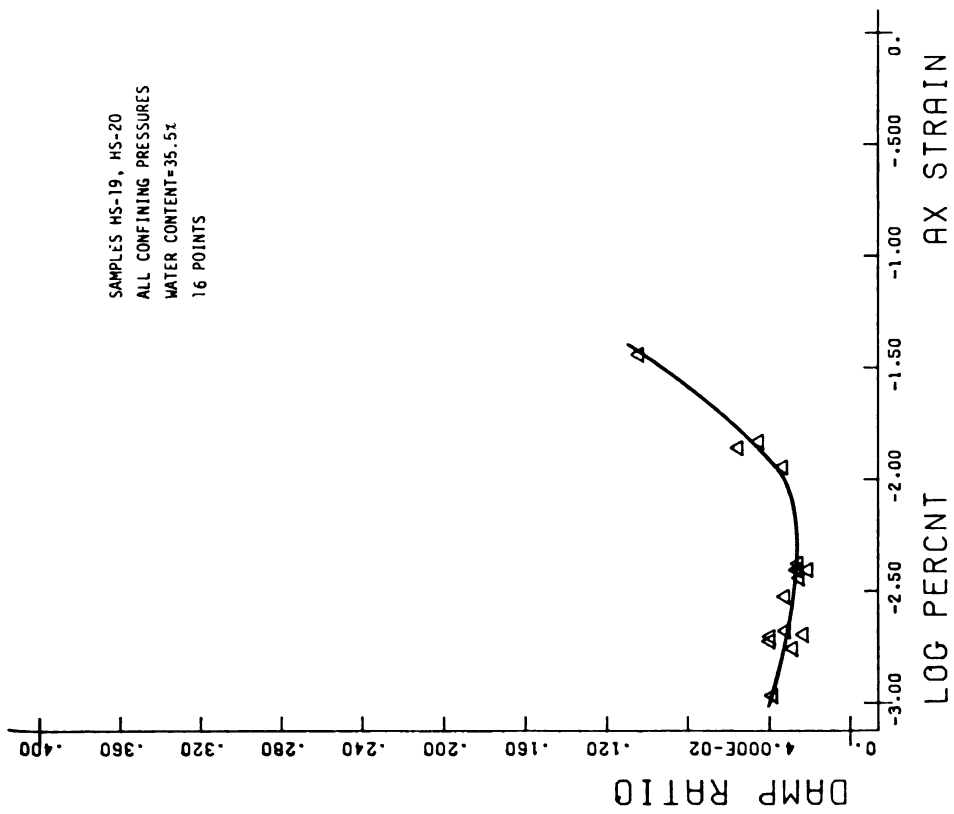


Fig. B-29H-SILTT-10F5

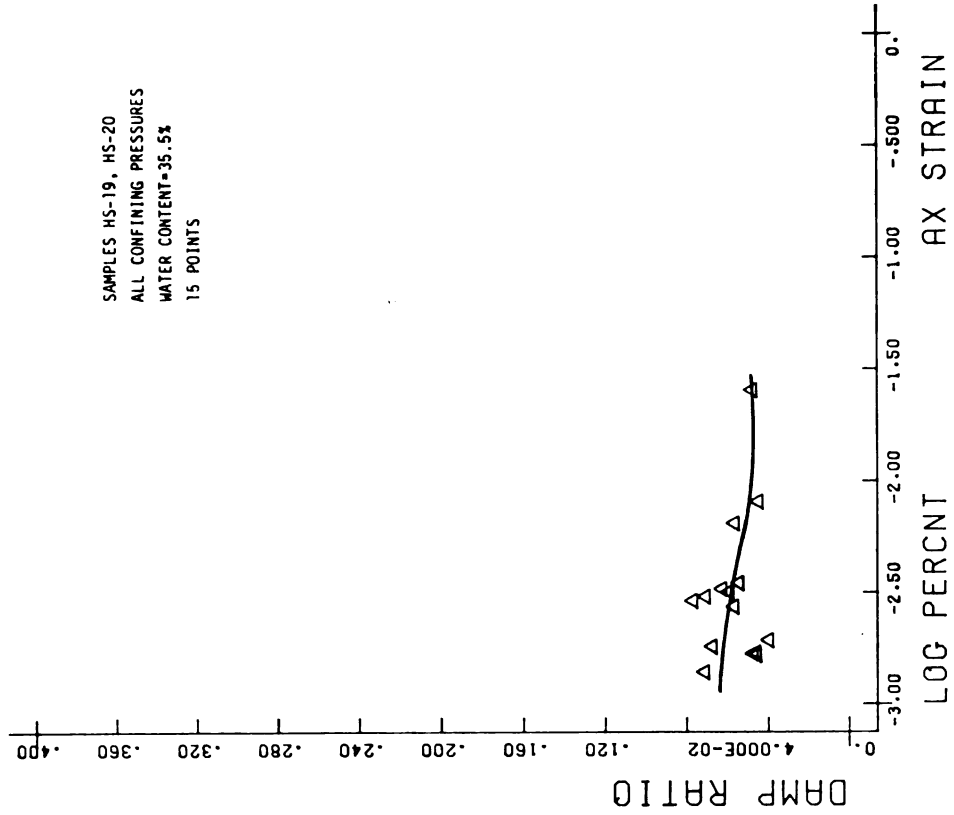


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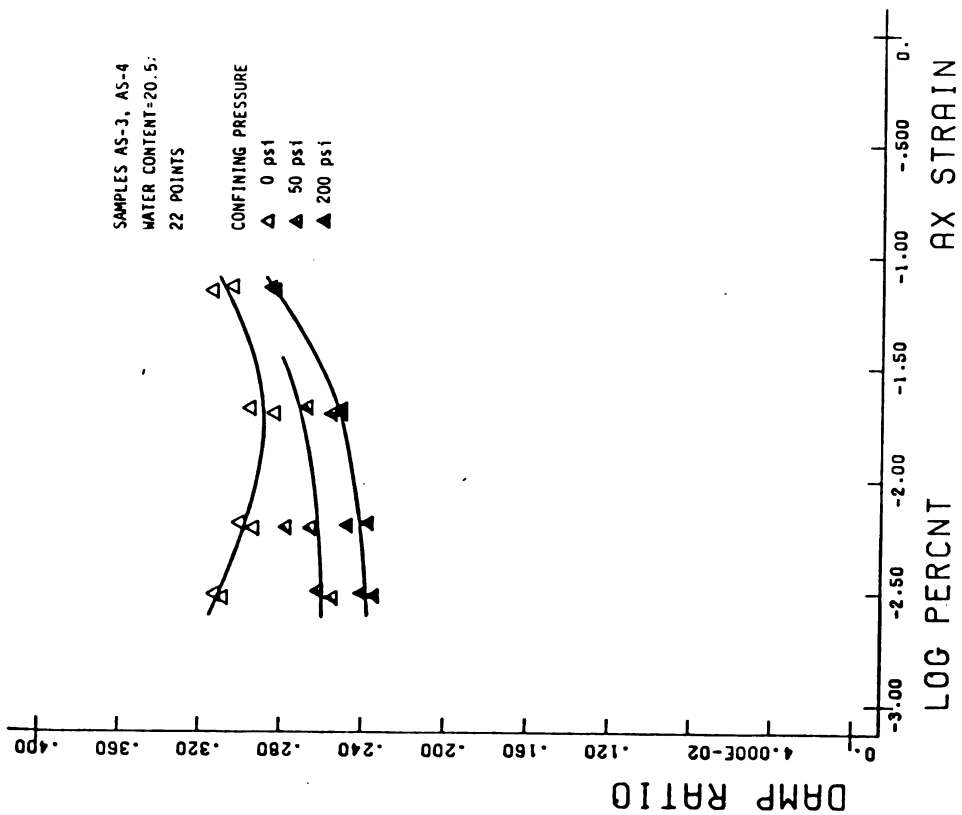


Fig. B-31A-SILTT-1F.05

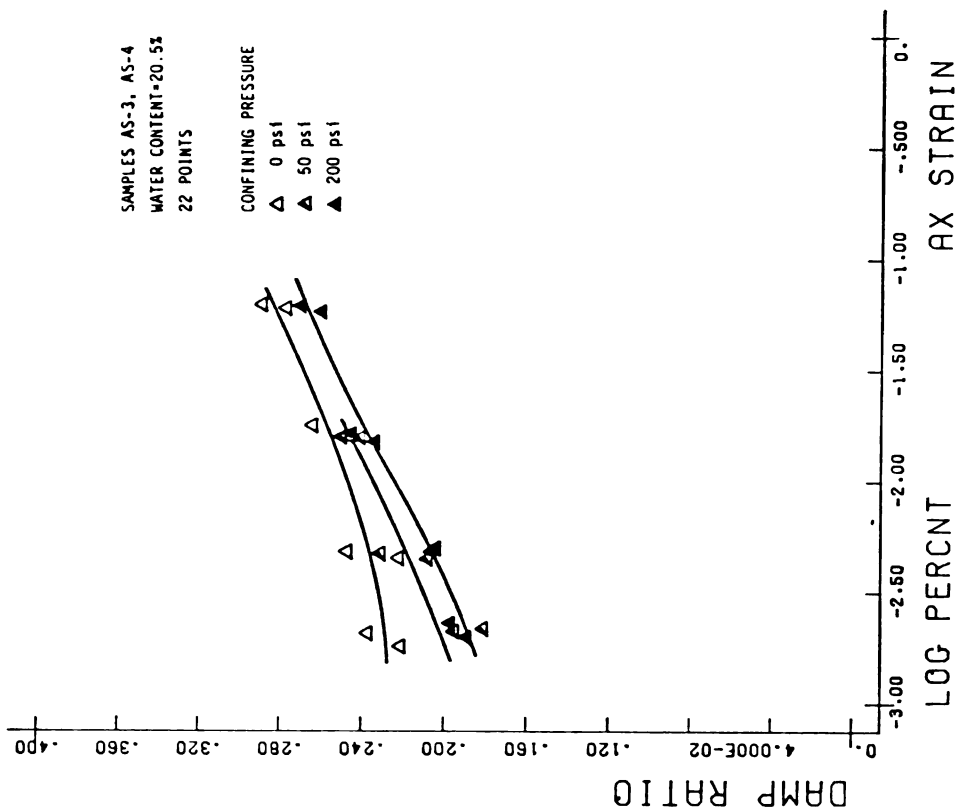


Fig. B-32A-SILTT-1F.3

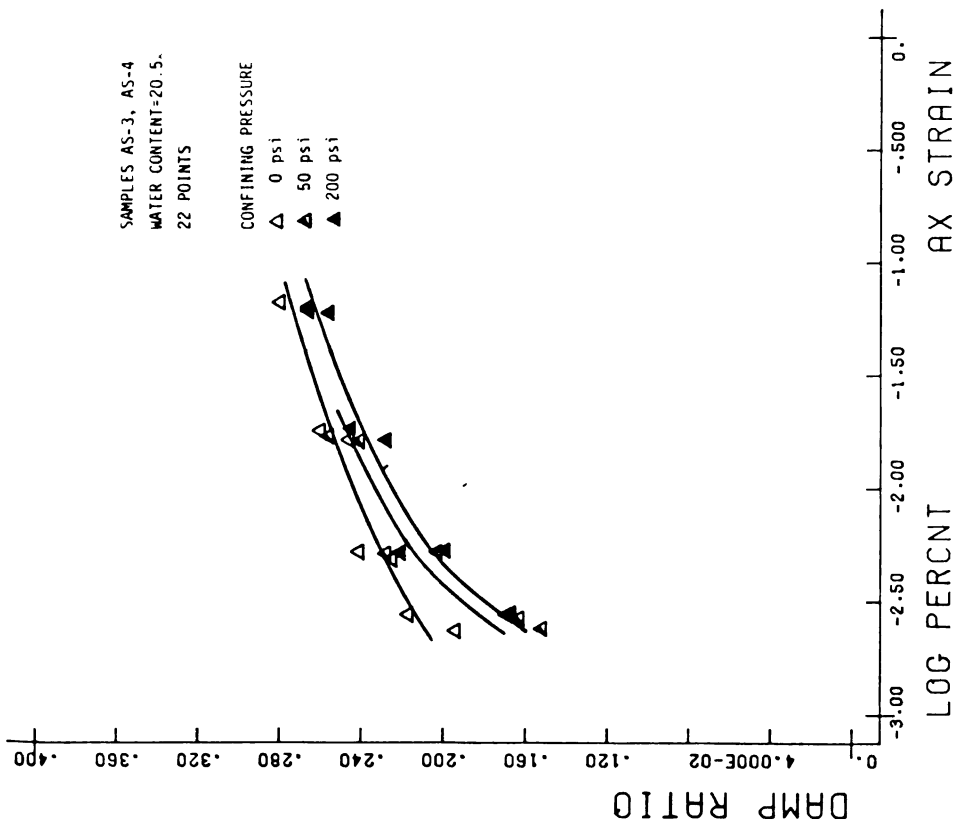


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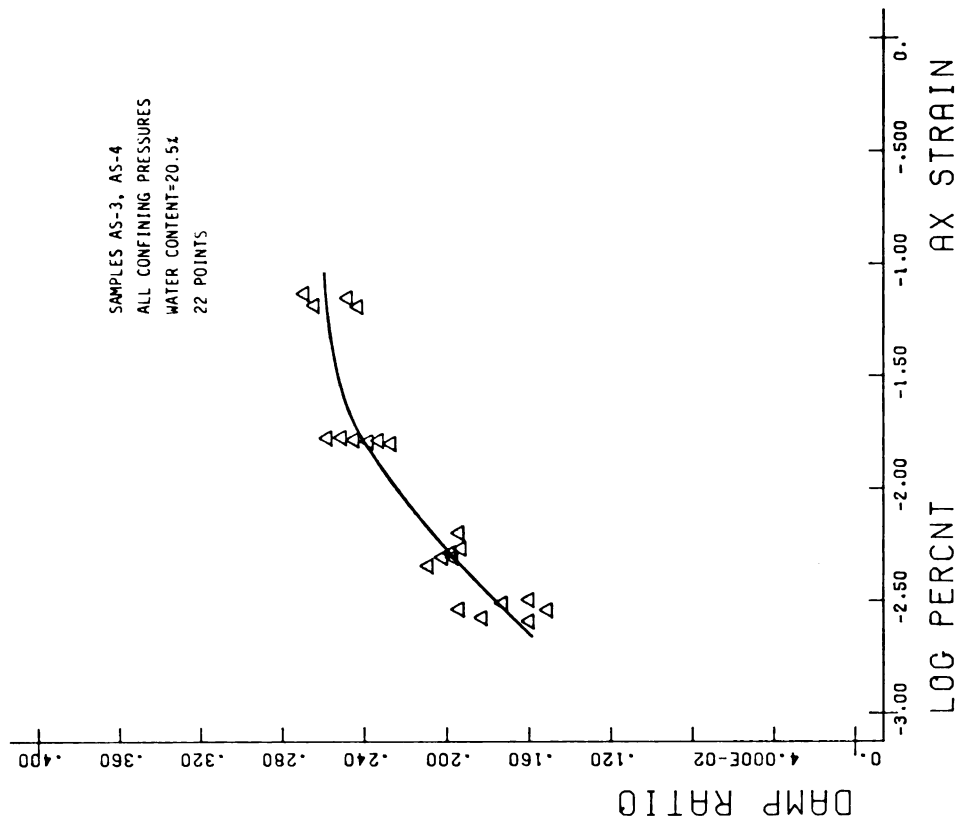


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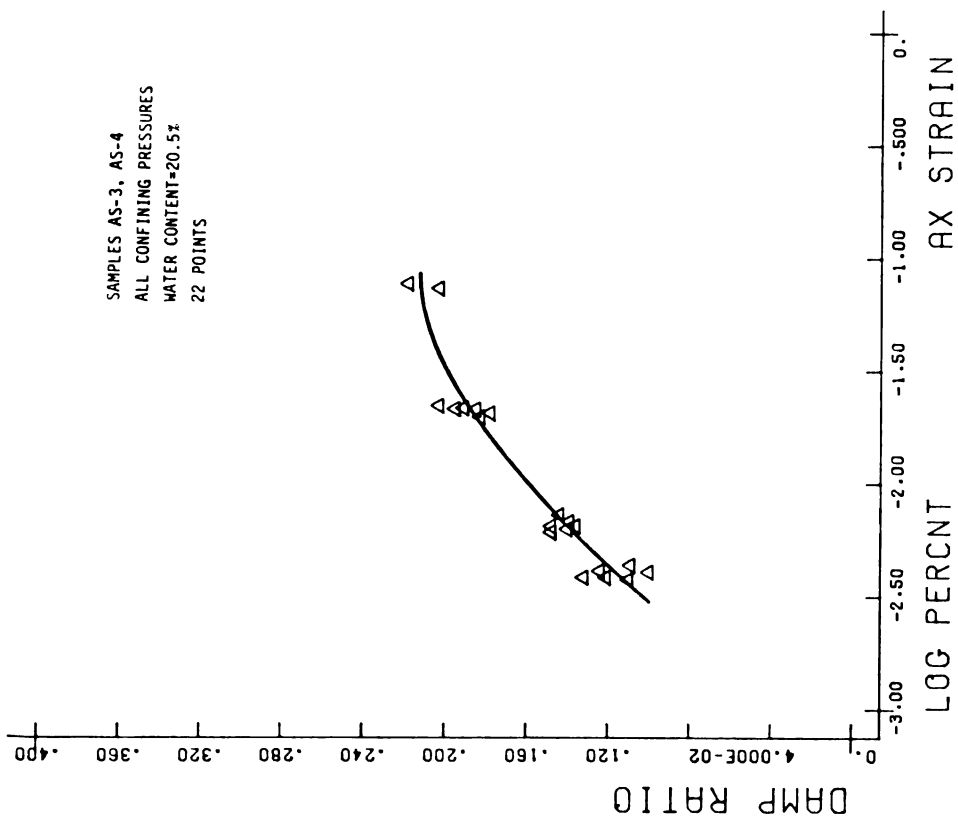


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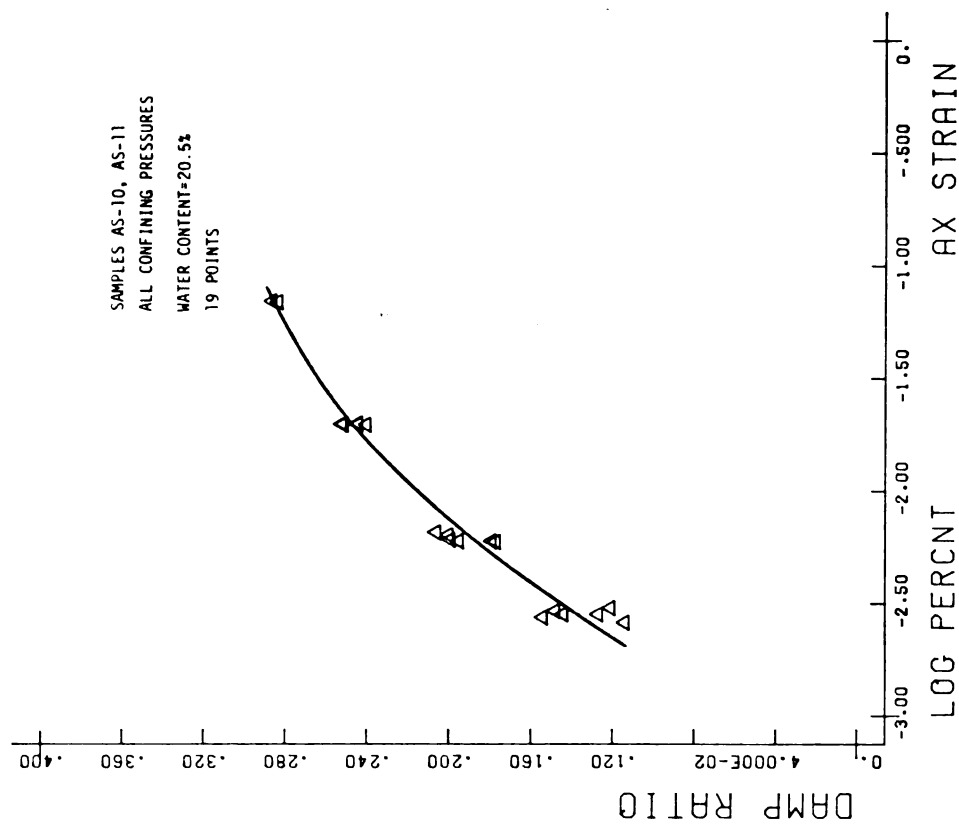


Fig. B-36A-SILTT-4F05

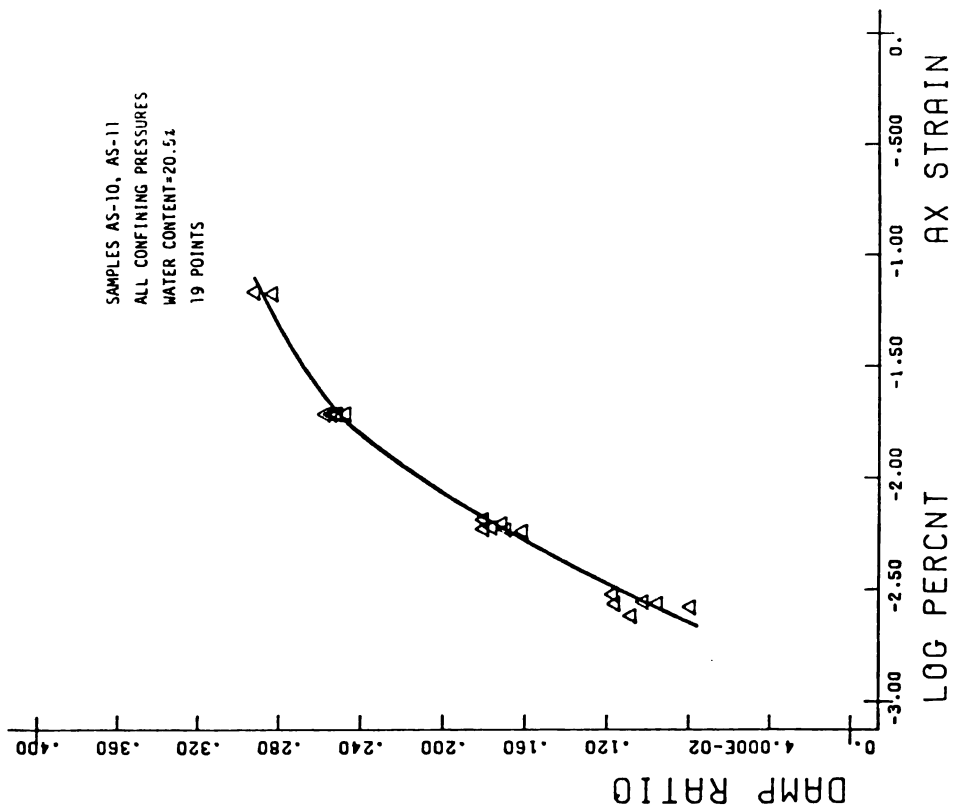


Fig. B-37 A-SILTT-4F3

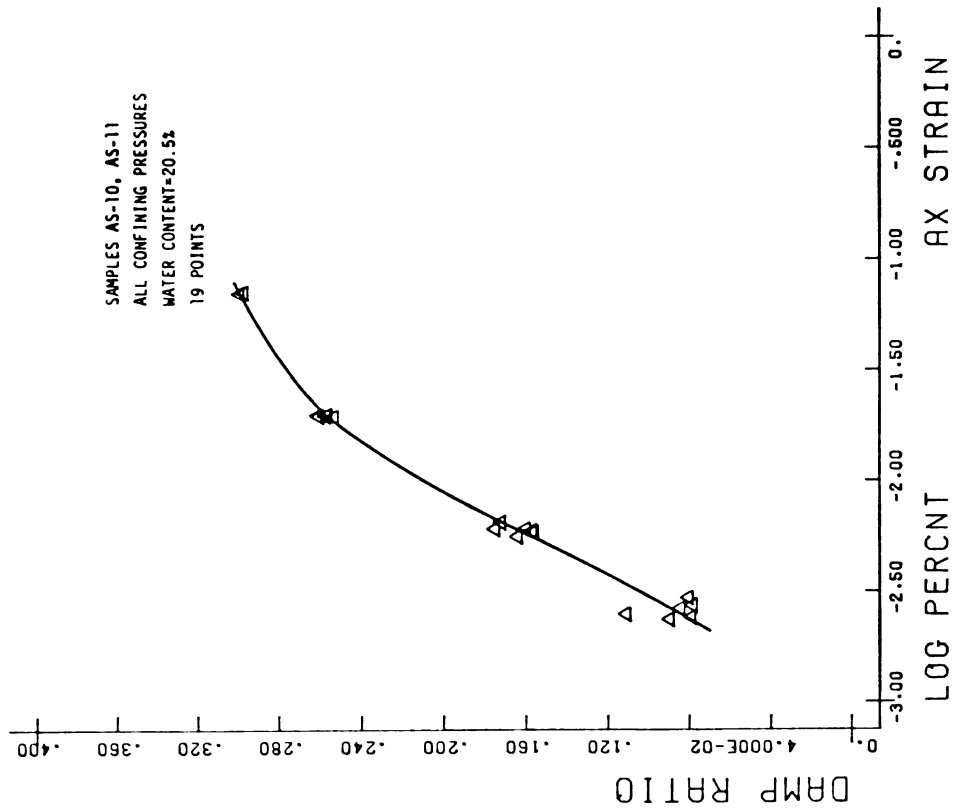


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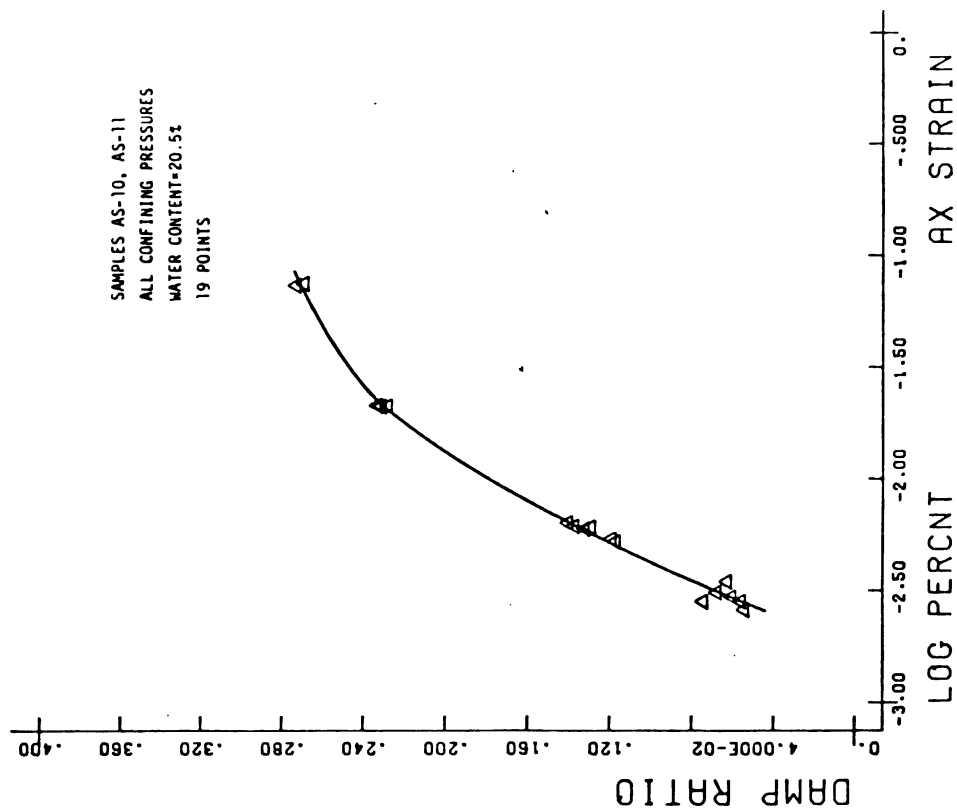


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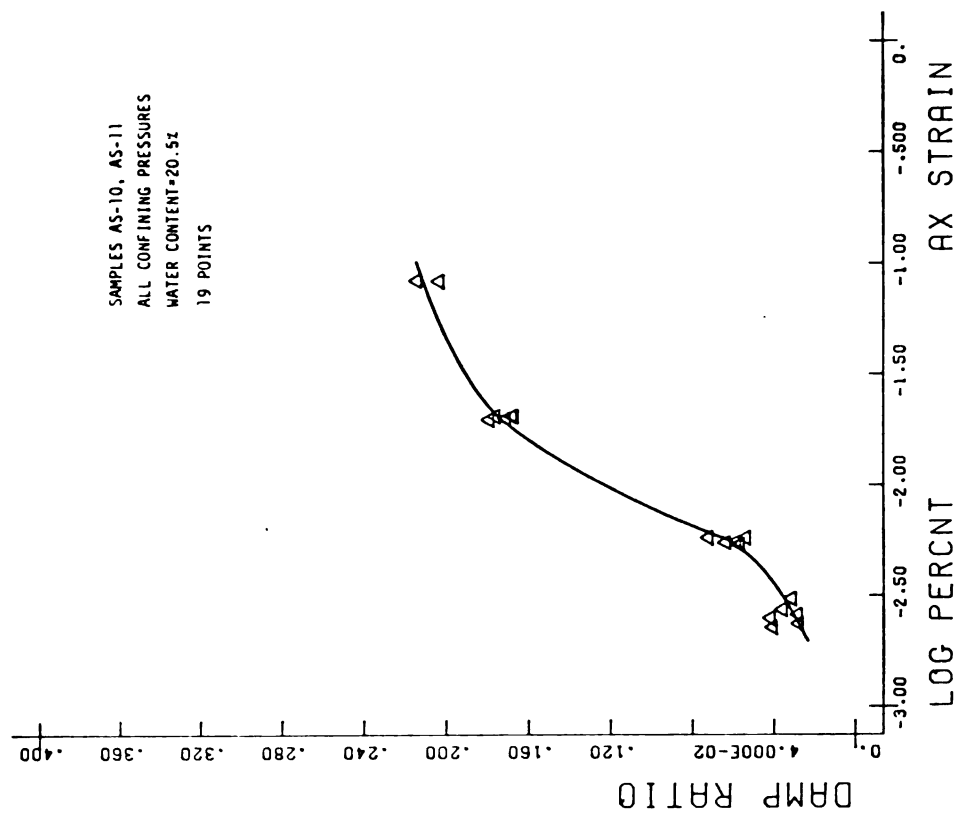
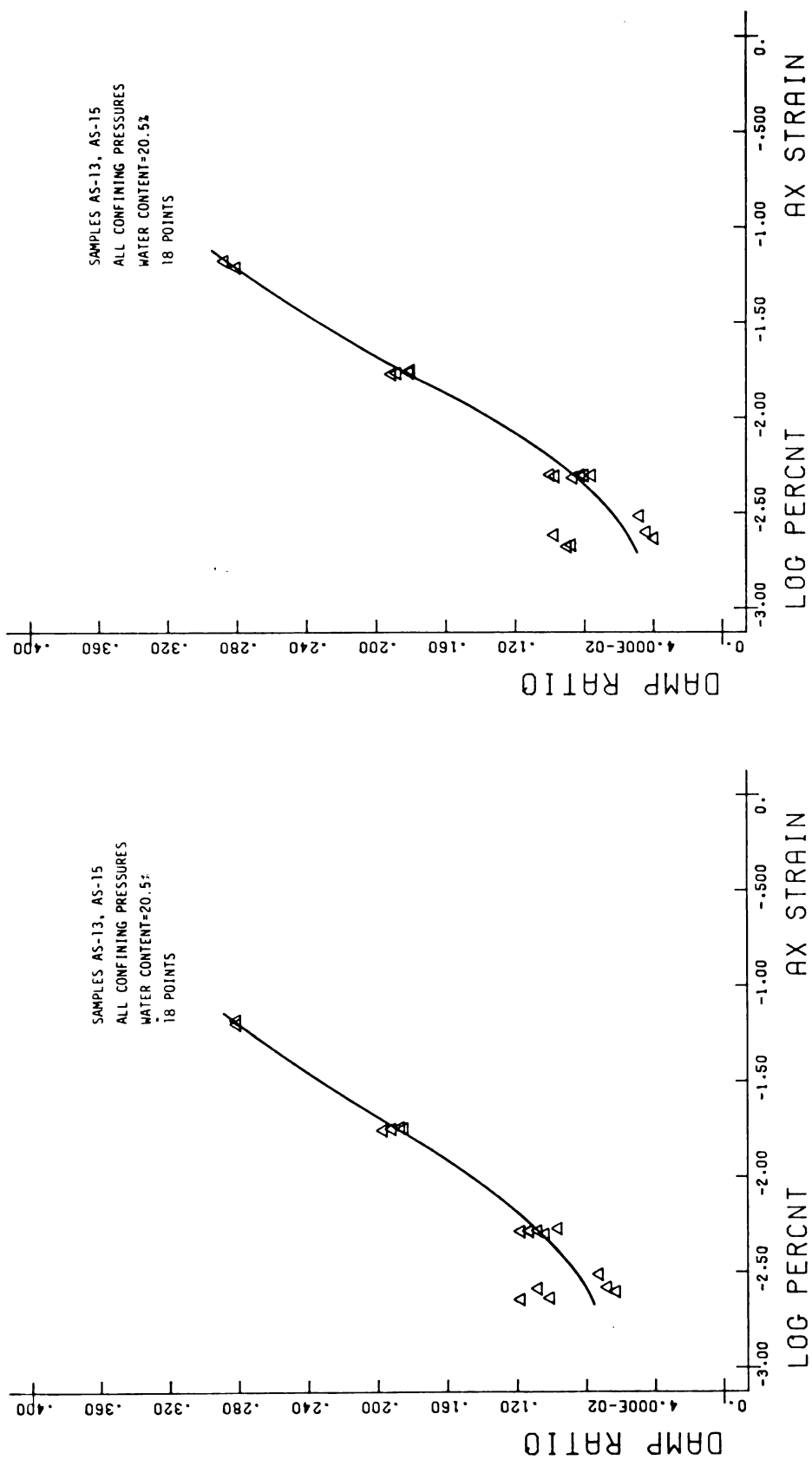


Fig. B-40A-SILTT-4F10



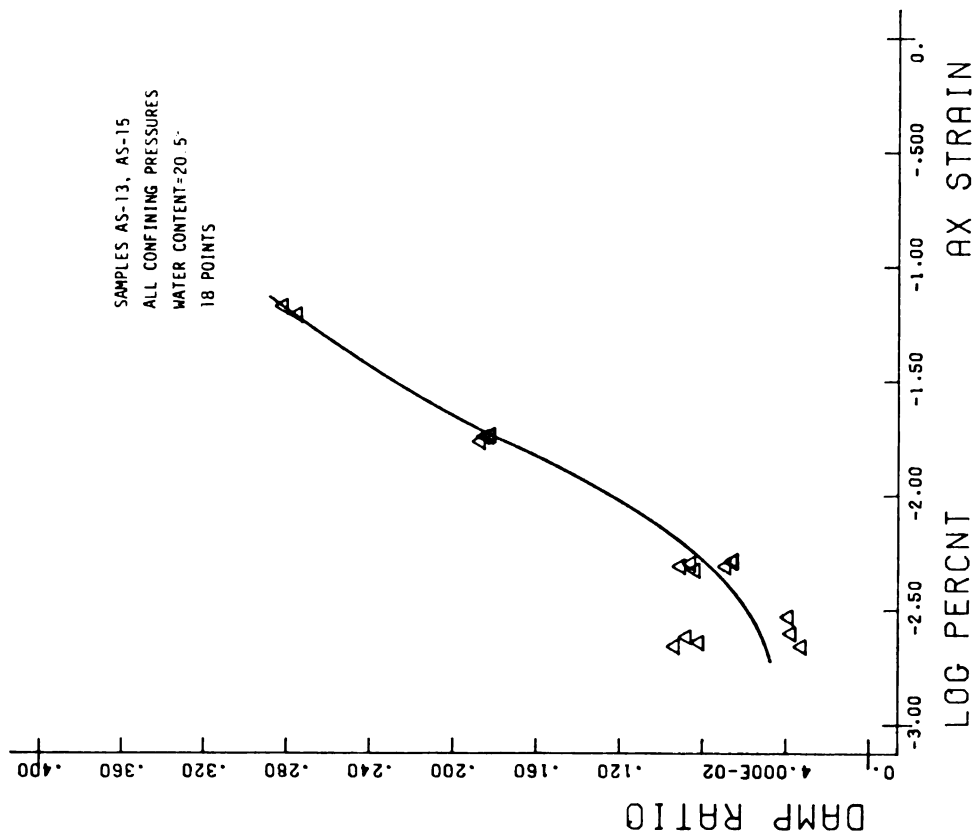


Fig. B-43A-SILTT-10F1

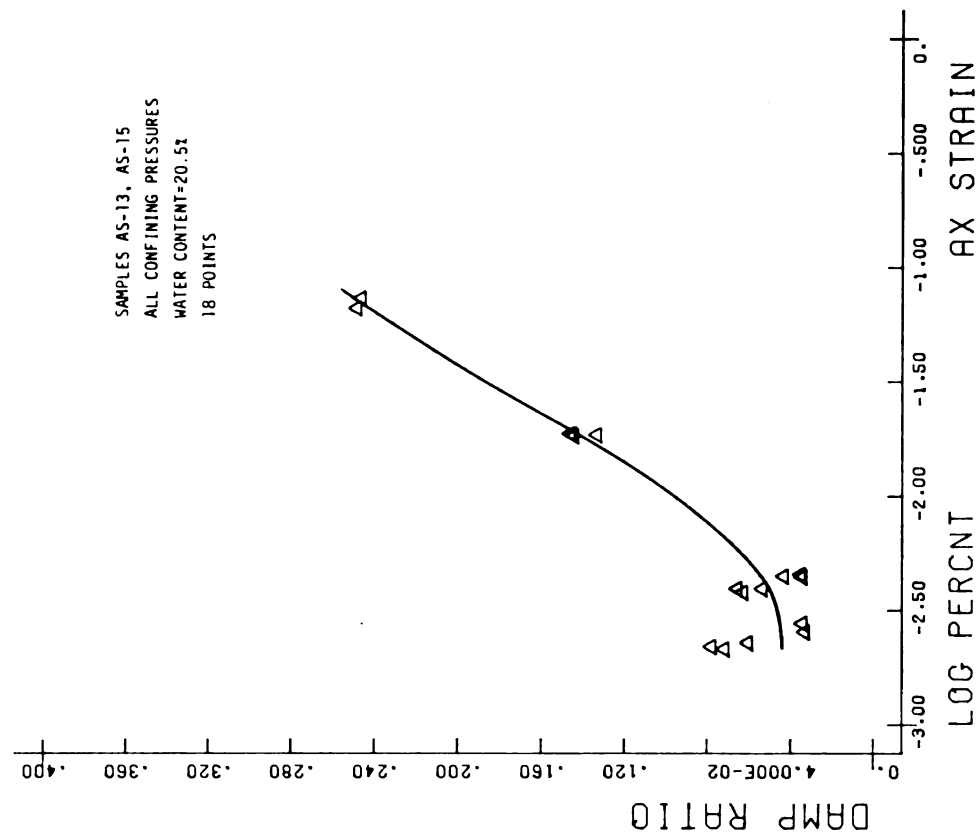


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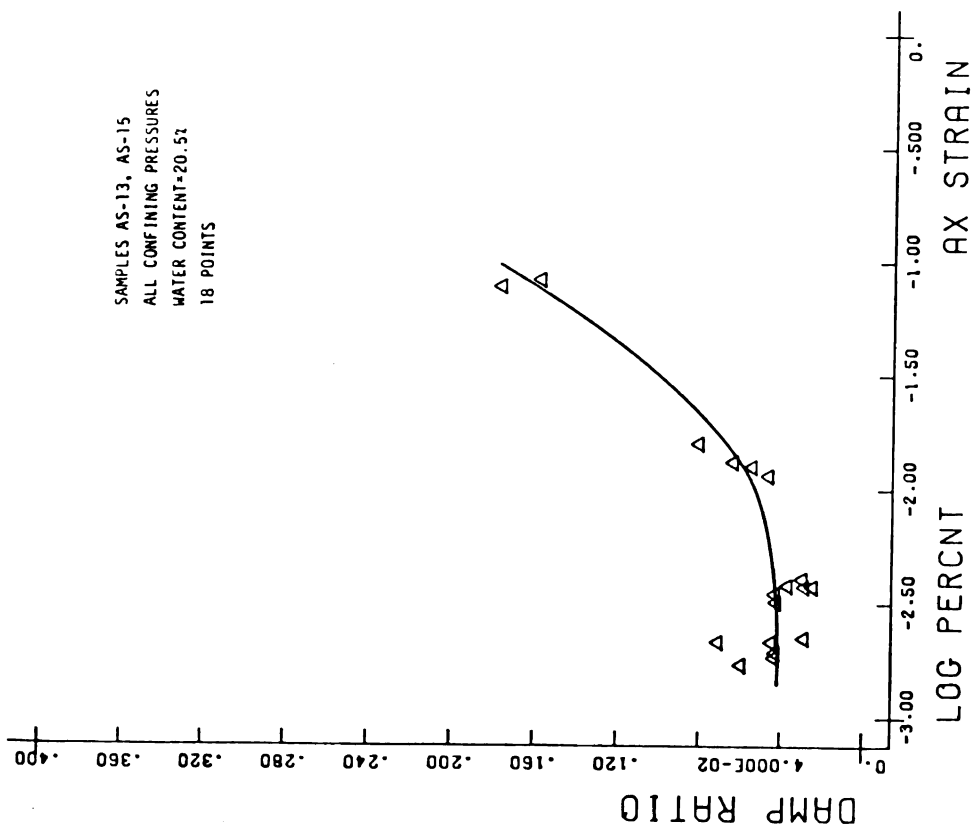


Fig. B-45A-SILTT-10F10

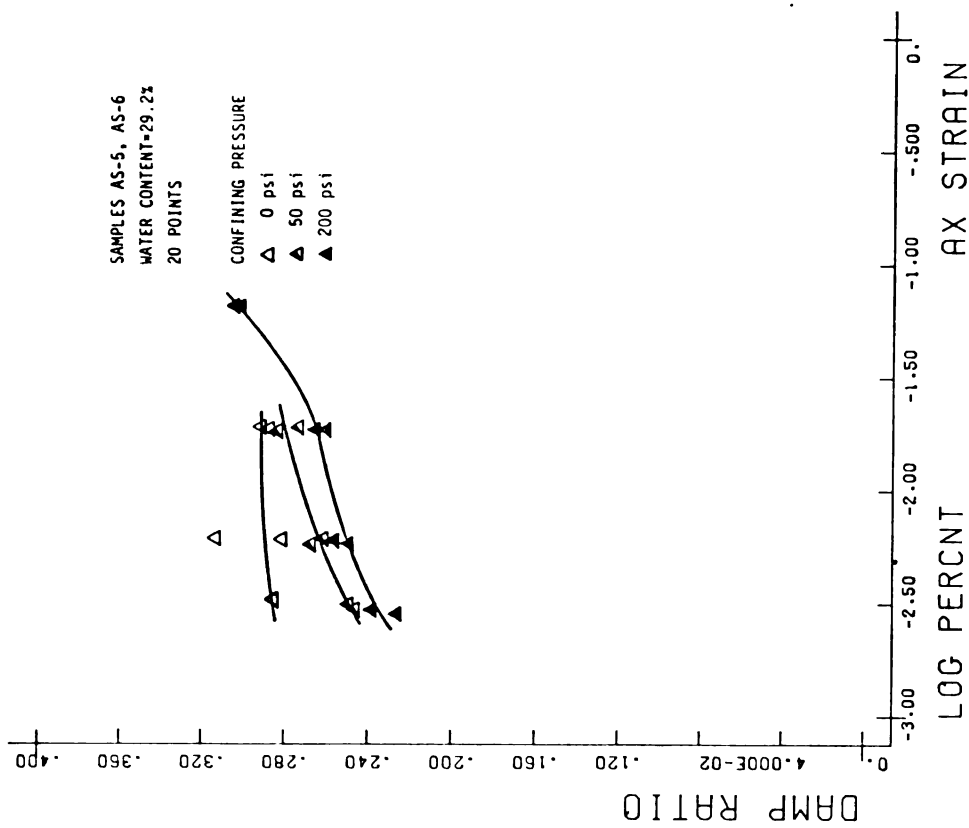


Fig. B-46A-SILTT-1F05

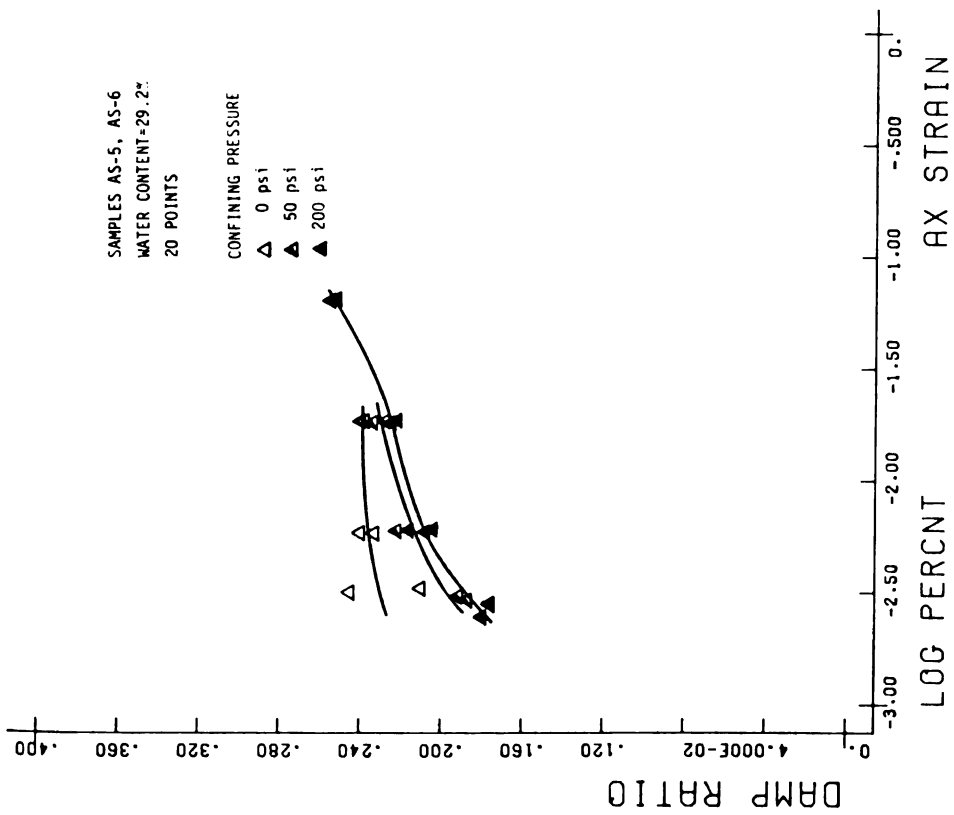


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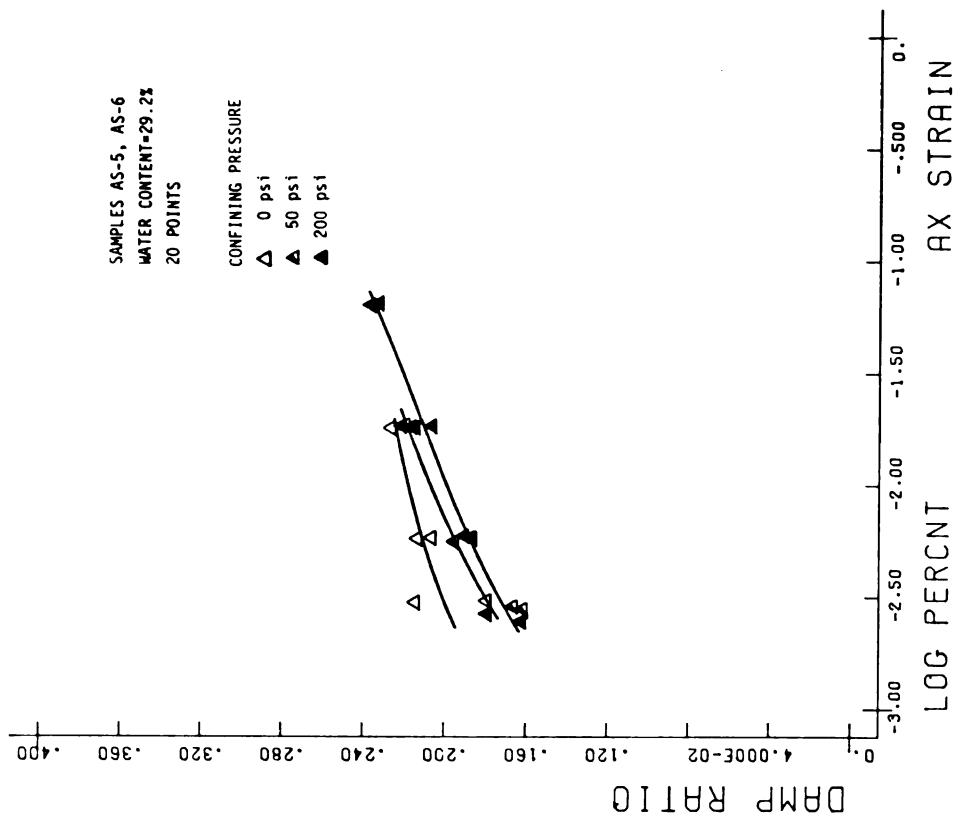


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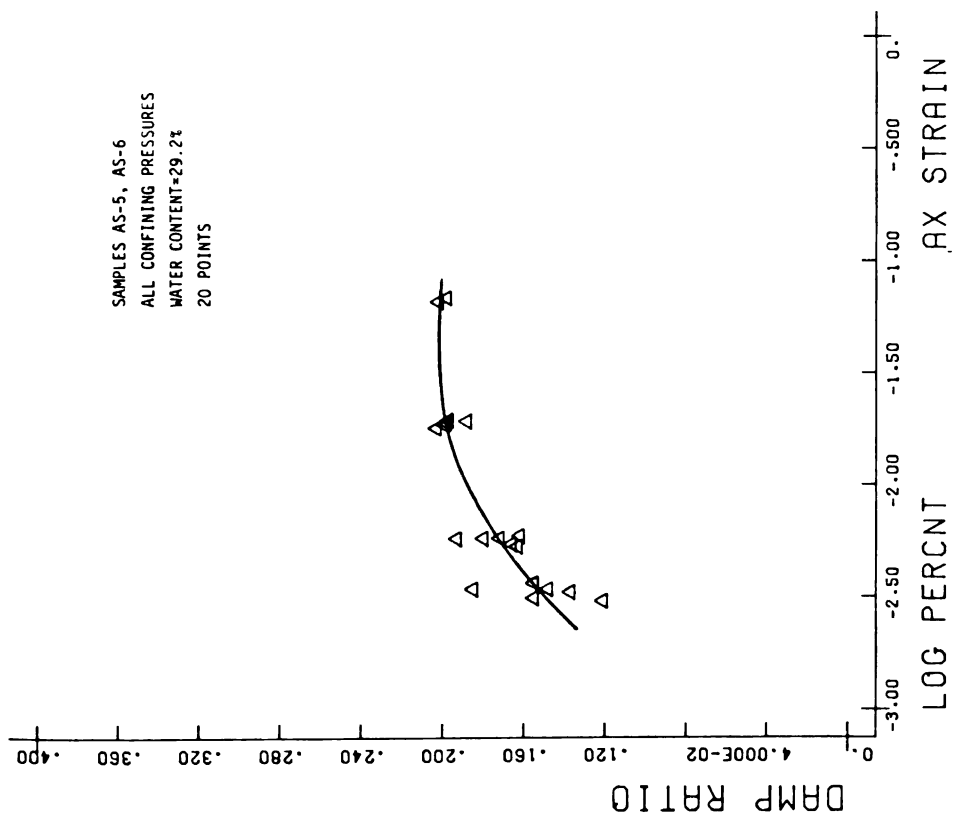


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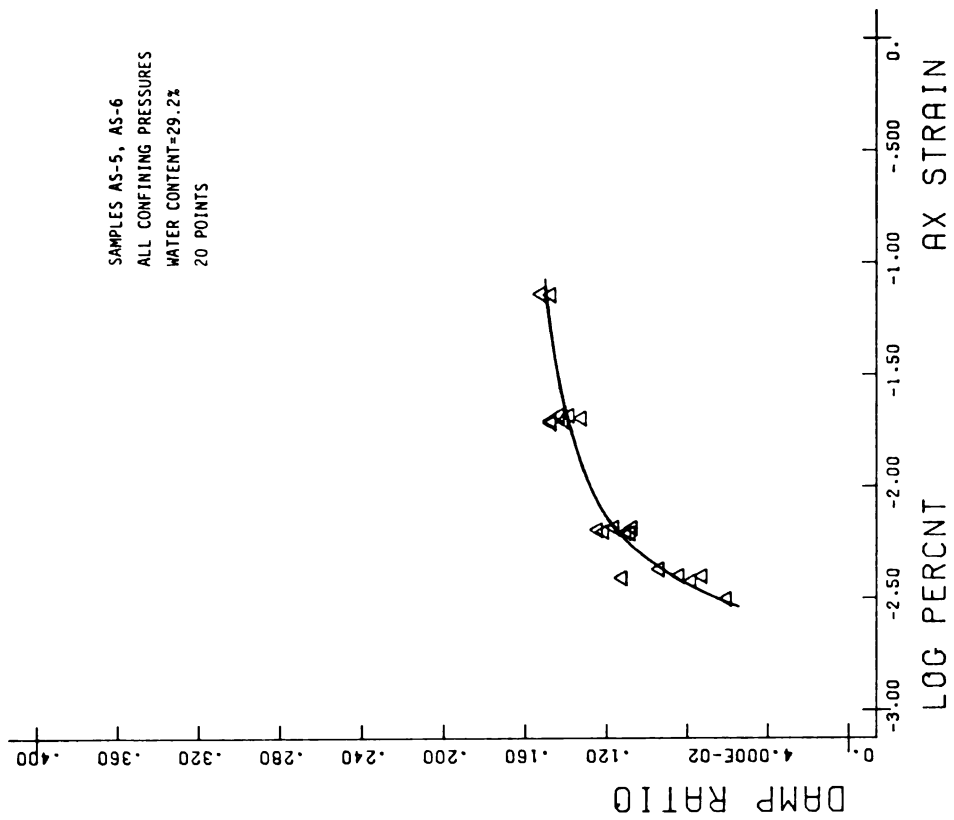


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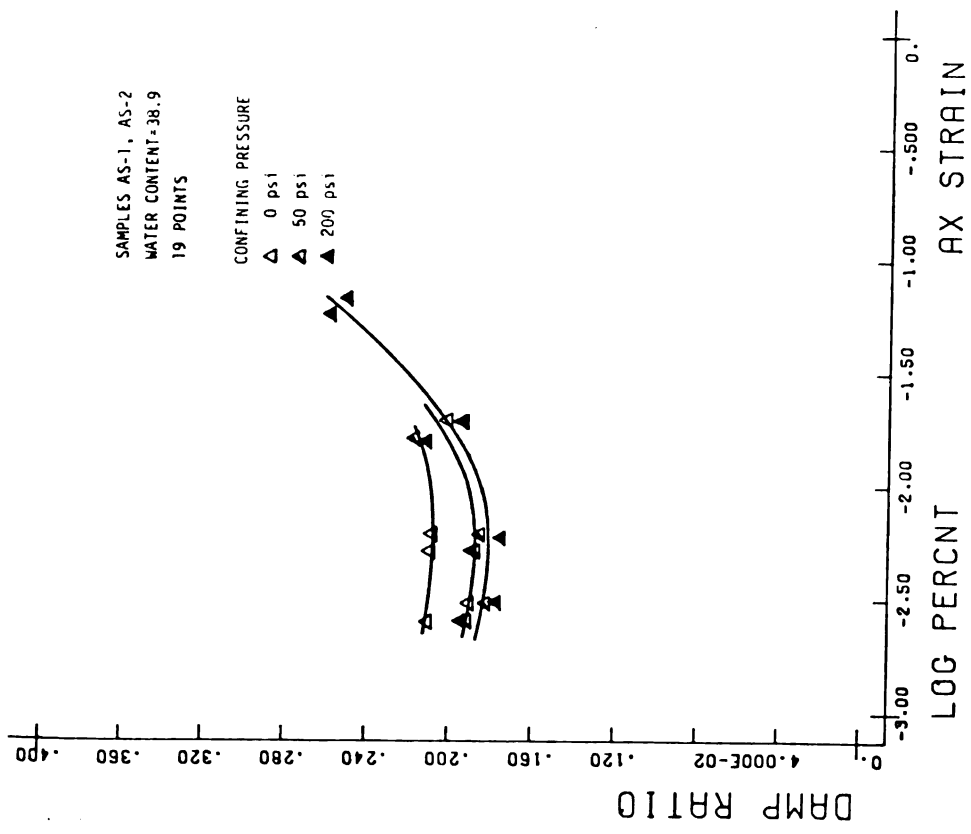


Fig. B-51A-SILTT-1F05

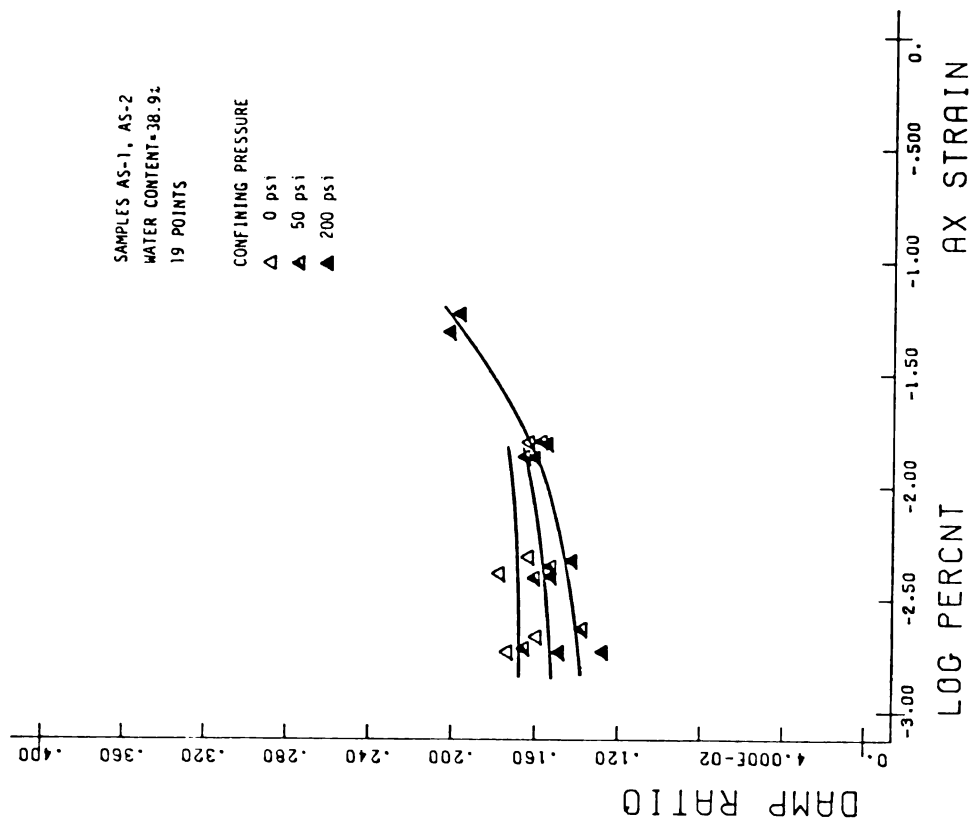


Fig. B-52A-SILTT-1F03

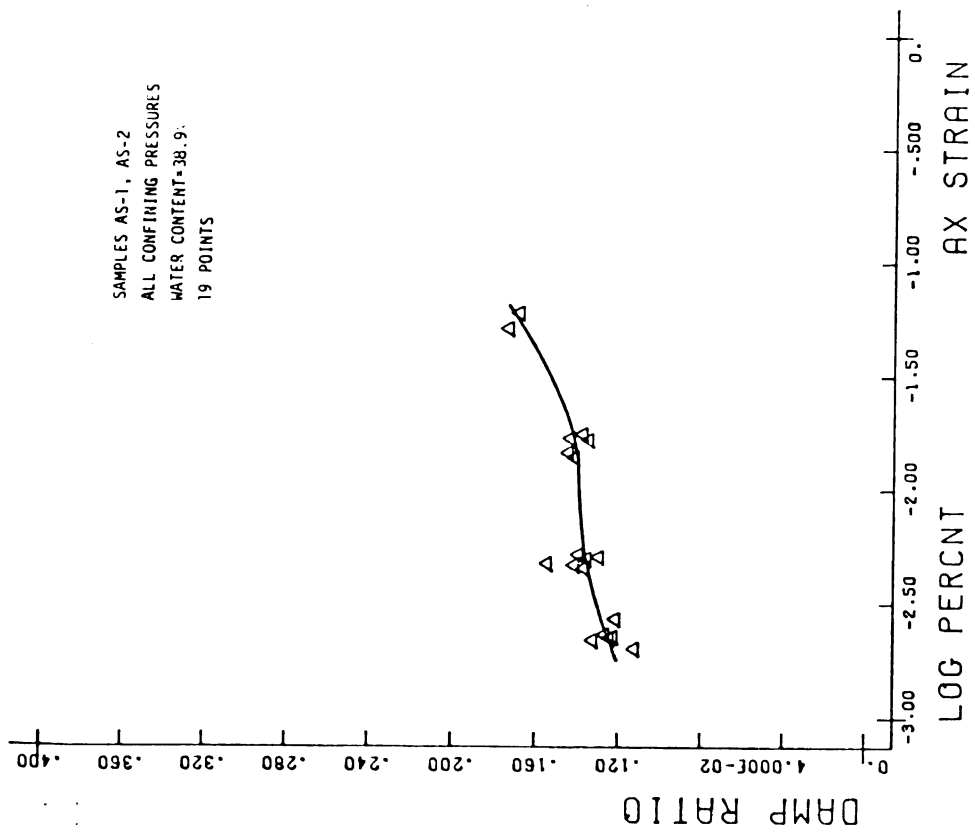


Fig. B-53A-SILTT-1F1

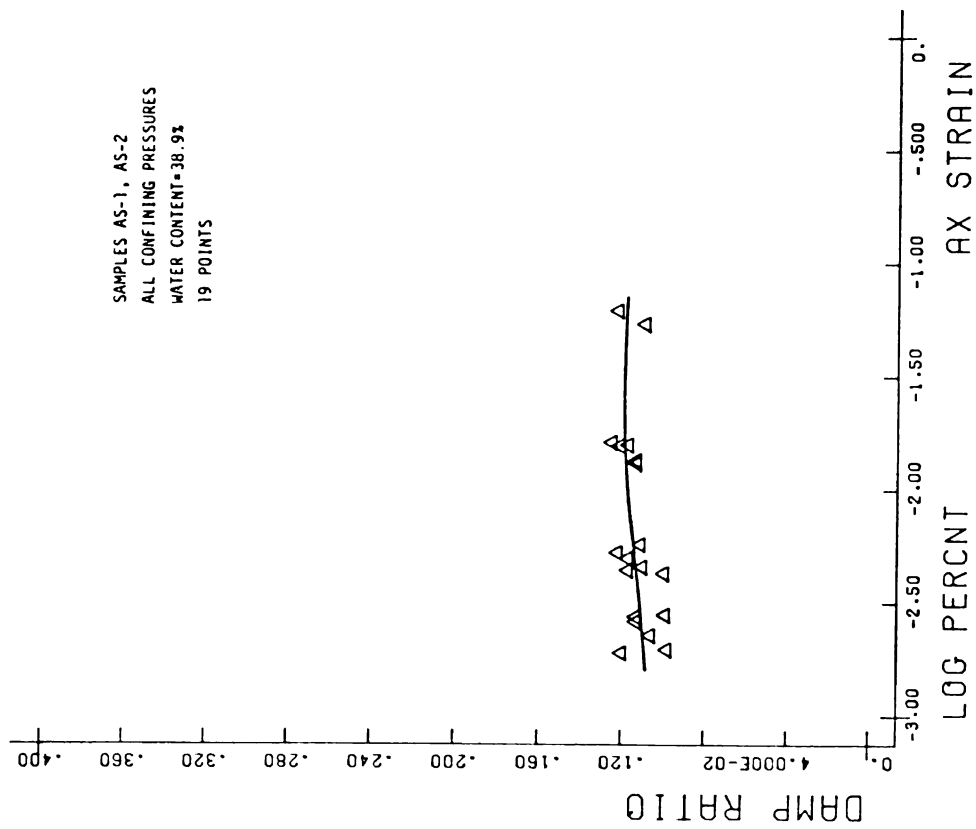


Fig. B-54A-SILTT-1F5

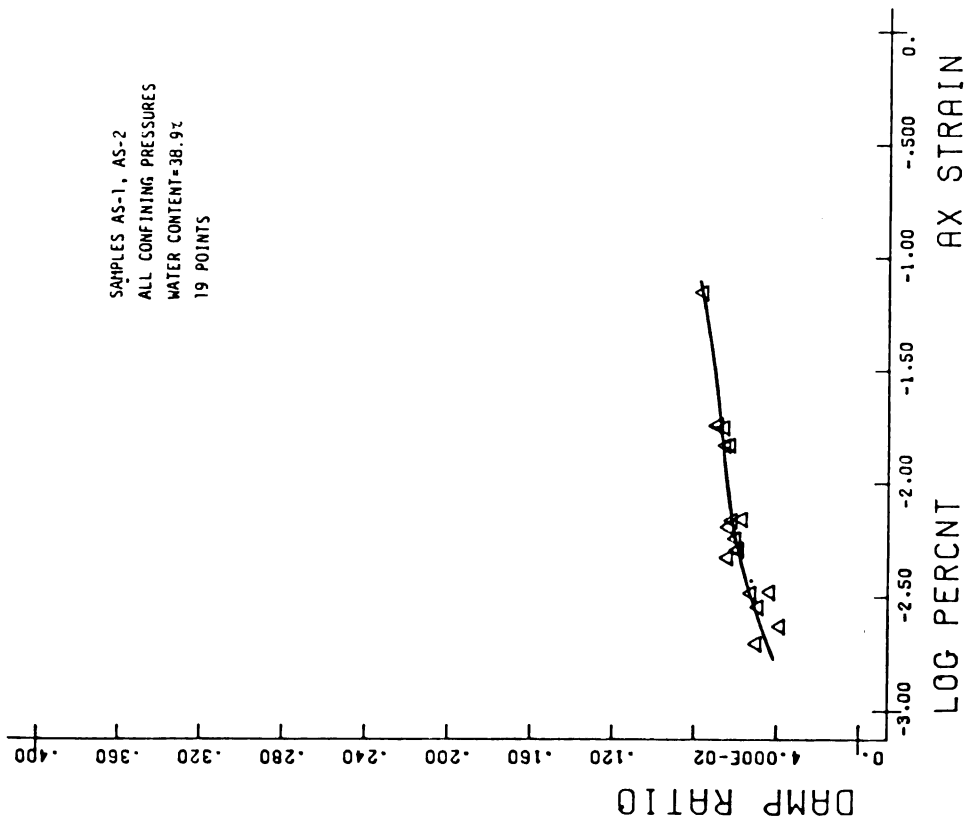


Fig. B-55A-SILTT-1F10

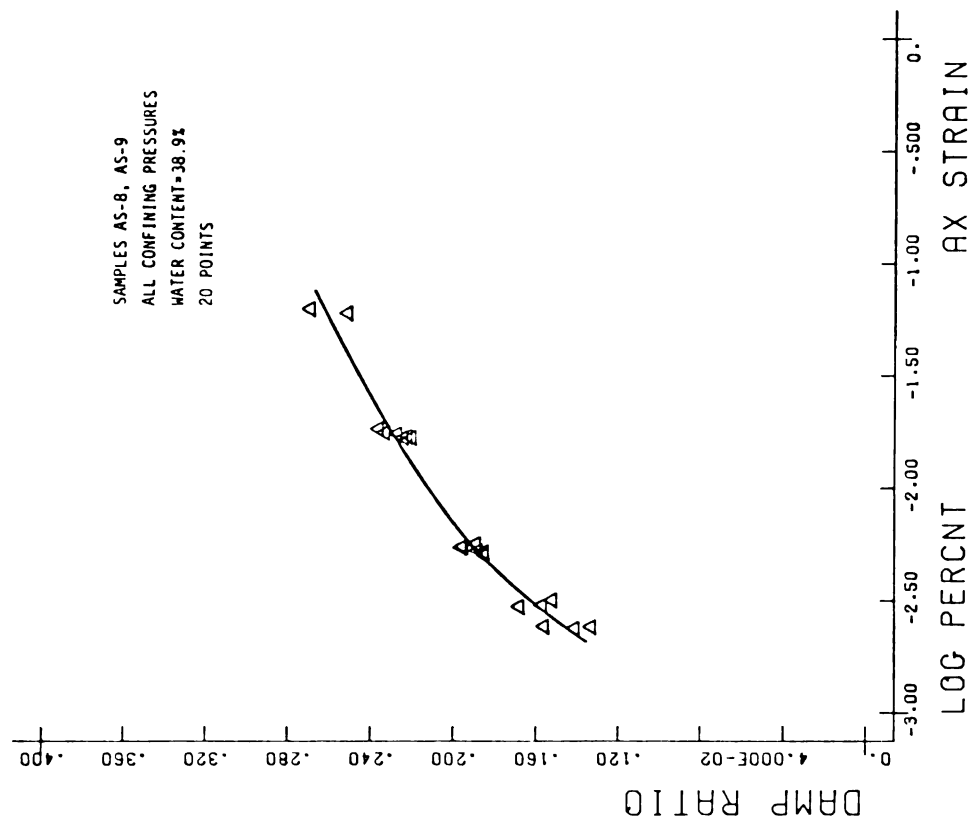


Fig. B-56A-SILTT-4F05

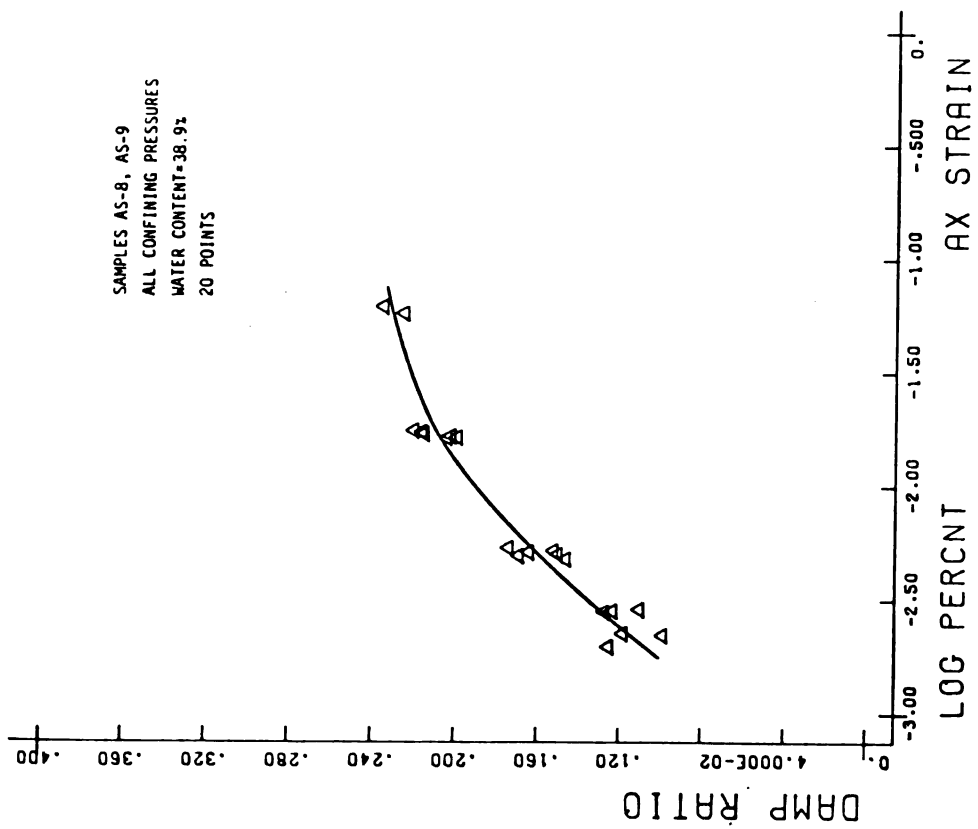


Fig. B-57A-SILTT-4F3

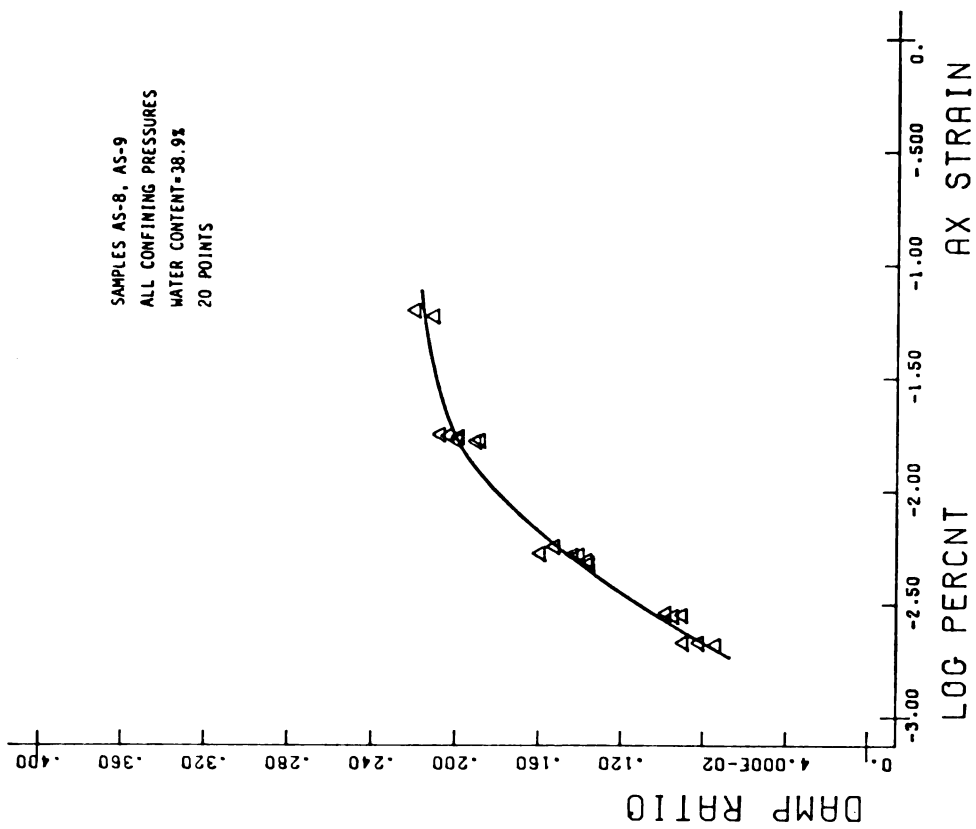


Fig. B-58A-SILTT-4F1

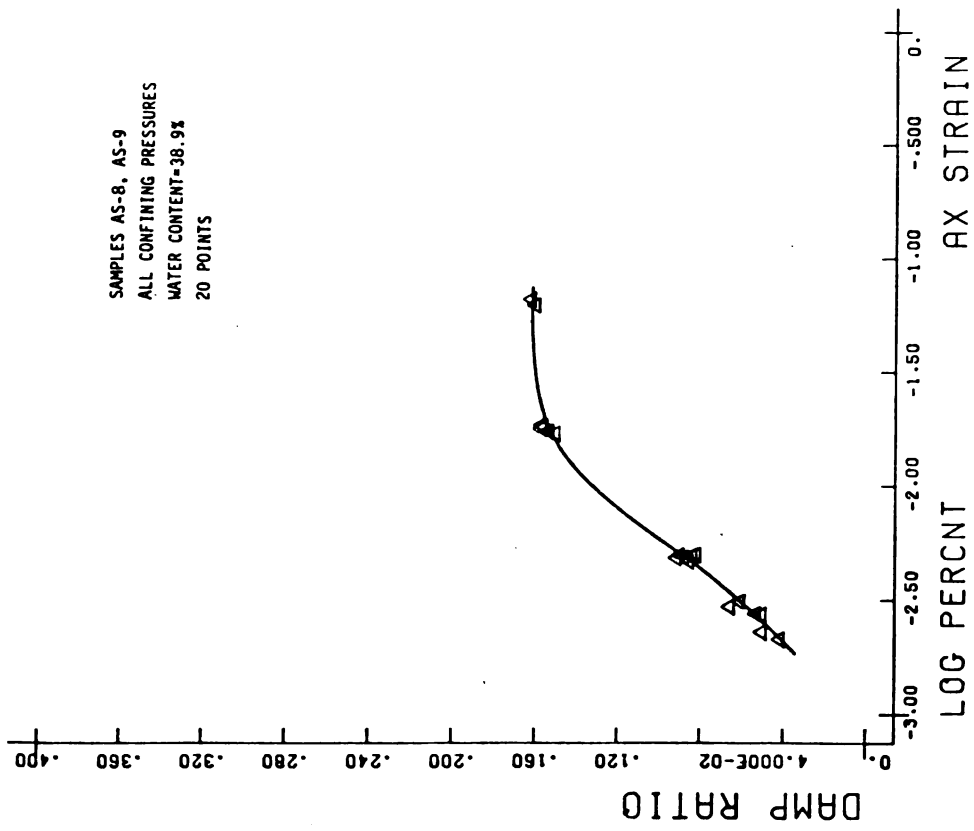


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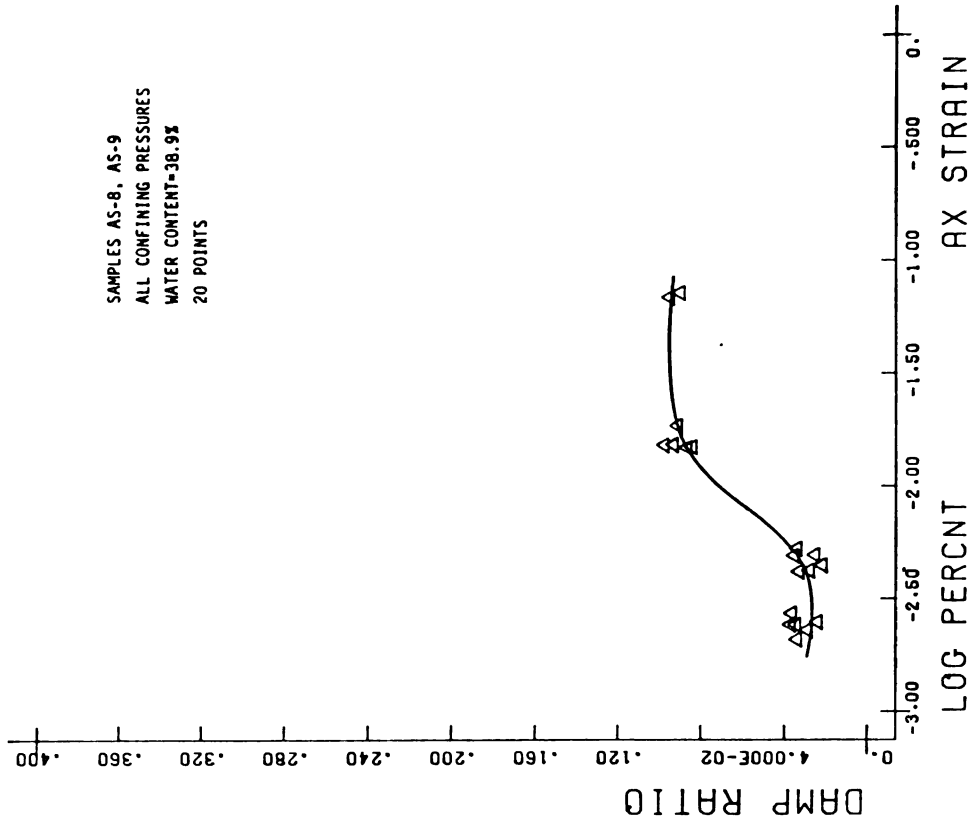


Fig. B-60A-SILTT-4F10

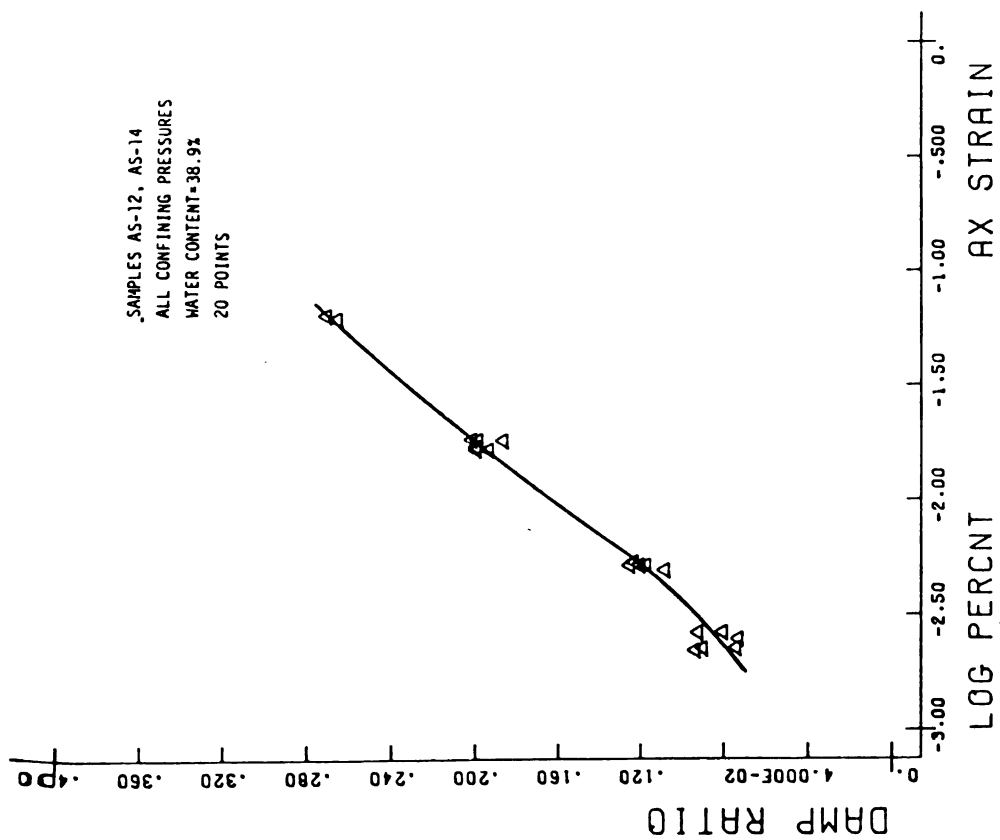


Fig. B-61A-SILTT-10F05

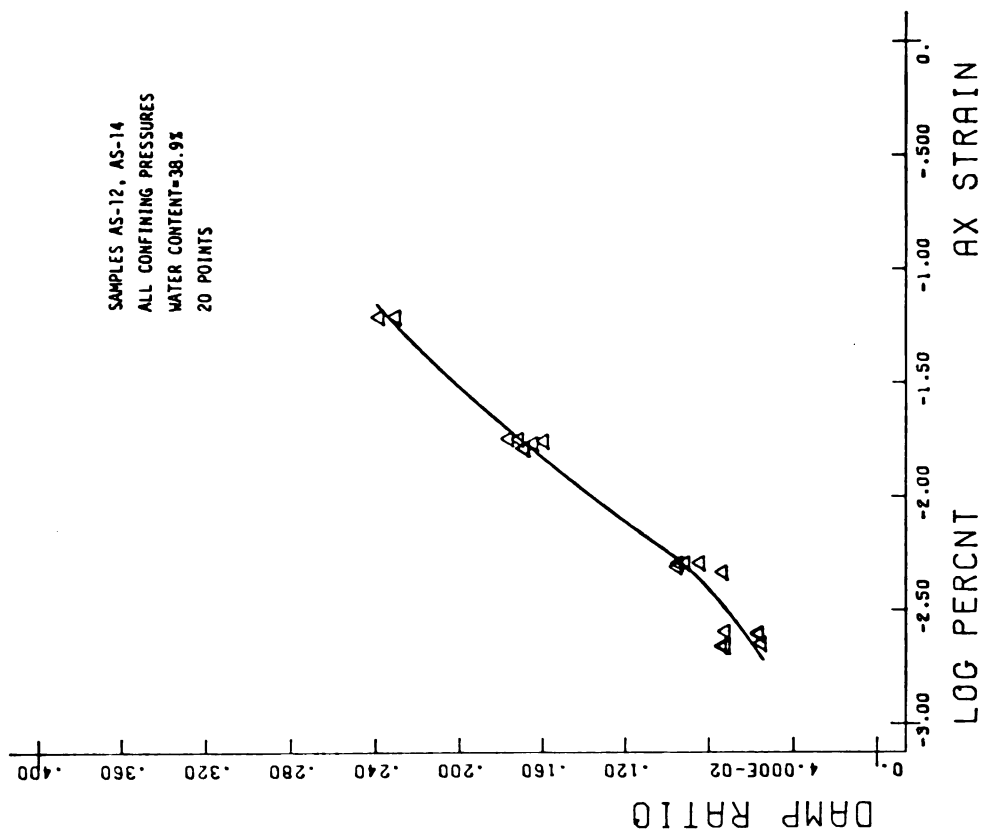


Fig. B-62A-SILTT-10F03

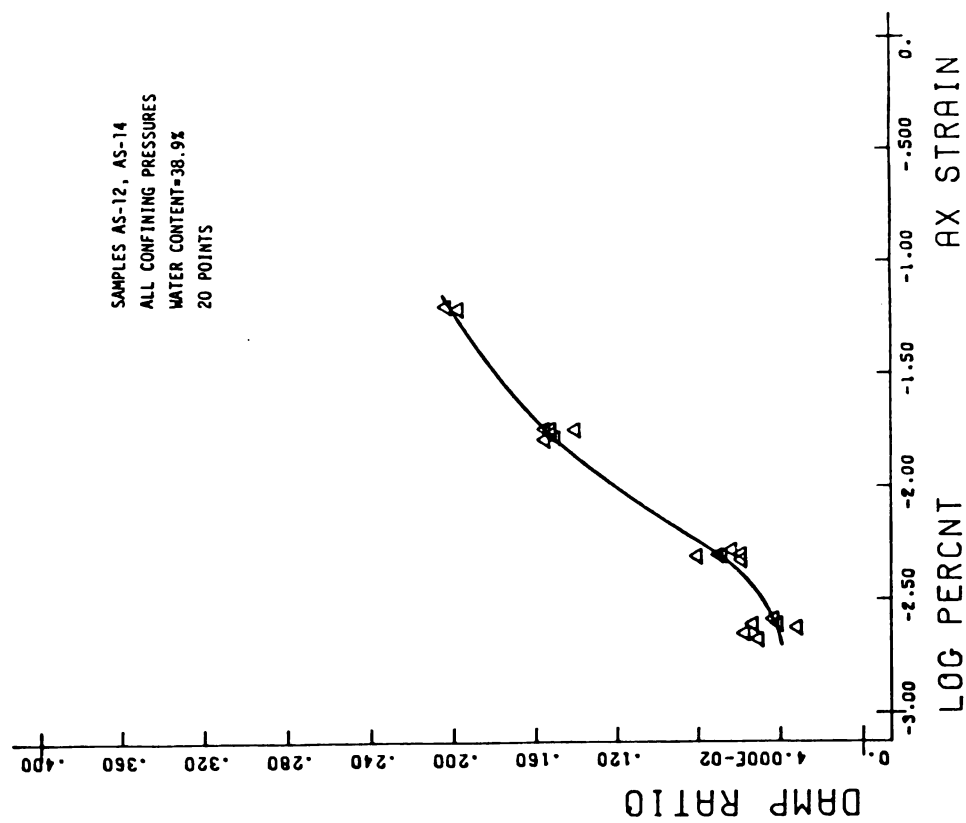


Fig. B-63A-SILTT-10F1

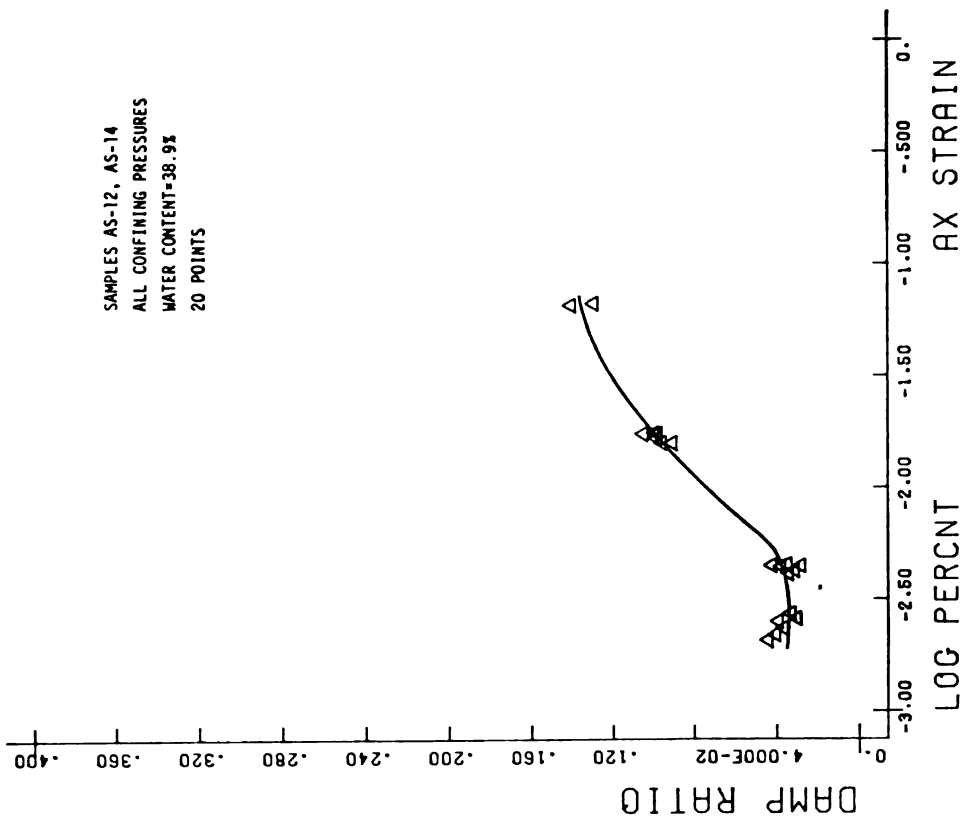


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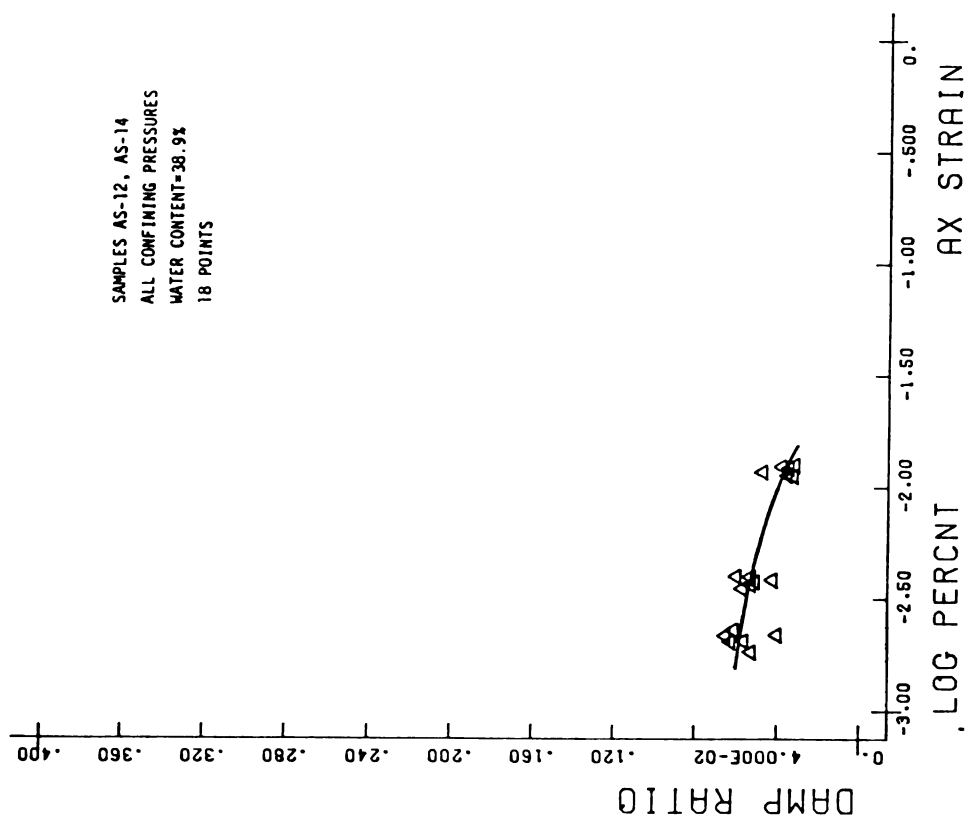


Fig. B-65A-SILTT-10F10

APPENDIX C
CYCLIC TRIAXIAL TEST RESULTS -
DYNAMIC YOUNG'S MODULUS OF FROZEN CLAY

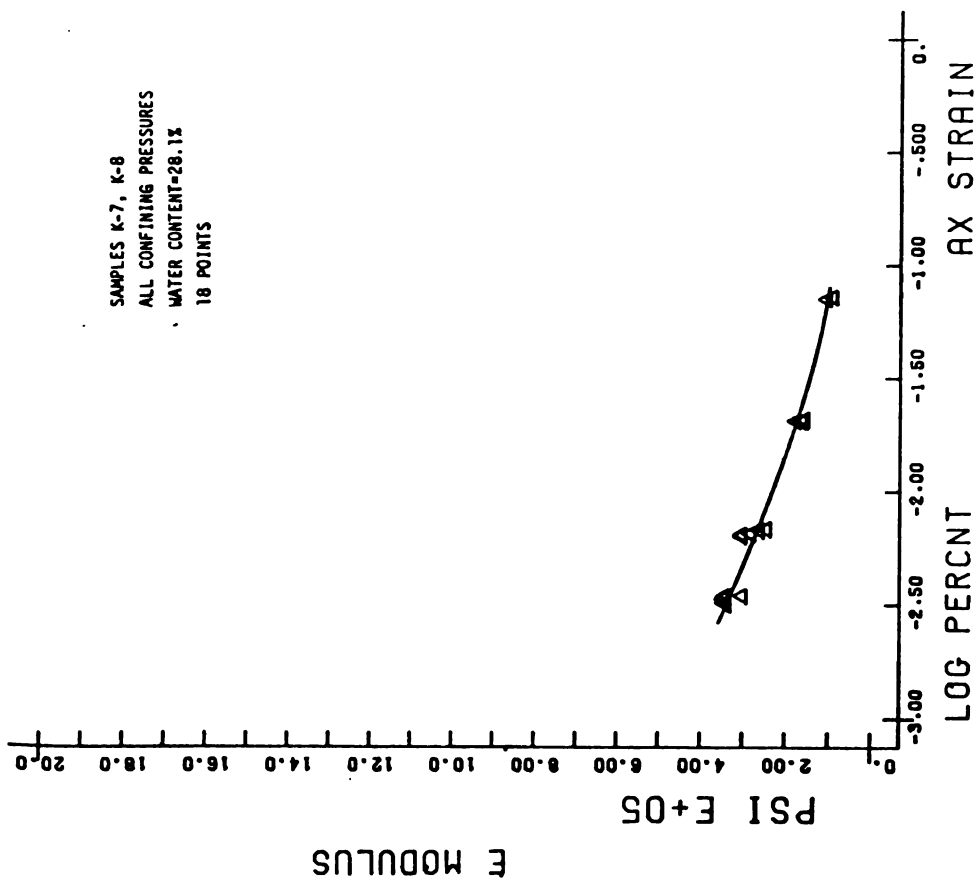


Fig. C-1 K-CLAYT-1F.05

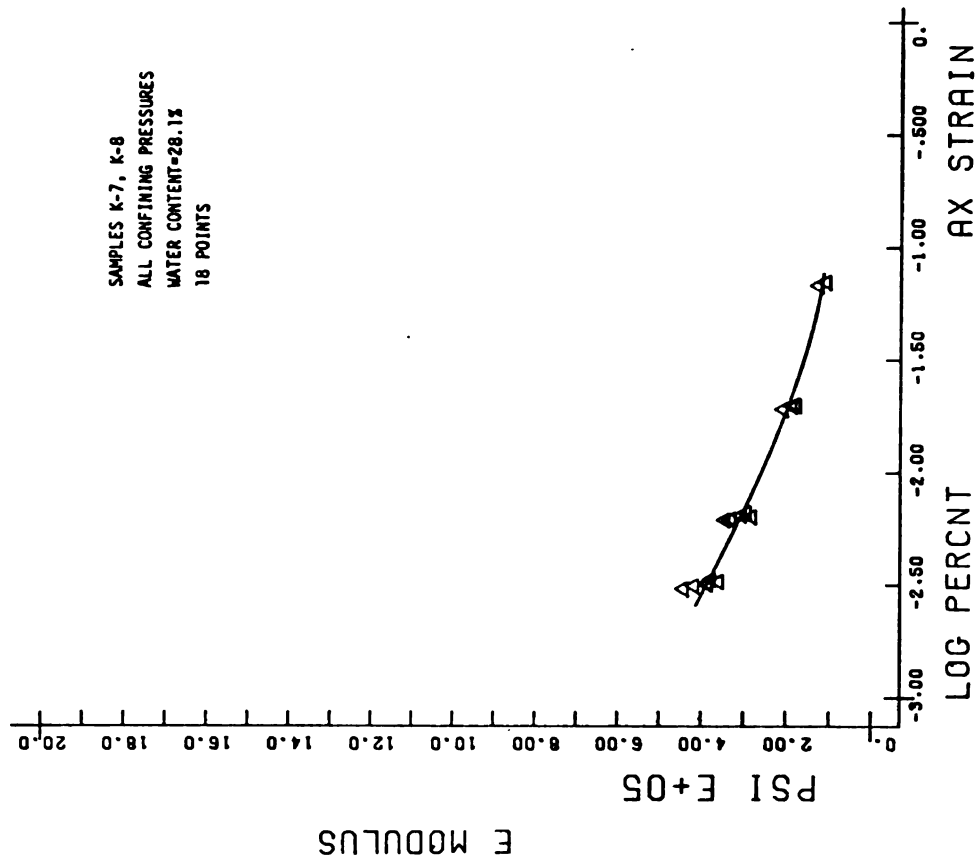


Fig. C-2 K-CLAYT-1F.3

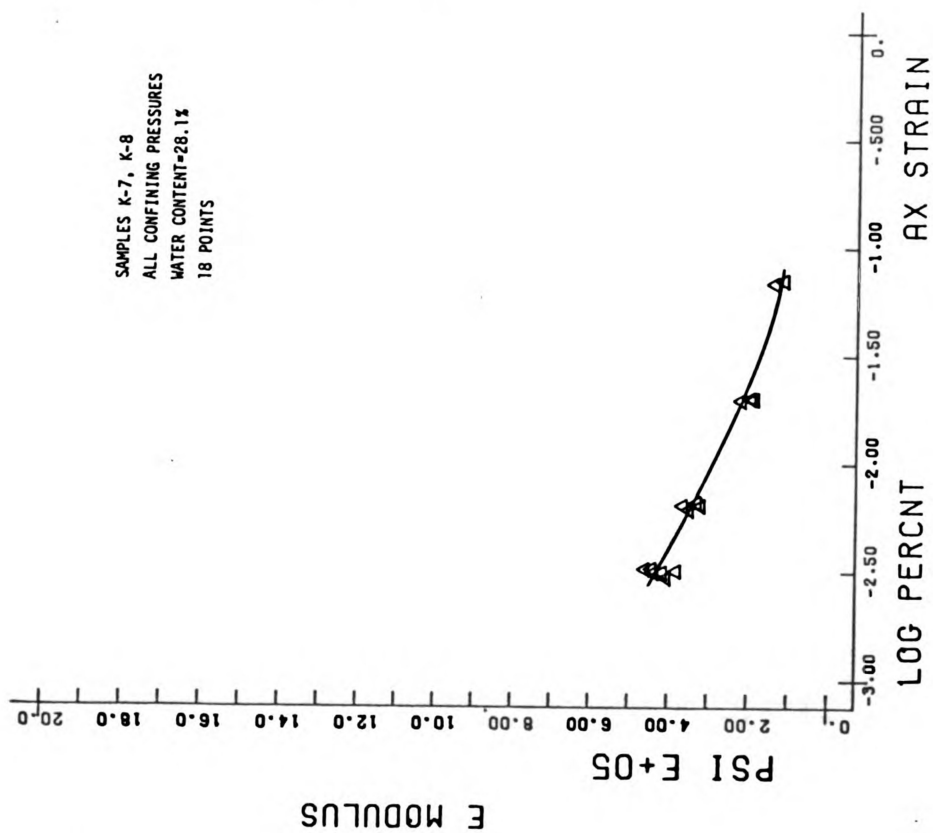


Fig. C-3 K-CLAYT-1F1

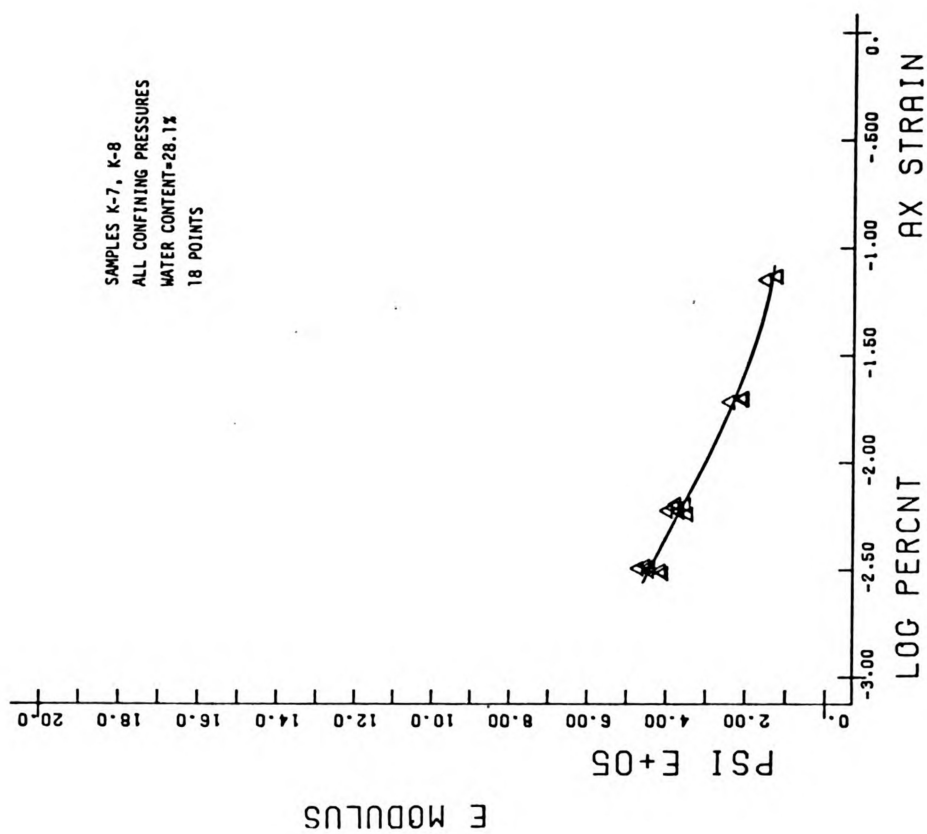


Fig. C-4 K-CLAYT-1F5

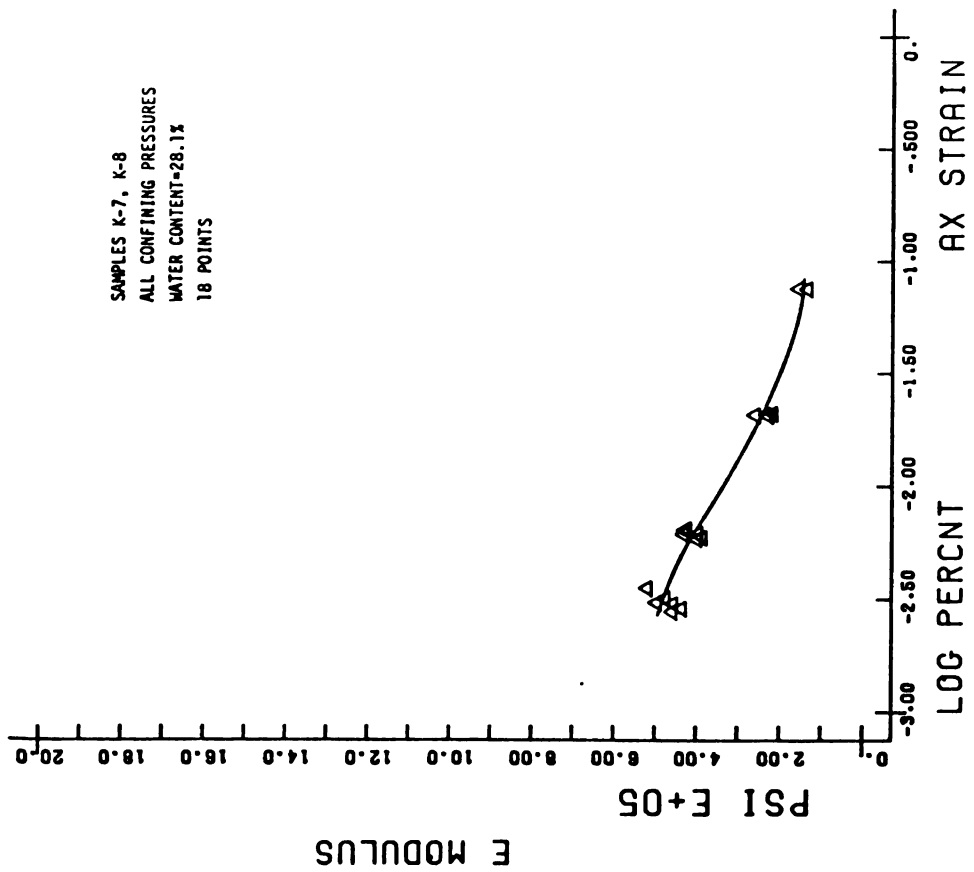


Fig. C-5 K-CLAYT-1F10

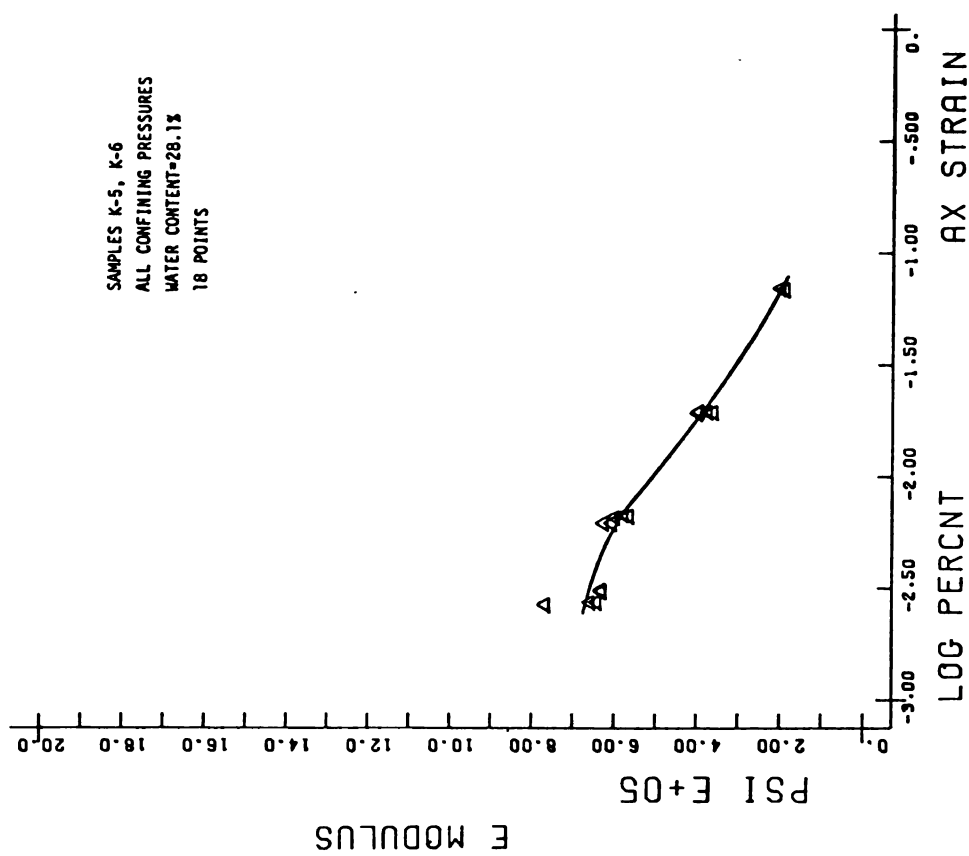


Fig. C-6 K-CLAYT-4F05

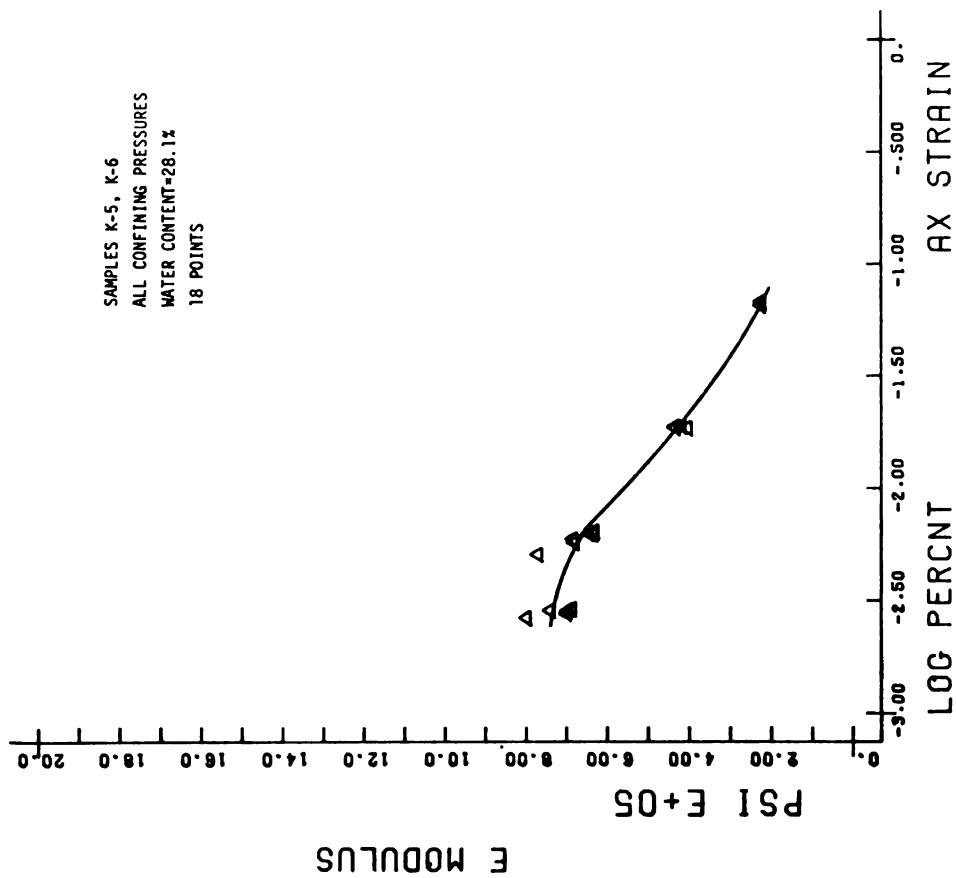


Fig. C-7K-CLAYT-4F3

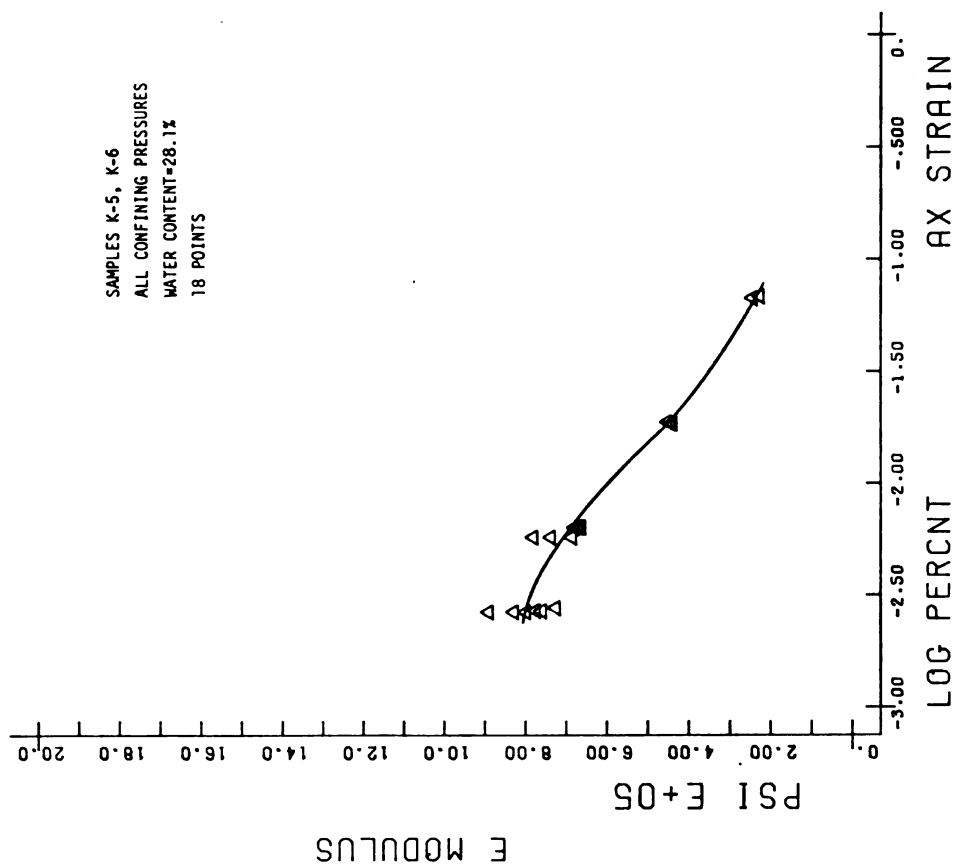


Fig. C-8K-CLAYT-4F1

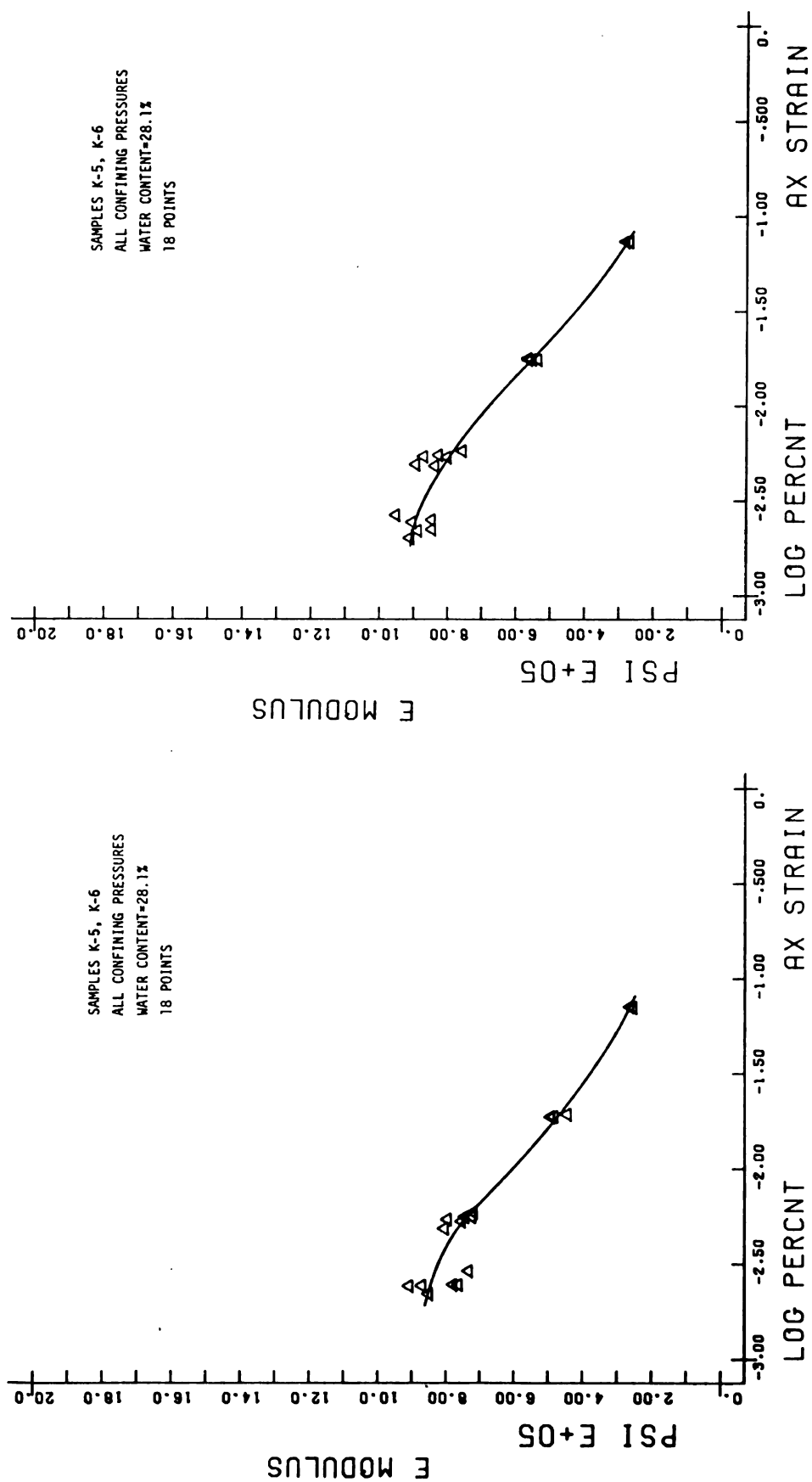


Fig. C-9 K-CLAYT-4F5

Fig. C-10 K-CLAYT-4F10

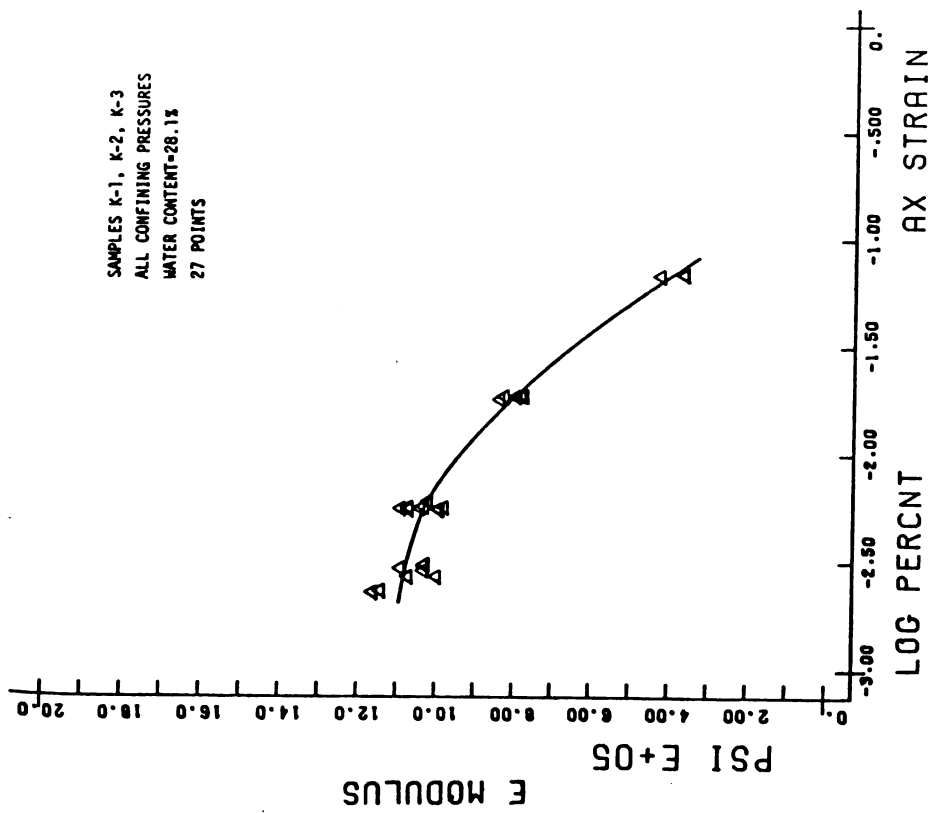


Fig. C-11K-CLAYT-10F.05

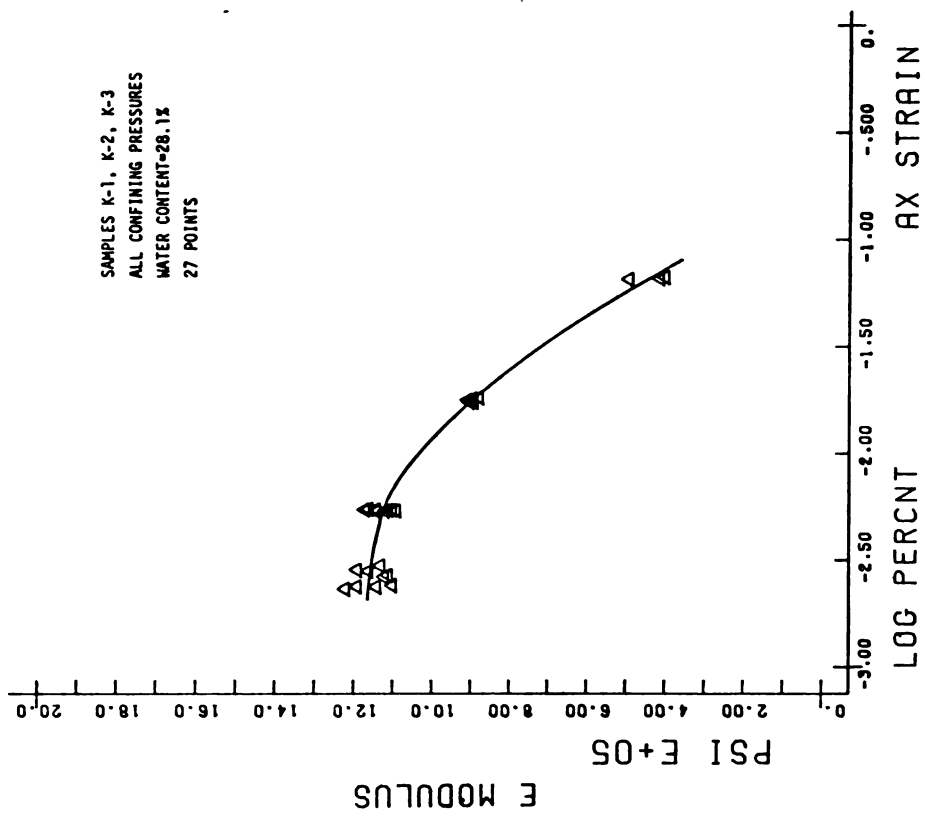


Fig. C-12K-CLAYT-10F.3

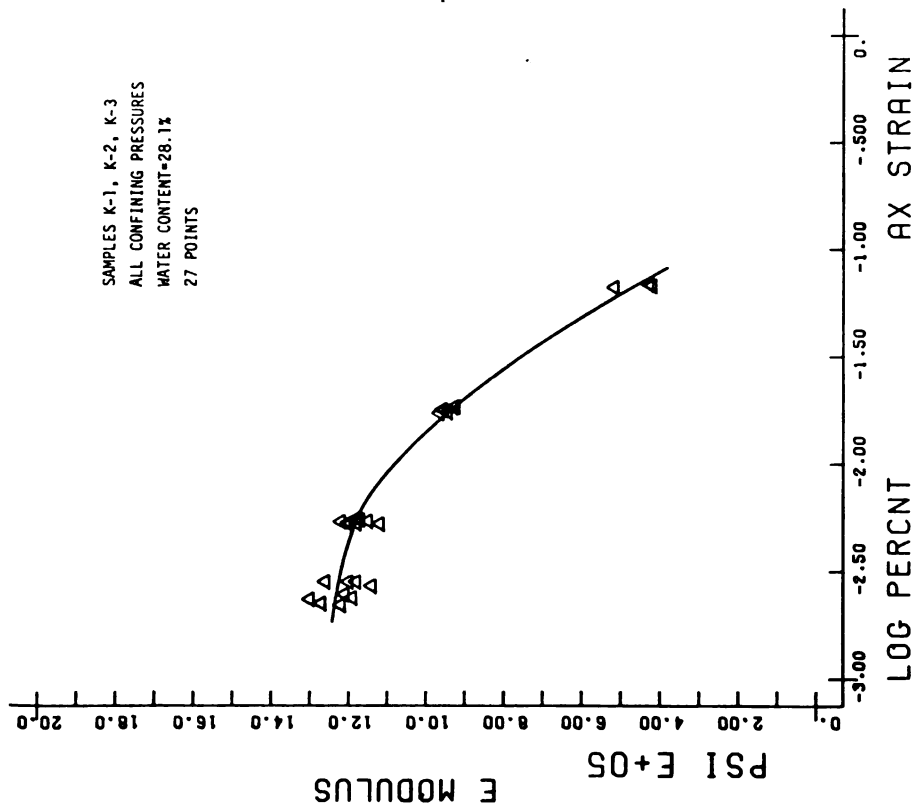


Fig. C-13K-CLAYT-10F1

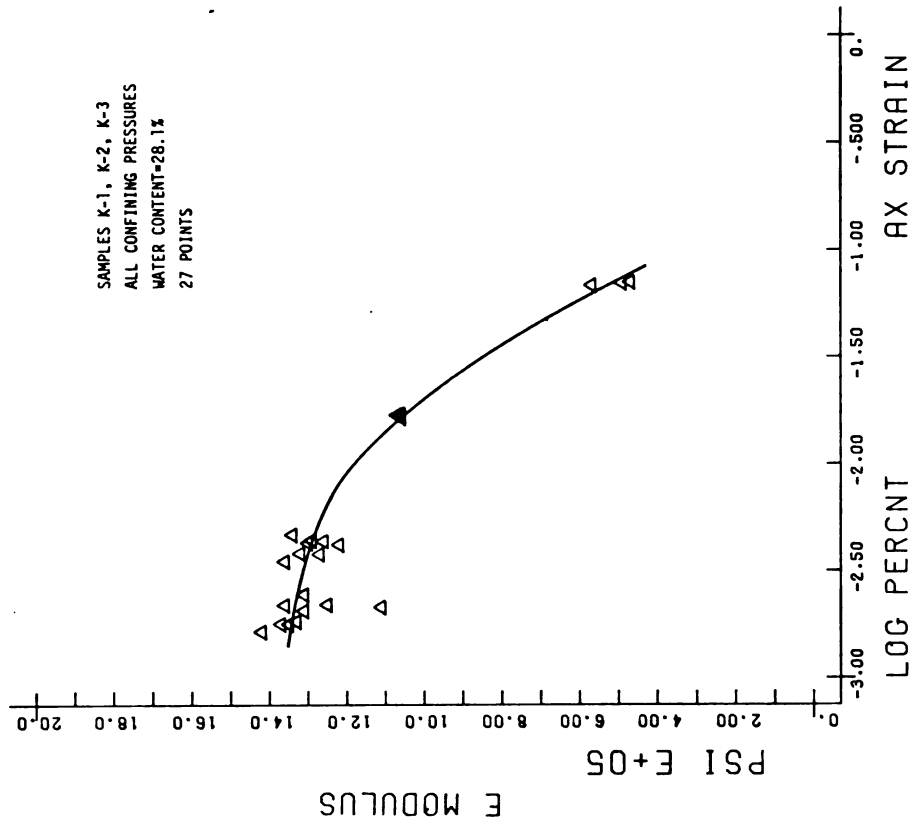


Fig. C-14K-CLAYT-10F5

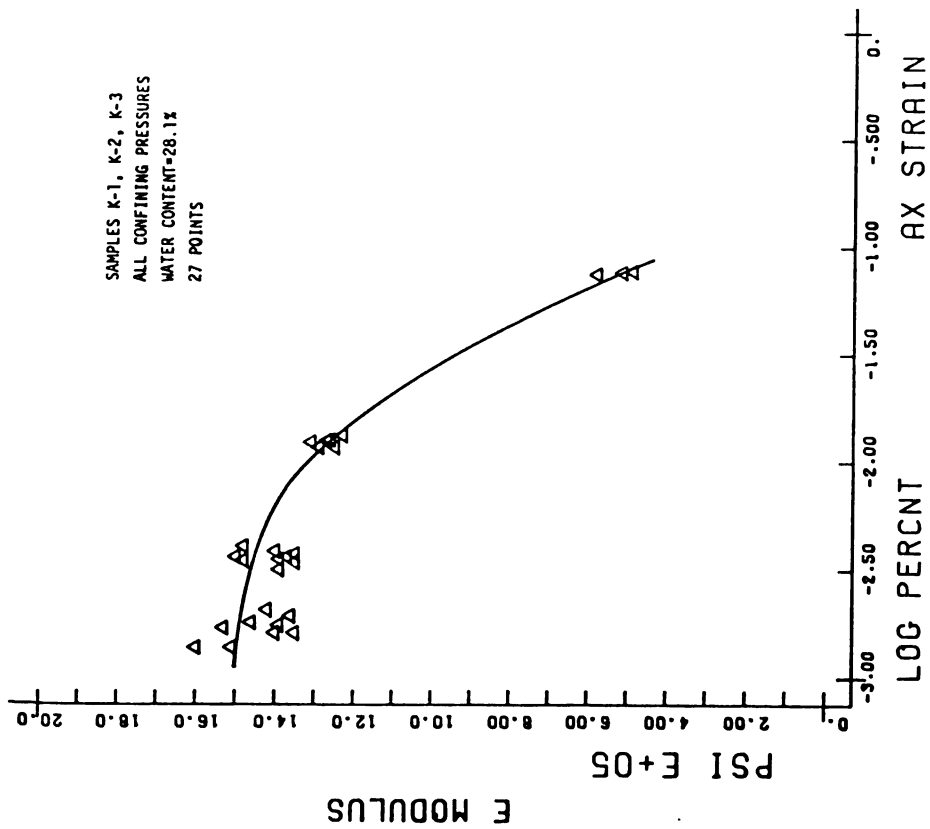


Fig. C-15 K-CLAYT-10F10

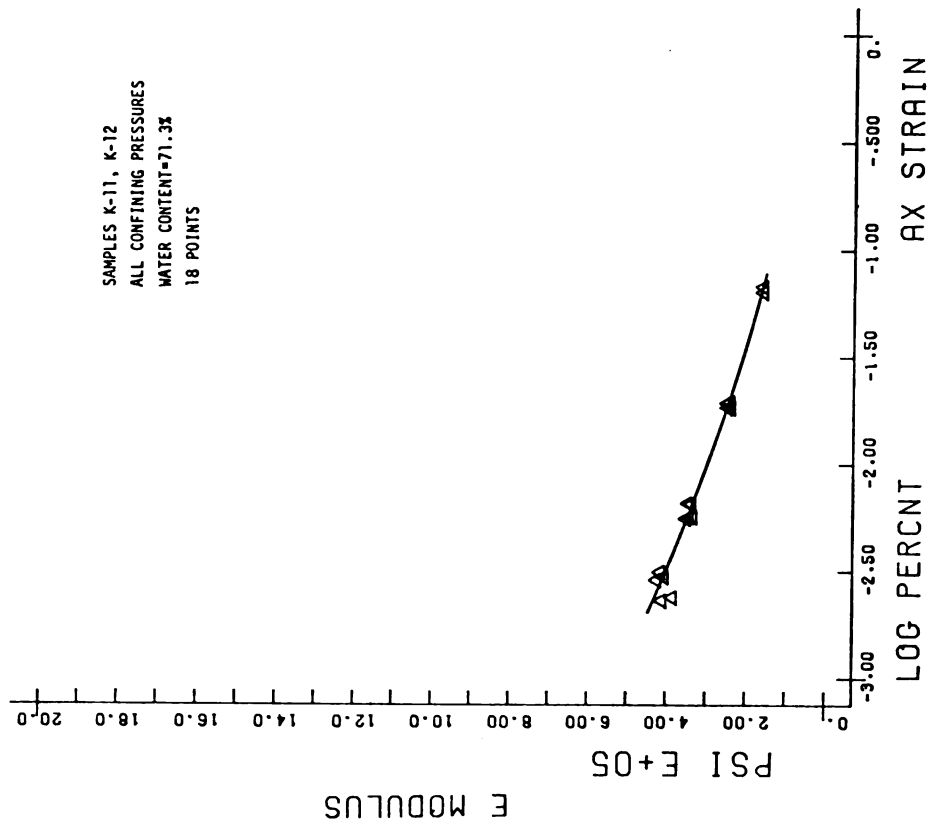


Fig. C-16 K-CLAYT-1F05

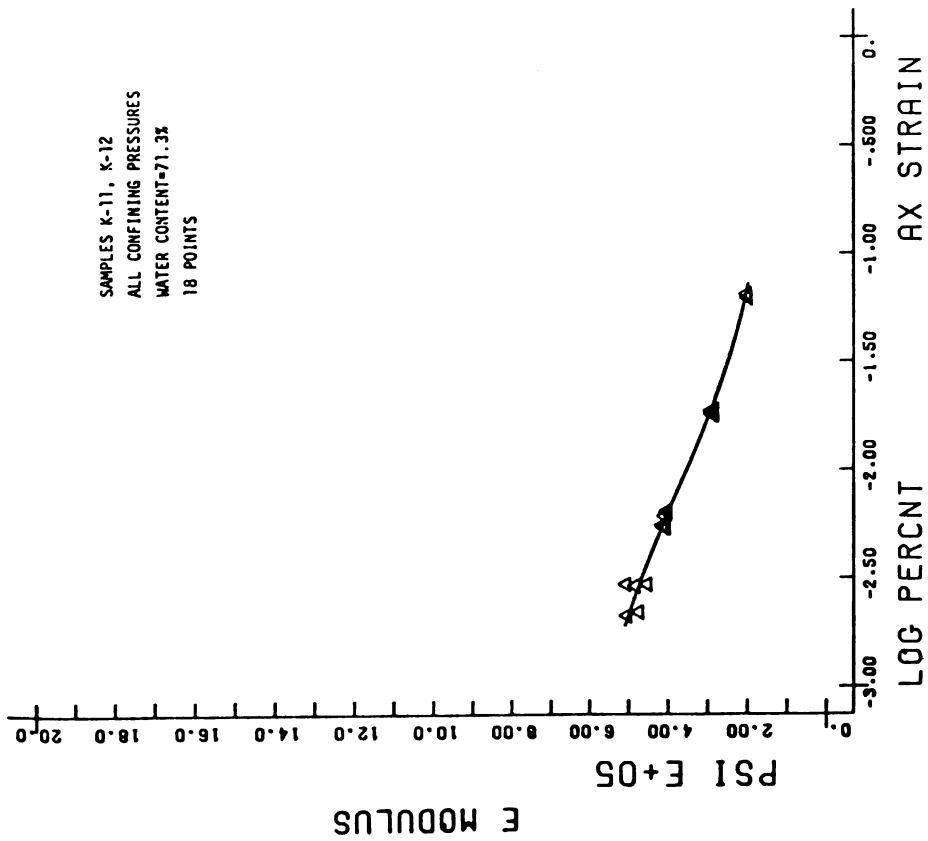


Fig. C-17 K-CLAYT-1F.3

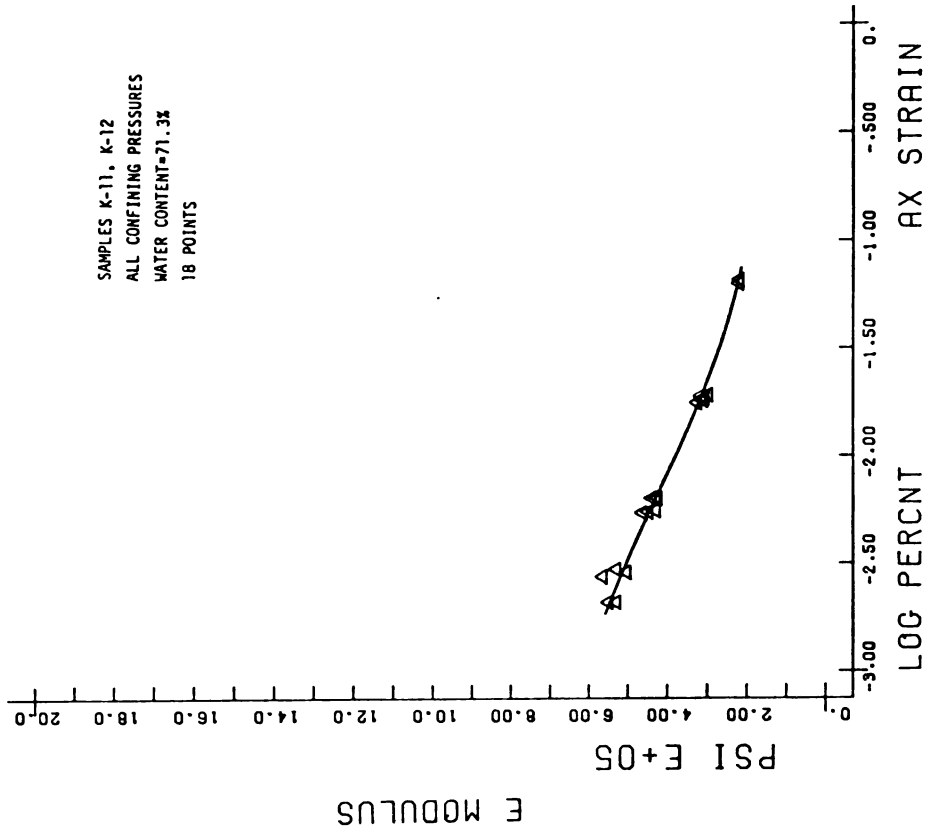


Fig. C-18 K-CLAYT-1F1

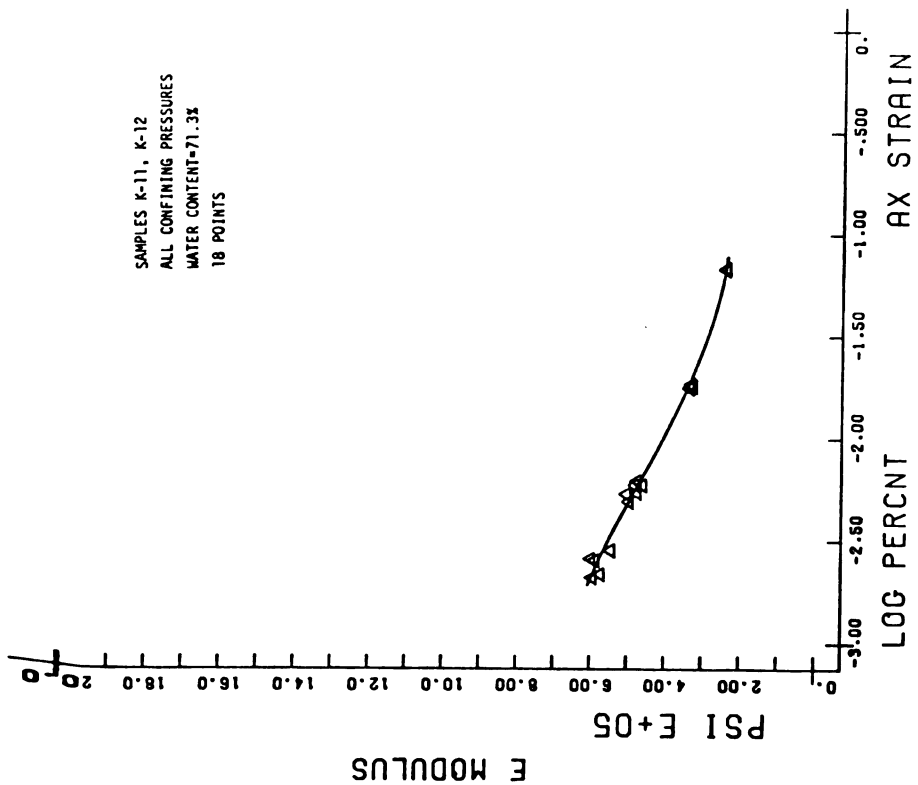


Fig. C-19K-CLAYT-1F5

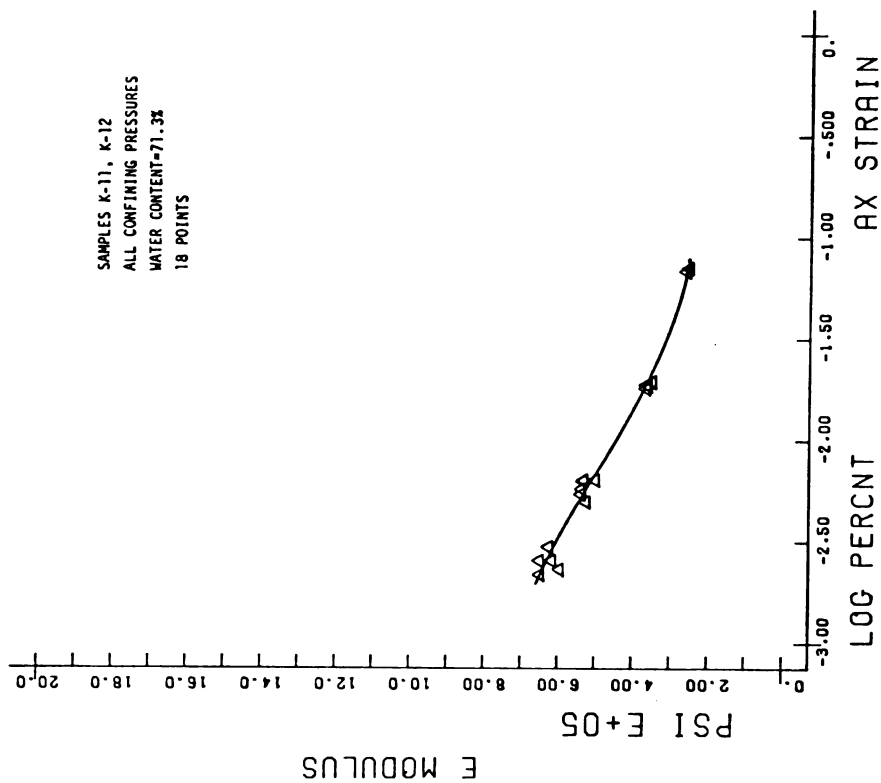


Fig. C-20K-CLAYT-1F10

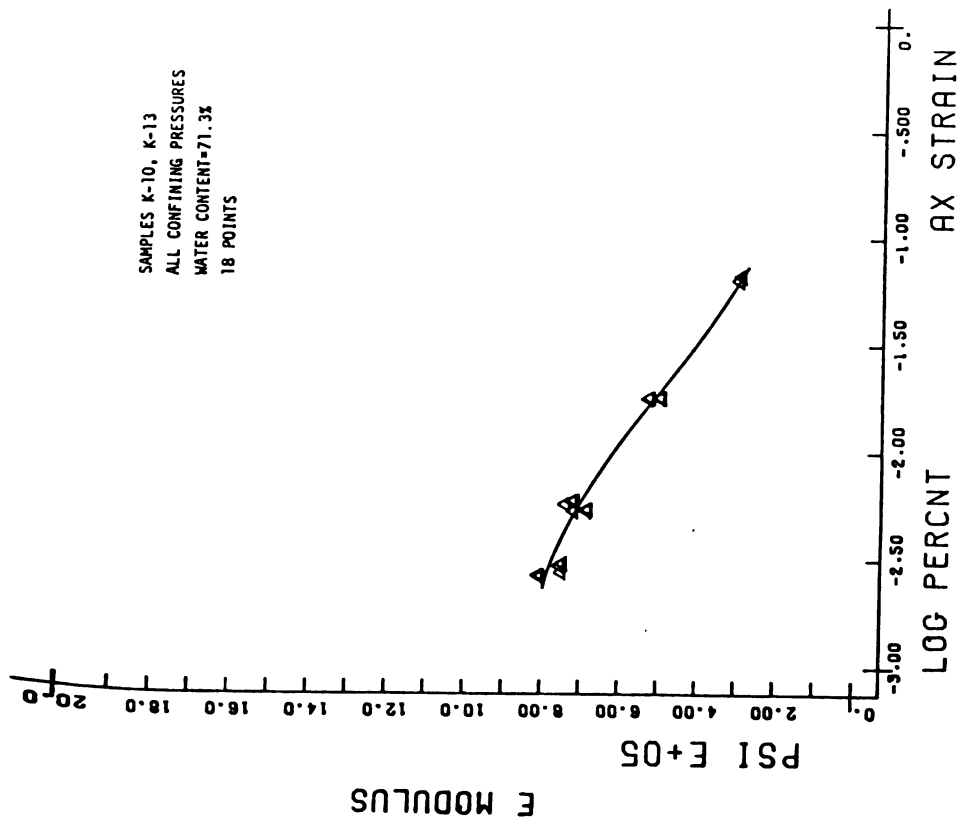


Fig. C-21 K-CLAYT-4F.05

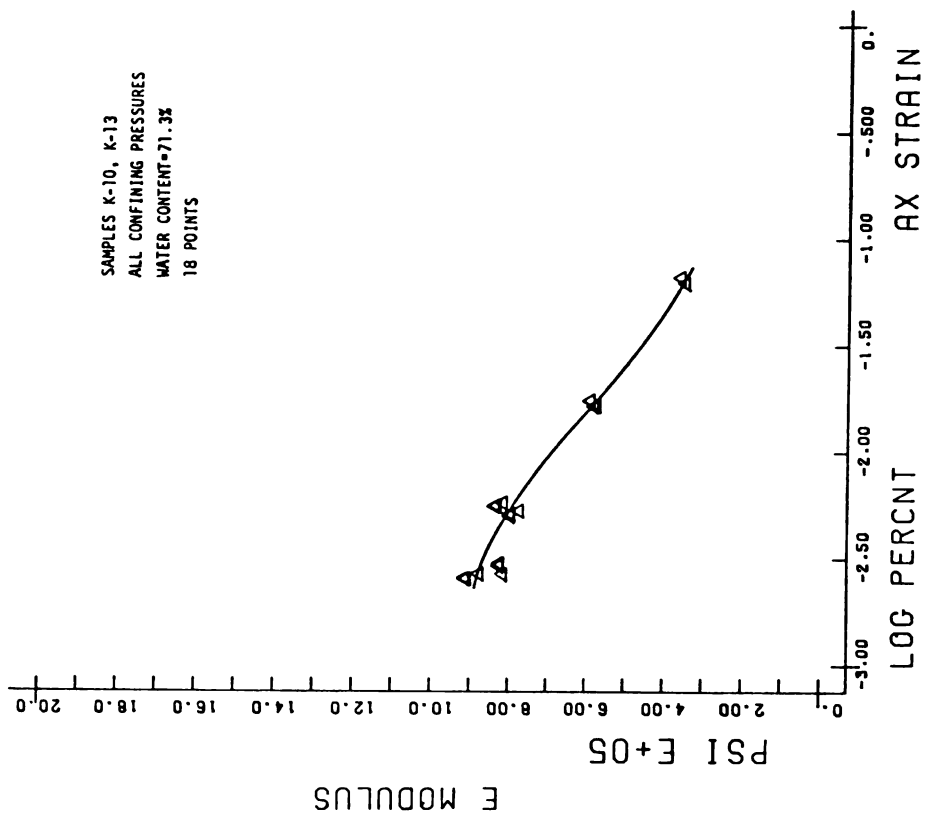


Fig. C-22 K-CLAYT-4F.3

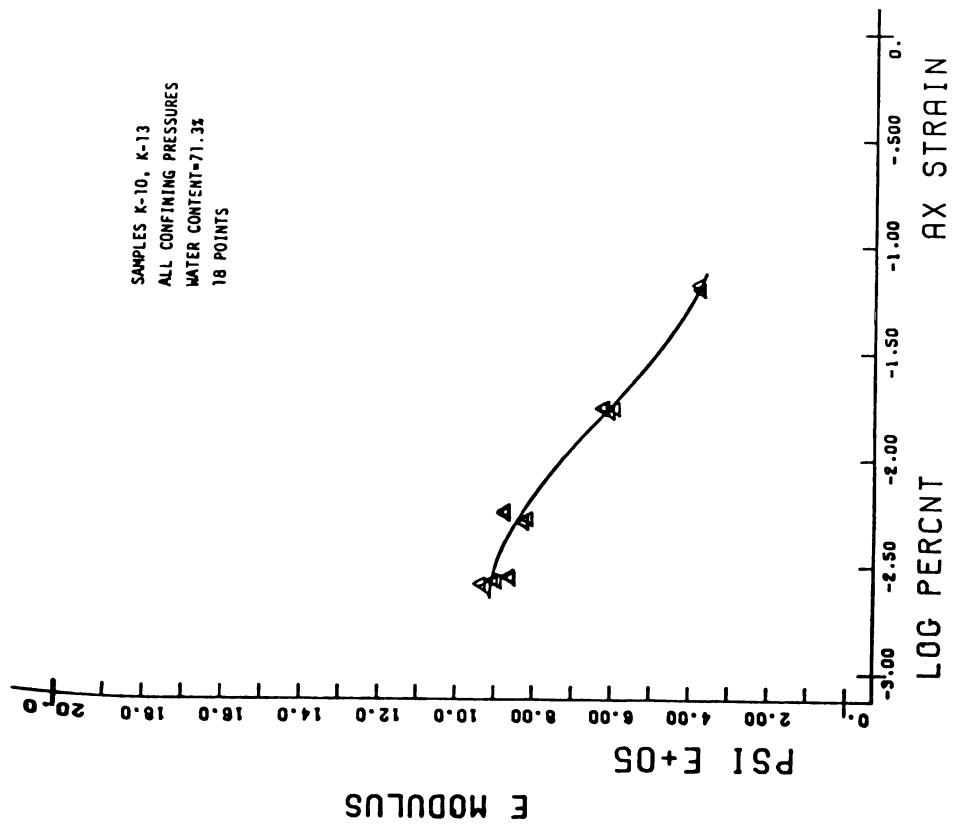


Fig. C-23 K-CLAYT-4F1

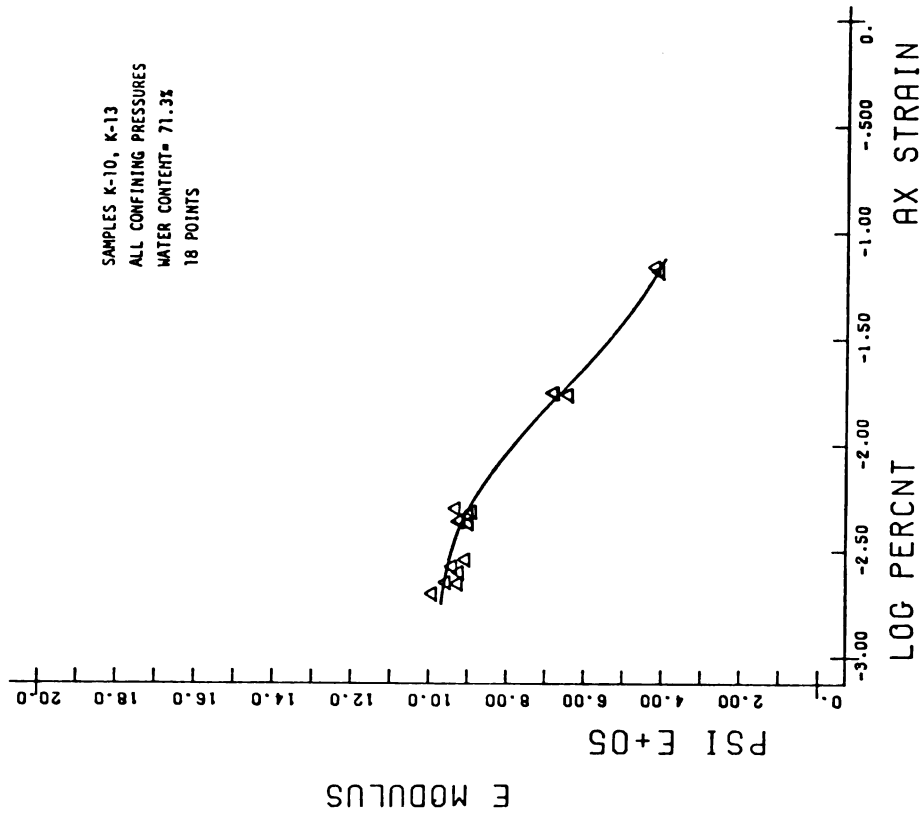


Fig. C-24 K-CLAYT-4F5

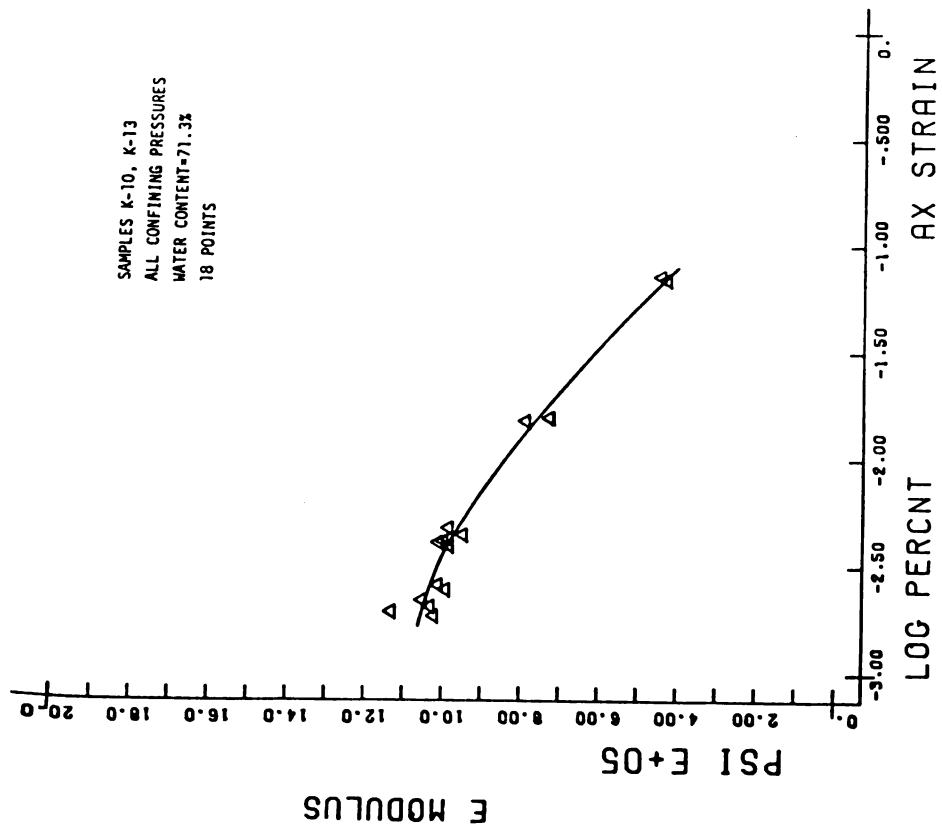


Fig. C-25 K-CLAYT-4F10

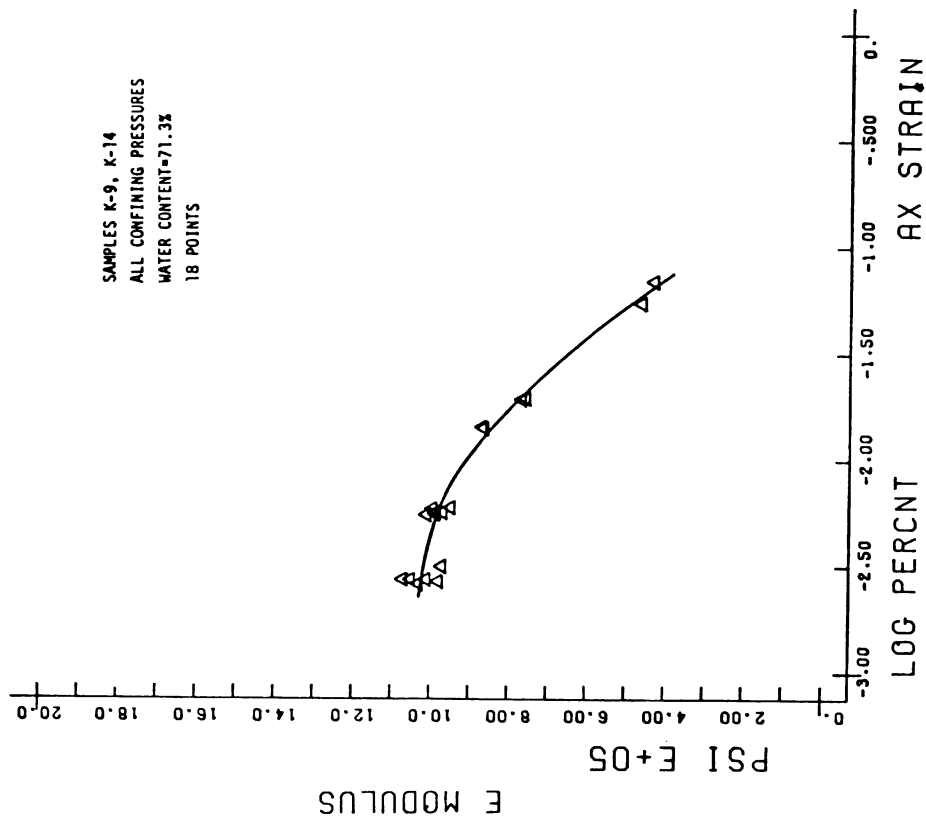


Fig. C-26 K-CLAYT-10F05

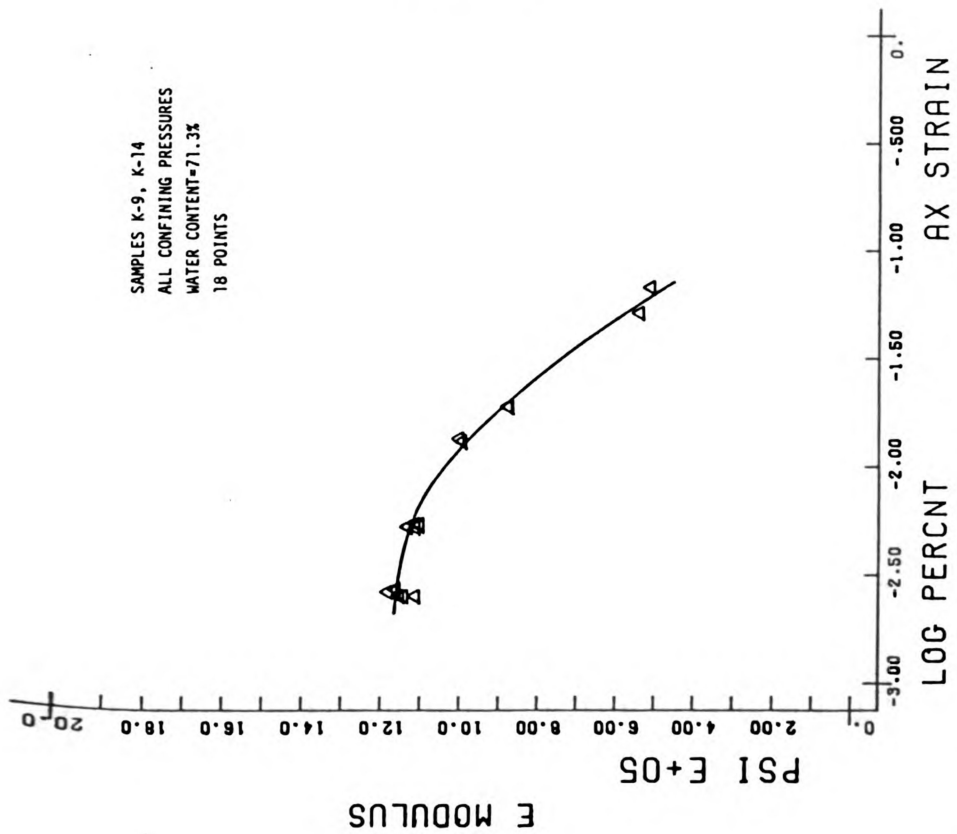


Fig. C-27K-CLAYT-10F.3

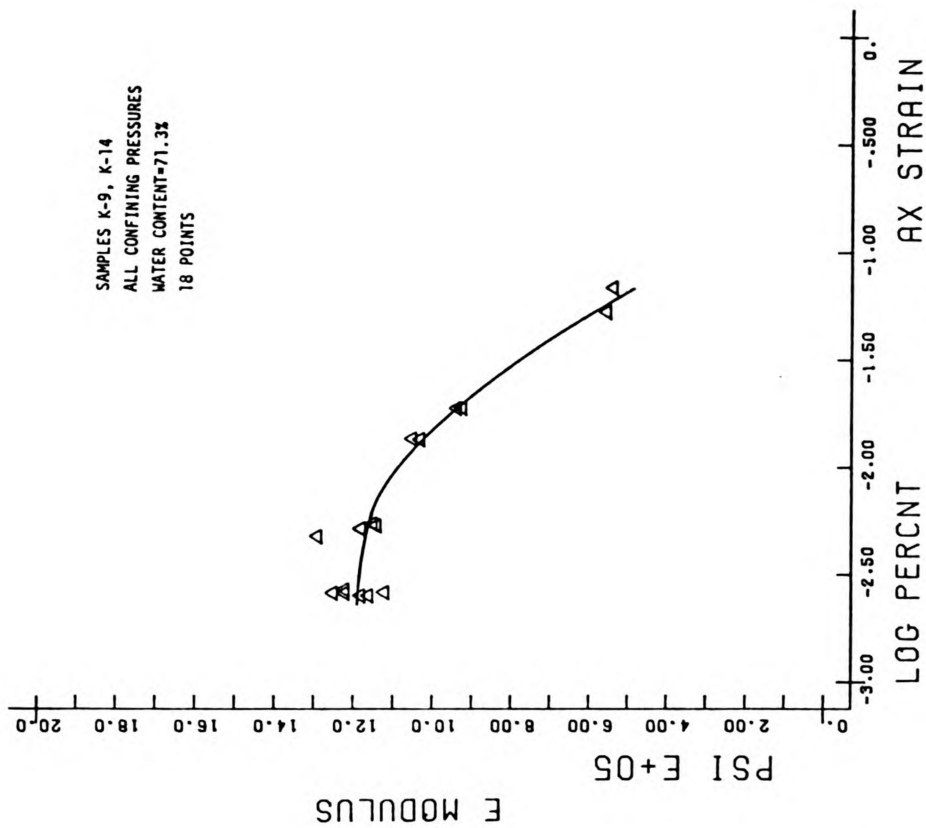


Fig. C-28K-CLAYT-10F1

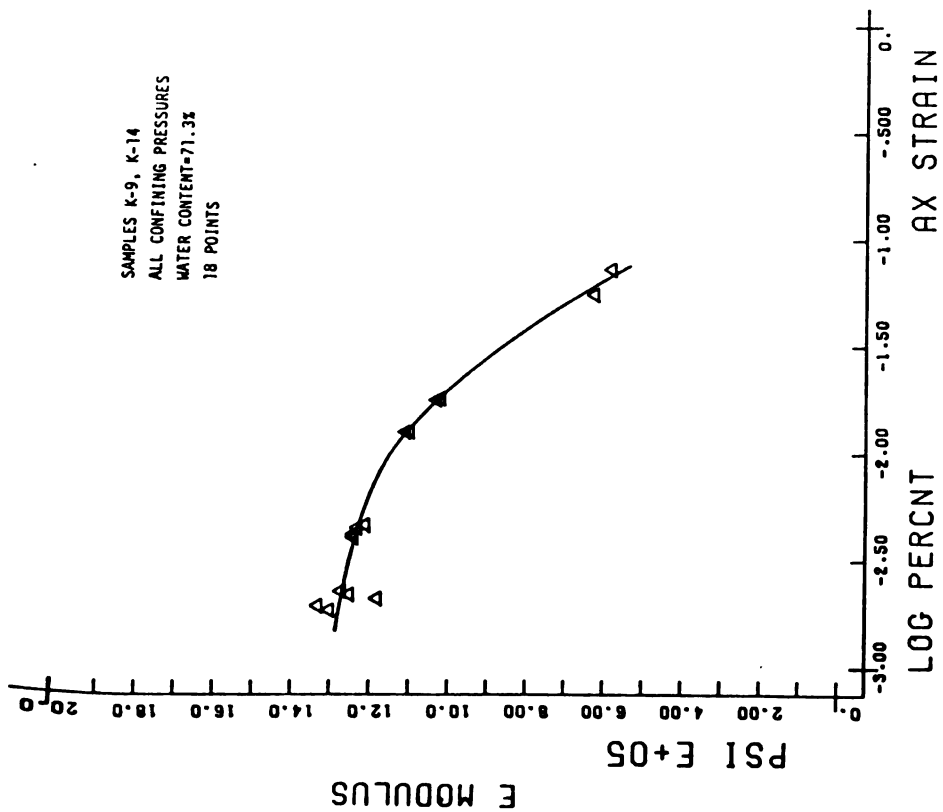


Fig. c-29K-CLAYT-10F5

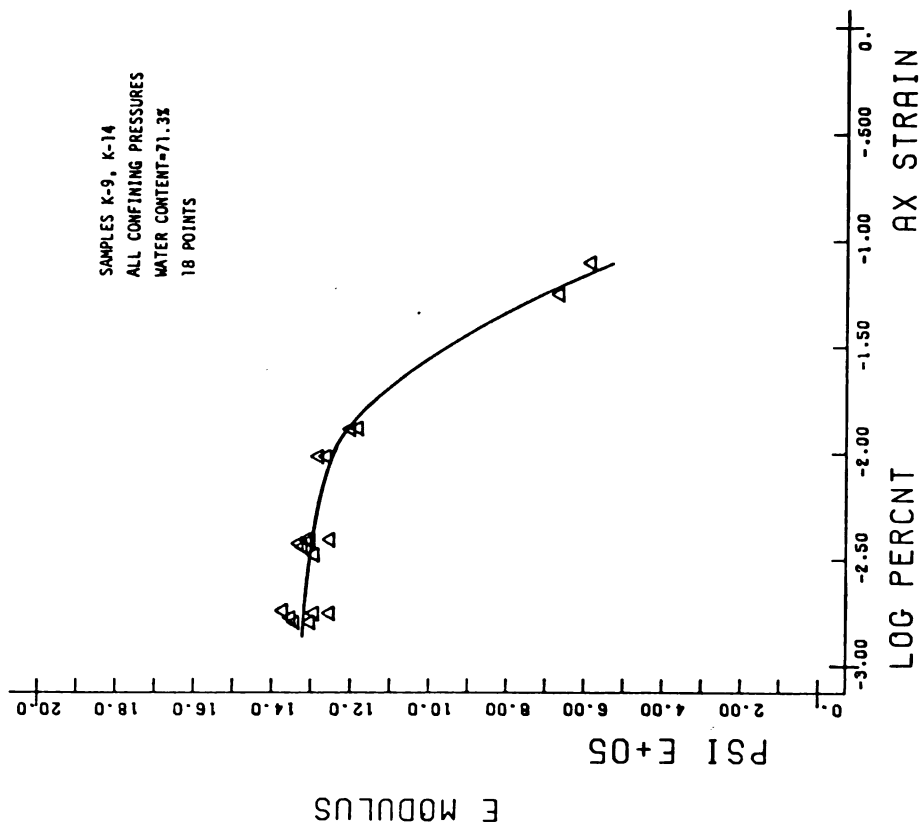


Fig. c-30K-CLAYT-10F10

APPENDIX D
CYCLIC TRIAXIAL TEST RESULTS -
DAMPING RATIO OF FROZEN CLAY

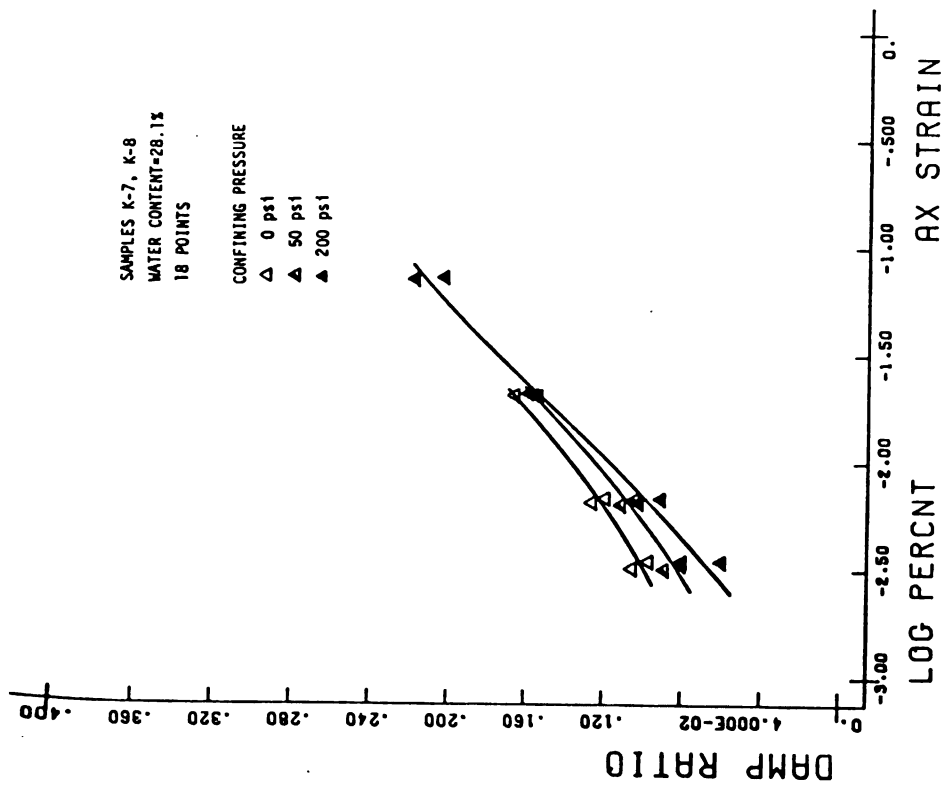


Fig. D-1 K-CLAYT-1F05

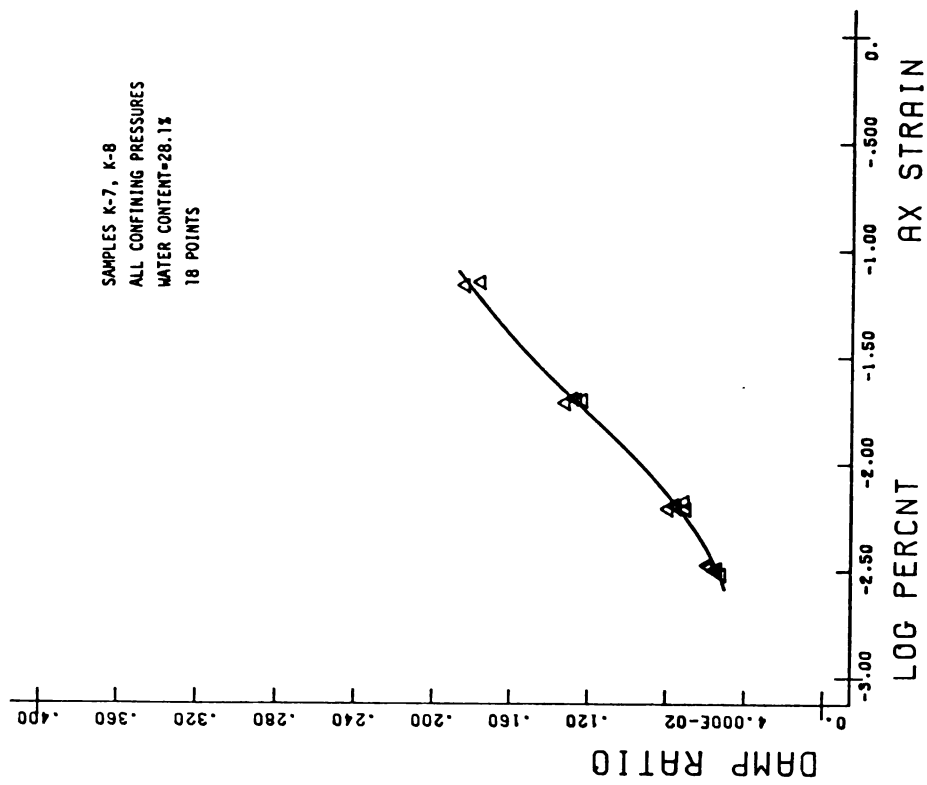


Fig. D-2 K-CLAYT-1F3

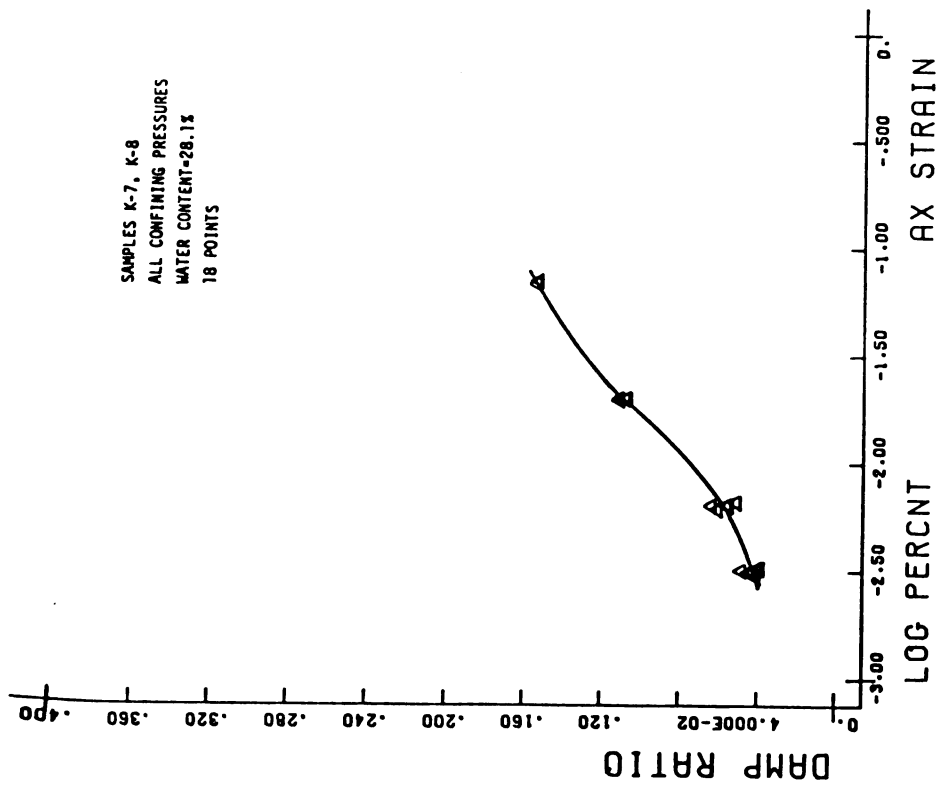


Fig. D-3 K-CLAYT-1F1

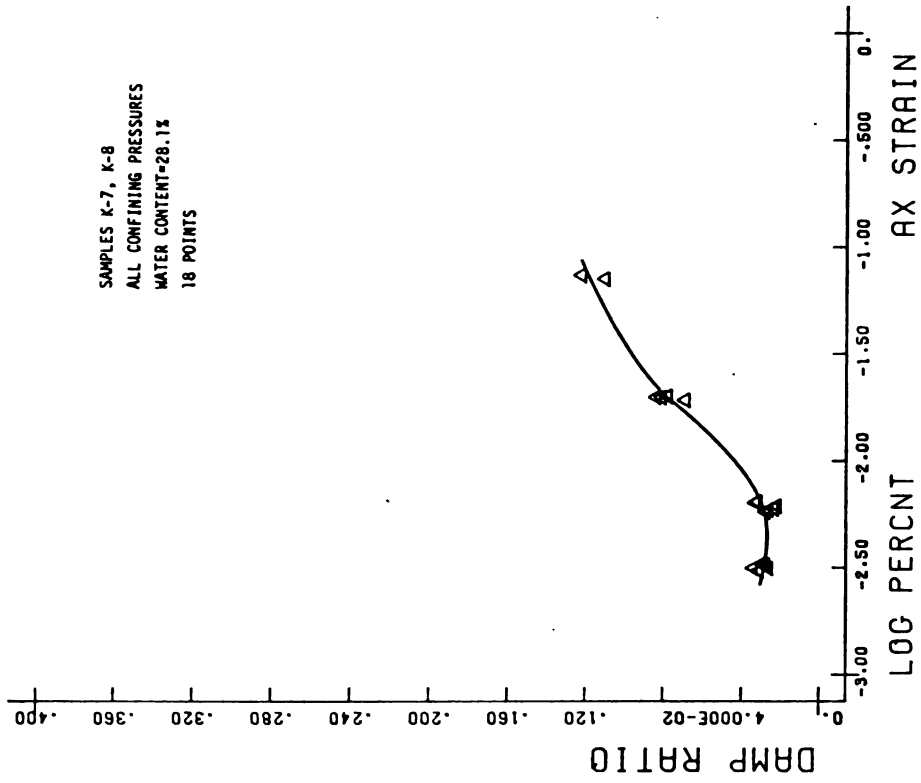


Fig. D-4 K-CLAYT-1F5

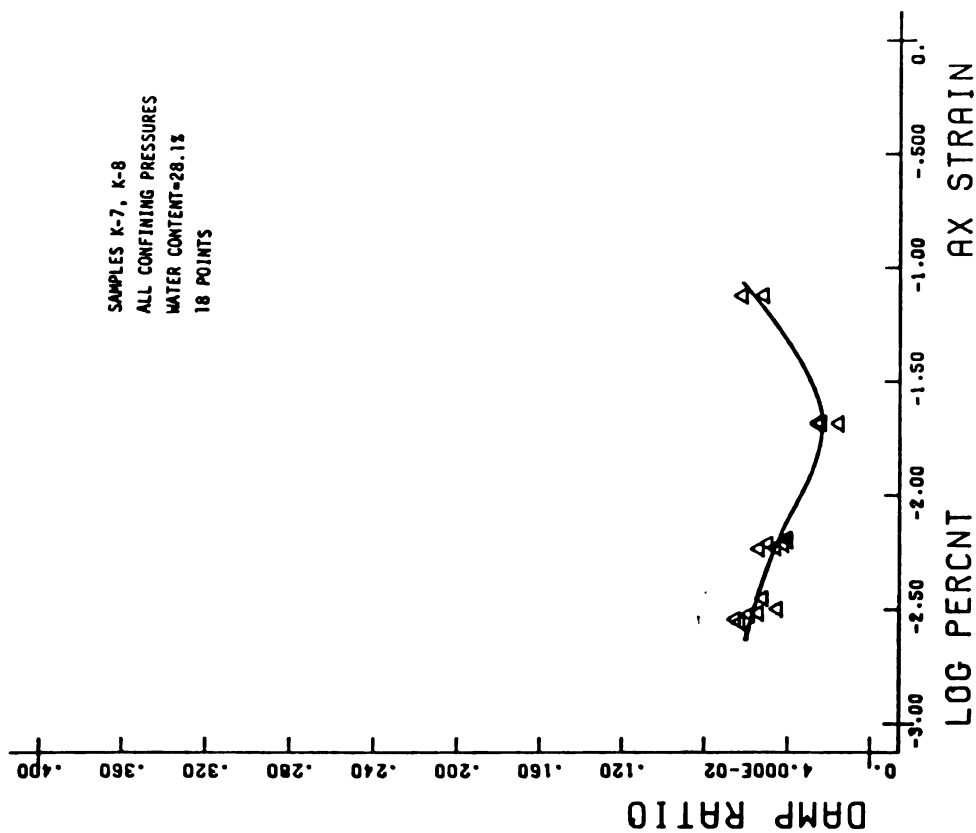


Fig. D-5 K-CLAYT-1F10

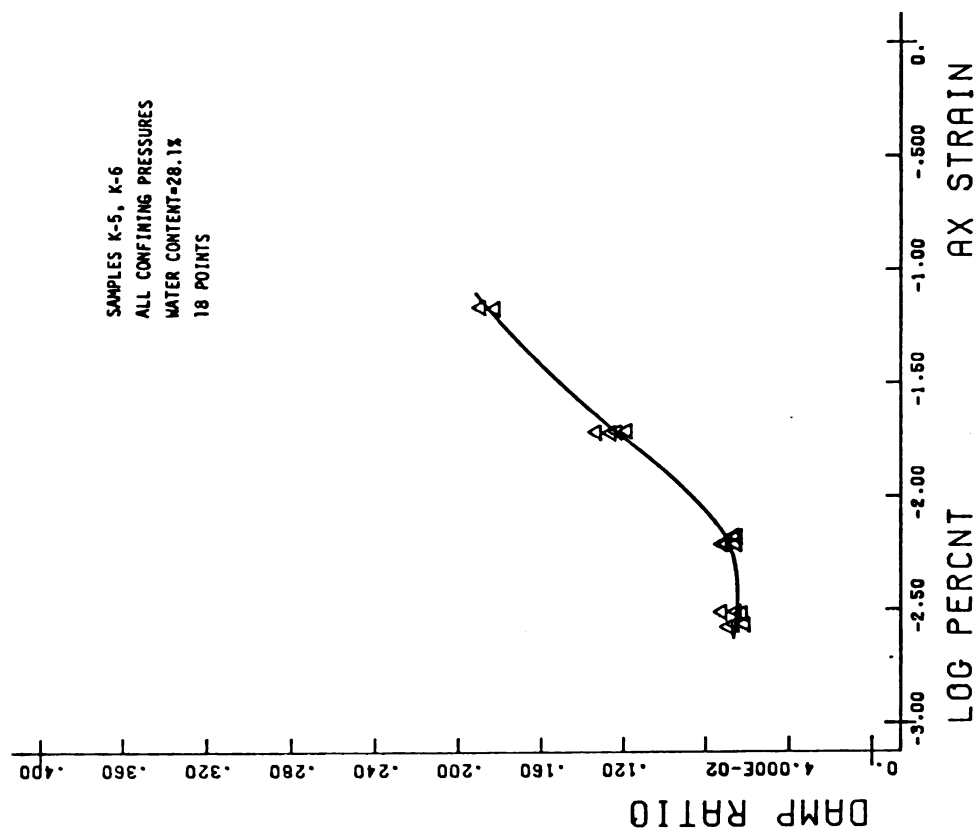


Fig. D-6 K-CLAYT-4F05

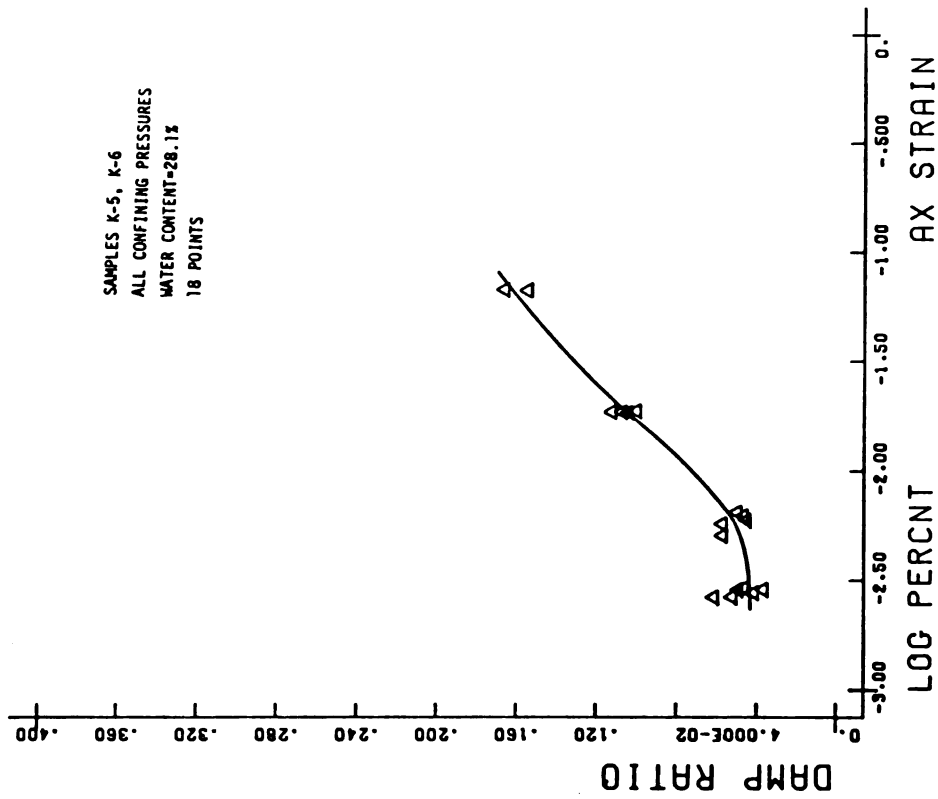


Fig. D-7 K-CLAYT-4F.3

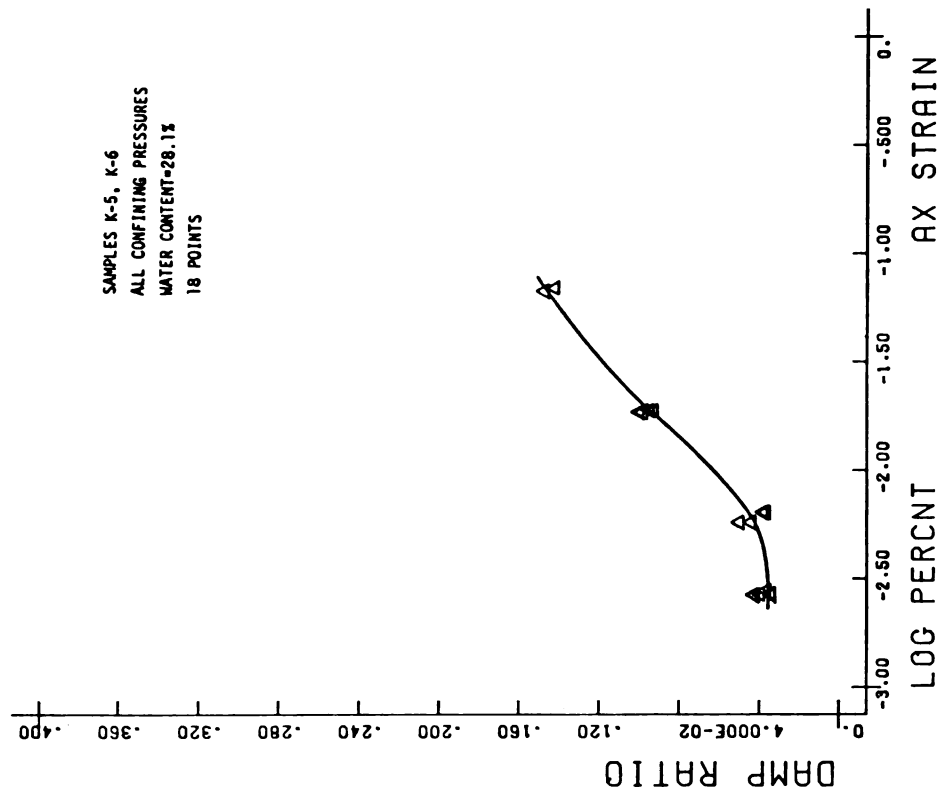


Fig. D-8 K-CLAYT-4F1

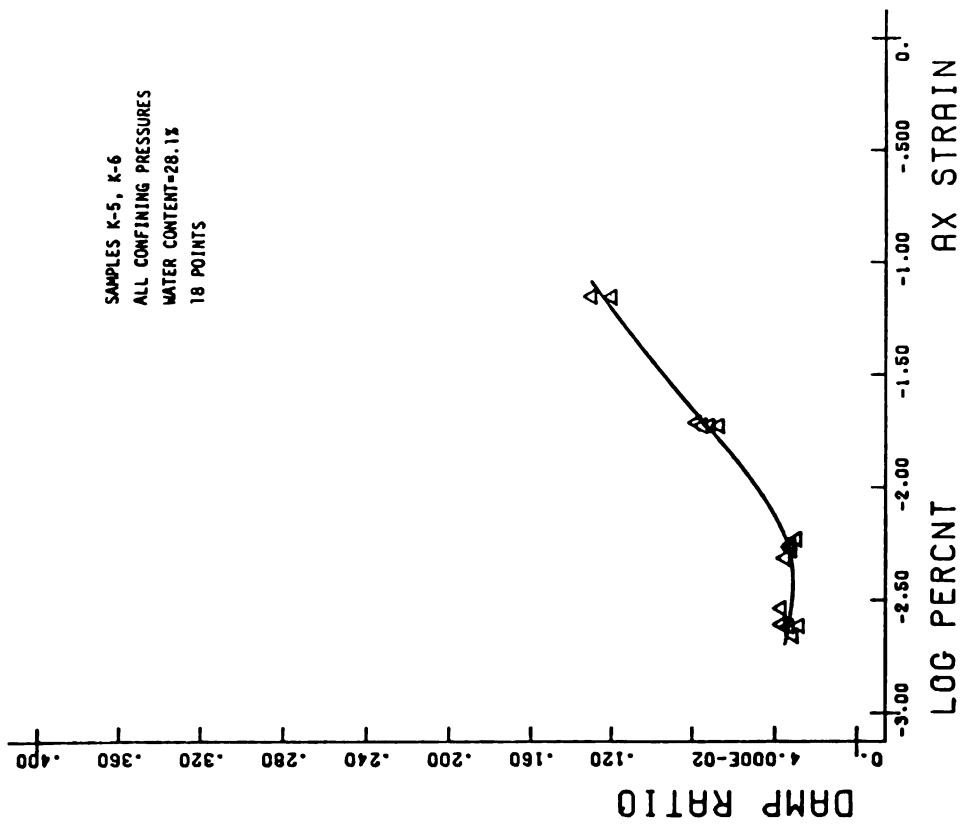


Fig. D-9 K-CLAYT-4F5

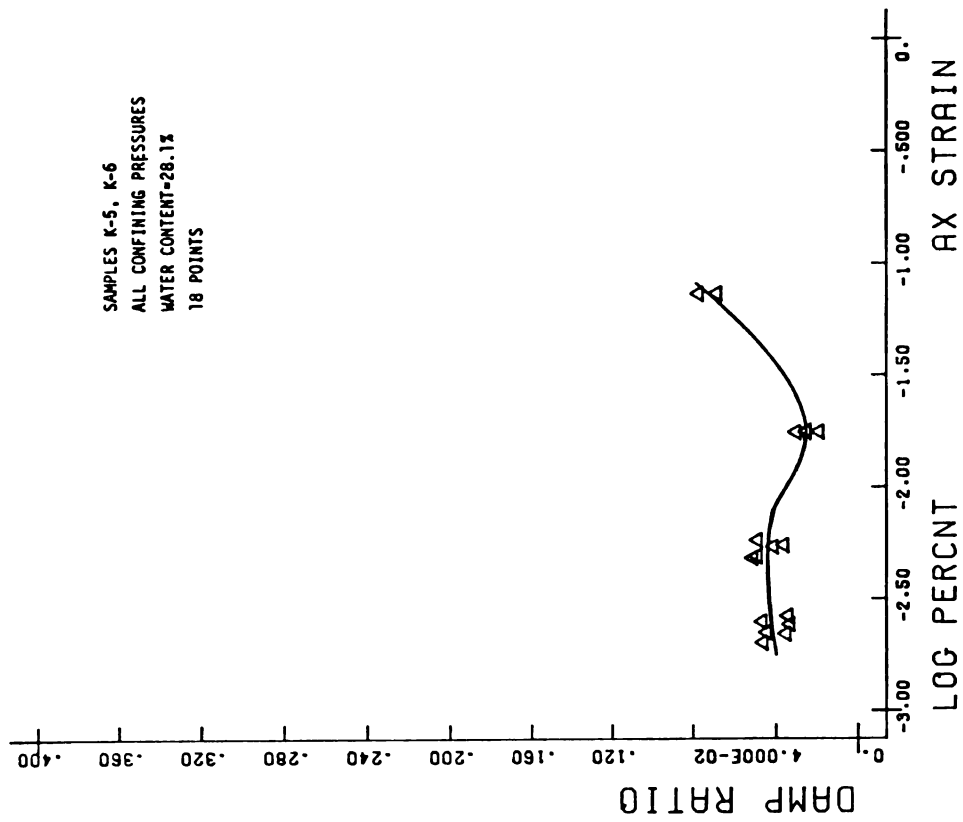


Fig. D-10 K-CLAYT-4F10

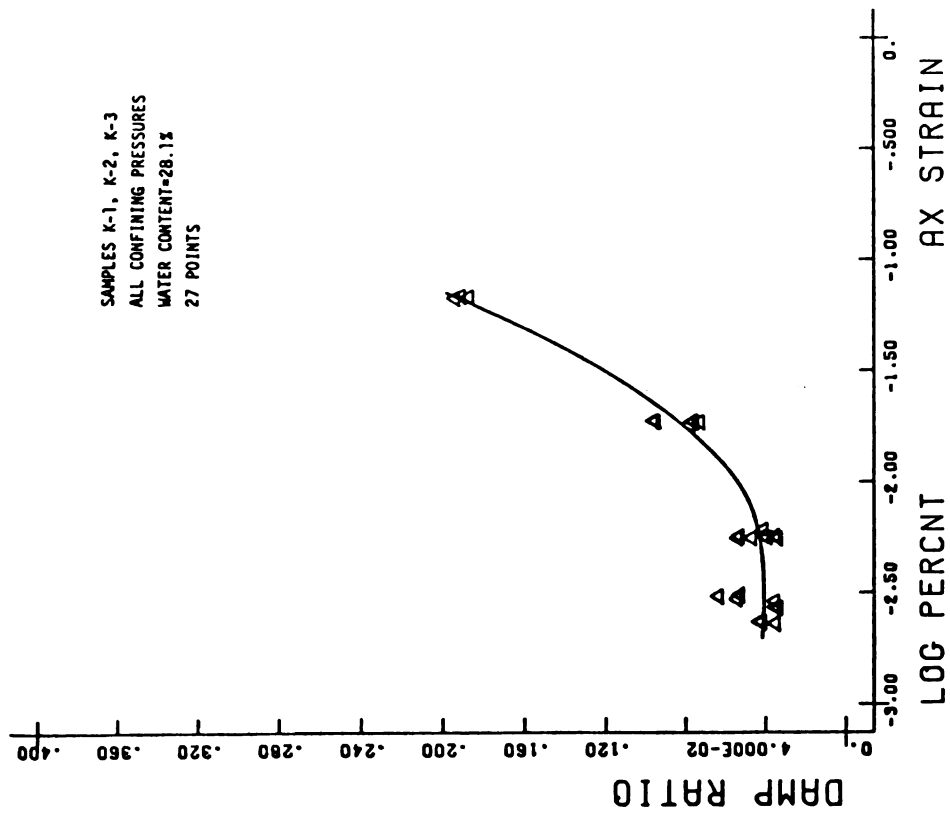


Fig. D-11K-CLAYT-10F05

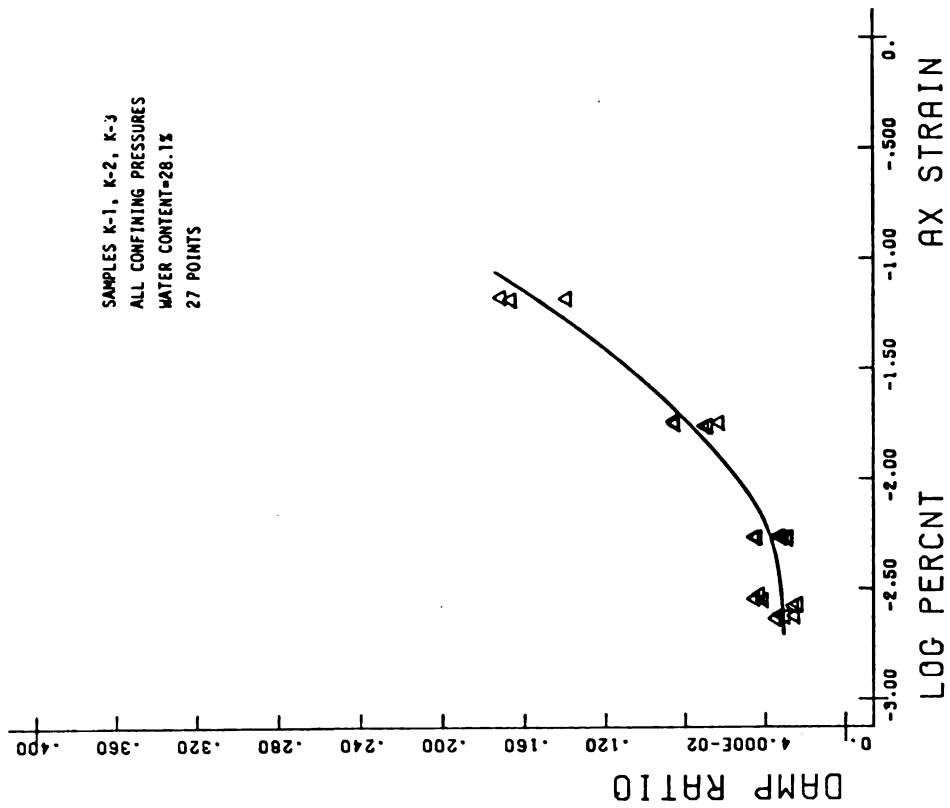


Fig. D-12K-CLAYT-10F3

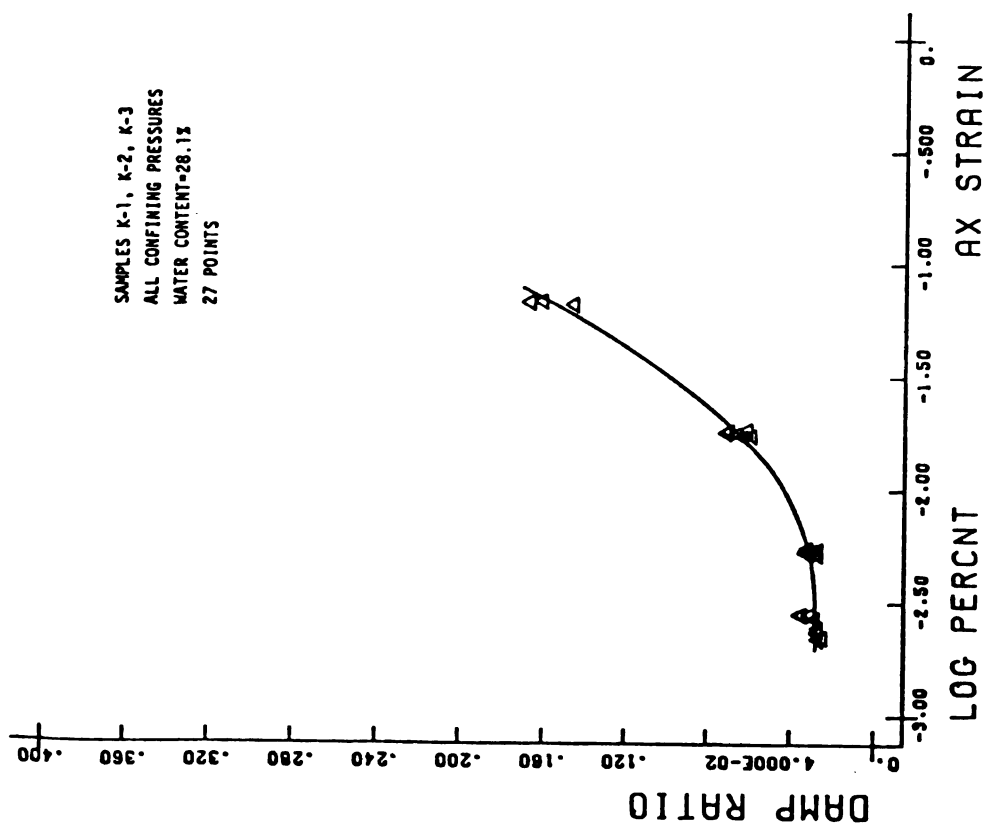


Fig. D-13K-CLAYT-10F1

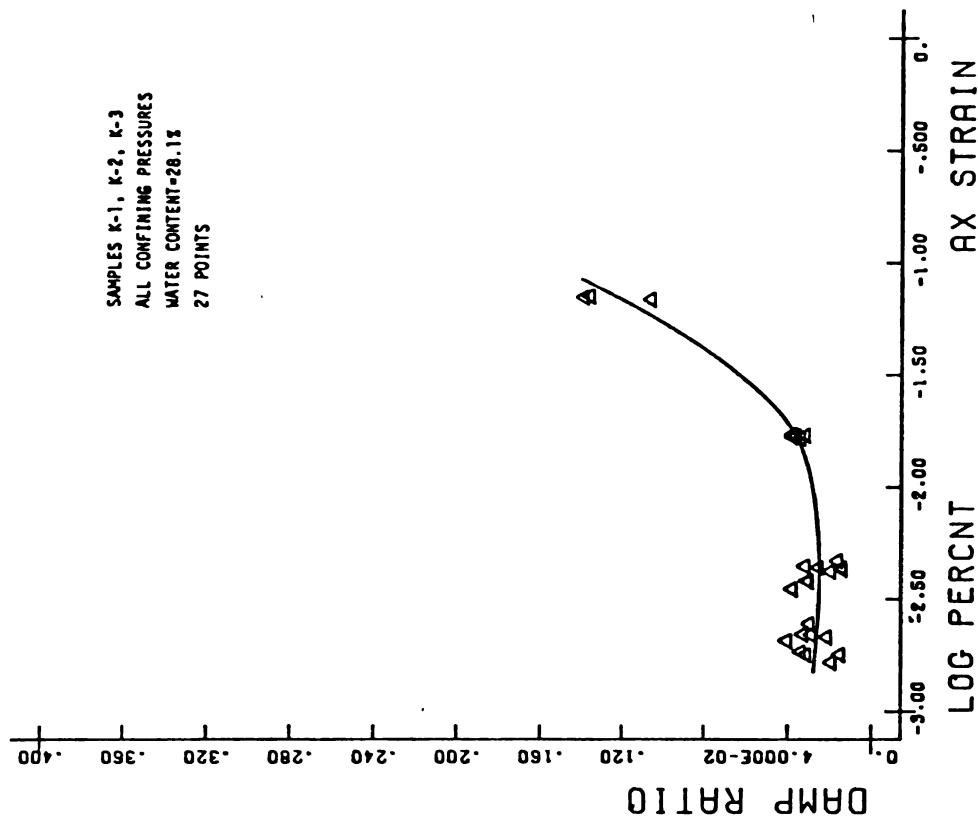


Fig. D-14K-CLAYT-10F5

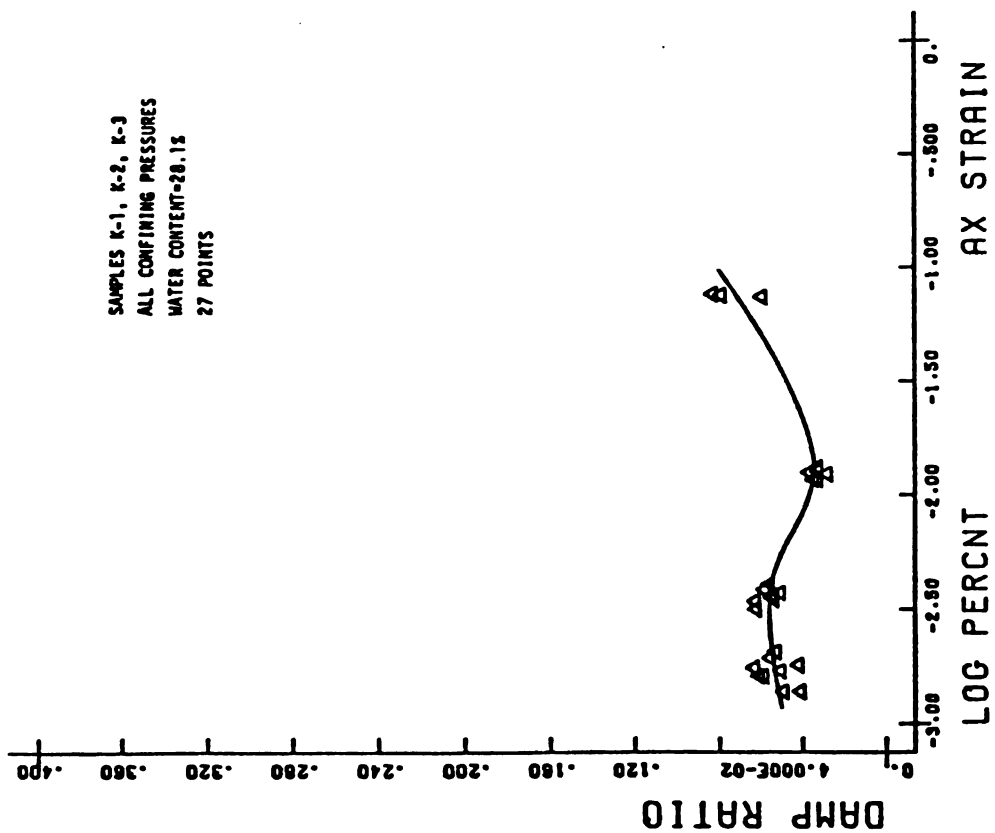


Fig. D-15K-CLAYT-10F10

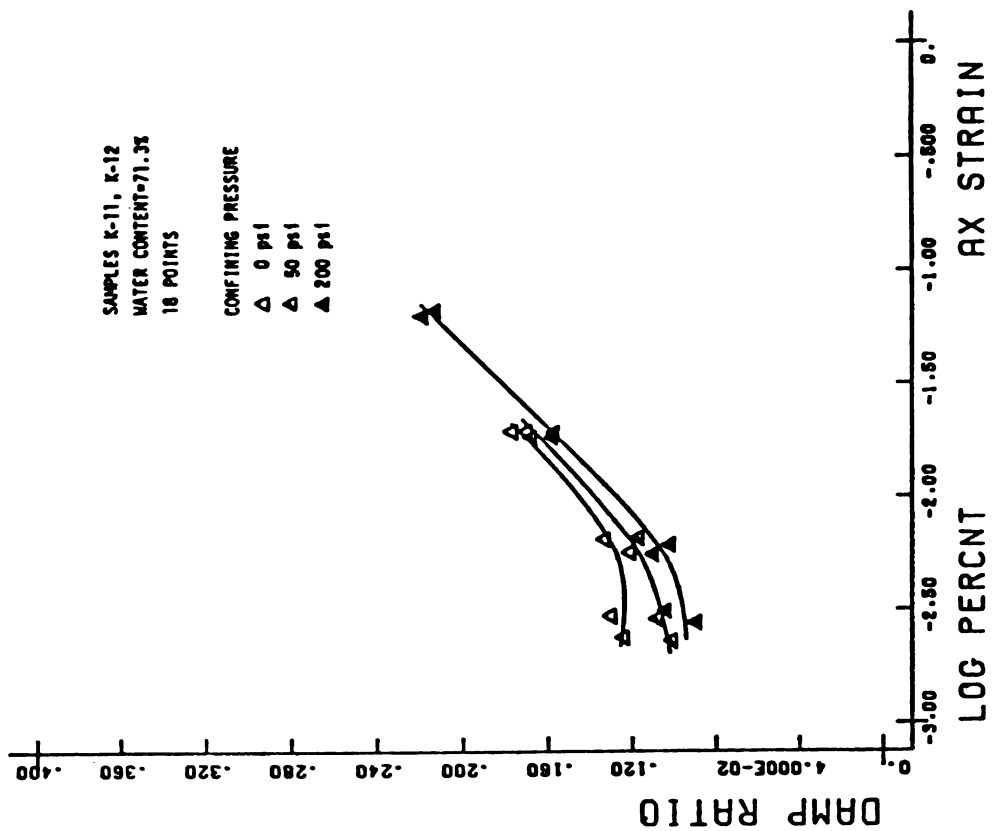


Fig. D-16K-CLAYT-1F05

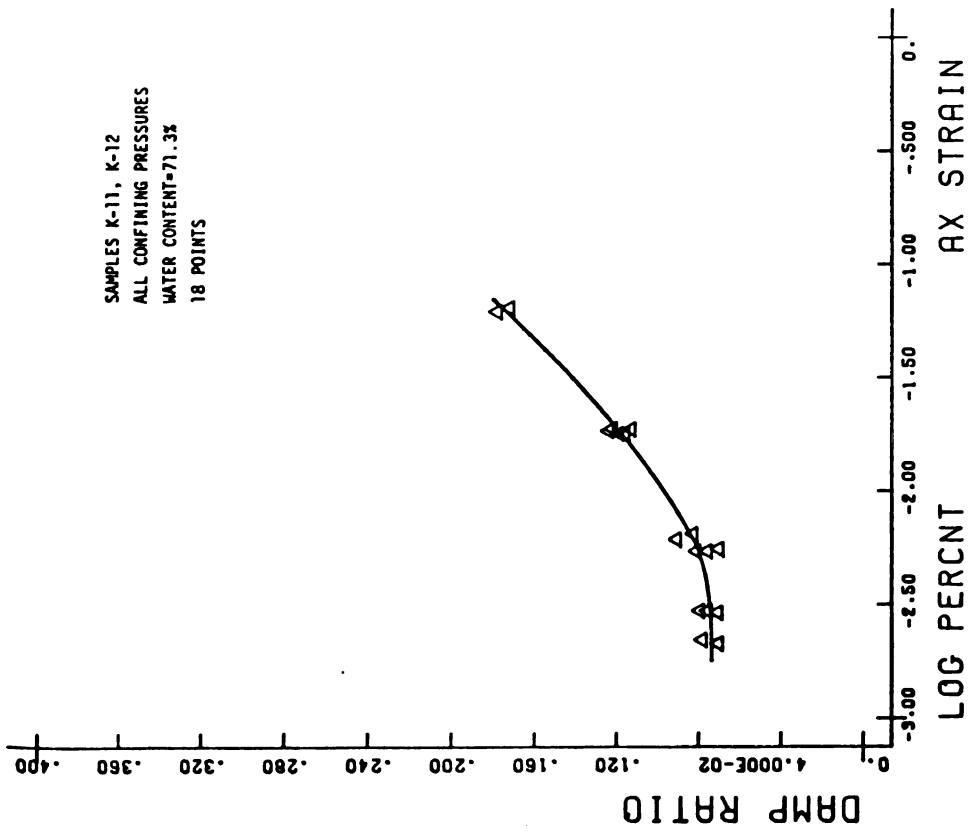


Fig. D-17K-CLAYT-1F.3

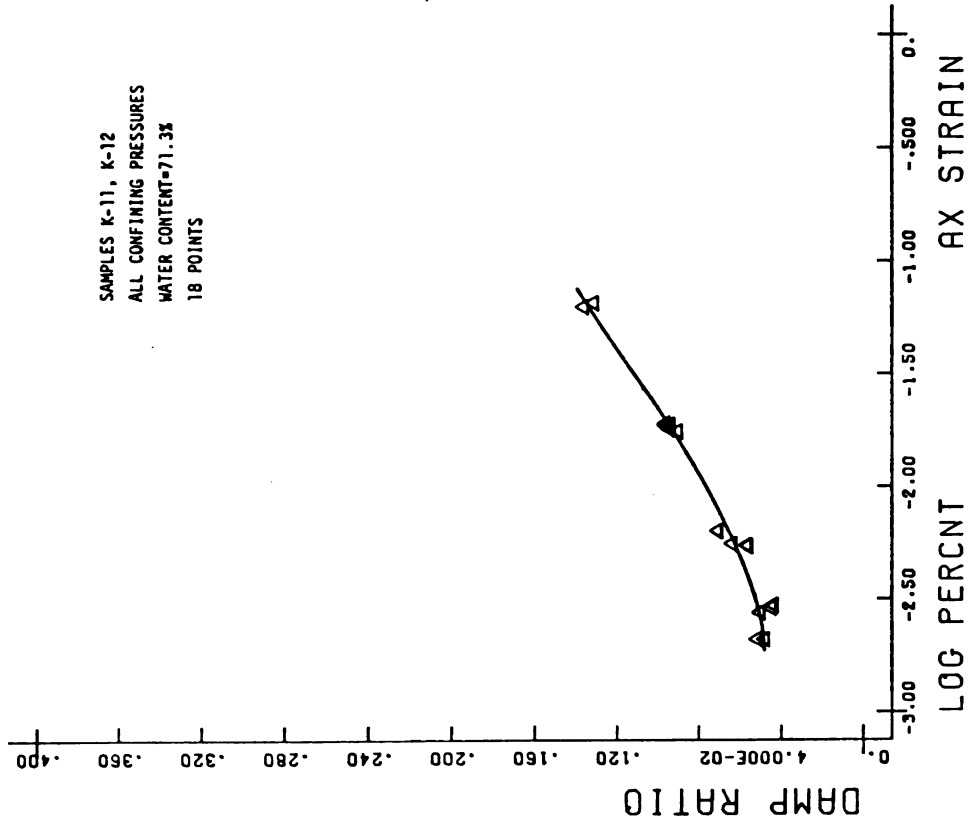


Fig. D-18K-CLAYT-1F1

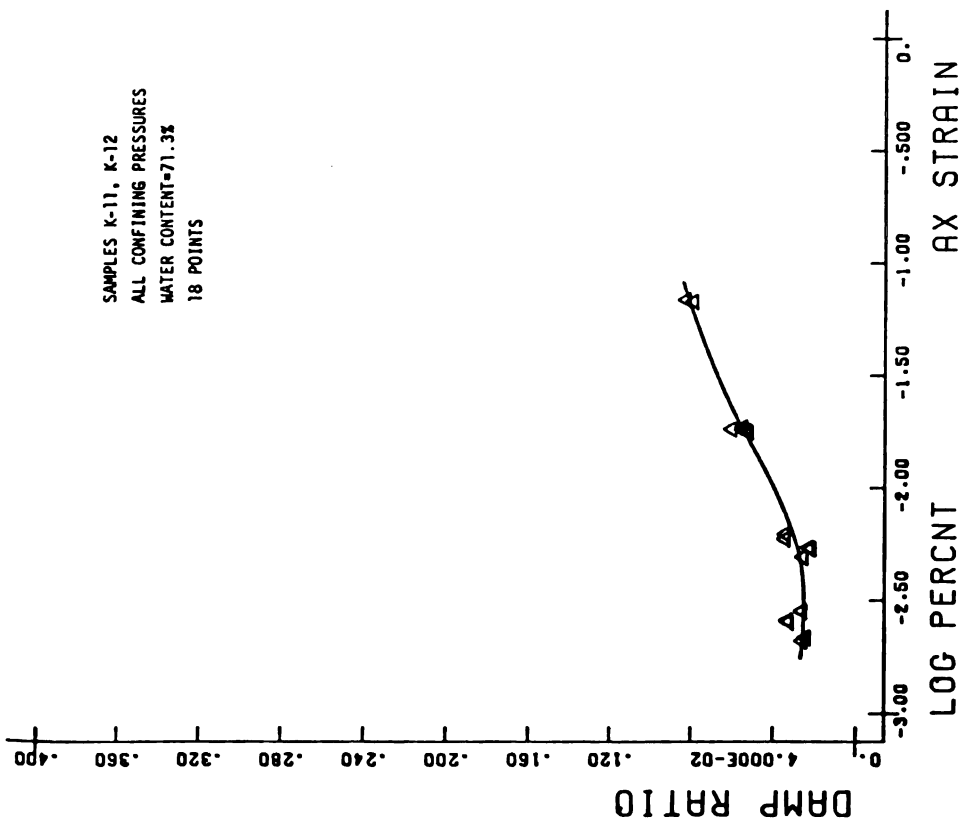


Fig. D-19K-CLAYT-1F5

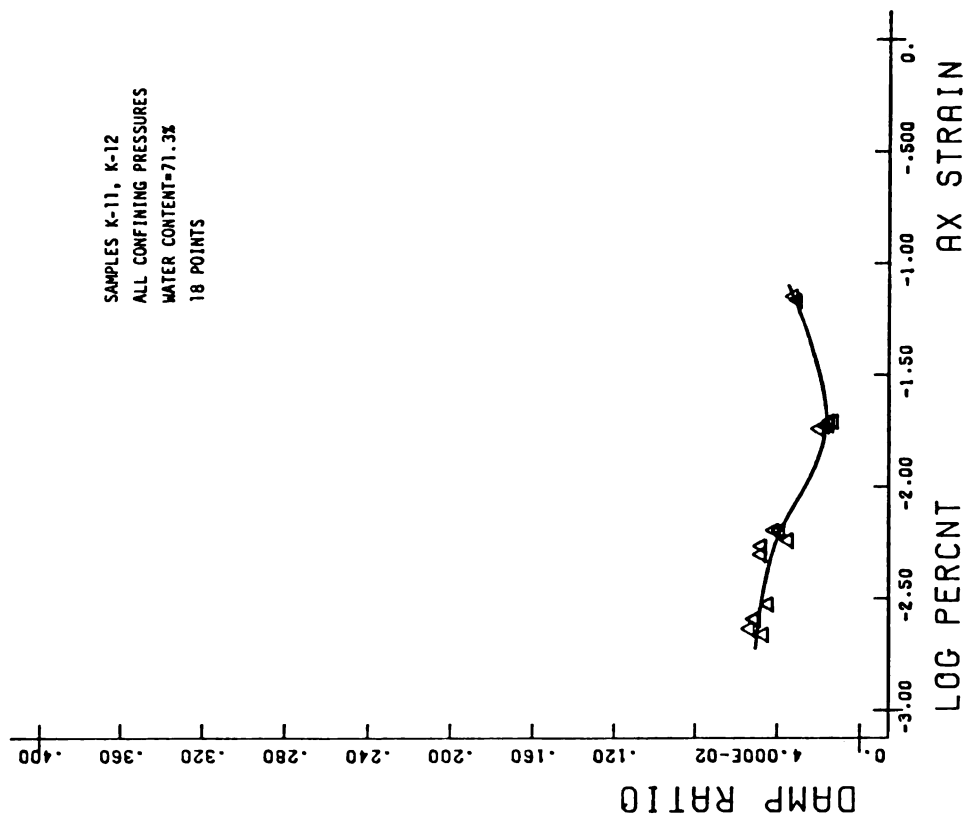


Fig. D-20K-CLAYT-1F10

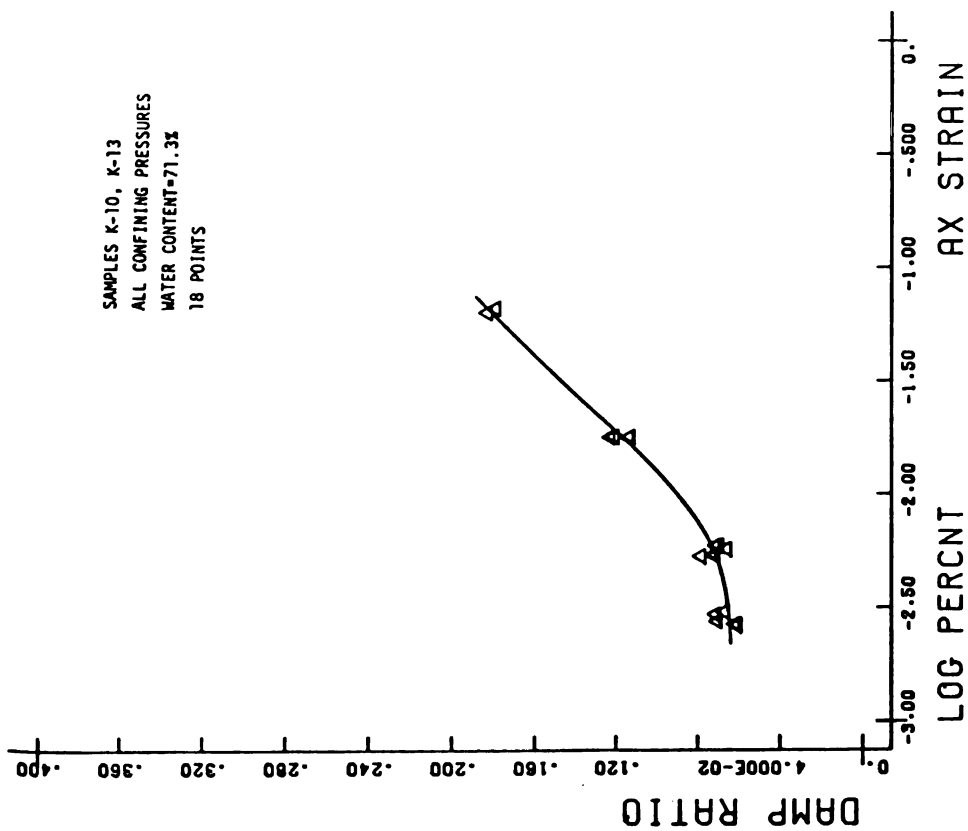


Fig. D-21K-CLAYT-4F.05

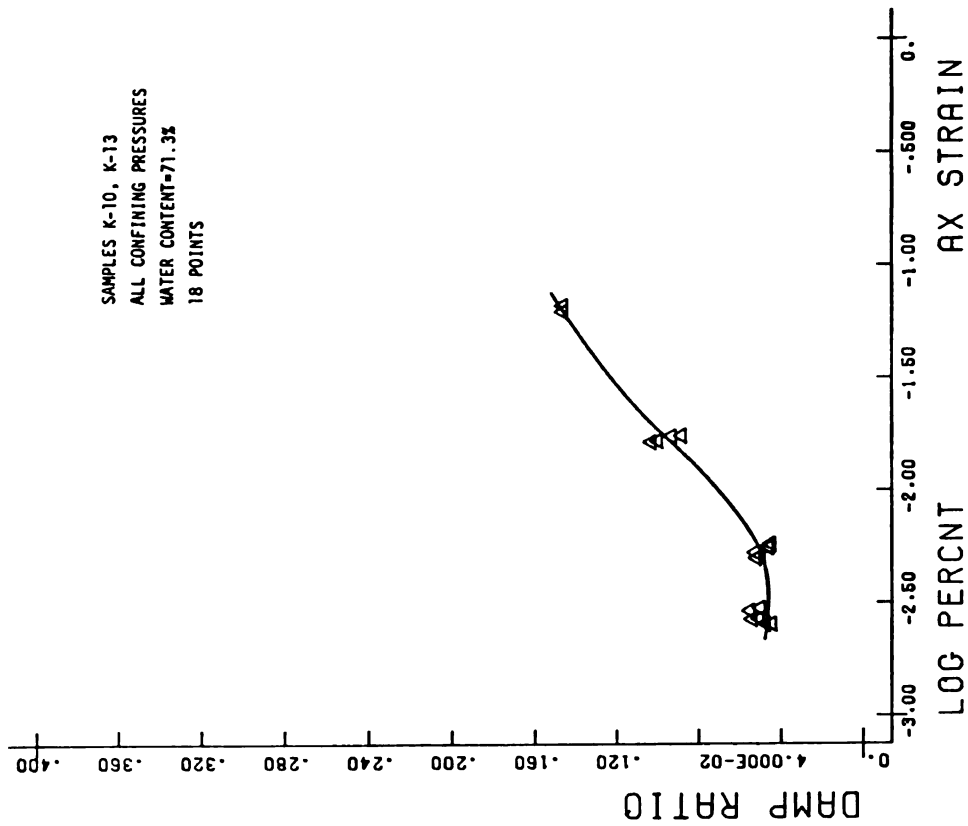


Fig. D-22K-CLAYT-4F.3

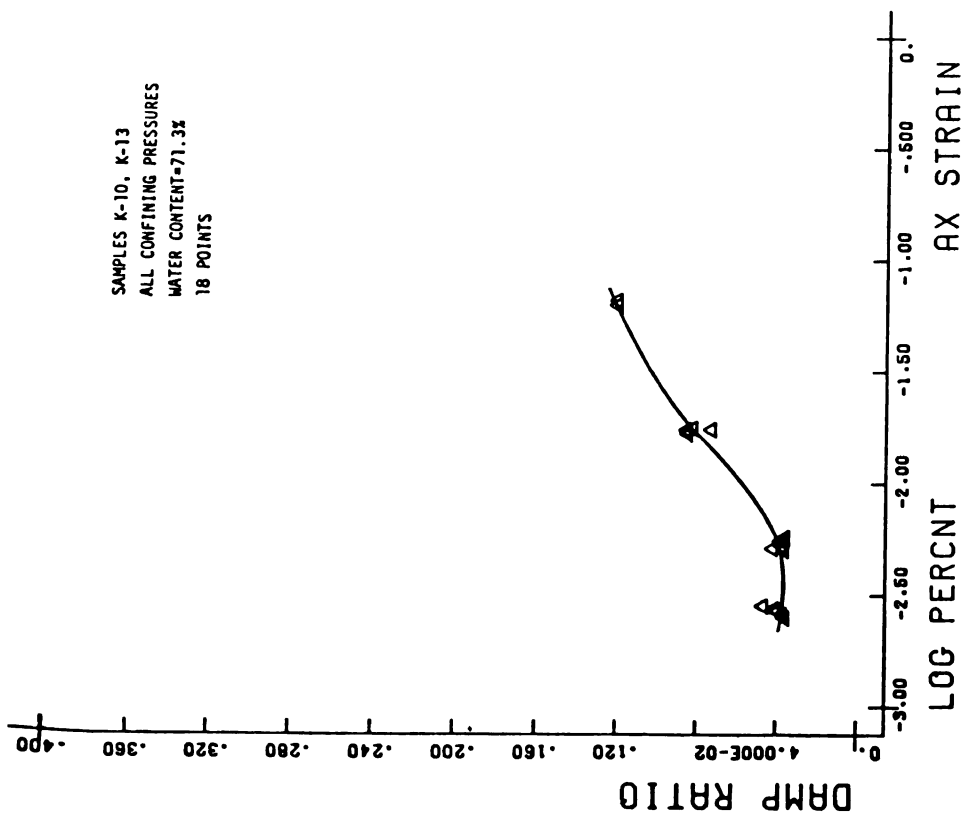


Fig. D-23K-CLAYT-4F1

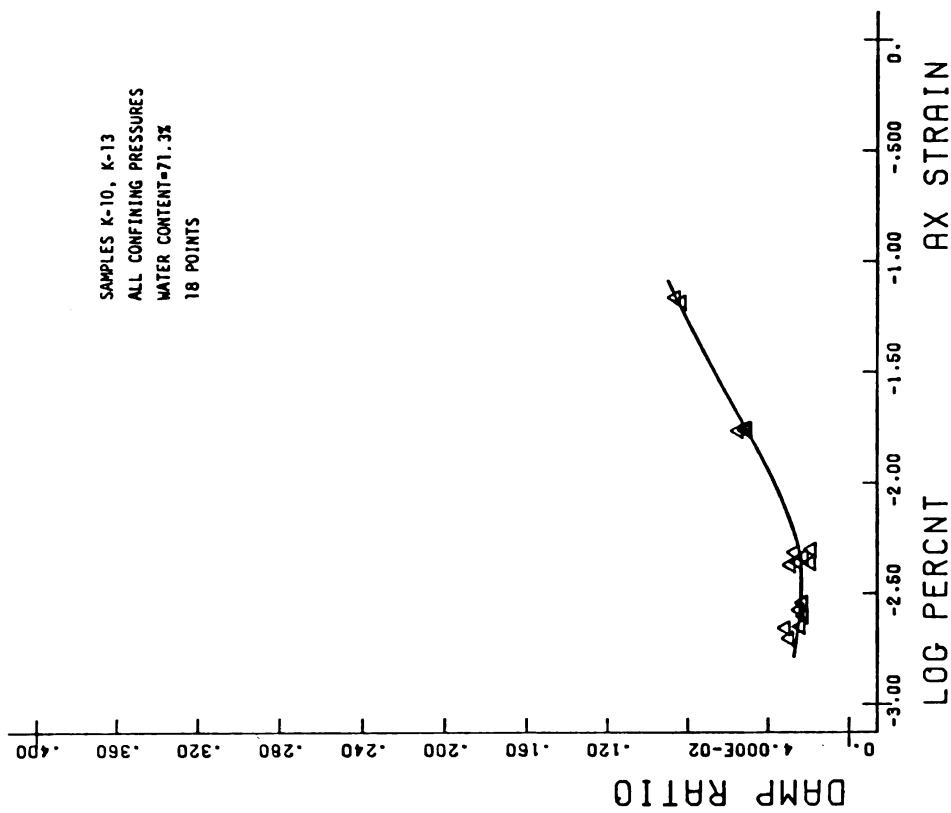


Fig. D-24K-CLAYT-4F5

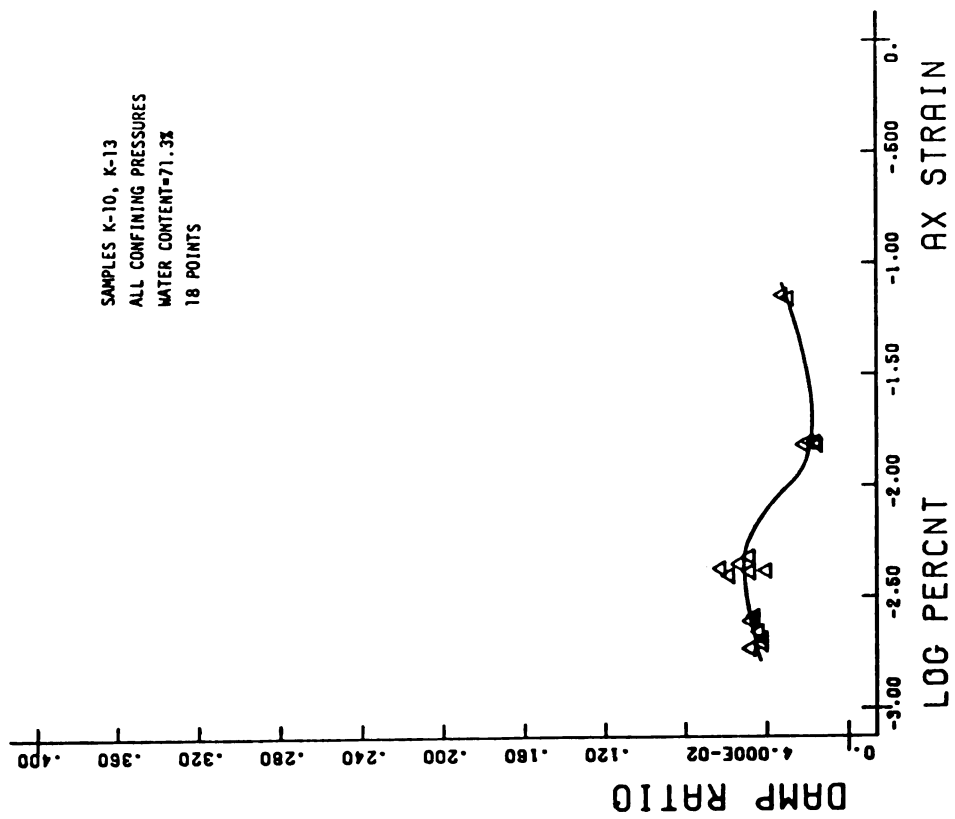


Fig. D-25K-CLAYT-4F10

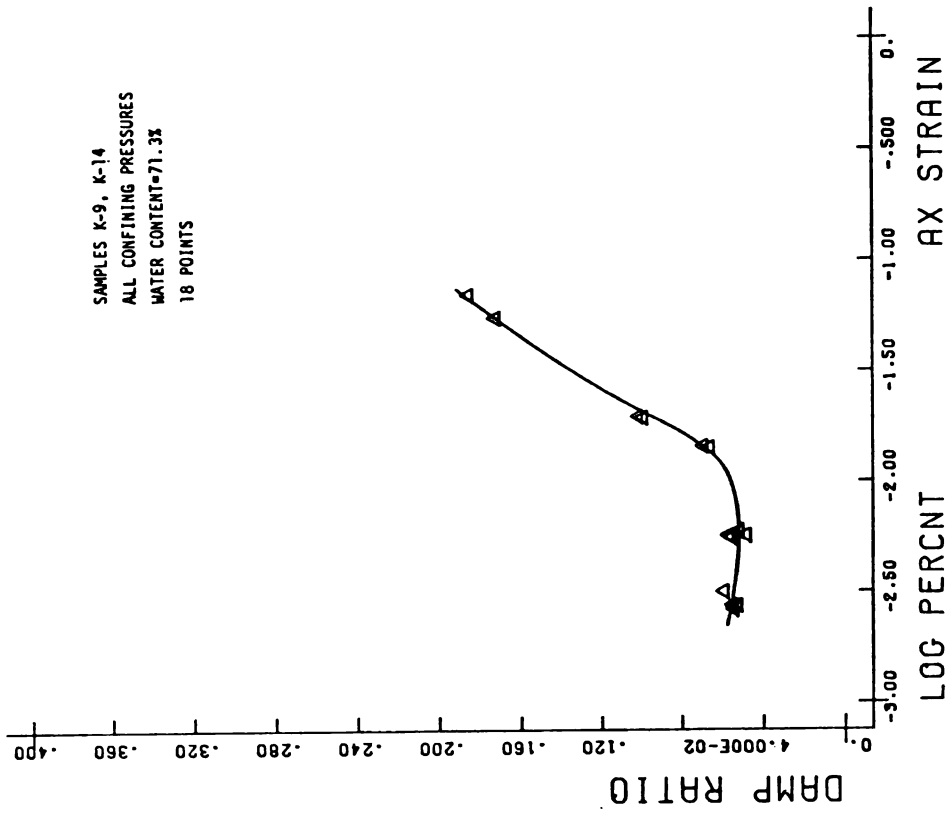


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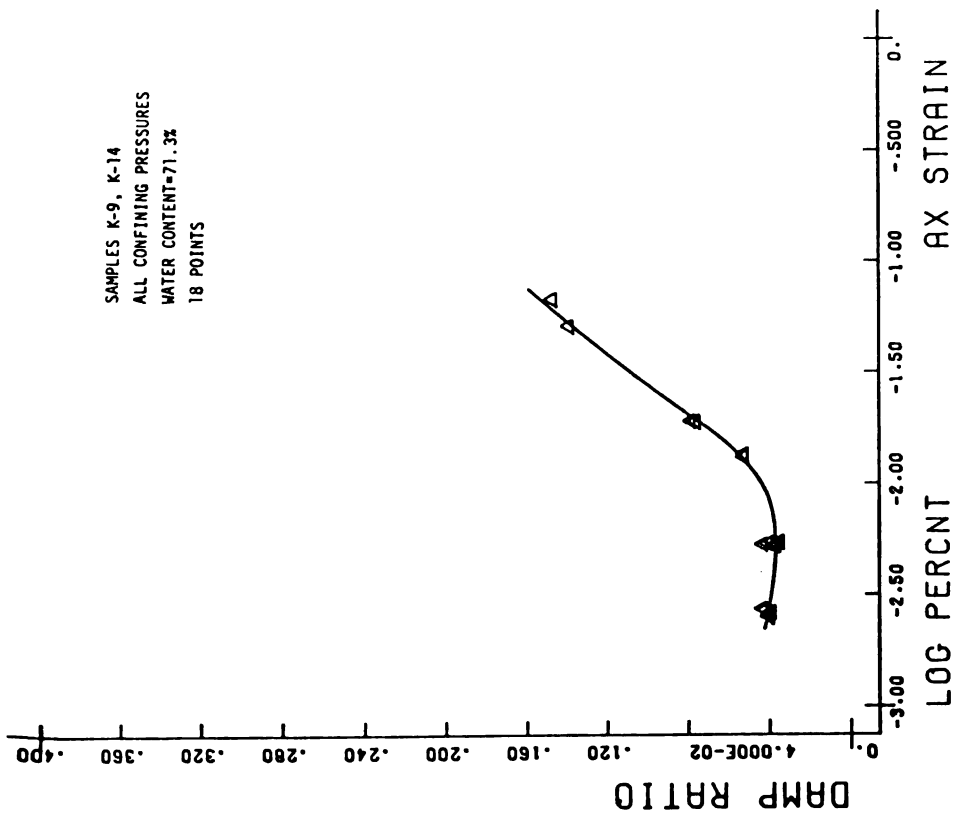


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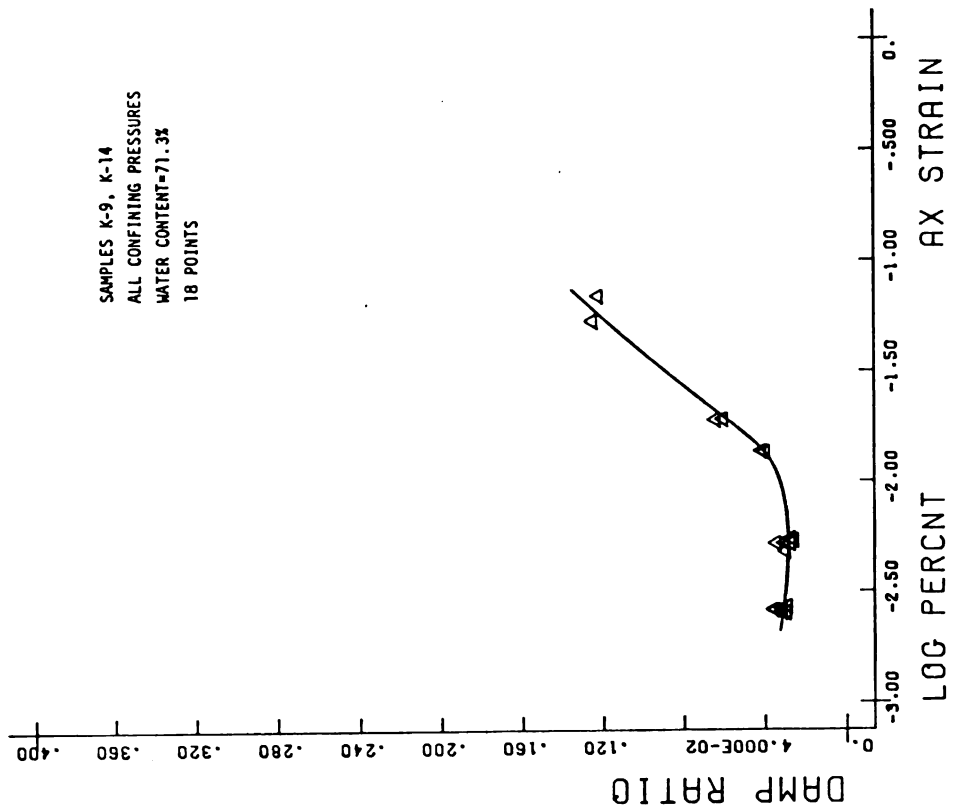


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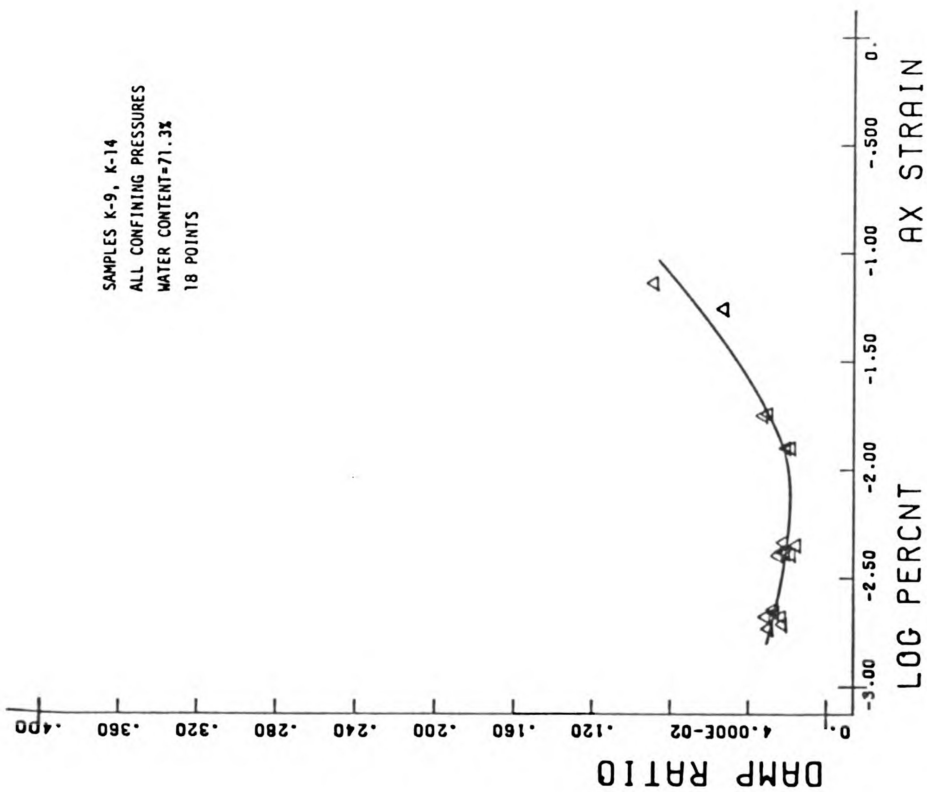


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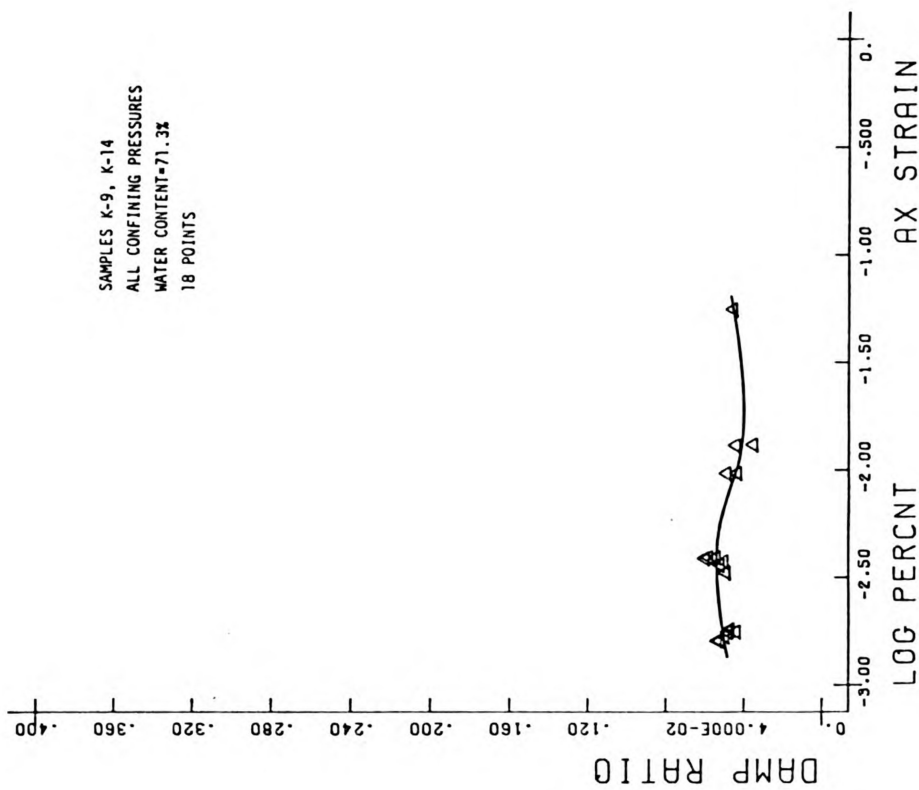


Fig. D-30K-CLAYT-10F10

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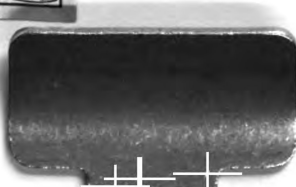
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